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THE ASTRONOMY AND ASTROPHYSICS REVIEW

The most metal-poor galaxies

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Abstract. Metallicity is a key parameter that controls many aspects in the formation and evolution of stars and galaxies. In this review we focus on the metal deficient galaxies, in particular the most metal-poor ones, because they play a crucial rôle in the cosmic scenery. We first set the stage by discussing the difficult problem of defining a global metallicity and how this quantity can be measured for a given galaxy. The mechanisms that control the metallicity in a galaxy are reviewed in detail and involve many aspects of modern astrophysics: galaxy formation and evolution, massive star formation, stellar winds, chemical yields, outflows and inflows etc. Because metallicity roughly scales as the galactic mass, it is among the dwarfs that the most metal-poor galaxies are found. The core of our paper reviews the considerable progress made in our understanding of the properties and the physical processes that are at work in these objects. The question on how they are related and may evolve from one class of objects to another is discussed. While discussing metal-poor galaxies in general, we present a more detailed discussion of a few very metal-poor blue compact dwarf galaxies like IZw18. Although most of what is known relates to our local universe, we show that it pertains to our quest for primeval galaxies and is connected to the question of the origin of structure in the universe. We discuss what do QSO absorption lines and known distant galaxies tell us already? We illustrate the importance of star-forming metal-poor galaxies for the determination of the primordial helium abundance, their use as distance indicator and discuss the possibility to detect nearly metal-free galaxies at high redshift from Lyα emission.

Keywords. Galaxies: abundances – Galaxies: compact – Galaxies: dwarf – Galaxies: Individual (IZw18) – Galaxies: Individual (SBS0335-052) – Galaxies: evolution – Galaxies: formation – Galaxies: ISM – Galaxies: stellar content

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1. Introduction – What is a metal-poor galaxy?

The discovery of extragalactic objects with very low heavy element abundance was made by Searle and Sargent (1972) who reported on the properties of two intriguing galaxies, IZw18 and IIZw40. They emphasised that they could be genuinely young galaxies in the process of formation, because of their extreme metal under-abundance, more than 10 times less than solar, and even more extreme than that of HII regions found in the outskirts of spiral galaxies. At the time of this discovery the general wisdom that most galaxies (in particular the ellipticals) had been formed over a short period during a dynamical free fall time of few 10^7 years (Eggen et al. 1962) started to be challenged (e.g. Searle and Zinn 1978). It is also during the 70s that the first hierarchical models of galaxy formation were constructed (Press and Schechter 1974). Because dwarf galaxies condense from smaller perturbations than giants, the Cold Dark Matter models (CDM) predict that low mass galaxies could still be forming at the present epoch. The discovery by Searle and Sargent (1972) has been an impressive stroke, since one of these two galaxies (IZw18) is still in the book of records, as we shall later elaborate more on. These two objects gave rise to many systematic searches for more objects in a quest for local genuine young galaxies or “unevolved galaxies”, depending upon the alternative viewpoints that some galaxies could be caught in the process of formation or that they simply were the result of a very mild evolution over the Hubble time. These galaxies had the advantage of being gas-rich, with spectra dominated by strong emission lines (see Fig. 6) favouring their detection. Many techniques have been employed to find them, sometimes at large distances despite their intrinsic low luminosity.

The last nearly three decades have brought a wealth of data from numerous studies on dwarf galaxies, including information on their chemical composition. It became clear that “metal-poor” would be analogous of “low mass” galaxies (Lequeux et al. 1979). For this reason, our review will largely focus on dwarf galaxies, but we shall address the question of the existence of large and massive proto-galaxies - essentially devoid of metals - at large redshift in the last section. The dwarf galaxies are not only interesting for understanding the process of galaxy formation. For the gas-rich ones with active star formation, one motivation to study them has been the hope to better understand the processes of massive star formation in low metallicity gas. They turn out to be test cases for chemical evolutionary models and offer the possibility to approach the primordial helium abundance with a minimum of extrapolation to early conditions. Many galaxies of different kinds can be identified as metal-poor and it is an interesting question to find out about the connections that bridge them together. Finally, a lot of new studies concentrate on the impact of massive star formation onto the interstellar matter (ISM) in star-bursting dwarf objects, that in turn can lead to constrain the supernovae rate, initial mass function (IMF), the metal dependence of the winds in Wolf-Rayet (WR) stars etc. In fact there are many issues in astronomy where it is essential to understand dwarf galaxies (actively forming stars or not).

A definition of what is a metal-poor galaxy is indeed necessary at this point. To define the metallicity (Z, i.e. the mass fraction of elements other than hydrogen and helium) of a galaxy requires some words of caution because in a given galaxy, depending on where one looks, this quantity may vary substantially. For example in our Galaxy, the bulge, the solar neighbourhood and the halo differ in metallicity. The most metal-poor halo stars have heavy element abundances 10^{-4} times that of the Sun (Cayrel 1996) while stars in the Galactic centre may be three times more metal rich than the Sun. On the other hand, the large ionised complexes in the ISM show a narrower range down to only 1/10 the solar value. Thus metallicity depends on what one looks at: stars or gas, and if one considers gas – what phase: neutral atomic, molecular or ionised? Moreover the metallicity of stars is found to depend on their age, and depends on which elements are investigated. That a star or nebula is deficient of a certain element does not automatically mean that the overall chemical abundances are low.

Thus, one must be careful in defining what metallicity means for a given galaxy before comparing observations and looking for trends. Another complication stems from the different techniques in use for determining chemical abundances. Metallicities of Local Group dwarf spheroidals (dSph) have largely been investigated through photometry of their resolved stellar populations, which are dominated by old stars, and they are found to be metal-poor, as measured by [Fe/H]. In general dSph galaxies contain little or no gas, and no HII regions. Dwarf irregular (dI) galaxies on the other hand usually have plenty of gas and ongoing star formation as witnessed by the presence of HII regions. It is relatively easy to derive metallicities, especially oxygen (O) of the ionised gas in HII regions explaining why most investigations are based on such. Hence the "metallicity" of dSphs and dIs measures quantities that are not directly comparable. For galaxies which have no HII regions and very low surface brightness, the only available spectroscopic method hitherto, has been to study individual bright stars which are within reach in nearby galaxies only. In more distant galaxies, individual stars are not observable and the metallicity has to be inferred from either absorption line spectra of an integrated stellar population (not necessarily homogeneous in age or composition) or from the nebular emission lines, if any. Again, the different methods in general measure different elements.

So what useful definitions of "metallicity" do we have at hand? The possibility of using the metallicity of the HII regions has the advantage of providing an "up to date" metallicity, while stars provide the metallicity of the cloud from where they were born, perhaps a Hubble time ago. Nebular abundances show large spatial abundance variations and gradients in some galaxies, e.g. giant spiral galaxies, like the Milky Way. Although measurable abundance inhomogeneities could be expected, most dwarf galaxies seem rather well mixed. A possible problem with metal-poor HII regions is self-pollution of fresh metals by winds from young massive stars, so that the abundance inferred from the nebular emission lines may not be representative of that in the local ISM (Kunth & Sargent 1986). On the other hand, the metallicity of the stars in a galaxy depends on which stellar population is studied. Thus it is not surprising, in particular for galaxies which have experienced continuous star formation, that stars have different abundances. Integrated spectra of galaxies provide a luminosity-weighted average of the metallicity. This average metallicity will change with time due to the photometric evolution of the stellar population, even if no new stars are formed.

A good, well defined, metallicity indicator would be the fraction of baryonic matter that has been converted into heavier elements by means of stellar nucleosynthesis. This material may have been returned to the ISM or may still be locked up in stars. Such a definition would indicate that our main interest goes beyond the element abundances themselves from the fact that they provide information about the history of a galaxy. The relative abundances and gas mass fractions might unveil different histories among galaxies with the same metallicities. However, it is clear from he above discussion that such a definition of metallicity remains impractical, since not directly measurable. However, we would like to keep this ideal definition in mind for the rest of the discussion.

Now we wish to go back to the question – What is a metal-poor galaxy? Under the assumption that various tracers give a plausible picture about the "ideal metallicity" we can now try to compare different kinds of galaxies. One of the most fundamental parameters for a galaxy is of course its mass. This mass, which may consist of stars, gas, dust, baryonic- and non-baryonic dark matter, is more difficult to measure, than e.g. the luminosity, but to the first approximation, mass and luminosity correlate. Based on their luminosity and size, galaxies can be divided into dwarfs and giants. It has been found that the metallicity of a galaxy in the local Universe correlates positively with its luminosity (although with a large scatter), thus also reflecting a positive correlation with mass. The reason for this behaviour is a fundamental issue to understand. One explanation could be that dwarfs evolve more slowly because of smaller mass densities, which to the first order fits with the observation that dwarfs, except dwarf elliptical/spheroidals, are more gas-rich than giants. Another possible explanation is that dwarfs have weaker gravitational potentials hence are more susceptible to loose metal enriched material from supernova driven winds.

A natural reference for element abundances and the ratio between them, could be the Sun. Thus a starting point could be that "metal-poor" means anything which has sub-solar abundances and vice versa for "metal rich", which implies that basically all local galaxies fainter than our Galaxy are metal-poor. High redshift neutral gas clouds, which may be the building blocks of today's galaxies, are observed to have metallicities down to $0.001Z_{\odot}$. Thus, there is a large range of metallicity to explore, and it is meaningful to distinguish between metal-poor, very metal-poor and extremely metal-poor. Since this review is called "the most metal-poor galaxies" it is natural that we focus on the latter two subclasses. What do we see locally? Among dSph we find metallicities extending down to 1/100 $Z_{\odot}$, while the LMC and SMC are at roughly 1/3 $Z_{\odot}$ and 1/8 $Z_{\odot}$ respectively. Dwarf irregulars have sub-solar abundances, ranging down to 1/40 $Z_{\odot}$. In addition there are many blue compact galaxies (BCGs) in the range 1/10 to 1/50 $Z_{\odot}$, with, as we shall show later, IZw18 at the extreme.

A more workable definition could use the minimum enrichment one predicts for a single burst of star formation, using the instantaneous recycling closed box model. Kunth and Sargent (1986) found that such minimal expected metallicity increment in a pristine HII region would be higher than or equal to the metallicity of IZw18. Similarly one finds that even converting only on the order of two percent of pristine gas in a galaxy to stars, results in a metallicity of 1/50 $Z_\odot$, i.e. the metallicity of IZw18. There are of course a lot of uncertainties that go into these calculations, but they can be a useful guide. Another, more practical guide, is to consider the O/H distribution of star forming dwarf galaxies studied over the last 30 years. This shows a peak around 1/10 $Z_\odot$ and drops sharply below that value. Moreover, for most models: of stellar winds, evolutionary tracks, WR-stars, star formation etc., a critical dependence on metallicity is seen around 1/10 $Z_\odot$. This is why we have adopted throughout this review the working hypothesis that galaxies with metallicity below 1/10 $Z_\odot$ will be considered as very metal deficient. Therefore galaxies like the Magellanic clouds will not be our main interest in this paper. Moreover, such a limit means that this review will be biased towards dwarf galaxies. In particular we will focus on blue compact galaxies (BCGs). The reason is partly due to selection effects: since blue compact galaxies have bright emission lines and high surface brightness, it is fairly easy to discover them and derive their metal content. Thus, there exists a lot of high quality data on BCGs, but we should keep in mind that very metal-poor galaxies may be as common among other types of dwarf galaxies.

Metallicities can be studied at great distances under special conditions. Observations of high redshift QSOs and radio galaxies (e.g. Dunlop et al. 1994), reveal the presence of dust and metal rich gas, suggesting that prior stellar nucleosynthesis has already taken place. High redshift QSO absorption line systems show a wide range of metallicities, from one thousandth solar up to 1/3 solar. Thus, while the average metallicity of the Universe certainly must have increased since the early epochs, the situation is more complex than a simple picture where high redshift means metal-poor, and low redshift metal-rich. Objects with high and low metallicities are found at all redshifts. Surely we expect objects that in the local Universe appear as metal deficient to be even more deficient at high redshift, if we could observe their precursors. Also the ancestors of the local metal rich galaxy population, i.e. the giant spirals and ellipticals, should have started out with very low abundances unless they were gradually built up by merging smaller galaxies. Currently, both the theoretical and observational pictures suggest that the latter is an important mechanism. Dwarf galaxies, the survivors who form the local metal-poor galaxy population, may thus be the principal building blocks of the Universe on large scales.

The structure of the rest of paper is as follows: In Sect. 2 we discuss how metallicities are measured and in Sect. 3 the physical mechanisms that control the metallicity of a galaxy. In Sect. 4 we review the physics of metal-poor galaxies in the local Universe, while in Sect. 5 turning to some key objects like IZw18. In Sect. 6 we discuss survey techniques, and the distribution in space and luminosity of metal-poor galaxies. In Sect. 7 we examine observed trends in the metal-poor galaxy population and various possible evolutionary links. In Sect. 8 we focus on cosmology and the high redshift Universe, and in Sect. 9 we conclude.

Throughout this paper we adopt 12+log(O/H)=8.91 as the solar oxygen abundance. As customary, element ratios given in square brackets represent logarithmic values with respect to solar values, e.g. [Fe/H] = log(Fe/H) $-$ log(Fe/H)$_\odot$. We use H_0 = 75km/s/Mpc, and rescale results from the literature based on other values of H_0 when necessary. A list of commonly used abbreviations and acronyms are given at the end of the paper.

2. How are metallicities measured?

Below we list the main ways that have been used to derive metallicities for metal-poor galaxies. One has to be aware that these different abundance estimators sample not only different elements, but also look-back times and population mixes.

*2.1. H*II *regions*

Abundances are relatively easy to measure in star-forming dwarf galaxies because they contain gas clouds in which large numbers of hot stars are embedded. Their spectra are dominated by nebular emission lines similar to those of high-excitation giant HII regions in late type spiral galaxies. What is observed in the optical are narrow emission lines superimposed on a blue stellar continuum (see Fig 6.). They are identified as helium and hydrogen recombination lines and several forbidden lines. Methods used in determining abundances are well understood and generally more reliable than those based on stellar absorption line data because transfer problems become of minor importance. From the optical, O, N, S, Ne, Ar and He lines are currently measured. With modern detectors fainter lines such as lines of Fe have been studied (Izotov and Thuan, 1999). The ultraviolet (UV) region is dominated by the hot stellar continuum and shows relatively weak emission lines except for those that originate in stellar winds. However there are a few notable exceptions and owing to the International Ultraviolet Explorer (IUE) and more recently the Hubble Space Telescope (HST) nebular carbon and silicon abundances have been determined.

Oxygen is the most reliably determined element, since the most important ionisation stages can all be observed. Moreover the [OIII]λ4363 line allows an accurate determination of the electron temperature. The intrinsic uncertainty in this method (reflecting a simplified conception of the HII region physics, possible problems with temperature fluctuations etc.) is of the order of $\sim$0.1 dex (Pagel 1997). Furthermore, when the electron temperature cannot be determined, empirical relations (cf. Pagel 1997) between the oxygen abundance and the [OII]λ3727 and [OIII]$\lambda\lambda$4959, 5007 strength relative to Hβ are used, though with lower accuracy (0.2 dex or worse). For other species, in general, one does not observe all the ionisation stages expected to be present in the photoionisation region and an ionisation correction factor must be applied to derive the total abundance of the element in question.

One important aspect of HII region abundances is that they can be obtained also at great distances. This makes them powerful tools also for studying high redshift galaxies, with the price that our view will be biased towards actively star-forming systems. For a discussion on possible problems associated with deriving abundances in very distant galaxies, see Kobulnicky et al. (1999).

2.2. Planetary nebulae

Planetary nebulae (PNe) enable a spectroscopic abundance determination, using the same technique as for HII regions. The intrinsic uncertainty due to temperature fluctuations (Peimbert 1967) and gradients is probably at least 0.1 dex (Pagel 1997). The derived oxygen abundances reflect the initial composition of the star since the ejected gas that forms the PN has not been enriched in oxygen by the central nucleosynthesis (however see remark below) and that moreover, the hot ejecta has not mixed with the surrounding colder ISM. The progenitor stars of PNe have masses up to several times that of the Sun, meaning that the derived O abundance traces the ISM abundance 0.1 to several Gyr ago, depending on the mass of the progenitor. This is a large range in lookback time over which significant chemical evolution may have occurred, and thus it is important to assess the mass of the progenitor star. A model that relates the oxygen abundance as derived from PNe and HII regions (i.e. the present ISM abundance) has been presented by Richer et al. (1997). They find that the abundance gap, the difference between these two abundance estimators, is a function of the star formation history and metallicity. The more extended the epoch of star formation has been and the higher the ISM metallicity, the larger the abundance gap.

While the PNe abundances of oxygen traces the ISM abundance at the birth of the progenitor star, this is not true for carbon and nitrogen which have been enriched during the stellar evolution (Pagel 1997, p. 199). Moreover for some types (PNe type I, cf. Peimbert and Serrano 1980) there might have been also enrichment of oxygen.

2.3. Photometry of resolved stellar populations

Colour-magnitude diagrams (CMDs) provide a photometric estimate of the stellar abundances, usually assumed to be represented by iron, from the colour of the red giant branch (RGB). Stars more massive than approximately 2 solar masses never ascend it and thus stars on the RGB have ages from approximately 1 to 15 Gyr, and their abundance reflects the ISM abundance of Fe when the stars were born. The width of the RGB provides a measure of the metallicity spread, of course convolved with the broadening from age dispersion and the photometric error function (see e.g. Lee et al. 1993).

The calibration of this method rests upon the comparison of the RGBs with those of old Galactic globular clusters with metallicity estimated from integrated spectroscopy or spectroscopy of individual giant stars (see Da Costa and Armandroff 1990). Therefore the RGB colour of an old population measures an average metallicity and is unable to reveal abundance ratios. Moreover, comparison with old Galactic globular clusters rests upon some degree of similarity between the two kinds of objects. However since it is now evident that the bulk of the stellar population in many dEs is younger than that of Galactic globular clusters, and has a considerable abundance spread, one must be aware that physically different properties of globular clusters and galaxies may possibly cause systematic errors.

Other metallicity indicators include the colour and morphology of the horizontal branch (HB) in the CMD (Grebel 1998), although this cannot be uniquely translated into metallicities due to poorly understood “second parameter effects”, also known from the study of HBs in globular clusters. Intermediate in character between photometric and spectroscopic abundance determinations is the fraction of carbon (C) stars among the late type giants, and the number of carbon rich (WC) to nitrogen rich (WN) Wolf-Rayet (WR) stars. Such indicators give only very crude guesses of the the metallicity. Moreover, each population sample stellar populations of different age and are not directly comparable.

A major drawback in using CMDs for abundance determinations is that it is limited to nearby galaxies, basically the Local Group and its immediate surroundings. Photometric abundances can also be derived using Strömgren photometry. However the relatively narrow filters employed, limit the usefulness of Strömgren photometry for extragalactic objects, a situation that could change with the new generation of large telescopes. There are also other photometric systems designed for metallicity sensitivity, e.g. the intermediate wide Washington system.

2.4. Stellar spectroscopy

In the nearest galaxies it is possible to spectroscopically determine the abundances of individual stars. While this method should yield accurate abundance determinations, it is not directly translatable into global values, since there are star to star variations and poor statistics; in practice, only few stars, and in general the most luminous, can be observed for each galaxy. The Magellanic Clouds have been accessible since more than a decade (Spite et al. 1986; Russell and Bessell 1989; see also Haser et al. 1998) as well as the most nearby dwarf satellites of the Milky Way with present instrumentation (e.g. Shetrone et al. 1998). Spectroscopic observations of young metal-poor stars would also be of great importance for improving models of stellar evolution and population synthesis.

With the new generation of 8m class telescopes, the distance to which individual luminous stars can be studied has been increased, and it is now possible to reach outside the Local Group. An outline of the merits of spectroscopy of luminous early type stars and on some work in progress can be found in Kudritzki (1998). In the near future the situation will change when 8m class telescopes are equipped with spectrographs that allow observations of many stars simultaneously with sufficient spectral resolution.

2.5. Estimates from spectroscopy and photometry of integrated light

In remote galaxies without HII regions, integrated spectroscopy may be used to derive metal abundances. This method have been widely employed e.g. for giant ellipticals. Absorption line features, such as the Mg_2 band, are compared to populations of observed or model stars to estimate metallicities (cf. Mould 1978; Worthey 1994). This method is difficult to use since the interplay between stellar population mixes, star formation history and stellar initial mass function (IMF), which influences the spectral shape and the absorption line strengths, is not known a priori; and it has turned out to be non trivial to transform the observed Mg_2 strengths into metallicity. In addition, there are indications of nonsolar [Mg/Fe] values (e.g. Worthey et al. 1992). Since, in general, the surface brightnesses of dwarf galaxies decrease with decreasing luminosity, even integrated spectroscopy is difficult and time consuming, and practically impossible for the really faint dwarfs.

Integrated photometry is a poor-man's tool. When no spectroscopic information may be obtained and the galaxy is too distant to resolve the stellar population, some constraints may be put on the metallicity (cf. Sect. 4.2.2) from integrated photometry under certain assumptions. However, as for the case of integrated spectroscopy (but to a much greater extent), the assumed population mix, star formation history, IMF, internal extinction etc., influence the broad-band colours and make the derived metallicity very uncertain. The infamous age–metallicity degeneracy is here acting in its full power. If some of these parameters can be constrained, this method may be used in a statistical sense for large samples.

2.6. Other methods

Another possible metallicity indicator is that of the cold (neutral) ISM in a galaxy, where problems with self pollution should be small or absent. By using background continuum sources, absorption lines from the neutral ISM may be used to estimate chemical abundances. Kunth et al. (1994) used UV-absorption lines arising in the neutral gas in the line of sight towards the young stellar association in IZw18 to derive oxygen abundances of the gaseous halo of IZw18. The method is similar to the one used for deriving abundances in QSO absorption line system. This method is rather unexplored for galaxies, but may prove to be of future use if the difficulties due to line saturation can be tackled or circumvented (Pettini and Lipman 1995)

X-ray observations have been used to derive metallicity of the hot intra cluster medium in rich galaxy clusters, and has recently been applied also to starburst galaxies (Persic et al. 1998). X-ray observations are interesting because they may provide a means of observing "hot" metals produced in the current star formation event that have not yet mixed with the photoionised gas, and to study abundances in gas expelled by "superwinds".

In principle, abundances may be derived also from radio observations. This has been done in the local ISM in our galaxy. For external galaxies they have not been applied much due to sensitivity problems. CO observations of dwarf galaxies are complicated by the fact that for low metallicities the CO flux depends both on the mass and metallicity of the molecular gas complex. These questions may be further addressed by space based infrared spectroscopy.

The chemical composition of the ISM has been studied in the ultraviolet (UV) with e.g. the IUE and HST satellite observatories. A relatively unexplored wavelength region is however the far UV. New space borne instruments like FUSE (far ultraviolet spectroscopic explorer) may be of importance here. Other methods include observations of supernova remnants (see Pagel 1997) and the concept of dynamical metallicity, cf. Haser et al. (1998).

3. What controls the metallicity of a galaxy?

Here we will discuss some mechanisms of importance for understanding why some galaxies are more metal-poor than others. It is unavoidable that this will include a discussion on nucleosynthesis and chemical evolution models, however this is not the main scope of this paper and excellent reviews can be found elsewhere, e.g. Pagel (1997), Matteucci (1996), Maeder (1992), Prantzos (1998).

3.1. Stellar evolution and nucleosynthesis

As the IGM condenses into galaxies it contains the primordial abundances of H, D, ^{3}He, ^{4}He and ^{7}Li. One of the beauties of some star-forming dwarf galaxies is that they can be so metal-poor that their abundance analysis bear strong cosmological implications. The current wisdom is that most of the element production in the Universe, apart from the early "Big Bang" nucleosynthesis, occurs in stellar interiors. Part of the products of stellar nucleosynthesis are released when stars die or in stellar winds from evolved stars, while another part remains locked up in stellar remnants: white dwarfs, neutron stars and black holes. These remnants may not be completely sterile since in a binary system, accretion onto a white dwarf may lead to a type Ia supernova.

The end products that enrich the ISM can be predicted from models of stellar evolution and nucleosynthesis. The returned mass in metals as a function of the initial mass is referred to as the stellar yield (Maeder 1992). The absolute and relative yield for different elements depend on stellar mass in a non-linear fashion. Moreover, the yields for the so called “secondary” elements depend themselves on the initial composition of the star. An example is ^{14}N, although observations strongly indicate the need also for primary production. Furthermore the mass-loss history of stars needs to be accounted for, since elements that would have been subject to further nucleosynthesis might have been ejected, and also the effects of stellar binarity. Unfortunately, the yields for many elements are still very uncertain, also for important elements like C and N (Prantzos, 1998), and this has to be kept in mind when interpreting abundances and abundance ratios. The oxygen yield is among the best determined ones, still the uncertainty is around a factor of two.

Low mass stars ($M < 1 M_\odot$) are long lived and simply lock up part of the gas, since their lifetimes are longer than or comparable to the age of the Universe. On the other hand they contribute to light and have imprinted in their chemical composition the conditions of the ISM at the time and place they were formed. Intermediate mass stars (between 1 and 8 $M_\odot$) undergo dredge-up processes that significantly affect the C and N abundances and even the ^{4}He abundance, and such stars are important contributors to these elements. Massive stars ($M > 8 M_\odot$) are short-lived and complete their evolution in less than 5×10^7 years. As such a star collapses and becomes a neutron star its envelope is ejected in a supernova explosion, carrying away the earlier nucleosynthesis products and the ones resulting from explosive nucleosynthesis in the inner layers. This picture is still uncertain since the initial masses for which this is valid are not well known and it has been argued that some of the most massive stars may collapse into black holes, without an associated SN explosion. Before their dramatic end, massive stars undergo mass-loss processes via stellar winds as exemplified by Wolf-Rayet stars and other variable stars (e.g. luminous blue variables) that can carry away some CNO processed material, reducing the yield of O and increasing that of C, N and He. The efficiency of stellar winds depend strongly on their chemical composition (Maeder 1992) since metals increase the opacity. At low metallicity the mass loss is small and the resulting He, C and O production is insensitive to the initial stellar composition, although it can be affected by the tendency of mass loss to increase with metallicity. Hence one expects the yields of these elements to be metallicity dependent. In addition to stars losing part of their mass, a galaxy as a whole may be subject to mass loss, which will influence the ISM abundances, (see Sect. 3.3). Since different elements are produced in stars of different mass, they enrich the ISM on different timescales. Massive stars constitute the main source of oxygen and other α-elements, thus these elements are ejected on short timescales. Also significant amounts of carbon and nitrogen are produced in massive stars. For iron, massive stars dominate, but on long timescales the contribution from SN-Ia produced in binary systems may be important.

The initial mass function (IMF, the distribution of stellar masses in a population of newly borne stars) is a critical issue. To predict the element production of a population of stars, the stellar yields have to be convolved with the IMF to form the *net* yield, defined as the mass of newly synthesised elements per unit mass locked up in remnants and long lived stars. Unfortunately, the IMF is not yet well determined even locally, and it is uncertain whether it is universal or depends on environment and metallicity.

In most extragalactic studies the IMF is assumed constant in time. This assumption needs to be examined with care although no observational evidence has convincingly contradicted it by now. The strongest claim by Terlevich and Melnick (1981) for IMF variations with metal content of gas has never been compelling. There have been some suggestions that starburst galaxies should have an IMF biased towards massive stars or deficient in low mass stars (cf. Scalo 1990). However there is no direct evidence for this or for a low mass cut-off in giant H II regions like 30 Doradus or in globular clusters. Marconi et al. (1994) argue that the chemical evolution of starburst galaxies is well understood with a normal Salpeter-like IMF. Currently it seems that, for massive and intermediate massive stars, the IMF is reasonably well described with a power-law and a slope close to Salpeter's (1955) original value while it flattens, but does not cut off, at masses below 1 $M_{\odot}$. For a discussion on the IMF, its derivation, and possible variations, see Scalo (1998). If the total mass involved in star formation at each instant is modest, the high mass part of the IMF will be badly populated and consequently predictions for nucleosynthesis and spectral evolution will be sensitive to statistical fluctuations.

3.2. Star formation history

The most important parameter of the chemical enrichment is expected to be the star formation history (SFH). Since massive stars dominate the production of most elements, the metal production rate will to a first approximation be directly proportional to the star formation rate. Likewise, in a simple chemical evolution picture, the metallicity is a function of the fraction of gas turned into stars.

Star formation (SF) seems to occur in different modes: one being relatively undramatic with continuous star formation at a regular pace while in "bursting" galaxies, star formation may be dominated by a small number of short intense bursts of star formation separated by extremely long intervals of time. While the latter scenario is mainly observed in blue compact galaxies it is believed to occur also in dwarf and giant elliptical galaxies. An intermediate picture is that of "gasping" SF, characterised by extended star formation episodes separated by moderately long periods of less active SF, which probably is the most realistic picture for many dwarf irregular galaxies. While a starburst produces a lot of metals, the supernovae and stellar winds may eject gas into the intergalactic medium on short time scales. If, on the other hand, the SF is continuous, the energetic feedback from dying stars will have less influence on the ISM. Different scenarii for SF regulation have been implemented with stochastic self-propagating star formation, self regulated star formation and also a gas density threshold. Moreover interactions, mergers and stripping may play an important rôle in regulating the SF.

Discrete star-bursting behaviour in dwarf galaxies may strongly affect the abundance ratio of elements such as N, Fe and C which partly come from longer lived intermediate mass stars as compared to O (Garnett 1990, Gilmore and Wyse 1991, Richer and McCall 1995). In particular, this could explain the tendency of C/O and Fe/O to increase with O/H especially at low O/H, but this awaits more accurate measurements of these ratios in extremely metal-poor galaxies. Moreover, since the net yield for many elements appears to be metallicity dependent (Maeder 1992), element production by subsequent generations of stars will depend on how fast the ISM is enriched and hence the star formation history. In addition, variations in element ratios could affect nucleosynthesis and thus the net yields for a given stellar generation.

A last note concerns “starbursts”: This notion is frequently used in the literature to describe regions/galaxies with varying degree of active star formation. A proper definition of a starburst is that it involves an unsustainably high star formation rate (SFR) in terms of the gas consumption timescale or the timescale to build up the observed stellar mass (i.e. the time averaged SFR is much lower than the present). Many galaxies have SFRs fluctuating with time, but this does not necessarily imply that the SFR is unsustainable over a Hubble time.

3.3. Outflows and Inflows

When massive stars are about to end their lives they explode as a supernovae (SNe). The energy output from a SN is over a short period, comparable to that of a whole galaxy. In a galaxy with a high local star formation rate, the collective action of supernovae may lead to a galactic superwind, which may cause loss of gas. Stellar winds can also contribute to the energetics of the ISM at the very early stage of a starburst (Leitherer et al. 1992). The relative importance of winds compared to SNe increases with metallicity.

A continuous wind proportional to the star formation rate has been applied in models predicting the evolution of starburst galaxies. But since different elements are produced on different timescales, it has been proposed that only certain elements are lost (or in different proportions) hence reducing the effective net yield of those metals as compared to a simple chemical evolution model (Matteucci and Chiosi 1983, Edmunds 1990). The SNe involved in such a wind are likely to be of type II because type Ia SNe explode in isolation and will less likely trigger chimneys from which metals can be ejected out of the plane of a galaxy. In this framework O and part of Fe are lost while He and N (largely produced by intermediate stars) are not. This would result in a cosmic dispersion in element ratios such as N/O between galaxies that have experienced mass loss and those that have not.

In a dwarf galaxy which has a weaker gravitational potential, these effects may result in gas loss from the galaxy. Recently galactic winds have been observationally investigated in dwarf galaxies (e.g. Israel and van Driel 1990, Meurer et al. 1992; Marlowe et al. 1995; Martin 1996,1998). In VII Zw403 Papaderos et al. (1994) detected extended X-ray plumes which they interpreted as the result of outflows of hot gas. Lequeux et al. (1995) and Kunth et al. (1998) have shown that the escape of the Lyα photons in star-forming galaxies strongly depends on the dynamical properties of their interstellar medium. The Lyman alpha profile in the BCG Haro2 indicates a superwind of at least 200 km/s, carrying a mass of $\sim 10^7 M_\odot$, which can be independently traced from the Hα component (Legrand et al. 1997a). However, high speed winds do not necessary carry a lot of mass. Martin (1996) argues that a bubble seen in IZw18 (see also Petrosian et al. 1997) will ultimately blow-out together with its hot gas component. Although little is known about the interactions between the evolving supernova remnants, massive stellar bubbles and the ISM it is possible that an outflow takes the fresh metals with it, and in some cases leaves a galaxy totally cleaned of gas.

Will the gas leave a galaxy or simply stay around in the halo? Tenorio-Tagle et al. (1999) point out that superbubbles may initially expand with speeds that well exceed the local escape velocity of the galaxy but their motion into the gaseous halo causes a continuous deceleration lowering the velocity to values well below the escape speed. In such a case, ejecta condense into a cold phase, forming droplets that fall back and settle down onto the disc of the galaxy hence changing the composition of the ISM (the "Galactic fountain" model). Similarly in chemodynamical models (Hensler and Rieschick 1998, and references therein), the gas cools and falls back. Modelling the effect of SNe feedback on the ISM, De Young and Heckman (1994) suggested that the smallest dwarfs could have their entire ISM removed by a superwind. However, using models including dark matter, MacLow and Ferrara (1999) and Ferrara and Tolstoy (1999) conclude that winds are not very efficient in ejecting the ISM. Outflows are in most cases confined to the galaxy and "blow-away" occurs only for the smallest (luminous mass $M_{lum} < 10^7 M_{\odot}$) galaxies considered, while in other cases the mass loss is very modest. Winds may however still be efficient in ejecting fresh metals. Ferrara and Tolstoy (1999) nevertheless argue that outflows are not likely to be more metal rich than the average ISM value. Moreover, in their model, the SFR is a function of mass density which results in a mass–metallicity relation. Since the least massive dwarfs loose their entire ISM after the first star formation event, this results in a minimum expected ISM metallicity for a gas rich dwarf of 12+log(O/H)=7.2, i.e. the abundance of IZw18. Many assumptions go into these calculations, which must be further examined. Murakami and Babul (1999) showed that in high density environments the IGM pressure could confine outflows to the parent galaxies, inhibiting mass loss (cf. Babul and Rees 1992).

It is clear that the rôle of galactic winds in regulating the chemical evolution is not a settled issue yet. If the metallicity–luminosity relation (cf. Sect. 4.1, 4.2 and 7.1) holds from gas-rich to gas-poor systems then the loss of metals due to galactic winds should be a second order effect (Skillman 1997).

It is also possible that a galaxy is subject to infall of gas, although evidence for this is scarce. Infalling gas may come from external galaxies, stolen in the process of interaction or from an external origin, perhaps via isolated pristine HI clouds (if such clouds exist). There is evidence that blue compact galaxies and low surface brightness galaxies (LSBGs) are sometimes associated with HI clouds (Taylor 1997), which in general have optical counterparts (Taylor, private communication). A third possibility is that gas expelled in a previous superwind falls back on its host galaxy. There are indications that infall of metal-poor gas, perhaps in the form of gassy dwarf galaxies, may have had major impact on the chemical evolution of the disc of our Galaxy (Edvardsson et al. 1993). However one should recall that the existence of infalling gas on the Galactic disc is well established, as inferred from high velocity clouds (Mirabel 1989). Infall of unpolluted gas could act as to lower the ISM abundance. Generally, models of Galactic chemical evolution including infall assume pristine gas, but results with pre-enriched matter do not differ as long as the metallicity does not exceed $0.1 Z_{\odot}$ (Tosi 1988).

3.4. Mergers and interactions

It has become evident that interactions and merging between galaxies is a major driver in the evolution of galaxies, affecting the number evolution and morphological mix of the galaxy population. Mergers and interactions will also affect the star formation activity in galaxies, and in this respect be important for chemical evolution. Gas flow or accretion may lead to increased star formation (SF) activity or starbursts, whereas stripping or harassment in rich environments may inhibit SF. Gas accretion may also affect ISM abundances even if new star formation is not triggered, and may also provide a means for large scale mixing of the ISM.

Are some dwarfs ejected debris from interacting disc galaxies, and what consequences for their chemical evolution would this have? One would expect rather high metallicities, but if the process occurred long ago, before the interacting giants were enriched, this is not necessarily true. Evidence that dwarf-like objects are being formed within the gaseous tails of the encounters is now quite well established (e.g. Duc and Mirabel 1994, 1998), although their ultimate fate is unknown. Abundance analysis shows that their metal content is comparable to that of the parent galaxies re-enforcing the view that the gas from which they originate comes from the central regions of their parents. Another aspect is that many metal-poor dwarf galaxies in clustered environments may have been swallowed or torn apart by massive galaxies. The Sagittarius dwarf galaxy, a recently discovered Gallactic satellite (Ibata et al. 1994), may perhaps be such a case.

3.5. Mixing

Measured abundances in interstellar gas will of course depend on how well, and on what timescale, the ISM is mixed and on what timescale fresh metal cools and becomes visible. Kunth and Sargent (1986) argue that HII regions are self-polluted within the ongoing burst providing the ejected oxygen can recombine fast enough to be observed in the HII zone while some can become neutral and be observed in the HI cloud. Pantelaki and Clayton (1987) dismiss this possibility from the fact that most of the ejecta should remain for a long time in the hot gas generated by SN events. Spiral galaxies display radial abundance variations, indicating that radial mixing is inefficient. On the other hand, barred spirals display smaller abundance gradients, since bar perturbations induce radial gas flows. Roy and Kunth (1995) discuss mixing processes in the ISM of gas rich galaxies, and conclude that dwarf galaxies are expected to show kpc scale abundance inhomogeneities. On the other hand, chemodynamical models (Hensler and Rieschick 1998), predict that the ISM will be well mixed and chemically homogeneous through cloud evaporation.

The observational situation is still not completely clear and rather few dwarfs have been subject to high quality studies of their chemical homogeneity. Most dwarf irregulars seem rather homogeneous (Kobulnicky and Skillman 1996, Kobulnicky 1998) with the exception of NGC 5253 where local N/H overabundances has been attributed to localised pollution from WR stars (Kobulnicky et al. 1997). There is also marginal evidence for a weak abundance gradient in the LMC (on the scale of several kpc, Kobulnicky 1998). The situation is less clear in BCGs: In IIZw40, Walsh and Roy (1993) found a factor two variation in the oxygen abundance. IZw18 appears to be rather homogeneous (e.g. Skillman and Kennicutt 1993, Vilchez and Iglesias-Páramo 1998, Legrand et al. 1999) while recent spectroscopy of SBS0335-052 (Izotov et al. 1999b) reveals small but significant variations in accordance (though to a much lesser extent) with previous results (Melnick et al. 1992).

The possibility that metallicities in the neutral gas phase are orders of magnitude below the HII region abundances would be an ultimate test of large scale inhomogeneities. Recent O/H abundance determination in the HI envelope of the very metal-poor compact dwarf IZw18 (Kunth et al. 1994) suggests the possibility of a striking discontinuity between the HI and HII gas phases: the measured O/H in the cold gas appears to be 30 times lower (i.e. $\sim$1/1000 $Z_\odot$) than that of the associated HII region. Note however that Pettini and Lipman (1995) have strongly warned against the use of the OI interstellar lines in deriving O/H for the neutral gas, mainly because these lines are saturated and the velocity dispersion is unknown (see also van Zee et al. 1998). A further HST observation of O and S lines in IZw18 has unfortunately not produced consistent results (unpublished). Nevertheless Thuan et al. (1997) circumvented these problems in the case of SBS0335-052 although their result awaits independent measurement of unsaturated lines such as the SIIλ1256 multiplet.

A crucial question would be how to interpret the presence of metals in the HI zone. If indeed IZw18 experiences its very first episode of star formation, the oxygen present in the ionised gas should originate from the ongoing burst and one can speculate that metals in the HI were produced at an earlier epoch from population III stars prior to the collapse of the proto galaxy. On the other hand the enrichment in the neutral gas could originate in a previous burst allowing for a time scale long enough to homogenise a cold cloud of 1 kpc diameter as discussed by Roy and Kunth (1995), but see Tenorio-Tagle (1996). To circumvent the problem, Legrand (1998) has conjectured that in between bursts, IZw18 had maintained a minimum continuous star formation rate of only $10^{-4} M_{\odot}$/yr over the last 14 Gyrs. Such a SFR is comparable to the lowest SFR observed in low surface brightness galaxies. This scenario nicely explains the lack of galaxies with metallicities below IZw18, the absence of HI clouds without optical counterparts and the homogeneity of the metal abundances in dwarf galaxies. The question of the metallicity of the cold neutral gas is indeed very important for understanding how much enrichment has really occurred, since for many galaxies, a considerable fraction of the total baryonic mass is in the form of neutral hydrogen. If some dwarfs are not well mixed on large scales (e.g. LSBGs which have large HI-discs) they would appear more metal-rich after converting a given fraction of gas into stars, because one would be observationally biased towards the star-forming, more metal rich regions. On the other hand, if some dwarfs can mix their whole ISM on not too long timescales, the fresh metals will be efficiently diluted and the galaxy appear more metal-poor. Galaxies with very turbulent ISM and those involved in mergers could possibly mix more easily on large scales.

Once ejected into the ISM, part of the metals may be locked up into dust grains. This is observed in the local ISM for some elements (see e.g. Pagel 1997) and may result in strange element ratios and apparent under-abundances in extragalactic HII regions, although the effect is believed to be small for HII regions, due to grain destruction. In fact Bautista and Pradhan (1995) find that in the Orion nebula, the depletion of iron into dust grains is probably a minor effect. In the colder gas associated with damped Lyα systems (see Sect. 8.2) depletion onto dust grains may be important for some elements.

3.6. Chemical evolution models

WIth assumptions about stellar yields, IMF and star formation history, models of the chemical evolution of galaxies can be constructed. Various assumptions such as instantaneous recycling and closed box (i.e. the total mass of the system is conserved and perfectly mixed at all times) allows one to construct simple analytic models (cf. Pagel 1997). In the simplest case, with a constant net yield, the ISM abundance will be a simple function of gas mass fraction ($\mu_{\rm gas} = M_{\rm gas}/M_{\rm gas+stars}$). However, many of the effects mentioned above are likely to complicate the real picture.

Many dwarfs are believed to undergo short bursts of star formation separated by long quiescent epochs. Several additional ingredients were added to the closed-box models when it was realised that they could not account for the observed Z-$\mu_{\rm gas}$

distribution by simply changing the number of bursts from galaxy to galaxy. Models with normal or differential winds (selectively enriched in heavy elements) have been applied to starburst galaxies (see Matteucci 1996 for a review). They seem to be successful in reproducing the observed He/H vs. O/H distribution with a number of bursts between 7 and 10 in general, differential winds and various amounts of primary and secondary nitrogen from intermediate stars. This is in agreement with Pilyugin's conclusions (Pilyugin 1992, 1993) although other possibilities have been explored. For instance, one can vary the IMF from galaxy to galaxy by changing the slope of the lower mass cut-off (Marconi et al. 1994) while Olofsson (1995) proposed that different behaviour of N/O versus O/H can be attributed to an effect of mass loss as a function of metallicity. On the other hand individual galaxies do not fit into these schemes whenever one enters into details. A few galaxies for instance tend to have large N/O for their their O/H. The galaxy IZw18 falls into this category and one is forced to assume that N is produced as a primary element in massive stars. Even this assumption does not relax the need for a strong star formation efficiency (expressed as the inverse of the time scale of star formation) and strong O-enriched winds (Kunth et al. 1995). Note that recent work, e.g. by Izotov and Thuan (1999) on low metallicity BCGs, shows a reduced scatter for N/O and C/O at low abundances, to some extent removing the need for all the mechanisms originally invoked to produce a scatter. Clearly, the way that chemical evolution in metal-poor galaxies proceeds is far from beeing a settled issue.

More sophisticated "chemodynamical" models attempt to describe both the star formation history, its impact on the abundances and the interaction with the ISM in a self consistent way. Lately, these models have been applied to dwarf galaxies with some success (Hensler and Rieschick 1998). Recent models of the chemical evolution versus redshift in the Universe by Cen and Ostriker (1999) predict that metallicity shows a stronger dependence on the local density (i.e. galaxy mass) than on redshift, hence objects with high and low abundances are found at all z. In the local Universe, these models predict that any region denser than the cosmic average (a minimum requirement for a galaxy) should have a metallicity of $0.01 Z_\odot$ or higher.

4. The general properties of metal-poor galaxies

Here we will give an overview of the observed properties and chemical abundances of metal-poor galaxies, while in Sect. 5 we will discuss a few of these in more detail. As a metal-poor galaxy is in general a dwarf galaxy, this section will be biased towards dwarf galaxies.

Dwarf galaxies come in different kinds, with different properties and metallicities. There is a partial overlap in the classification and physics of metal-poor galaxies. At faint absolute magnitudes the dwarf irregular (dI), dwarf elliptical (dE) and low surface brightness galaxy (LSBG) classes converge. Moreover blue compact galaxies (BCGs) to some extent overlap with actively star forming dIs. The possible connections between different types of galaxies will be further discussed in Sect. 7.2. A lot of the data on dI and dE/dSph galaxies are from the Local Group. It is not our intent here to give a general description of the Local Group dwarfs, recent and excellent reviews can be found in e.g. Mateo (1998, which also contains a compilation of very useful data) and Grebel (1998); see also the book "Stellar astrophysics for the Local Group" (eds. Aparicio et al. 1998) and the proceedings of the recent IAU symposium "The Stellar Content of Local Group Galaxies" (eds. Whitelock and Cannon 1999).

Here we will only focus on those points that are relevant for the understanding of the most metal-poor galaxies.

As we have mentioned, metallicity correlates with luminosity for galaxies, at least in the local Universe. More metal rich galaxies are on average more luminous and have in addition higher surface brightness. This produces a bias against detecting metal-poor galaxies. Moreover, except for HII region spectroscopy, most ways of measuring metallicity discriminate against low luminosity galaxies.

4.1. Dwarf irregular galaxies

Dwarf irregulars are in general well described by exponential surface brightness profiles. They contain fair amounts of neutral and perhaps molecular gas and in general show evidence for star formation, at low (or moderate) rates. There are some examples of galaxies of intermediate type between dI and dE, e.g. the Local Group dwarfs Pegasus and Phoenix. Such galaxies have no signs of ongoing star formation, but contain gas (Mateo 1998). Dwarf irregulars partially overlap BCGs in the classification criteria, i.e. many BCGs are indeed irregular, and dIs often contain bright HII regions which may be picked up in emission line surveys. Of course the transition is gradual and to some extent arbitrary. There is also some overlap with the LSBG class of galaxies discussed in Sect. 4.3.

The Local Group contains around a dozen (depending on the magnitude limit) dIs most of which are rather metal-poor. Dwarf irregulars are also found in the local field and in nearby clusters and groups, but metallicity determinations become rarer with increasing distance.

Dwarf irregulars in general show ongoing star formation and HII regions. The star formation history (SFH) of Local Group dIs has been reviewed recently by Grebel (1998), and Mateo (1998). Most dIs seem to have experienced more or less continuous star formation over a Hubble time. Many Local Group dIs show evidence for an episodic star formation history to a varying degree (e.g. Leo A, Tolstoy et al. 1998), but it is difficult to say if the past SFH should be described in terms of short bursts or more extended periods of increased SF as compared to the time averaged value. There seems to be no clear pattern when comparing different galaxies, i.e. no support for co-ordinated bursts. Star formation in dIs is probably governed by different mechanisms than in spiral galaxies, i.e. there are no density waves available for triggering star formation. Despite their closeness, it is quite fair to say that the regulation of star formation in the Local Group dIs (and dEs too) is not yet well understood. Interactions, ram-pressure stripping, superwinds and other recipes have been suggested as processes governing the star formation history and morphological segregation, but results are still inconclusive.

Young and Lo (1996, 1997b) find that neutral hydrogen in dIs exists in two phases and that the presence of cold HI may be the key factor by which a dI is presently forming stars or not. Intermediate dE/dI types do in some cases have gas, but not in the form of cold HI, which could explain the lack of present star formation (Young and Lo 1997b). The HI content of dIs in the nearby Universe has been investigated by e.g. Thuan and Seitzer (1979), Schneider et al. (1992, 1998) and Côté et al. (1997); see Skillman (1996) for a review. The dynamics of dIs can be investigated through HI rotation curves, and dIs (as most other dwarfs) turn out to be dominated by dark matter (cf. Mateo 1998).

4.1.1. Chemical abundances of dwarf irregular galaxies

Dwarf irregular galaxies are in general metal-poor. Nebular abundances in Local Group dIs range between roughly one third of solar (e.g. LMC) and $\sim$ 1/40 of solar. Abundances of dIs are usually derived from HII regions. For some dIs there exist also metallicity estimates of [Fe/H] using the same technique as generally used for dEs colour-magnitude diagrams (CMDs).

We present in Table 1 some basic properties for the most metal-poor (oxygen abundance less than or equal to 1/10 of the solar value) Local Group dIs. Some dIs (Leo A, SagDIG and Sextans A) do indeed have oxygen abundances comparable to the most metal-poor blue compact galaxies. If available, we present also [Fe/H] values based on stellar photometry, absolute B-magnitudes and the logarithm of the estimated total (dynamical) mass expressed in solar masses.

Table 1. The most metal-poor Local Group dIs (data from Mateo 1998). The second column gives 12+log(O/H), and the third column [Fe/H]. The fourth and fifth columns give the integrated absolute B-band magnitude and the logarithm of the derived dynamical mass (in solar masses), respectively.

Galaxy name	12+log(O/H)	[Fe/H]	M_B	log($\mathscr{M}$)
Leo A	7.3		-11.3	7.0
SagDIG	7.42		-12.1	7.0
Sextans A	7.49	-1.9	-14.2	8.6
Gr 8	7.62		-11.2	7.6
EGB 0427+63	7.62		-11.6	
WLM	7.75	-1.5	-13.9	8.2
IC 1613	7.8	-1.3	-14.2	8.9
Sextans B	7.84	-1.2	-13.8	8.9
Pegasus	7.93	-1.0	-12.3	7.8

Only for a few dIs have abundances of individual stars been determined. For the Magellanic Clouds, Pagel (1992) concludes that the agreement between stellar and gaseous heavy element abundances is about as good as can be expected in view of the uncertainties. However, for NGC 6822, metal lines of early type stars are considerably weaker than expected from the measured nebular oxygen abundance (Massey et al. 1995). If there is a real discrepancy, this is worrying since one argues that ISM oxygen abundances can be obtained with high accuracy. Direct spectroscopic observations of individual stars in more dIs are much needed.

Skillman et al. (1989) confirmed in a seminal paper a strong correlation between absolute magnitude and metallicity for local dIs in the sense that the fainter systems have lower metallicities. This was hinted already in some earlier papers: e.g. Lequeux et al. (1979), Kinman and Davidson (1981). The existence of a relation between metallicity and luminosity constitutes a fundamental observation that we need to understand to address the chemical evolution of dwarf galaxies. The metallicity–luminosity relation for dIs and other galaxies will be further addressed in Sect. 7.1. More recent work in this area include that of Richer and McCall (1995) and Hidalgo-Gámez and Olofsson (1998). The comparison of dIs and dEs is not straightforward, as will be discussed in next section, since different chemical elements are sampled in general.

The best studied dIs reside in the Local Group, but plenty of observations of relatively nearby dIs outside the Local Group can be found in the literature (e.g.

Skillman et al. 1989). The use of HII regions for determining oxygen abundances makes even relatively distant dIs accessible for chemical investigation of their ISM. Dwarf irregulars in the M81 group have been studied by Skillman et al. (1994) and Miller & Hodge (1996), and dIs in the Sculptor group by Miller (1996). Abundances are similar to Local Group dIs and follow the same metallicity–luminosity relationship (Skillman et al. 1989, Skillman 1998). A sample of quiescent dwarfs (dIs/LSBGs) studied by van Zee et al. (1997b,c) shows again typical Local Group abundances and adheres to the metallicity–luminosity relation; see also the section on LSBGs (4.3.1). The most metal-poor dIs are included in Table 3.

Vilchez (1995) presented a spectrophotometric study of star forming dwarf galaxies (dIs and BCDs) in different environments, from low density to the core of the Virgo cluster. For a given luminosity, the high density environment dwarfs are systematically overabundant ($\sim$0.5 dex) with respect to dwarfs in low density environments and the Skillman (1989) relation. However, metallicities especially for dwarfs in Virgo are uncertain and the observed over-metallicity may be spurious. Later work by Lee et al. (1998) finds O-abundances of 12+log(O/H) = 8.0 to 8.3 for absolute magnitudes $-15 > M_B > -16$ indicating that the systematic overabundance of Virgo dIs with respect to local ones is small or non-existent. Some cluster dwarfs seem to be anomalously metal rich (perhaps related to the "tidal dwarfs", see below), while others appear to be rather normal (Vilchez 1999; private communication). It now appears that dwarf galaxies can be spawned in the process of violent galaxy interactions. These "tidal dwarfs" will be discussed separately in Sect. 4.5.

Carbon abundances have been determined for a few dIs by Garnett et al. (1995) and Kobulnicky and Skillman (1998), although most galaxies in these investigations are rather BCGs, revealing a strong positive correlation between [O/H] and [C/O]. Nitrogen abundances exist for more dIs (e.g. Garnett 1990), but rarely for the most metal-poor Local Group dIs. The typical [N/O] values for metal-poor dIs are of the same order as those of BCGs. The [C/O] and [N/O] nebular abundance ratios will be further discussed in the BCG section.

4.2. Dwarf elliptical/spheroidal galaxies

Let us first say a few words about the nomenclature. Luminous Elliptical galaxies follow a well defined relation between luminosity and central surface brightness in the sense that more luminous objects have lower central surface brightness (a projection of the fundamental plane), whereas the opposite relation appears to hold for "diffuse" early type dwarfs, and late type galaxies (e.g. Binggeli 1994). Thus the kind of galaxy classically termed dwarf elliptical (like Fornax) appears to be physically distinct from non-dwarf elliptical galaxies (like M87), see Binggeli (1994) and Kormendy and Bender (1994). This has created some debate on what to call low mass ellipsoidal galaxies. Ferguson and Binggeli (1994) proposed to call objects with $r^{1/4}$ profiles (e.g. M32 and giant elliptical galaxies) *elliptical* (E) and those with more exponential profiles *dwarf elliptical* (dE). Kormendy and Bender (1994) calls the latter class *spheroidal* and uses the prefix dwarf to indicate the low luminosity galaxies in each class. Lately, the clear structural distinction between these two classes of objects has begun to be smeared out: Jerjen and Binggeli (1997) show that, as luminosity increases, the luminosity profiles of low mass ellipsoids approach those of giant ellipticals, if the central 0.3 kpc is excluded. In this review we will be primarily interested in the low luminosity low metallicity systems, which we will refer to as dEs, or occasionally dSph (when speaking specifically about the satellites of our Galaxy), which have nearly exponential profiles.

Dwarf elliptical galaxies were long thought to be made up of exclusively old stars, but it has now become evident that many seem to have experienced several star formation episodes, and in many cases quite recently (Grebel 1998). This makes the distinction between dEs and dIs less clear. The SFH in Local Group dEs are mainly explored through their resolved stellar populations, e.g. by means of colour magnitude diagrams. A famous example of a CMD revealing distinct and well separated episodes of star formation is that of the Carina dwarf galaxy (Smecker-Hane et al. 1994).

Masses have been derived for many local dEs using measured velocity dispersions of their stars and they tend to be dark matter dominated (cf. Mateo 1998). Most dEs are very gas poor. In fact, the gas content is sometimes lower than what one would expect from mass loss from the old stellar population alone. The best known example is NGC 147 where neither HI (Young and Lo 1997a) nor CO (Sage et al. 1998) has been found. Thus there might be a mechanism that removes gas, or the gas is in a phase which is not observable. In other dEs, the gas content is in rough agreement with expectations from stellar mass loss (Young and Lo 1997a). An interesting case is the Sculptor dwarf that has no HI within its optical extent, but some well outside in the halo, perhaps moved there by a superwind (Carignan et al. 1998).

Most data on dEs come from the Local Group population, but dEs also exist in large number in galaxy clusters like Virgo, Fornax and Leo. There appear to be very few pure field dEs (i.e. not accompanying a giant galaxy, Binggeli et al. 1990), but their luminosity function is not well known since faint dEs have in general low surface brightness hence may be absent in many surveys (cf. Sect. 6). In the Local Group, new dEs are still beeing discovered (e.g. Armandroff et al. 1998), implying that not even locally do we have a complete picture about the dE population.

4.2.1. Chemical abundances of Local Group dE/dSph galaxies

Aaronson (1986) showed that dEs seemed to follow a tight relation between metallicity ([Fe/H]) and optical luminosity. This has later been confirmed and a rather tight luminosity metallicity relation for dwarf ellipticals is now quite well established (Caldwell 1998). Metallicity data for dEs based on CMD analysis, can be found at several places in the literature (see Mateo 1998 for a recent compilation). These data also reveal that most dEs have a considerable spread in metallicity as measured from the width of the RGB.

Stellar spectroscopic abundances exist for several of the Milky Way satellites, e.g. the Sextans dSph (Suntzeff et al. 1993). Another well studied galaxy is Draco, where Shetrone et al. (1998) found $-3.0 < [\mathrm{Fe/H}] < -1.5$ confirming earlier findings of a substantial metallicity spread (Lehnert et al. 1992). The metallicity derived from a CMD is [Fe/H] = -2.0 ± 0.15.

Richer and McCall (1995) made a spectroscopic study of planetary nebulae (PNe) in local dEs, including data from the literature on the Fornax dwarf. They also revisit the metallicity–luminosity relation for dwarf irregulars by Skillman et al. (1989), using new determinations of the distance and metallicity. Their PN spectra have rather low signal to noise requiring empirical relations between [OIII]λ5007 and Hβ to estimate lower bounds on the oxygen abundances in the three dEs, from which they make a transformation to a "mean oxygen abundance". They claim these to be systematically higher in dEs than in dIs of the same luminosity. Although based on a sound line of reasoning their derivation of the ISM mean oxygen abundance involves several steps, and must be regarded as quite uncertain. Thus, while tentatively very important, these results need to be quantitatively confirmed for a larger sample of PNe in more galaxies, with higher S/N and better spectral coverage. Recently, PNe were studied also in the Sagittarius dwarf (Walsh et al. 1997).

Richer and McCall (1995) also claim that [O/Fe] is systematically higher in dEs than dIs, where the latter class was represented by the Magellanic Clouds. The Fe abundance adopted for LMC and SMC are based on young supergiants, and thus do not measure the same stellar generation as in the dEs. To compensate for this, they modify the abundance ratios.

If one instead compares the Magellanic Cloud O-abundances with [Fe/H] estimates from field stars with ages comparable to those of the red giants in the dEs (e.g. Hilker et al. 1995) the Magellanic Cloud [O/Fe] values increase and thus the difference compared to the dEs decreases. In Fig. 1 we plot [Fe/H] vs. [O/H] for all nearby dwarfs with both elements measured. It is clear that the overabundance over oxygen with respect to iron seems to be a general feature of local dwarfs (see also Fig. 7 in Mateo 1998) as it is for giant halo stars (Barbuy 1988) and metal-poor unevolved halo stars in our Galaxy (Israelian et al. 1998). There is no indication that [O/Fe] is significantly higher in dEs than dIs. In a later work, Richer et al. (1998) find [O/Fe] to be systematically higher in dEs than e.g. in M32 and the Galactic bulge, but similar to the galactic halo, and they suggest that the star formation timescale has been shorter in dEs than ellipticals and spiral bulges.

Now, how metal-poor are the Local Group dEs? As was discussed above, [Fe/H] measured from CMDs tends to be systematically smaller than [O/H] measured from HII regions with up to 0.5 dex, making these two quantities difficult to compare. Of the Local Group dEs, a dozen have [Fe/H] ≤ -1.5, and the lowest value, [Fe/H] = -2.2, is found for the Ursa Minor dSph, see Table 2. In summary, many Local Group dEs are very metal poor, which probably is related to their intrinsic faintness. Taking the average offset between [Fe/H] and [O/H] into account, Mateo (1998) concludes that dEs appear to be more metal rich in view of their luminosities, in agreement with Richer and McCall (1995).

4.2.2. Abundances of dEs outside the Local Group

Unfortunately, very little is known about the chemical abundances of dEs outside the Local Group. The M81 group is near enough that the study of colour magnitude diagrams is feasible with powerful telescopes. Caldwell et al. (1998) report on HST photometry of two dEs in the M81 group, concluding that their metallicities are similar to those of Local Group dEs with the same luminosity. Of course two data points is far too little to assess whether the Local Group dE population is typical of dEs in general, but this investigation nicely shows that it is feasible to obtain CMDs of dEs outside the Local Group.

Held and Mould (1994) obtained integrated spectra of 10 *nucleated* dEs in the Fornax cluster, and derived metallicities in the range [Fe/H] = -1.4 to -0.7. They found that the metallicities are tightly correlated with the UBV-colours. The range in luminosity is too small to deduce any relationship with the metallicity, but interestingly the median metallicity, $\langle$[Fe/H]$\rangle$ = -1.1, and luminosity, $\langle M_V \rangle = -16.1$ (assuming a distance of 18.6 Mpc for the Fornax cluster, Madore et al. 1999), is in perfect agreement with the metallicity–luminosity relation for local dEs of Caldwell et al.

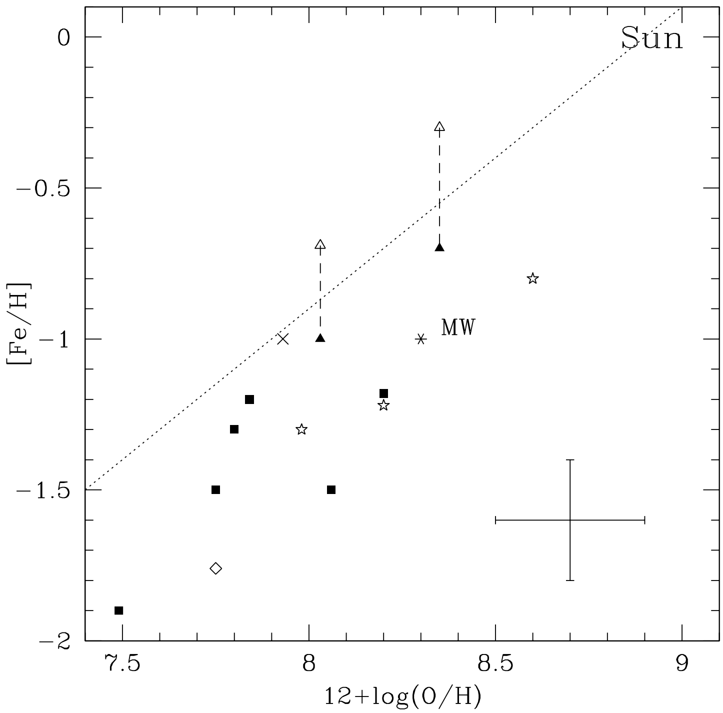

Fig. 1. [Fe/H] vs. 12+log(O/H) for all local dwarf galaxies where both iron and oxygen abundances have been obtained (data taken from Mateo 1998), plus the Magellanic clouds, a BCG, the Sun and the Milky Way halo. dIs are denoted by filled squares, dI/dE intermediate type (Pegasus) by a cross, and dE (Sagittarius) by an asterisk; stars are the dEs studied by Richer & McCall with oxygen abundances from planetary nebulae. The triangles joined by dashed line represent the Magellanic clouds, where for the open symbols the [Fe/H] are based on young supergiants, while for the filled symbols the [Fe/H] have been determined from Strömgren photometry of the field population. The open diamond indicates the location of the nearby BCG VII Zw403 (see Sect. 4.4.7). The location of Milky Way halo stars is indicated with "MW" (from Richer and McCall 1995), and that of the Sun with "Sun". The dotted line corresponds to solar [O/Fe]. In general (except for the open triangles) Fe/H traces an older stellar population than O/H to some extent explaining the apparent general deficiency of iron, with respect to oxygen. The typical errors are around 0.2 dex for both quantities, as illustrated by the error bars in the lower right corner.

(1998). The tight correlation between metallicity and colour is quite remarkable since the large metallicity spread at a given luminosity indicates very different enrichment histories. The colour-metallicity relation also offers some hope to obtain metallicity information from photometry of distant galaxy populations. One should, however, keep in mind that the relation was established from a biased sample of nuclei of galaxies with uniform luminosity and morphology.

Although the Virgo cluster is known to be very rich in dEs, their metallicities are to a large extent unknown. Based on optical and near infrared colours Thuan (1985) concluded that Virgo cluster dEs had metallicities in the range: $1/3Z_{\odot}$ to $Z_{\odot}$. These conclusions were based on comparisons with models that are now outdated. Since the possibility of using photometry for metallicity estimates is of interest for

Table 2. The most metal-poor dE/dSph galaxies in the Local Group, including all galaxies with [Fe/H]≤ −1.0. The second column gives [Fe/H], and the third column gives nebular oxygen abundances, when available. As discussed in the text, there is a tendency for the measured abundance of oxygen to be higher than that of iron, with respect to the solar values. The fourth and fifth columns give the integrated absolute V-band magnitude and the logarithm of the dynamical mass (in solar masses), respectively. All data taken from Mateo (1998).

Galaxy name	[Fe/H]	12+log(O/H)	M_V	$\log(\mathcal{M})$
Ursa Minor	-2.2		-8.9	7.36
Draco	-2.0		-8.8	7.34
Carina	-2.0		-9.3	7.11
Andromeda III	-2.0		-10.3	
Leo II	-1.9		-9.6	6.99
Phoenix	-1.9		-10.1	7.52
LGS 3	-1.8		-10.5	7.11
Antlia	-1.8		-10.8	7.08
Sculptor	-1.8		-11.1	6.81
Sextans dSph	-1.7		-9.5	7.28
Tucana	-1.7		-9.6	
Andromeda II	-1.6		-11.1	
Andromeda I	-1.5		-11.9	
Leo I	-1.5		-11.9	7.34
Fornax	-1.3	8.0	-13.2	7.83
NGC 185	-1.2	8.2	-15.5	8.11
NGC 147	-1.1		-15.5	8.04
M32	-1.1		-16.7	9.33
Sagittarius	-1.0	8.3	-13.4	

the study of distant faint galaxies we decided to reassess this finding. To do this we have compared the photometric data by Thuan (1985), Bothun and Caldwell (1984), James (1991,1994), and Zinnecker and Cannon (1986) with a new set of models by Bruzual and Charlot (2000). Special care was taken when modelling galaxies with inhomogeneous data (e.g. different aperture sizes). When using simple stellar populations (where all stars have the same age and metallicity) and a standard Salpeter or Scalo IMF, the resulting metallicities are in the range from less than $1/10 Z_\odot$ to $Z_\odot$, with a median around $1/3 Z_\odot$, and a typical age of 3 Gyr. Models with exponentially decreasing SFR (e-folding time 3 Gyr) produced slightly better fits with similar metallicity and a median age of 11 Gyr. Assuming a distance of 16.2 Mpc to the Virgo cluster (Macri et al. 1999) we find a median luminosity $\langle M_V \rangle = -15.3$, which with a median metallicity of $\langle$[Fe/H]$\rangle \approx -0.5$ means that the Virgo dEs are more metal rich by $\approx$ 0.5 dex as compared to the $M_V - Z$ relation for local dEs by Caldwell et al. (1998). Thus, either the Virgo cluster dEs are overabundant, or perhaps more likely, the photometrically derived metallicities are too high. We find no clear trend between metallicity and luminosity in this analysis.

In conclusion, the photometric data on Virgo dEs indicate that these galaxies have metallicities typically around 0.3 $Z_\odot$ (in rough agreement with Thuan's earlier result). Today it would be possible to probe fainter systems using CCDs and modern near-IR arrays, although it is not yet clear how powerful a tool optical/near-IR colours are in deriving metallicities. Note that recent spectroscopy for six dEs in the Virgo cluster gives metallicities ranging from a few tenths of solar to solar, with small radial gradients as compared to giant ellipticals (Gorgas et al. 1997). Their median inferred [Fe/H] and luminosity is in rough agreement with the relation for local dEs by Caldwell et al. (1998). Spectroscopic metallicity determination of intrinsically faint dEs outside the Local Group is now feasible with 8-10m class telescopes, and should be pursued.

4.3. Low surface brightness galaxies

A low surface brightness galaxy (LSBG) is, as the name implies, a galaxy with surface brightness fainter than $\mu_{B,0}$ = 23 mag/arcsec^2 (the central B-band surface brightness). This class spans from tiny dwarfs, sometimes similar to dSph galaxies, to luminous giants like Malin 1 (Bothun et al. 1987). The latter are in general not metal-poor by our standards, and will not be considered here. Instead, we will be interested in the LSBGs with low integrated luminosities (the dwarf LSBGs). Many dEs could in fact classify as LSBG, but we will reserve this name for late type galaxies, often gas rich, keeping in mind that dEs in general have comparable surface brightness. Low surface brightness gas poor galaxies (as observed e.g. in Virgo, e.g. Binggeli et al. 1984) will be covered by the dE class. Dwarf irregulars with low surface brightness, will be included in our LSBG class. The appearance of a typical LSBG on the digitised sky survey is shown in Fig. 2.

The LSBGs pose a severe problem for the general understanding of the galaxy population. This is because their nature make them difficult to detect with most techniques that have been applied to survey the galaxy content of the Universe. A striking example is the not too distant giant (M_B = -21.1) Malin 2 (Bothun et al. 1990). With an integrated apparent magnitude of 14.65 it is bright enough to be included in most galaxy catalogues. The fact that it is not illustrates that despite the claims, galaxy catalogues are not magnitude limited, but rather surface brightness limited (cf. Disney and Phillipps 1983). This has the consequence that our view of the LSBG population is largely incomplete, and since dwarfs tend to be of low surface brightness, it is evident that we are lacking many local metal-poor LSBGs and dEs. See e.g. Bothun et al. (1997) for a general discussion on the problems of finding LSBGs. In view of these difficulties, the true space density of LSBGs is badly known, although some recent progress has been made.

Van der Hulst et al. (1993), studying HI properties of LSBGs, found that while the gas mass and gas mass fractions are high, the column density of HI is low due to very extended HI morphologies. The neutral gas densities are found to be lower than the empirical threshold for star formation found for normal high surface brightness galaxies (Kennicutt 1989) explaining the low star formation rates. A similar study was performed by van Zee et al. (1997a) who compared dwarf LSBGs with “normal” gas-rich dwarfs, finding no qualitative difference however and noting that both types were equally inefficient star formers. De Blok et al. (1996) found further support for low gas densities as compared to normal high surface brightness galaxies. Moreover the gas mass fraction is higher in LSBGs than other types of galaxies when measured with respect to the absolute blue luminosity (typically M_{HI}/L_B = 1, in solar units) or the dynamical mass (McGaugh and de Blok 1997). They suggest that the total mass density of a galaxy regulates its rate of evolution. The dynamical masses are of the order of $10^{10} M_\odot$ and the HI masses an order of magnitude smaller. It is likely that LSBGs have experienced continuous star formation at low rate (Bergvall & Rönnback 1994). Bell et al. (1999) suggest that the principal difference between blue and redder LSBGs is the e-folding timescale for star formation. The general conclusion seems

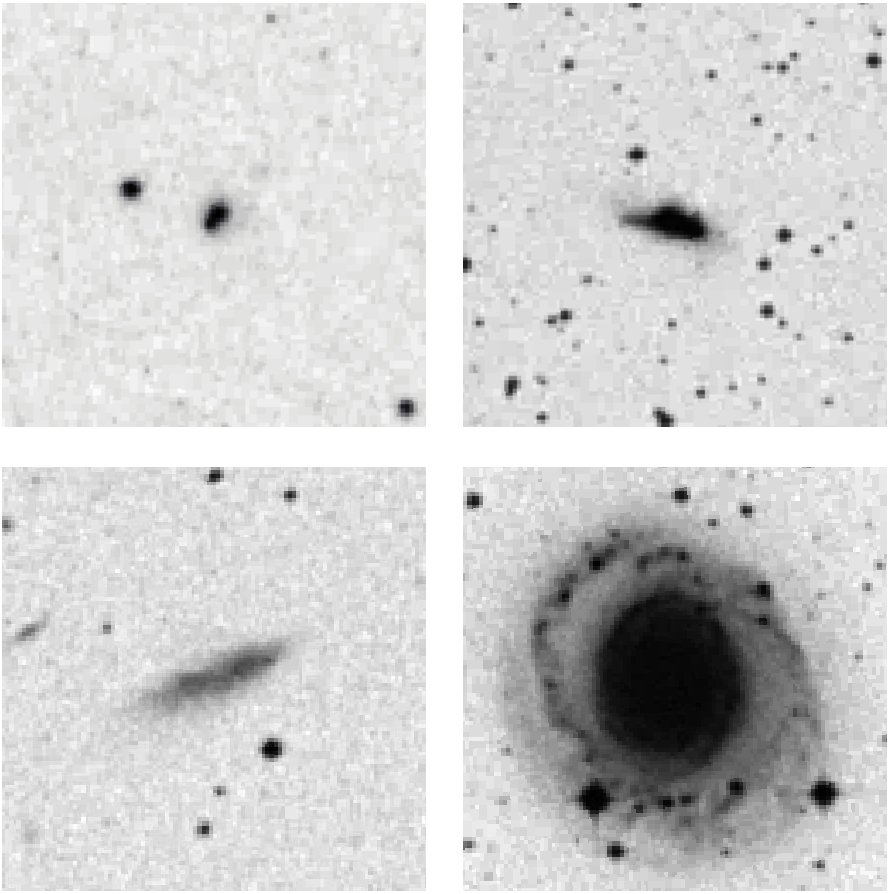

Fig. 2. Some galaxies as seen in the Digitized Sky Survey (obtained from *Sky View*). All images have dimension 3 $\times$ 3 arcminutes, north is up east is left. Top left: The "prototypical" BCG IZw18, distance (D) = 10 Mpc, M_B = -14, $Z \approx 1/50 Z_{\odot}$. Top right: ESO 338-IG04 (=Tol1924–416), a luminous metal-poor BCG, D = 38 Mpc, M_B = -19, $Z \approx 1/10 Z_{\odot}$. Bottom left: ESO 546-34, a metal-poor LSBG, D = 20 Mpc, M_B = -16, $Z \approx 1/20 Z_{\odot}$. Bottom right: The giant "normal" spiral NGC 6753 shown for comparison, D = 40 Mpc, M_B = -21.5

to be that LSBGs are gas rich and unevolved, both chemically and photometrically, which may be related to their low mass densities.

In view of their probably high space density and large gas mass fractions, the LSBGs constitute an important fuel reservoir for star formation in the Universe. Gas in LSBGs can be made accessible to other galaxies e.g. in collisions. Likewise, if the extended low density gas somehow can be forced to collapse, LSBGs may be sites of future starbursts. The possible physical relations with other galaxies will be addressed in Sect. 7.2. Moreover, there have been suggestions that LSBGs may be responsible for some of the metal line absorption systems seen in QSO spectra (e.g. Phillipps et al. 1993).

4.3.1. Chemical abundances of LSBGs

Despite their faintness, many LSBG contain HII regions and the metallicity of LSBGs have been investigated through the derivation of nebular oxygen abundances. McGaugh (1994) used an empirical determination of the oxygen abundance to find values of 12+log(O/H) ranging from 7.3 to 8.8, for individual HII regions with a strong peak around 8.4. There was often considerable scatter between HII regions in the same galaxies. Taking weighted averages, eight galaxies have O abundances less than 1/10 of the solar value, ranging down to $\sim$ 1/15, and the absolute B magnitudes of the metal-poor ($\leq$ 10% of solar) subsample range from -15.8 to -20.3 (for H_0=75 km/s/Mpc).

Similarly, Rönnback & Bergvall (1995) found that a sample of LSBGs with $M_B = -14$ to -18.5, and selected to have blue colours, all had low metallicities. Typical oxygen abundances are around 1/10 of solar, extending down below 1/20. They also derive N/O values. Five out of 13 galaxies had an oxygen abundance below 10% of solar, e.g. the remarkable edge-on galaxy ESO 146-G14 ($M_B = -16.6$) with 12+log(O/H)=7.6 (see also Bergvall and Rönnback 1995). Several of the galaxies in these two samples fall below the metallicity–luminosity relation for dIs, see Fig. 10.

Van Zee et al. (1997b,c), for a sample of quiescent LSBGs/dIs derive oxygen abundances ranging from 12+log(O/H)=7.6 to 8.3, matching perfectly the $M_B - Z$ relation for dIs (Fig. 10). A massive neutral hydrogen cloud was found in the Virgo cluster, by Giovanelli and Haynes (1989). It has an optical low surface brightness counterpart, with some central faint HII regions from which Salzer et al. (1991) derived 12+log(O/H)=7.66. De Blok and van der Hulst (1998) found no very metal-poor LSBGs in their investigation, but three galaxies examined for abundance gradients were found to have none. This together with small or non existent colour gradients (Rönnback & Bergvall 1994, de Blok et al. 1995, Patterson and Thuan 1996) suggests that the stellar populations are spatially homogeneous in age and metallicity. This is supported also by recent near infrared surface photometry (Bergvall et al. 1999).

There is only a weak correlation between metallicity and absolute blue luminosity (McGaugh 1994, and Bergvall & Rönnback 1994), see however Fig. 10. Metallicity and surface brightness are related in the sense that LSBGs have lower than average abundances for their absolute magnitudes as compared to high surface brightness galaxies. However, neither investigation found any strong correlation between surface brightness and oxygen abundance.

Some LSBGs have a too low surface brightness to be observable spectroscopically at the time of these studies. The new generation of 8-10m class telescopes may be used to investigate if late type galaxies with extremely low surface brightness are even more metal-poor. Also, new surveys for extremely low surface brightness galaxies may yield many new interesting metal-poor candidates, though abundances may be very difficult to obtain if the galaxies do not have HII regions. The most metal-poor LSBGs are included in Table 3.

4.4. Blue compact and HII galaxies

The concept of "compact galaxies" was introduced by Zwicky (1965) to denote galaxies barely distinguishable from stars on the Palomar Sky Survey plates. Originally, most studies of blue compact galaxies (BCGs) concerned objects from the lists of compact/emission line/UV-excess galaxies produced by Zwicky (1966), Haro (1956) and

Table 3. The most metal-poor galaxies. This Table contains all galaxies with 12+log(O/H)$<$ 7.65 that we in found the literature. The first column gives the most common name that is also recognized by the NASA/IPAC extragalactic database (NED). Alternative names are given below in some cases. A broad galaxy classification is given in column two. The coordinates are from NED (except for HS 0822+3542 and CS 0953-174). The heliocentric radial velocities in column 5 come mainly from NED, but we also quote the reference given by NED. Preference was given to HI-velocities if available. The sixth column gives 12+log(O/H), where uncertain values based on empirical methods (not utilising [OIII]λ4363) are marked with colon. Values marked by asterisks represent a weighted average of values from different HII regions and/or authors. The seventh column gives the absolute B-magnitude, from direct distance measurements or from radial velocity and H_0 = 75 km/s/Mpc. Values for M_B based on other values of H_0 were rescaled. A colon indicates that the magnitude is uncertain, either beacuse it is based on photographic data or because from other passband than B. The references are given in the footnotes.

Galaxy name	Type	α_{2000}	δ_{2000}	$v_{\rm hel}$	O/H	M_B	References		
		(h m s)	(° ′ ″)	(km/s)			$v_{\rm hel}$	O/H	M_B
UM 283 [a]	BCG	00 51 49.5	+00 33 53	4510	7.59	−16.7:	37	7	8
UM 133	BCG	01 44 41.3	+04 53 26	2098	7.63	−16.9	31	9	10
UM 382	BCG	01 58 09.4	−00 06 38	3598	7.45	−15.0	31	9	11
UM 408	BCG	02 11 23.5	+02 20 31	3598	7.63	−15.8	31	9	11
SBS 0335-052W	dI/BCG	03 37 38.4	−05 02 36	4017	7.21*	−14.4	33	14	15
SBS 0335-052E [b]	BCG	03 37 44.0	−05 02 38	4057	7.29	−16.7	33	4	15
Tololo 0618-402	BCG	06 20 03.8	−40 16 43	10493	7.61*	−17::	31	9	26
HS 0822+3542	BCG	08 25 55.4	+35 32 31	732	7.35	−12.6	1,2	1,2	1,2
IZw18 [c]	BCG	09 34 01.9	+55 14 26	750	7.18	−13.9	32	4	16
SBS 0940+544N [d]	BCG	09 44 16.7	+54 11 33	1685	7.43	−14.8:	34	4	13
CS 0953-174	BCG	09 55	−17	3540	7.58		30	9	27
KUG 1013+381 [e]	BCG	10 16 24.5	+37 54 44	1198	7.58	−15.1:	3	3	3
[RC2]A1116+51 [f]	BCG	11 19 33.3	+51 29 40	1351	7.60*	−13.9:	21	17,19	25
SBS 1159+545	BCG	12 02 02.4	+54 15 51	3537	7.49	−15.4:	35	4	13
Tololo 1214-277	BCG	12 17 18.2	−28 01 40	7795	7.56*	−17.6:	31	9	13
Tololo 65 [g]	BCG	12 25 46.9	−36 14 01	2698	7.40*	−15.3	31	9	12
[RC2]A1228+12 [h]	BCG	12 30 48.5	+12 02 42	1254	7.64	−13.2:	21	17	18
CG 389	BCG	14 17 01.7	+43 30 13	649	7.59	−14.1:	29	4	13
UGCA 20	LSB/dI	01 43 14.7	+19 58 32	498	7.58*	−14.0	41	42	28
ESO 546-G34	LSBG	02 58 37.3	−18 41 57	1568	7.64:	−15.5	21	5	5
UGC 2684	LSB/dI	03 20 23.2	+17 17 47	287	7.64:*	−12.8	41	43	28
ESO 489-G56	LSBG	06 26 17.0	−26 15 56	495	7.49	−13.7	39	6	6
ESO 577-G27	LSBG	13 42 46.9	−19 34 54	1410	7.57	−14.4	40	6	6
ESO 146-G14	LSBG	22 13 00.4	−62 04 03	1680	7.61	−16.6	38	5,36	5
DDO 53 [i]	dI	08 34 06.8	+66 10 52	19	7.62:	−13.8	21	22	22
UGC 4483	dI	08 37 03.0	+69 46 50	156	7.53*	−12.8:	21	4,23	20
Leo A	dI	09 59 23.9	+30 44 42	26	7.30	−11.3	24	22,24	24
Sextans A	dI	10 11 05.6	−04 42 28	325	7.49	−14.2	24	22,24	24
Gr8	dI	12 58 39.5	+14 13 02	215	7.62*	−11.2	24	24	24
DDO 187 [j]	dI	14 15 55.9	+23 03 13	154	7.36:	−13.4	21	22	22
Sag DIG [k]	dI	19 29 59.0	−17 40 41	−79	7.42:	−12.1	24	22,24	24

Table 3. continued.

Alternative names: [a] UCM 0049+001; [b] SBS 0335-052; [c] Markarian 116; [d] KUG 0940+544; [e] HS 1013+3809; [f] CG 1116+51; [g] Tol 1223-359, ESO 380-G27; [h] RMB 132, VCC 1313; [i] UGC 4459, VII Zw 238; [j] UGC 912; [k] ESO 594-G4;

References: 1: Kniazev et al. (1999, in prep.), Masegosa private comm. 2: Merlino et al. (1999). 3: Kniazev et al. (1998). 4: Izotov and Thuan (1999). 5: Bergvall et al. (1999). 6: Rönnback and Bergvall (1995). 7: Gallego et al. (1997). 8: Vitores et al. (1996), assuming $B-R$ = 0.6. 9: Masegosa et al. (1994). 10: Telles and Terlevich (1997). 11: Salzer et al. (1989a). 12: Lauberts and Valentijn (1989). 13: magnitude taken from NED. 14: Lipovetsky et al. (1999). 15: Papaderos et al. (1998). 16: Mazarella and Boroson (1993). 17: Kinman and Davidson (1981). 18: Young and Currie (1998). 19: French (1980). 20: Tikhonov and Karachentsev (1993). 21: RC3 (de Vaucoleurs et al. 1991). 22: Skillman et al. (1989). 23: Skillman et al. (1994). 24: Mateo (1998). 25: Arp and O'Connell (1975). 26: Estimated from continum flux in Terlevich et al. (1991), m_B = 18.5 $\pm$ 1, very uncertain. 27: Galaxy from the Cambridge survey. No data in literature on magnitude, nor accurate coordinates. 28: van Zee et al. (1997c). 29: Velocity from the NED-team. 30: Masegosa private communication. 31: Terlevich et al. (1991). 32: Gordon and Gottesman (1981). 33: Pustilnik et al. (1999b). 34: Augarde et al. (1994). 35: Pustil'nik et al. (1995). 36: Bergvall and Rönnback (1995) shows that if effects of shocks are taken into account O/H may be higher (12+log(O/H)=7.68). 37: Kinman and Hintzen (1981). 38: Mathewson and Ford (1996). 39: Gallagher et al. (1995). 40: Matthews and Gallagher (1996). 41: van Zee et al. (1997a). 42: van Zee et al. (1996). 43: van Zee et al. (1997b).

Markarian (1967). However, only a fraction of the objects in these lists are BCGs, the others being AGNs, normal spirals with nuclear star formation, HII regions in the outskirts of nearby spirals etc. Later, many apparently similar objects have been added, mostly from emission line surveys (cf. Sect. 6). This type of galaxy is sometimes also referred to as HII galaxies (Melnick et al. 1985b, Hazard 1986, Terlevich et al. 1991), since they have spectra reminiscent of Galactic HII regions (and were often discovered because of this property). Other types include "blue amorphous galaxies" (Sandage and Brucato 1979, Gallagher and Hunter 1987). Different notation reflects a focus on different physical aspects meaning that the classifications do not necessary overlap completely, and this loosely classified group may contain objects with different evolutionary history. Without arguing that any name is better than the other, we shall henceforth use the name BCGs, unless we want to draw attention to differences. Since many BCGs have been discovered by means of objective prism surveys, which are not very sensitive to the properties of the host galaxy, "ordinary" dIs with bright HII regions may "contaminate" samples selected in this way. Note also that not all galaxies denoted as BCGs in the literature are strictly compact according to a surface brightness criterion. BCGs have luminosities in the range $M_B \approx -12$ to $M_B \approx -21$. Those BCGs which are less luminous than $M_B \approx -17$ are commonly referred to as blue compact dwarfs (BCDs). Interestingly, even some luminous BCGs may be very metal-poor. In Fig. 2 we show the appearance of BCGs on the Digitized Sky Survey, and a LSBG and a normal spiral for comparison. In Fig. 5 and 9 we show high resolution images of the two most metal-poor BCGs, and in Fig. 6 a spectrum of one of them (IZw18).

The blue compact galaxies are the class of objects where most galaxies with low abundances as derived from HII regions have been found. The over-representation of BCGs is probably related to selection effects, since high surface brightness and prominent emission line spectra make it relatively easy to determine nebular abundances. Early studies (e.g. Arp 1965, Zwicky 1966) hinted that BCGs had dramatically different properties compared to "normal" dwarf and giant galaxies. The wide interest in low metallicity BCGs was triggered by the work of Sargent and Searle (1970) and Searle and Sargent (1972) where they showed two BCGs to be metal-poor and forming stars at high rates. They concluded that either these galaxies were young, now forming their first generation of stars, or that star formation occurred in short bursts separated by long quiescent periods (Searle et al. 1973). Today the latter explanation seems the correct one for the majority of BCGs, if not all.

4.4.1. Morphology and structure of BCGs

BCGs are smallish galaxies with high central surface brightness. The detailed morphology and surface photometry of BCGs have been studied by many investigators. The central morphology is often irregular due to the presence of active star formation, but this contains very little information on the extended light distribution which likely traces the dominant stellar mass.

Loose and Thuan (1986a) defined four subclasses depending on the morphology of the central star forming region and the surrounding host galaxy. Kunth et al. (1988) reached the similar conclusion that BCGs constituted a "mixed bag" of morphologies, including objects that appeared to be isolated extragalactic HII regions (e.g. Pox186), irregular morphologies, as well as more common cases with symmetric outer envelopes suggesting the presence of an old population. Salzer et al. (1989b) classified the emission line galaxies in the UM survey according to morphology and emission line properties. Telles et al. (1997) divided HII galaxies into two classes: Type I which have irregular morphology and are more luminous, while Type II have symmetric and regular outer structure. The existence of regular haloes, if corresponding to stellar emission, is in itself suggesting fairly high ages since relaxation times are of the order of a few times 10^8 years. Of course the stars may be younger if they formed later on in an already relaxed gaseous disc.

Quantitative surface photometry reaching faint isophotal levels began with the development of CCD detectors. Bergvall (1985) found that ESO 338-IG04 (=Tol1924–416) followed an exponential like surface brightness distribution in the I-band, suggesting the presence of an old stellar disc. Loose and Thuan (1986b) on the contrary found Haro2 to follow a more elliptical like light distribution, with some suggestion of redder colours in the halo. Similar results were obtained by Kunth et al. (1988).

The shape of surface brightness profiles in BCGs has been subject to some debate and both exponential and $r^{1/4}$ laws have been claimed to best match the data. Papaderos et al. (1996a) have proposed that profiles in general can be fit with a three-component model, with an exponential light profile in the outer parts. Exponential outer profiles were also found by Telles and Terlevich (1997). On the other hand Doublier et al. (1997) find $r^{1/4}$ profiles in a substantial fraction of objects, while the rest have exponential light profiles. We note however that these studies do not compare easily because only a few objects are in common. For most BCGs the shape of the profile changes with radius, meaning that the fitting shape will be uncertain and critically depend on the sensitivity limits. Bergvall and Östlin (1999) go deeper than other published studies (to levels fainter than μ_B = 28 mag/arcsec^2), and claim that $r^{1/4}$ types laws are favoured when using deep red (R or I band) data, but that discs provide decent fits to the outer parts, and are favoured for B-band data. The shape of the luminosity profiles depends on how one constructs them, and especially the amount of central excess (identified with the "starburst" component) depends critically on the chosen method (Marlowe et al. 1997). Several investigators have found high underlying surface brightness (μ_B = 20 to 23 mag/arcsec^2) and short scale lengths in BCGs as compared to other dwarf galaxies (Papaderos et al. 1996a, Telles and

Terlevich 1997, Marlowe et al. 1997). Bergvall and Östlin (1999) find much lower central surface brightness values when using deeper data for a sample of luminous BCGs. Thus there might be differences arising from the different nature of the objects, but also from different observational methodology. Now, one can ask what meaning the shape of the luminosity profile really has? Most dIs and LSBGs, and faint dEs, are well described by exponential like laws, while $r^{1/4}$ laws are found in ellipticals of high and low (e.g. M32) luminosity. Recently, Jerjen and Binggeli (1997) showed that brighter dEs gradually approach the luminosity profiles of Ellipticals, although they never become as curved as $r^{1/4}$. A systematic homogeneous survey at faint isophotal levels, including all known types of low luminosity galaxies would be illuminating and moreover useful in understanding relations between dwarfs. For an example, see Fig. 8 where we show a luminosity profile of IZw18.

In general, the central parts of BCGs contain one or a few star forming knots (often found to be composed of many individual bright star clusters), which may be identified with the "starburst" region. The central knots in most cases give rise to excess surface brightness. To quantify the strength of the starburst the excess light may be integrated and compared to the underlying galaxy light. This gives rather modest starbursts in most BCGs, amounting to a brightening with typically less than one magnitude in the blue (Marlowe et al. 1999, Papaderos et al. 1996b). Given that it must have a low mass to light ratio, this suggests that the starburst contains only a minor fraction of the integrated stellar mass, and that the subsequent fading in luminosity will be very moderate. Of course, some of these galaxies may already have passed their SFR peak and be in the process of fading. However, the amount of central excess depends on how luminosity profiles were constructed and to what depth the profiles are fitted, and moreover depends on an a priori assumption of the true shape of the underlying galaxy. If whatever creates the increased star formation does so, not only in the centre, but throughout the galaxy in question, the "burst strength" will be underestimated. Colour profiles can here yield useful additional information.

4.4.2. The age of the underlying population

To detect underlying old populations it is essential to reach faint isophotal levels, and moreover to take into account the possible contamination from gas ionised by UV-photons leaking out from the central starburst. Thuan (1983) attempted to constrain the star formation histories by NIR aperture photometry and concluded that BCGs were old. However, this was based on central colours and old models, and the data do no longer allow for an unambiguous conclusion. Surface photometry or resolved star photometry would be the preferred method to investigate ages of BCGs. With modern detectors, it is feasible to make surface photometry of metal-poor BCGs at faint levels in the near IR. Bergvall and Östlin (1999) found a very clear signal in $V-J$ of old stars formed on rather short timescales in the haloes of some luminous BCGs, while e.g. $B-V$ remained inconclusive, illustrating the power of NIR observations.

Loose and Thuan (1986b) and Kunth et al. (1988) found $B-R$ colours to redden with increasing radius, suggesting the presence of underlying old populations. Optical surface photometry has continued to unveil red haloes in most BCGs studied in detail (Papaderos et al. 1996, Doublier et al. 1997,1999; Marlowe et al. 1999) and Telles and Terlevich (1997) found the underlying colours to be consistent with those of blue LSBGs and amorphous galaxies. However ages and star formation histories are not yet well constrained, since model predictions are degenerate. In many cases, the most influential parameter is the assumed shape of the star formation history which is what one wants to determine ultimately. Depending on how deep the halo is to be probed, and what pass band is used, different ages are obtained for the underlying population, indicating that composite stellar populations are present, or that nebular emission contributes to the colours, or both. For an example of colour profiles revealing a redder halo, see Fig. 8.

Nevertheless, all these studies demonstrate that the majority of BCGs are not young. Cases were no underlying populations have yet been found exist, but as more detailed studies are performed, old populations turn up in most young galaxy candidates, as e.g. in the previous young galaxy candidates Pox186 (Kunth et al. 1988; Doublier et al. 1999) and ESO 400-G43 (Bergvall and Jörsäter 1988; Bergvall and Östlin 1999).

4.4.3. Ongoing star formation, starbursts and star clusters

The present star formation process is another important aspect of BCGs, since they offer fine laboratories for studying vigorous star formation in metal-poor environments with relatively small extinction problems. The ongoing star formation has been studied by means of spectral synthesis of either integrated colours (Thuan 1983, Bergvall 1985) or spectral energy distributions (Lequeux 1981, Thuan 1986, Fanelli et al. 1988, etc.) or both. This gives information on the current star formation event and in general short bursts are found to best match the data (e.g. Mas-Hesse and Kunth 1999). However this does not exclude longer star formation episodes as the following example illustrates: if star formation propagates through a galaxy, but typically takes place in individual luminous short lived HII regions, from studying the most luminous HII region one might get the illusion to witness a sudden starburst event although the average SFR might have been continuous. With this in mind, we can use spectral synthesis to investigate the duration of individual star-forming events, the initial mass function (IMF), the stellar content (e.g. WR stars), and other interesting properties.

That most BCGs are not necessarily efficient star formers was shown by Sage et al. (1992) who investigated the neutral and molecular gas, infrared and optical properties of a small sample of BCGs and dIs. Most galaxies were found to be not more efficient than normal spirals in forming stars, the star formation efficiencies being high only when compared to other dwarfs. However compact star clusters (see below) require high SFRs to be gravitationally bound and there are indeed BCGs which appear to be very efficient star formers, and true dwarf analogues of giant starbursts.

Detailed studies have revealed that star formation in BCGs and dwarf starbursts often take place in dense “super star clusters” (e.g. NGC1569, Arp and Sandage 1985; NGC1705, Melnick et al. 1985a). Super star clusters (SSCs) are comparable in luminosity to R136 (the central cluster of 30 Doradus in the LMC), and are sometimes much more luminous. It has been proposed that these may be newly born globular clusters, although it is still quite uncertain whether they are massive enough and if they are gravitationally bound. Conti and Vacca (1994) studied He2-10 and Meurer et al. (1995) nine starbursts galaxies, both using the HST/FOC, to find bright SSCs with UV luminosities close to those expected for proto globular clusters. Östlin et al. (1998) studied the luminous metal-poor BCG ESO 338-IG04 (=Tol1924–416) with the HST/WFPC2 and found more than hundred luminous star clusters whose ages and masses were estimated from multicolour photometry. It would be interesting to know to what extent it is a general feature of BGCs to reveal young star clusters when studied with enough spatial resolution. Given that special conditions may be required for SSCs to form, their presence and abundance can yield important insights into the starburst mechanism. Similar objects are found in massive starbursts (e.g. M82, O'Connell et al. 1995), merging galaxies (e.g. the *Antennae*, Whitmore & Schweizer 1995), and in the circum-nuclear regions of giant barred spirals (e.g. Barth et al. 1995). Ho and Filipenko (1996) managed to determine the velocity dispersion of SSCs in NCG1569 and NGC1705 and showed that they have masses on the order of $10^5 M_\odot$, comparable to old Galactic GCs.

Bound massive star clusters offer an alternative way to probe the SFH in BCGs (and other galaxies). Thuan et al. (1996) found old GCs around Mrk996, and Östlin et al. (1998) in addition to old ones a rich population of intermediate age ($\sim$ 2.5 Gyr) GCs in ESO 338-IG04, revealing a former starburst event. In view of the many young SSCs at least a fraction could survive to become GCs. Moreover, young SSCs may be used to investigate the recent evolution of the starburst because they represent true "simple stellar populations" (coeval on a time scale of around one million year) and should be chemically homogeneous. In the case of ESO 338-IG04 it is clear from the age distribution of young SSCs that the present burst has been active for at least 30 Myrs (Östlin et al. 1998, 1999c).

4.4.4. The Wolf-Rayet galaxies

Wolf-Rayet (WR) stars are considered to be highly evolved descendants of the most massive O-stars. They are extreme Population I stars and have spectra characterised by broad emission lines resulting from dense, high-velocity winds. These stars are detectable in external galaxies by their prominent emission lines at around 4650-4690 Å (the "Wolf-Rayet bump"). This bump has been detected in many emission line galaxies (Allen et al. 1976, Kunth & Sargent 1981, Kunth & Joubert 1985, Conti 1991, Vacca & Conti 1992; see Schaerer et al. 1999 for the latest updated catalogue), providing a new insight on the process of massive star formation in metal-poor galaxies. Arnault et al. (1989), Cerviño & Mas-Hesse (1994), Meynet (1995) and Schaerer & Vacca (1998) have discussed the dependence of the WR bump strength on the parameters that define the star-forming episodes (metallicity, age, IMF slope, etc.). The two most interesting properties of the Wolf-Rayet bump is its strong dependence on metallicity and the constraints it can impose on the age of the cluster. Since the WR phenomenon is tightly coupled to the generation of strong stellar winds, its incidence decreases significantly with decreasing metallicity, so that at $Z = 1/20\ Z_\odot$ only very massive stars (initial mass $>$ 80 $M_\odot$) might become WR stars. This small mass range implies that the detection of the WR bump in low metallicity galaxies can provide important information on the upper mass limit of the IMF.

The relative population of WR to O stars is usually measured through the $L(WR)/L(H\beta)$ ratio, the luminosity of the WR-bump over the $H\beta$-luminosity. To compare with model predictions it is necessary to integrate over the whole ionised region which poses some observational technical problems. The measurements of this ratio might also be strongly affected by differential extinction. Since $L(WR)$ is of stellar origin, it should be affected by the same extinction as the stellar continuum. On the other hand, $L(H\beta)$ is of nebular origin and might suffer from a larger amount of extinction. Ignoring this effect may lead to a significant overestimation of the $L(WR)/L(H\beta)$ ratio. Schmutz and Vacca (1999) have questioned the use of the 4640Å emission feature which may not entirely be due to WR stars but to large numbers of O stars or contamination from other nebular lines. Observations show that very short bursts are compatible in general with a Salpeter IMF and a large upper mass cut-off. Recent results by Cerviño (1998) show that if a significant fraction of massive stars are formed in binary systems, mass transfer episodes can lead to the formation of WR stars during longer periods of time than predicted by models based on the evolution of single stars alone. Therefore, age calibrations through WR features has to be taken with caution.

Schaerer (1996) has evaluated the effect of the evolution of the WR stars population on the HeII narrow emission line at 4686 Å, by combining model atmospheres accounting for stellar winds with evolutionary tracks. He concludes that for metallicities in the range $Z = 1/5\ Z_{\odot}$ to $Z_{\odot}$, a strong nebular HeII emission line should originate in early WR phases when WC stars begin to appear. The HeII emission line is indeed detected in a few objects with very young stellar populations, below 3 Myr, and therefore starting to produce WR stars (NGC 2363 and Mrk 36), in good agreement with the scenario proposed by Schaerer. This is also supported by the detection of WR stars in IZw18 (that came as a surprise in view of its very low metallicity) (see Fig 7; Legrand et al., 1997b, Izotov et al. 1997a). A last argument is the spatial distribution of the nebular HeII lines that follows that of the WR features (Legrand et al. 1997b, Maiz-Apellaniz et al. 1998, and De Mello et al. 1998). Other broad emission lines from CIV at 5805Å originating from WC stars (representing more evolved phases than WN stars) are currently observed (Schaerer et al. 1997,1999). The observations of WR features in low metallicity objects is indeed a challenge to our understanding of the WR phases and forces to reassess the metallicity dependence of stellar winds, the binary channel for WR production and the effect of rotation onto the evolution of massive stars (Maeder and Meynet, private communication).

4.4.5. Gas content and dynamics of BCGs

The kinematics of galaxies may be investigated by means of the motion of their stars or gas. In BCGs the former is in general not possible, due to the absence of strong absorption lines, and studies have been restricted to the gas phases.

Chamaraux et al. (1970) were the first to detect neutral hydrogen in a BCG, namely IIZw40, and more BCGs were detected in various surveys (not only targeting BCGs): Lauqué (1973), Bottinelli et al. (1973, 1975), Chamaraux (1977). Gordon and Gottesman (1981) and Thuan and Martin (1981) conducted the first extensive systematic surveys of neutral hydrogen in BCGs, and in total more than 200 BCGs, predominantly in the northern hemisphere, were observed and the majority detected. BCGs have been found to be gas rich. The ratio of neutral hydrogen mass to integrated blue luminosity is typically in the range $0.1 \leq M_{HI}/L_B \leq 1.0$ (in solar units, Thuan and Martin 1981, Gordon and Gottesman 1980). Thus BCGs are as gas rich as spirals and dIs, but less than LSBGs (Staveley-Smith et al. 1992).

HI interferometry of IIZw40 was reported by Gottesman and Weliachew in 1972, providing the first spatially resolved investigation of HI in a BCG. This was followed by studies of IIZw70+71 by Balkowski et al. (1978) and IZw18 by Lequeux and Viallefond (1980) and Viallefond et al. (1987) who suggested the existence of dark matter (perhaps molecules) to account for the dynamical mass. Bergvall and Jörsäter (1988) provided a detailed mass model for ESO 400-G43 and also found evidence for dark matter dominated dynamics in agreement with recent findings by Meurer et al. (1996, 1998) and van Zee et al. (1998c). A substantial fraction of BCGs seems to have HI companions (Taylor 1997), probably representing uncatalogued gas rich LSBGs.

There is a current view suggesting that the formation of stars depends primarily on the amount of molecular gas. However the situation in low metallicity gas is still under debate. Many attempts to detect CO in BCGs galaxies have been reported so far (Combes 1986, Young et al. 1986, Arnault et al. 1988, Sage et al. 1992, Israel et al. 1995, Gondhalekar et al. 1998) but the CO luminosity of BCGs is very low, in comparison with their observed star formation rate, mostly yielding only upper limits. This lack of detection may be because the low metallicity of BCGs hides the true molecular phase by a low CO to H_2 conversion factor. However other explanations may be invoked as well: the CO excitation could be lower than for molecular clouds in our Galaxy, or the molecular clouds in BCGs could be UV-photodissociated as a result of high star formation rates. Gondhalekar et al. (1998) conclude that the CO luminosity correlates rather weakly with the FIR luminosity, i.e. FIR luminosity may not be a good tracer of molecular gas. Obviously the lack of CO detection does not preclude the presence of H_2 molecules in these gas-rich galaxies. In fact there are mechanisms by which molecular hydrogen can be formed in absence of grains from hydrogen atoms in gaseous phase via a reaction involving negative hydrogen ions (Lequeux and Viallefond 1980). It is therefore possible that in star-forming galaxies with well localised massive star formation surrounded by huge HI gaseous envelopes that the molecular hydrogen is abundant and makes up a significant fraction of the dark matter dynamically detected (Lequeux and Viallefond 1980, Lo et al. 1993). New capabilities such as the FUSE mission will offer the unique possibility to detect for the first time cold H_2 in absorption against the stellar continuum of blue massive stellar clusters. IZw18 will be the first target to be searched for H_2.

Östlin et al. (1999a,b) investigated the Hα velocity fields of a sample of luminous BCGs utilising scanning Fabry-Perot interferometry. The velocity fields were found to be complex, and in many cases showed evidence for dynamically distinct components, e.g. counter rotating features. Their analysis suggests that mergers involving gas rich dwarfs are the best explanations for the starbursts in these systems. Masses were modelled both dynamically and photometrically, and some galaxies showed apparent rotational mass deficiencies which could be explained if the studied BCGs are not primarily supported by rotation, if stars and gas are dynamically decoupled (e.g. due to gas flows) or if the galaxies are not in dynamical equilibrium. There are also indications that the width of emission lines in BCGs is related to virial motions and may provide dynamical mass estimates (see Sect. 7.1, and Melnick et al. 1987).

Flows in the ionised gas have been detected in several BCGs (Marlowe et al. 1995; Martin 1996, 1998; Meurer et al. 1997), and suggested by X-ray observations in VIIZw403 (Papaderos et al. 1994). Flows have also been found from studies of the Lyα emission. Although Lyα emission in starbursts is expected to be strong, it turns out that dust is very effective in suppressing this line because the effects of resonant scattering in a gas-rich medium dramatically reduce the effective mean free path of the Lyα photons. On the other hand this mechanism does not explain why in many galaxies with little dust content such as IZw18 (Kunth et al. 1994) Lyα is seen in absorption whereas in dustier ones such as Haro2 (Lequeux et al. 1995) the line is seen in emission but with a clear P-Cygni profile. Kunth et al. (1998) found that the strength of Lyα emission is in fact only weakly correlated with metallicity and suggested that the dynamical state of ISM is also a major regulating mechanism. A new model explains Lyα profiles in starburst galaxies by the hydrodynamics of superbubbles powered by massive stars (Tenorio-Tagle et al. 1999).

4.4.6. Starburst triggers in BCGs

Searle and Sargent (1972) had already speculated on the reasons for a sudden increase of the star formation rate in BCGs, followed by long quiescent phases. The regulation of their star formation histories in general, is of course a very important question, intimately linking to the physical relations between BCGs and other dwarfs, which will be addressed in Sect. 7.2. Moreover, given the heterogeneity of BCGs as a class the possibility that different mechanisms operate is not excluded. The star formation rate in BCGs (even the mass averaged value, cf. 3.2) varies considerably, and some are rather star forming dwarfs than starburst ones. Given the increased central HI densities (van Zee et al. 1998c) it is evident that some mechanism that can concentrate gas in the centres is needed.

A scenario with statistical fluctuations proposed by Searle et al. (1973), has been further elaborated by Gerola et al. (1980). The basic ingredients are a positive feedback of star formation which in combination with the small masses of BCGs give rise to large fluctuations in the SFRs. A popular explanation is that supernova driven winds halt star formation by expelling the gas. Later, the lost gas might accrete back on the galaxy and create a new starburst (Tayler 1975, Dekel and Silk 1986, Silk et al. 1987, Babul and Rees 1992). A problem with models where the precursor accretes gas continuously is the time scale for onset of rapid star formation, – why would the galaxy wait to form stars for a long time, then suddenly (on time scales of the order of 10^7 years) burst into an unsustainable star formation rate?

It is well known that mergers between giant galaxies can produce impressive starbursts (Sanders et al. 1988), and it is possible that mergers are key mechanism in building up the galaxy population and regulating starburst activity (Lacey et al. 1993). Therefore this possibility is attractive also for explaining dwarf starbursts, i.e. BCGs. It is evident that there are at least a few BCGs that seem to be interacting/merging in some form (e.g. IIZw40, He2-10, and galaxies in Östlin et al. 1999a,b). Moreover, many of these BCGs show Super Star Clusters (SSCs) of the same kind as those found in giant mergers.

On the other hand several studies indicate that many BCGs are pretty isolated (cf. Sect. 6.3). However there might be low surface brightness or pure HI companions missing in present catalogues. A related question is whether tidal interactions are strong enough to ignite bursts in dwarfs that, like BCGs (Salzer 1989) are not accompanied by giant galaxies. First, tidal forces between dwarfs are too modest to trigger radial gas flows unless the galaxies are almost in contact (Campos-Aguilar et al. 1993). Moreover it is uncertain whether dwarfs are at all unstable against tidal perturbations (Mihos et al. 1997). Perhaps a direct contact is needed to trigger dwarf starburst explaining why pairs are rare since one would only pick up the burst once the merger is already in progress. While mergers would be sufficient for producing BCGs it is uncertain how common they are. The environments of isolated BCGs should be studied in more detail for this purpose.

4.4.7. The chemical abundances of BCGs

Blue compact galaxies (BCGs) include galaxies with the lowest measured abundances as derived from HII regions. Since both BCGs and dIs in general possess bright HII regions, many investigations of nebular abundances deal with objects of both classes, which in any case are not always very distinct. Very little is known about the

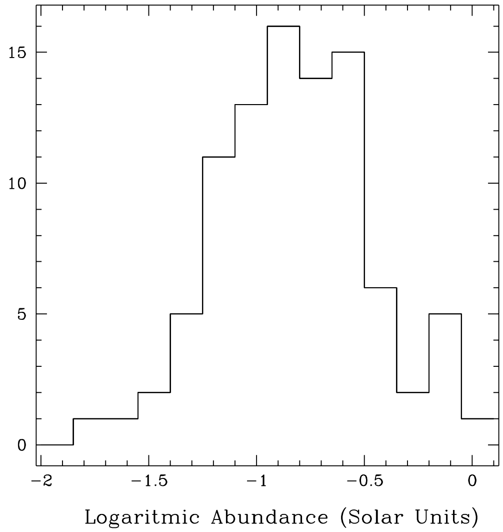

Fig. 3. The metallicity distribution of BCGs/HII-galaxies from Terlevich et al. (1991), as measured by their oxygen abundances. Note the peak at ∼1/10:th $Z_\odot$, which at least partly may be due to selection effects. (Courtesy R. Terlevich)

metallicity of the stellar population of BCGs. Schulte-Ladbeck et al. (1999), using a colour magnitude diagram, derive [Fe/H]= -1.92 for the old population in VIIZw403, one of the most nearby BCGs, which has a previously reported oxygen abundance of 12+log(O/H) $\approx$ 7.7 (Tully et al. 1981, Izotov and Thuan 1999); it is included in Fig. 1. Mas-Hesse and Kunth (1999), from the correlation between the strength of the stellar absorption lines from massive stars (CIV and SiIV) and O/H as obtained from the nebular lines, argue that the metallicity of the young stellar populations is similar to the gas metallicity.

The metallicity of BCGs was first addressed by Searle and Sargent (1972), who showed that the abundances of oxygen and neon in I Zw18 and II Zw40 were subsolar. Their work has been followed by numerous investigations over the years which have established their nature as metal-poor galaxies, as regards oxygen: Alloin et al. (1978), Lequeux et al. (1979), French (1980), Kinman and Davidson (1981), Kunth and Sargent (1983), Kunth and Joubert (1985), Campbell et al. (1986), Izotov et al. (1991), Peña et al. (1991), Pagel et al. (1992), Gallego et al. (1997) and others. A recent investigation of a large sample of 80 HII-galaxies can be found in Masegosa et al. (1994). Izotov and Thuan (1999) present O, N, Ne, S, Ar and Fe abundances for 50 BCGs, and in addition C and Si abundances for 7 of these, thereby constituting the largest homogeneous high quality source of information for metal-poor BCGs.

The abundances of heavy elements in these objects range between $1/2\ Z_\odot$ and $1/50\ Z_\odot$, making them among the least chemically evolved objects in the universe. Figure 3 shows the distribution for oxygen abundance among HII galaxies. Oxygen is assumed to be representative of the total metallicity of the entire galaxy, although claims have been reported that this may only concern the HII region because of incomplete mixing (Kunth and Sargent 1986, Kunth et al. 1994, Roy and Kunth 1995, see Sect. 3.5). Figure 3 reveals that the oxygen abundance in this class of objects peaks slightly above 1/10 of the solar value. This peak may be related to selection effects since many surveys have selected galaxies with strong forbidden oxygen emission lines, which happen to be strongest for an oxygen abundance of around ten percent of the solar value. There is indeed another strong selection bias in Fig. 3 because it includes only galaxies with "measurable" electron temperatures (through the use of [OIII]λ4363) hence restricts the sample to abundances lower than 12+log[O/H] $\approx$ 8.5. The apparent low abundance cut-off is bounded by IZw18 (Sect. 5). The utter lack of known galaxies with abundances smaller than IZw18, despite concentrated observational efforts (see Sect. 6) has been a puzzle. Kunth and Sargent (1986) suggested that IZw18 could indeed be a primordial galaxy in which the observed HII regions have been self-enriched in the current burst. This idea has been tested by several distinct approaches, but we will see (Sect. 5.1.2) that there are many indications that IZw18 is in fact old.

According to Izotov and Thuan (1999), nine BCGs more metal-poor than 1/20 of solar exists. These are: IZw18, SBS 0335-052, SBS 0940+544, SBS 1159+545, UGC 4483, CG 389 (Izotov and Thuan 1999); CG 1116+51 (French 1980); Tololo 65 and Tololo 1214-277 (Pagel 1992). However another half dozen examples can be found in the literature, with the most metal poor being UM 382 12+log(O/H)= 7.45 (Masegosa et al. 1994). In Table 3 we list all known BCGs with oxygen abundances $\sim$1/20 solar and below. As we discuss in Sect. 6.1.5 the number of very metal-poor galaxies will probably increase significantly in the near future. In total there are more than a dozen very metal-poor ($Z \leq 1/20 Z_{\odot}$) BCGs known, while the number of BCGs with $Z \leq 1/10 Z_{\odot}$ is several times larger.

4.4.8. Abundance ratios in BCGs

Oxygen is normally considered as representative of the metallicity of BCGs. However HII region abundance analysis can also provide abundances of other elements. Especially nitrogen, helium and carbon have been investigated. In addition α elements such as argon, neon and sulphur may be studied. Lately, iron has been added to the list. The study of helium in BCGs offers a route towards determining the primordial He abundances, and will be discussed separately in Sect. 8.1. In Fig. 4 we show C/O and N/O vs. O/H for BCGs.

The investigation of carbon abundance in the HII gas poses some difficulties since there are no strong emission lines in the optical regions. The investigation of carbon abundances in BCGs began with the International Ultraviolet Explorer (IUE) satellite and has continued with the HST. Garnett et al. (1995) presents C/O ratios for seven galaxies, including some BCGs, and three others are presented by Kobulnicky and Skillman (1998). Thus carbon abundances are still not very well explored in BCGs. Garnett et al. (1995) found that C/O increases with increasing oxygen abundance. The average value of this ratio is rather low, as compared to solar, except possibly for IZw18 which has C/O about a factor of two larger than predicted from stellar nucleosynthesis (Garnett et al. 1997).

The relative abundance of nitrogen to oxygen increases with O/H (Pagel and Edmunds 1981, Serrano and Peimbert 1983, Torres-Peimbert et al. 1989), implying a secondary origin of N in the CNO cycle. Such a behaviour was not seen at very low O/H (Lequeux et al. 1979; Kunth and Sargent 1983; Campbell et al. 1986) indicating that nitrogen is mainly a primary element in very metal-poor gas. The current interpretation of this behaviour from stellar nucleosynthesis models is that intermediate stars produce primary nitrogen by hot-bottom burning. In such a phase, the third dredge-up brings carbon-rich material from the core onto the hydrogen burning shell (Renzini and Voli 1981; van der Hoek and Groenewegen 1997). The scatter of the N/O versus O/H diagram has been considered as larger than the observational uncertainties (although they were nearly comparable two decades ago). Time delays between the production of oxygen due to massive stars and that of nitrogen is likely part of the explanation although this point of view has been challenged by recent data from Izotov and Thuan (1999). Indeed their high signal to noise observations not only suggest a small intrinsic dispersion of log N/O ($\pm$0.02 dex) at low metallicities but a similar behaviour is found for C/O and other ratios, see Fig. 4. The disagreement with Garnett et al. (1995,1997) comes mainly from the reassessment of C/O in IZw18, the abundances of which are thoroughly discussed in Sect. 5.1.1. Izotov and Thuan (1999) find positive correlations between C/O and N/O with O/H but for 12+log(O/H) $\leq$ 7.6, C/O and N/O remain constant and independent of O/H. They

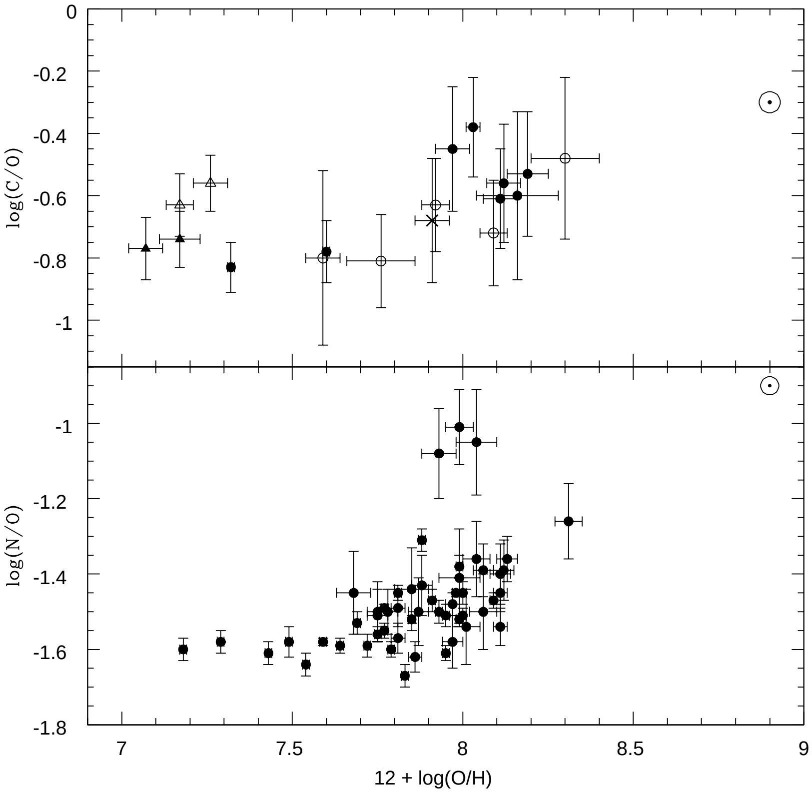

Fig. 4. Element ratios in BCG and dIs: **Top:** The relation between oxygen abundance and C/O. Filled symbols are from Izotov and Thuan 1999, which includes a reanalysis of previously published data. The open circles are from Garnett et al. (1995). The cross is ESO 338-IG04 (Bergvall 1986, Masegosa et al. 1994). The open triangles show the location of the NW and SE regions in IZw18 from Garnett et al. (1997), while the filled triangles show the same regions as derived by Izotov and Thuan (1999). **Bottom:** The relation between oxygen abundance and N/O for BCGs, data taken from Izotov and Thuan (1999).

conclude that galaxies with such low abundances are genuinely young (less than 40 Myr old), now making their first generation of stars. Moreover they suggest that all galaxies with $7.6 \leq 12+\log(O/H) \leq 8.2$ have ages from 100 to 500 Myr. Thus, the question raised by Searle and Sargent almost 30 years ago would after all have a positive answer. However, there are independent data suggesting that these galaxies do in fact contain old stars (see Sect. 5). Moreover, there are definitely many BCGs with $12+\log(O/H) < 8.2$ which have been convincingly shown to be much older than 500 Myr, e.g. ESO 338-IG04 from its globular clusters (Östlin et al. 1998). Moreover, as we shall discuss below, there are alternative interpretations of the abundance patterns which do not require the galaxies to be young.

HII regions in the outskirts of spiral galaxies may have C/O values as low as those of the most metal-poor galaxies, and HII regions in spiral galaxies follow the same C/O vs. O/H relation as dwarf galaxies (Garnett et al. 1999). This suggests that they evolve chemically in the same manner. Now, the discs of spiral galaxies are several Gyr old, still the C/O ratio is as low as in the most metal-poor BCGs, clearly indicating that C/O is not simply a function of age. The observed trend of C/O vs. O/H could equally well be explained by a metallicity dependent yield (Maeder 1992). Gustafsson et al. (1999) studied the carbon abundances of disc stars in our Galaxy and concluded that the observed relation could be explained if carbon production occurs mainly in massive WR(WC) stars. In this scenario, C/O would be mainly a function of metallicity and not age.

A similar pattern is seen for N/O observations of HII regions in spirals. Outlying HII regions appear to have N/O similar to the most metal-poor galaxies (van Zee et al. 1998b). Moreover, the low surface brightness galaxies studied by Rönnback & Bergvall (1995) which are still fairly old systems have N/O comparable to those of the most metal-poor BCGs (Bergvall et al. 1999). Pilyugin (1999) finds that if significant N production occurs in intermediate mass stars, and the heavy element abundances have not been polluted by the present star formation event (i.e. the time scale for cooling of fresh metals is longer than the typical lifetime of a giant HII region) the constant N/O found at low metallicity is consistent with the presence of previous starbursts, i.e. high ages. It is also worth commenting that if the time scale for recycling is longer than the duration of a typical burst of star formation, this can explain the lack of abundance gradients in dwarfs (Sect. 3.5).

The elements Ne, Si, S and Ar all shows a constant abundance relative to oxygen, independent of O/H as expected from stellar nucleosynthesis, since they are products of α-processes (Izotov & Thuan 1999). Finally the Fe/O abundance ratio in BCGs is on average 2.5 times smaller than in the Sun with a mean $[O/Fe] = 0.40 \pm 0.14$ with no dependence on oxygen abundance (Izotov and Thuan 1999). The scatter is surprisingly small considering the short time scale for the production of oxygen as compared to iron production because different stellar masses are involved. If real, it would imply that Fe could have been produced by explosive nucleosynthesis of SNe type II for both O and Fe at the early stage of chemically unevolved galaxies.

4.4.9. Summary on BCG metallicities

In summary we find that the study of heavy elements in BCGs shows that these systems are chemically unevolved but does not allow to infer a young age in terms of galaxy formation. In the range $7.1 < 12 + \log(O/H) < 8.3$ more than 100 objects have good quality data. Alpha-elements (Ne, Si, S and Ar) have abundances relative to oxygen that show no dependence on oxygen abundance and are close to solar values and similar to that in halo stars and distant galaxies. At low metallicities, C/O is constant, independently of the oxygen abundance but more metal deficient galaxies should be observed to confirm the presence or absence of a trend. The behaviour of N/O indicates a primary origin as anticipated already by several investigators (see Matteucci 1996, and references therein). The conclusion that N, C, Fe and O are produced only by massive stars in the most metal-poor systems (Izotov and Thuan 1999) needs to be checked by independent observers with larger samples. There is a possibility that metals observed in the most metal-poor galaxies originate from previous population III star enrichments, previous bursts or continuous star formation at very low rate. In this case the minimum metallicity should be increasing with time, consistent with quasar absorption line data (Lu et al. 1996), although admittedly the connection to dwarfs is not clear. The question of young galaxies has to be further addressed before it can be settled, but as we have seen, most BCGs (including objects with less than 1/10 solar metallicity) are definitely not young. Even the best candidates I Zw18 and SBS 0335-052 seems to be old although Izotov, Thuan and their collaborators still dispute this.

While abundances and abundance ratios are the footprints of the past chemical evolution, many factors need to be taken into account to unveil the enrichment history and chemistry alone is of limited value in constraining the history of galaxies. Still, the set of data presented by Izotov & Thuan (1999) is probably unique with respect to data quality, homogeneity and the large number of atomic species included, making it a most valuable tool.

4.5. Tidal dwarfs

Zwicky (1956) proposed that dwarf galaxies could be formed from debris when large galaxies collide, an idea that was further addressed by Schweizer (1978). Though not a real morphological class of its own, this group of galaxies have a common history which is likely to have a considerable impact on their chemical composition. If dwarfs can form from material originating in giant galaxies we would expect them to be comparatively metal rich for a given luminosity. Some recent progress in this field (Mirabel et al. 1992, Duc & Mirabel 1994, 1998) suggests that, even though the final fate of dwarf galaxoids forming in mergers is uncertain, they have metallicities that are systematically higher than in other dwarfs of similar luminosity. Tidal dwarfs thus appear to be a fundamentally distinct class of galaxies. Moreover, their future evolution is uncertain: are they stable, do they contain dark matter, how will they be affected by future interactions with their parent galaxy?

In rich clusters, where interactions should have been frequent, explaining the presence of cD galaxies and the overabundance of ellipticals, we would expect a larger fraction of tidal dwarfs. If they can survive and escape their progenitor, dwarfs in clusters must be more metal rich than field dwarfs. There are preliminary indications that this may be the case (as well as indications that it is not, cf. Sect. 4.1.1.). Of course, galaxies may simply evolve faster in high density environments. Interactions with other galaxies and the intercluster medium may stimulate star formation in dwarfs and make the chemical evolution clock run faster.

In view of their chemical abundances, it is not likely that the local dwarfs have formed this way. But what if this process occurred early in the Universe, at high redshifts when the parent galaxies were not yet significantly enriched?

5. Individual bona fide metal-poor galaxies

5.1. IZw18

The blue compact galaxy IZw18 (also known as Markarian 116) was first described by Zwicky in 1966. IZw18 is the galaxy with the lowest known metallicity as derived from the ionised gaseous component. Its oxygen abundance is only ∼1/50 of that of the Sun. Thus, often being referred to as "the most metal-poor galaxy known", it is still two orders of magnitude more metal rich than the most metal-poor stars in the Milky way. It is intriguing that while IZw18 was the first BCG (together with II Zw40) in which ionised gas abundances were investigated (Searle & Sargent 1972), it remains still the most metal-poor BCG known, despite large efforts in searching for more metal-poor ones.

Neutral hydrogen in IZw18 was detected by Chamaraux (1977), and further investigated using aperture synthesis by Lequeux and Viallefond (1980) who derived $M_{\rm HI} = 7 \cdot 10^7 M_\odot$. Viallefond et al. (1987) mapped the galaxy in HI with VLA and from the velocity field inferred a mass $M_{dyn} \approx 9 \cdot 10^8 M_\odot$. Van Zee et al. (1998a) made a high resolution VLA study of IZw18 which revealed a complex HI morphology and velocity field. A complex velocity field was also found in the ionised component (Martin 1996, Petrosian et al. 1996). Molecular gas has not been detected, not surprising given the low metallicity. Moreover, low extinction is reported in most studies and the galaxy is not detected by the InfraRed Astronomical Satellite IRAS (IZw18 has not been observed with the Infrared Satellite Observatory, ISO), indicating a low dust content. Deep spectra revealed that IZw18 contains Wolf-Rayet stars (Fig. 7; Legrand et al. 1997b; Izotov et al. 1997a) showing that such can exist even at very low metallicities. HST imaging in the optical (Hunter and Thronson 1995, Dufour et al. 1996) and near infrared (Östlin 1999a) resolves the galaxy into individual luminous stars, and shows that the star formation has been active for at least 30 Myrs, with indications of an even older stellar population (see below). In Fig. 5 we show an Hα and V-band images, and in Fig. 6 an optical spectrum of IZw18.

5.1.1. Chemical abundance of IZw18

The first estimate of the metallicity of IZw18 came from Searle and Sargent (1972) who showed that the oxygen abundance was below one tenth of solar, while the He abundance appeared to be normal. Alloin et al. (1978) derived 12+log(O/H)=7.2, which is close to most recent determinations, in particular by Izotov and Thuan (1999) who give 12+log(O/H)=7.18, or 1/50 of the Sun. Values of O/H in the range 1/30 to 1/60 of the solar value have been quoted over the last 20 years. The oxygen abundance seems to be constant, within the errors, over the optical face of the galaxy (e.g. Skillman and Kennicutt 1993, Vilchez and Iglesias-Páramo 1998, Legrand et al. 1999).

C/O was first derived by Dufour et al. (1988) who found [C/O]= -0.27 from IUE and ground based optical observations, an unexpectedly high value: higher than [C/O] in dwarfs like the LMC, indicating that the chemistry in IZw18 is anomalous. This value was later revised down by Dufour and Hester (1990) to [C/O]= -0.5. Garnett et al. (1995) used the Faint Object Spectrograph (FOS) on HST but only got a lower limit [C/O] > -1.3. Later, they re-observed IZw18 with the FOS and found [C/O]= -0.63 and -0.56 for the north-west (NW) and south-east (SE) regions respectively (Garnett

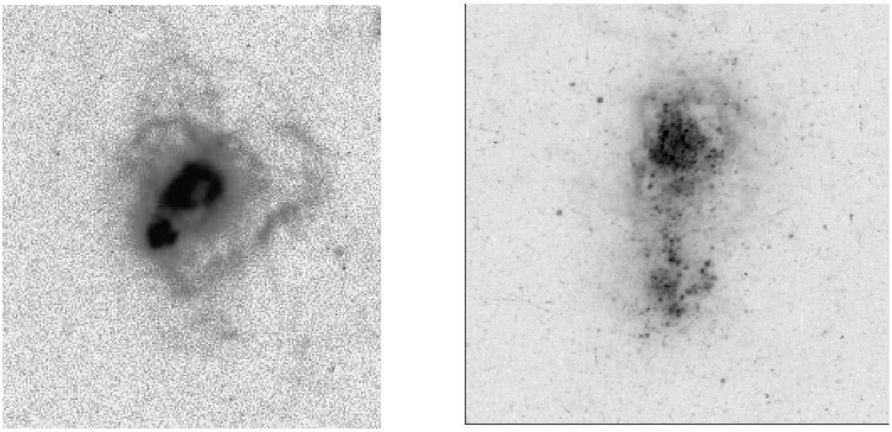

Fig. 5. Left: Continuum subtracted Hα image of IZw18. Note the complex structure and very extended filaments. The dimension is 45 $\times$ 45 arcseconds, north is up, east is left. In the upper right corner, the faint Hα nebula in the companion galaxy is visible. The image was obtained at the Nordic Optical Telescope with 0.65” seeing (Östlin). **Right:** A V-band (F555W) image of IZw18 obtained with the Planetary Camera of WFPC2 onboard HST (cf. Hunter and Thronson 1995). The dimension is 17 $\times$ 17 arcseconds, North is up left, east is down left. (Obtained from the HST archive.) At a distance of 10 Mpc, 1 arcsecond corresponds to 48 pc.

et al. 1997). These values are again rather high when compared to other metal-poor dwarfs and Garnett et al. (1997) proposed that a carbon enrichment from an intermediate age population had occurred previous to the current star formation burst. Recently, Izotov and Thuan (1999) reanalysed the HST data by Garnett et al. (1997), now finding [C/O]= -0.77 and -0.74 for the NW and SE regions respectively. Their lower C/O follows mainly from a higher adopted electron temperature based on new ground based spectra. Izotov and Thuan (1999) also found indications of a temperature gradient, giving rise to the apparent abundance difference between the NW and SE components. These last [C/O] values for IZw18 follow nicely the trend for other very metal-poor galaxies (see Fig. 4). However, the fact that the [C/O] determination has changed so much with time is of course not satisfying. Hence the new value adopted by Izotov and Thuan (1999) should perhaps not be taken at face value since part of their disagreement with other authors might be associated with the imperfect match between HST and ground based apertures. A deep HST UV+optical spectrum with a single instrument like STIS could resolve this issue.

Similar problems were encountered with the study of the nitrogen to oxygen ratio in IZw18 that first yielded lower limits until Dufour et al. (1988) were able to derive [N/O]= -1.36. Izotov and Thuan (1999) recently derived a lower [N/O] of -1.60 in perfect agreement with their overall trend that [N/O] stays constant at low [O/H] in metal-poor galaxies, contrary to previous findings (see Fig. 4). The helium abundance of IZw18 has been a concern for some time. Its value is of special importance for deriving the primordial helium abundance, since IZw18 has the lowest known ISM heavy element abundance of galaxies. Searle and Sargent (1972) found a rather normal He abundance, that later was revised down, e.g. Y = 0.21 (Davidson and Kinman 1985), and Y = 0.226 (Pagel et al. 1992). These values were rather low in view of

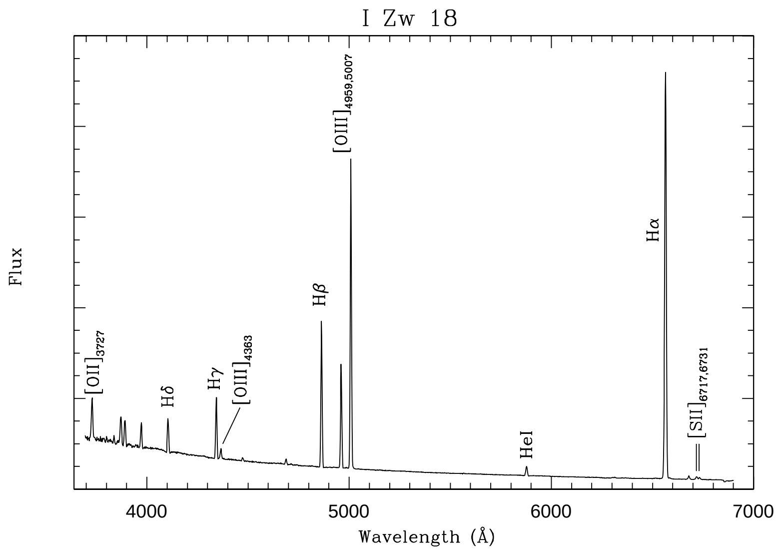

Fig. 6. An spectrum of IZw18, with the most important emission lines labelled. Note the very blue continuum. That IZw18 is a very low abundance object can be seen by noting the following: [OIII]$\lambda\lambda$4959, 5007 and [OII]λ3727 are rather weak with respect to Hβ, while [OIII]λ4363 is relatively strong, and moreover the nitrogen and sulphur lines are very weak. (Plotted from a spectrum provided by F. Legrand).

the standard big bang nucleosynthesis (SBBN) theory. Izotov and Thuan (1998a,b) find Y = 0.242, in comfortable agreement with SBBN.

Kunth et al. (1994) attempted to measure the oxygen abundance in the neutral gas cloud surrounding IZw18 by using UV absorption lines, observed with the GHRS onboard HST. They found that the oxygen abundance could be as low as 1/1000 of the solar value, indicating near pristine gas with abundances lower than what is found in QSO absorption line systems. However the use of saturated lines was criticised by Pettini and Lipman (1995). Van Zee et al. (1998) argue that the HI velocity dispersion together with the measured OI line of Kunth et al. (1994) imply an oxygen abundance $\geq$1/60 of the solar value, suggesting that the chemical enrichment products are well mixed.

5.1.2. On the age of IZw18

Izotov and Thuan (1999) come to the conclusion that all galaxies with 12+log(O/H) $<$ 7.6 must be younger than 40 Myr, thus in practise newly born galaxies; and this would be very much so for IZw18 with its record low abundance (12+log(O/H)=7.18). There are however other possible interpretations of the abundance ratios of metal-poor galaxies (as we already pointed out in Sect. 4.4.8). Moreover there is some independent evidence suggesting that IZw18 does indeed host an old underlying population.

The age of IZw18 has been debated ever since the early seventies when the intriguing properties of this galaxy were first realised. Being the most metal-poor galaxy, it is of course one of the most promising candidates for a genuinely young galaxy. The absence of an outer regular envelope made IZw18 a good young galaxy

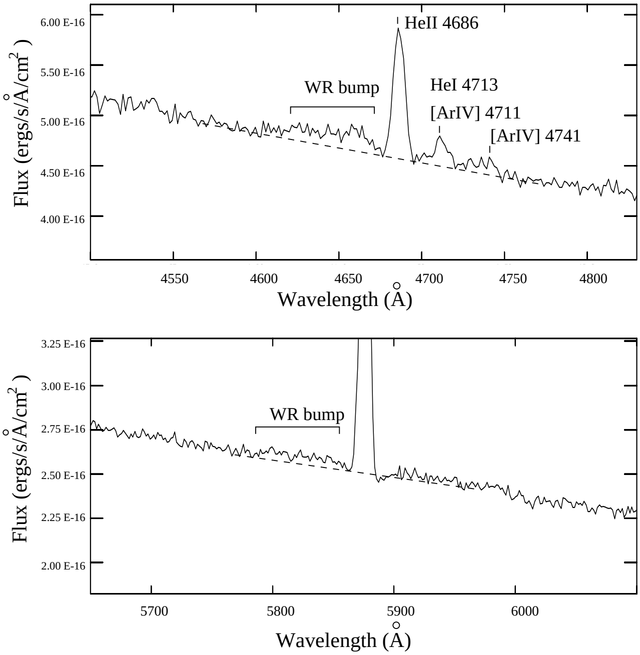

Fig. 7. This figure shows the very weak Wolf-Rayet features detected in a high S/N spectrum of IZw18 (Legrand et al. 1997b; see also Izotov et al. 1997a). (Courtesy F. Legrand).

candidate. Thuan (1983) argued from near infrared aperture photometry that the galaxy was old, but comparing his colours with the recent Bruzual and Charlot (2000) leads to a different conclusion. Moreover the apertures only cover the central part of the galaxy which is dominated by young stars irrespective of the possible presence of an underlying population.

Pantelaki and Clayton (1987) claimed a high age for IZw18 based on the observed C/O and N/O ratios, but these were later revised downwards. A similar argument was given by Garnett et al. (1997) from their new C abundance, that however was revised downwards recently by Izotov and Thuan (1999) weakening the conclusion. In view of the uncertainties on the N/O and C/O ratios and yields, and that these ratios are subtle to interpret anyway, it is clear that they give very limited constraints on the star formation history in IZw18. The chemical evolution model used by Kunth et al. (1995) and the spectro-chemical evolution model of Legrand (1998) also suggest that IZw18 is not young. The latter one predicts that IZw18 could have experienced a low but continuous star formation rate for several Gyr prior to the present burst. Of course the difficulties outlined in Sect. 3 make all constraints on galaxy ages derived from chemistry very uncertain.

IZw18 has been imaged in the optical by HST by two different groups (Hunter and Thronson 1995; Dufour et al. 1996), both finding a resolved population of young massive stars. There was no evidence for old stars, but none against, since the observations were not sufficiently deep to allow old stars to be detected. These data

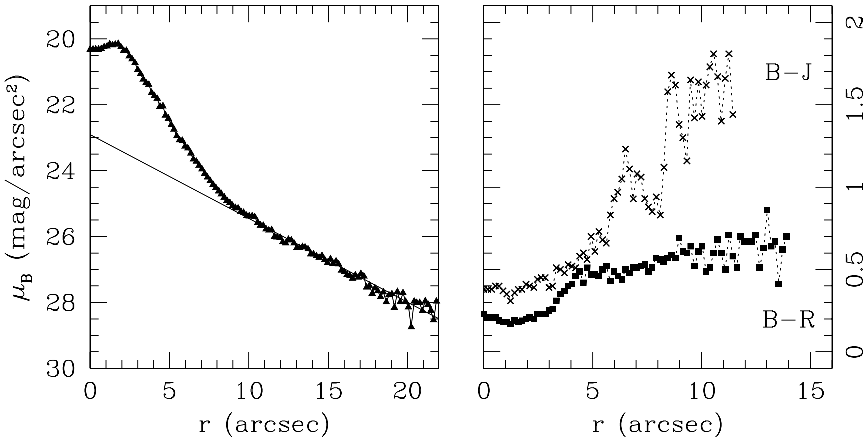

Fig. 8. Luminosity and colour profile of IZw18. **Left panel:** the radial surface brightness profile of IZw18 in B. Note the apparent exponential shape of the profile for radii greater than 10 arcseconds, indicating an underlying low surface brightness component with $\mu_{B,0}$ = 23 mag/arcsec^2. **Right panel:** $B - R$ (filled squares) and $B - J$ (crosses) profiles of IZw18; note the red colours at large radius. From deep images obtained at the Nordic Optical Telescope (NOT) and the UKIRT (Östlin 1999c, in prep).

sets were recently reanalysed by Aloisi et al. (1999) and give support for an age in excess 0.5 Gyr. Östlin (1999a) studied the resolved stellar population in the near infrared with NICMOS onboard HST, and found that while the NIR colour magnitude diagram was dominated by stars 10-20 Myr old, numerous red AGB stars require a much higher age in agreement with Aloisi et al. (1999). The NICMOS data require stars older than 1 Gyr to be present, and an age as high as 5 Gyr is favoured. This holds even if a distance slightly higher than the customary 10 Mpc is adopted.

In Fig. 8 we show surface brightness and colour ($B - R$ and $B - J$) profiles of IZw18 from deep CCD images obtained at the Nordic Optical Telescope and infrared images from the UKIRT (Östlin 1999c). The colours rise continuously with increasing radius and reach $B-R$ = 0.6 (cousins R) and $B-J$ = 1.6 at a radius of 10 arcseconds. If due to purely stellar emission, a single stellar population model with a metallicity of $1/50Z_\odot$ (Bruzual and Charlot 2000) indicates an age of log(age) = 9.1 ± 0.1 for both colours, irrespective of IMF (Salpeter, Scalo or Miller-Scalo). With a more realistic assumption of a more or less continuous star formation rate (e.g. for an exponentially decaying SFR with e-folding time τ = 3 Gyr) we predict an age of at least 5 Gyr. One possible caveat is that there might be a substantial contribution from ionised gas to the colours, but we believe that this is not a dominant effect. The B-band profile has an exponential shape for radii greater than 10 arcseconds; fitting a disc to the outer parts yields a central surface brightness of $\sim$ 23 mag/arcsec^2 and an integrated disc luminosity $M_B = -11.8$. With a mass to light ratio for a 10^9 years old single stellar population, the disc luminosity is equivalent to a stellar mass of $\sim 5 \cdot 10^6 M_\odot$, but may be a factor of two higher if the SFR has been continuous (cf. the predictions by Legrand 1998). With a mass of the young population of $\sim 10^6 M_\odot$ this means that while difficult to detect, the old population dominates the stellar mass. This suggests that IZw18 could be hosted by a low surface brightness galaxy.

Thus, although not foolproof, photometry (of individual stars and surface photometry) now indicates that the galaxy is in fact old, although Izotov et al. (1999a) in a last attempt to resurrect its youth, suggested that the distance of IZw18 has been severely underestimated.

5.1.3. The companion of IZw18

Zwicky noted what he called a “flare” at the north west of IZw18, which has turned out to be a separate galaxy. Hα images showed nebulosity close to the centre of this putative companion galaxy (Fig. 5), suggesting that it had the same redshift as IZw18 (Dufour and Hester 1990, Östlin et al. 1995). This was later confirmed by spectroscopy (Petrosian et al. 1996, Dufour et al. 1996). The HST imaging study by Dufour et al. (1996) was able to resolve several young ($\sim$ 80 Myr) luminous stars, see also Aloisi et al. (1999). It is located in the same HI cloud as IZw18 and its location coincides with a peak in the HI column density (van Zee et al. 1998a).

In view of its position, just a kpc away from IZw18, its chemical composition would be of considerable interest. This galaxy is fainter than IZw18 but still very blue. However spectra have failed to unambiguously detect any oxygen lines, and consequently its metallicity is not known. The problem is that the galaxy has very low central surface brightness (μ_B = 22.7 mag/arcsec^2, Östlin 1999c) making spectroscopy difficult.

5.2. SBS0335-052

For a long time I Zw18 seemed to play in its own league, with no other BCG coming really close to its low oxygen abundance in the HII-gas. However the entrance of SBS0335-052 on the stage changed the situation. This galaxy was found in the Second Byurakan Survey (SBS, Markarian and Stepanian 1983). A number of papers from 1990 and onwards have shown it to be a galaxy with an oxygen abundance comparable to that of IZw18 (Izotov et al. 1990, 1997b; Melnick et al. 1992). Melnick et al. (1992) and Izotov et al. (1997b) both find an oxygen abundance of 1/40 of the solar value. The analysis by Melnick et al. (1992) suggest that the O abundance may be a factor of two higher in a north-western HII region. Thuan et al. (1997) argues that the oxygen abundance in the neutral gas may be even smaller by a factor 100. Mid infrared observations with ISO revals the presence of dust, and a gas to dust ratio typical for more metal rich BCGs (Thuan et al. 1999). VLA observations have revealed an HI mass of $\sim 2 \times 10^9 M_\odot$ and a dynamical mass a factor of a few larger (Pustilnik et al. 1999). An image of SBS0335-052 from the HST archive (see also Thuan et al. 1997) is shown in Fig. 9 and reveals a complex morphology. Like IZw18, SBS0335-052 has a faint companion galaxy (Sect. 5.2.1).

There have been several claims that this galaxy is a truly young galaxy, not containing any underlying old population, (Thuan et al. 1997, Izotov et al. 1997b, Papaderos et al. 1998). The argument put forward is the low metallicity and the lack of any underlying population in surface photometric data. However Lipovetsky et al. (1999) in their study of the companion, present also surface photometry of SBS0335-052. The $R-I$ colours at a radius of 10 arcseconds is $(R-I)$ = 0.4 which indicates

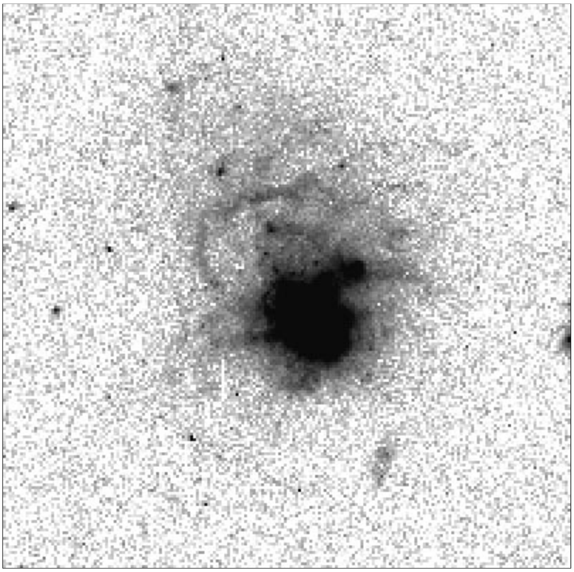

Fig. 9. SBS0335-052 imaged with the Hubble Space Telescope in the V-band, cf. Thuan et al. (1997). The size of the image is 20 × 20 arcseconds corresponding to 5.2 × 5.2 kpc. Note the extended complex filaments. (Obtained from the HST archive.)

an age of several Gyr for a single stellar population model with metallicity 2% solar and a standard Salpeter IMF (Bruzual and Charlot 2000). Nebular gas contamination cannot account for this, since that would make $R-I$ bluer, leading to an underestimate of the age. Even allowing for an internal extinction of $E(B-V)$ = 0.2 an age of 1 Gyr or more is required. Changing IMF, or metallicity (to 20% solar) still leads to an age in excess of 1 Gyr. Relaxing the assumption of instantaneous star formation, and allowing for more realistic SFHs would increase the age to around 10 Gyr (for τ = 3 Gyr, cf. Sect. 5.1.2). Thus, in view of the surface photometry presented by Lipovetsky et al. (1999), the age of >1 Gyr can be regarded as a conservative lower limit. Moreover the presence of red star clusters (Östlin 1999b) suggests an age of several Gyr. These star clusters were discussed by Papaderos et al. (1998) but the models they used to interpret the ages do not agree with other published models, but are systematically off-set, apparently leading to an underestimate of the age of the clusters. Thus, SBS0335-052, like IZw18, is probably not a genuinely young galaxy. In some sense SBS 0335-052 is more extreme than IZw18 in that despite being almost as metal-poor as IZw18, it is more luminous (M_B = -16.7) and thus lies further off the metallicity–luminosity relation for dIs, see Fig. 10.

5.2.1. The companion of SBS0335-052

Like IZw18, SBS 0335-052 also has a physical companion, SBS 0335-052W at a projected distance of 22 kpc (Pustilnik et al. 1999). Lipovetsky et al. (1999) found an oxygen abundance of 12+log(O/H)=7.2, even lower than that of SBS 0335-052, and fully comparable to IZw18. This companion, though blue is not very compact and it has evidently avoided inclusion in any BCG catalogue. Its central R surface brightness and SFR is rather low, comparable to a “normal” dI. The fact that both

SBS0335-052 and its companion resides in the same HI cloud but at least 22 kpc apart, poses a problem for the youth hypothesis since it would require a coordinated ignition of star formation in the two clouds.

5.3. Summary

The most metal-poor BCGs: IZw18 and SBS0335-052 (and its companion), are probably not young galaxies. Nevertheless they are important laboratories for studying star formation at low abundances and the evolution of dwarf galaxies. The metallicities of their old stellar populations cannot be assessed with any accuracy. There is nothing that requires these galaxies to be more metal-poor than the most extreme dSph galaxies which have [Fe/H] $\lesssim -2$, see Table 2 (their oxygen abundances are still not known).

In addition to these galaxies, there are more than a dozen other BCGs with abundance 12+log(O/H)$\approx$ 7.6 or lower, and more objects are about to be discovered (cf. Sect. 6.1.5). The Local Group, and its immediate surroundings, contains another half dozen dI with very low metallicity. Moreover there are many dE/dSph galaxies in the neighbourhood with [Fe/H] ≈ -2. In addition, LSBGs have proven a good hunting ground for very metal poor galaxies. In Table 3 below we present all known galaxies with 12+log(O/H)$\approx$ 7.6 or lower. When several measurements (representing different HII regions) for the same galaxy were available we took weighted linear averages; and the same was done if there were differing O/H determinations of similar quality in the literature (in this case, only galaxies for which the weighted average was lower than the limit were included in the table). These galaxies, taken together form an important, yet hardly homogeneous, set of data for investigating dwarf galaxy evolution. Another interesting class, to which IZw18 and SBS0335-052 and its companion belong, is galaxies with low abundances with respect to their integrated luminosities, see Sect. 7.1.

6. Surveys for metal-poor galaxies and their space and luminosity distributions

6.1. Surveys

Haro (1956) used multiply exposed large scale plates to search for emission line galaxies. He identified a number of compact galaxies with strong emission lines. Zwicky (1971) envisioned that galaxies would evolve into highly concentrated densities as for neutron stars and produced several lists of “compact galaxies” selected form the Palomar sky survey. A nearly contemporary line of research was opened by Markarian (1967) who focused on ultraviolet excess galaxies at the Byurakan observatory. The underlying assumption was completely opposite however since V.A. Ambartsumian had the view that galaxy nuclei originated from explosive events.

Many metal-poor galaxies known at present undergo enhanced star formation event. This type of activity has obviously favoured their discovery (a metal-poor galaxy not necessarily needs to be an active one!). Following the early discovery of two bona fide metal-poor galaxies by Searle and Sargent (1972) that indeed turned out to experience an active star formation episode many astronomers have embarked in the building of large samples of such objects. Surveys were aimed to study their statistical importance in the Universe as a function of time, their relation to large structures and their contribution to the luminosity function.

One way to select star-forming galaxies is to rely on their ultraviolet excess and emission line spectrum. This property is not completely unambiguous since it is shared to some extent by active galactic nuclei (AGN). There are complications of course, mainly because of the effect of dust that reduces the UV flux and re-radiate the Lyman continuum photons in the far infrared (IR excess in IRAS 60 micron band). Follow-up observations need to distinguish the full population of starbursts from the AGN with non thermal activity.

6.1.1. Ground-based selection

Ground-based surveys have used morphological criteria, colour selection and emission line selection. Lists of blue compact galaxies were pioneered by Zwicky, followed by Fairall and others who isolated objects from their anomalous high surface brightness as seen on the Palomar Sky Survey. Spectroscopic follow ups have revealed a large proportion of HII galaxies and AGNs (Kunth et al. 1981).

The colour selection proceeds by searching for blue or ultraviolet excess objects involving various techniques such as the use of very low dispersed images or multiple colour direct images. Dispersed images have been used by the First and Second Byurakan Surveys (FBS, SBS) by Markarian (1967) on IIaF emulsion and later the University Michigan survey (UM, MacAlpine et al. 1977) and Case survey (Pesch and Sanduleak 1983) with IIIaJ emulsion. The second method has been pioneered by Haro (1956) and extensively developed by the Kiso Observatory Survey (Takase and Miyauchi-Isobe 1984). Low resolution slitless spectroscopy enables to detect [OII]λ3727, Hβ, [OIII]$\lambda\lambda 4959, 5007$ and Hα lines depending on the chosen emulsion or filter. Good seeing and excellent guiding are a requisite to avoid trailing and loss in detectivity. These techniques face a trade off between the dispersion and the spectral range covered. The higher the dispersion, the easier it becomes to detect weak emission lines against the continuum, while a narrow spectral range cuts significantly the sky background at the expense of the redshift range. The recent surveys described in Gallego et al. (1997) and Salzer (1999) use the Hα line which can be bright even in low-excitation or very metal-poor objects. Because each technique involves specific observational biases, modern surveys tend to combine various approaches. The use of large CCD arrays equipped with scanning Fabry Perot interferometry or slitless spectroscopy offer deeper limits at the expense of the reduced field of view. In the future, these combinations will probe distant HII galaxies populations. The most difficult problem that these surveys have to face is that of the follow-up observations (Terlevich et al. 1991). Getting even a rough oxygen abundance for faint galaxies requires long telescope time and suggests the use of multi-object-spectroscopy.

6.1.2. Selection effects at work

Selection effects have to be considered in comparing objects drawn from different surveys and for the derivation of a luminosity function, as first pointed out by Wasilewski (1983) and summarized by Comte (1998), who noted that selected populations have different statistical properties that depend on their selection modes. Emission line selected samples span a broader range of colours than purely UV-excess objects. This is not a surprise, but Salzer et al. (1997a) pointed out that very blue objects selected from their emission lines were also missed by the Markarian surveys. Similarly the distribution of emission line equivalent widths strongly depends on the choice of the dispersion. Very young starbursts are favoured in emission line surveys while ageing bursts are more easily picked out in “continuum” surveys. Finally Hα surveys present no prejudice in favour of a given metallicity.

6.1.3. How metal-poor galaxies can be found?

Clearly, despite their strong emission lines metal-poor compact dwarf galaxies are difficult to detect simply because they are fainter than $L^\star$ (the characteristic galaxy luminosity for a Schechter type luminosity function, cf. Schechter 1976, Binggeli et al. 1988) galaxies (a kind of Malmqvist bias). Only metal-poor galaxies with metallicity of the order of 0.1 solar that undergo starbursts are easy to pick out just because oxygen is the major cooling species, hence the [OIII] lines at 4959 and 5007 Å are particularly strong. But as one moves to more deficient objects, say below 0.01 solar, forbidden lines fade and the dominant cooling agents are H and He (Kunth and Sargent 1986).Therefore a combination of Hα objective-prism spectroscopy and UV-excess searches should be promising. Comte (1998) suggests a mid-UV imaging survey from balloon borne or orbiting instruments. So far the SBS and UM surveys has given a handful of new galaxies but never with metallicity below 1/50 solar. Why this is so? It may be that extreme metal-poor star-forming galaxies are very rare or do not exist locally.

6.1.4. HI clouds

Because it was observationally difficult to confirm the recurrent burst picture against the idea that blue compact dwarf galaxies are young, several HI surveys have provided independent clues. In their decisive early HI survey, Lo and Sargent (1979) showed that the space density of protogalactic clouds required by the youth hypothesis must be at least 8 Mpc^{-3}, each cloud having a mass of about $5 \times 10^8 M_\odot$ which is 2 to 3 orders of magnitude higher than what they found. HI-selected sample of clouds unavoidably turn out to have optical counterparts. In all cases, possible local HI primeval clouds have been found to be associated with stars (Djorgovski 1990, Impey et al. 1990, McMahon et al. 1990, Salzer et al. 1991, Chengalur et al. 1995). Since then, other surveys have been carried out to find isolated HI clouds but without success (Briggs 1997). Some interesting examples of HI without coincident optical emission were however provided by “off-scans” in 21cm line studies (Schneider 1989, Giovanelli and Haynes 1989, Chengalur et al. 1995, Giovanelli et al. 1995) but they are likely to be associated with (or bridge) nearby large visible galaxies. Tyson and Scalo (1988) have suggested that the majority of dwarf galaxies may be in a quiescent state, not forming young stars, and that they might consequently be missed by optical selection methods. A recent analysis of HI-selected galaxies (Szomoru et al. 1994) shows that HI searches do not yield a population of optically underluminous galaxies. Some faint nearby galaxies with strong emission lines remaining undetected in HI must have very little gas or store their gas in ionised or molecular form. Interestingly, the recent work by Schneider et al. (1998) shows that the HI mass function may become steeper at faint masses, in analogy with an upturn in the optical luminosity function at faint luminosities. Detection limits for HI surveys remain quite high ($N_{HI} \sim 10^{18}$cm^{-2}) hence smaller pockets may still be hidden. On the other hand, isolated HI clouds with masses and sizes comparable to present dwarf galaxies would be easily seen with modern radio telescopes hence they must be very rare. This conclusion is reinforced by the damped QSO absorption lines that tend to occur in the haloes of bright galaxies and not in smaller HI clouds (Lanzetta et al. 1995; however see discussion in Sect. 8.2). It has been noted that the diffuse ionising background could drive HI clouds under the detection limits of current surveys (see Corbelli and Salpeter 1993a,b).

6.1.5. New objective-prism surveys in progress

Evidently, the quest for finding more metal-poor galaxies is not over. The KISS (KPNO International Spectroscopic Survey, see Salzer 1999) is a CCD based objective prism survey. It selects candidates from their Hα emission, an advantage in searching for low metallicity systems. However an Hα survey produces not only BCGs, but also AGN etc. The real advantage is the usage of CCD detectors which enables a more than fivefold increase in limiting distance compared to photographic surveys. KISS finds on average 17 emission line galaxies per square degree (i.e. 170 times more than the original Markarian survey). Follow-up spectroscopy to investigate low metallicity candidates is under way (Salzer, private communication).

In an attempt to detect low metallicity galaxies, the Calan-Tololo survey plates have been searched by eye for objects without visible continuum, but with strong emission lines (Maza et al. 1999, in preparation). Interesting candidates are selected for spectroscopic follow up. More than two dozen galaxies with oxygen abundance of 1/10 $Z_\odot$ or less have been found so far, and of these 8 are around 1/20 $Z_\odot$ (Masegosa and Maza, private communication).

The HSS (Hamburg/SAO Survey) selects emission line dwarf galaxy candidates from the Hamburg quasar survey plates. The HSS has already yielded many new emission line dwarf galaxies (Ugruymov et al. 1999, Pustilnik et al. 1999a), and the follow-up study is well in progress. The dwarf (M_B = -12.6) HS 0822+3542 was recently found to have an oxygen abundance of only 12+log(O/H)=7.35 (Merlino et al. 1999, Kniazev et al. 1999), i.e. not far from that of SBS 0335-052 (see also Table 3).

Other recent work includes the UCM (Universidad Complutense Madrid) survey, based on an Hα selection, yielding objects from tiny BCGs to AGN, but mainly relatively luminous ones (cf. Gallego et al. 1997). For a recent review of surveys for star forming galaxies, see Comte (1998).

Whereas objective prism and UV-excess surveys are good at picking up high surface brightness dwarfs with emission lines, we have shown that very metal-poor galaxies also come in other brands. In particular, since metallicity, luminosity and surface brightness are positively correlated we expect the existence of very metal-poor LSB dwarfs, like dEs and LSBGs. Surveys for such galaxies could be rewarding in the hunt for the “most metal-poor galaxies”, although abundances will be more difficult to determine, especially for dEs lacking HII regions. New dEs are still found in the Local Group and its vicinity, and several surveys for LSBGs in the local Universe have been undertaken, and should strongly benefit from new wide field CCD cameras and projects like the Sloan Digital Sky Survey. To get a picture about work in progress, see the recent conference volume “The low surface brightness universe” by Davies et al. (1999).

6.2. Luminosity function

How do active star forming galaxies, in particular dwarf systems contribute to the luminosity function (LF) as compared to normal galaxies? To some extent, although somewhat paradoxical, the LF of local objects is more difficult to derive. Completeness problems are severe and combined with the need of large spatial coverage. Even when samples become large enough, the problem remains to establish the nature of selected objects. Low dispersion spectra must be used and require a diagnostic diagram to disentangle HII region-like spectra from AGN. Most LF determinations use a Schmidt estimator (Schmidt 1968) combined with a V/Vm test for completeness. One must bear in mind that such a test may not be adequate if large structures of our local Universe are not sufficiently averaged out. The very faint end of the LF is naturally the most difficult to establish. Deep CCD imaging using narrow-band filters complemented by follow up spectroscopy (Boroson et al. 1993), dedicated to this problem points towards a moderate slope of the LF at low luminosities in agreement with larger samples from the Case surveys or the UM. These studies are not in agreement with others, showing that this problem will be settled only by a better understanding of selection biases. Certainly surveys involving CCD techniques will allow to build larger and deeper samples.

The space density of dwarf emission line galaxies has been addressed by Salzer (1989), who finds $\sim$ 0.03 galaxies per Mpc^3, corresponding to $\sim$7% of the local field galaxy density based on the UM survey. This number is dominated by intrinsically faint systems. A rough calculation of the space density of SBS galaxies from Pustilnik et al. (1995) immediately shows these to be an order of magnitude less abundant, probably an effect of different selection criteria. The Case survey is even richer than the UM survey and the emission line galaxies (ELGs), which it contains, may contribute up to one third of the field galaxy population (Salzer et al. 1995). The reason is that the Case survey also is sensitive to galaxies with a low level of HII activity. A comparison of derived space densities of emission line/UV-excess dwarfs is given by Comte et. al. (1994) and Gallego et al. (1997). These differences demonstrate once more that different surveys effectively target different types of galaxies.

6.3. The spatial distribution of metal-poor galaxies

Normal giant galaxies are found both in clusters and low density environments in the field. In particular giant ellipticals are strongly clustered and are predominantly found near the centres of rich clusters, while spiral galaxies are less clustered. The difference in the galaxy population in clusters and the field is an important observable, but not easy to interpret in view of the various effects that may affect galaxies in different environments: merging, interactions, harassment, dynamical disruption, stripping, cooling flows, pressure confinement by hot gas etc.

Dwarf elliptical galaxies are found predominantly in clusters or as companions of giant field galaxies (Binggeli et al. 1990) and there appears to be a lack of isolated field dEs. The last point may in part be due to selection effects, since low luminosity dEs have low surface brightness and may therefore have been missed by most local surveys. New dE members of the Local Group are still being discovered (Armandroff et al. 1998, Karachentsev and Karachentseva 1999) illustrating the point that our view of even local dEs are largely incomplete. Dwarf irregulars follow the same structures as those outlined by massive galaxies (Thuan et al. 1987; Comte et al. 1994).

The LSBGs are less clustered than "normal" (giant) galaxies (e.g. Bothun et al. 1986a, 1993; Mo et al. 1994), in the sense that they tend to avoid clusters, and are not found close to field galaxies. However, this is based on comparison with galaxy catalogues that are badly incomplete for dwarf galaxies, and especially for LSBGs and dEs. Therefore not much can be said from these studies about how LSBGs cluster with other LSBGs and faint dwarfs. Large volume limited samples of LSBGs are required for this purpose. Taylor (1997) finds from a VLA study of their environments, that about one quarter of the LSBGs appear to have HI companions, with a detection limit of $\sim 10^7 M_\odot$. These HI companions tend to have faint optical counterparts (Taylor, private communication), and are thus likely to be LSBGs themselves. This suggests that LSBGs need not to be extremely isolated. It is however clear that LSBGs avoid massive giant galaxies, which is understandable since LSBGs close to giant galaxies have a high probability to interact which would lead to increase their star formation rate, thus transforming the LSBG into a high surface brightness galaxy.

Iovino et al. (1985) presented results suggesting that HII galaxies are less clustered than normal giants. Salzer (1989) investigated the spatial distribution of ELGs in the UM catalogue, finding that the ELGs follow in most parts the structures outlined by bright normal galaxies, but tend to avoid the regions with the highest galaxy density. On the other hand Comte et al. (1994) showed that KISO ultraviolet excess galaxies were distributed in a similar manner to "normal" galaxies. The spatial distribution of the SBS sample was investigated by Pustilnik et al. (1995) who found similar results, but in addition a significant fraction ($\sim$ 20%) was found in voids. Most HII galaxies/BCGs seem to be rather isolated when compared to existing galaxy catalogues and redshift surveys (Campos-Aguilar et al. 1993, Telles and Terlevich 1995). But these results mainly show that BCGs avoid giant galaxies, since these constitute the catalogues used for comparison. No constraint can be imposed on the clustering with other dwarf galaxies, e.g. LSBGs. The latter have indeed been found to be common companions to HII galaxies from the studies by Taylor and collaborators (cf. Taylor 1997). A recent study (Telles and Maddox 1999) attempts to address also the dwarf-dwarf clustering by comparing BCGs with APM (automatic plate measuring machine) catalogues, which contains more low luminosity galaxies, and comes to similar conclusions as previous studies in the sense that BCGs mainly populate environments less dense than normal galaxies. However, even the APM is badly incomplete for LSBGs, which are the likely companions in view of Taylor' results.

Given the apparent tendency of BCGs to avoid dense environments, such as rich clusters, it has been speculated whether the voids may be filled with BCGs and other faint dwarfs such as LSBGs. If so the current view of the baryonic matter distribution in the Universe would be very biased, and a large mass fraction would have been missed. This would be in agreement with "biased" galaxy formation theories (e.g. Dekel and Silk 1986) where dwarfs arise from low density peaks in the primordial density fluctuation spectrum. There have been some studies addressing this question: Pustilnik et al. (1995) found that 20% of BCGs may reside in voids. Popescu et al. (1997) finds some void galaxies, but show that the voids are not filled by an undiscovered population of BCGs. Similar results are reached by Lindner et al. (1999). BCGs in or near voids are predominately found near the borders (Lindner et al. 1996). The cases for other types of dwarfs, e.g. LSBGs, are less clear, but there is presently nothing that points toward a large density of any galaxy type in void, although this should be further investigated.

Dwarf irregular galaxies seem to be abundant in most environments, both in rich clusters and as pure field galaxies (Binggeli et al. 1980). However there are few studies addressing the dIs directly, and we have already seen that this class generally encompasses many different kinds of low mass irregular galaxies, including BCGs and LSBGs.

In conclusion, metal-poor BCDs and LSBGs avoid rich cluster environments, but may have neighbours of the LSBG type. Dwarf ellipticals are found in clusters or nearby luminous galaxies, while dIs are found in most environments (Binggeli et al. 1990).

7. Global relations and evolutionary links

7.1. The metallicity–luminosity relation, and other empirical relations

As we saw in sections 3.1 and 3.2, the metallicity of dEs and dIs correlate positively with their luminosity (Aaronson 1986, Lequeux et al. 1979, Kinman and Davidson 1981, Skillman et al. 1989). Whether they follow the same relation is a subject of debate due to the uncertain scaling between [O/H] and [Fe/H], (see Sect. 4.2.1; and Richer and McCall 1995). It would be instructive to examine the location of BCGs and LSBGs in the metallicity–luminosity diagram. The luminosity is usually represented by the B-band absolute magnitude which might be significantly affected by ongoing star formation, especially in BCGs, and thus is not necessarily a good estimator of the stellar mass. Indeed, NIR magnitudes would be a better choice, but data are rather scarce. Earlier work indicates that BCGs follow such a metallicity–luminosity relation, but with considerable scatter (Kunth 1986, Campos-Aguilar et al. 1993).

In Fig. 10, we show the oxygen abundance vs. luminosity diagram for dIs (crosses), BCGs (filled symbols) and LSBGs (open symbols), based on data collected from the literature, with available abundances and integrated B magnitudes. In addition we show the location of candidate tidal dwarfs and dEs with measured nebular oxygen abundances. For the BCGs we have divided the sample into morphological subtypes according to the classification schemes by Telles et al. (1997) and Loose and Thuan (1986a). Galaxies with regular outer isophotes, classified as Type II according to Telles et al. (1997) or as iE or nE according to Loose and Thuan (1986a), will be referred to as Type II, while "irregular" ones will be referred to as Type I following Telles et al. (1997). If there is no classification in the literature, but published images are available, we classified the galaxies according to this scheme. The solid line shows the $M_B - Z$ relation for dIs by Richer and McCall (1995), while the short and long dashed lines shows the relation for dEs (see caption).

At first sight many BCGs do not appear extreme when compared to the normal dIs. Indeed some BCGs are more metal rich than dIs at a given luminosity, while the opposite would be expected if BCGs were bursting dIs. These BCGs may be in a post burst stage and the fresh metals may have become "visible" already. Secondly, some "extreme BCGs" appear much more metal-poor at a given luminosity. These extreme BCGs (XBCGs) are 3 magnitudes brighter or more at a given metallicity, or equivalently 0.5 dex less metal rich at a given luminosity as compared to the dI relation. There is a tendency for the Marlowe et al. (1999) blue amorphous galaxies to lie above the dI relation. Galaxies of Type II follow the dI relation in a broad sequence, while Type I have a tendency to fall below the dI relation. The same phenomenon is seen for four galaxies from the sample by Östlin et al. (1999a), of which three have irregular morphology (Type I). The most metal-poor galaxies also have irregular morphologies and fall far below the dI relation. Thus the BCGs span a factor of 10 in metallicity at a

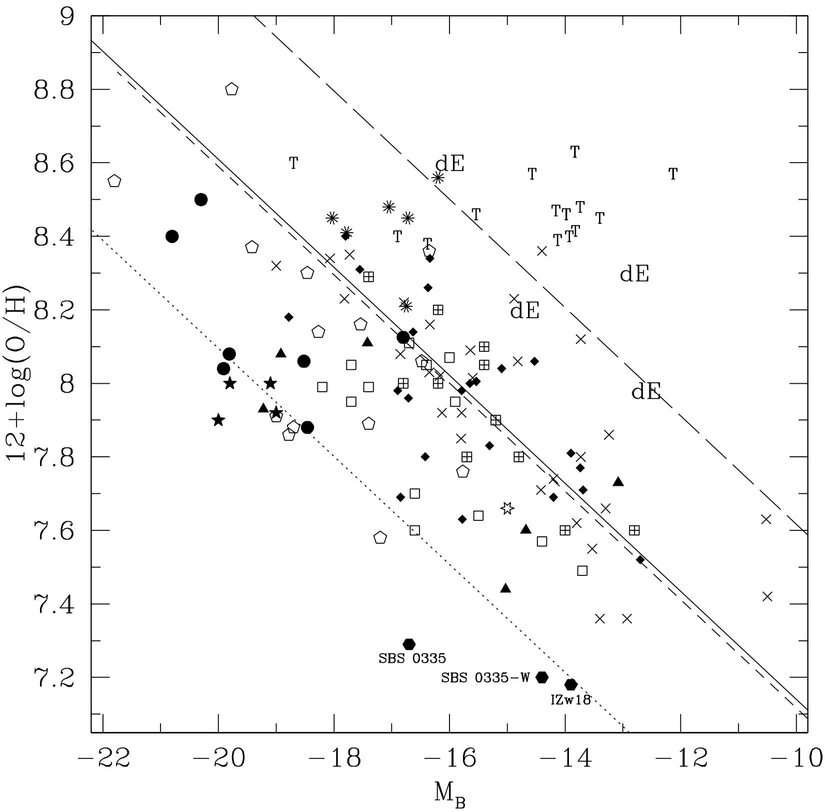

Fig. 10. The luminosity versus metallicity diagram for dwarf galaxies. The crosses represent dIs taken from Richer and McCall (1995) and Skillman et al. (1989). Filled symbols represent galaxies classified as BCGs or HII-galaxies: The small filled diamonds are "regular" galaxies which can be classified as Type II or iE/nE according to Telles et al. (1997) and Loose and Thuan (1986a), respectively, while filled circles are galaxies that can be classified as Type I (see text for description of types). Filled triangles are BCGs for which no classification or images were available. The three most metal-poor galaxies are labelled and shown as filled hexagons; their morphology are indicative of Type I. The filled stars are luminous BCGs from Östlin et al. (1999a,b), three of which are of Type I. The asterisks show the location of "blue amorphous galaxies" (Marlowe et al. 1999, except for II Zw40 which is the filled circle falling on the short dashed line). LSBGs are shown as open squares (blue LSBGs, Bergvall et al. 1999, Rönnback and Bergvall 1985) and open pentagons (McGaugh 1994, McGaugh and Bothun 1994). The open star is HI 1225+01, the HI-cloud in Virgo (Salzer et al. 1991). The boxes with plusses inside are quiescent (dI/LSBG) dwarfs from van Zee et al. (1997b,c). Candidate tidal dwarfs (Mirabel et al. 1992, Duc and Mirabel 1994, 1998) are shown as "T", and dEs are shown as "dE" (data from Mateo 1998). The solid line shows the $M_B - O/H$ relation for dIs from Richer and McCall (1995), while the dotted line shows the same relation offset by 3.5 magnitudes, indicating the location of XBCGs. The short dashed line shows the $M_V - Z$ relation for dE/dSph from Caldwell (1998) assuming $(B - V)$ = 0.75 and [O/H] = [Fe/H], while the long dashed line shows the same relation assuming [O/H] = [Fe/H] + 0.5. When necessary, we have rescaled absolute magnitudes to H_0 = 75km/s/Mpc. Metallicities of BCGs from: Izotov and Thuan (1999), Lipovetsky et al. (1999), Bergvall and Östlin (1999), Telles and Terlevich (1997), van Zee et al. (1998), Kunth and Joubert (1985), Alloin et al. (1978), Thuan et al. (1996), Masegosa et al. (1994). Absolute B-magnitudes for BCGs from: Telles and Terlevich (1997, assuming $B - V$ = 0.5), Papaderos et al. (1996a, 1998), Östlin et al. (1999a), Thuan et al. (1996), Mazzarella and Boroson (1993), Salzer et al. (1989a), Schulte-Ladbeck et al. (1998).

given luminosity. The intriguing XBCGs include IZw18 and SBS 0335-052, ESO 338-IG04 (=Tololo 1924-516), ESO 400-G43, Haro 11(=ESO 350-IG38), ESO 480-IG12 (Östlin et al. 1999a,b; Bergvall and Östlin 1999); UM 133, UM 448, C 0840+1201 (Telles and Terlevich 1997), UM 420, UM 469 and UM 382 (Masegosa et al. 1994, and Salzer et al. 1989a). LSBGs occupy locations in the range from dIs to XBCGs (see also Bergvall and Rönnback 1994, Bergvall et al. 1998). While enriched galactic winds could possibly explain the extreme metal deficiency of the least massive dwarfs, the existence of XBCGs in general cannot be understood in this way. While suggestive of important differences between different samples and types, these trends should be regarded as preliminary and should be put on more solid ground.

Another important relation, between HI mass and blue luminosity, has been addressed by several authors. A positive correlation was found by Chamaraux (1977) for a sample of Zwicky BCGs. It has been found (e.g. Staveley-Smith et al. 1992) that for gas rich dwarfs, the hydrogen mass to blue luminosity decreases with increasing luminosity, i.e. low luminosity galaxies are more HI rich, and have apparently converted a smaller fraction of their neutral gas content into stars. Moreover, LSBGs have proportionally more HI than BCG in the sense that they have higher $M_{H\mathrm{I}}/L_B$ values (see e.g. fig 1a in Bergvall et al. 1998). BCGs and dIs seem to have similar $M_{H\mathrm{I}}/L_B$ ratios. McGaugh and de Blok (1997) showed that, for a sample of disc galaxies (extending from normal spirals to LSB dwarfs), $M_{H\mathrm{I}}/L_B$ increases systematically with decreasing surface brightness, and is typically $M_{H\mathrm{I}}/L_B = 1$ (solar units) for LSBGs. LSBGs have low mass densities and have thus been inefficient in converting HI to stars and metals. Thus, to a first approximation, metallicity anticorrelates with the gas mass fraction (cf. Lequeux et al. 1979, Kinman and Davidson 1981, Pagel 1997) as expected from closed box models, but this cannot be the whole explanation (Matteucci and Chiosi 1983). Dust–to–gas ratios positively correlate with metallicity for dIs, while BCGs appear comparably more dust rich (Lisenfeld and Ferrara 1998), although in many BCGs one can only put upper limits to the dust content. The general relation between surface brightness and luminosity for dwarf and late type galaxies (Ferguson and Binggeli 1994), implies that dwarfs have low mass densities and/or are inefficient star formers. It has been argued that this could be a pure selection effect, since faint low surface brightness would be more difficult to detect (Phillipps et al. 1988).

Terlevich and Melnick (1981) report a positive correlation between the Hβ luminosity, the Hβ line width, and linear size for giant HII regions and HII galaxies. Subsequent work confirmed a dependence also on metallicity (Melnick et al. 1987, se also Campos-Aguilar et al. 1993). This also opened up the interesting possibility to use HII-galaxies as distance indicators (Melnick et al. 1987, 1988; see Sect. 8.6). If, as Melnick et al. (1987) argue, the Hβ line-width is due to virial motions, this relation reflects an underlying dependence on galaxy mass. Whereas this relation cannot hold for dwarfs irregulars with low star formation activity, it is striking that low mass galaxies with strong star formation activity seems to form a well defined sequence. This relation may reflect an intrinsic upper limit, perhaps regulated by feedback, on the possible star formation rate (directly proportional to the Hβ luminosity) as a function of mass or mass density. These galaxies would then represent the most efficient star formers with respect to their mass. Similarly, Meurer et al. (1997) find an upper limit on the bolometric surface brightness in starbursts at high and low redshifts, implying the existence of a physical mechanism limiting the global areal star formation rate in galaxies.

7.2. Evolutionary scenarios and connections

Like all other galaxies, dwarf galaxies evolve: the extremely gas poor dEs must have originally contained gas to form their observed stellar populations. Moreover, many BCGs have unsustainable star formation rates and therefore represent a transient stage, unless they form stars with a very different IMF. Thus, evolutionary connections between different dwarf types must exist, unless some initial conditions determined the future evolution of different types of galaxies. Even if links exist, there might be several different, physically distinct channels in the evolution of dwarfs. A discussion like this necessarily becomes speculative, and we invite the readers to make their own judgement.

Several evolutionary scenarios that link different types of dwarfs have been discussed over the years. One can think of two different types of evolution, either *internal* or *passive* where the evolution of a galaxy proceeds, according to its physical (initial) conditions or through *external* effects such as mergers, or interactions with galaxies or intergalactic matter. In the latter case, the environment will be a key parameter. Possibly, cluster and field galaxies evolve in a similar manner, but the clock runs faster in a high density environment. Since dEs are found in clusters or as companions to field giants, their evolution is likely related to their environment.

Lin and Faber (1983) suggested that the dSph satellites of the Milky Way were dIs that had lost their gas by ram pressure stripping (see also van den Bergh 1994). It was later pointed out that this could not be the general explanation since, on average, dEs have higher surface brightness than dIs at a given luminosity (Bothun et al. 1986, Ferguson and Binggeli 1994). However, this is mainly a problem for relatively luminous dEs (Skillman and Bender 1995). Searle et al. (1973) and Thuan (1985) proposed that BCGs originate in low surface brightness dIs, an idea that was further elaborated by Davies and Phillipps (1988) where they suggested that dIs evolve into dEs after a number of bursts in the BCG stage. The star formation is regulated by continuous gas infall from the halo, but this model includes no physics to explain the suggested behaviour. One can also imagine a cyclic BCG-dE scenario where a starburst in a BCG gives rise to a superwind, which expells the gas and halts star formation. The expelled gas later cools and falls back on the galaxy, creating a new starburst. Silk et al. (1987) proposed that the BCG phenomenon could be explained by gas expelled from dwarfs at high redshift, now accreting on dwarf ellipticals (see also Babul and Rees 1992). However, this can hardly work for the field BCGs since there are seemingly very few dEs to accrete onto. Gas loss through supernovae driven winds has been a popular mechanism for forming dEs (Larson 1974, Vader 1986, Dekel and Silk 1986), but although outflows are observed in some nearby dwarfs (Sect. 3.3) they do not appear capable of clearing a galaxy of its ISM. Galaxies that have managed to retain gas until the present epoch are unlikely to loose it now, and become dEs (Ferrara and Tolstoy 1999). Skillman and Bender (1995) point out that the majority of Local Group dEs/dSph formed most of their stars in an initial burst, while dIs have had more extended SFHs. However, there has been quite some progress in recent years in unveiling the SFHs of Local Group dwarfs, and the distinction between SFHs of dIs and dEs has been somewhat blurred (Sect. 4.1, 4.2; Grebel 1998). Despite being gas poor, most Local Group dEs have significant young or intermediate populations, and in active SF phases they would appear as BCGs or dIs depending on the extent of these episodes. The best example is probably Carina (Smecker-Hane et al. 1994) which went through a major SF episode some Gyrs ago, demonstrating that dI-dE transitions may have occurred fairly recently. A thorough discussion on the the origin of dEs is given by Ferguson and Binggeli (1994), see also Skillman and Bender (1995). Meurer et al. (1992) argued that BCGs like NCG 1705 could evolve into nucleated dEs. Similarly, it has been suggested that compact galaxies at higher redshifts (z = 0.5 to 1) are the progenitors of the present day dEs (Koo et al. 1995). Since outflows seem rather inefficient, the only way for field BCGs to evolve into dEs (of some kind) is through total gas consumption, which requires very high star formation efficiencies. Field dEs appear too rare, and field Es typically too massive to be the successors of most BCGs, but it may apply for the most massive BCGs, especially those seemingly involved in mergers.

Many dIs appear more simple and able to form stars at more or less continuous rates over long time scales. Although the details of their star formation activity are not completely understood, there is less *need* for evolutionary connections since their star formation activity is typically sustainable over a Hubble time or more. Given the arguments above, dIs are not likely to passively evolve into dEs (unless perhaps on timescales comparable to the age of the Universe or longer). However there might be connections to dEs (especially in clusters) and BCGs (some of which may fade into dIs). Given their large number and richness in gas, LSBGs may serve as important fuel for star formation.

Constraints on BCG evolution from photometric structure: BCGs have on average higher central surface brightnesses than dIs, even after the starburst component has been subtracted (Papaderos et al. 1996b, Marlowe et al. 1999), which argues against links between BCGs and dEs/dIs, unless the structure can change during the bursting phase. (Note however that this may be an artefact due to insuffiently deep data, see Sect. 4.4.1). Papaderos et al. (1996b) propose that in the initial phase a BCG may contract because of accretion, while the successors of BCGs may expand due to gas loss. However the required expansion/contraction necessary to explain structural differences would require at least 50% of mass loss/gain (Marlowe et al. 1999) which is quite unrealistic given the apparent inefficiency of winds, the observed gas mass fractions and large DM content of dIs. Marlowe et al. (1999) also note that the burst, as defined from excess surface brightness over a disc fit, is quite modest, and that a similar excess is seen in some dIs (although the underlying surface brightness is lower). Then BCGs may simply be regarded as unusually active dIs, because of higher central mass densities (van Zee 1998c). In the non burst phase, they will be classified as a high surface brightness dIs or as amorphous galaxies or BCGs with low emission line equivalent widths. This may be the case for many BCGs, especially those close to the dI relation in Fig. 10, but hardly for the XBCGs discussed below.

Constraints from luminosity, metallicity, and gas content: Some BCGs are much more metal-poor at a given luminosity than the dIs forming the basis of the metallicity–luminosity diagram. We called such objects “extreme BCGs” (XBCGs). Thus, under the conservative assumption that the current burst has not yet affected the observed nebular abundances, a dI would need to brighten by 3 magnitudes to become an XBCG. That amount of brightening is not observed from profile fitting and is unrealistic in view of the observed HI masses as the following example illustrates:

Imagine a typical dI with M/L_B = 2 for its stellar population, on which we add a 10 Myr old burst. The burst should have $M/L_B > 0.05$ for a Scalo IMF (Bruzual and Charlot 2000). To accomplish a brightening with 3 magnitudes, the burst has to be 15 times brighter than the underlying galaxy, and hence make up more than one third of the total stellar mass. This would require, for realistic star formation efficiencies of say 10%, that the dI precursor had a neutral hydrogen mass several times larger than its total stellar mass. The observed gas mass fractions are much lower, and therefore XBCGs cannot originate in bursting dIs (see also Bergvall et al. 1998). On the other hand, a LSBGs turning on a burst would need to increase its absolute luminosity with only ~ 1.5 magnitudes to meet the location of XBCGs in the $M_B - Z$ diagram. This would simultaneously reproduce the $M_{H\text{I}}/L_B$ values for BCGs (Bergvall et al. 1998). Thus LSBGs are more likely to be the precursors of XBCGs than dIs. Moreover, Telles and Terlevich (1997) found the colours of the underlying component in BCGs to be consistent with those of blue LSBGs. This argument against dI–BCG evolution does however not apply to BCGs which are found close to, or above, the metallicity–luminosity relation for dIs. These galaxies must definitely have a different history from the XBCGs.

Mass vs. metallicity: Another indication that dIs like those in the Local Group are not the progenitors of the most metal-poor BCGs comes from a comparison with total mass, rather than absolute blue magnitude. Data for BCGs are scarce, but taking IZw18 (van Zee et al. 1998a), SBS 0335-052 (Papaderos et al. 1998) and luminous BCG from the Östlin (1999a,b) sample and comparing them to Local Group dIs (data from Mateo 1998) it is clear that XBCGs appear to be an order of magnitude more massive than dIs at a given metallicity. Thus the scatter in the metallicity–luminosity diagram is not primarily due to various degrees of star formation affecting the B-luminosity. Interestingly, metal-poor LSBGs (like ESO146-IG14, Bergvall and Rönnback 1995; and some galaxies in the sample of de Blok et al. 1996 and McGaugh 1994) fall on the XBCG mass-metallicity relation. However, three BCGs studied by van Zee et al. (1998) and NGC1705 (Meurer et al. 1998) fall in the dI range. Quiescent dwarfs (dI/LSBG) from van Zee et al. (1997,1997) overlap with BCGs. The BCGs overlapping with dIs are of the regular type II. This comparison indicates that different types may indeed have a different origin, but we caution that this excursion into studying the mass versus metallicity was based on inhomogeneous data from various sources, using various methods. Thus, it should not be taken at face value, but as a motivation for further studies.

Dwarf mergers? Several investigators have noted the wide range of morphologies displayed by BCGs (see Sect 4.4.1). Telles et al. (1997) note that luminous BCGs (Type I) on average have a more perturbed morphology and Telles and Terlevich (1997) speculate that this may be related to mergers or interactions, but they note that merging is disfavoured, based on the clustering properties of BCGs. As we discussed in Sect. 6.3 this conclusion might be too pessimistic since the present investigations may be incomplete for dwarfs, especially LSBGs. Taylor et al. (1993, 1995, 1996a, 1996b) investigated the HI environment of BCGs and LSBGs finding that 60% and 30% of them respectively have HI companions with faint optical counterparts, with a typical detection limit of $10^7 M_\odot$. From the higher fraction of HI companions around BCG, Taylor (1997) argue that LSBGs are not the likely progenitors of BCGs. However, this may be a selection bias in the sense that the more frequent are the HI companions, the more probable mergers will be.

From a kinematical morphological study Östlin et al. (1999a,b) found that a sample of luminous BCGs (most of them XBCGs) were likely the product of mergers, involving gas rich dwarfs or HI-clouds. A merger can provide the necessary change of the structure of the host and offers a mean for changing the kinematics of galaxies, from rotating (like dIs) to essentially non-rotating (like E and dE). A critical point, especially if some BCGs are to evolve into E/dE, is how efficient the gas consumption may be? Galaxies with a large gaseous disc at moderate column densities are not likely to be able to consume this gas on a short timescale. In mergers, the star formation efficiency might be higher, especially if globular clusters are able to form (Goodwin 1997). Van Zee et al. (1998c) point out that BCGs have higher central HI densities than normal dIs. This is a natural explanation for the high star formation rates, but some mechanism is needed to put the gas where it is, since the gas consumption time scale is rather short. If gas consumption is less efficient, perhaps because gas settles into a rotating disc, the merger remnant would rather evolve into a dI or an amorphous galaxy. If a merging gas rich dwarf contains a rather unpolluted HI halo, this could dilute the metal enriched ISM and lower the observed abundances, to produce XBCGs. Clearly, mergers would be able to explain many properties of BCGs, but of course this does not imply that merging is the general mechanism, especially concerning those with regular morphology. The absence of morphological perturbations in Type II BCGs may however be an observational effect. Since these systems are on the average fainter, their underlying components have low surface brightnesses, and thus morphological irregularities such as tails will have low surface brightnesses and be difficult to detect.

We have fast outlined some ideas about evolutionary connections. It is clear that the overall picture is not yet well understood. There is probably no unified scheme that can explain all dwarfs. The origin and evolution of dE/dSph galaxies is probably related to their environment, and it cannot be ruled out that some dE/dSphs are stripped dIs, although dIs are not likely to passively evolve into dEs. Many BCG-like galaxies may simply be extreme dIs. Some BCGs, especially the XBCGs, may be triggered by mergers involving gas-rich galaxies such as LSBGs. Of course if some BCGs are truly young, their progenitors must be pure gas clouds and not visible as galaxies. Such gas clouds have however not been found, and although the existence of genuinely young BCGs at the current epoch cannot be ruled out, we do not consider that there is any BCG where there is an unambiguous evidence for pure youth (cf. Sect. 4.4.2 and 5).

8. Metal-poor galaxies, cosmology and the early Universe

8.1. The primordial helium abundance

According to conventional wisdom, helium is mainly produced during the first few minutes of our observed Universe and subsequent stellar nucleosynthesis has added at most 10 to 20% to its primordial value. An accurate measurement of the primordial Helium is critical for our understanding of the origin of the Universe because, under the assumption of the standard hot Big Bang model of nucleosynthesis, it will eventually provide a fundamental parameter in cosmology, that is, the nucleon density in the early Universe. Up to now, the most accurate method of measuring helium abundance consists of observing diffuse gas which has been ionised by the ultraviolet photons from hot stars in star forming dwarf galaxies, in particular BCGs. The goal being to measure Y, the helium mass fraction present in ionised gas of low heavy element abundance. Early studies have pioneered a method by which one can extrapolate the He/H versus O/H relation to the primordial abundance, Y_p, as the oxygen abundance tends to zero (Peimbert & Torres-Peimbert 1974; Lequeux et al. 1979). The extrapolation is rendered easier by choosing extreme metal-poor galaxies. Extensive searches are still underway to select blue low mass galaxies with even lower oxygen abundance and of highest excitation. This last point is crucial, since a good oxygen and helium abundance determination is only possible if the temperature of the gas can be obtained from the very few critical forbidden line ratios which can be properly measured (Kunth and Sargent 1983). Because useful constraints can only be achieved if the He abundance is measured to better than 5% accuracy this exercise needs care at each step that from the observations leads to the final derivation. Problems connected with fluorescent and collisional excitation affecting the helium lines must be addressed as well as the effect induced by electron temperature fluctuations. Another irritating question is the amount of neutral helium to correct for, because it remains undetected (Masegosa et al. 1994). The stellar population, due to the most recent burst of star formation, produces underlying absorption in the H and He nebular lines (Izotov and Thuan 1998a). To circumvent this difficulty, high resolution spectroscopic data are needed. Despite improved observations, the scatter in the Y vs Z diagram has remained large (see e.g. Kunth 1996). Is this due to systematic errors or an intrinsic cosmic dispersion? It has been argued that galaxies with high Y might be affected by localised pollution from Wolf-Rayet (WR) stars (Pagel et al. 1986, 1992), and hence that galaxies showing (WR) features should be excluded from the analysis. However, this has been disputed by Esteban and Peimbert (1995) and Kobulnicky and Skillman (1996) who find no evidence for localised pollution in WR galaxies.

The problem of the recombination coefficients for helium has been a subject of controversy after Smits (1991) published new values that differed from those of Brocklehurst (1972), but these calculations were discovered later on to be in error by Smits himself (1996). A new grid of emissivities improving the predictions for He emission lines are now available (Benjamin et al. 1999). Problems inherent to the observations and reduction processes have also been considered and have led to at least two distinct approaches. One method (Skillman et al. 1994) involves repeated observations with different systems (telescopes, standard stars, reduction procedures, etc.) while Thuan and Izotov (1998a) have favoured an approach by which the same procedure (telescope, etc.) is used to ensure more homogeneity of the data. Reviews of some problems in connection with deriving the primordial He abundance can be found in Terlevich et al. (1996) and Kunth (1996).

The last estimate of the primordial helium abundance (Izotov and Thuan, 1998a) using a "self-consistent" treatment, gives $Y_p = 0.244 \pm 0.002$ (see Fig. 11), a value slightly higher than that of Pagel et al. (1992), i.e. more in line with the predictions of the Standard Big Bang nucleosynthesis. Perhaps equally important, is a considerable scatter in the helium values at a given metallicity: an indication of possible differences in the chemical evolution history of these dwarf galaxies. This scatter remains, although observational errors have been considerably reduced over the last decade with the advent of linear detectors. The new Izotov and Thuan (1998a) data are available in a way that offers the possibility to check various pending observational problems (such as a grating "second order" contamination that is possibly present beyond 7200Å and may affect redshifted objects in the 7065Å HeI line) and perform independent analysis. Their work however still leaves room for further investigation in particular to check the importance of underlying stellar absorption that may artificially

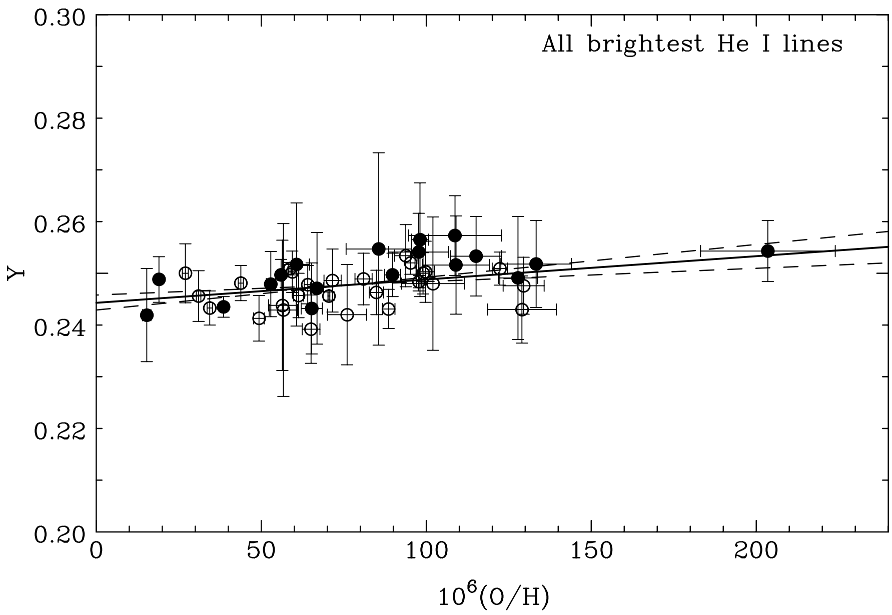

Fig. 11. Example of recent derivation of the primordial He abundance through regression analysis. The meaning of filled vs. open symbols is described in Izotov and Thuan (1998). (Courtesy T.X. Thuan.)

weaken some HeI lines. It is for this unfortunate reason that region NW in the most deficient metal-poor IZw18 is difficult to use and has been alternatively rejected and reintroduced by Izotov and Thuan (1998a,b) in the final derivation of Y_p. The advent of 2D spectroscopy will also help to better take into account stratification effects in the nebula and localise possible contaminations due to WR stars and supernovae.

8.2. QSO-absorption line systems

Spectra of high redshift QSOs display absorption lines from intervening HI clouds, arising when the QSO continuum is absorbed at the local rest wavelength of the resonant Lyα line. The QSO absorption systems come with a range of column densities from below 10^{14}cm^{-2}, the Lyα forest, to more than 10^{20}cm^{-2}, the Damped Lyα systems (DLAs).

Metal absorption lines associated with QSO absorption line systems can be used to study the metallicity and its temporal evolution in interstellar/intergalactic gas. This field of research has experienced rapid progress recently thanks to the new generation of 10m class telescopes. Now even low density Lyα forest systems can be studied (but not those with too low N_H) and have been found to contain heavy elements, on average [C/H]~ -2.5, although the metallicities are still very uncertain due to the limited understanding of the physical condition in these systems (Pettini 1999).

The DLAs are better understood in terms of physics though their true nature is still not clear, and are on average more metal rich. At redshifts above $z = 1.5$ Pettini et al. (1997) and Prochaska and Wolfe (1999) determined an average zinc (where problems with dust depletion are expected to be small) abundance of [Zn/H]= -1.15. There is a large scatter at all redshifts, and no strong trend in metallicity with redshift (but see also Lu et al. 1996). It is generally assumed that DLAs are associated with galaxies at an early stage of evolution. It is not clear whether all remote galaxies at redshift larger than 2 are chemically young systems or whether damped Lyα lines preferentially pick out unevolved systems.

Pettini et al. (1995) explore the possibility to measure the N/O ratio at a metallicity lower than those of the most metal-poor dwarf galaxies known. They find that relative to the Sun, N is more underabundant than O by at least a factor of 15 in agreement with Lu et al. (1996, 1998). Izotov and Thuan (1999) attribute this low N/O to uncertainties related to unknown physical conditions in the interstellar medium of high-redshift galaxies that make the correction factors for unseen low-ionisation species difficult to assess. On the other hand Pilyugin (1999) manages to account for the discrepant behaviour of DLAs and low metallicity BCGs, if assuming (among other things) that DLAs have had their last star formation event less than 1 Gyr ago, whereas the observed metals in the most metal-poor BCGs have been produced in a previous event, more than 1 Gyr ago.

Vladilo (1998) proposes that the abundance pattern in DLAs is more consistent with them being dwarf galaxies rather than disc galaxies. By dwarf galaxy, an LMC like galaxy was considered, i.e. much more massive than the most metal poor dwarfs which have narrow HI profiles, but consistent with the most luminous BCGs and dIs. However it is not clear whether this agrees with the observed kinematics of DLAs (Prochaska and Wolfe 1997). Observations of galaxies associated with lower redshift DLAs present a wide variety of morphologies (Le Brun et al. 1997). Thus it may be the case that DLAs are not linked with a specific kind of galaxy, but with all sorts of galaxies.

Although the nature of DLA galaxies and their relation to galaxies seen at low redshift is far from clear (Pettini 1999), they are among the most metal poor galaxies known. With a dozen 10m class telescopes available in the beginning of the next decade, there is good hope that our understanding of these systems will significantly improve.

8.3. Star forming galaxies at high redshift

It has been conjectured that primeval galaxies would be nearly dust free and devoid of metals at their early stages (but see Puget and Guiderdoni 1999). The search for “normal” galaxies (i.e. where light is generated by stars) at high redshifts has seen a tremendous progress in the last years thanks to programs employing the Lyman break technique (cf. Steidel et al. 1995, 1996, 1999), and projects like the Hubble Deep Field (HDF, Williams et al. 1996). Steidel and collaborators (1996) have shown that on the order of a few percent of the galaxies at faint optical magnitudes ($\mathscr{R} \sim 25$) are actively star forming galaxies at redshift greater than 3. With the assumption that the bulk of emission is produced by photoionisation of stars, their star formation rate is found to range from a few up to a thousand solar masses per year, hence much larger than in local metal-poor, low mass, galaxies such as IZw18. Morphologically many appear to be star-forming spheroids smaller than the bulge of a spiral galaxy. They may be part of the reservoir from which many of today’s luminous galaxies were formed through hierarchical merging. Presently, the true mass and the metallicity of these galaxies is poorly known. Only a few have been followed up using near-infrared

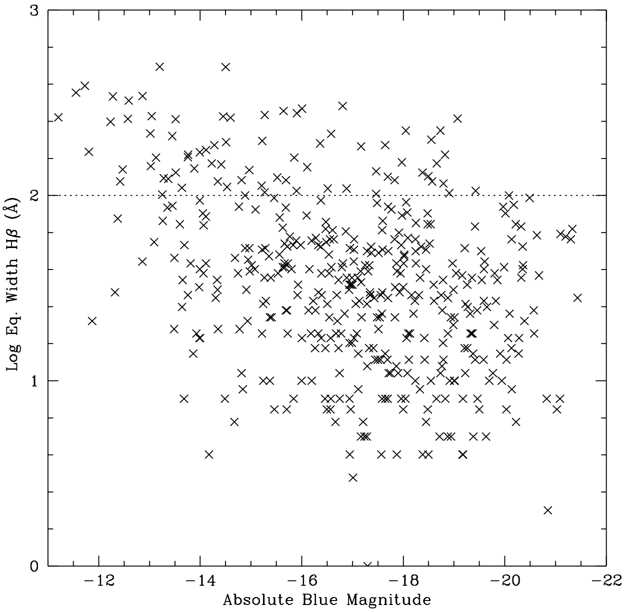

Fig. 12. The relation between absolute blue magnitude and equivalent width of Hβ for a sample of HII galaxies (Terlevich et al. 1991). The apparent trend may in part be due to selection effects. (Courtesy R. Terlevich)

spectroscopy (Pettini et al. 1998) showing that their dust content (as obtained from rest-frame visible light) does not require a major reassessment for the star formation rates derived from the rest frame UV. Masses obtained from line-widths lead to masses of $10^{10} M_{\odot}$, hence larger than that of the local dwarf galaxies we have reviewed throughout this paper, and furthermore these may even be underestimated (Pettini et al. 1998). There are indications that energetic outflows are taking place, similar to what is now observed in local starbursts (Kunth et al. 1998). Broadened interstellar lines are most likely the result of mechanical input from winds and supernova. Metallicity estimates using synthetic stellar-wind profiles calibrated against a local star-forming galaxy sample suggest Magellanic Cloud-like composition (Leitherer 1999). Although many galaxies are found to be extremely dusty even at large redshift (Puget and Guiderdoni 1999), it is possible that there exists an intrinsically fainter population of dust-free star-forming galaxies that could represent the earliest phases of galaxy formation. New Lyα emitters are now found at high-redshift from surveys using large telescopes with narrow-band filters (Hu et al. 1998, Pascarelle et al. 1998). Limits down to a few 10^{-18}erg/cm^2/s are now reachable and give access in principle, to galaxies with fainter continuum magnitudes than the Lyman break galaxies (see Fig. 12). On the other hand local starbursts (Kunth et al. 1998) indicate that an unknown fraction of the youngest galaxies may not be Lyα emitters. The systematic search and discovery of this kind of objects should offer the opportunity of studying processes of star and galaxy formation and evolution at a substantial cosmological look-back time. Unfortunately even the brightest emission lines objects are difficult to follow up, and only the advent of 8m class telescopes with near-IR spectrographs will allow to tackle the difficult task of measuring metal abundances.

Deep optical galaxy counts have shown a strong excess of faint blue galaxies, which however is absent in near-infrared K-band surveys (Tyson 1988). Redshift surveys find that the bulk of this faint population is at intermediate redshifts ($z < 0.6$; see e.g. Broadhurst et al. 1988; Colles et al. 1990; Lilly, Cowie & Gardner 1991). It has been proposed (see also Cowie et al. 1991, Babul and Rees 1992), that the faint blue excess could be explained by a population of star bursting dwarf galaxies at intermediate redshifts. It has been demonstrated that the blue excess can be identified with a population of irregular/peculiar galaxies (e.g. Glazebrook et al. 1995, see Ellis 1997 for a review).

Spectroscopic follow up of compact galaxies in the flanking fields around the Hubble Deep Field (HDF) have shown these to be active star forming galaxies at $0.4 < z < 1.4$ with narrow emission line. In many respects these objects are similar to the most luminous local BCGs and HII galaxies (e.g. Guzmán et al. 1997). Their metallicities are largely unknown but do not seem to be very low. Similar high redshift blue compact galaxies were found in the Canada-France redshift survey (Schade et al. 1995, Hammer et al. 1997). Kobulnicky and Zaritsky (1999) studied rather luminous emission line galaxies at redshift 0.1 to 0.5, and found oxygen abundances from $1/5Z_{\odot}$ to $Z_{\odot}$, and N/O values consistent with local galaxies of similar metallicity.

If, as in the local Universe, low metallicity galaxies at high redshift would be dwarf galaxies of low or moderate luminosity, they would be missing in existing surveys. Indeed, the luminosity function of LBGs at faint magnitudes is very steep, indicating a large population of intrinsically fainter objects lurking below the current detection threshold (Steidel et al. 1999).

8.4. Metal production at high redshift

The work of Steidel and collaborators (e.g. Steidel et al. 1996) has confirmed a substantial population of star-forming galaxies at $z \sim 3$, with a comoving number density of roughly 10 to 50% that of present day luminous ($L \geq L^{\star}$) galaxies. From these data it has been possible to sketch - although with large uncertainties and questions - the star-forming history of the Universe at high redshifts (Madau et al. 1996). From this work, and other similar samples, e.g. from the HDF, the overall SFR of the galaxy population seems to increase from $z = 0$ to $z = 2$, during which time a significant fraction of the heavy elements in the Universe are formed, while it tails off again towards higher redshift. Recently, Steidel et al. (1999) questioned the decrease in the number of star forming galaxies at high redshift, and suggest that the cosmic star formation rate as inferred from Lyman break galaxies has been constant from $z = 1$ to $z = 4$. Recent results from sub-mm observations of redshifted dust emission with the SCUBA bolometer array (e.g. Hughes et al. 1998) and from the ISO satellite (Aussel et al. 1999; Puget and Guiderdoni 1999) suggest that a significant amount of high redshift star formation may be dust obscured, meaning that estimates of the cosmic metal production rate from optical observations might be too low. The cosmic metal production history may also be constrained by observations of the extragalactic background at different wavelengths (see Pagel 1997 for a discussion).

Numerical simulations by Cen and Ostriker (1999) predict the evolution of the metal content of the Universe as a function of density, by incorporating star formation and its feedback on the IGM. At a given density (corresponding e.g. to a rich cluster, a disc galaxy, dwarf etc.) their models predict an evolution with redshift, but more importantly, the metallicity is found to be a strong function of density. At low redshift, low density environments will still be very metal-poor as suggested by the presence of very metal-poor gas-rich dwarf galaxies, and Lyα absorption systems (Shull et al. 1998). Ferrara and Tolstoy (1999) find in their simulations of the feedback from star formation on the ISM in dwarf galaxies, that low mass galaxies could be the main contributor to metals in the IGM.

The idea of so called population III objects has been discussed for quite a while. These hypothetical objects would be (or host) the first generation of stars, appearing before the main epoch of galaxy formation, and thus be a source of pre enrichment in the Universe. The subject remains speculative, but the existence of Pop III stars cannot be ruled out (Cayrel 1996).

8.5. The rôle of dwarfs in hierarchical structure formation

What rôle do metal-poor dwarf galaxies play in the hierarchical build-up of galaxies in the early Universe. Observations suggest high merger frequencies at high redshift, but what is merging? Certainly not just normal spirals but more likely dwarfs that may or may not have counterparts in the local Universe.

If galaxies form by the cooling and condensation of gas within dark matter halos, the ability to detect them depends on the sizes of the pieces out of which galaxies are assembled and on the time interval during which this takes place. There have been suggestions that the principal galaxy building blocks are to be found throughout the redshift range of about $z = 2$ to 5. In any case, such young galaxies would, in their earliest phase, be expected to have strong emission lines but faint continua and would hence fall far below the magnitude threshold of current Lyman break surveys. In fact there is a trend for local galaxies (see for instance the Terlevich et al. 1991, catalogue of H II galaxies, and Fig. 12) with very strong emission lines to have fainter magnitudes. Moreover, if galaxies are more inclined to be in groups and clusters at the time of formation they offer an interesting challenge for existing CDM models. HST images obtained by Pascarelle et al. (1998) have revealed emitting objects in sheets or clustered in ways that fit the theoretical picture of Rauch et al. (1997). Observations suggest high merger frequencies at high redshift, but again the nature of the merging blocks (masses and metallicity) remains to be investigated.

Have today's giant galaxies (big spirals and ellipticals) ever been metal-poor? The intuitive answer would of course be – yes. But, if massive galaxies are built up by successive merger of small galaxies, it is possible that they were already rather metal rich when reaching a total mass comparable to that of an $L^{\star}$ galaxy. In that case, the only metal-poor galaxies at any redshift will be low mass galaxies, difficult to study at cosmological distances.

A long standing problem in galaxy formation models is the so called overcooling problem (White and Rees 1978), leading to an overproduction of dwarf galaxies at the expense of massive galaxies, in disagreement with observations of the luminosity function of galaxies. This problem still remains in current galaxy formation models (cf. Somerville and Primack 1998). Various mechanisms, have been proposed such as SN feedback and a high UV background keeping dwarf sized clouds ionised, preventing them to cool (Efstathiou 1992). The problem may be somewhat relaxed if most dwarfs have merged into giants or have been disrupted. If some low mass galaxies formed before the Universe was re-ionised and subsequently experience a blow-out of their ISM, they could represent population III objects, responsible for cosmic metal enrichment at very early epochs (see Ferrara and Tolstoy 1999 and references therein).

8.6. H II *galaxies as distance indicators*

It is established that giant extragalactic H II regions (GEHRs) display a correlation between their intrinsic luminosities and the width of their emission lines, the σ–L(Hβ) relation (Terlevich & Melnick 1981). Melnick et al. (1987,1988) have shown that the relation found for GEHRs holds also for H II galaxies. The scatter in the σ–L(Hβ) relation is small enough that it can be used to determine distances.

Recent work with HIRES at the Keck (Koo et al. 1995, Guzmán et al. 1996) has shown that a large fraction of the numerous compact galaxies found at intermediate redshifts have kinematical properties similar to those of luminous local H II galaxies. They exhibit fairly narrow emission line widths (σ = 30 to 160 km/s) rather than the 200 km/s typical for galaxies of similar luminosities. In particular galaxies with $\sigma < 65$ km/s seem to follow the same relations in σ, M_B and L(Hβ) as the local ones. Recent infrared spectroscopy of Balmer emission lines in a few Lyman break galaxies at z = 3 (Pettini et al. 1998) suggests that these adhere to the same relation, although this has to be confirmed for a larger sample. This opens the important possibility of applying the distance estimator and map the Hubble flow up to extremely high redshifts and simultaneously to study the behaviour of starbursts of similar luminosities over a huge redshift range. It may prove to be a useful method to measure q_0 because the redshift interval of present day applicability considering the most luminous H II galaxies is larger than for methods involving SNe, allowing a good discrimination between deceleration (q_0) and curvature (Λ). Possible complications concern the treatment of the effects of metallicity and extinction in these systems.

9. Summary and conclusions

Extreme properties are often sought for in astronomy as one way to sharpen our understanding of fundamental concepts. In such a context, metallicity proves to be of crucial importance. Because metals build up as a function of time after the release of nucleosynthesis products, the most metal-poor galaxies help us to understand the primordial Universe and the subsequent formation and evolution of galaxies.

We have discussed in this paper the reason why local metal-poor galaxies are found amongst the dwarfs. Whether this property remains true at high redshift where protogalaxies begin to form, is certainly a challenging question. If the hierarchical model of galaxy formation is correct and if building block galaxies are similar to the well-studied dwarfs we discussed in this review they may be unreachable observationally, even with the advent of the most recent large telescopes. On the other hand, large, massive and gas-rich proto-galaxies may have some properties similar to those of the most unevolved objects we see today. The same applies to the distant starbursts that have been found using Lyman break techniques or Lyα emission searches.

Evolution versus formation has been a clear issue in order to characterise the few known extreme star-forming dwarfs like IZw18. Most of the properties of these galaxies: blue colours, gas and dust content, and extreme metal deficiency once led to the belief that, although rare, small condensations were able to produce genuinely young galaxies at the current cosmic epoch. This question has indeed received a lot of attention in the recent years but we consider it as somewhat “passé”. In most cases - but for a few intriguing ones - an old underlying stellar population has been found, revealing one or several previous bursts of star formation. The same seems to apply to dwarf gas-poor galaxies as one can tell from the study of their colour magnitude diagrams. The problem of the existence of local young galaxies may not be completely solved yet but its importance is less acute, since in any case, there is no significant population of dwarf galaxies still in the process of formation. Evidences that most of the galaxies were formed at ealier epochs come from a more direct view of what the Universe looks like at high redshift and also the hint that the metal production rate in the Universe has passed its peak. The question of present cosmological interest would rather be to determine the epoch when the bulk of dwarfs were formed. Was the formation of dwarfs confined to very high redshifts, or was it still going on at intermediate redshifts where the faint blue galaxies emerge and the Universe was about 2/3 its present age?

Nevertheless, for years, local extremely metal poor galaxies turned out to be our best test laboratory. We have learned a lot about the properties of their massive stars (formation and evolution, appearance of WR stars), the evolution of the dynamics of the gas in the gravitational potential of the parent galaxy as a superbubble evolves and the chemical enrichment of the interstellar medium after the fresh products are well mixed. We have discussed their dynamical properties and interactions with companions in order to understand the triggering mechanism that ignites their bursts of star formation. These galaxies have been modelled to constrain the scenario of the starbursts, with the major motivation of describing how various classes of dwarfs could be linked together into one or several evolutionary scenarios. This is not completely settled yet and a lot of work is still needed both theoretically and observationally in this area. Surveys are aimed to build luminosity functions that will help in answering some of the above questions and also produce new targets that will open the possibility to investigate the properties of metal-poor galaxies at much larger redshift. We clearly enter a new area in which metal-poor galaxies and the sub class of metal-poor dwarf galaxies will observationally begin to be considered in cosmology. They enter in the study of the cosmic metal enrichment, the possibility to establish new distance indicators, the study of the yield of heavy elements and the derivation of the primordial helium, and finally the rôle these galaxies play in the hierarchial buildup of structures in the Universe.

Will we ever find a metal-free galaxy? In our local universe we concur that young galaxies (hence possible metal free candidates) are unlikely to be found. In fact we have stressed that the most metal poor known dwarf galaxies are orders of magnitudes more metal rich than the most extreme halo stars in our Galaxy (Cayrel 1996). The metallicity distribution of the Galactic disc stars and the so-called G-dwarf problem (Pagel 1997) indicate pre-enrichment before the disc formed. The oldest known systems in our Galaxy (and the Universe), the halo globular clusters, have metallicities similar to local dwarf spheroidal galaxies. Hence, the oldest globular clusters were self enriched or formed from pre-polluted material. At high redshift the challenge is to pick up galaxies at the epoch of formation. If our Galaxy is a representative case we do not expect pristine (or nearly pristine, with abundances much lower than the most metal-poor local dwarf galaxies) matter to be found anywhere but in dwarfs or sub galactic clumps.

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Appendix: A list of some used abbreviations and acronyms:

BCD: blue compact dwarf galaxy
BCG: blue compact galaxy
C: carbon
CDM: cold dark matter
dE: dwarf elliptical galaxy
dI: dwarf irregular galaxy
dSph: dwarf spheroidal galaxy
DLA: damped Lyman alpha
E: elliptical galaxy
ELG: emission line galaxy
FBS: first Byurakan survey
FOS: Faint Object Spectrograph (HST istrument)
Fe: iron
GC: globular cluster
H: hydrogen
He: helium
HST: Hubble Space Telescope
IGM: intergalactic medium
IMF: stellar initial mass function
IR: infrared
IRAS: infrared astronomical satellite
ISM: interstellar medium
ISO: infared space observatory
$L^\star$: the characteristic galaxy luminosity in the galaxy luminosity funtion
LF: luminosity function (of galaxies)
LBG: Lyman break galaxy
LMC: Large Magellanic Cloud
LSBG: low surface brightness galaxy
N: nitrogen
O: oxygen
QSO: quasar, quasi stellar object
S: Sulphur
SBS: second Byurakan survey
SF: star formation

SFR: star formation rate
SFH: star formation history
SMC: Small Magellanic Cloud
SSC: super star cluster
UV: ultraviolet
VLA: Very Large Array
WR: Wolf-Rayet
XBCG: extreme blue compact galaxy
Y: helium abundance
Z: metallicity, heavy element abundance
z: redshift

References

Aaronson M., 1986, in “Star-forming dwarf galaxies and related objects”, Eds. Kunth D., Thuan T.X., Tran Thanh Van J., Éditions Frontières, p. 125

Allen D.A, Wright A.E, Goss W.M. 1976, MNRAS, 177, 91

Alloin D., Bergeron J., Pelat D., 1978, A&A 70, 141

Aloisi A., Tosi M., Greggio L., 1999, AJ 118, 302

Aparicio A., Herrero A., Sánchez F., Eds., “Stellar Astrophysics for the Local Group”, Cambridge University press, 1998

Armandroff T.E., Davies J.E., Jacoby G.H., 1998, AJ 116, 2287

Arnault P., Kunth D., Casoli F., Combes F., 1988, A&A 205, 41

Arnault Ph., Kunth D., Schild H. 1989, A&A, 224, 73

Arp H., 1965, ApJ 142, 383

Arp H., O’Connell R.W., 1975, ApJ 197, 291

Arp H., Sandage A., 1985, ApJ 90, 1163

Augarde R., Chalabaev A., Comte G., Kunth D., Maehara H., 1994, A&AS 104, 259

Aussel H., Cesarsky C.J., Elbaz D., Starck J.L., 1999, A&A 342, 313

Babul A., Rees M.J., 1992, MNRAS 255, 346

Balkowski C., Chamaraux P., Weliachew L., 1978, A&A 69, 263

Barbuy B., 1988, A&A 191, 121

Barth A.J., Ho L.C., Fillipenko A.V., Sargent W.L., 1995, AJ 110, 1009

Bautista M.A., Pradhan A.K., 1995, ApJ 442, L65

Bell E.F., Bower R.G., de Jong R.S., Hereld M., Rauscher B.J., 1999, MNRAS 302, L55

Benjamin R.A., Skillman E.D., Smits D.P., 1999, ApJ 514, 307

Bergvall N. 1985, A&A 146, 269

Bergvall N., Jörsäter S., 1988, Nature 331, 589

Bergvall N., Östlin G., 1999, in preparation

Bergvall N., Rönnback J., 1994, in “ESO/OHP worshop on dwarf galaxies”, Eds. Meylan G., Pruginel P., ESO Conference and Workshop proceedings No. 49, p. 433

Bergvall N., Rönnback J., 1995, MNRAS 273, 603

Bergvall N., Östlin G., Pharasyn A., Rönnback J., Masegosa J., 1998, in Highlights in Astronomy, Ed. Andersen J., Vol. 11A, p. 103

Bergvall N., Rönnback J., Masegosa J., Östlin G., 1999 A&A 341, 697

Binggeli B., 1994, in “ESO/OHP worshop on dwarf galaxies”, Eds. Meylan G., Prugniel P., ESO Conference and Workshop proceedings No. 49, p. 13

Binggeli B., Sandage A., Tarenghi M., 1984, AJ 89, 64

Binggeli B., Sandage A., Tammann G.A., 1988, ARA&A 26, 509

Binggeli B., Tarenghi M., Sandage A., 1990, A&A 228, 42

Boroson T.A., Salzer J.J., Trotter A., 1993, ApJ 412, 524

Bothun G.D., Caldwell C.N., 1984, ApJ 280,528

Bothun G.D., Beers T.C., Mould J.R., Huchra J.P., 1986a, ApJ 308, 510

Bothun G.D., Mould J.R., Caldwell N., MacGillivray H.T., 1986b, AJ 92, 1007 Bothun G.D., Impey C.D., Malin D.F., Mould J., 1987, AJ 94, 23
Bothun G., Schombert J., Impey C., Schneider S., 1990, ApJ 360, 427
Bothun G.D., Schombert J.M., Impey C.D., Sprayberry D., McGaugh S.S., 1993, AJ 106, 530
Bothun G., Impey C., McGaugh S., 1997, PASP 109, 745
Bottinelli L., Gougenheim L., Heidmann J., 1973, A&A 22, 281
Bottinelli L., Duflot R., Gougenheim L., Heidmann J., 1973, A&A 22, 281
Briggs F.H., 1997, Pub.Ast. Soc of Australia 14,31
Broadhurst T.J., Ellis R.S., Shanks T., 1988, MNRAS 235, 827
Brocklehurst M., 1972, MNRAS 157, 211
Bruzual G., Charlot S. 2000, in preparation
Caldwell, Amandroff, Da Costa, Seitzer, 1998, AJ 115, 535
Campbell A., Terlevich R., Melnick J., 1986, MNRAS 223, 811
Campos-Aguilar A., Moles M., Masegosa J., 1993, AJ 106, 1784
Carignan C., Beaulieu S., Côté S., Demers S., Mateo M., 1998, AJ 116, 1690
Cayrel R., 1996, A&AR 7, 217
Cen R., Ostriker J.P., 1999, ApJ 519, L109
Chamaraux P., 1977, A&A 60, 67
Chamaraux P., Heidmann J., Lauqué R., 1970, A&A 8, 424
Chengalur J.,N., Giovanelli R., Haynes M.P., 1995, AJ 109, 2415
Cerviño M. 1998, Ph. D. Thesis, Universidad Complutense de Madrid
Cerviño M., Mas-Hesse J.M., 1994, A&A, 284, 749
Colless M., Ellis R.S., Taylor K., Hook R.N., 1990, MNRAS 244, 408
Comte G., 1998, Astrophysics, 41, 89
Comte G., Augarde R., Chalabaev A., Kunth D., Maehara H., 1994, A&A 285, 1
Combes F., 1986, in “Star-forming dwarf galaxies and related objects”, Eds. Kunth D., Thuan T.X., Tran Thanh Van J., Éditions Frontières, p. 307;
Conti P. 1991, ApJ, 377, 115
Conti P., Vacca W., 1994, ApJ, 423, L97
Corbelli E., Salpeter E.E, 1993a, ApJ 419,94
Corbelli E., Salpeter E.E, 1993b, ApJ 419,104
Côté S., Freeman K.C., Carignan C., Quinn P.J., 1997, AJ 114, 1313
Cowie L.L., Songaila A.A., Hu E.M., 1991, Nature 354, 460
Da Costa G.S., Armandroff T.E., 1990, AJ 100, 162
Davies J.I., Phillipps S., 1988, MNRAS 233, 553
Davies J., Impey C., Phillipps S., eds., “The Low Surface Brightness Universe”, proc. IAU Col. 171, pub. PASP conf ser. No. 170
de Blok W.J.G., van der Hulst J.M., 1998, A&A 335, 421
de Blok W.J.G., McGaugh S.S., van der Hulst J.M., 1996, MNRAS 283, 18
de Blok W.J.G., van der Hulst J.M., Bothun G.D., 1995, MNRAS 274, 235
Dekel A., Silk K., 1986, ApJ 303, 39
De Mello D.F., Schaerer D., Heldmann J., Leitherer C. 1998, ApJ, 507,199
de Vaucouleurs G., de Vaucouleurs A.; Corwin J.R., Buta R.J., Paturel G., Fouque P., Third reference catalogue of bright galaxies (RC3), version 9, 1991, New York : Springer-Verlag
de Young D.S., Heckman T.M., 1994, ApJ 431, 598
Disney M., Phillipps S., 1983, MNRAS 205, 1253
Djorgovski S., 1990, AJ 99, 31
Doublier V., Comte G., Petrosian A., Surace C., Turatto M., 1997, A&AS 124, 405
Doublier V., Kunth D., Courbin F., Magain P, 1999, A&A accepted (astroph/9902294)
Duc P.-A., Mirabel I.F., 1994, A&A 289, 83
Duc P.-A., Mirabel I.F., 1998, A&A 333, 813
Dufour R.J., Hester J.J., 1990, ApJ 350, 149
Dufour R.J., Garnettt D.R., Shields G.A., 1988, ApJ 332, 752
Dufour R.J., Garnettt D.R., Skillman E.D., Shields G.A., 1996, in “From Stars to Galaxies: The Impact of Stellar Physics on Galaxy Evolution”, Eds. Leitherer C., Fritze-von-Alvensleben U., Huchra J., ASP Conf. Ser. 98, p.358
Dunlop J.S., Hughes D.H., Rawlings S., Eales S.A., Ward M.J., 1994, Nature 370, 347
Edmunds M.G., 1990, MNRAS 246,678

Edvardsson B., Andersen J., Gustafsson B., Lambert D.L., Nissen P.E., Tomkin J., 1993, A&A 275, 101
Efstathiou G., 1992, MNRAS 256, P43
Eggen O.J., Lynden-Bell D., Sandage A.R., 1962, ApJ 136, 748
Ellis R.S., 1997, ARA&A 35, 389
Esteban C., Peimbert M., 1995, A&A 300, 78
Fanelli M.N., O'Connell R.W., Thuan T.X., 1988, ApJ 334, 665
Ferguson H., Binggeli B., 1994, A&AR 6, 67
Ferrara A., Tolstoy E., 1999, MNRAS submitted, (astroph/9905280)
French H.B., 1980, ApJ 240, 41
Gallagher J.S., Hunter D.A., 1987, AJ 94, 43
Gallagher J.S., Littleton J.E., Matthews L.D., 1995, AJ 109, 2003
Gallego J., Zamorano J., Rego M., Vitores A.G., 1997, ApJ 475, 502
Garnett D.R., 1990, ApJ, 363, 142
Garnett D.R., Skillman E.D., Dufour R.J., Peimbert M., Torres-Peimbert S., Terlevich R.J., Terlevich E., Shields G.A., 1995, ApJ 443, 64
Garnett D.R., Skillman E.D., Dufour R.J., Shields G.A., 1997, ApJ 481, 174
Garnett D.R., Shields G.A., Peimbert M., Torres-Peimbert S., Skillman E.D., Dufour R.J. Terlevich E., Terlevich R.J., 1999, ApJ 513, 168
Gerola H., Seiden P.E., Schulman L.S., 1980, ApJ 242, 517
Gilmore G., Wyse, R.F.G., 1991, ApJ 367, L55
Giovanelli R., Haynes M.P., 1989, ApJ 346, L5
Giovanelli R., Scodeggio M., Solanes J.M., Haynes M.P., Arce H., Sakai S., 1995, AJ 109, 1451
Glazebrook K., Ellis R.S., Santiago B., Griffiths R., 1995, MNRAS 275, L19
Gondhalekar P.M., Johansson L.E.B., Brosch N., Glass I.S., Brinks E., 1998, A&A 335, 152
Gordon D., Gottesman S.T., 1981, AJ 86, 161
Goodwin S.P., 1997, MNRAS 284, 785
Gorgas J., Pedraz S., Guzmán R., Cardiel N., Gonzáles J., 1997, ApJ 481, L19
Gottesman S.T., Weliachew L., 1972, Astrophys. Letters. 12, 63
Grebel E., 1998, in "The Stellar Content of Local Group Galaxies", Eds. Whitelock P. and Cannon R., IAU symposium 192, Publisher: Astron. Soc. of the Pacific., p.17
Gustafsson B., Karlson T., Olsson E., Edvardsson B., Ryde N., 1999, A&A 342, 426
Guzmán R., Koo D.C., Faber S.M., Illingworth G.D., Takamiya M., R.G. Kron, Bershady M., 1996, ApJ 460, L5
Guzmán R., Gallego J., Koo D.C., Phillips A.C., Lowenthal J.D., Faber S.M., Illingworth G.D., Vogt N.P., 1997, ApJ 489, 559
Hammer F., Flores H., Lilly S.J., Crampton D., Le Fèvre O., Rola C., Mallen-Ornelas G., Schade d., Tresse L., 1997, ApJ 481, 49
Haro G., 1956, Bol Obs. Tonantzintla y Tacubaya 2, 8
Haser S., Pauldrach A., Lennon D., Kudritzki R.-P., Lennon M., Puls J., Voels S., 1998, A&A 330, 285
Hazard C., 1986, in "Star-forming dwarf galaxies and related objects", Eds. Kunth D., Thuan T.X., Tran Thanh Van J., Éditions Frontières, p. 9
Held E.V., Mould J.R., 1994, AJ 107, 1307
Hensler G., Rieschick A., 1998, in Highlights in Astronomy, Ed. Andersen J., Vol. 11A, p 139, (Kluwer)
Hilker M., Richtler T., Gieren W., 1995, A&A 294, 648
Hidalgo-Gámez A.M., Olofsson K., A&A 334, 45
Ho L.C., Filippenko A.V., 1996, ApJ 472, 600
Hu E.M., Cowie L.L. & McMahon R. G., 1998, ApJ 502, L99
Hughes D.H., Serjeant S., Dunlop J., et al. Nature 394, 241
Hunter D.A., Thronson H.A. Jr, 1995, ApJ 452, 238
Ibata R.A., Gilmore G., Irwin M.J., 1994, Nature 370, 194
Impey C., Bothun G., Malin D., Stavely-Smith L., 1990, ApJ 351, L33
Iovino A., Melnick J., Shaver P., 1988, ApJ 330, L17
Israel F.P., van Driel W., 1990, A&A 236, 323
Israel F.P., Tacconi L.J., Baas F., 1995, A&A 295, 599
Israelian G., Lopez R.J.G., Rebolo R., 1998, ApJ 507,805
Izotov Y.I., Thuan T. X., 1998a, ApJ, 500, 188
Izotov Y.I., Thuan T.X., 1998b, ApJ, 497, 227
Izotov Y.I., Thuan T.X., 1999 ApJ 511, 639

Izotov Yu.I., Guseva N.G., Lipovetskii V.A., Kniazev A.Yu, Stepanian J.A., 1990, Nature 343, 238
Izotov Y.I., Lipovetsky V.A., Guseva N.G., Kniazev A.Y., Stepanian J.A., 1991, A&A 247, 303
Izotov Y.I., Foltz C.B., Green R.F., Guseva N.G., Thuan T.X. 1997a, ApJ, 487, L37
Izotov Y., Lipovetsky V.A., Chaffee F.H., Foltz C.B., Guseva N.G., Kniazev A.Y., 1997b, ApJ 476, 698
Izotov Y.I., Papaderos P., Thuan T.X., Fricke K.J., Foltz C.B., Guseva N.G., 1999, A&A submitted, (astroph/9907082)
Izotov Y.I., Chaffee F.H., Foltz C.B., Green R.F., Guseva N.G., Thuan T. X., 1999b, ApJ accepted, (astroph/9907228)
James P., 1991, MNRAS 250, 544
James P., 1994, MNRAS 269, 176
Jerjen H., Binggeli B., 1997, in "The second Stromlo symposium: the nature of elliptical galaxies" eds. Arnaboldi M., Da Costa G.S., Saha P., ASP conf. ser. Vol 116, p. 239
Karachentsev I.D., Karachentseva V.E., 1999, A&A 341, 355
Kennicutt R.C.Jr, 1989, ApJ 344, 685
Kinman T.D., Davidson K., 1981, ApJ, 243, 127
Kinman T.D., Hintzen P., 1981, PASP 93, 405
Kniazev A. Yu., Pustilnik S.A., Ugryumov A.V., 1998, Bull. Spec. Astrophys. Obs. 4, 23
Kniazev A. Yu., et al. 1999, in preparation
Kobulnicky H.A., 1998, in "Abundance Profiles: Diagnostic Tools for Galaxy History", Eds. Friedli D., Edmunds M., Robert C., Drissen L., ASP Conf. Ser. Vol. 147, p. 108
Kobulnicky H.A., Skillman E.D., 1996, ApJ 471, 211
Kobulnicky H.A., Skillman E.D., 1998, ApJ 497, 601
Kobulnicky H.A., Skillman E.D., Roy J.-R., Walsh J.R., Rosa M.R., 1997, ApJ 477, 679
Kobulnicky H.A., Kennicutt R.C. Jr, Pizagno J.L., 1999 ApJ 514, 544
Kobulnicky H.A., Zaritsky D., 1999, ApJ 511, 118
Kormendy J., Bender R., 1994, in "ESO/OHP worshop on dwarf galaxies", Eds. Meylan G., Prugniel P., ESO Conference and Workshop proceedings No. 49, p. 161
Koo D.C., Guzmán R., Faber S.M., Illingworth G.D., Bershady M.A., Kron R.G., Takamiya M., 1995, ApJ 440, L49
Kudritzki R.P., 1998, in "Stellar astrophysics for the Local Group", eds. Aparicio A., Herrero A., Sanchez F., Cambridge university press
Kunth D., 1986, in "Star-forming dwarf galaxies and related objects", Eds. Kunth D., Thuan T.X., Tran Thanh Van J., Éditions Frontières, p. 183
Kunth D., 1996, in "The Sun and Beyond", eds. Tran Thanh Van J., Celnikier L., Chong Trong H., Éditions Frontières, p. 357
Kunth D., Joubert M. 1985, A&A, 142, 411
Kunth D., Sargent W.L.W. 1981, A&A, 101, L5
Kunth D., Sargent W.L.W., 1983, ApJ 273, 81
Kunth D., Sargent W.L.W., 1986, ApJ 300, 496
Kunth D., Schild H. 1986, A&A, 169, 71
Kunth D., Sargent W.L.W., Kowal C., 1981, A&AS 44, 229
Kunth D., Maurogordato S., Vigroux L., 1988, A&A 204, 10
Kunth D., Lequeux J., Sargent W.L.W., Viallefond F., 1994 A&A 282, 709
Kunth D., Matteucci F., Marconi G. 1995, A&A, 297, 634
Kunth D., Mas-Hesse J.M., Terlevich E., Terlevich R., Lequeux J., Fall S.M., 1998, A&A 334,11
Lacey C., Guiderdoni B., Rocca-Volmerange B., Silk J., 1993, ApJ 402, 15
Lanzetta K.M., Bowen D.B., Tytler D., Webb J.K., 1995, ApJ 442,538
Lauberts A., Valentijn E.A., 1989, "The surface photometry catalogue of the ESO-Uppsala galaxies", ESO
Lauqué R., 1973, A&A 23, 253
Larson R.B., 1974, MNRAS 169, 229
Le Brun V., Bergeron J., Boissé P., Deharveng J.M., 1997, A&A 321, 733
Lee M.G., Freedman W., Mateo M., Thompson I., Roth M., Ruiz M.-T., 1993, AJ 106, 1420
Lee H., McCall M.L., Richer M.G., 1998, BAAS 193, 5304
Lee H., McCall M.L., Richer M.G., 1998 in "Abundance profiles: diagnostic tools for galaxy history", eds. Friedli D., Edmunds M., Robert C., Drisen L., ASP conf. ser. 147, p. 313
Legrand F., 1998, PhD Thesis, Institut d'Astrophysique de Paris
Legrand F., Kunth D., Mas-Hesse J.M., Lequeux, J. 1997a, A&A 326, 929
Legrand F., Kunth D., Roy J.-R., Mas-Hesse J.M., Walsh J.R., 1997b, A&A 326, 17

Legrand F., et al., 1999, in preparation
Lehnert M.D., Bell R.A., Hesser J.E., Oke J.B., 1992, ApJ 395, 466
Leitherer C., 1999, in “Chemical evolution from zero to high redshift”, Eds. Walsh J., Rosa M., Lecture notes in Physics (Berlin:Springer) in press. (STSCI preprint 1312)
Leitherer C., Robert C., Drissen L., 1992, ApJ 401, 596
Lequeux J., Viallefond F., 1980, A&A 91, 269
Lequeux J., Peimbert M., Rayo J.F., Serrano A., Torres-Peimbert S., 1979, A&A 80, 155
Lequeux J., Maucherat-Joubert M., Deharveng J.M., Kunth D., 1981, A&A 103, 305
Lequeux J., Kunth D., Mas-Hesse J.M., Sargent W.L.W., 1995, A&A,301,18
Lilly S.J., Cowie L.L., Gardner J.P., 1991, ApJ 369, 79
Lin D.N.C., Faber S.M., 1983, ApJ 266, L21
Lindner U., Einasto M., Einasto J., Freudling W., Fricke K., Lipovetsky V., Pustilnik S., Izotov Y. Richter G., 1996, A&A 314, 1
Lindner U., Fricke K.J., Einasto J., Einasto M., 1998, in Highlights of Astronomy, Ed. Andersen J., Vol. 11A, p 111
Lisenfeld U., Ferrara A., 1998, ApJ 496, 145
Lipovetsky V.A., Chaffe F.H., Izotov Y.I., Foltz C.B., Kniazev A.Y., Hopp U., 1999, ApJ 519, 177
Lo K.Y., Sargent W.L.W., 1979, ApJ 227, 756
Lo K.Y., Sargent W.L.W., Young K., 1993, AJ 106, 507
Loose H.-H., Thuan T.X., 1986a, in “Star-forming dwarf galaxies and related objects”, Eds. Kunth D., Thuan T.X., Tran Thanh Van J., Éditions Frontières, p. 73
Loose H.-H., Thuan T.X., 1986b, ApJ 309, 59
Lu L., Sargent W.L.W., Barlow T.A., Churchill C.W., Vogt S.S., 1996, ApJS 107, 475
Lu L., Sargent W.L.W., Barlow T.A., 1998, ApJ 115, 55
MacAlpine G.M., Smith S.B., Lewis D.W., 1977, ApJSS 34, 95
MacLow M.-M., Ferrara ., 1999, ApJ 513, 142
Macri L.M., Huchra J.P., Stetson P.B., et al., 1999, ApJ 521, 155
Madau P., Ferguson H.C., Dickinson M.E., Giavalisco M., Steidel C.C., Fruchter A., 1996, MNRAS 283, 1388
Madore B.F., Freedman W.L., Silbermann N., et al., 1999, ApJ 515, 29
Maeder, A. 1992, A&A, 264,105
Maiz-Appelaniz J., Mas-Hesse J.M., Munoz-Tunon C., Vilchez J.M., Castaneda H.O., 1998, A&A 329, 409
Marconi G., Matteucci F., Tosi M., 1994, MNRAS 270, 35
Markarian B.E., 1967, Afz 3,24
Markarian B.E., Stepanian D.A., 1983, Afz 19, 639
Marlowe A.T., Heckman T.M., Wyse R.F.G., Schommer R., 1995, ApJ, 438, 563
Marlowe A.T., Meurer G.R., Heckman T.M., Schommer R., 1997, ApJS 112, 285
Marlowe A.T., Meurer G.R., Heckman T.M., ApJ accepted, (astroph/9904089)
Martin C., 1996, ApJ 465, 680
Martin C., 1998, ApJ 506, 222
Masegosa J., Moles M., Campos-Aguilar A., 1994, ApJ 420, 576
Mas-Hesse J.M., Kunth D., 1999, A&A accepted (astroph/9812072)
Massey P., Armandroff T., Pyke R., Patel K., Wilson C., 1995, AJ 110, 2715
Mateo M., 1998, ARA&A 36, 435
Mathewson D.S., Ford V.L., 1996, ApJS 107, 97
Matteucci F., 1996, Fund. Cosm. Phys. 17, 283
Matteucci F., Chiosi C., 1983, A&A 123, 121
Matthews L.D., Gallagher J.S., 1996, AJ 111, 1098
Maza et al. 1999, in preparation
Mazzarella J.M., Boroson T.A., 1993, ApJS 85, 27
McGaugh S., 1994, ApJ 426, 135
McGaugh S.S., Bothun G.D., 1994, AJ 107, 530
McGaugh S.S., de Blok W.J.G., 1997, ApJ 481, 689
McMahon R.G., Irwin M.J., Giovanelli R., Haynes M.P., Wolfe A.M., Hazard C., 1990, ApJ 359, 302
Melnick J., Moles M., Terlevich R., Garcia-Pelayo J.M., 1987, MNRAS 226, 849
Melnick J., Moles M., Terlevich R., 1985a, A&A 149, L24
Melnick J., Terlevich R., Eggleton P.P., 1985b, MNRAS 216, 255

Melnick J., Terlevich R., Moles M., 1988, MNRAS 235, 297
Melnick J., Heydari-Malayeri M., Leisy P., 1992, A&A 253, 16
Merlino S., Masegosa J., Kniazev A., Pustilnik S., Ugryumov A., Izotov Y., Marquez I., 1999, in "Astrophysics with the NOT", Ed Piirola V., in press.
Meurer G.R., Freeman K.C., Dopita M.A., Cacciari C., 1992, AJ 103, 60
Meurer G.R., Heckman T.M., Leitherer C., Kinney A., Robert C., Garnett D.R., 1995, AJ 110, 2665
Meurer G.R., Carignan C., Beaulieu S., Freeman K.C., 1996, AJ 111, 1551
Meurer G.R., Heckman T.M., Lehnert M.D., Leitherer C., Lowenthal J., 1997, AJ, 114, 54
Meurer G.R., Staveley-Smith L., Killeen N.E.B., 1998, MNRAS 300, 705
Meynet G. 1995, A&A, 298, 767
Mihos C.J., McGaugh S.S., de Blok W.J.G., 1997, ApJ 477, L79
Miller B.,W., 1996, AJ 112, 991
Miller B.W., Hodge P., 1996, ApJ 458, 467
Mirabel I.F., 1989, in "Structure and Dynamics of the Interstellar Medium, Proceedings of IAU Colloq. 120" Eds. Tenorio-Tagle G., Moles M., Melnick J., Lecture Notes in Physics (Springer), Vol. 350, p.396
Mirabel I.F., Dottori H., Lutz D., 1992, A&A 256, L19
Mo H.J., McGaugh S.S., Bothun G.D., 1994, MNRAS 267, 129
Mould J.R., 1978, ApJ 20, 434
Murakami I., Babul A., 1999, MNRAS in press, (astroph/9906084)
O'Connell R.W., Gallagher J.S. III, Hunter D.A., Colley W.N., 1995, ApJ 446, L10
Olofsson K., 1995, A&A 293, 652
Östlin G., 1998, PhD Thesis, Uppsala University
Östlin G., 1999a, ApJ submitted
Östlin G., 1999b, in preparation
Östlin G., 1999c, in preparation
Östlin G., Bergvall N., Rönnback J., 1998, A&A 335, 85
Östlin G., Amram P., Masegosa J., Bergvall N., Boulesteix J., 1999a, A&AS 147, 419
Östlin G., Amram P., Bergvall N., Masegosa J., Boulesteix J., 1999b, A&A submitted
Östlin G., Bergvall N., et al. 1999c, in preparation
Pagel B.E.J., 1993, in "New Aspects of Magellanic Cloud Research", Eds. Bashek B., Klare G., Lequeux J., Lecture notes in Physics 416 (Berlin:Springer) p. 330
Pagel B.E.J., 1997, "Nucleosynthesis and chemical evolution of galaxies", Cambridge University press
Pagel B.E.J., Edmunds M.G., 1981, ARA&A,19, 77
Pagel B.E.J., Terlevich R.J., Melnick J., 1986, PASP 98, 1005
Pagel B.E.J., Simonson E.A., Terlevich R.J., Edmunds M.G., 1992, MNRAS 255, 325
Pantelaki I., Clayton D.D., 1987, in "Starbursts and galaxy evolution", Eds. Thuan T.X., Montmerle T., Tran Thanh Van J., Éditions Frontières, p. 145
Papaderos P., Fricke K.J., Thuan T.X., Loose H.-H., 1994, A&A 291, 13
Papaderos P., Loose H.-H., Thuan T.X., Fricke K.J., 1996a, A&AS 120, 207
Papaderos P., Loose H.-H., Thuan T.X., Fricke K.J., 1996b, A&A 314, 59
Papaderos P., Izotov Y.I., Fricke K.J., Thuan T.X., Guseva N.G., 1998, A&A 338, 43
Pascarelle S.M., Windhorst R.A., Keel W.C., 1998, AJ 116, 2659
Patterson R.J., Thuan T.X., 1996, ApJS 107, 103
Peimbert M., 1967, ApJ 150, 825
Peimbert M., Serrano A., 1980, Rev. Mex. Astron. Astrofis., 5, 9
Peimbert M., Torres-Peimbert S., 1974, ApJ 193, 327
Peña M., Ruiz M.T., Maza J., 1991, A&A 251, 417
Persic M., Mariani S., Cappi M., Bassani L., Danese L., Dean A.J., Di Cocco G., Franceschini A., Hunt L.K., Matteucci F., Palazzi E., Palumbo G.G.C., Rephaeli Y., Salucci P., Spizzichino A., 1998, A&A 339, L33
Pesch P., Sanduleak N., 1983, ApJS 51, 171
Petrosian A.R., Boulesteix J., Comte G., Kunth D., LeCoarer E., A&A 318, 390
Pettini M., 1999, in "Chemical evolution from zero to high redshift", Eds. Walsh J., Rosa M., Lecture notes in Physics (Berlin:Springer) in press. (astroph/9902173)
Pettini M., Lipman K., 1995, A&A 297, 63
Pettini M., Lipman K., Hunstead R.W., 1995, ApJ 451, 100
Pettini M., Smith L.J., King D.L., Hunstead R.W., 1997 ApJ 486, 665

Pettini M., Kellogg M., Steidel C.C., Dickinson M., Adelberger K.L., Giavalisco M., 1998, ApJ 508, 539
Phillipps S., Davies J.I., Disney M.J., 1988, MNRAS 233, 485
Phillipps S., Disney M.J., Davies J., 1993, MNRAS 260, 453
Pilyugin L.S., 1992, A&A 260, 58
Pilyugin L.S., 1993, A&A 277, 42
Pilyugin L.S., 1999, A&A accepted, atro-ph/9904157
Popescu C.C., Hopp U., Elsässer H., 1997, A&A 325, 881
Prantzos N., 1998, in “Abundance Profiles: Diagnostic Tools for Galaxy History”, Eds. Friedli D., Edmunds M., Robert C., Drissen L., ASP Conf. Ser. Vol. 147, p. 171
Press W.H., Schechter P., 1974, ApJ 187, 425
Prochaska J.X., Wolfe A.M., 1997, ApJ 487, 73
Prochaska J.X., Wolfe A.M., 1999, ApJS 121, 369
Puget J.L., Guiderdoni B., 1999, in “Space Infrared Astronomy, today and to-morrow”, eds. F. Casoli, F. David, J. Lequeux, EDP Sciences/Springer-Verlag, in press
Pustil’nik S., Ugryumov A.V., Lipovetsky V.A., Thuan T.X., Guseva N., 1995, ApJ 443, 499
Pustilnik S.A., Engels D., Ugryumov A.V., et al., 1999a, A&AS 137, 299
Pustilnik S.A., Brinks E., Thuan T.X., Lipovetsky V.A., Izotov Y.I., 1999b, in prep
Rauch M., Heahnelt M.G., Steinmetz M., 1997, ApJ 481, 601
Renzini A., Voli M., 1981, A&A 94, 175
Richer M.G., McCall M.L., 1995, ApJ 445, 642
Richer M.G., McCall M.L., Arimoto N., 1997, A&AS 122, 215
Richer M.G., McCall M.L., Stasińska G., 1998, A&A 340, 67
Rönnback J., Bergvall N., 1994, A&AS 108, 193
Rönnback J., Bergvall N., 1995, A&A 302, 353
Roy J.-R, Kunth D., 1995, A&A 294, 432
Russell S.C., Bessell M.S.,1989, A&AS 70, 865
Sage L.J., Salzer J.J., Loose H.-H., Henkel C., 1992, A&A 265, 19
Sage L.J., Welch G.A., Mitchell G.F., 1998, ApJ 507, 726
Salpeter E.E., 1955, ApJ 121, 161
Salzer J.J., 1989, ApJ 347, 152
Salzer J.J. 1999, in ”Dwarf Galaxies and Cosmology”, eds. Thuan et al., Editions Frontieres in press
Salzer J.J., MacAlpine G.,M., Boroson T.A., 1989a, ApJSS 70, 447
Salzer J.J., MacAlpine G.,M., Boroson T.A., 1989b, ApJSS 70, 479
Salzer J.J., di Serego Alighieri S., Matteucci F., Giovanelli R., Haynes M.P., 1991, AJ 101,1258
Salzer J.J., Moody J.W., Rosenberg J.L., Gregory S.A., Newberry M.V., 1995, AJ 109, 2376
Sandage A., Brucato R., 1979, AJ 84, 472
Sanders D.B., Soifer B.T., Elias J.H., Madore B.F., Matthews K., Neugebauer G., Scoville N.Z., 1988, ApJ 325, 74
Sargent W.L.W., Searle L., 1970, ApJ, 162, L155
Scalo J., 1990, in “Windows on Galaxies”, Eds. Fabbiano G., Gallagher J.S., Renzini A., Dordrecht:Kluwer, p. 125
Scalo J., 1998, in “The stellar initial mass function”, Eds. Gilmore G., Howell D., ASP Conf. Ser. 142, p. 201
Schade D., Lilly S.J., Crampton D., Hammer F., Le Fèvre O., Tresse L., 1995, ApJ 451, L1
Schaerer D. 1996, ApJ, 467, L17
Schaerer D., Vacca W.D. 1998, ApJ, 497, 618
Schaerer D., Contini,Th., Kunth D., Meynet G. 1997, ApJ 481, L75
Schaerer D., Contini,Th., Kunth D. 1999, A&A, 341, 399
Schechter P., 1976, ApJ 203, 297
Schmidt M., 1968, ApJ 151, 393
Schmutz W., Vacca W.D., 1999, New Astronomy, submitted
Schneider S.E., 1989, ApJ, 343, 94
Schneider S.E., Thuan T.X., Mangum J.G., Miller J., 1992 ApJS 81, 5
Schneider S.E., Spitzak J.G., Rosenberg J.L., 1998, ApJ 507, L9
Schulte-Ladbeck R.E., Crone M.M., Hopp U., 1998, ApJ 493, L23
Schulte-Ladbeck R.E., Hopp U., Crone M.M., Greggio L., 1999, ApJ 525, 709
Schweizer F., 1978, in “Structure and properties of nearby galaxies (IAU symposium 77)” eds. Berkhuijsen E.M., Wielebinski R., Reidel Dordrecht, p. 279

Searle L., Sargent W.L.W., 1972, ApJ 173, 25
Searle L., Sargent W.L.W., Bagnuolo W.G., 1973, ApJ 179, 427
Searle L., Zinn R., 1978, ApJ 225, 357
Serrano A., Peimbert M., 1983, Rev. Mex. Astron. Astrofis.,8,117;
Shetrone M.D., Bolte M., Stetson P.B., 1998, AJ 115, 1888
Shull M.J., Penton S.V., Stocke J.T., Giroux M.L., van Gorkom J.H., Lee Y.H., Carilli C., 1998, ApJ 116, 2094
Silk J., Wyse R.F.G., Shields G.A., 1987, ApJ 322, L59
Skillman E.D., 1996, in "The Minesota lectures on extragalactic neutral hydrogen", ed. Skillman E.D., ASP Conf. Ser. 106, p. 208
Skillman E.D., 1997, Rev. Mex. Astron. Astrofis. Ser. Conf. 6, 36
Skillman E.D., 1998, in "Stellar astrophysics for the Local Group", eds. Aparicio A., Herrero A., Sanchez F., Cambridge university press
Skillman E.D., Bender R., 1995, Rev. Mex. Astron. Astrofis. Ser. Conf., 3, 25
Skillman E.D., Kennicutt R.C., 1993, ApJ 411, 655
Skillman E.D., Kennicutt R.C., Hodge P.W., 1989, ApJ 347, 875
Skillman E.D., Terlevich R.J., Kennicutt R.C., Garnett D.R., Terlevich E., 1994, ApJ 431, 172
Smecker-Hane T.A., Stetson P.B., Hesser J.E., Lehnert M.D., 1994, AJ 108, 507
Smits D.P., 1991, MNRAS 251, 316
Smits D.P., 1996, MNRAS 278, 683
Somerville R.S., Primack J.R., 1999, MNRAS accepted (astroph/9802268)
Spite M., Cayrel R., Francois P., Richtler T., Spite F., 1986, A&A 168,197
Staveley-Smith L., Davies R.D., Kinman T.D., 1992, MNRAS 258, 334
Steidel C.C., Pettini M., Hamilton D., 1995, AJ, 110, 2519
Steidel C.C., Giavalisco M., Pettini M., Dickinson M., Adelberger K.L., 1996, ApJ 462, L17
Steidel C.C., Adelberger K.L., Giavalisco M., Dickinson M., Pettini M., 1999, ApJ 519, 1
Suntzeff N.B., Mateo M., Terndrup D.M., Olszewski E.W., Geisler D., Weller W., 1993, ApJ 418, 208
Szomoru A., Guhathakurta P., van Gorkom J.H., Knapen J.H., Weinberg D.H., Fruchter A.S., 1994, AJ 108, 491
Takase B., Miyauchi-Isobe N., 1984, Tokyo Astr. Observ. Annals, 2nd Ser.,Vol 19, 595
Tayler R.J., 1976, MNRAS 177, 39
Taylor C.L., 1997, ApJ 480, 524
Taylor C.L., Brinks E., Skillman E.D., 1993, AJ 105, 128
Taylor C.L., Brinks E., Grashuis R.M., Skillman E.D., 1995, ApJS 99, 424
Taylor C.L., Brinks E., Grashuis R.M., Skillman E.D., 1996a, ApJS 102, 189 (erratum)
Taylor C.L., Thomas D.L., Brinks E., Skillman E.D., 1996b, ApJS 107, 143
Telles E., Maddox S., 1999, MNRAS submitted (astroph/9903037)
Telles E., Terlevich R., 1995, MNRAS 275, 1
Telles E., Terlevich R., 1997, MNRAS 286, 183
Telles E., Melnick J., Terlevich R., 1997, MNRAS 288, 78
Tenorio-Tagle G., 1996, AJ 111, 1641
Tenorio-Tagle G., Silich S.A., Kunth D., Terlevich E., Terlevich R., 1999, MNRAS in press, (astroph/9905324)
Terlevich R., Melnick J., 1981, MNRAS 195, 839
Terlevich R., Melnick J., Masegosa J., Moles M., Copetti M.V.F., 1991, A&AS 91, 285
Terlevich E., Skillman E.D., Terlevich R., 1996 in "The interplay between massive star formation, the ism and galaxy evolution", Eds. Kunth D., Guiderdone B., Heydari-Malayeri M., Thuan T.X., Édition Frontières, p. 395,
Thuan T.X., 1983, ApJ 268, 667
Thuan T.X., 1985, ApJ 299, 881
Thuan T.X., 1986a, in "Star-forming dwarf galaxies and related objects", Eds. Kunth D., Thuan T.X., Tran Thanh Van J., Éditions Frontières, p. 105
Thuan T.X., Martin G.E., 1981, ApJ 247, 823
Thuan T.X., Seitzer P.O., 1979, ApJ 231, 680
Thuan T.X., Gott J.R, Schneider S.E., 1987 ApJ 315, L93
Thuan T.X., Izotov Y.I., Lipovetsky V.A., 1996, ApJ 463, 120
Thuan T.X., Izotov Y.I., Lipovetsky V.A., 1997, ApJ 477, 661
Thuan T.X., Sauvage M., Madden S., 1999, ApJ 516, 783

Tikhonov N.A., Karachentsev I.D., 1993, A&AS 275, 39
Tolstoy E., Gallagher J.S., Cole A.A., Hoessel J.G., Saha A., Dohm-Palmer R.C., Skillman E.D., Mateo M., Hurley-Keller D., 1998, AJ 116, 1244
Torres-Peimbert S., Peimbert M., Fierro J., 1989, ApJ 345, 186
Tosi M., 1988, A&A 197, 47
Tully B.R., Boesgaard A.M., Schempp W.V., 1980 in "Photometry, Kinematics and Dynamics of Galaxies", Ed. Evans D.S., Knudsen, p. 325
Tyson J.A., 1988, AJ 96, 1
Tyson N.D., Scalo J.M., 1988, ApJ 329, 618
Ugryumov A.V., Engels D., Lipovetsky V., et al., 1999, A&AS 135, 511
Vacca W.D., Conti P.S., 1992, ApJ 401, 543
Vader J.P., 1986, ApJ 305, 669
van den Bergh S., 1994, ApJ 428, 617
van der Hoek L.B., Groenewegen M.A.T., 1997, A&AS 123, 305
van der Hulst J.M., Skillman E.D., Smith T.R., Bothun G.D., McGaugh S., de Blok W.J.G., 1993, AJ 106, 548
van Zee L. Haynes M.P., Salzer J., Broeils A.H., 1996, 112, 129
van Zee L., Haynes M.P., Salzer J., Broeils A.H., 1997a, AJ 113, 1618
van Zee L., Haynes M.P., Salzer J., 1997b, AJ 114, 2479
van Zee L., Haynes M.P., Salzer J., 1997c, AJ 114, 2497
van Zee L., Westpfahl D., Haynes M.P., Salzer J., 1998a, AJ 115, 1000
van Zee L., Salzer J., Haynes M.P., 1998b, ApJ 497, L1
van Zee L., Skillman E.D., Salzer J., 1998c, AJ 116, 1186
Viallefond F., Lequeux J., Comte G., 1987, in "Starbursts and galaxy evolution", Eds. Thuan T.X., Montmerle T., Tran Thanh Van J., Éditions Frontières, p. 139
Vílchez J.M., 1995, AJ 10, 1090
Vílchez J.M., 1999, in "Chemical evolution from zero to high redshift", eds. Walsh J., Rosa M., Lecture Notes in Physics, Berlin:Springer, in press
Vílchez J.M., Iglesias-Páramo J., 1998, ApJ 508, 248
Vitores A.G., Zamorano J., Rego M., Alonso O., Gallego J., 1996, A&AS 118, 7
Vladilo G., 1998, ApJ 493, 583
Walsh J.R., Roy J.-R., 1993, MNRAS 262, 27
Walsh J.R., Dudziak G., Minniti D., Ziljstra A.A., 1997, ApJ 487, 651
Wasilewski A.J., 1983, ApJ 272, 68
White S.D.M., Rees M.J., 1978, MNRAS 183, 341
Whitmore B.C., Schweizer F., 1995, AJ 109, 960
Williams R.E., Blacker B., Dickinson M., et al., 1996, AJ 112, 1335
Worthey G., 1994, ApJS 95, 107
Worthey G., Faber S.M., Gonzalez J.J., 1992, ApJ 398, 69
Young C.K., Currie M.J., 1998, A&AS 127, 367
Young J.S., Kenney J.D., Tacconi L., Claussen M.J., Huang Y.-L., Tacconi-Garman L., Xie S., Schloerb F.P., ,1986 ApJ 311, L17
Young L., Lo K., 1996, ApJ 462, 203
Young L., Lo K., 1997a, ApJ 476, 127
Young L., Lo K., 1997b, ApJ 490, 710
Zinnecker H., Cannon R.D., 1986, in "Star forming dwarf galaxies and related objects", Eds. Kunth D., Thuan T.X., Tran Thanh Van J., Éditions Frontières, p. 155
Zwicky F., 1956, Ergebnisse der Exakten Naturwissenschaften 29, 344
Zwicky F., 1965, ApJ 142, 1293
Zwicky F., 1966, ApJ 143, 192
Zwicky F., 1971, Catalogue of selected compact galaxies and of post-eruptive galaxies