

Cosmic Star Formation History and the Brightness of the Night Sky

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Abstract. I review the constraints imposed by the observed extragalactic background light (EBL) on the history of the stellar birthrate in galaxies. At faint magnitudes, the logarithmic slope of the galaxy counts is flatter than 0.4 in all seven *UBVIJHK* optical bandpasses of the *Hubble Deep Field-South* imaging survey. The integration of the number counts provides a lower limit to the surface brightness of the optical extragalactic sky of $15 \text{ nW m}^{-2} \text{ sr}^{-1}$, comparable to the intensity of the far-IR background from *COBE* data. If the initial mass function has a Salpeter slope with a lower mass cutoff consistent with observations of M subdwarf disk stars, a lower limit of $\Omega_* > 0.005 I_{50}$ (at Hubble constant $50 \text{ km s}^{-1} \text{ Mpc}^{-1}$) is derived for the visible (processed gas + stars) mass density needed to generate an extragalactic background light (EBL) at a level of $50 I_{50} \text{ nW m}^{-2} \text{ sr}^{-1}$. The current ‘best-guess’ estimate to Ω_* is $0.012 I_{50}$, about 16% of the nucleosynthetic baryon density. The contribution of quasar activity to the observed EBL is unlikely to exceed 20%.

1 Introduction

Recent progress in our understanding of faint galaxy data made possible by the combination of *Hubble Space Telescope* (*HST*) deep imaging and ground-based spectroscopy has dramatically increased our knowledge of the evolution of the stellar birthrate in optically-selected galaxies from the present-epoch up to $z \approx 4$ [12], [31], [21]. The explosion in the quantity of information available on the high-redshift universe at optical wavelengths has been complemented by the measurement of the far-IR/sub-mm background by DIRBE and FIRAS onboard the *COBE* satellite [19], [15], [27], by the detection of distant ultraluminous sub-mm sources with the SCUBA camera [28], [9], and by theoretical progress made in understanding how intergalactic gas follows the dynamics dictated by dark matter halos until radiative, hydrodynamic, and star formation processes take over [2], [30], [24]. The IR data have revealed the ‘optically-hidden’ side of galaxy formation, and shown that a significant fraction of the energy released by stellar nucleosynthesis is re-emitted as thermal radiation by dust [8], [18]. The underlying goal of all these efforts is to understand the growth of cosmic structures, the internal properties of galaxies and their evolution, and ultimately to map the star formation history of the universe from the end of the cosmic ‘dark age’ to the present epoch.

In this talk I will focus on the galaxy number-apparent magnitude relation and its first moment, the integrated galaxy contribution to the extragalac-

tic background light (EBL). The logarithmic slope of the differential galaxy counts is a remarkably simple cosmological probe of the history of stellar birth in galaxies, as it must drop below 0.4 to yield a finite value for the EBL. The recently released *Hubble Deep Field-South* (HDF-S) images, together with other existing *HST* and ground-based observations, provide a unique dataset to estimate the spectrum and amplitude of the optical EBL from discrete sources. Together with the far-IR/sub-mm background, the optical EBL is an indicator of the total luminosity of the universe, as the cumulative emission from young and evolved galactic systems, as well as from active galactic nuclei (AGNs), is recorded in this background. As such it provides, for a given initial mass function, a quantitative estimate of the baryonic mass that has been processed by stars throughout cosmic history.

Unless otherwise stated, an Einstein-de Sitter (EdS) cosmology ($\Omega_M = 1$, $\Omega_\Lambda = 0$) with $H_0 = 100 h \text{ km s}^{-1} \text{ Mpc}^{-1}$ will be adopted in this talk. All magnitudes will be given in the AB system. The work presented here has been done in collaboration with L. Pozzetti.

2 Galaxy counts

The HDF-S dataset includes deep near-IR NICMOS images and the deepest observation ever made with the STIS 50CCD filterless imaging mode. The galaxy sample used here was extracted from version 1 of the HDF-S catalog on ftp://archive.stsci.edu/pub/hdf_south/version1/. At near-IR wavelengths (in the F110W, F160W, and F222M bandpasses, corresponding to the *J*, *H*, and *K* filters), it consists of 425 objects detected in the *J + H* image, over a field of $50'' \times 50''$. The 50CCD (corresponding roughly to a *V + I* filter) STIS catalog consists of 674 objects detected again over a field of the same size.

Figure 1 shows the HDF-N and -S galaxy counts compiled directly from the catalogs, as a function of AB isophotal magnitudes in the *UBVIJHK* bandpasses for all galaxies with signal-to-noise ratio $S/N > 3$ within the band. No correction for detection completeness have been made. A compilation of existing *HST* and ground-based data is also shown [22], [25]. All magnitudes have been corrected to the AB system, while the second order colour corrections for the differences in the filter effective wavelengths have not been applied to the ground-based data (for the typical colours of galaxies in the HDF these corrections are less than 0.1 mag). The HDF optical counts agree well with previous surveys, to within 20% in the magnitude range $22 < m_{\text{AB}} < 26$. One should note, however, that different algorithms used for ‘growing’ the photometry beyond the outer isophotes of galaxies can significantly change the magnitude of faint galaxies. According to [3], roughly 50% of the flux from resolved galaxies with $V > 23$ mag lie outside the standard-sized apertures used by photometric packages. An extragalactic sky pedestal created by the overlapping wings of resolved galaxies may also contribute significantly to the sky level, and would be undetectable except

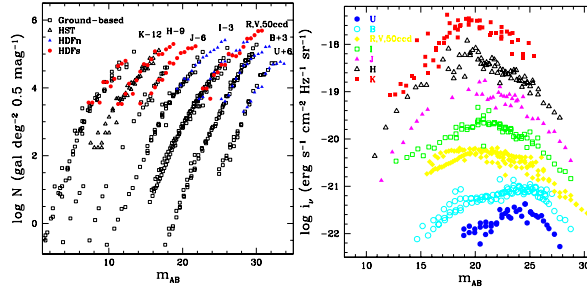


Fig. 1. *Left:* Differential $UBVIJHK$ galaxy counts as a function of AB magnitudes. The sources of the data points are given in the text. Note the decrease of the logarithmic slope $d \log N/dm$ at faint magnitudes. *Right:* Extragalactic background light per magnitude bin, $i_\nu = 10^{-0.4(m_{AB}+48.6)}N(m)$, as a function of U (filled circles), B (open circles), V (filled pentagons), I (open squares), J (filled triangles), H (open triangles), and K (filled squares) magnitudes. For clarity, the $BVIJHK$ measurements have been multiplied by a factor of 2, 6, 15, 50, 150, and 600, respectively [22].

by absolute surface photometry [3]. Also, at faint magnitude levels, distant objects which are brighter than the nominal depth of the catalog may be missed due to the $(1+z)^4$ dimming factor. All these systematic errors are inherent in *HST* faint-galaxy photometry; as a result, our estimate of the integrated flux from resolved galaxies will typically be too low, and must be strictly considered as a *lower limit*.

3 The extragalactic background light

The contribution of known galaxies to the optical EBL can be calculated directly by integrating the emitted flux times the differential number counts down to the detection threshold. I have used the compilation of ground-based, *HST*, and HDF data shown in Figure 1 to compute the integrated flux at $0.35 \lesssim \lambda \lesssim 2.2 \mu\text{m}$.

In all seven bands, the slope of the differential number-magnitude relation is flatter than 0.4 above $m_{AB} \sim 20$ (25) at near-IR (optical) wavelengths, and this flattening appears to be more pronounced at the shorter wavelengths. The leveling off of the counts is clearly seen in Figure 1, where the function $i_\nu = 10^{-0.4(m_{AB}+48.6)}N(m)$ is plotted against apparent magnitude in all bands. While counts having a logarithmic slope $d \log N/dm_{AB} = \alpha \geq 0.40$ continue to add to the EBL at the faintest magnitudes, it appears that the HDF survey has achieved the sensitivity to capture the bulk of the near-

ultraviolet, optical, and near-IR extragalactic light from discrete sources. The flattening at faint apparent magnitudes cannot be due to the reddening of distant sources as their Lyman break gets redshifted into the blue passband, since the fraction of Lyman-break galaxies at (say) $B \approx 25$ is only of order 10% [32]. Moreover, an absorption-induced loss of sources cannot explain the similar change of slope in the $V, I, J, H,$ and K bands. While this suggests that the surface density of optically luminous galaxies is leveling off beyond $z \sim 1.5$, one should worry about the possibility of a significant amount of light being missed at faint magnitudes.

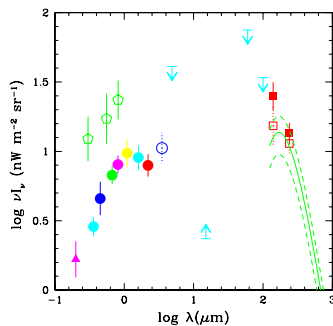


Fig. 2. Spectrum of the optical extragalactic background light from resolved sources as derived from a compilation of ground-based and space-based galaxy counts in the $UBVIJHK$ bands (*filled dots*), together with the FIRAS 125–5000 μm (*solid and dashed lines*) and DIRBE 140 and 240 μm (*filled squares*) detections [19], [15]. The *empty squares* show the DIRBE points after correction for WIM dust emission [20]. Also plotted (*filled triangle*) is a FOCA-UV point at 2000 \AA [1], and a tentative detection at 3.5 μm (*empty dot*) from *COBE*/DIRBE observations [7]. The empty pentagons at 3000, 5500, and 8000 \AA are recent detections from absolute photometry [3]. Upper limits are from [19], the lower limit from [10]. Note that the values obtained by integrating the brightness of resolved galaxies are strict lower limits to the EBL intensity.

The spectrum of the optical EBL is shown in Figure 2, together with the recent results from *COBE*. The value derived by integrating the galaxy counts down to very faint magnitude levels (because of the flattening of the number-magnitude relation most of the contribution to the optical EBL comes from relatively bright galaxies) implies a lower limit to the EBL intensity in the 0.2–2.2 μm interval of $I_{\text{opt}} \approx 15 \text{ nW m}^{-2} \text{ sr}^{-1}$. Including the tentative detection at 3.5 μm by [7] would boost I_{opt} to $\approx 19 \text{ nW m}^{-2} \text{ sr}^{-1}$. Recent estimates of the optical EBL at 3000, 5500, and 8000 \AA from absolute surface photometry by [3] lie between a factor of two to three higher than the integrated light from galaxy counts. Applying this correction fac-

tor to the range 3000–8000 Å gives an optical EBL intensity in excess of $25 \text{ nW m}^{-2} \text{ sr}^{-1}$ in the interval 0.2–3.5 μm . The *COBE*/FIRAS [15] measurements yield $I_{\text{FIR}} \approx 14 \text{ nW m}^{-2} \text{ sr}^{-1}$ in the 125–2000 μm range. When combined with the DIRBE [19], [27], [20] points at 140 and 240 μm , one gets a far-IR background intensity of $I_{\text{FIR}}(140 - 2000 \mu\text{m}) \approx 20 \text{ nW m}^{-2} \text{ sr}^{-1}$. The residual emission in the 3.5 to 140 μm region is poorly known, but it is likely to exceed $10 \text{ nW m}^{-2} \text{ sr}^{-1}$ [8]. A ‘best-guess’ estimate to the total EBL intensity observed today is then

$$I_{\text{EBL}} = 55 \pm 20 \text{ nW m}^{-2} \text{ sr}^{-1}. \quad (1)$$

In the rest of my talk, I will adopt a reference value for the background light associated with star formation activity over the entire history of the universe of $50 I_{50} \text{ nW m}^{-2} \text{ sr}^{-1}$.

4 EBL from quasar activity

A direct estimate of the contribution of quasars to the EBL depends on the poorly known bolometric correction and the possible existence of a distant population of dusty AGNs with strong intrinsic absorption, as invoked in many models for the X-ray background. These Type II QSOs, while undetected at optical wavelengths, could contribute significantly to the far-IR background. It is in principle possible to bypass some of the above uncertainties by weighing the local mass density of black holes remnants [29]. Recent dynamical evidence indicates that supermassive black holes reside at the center of most nearby galaxies. The available data (see Fig. 3) show a correlation (but with a large scatter) between bulge and black hole mass, with $M_{\text{BH}} \approx 0.006 M_{\text{sph}}$ as a best-fit [23]. The mass density in old spheroidal populations today is estimated to be $\Omega_{\text{sph}} h = 0.0018^{+0.0012}_{-0.00085}$ [16], implying a mean mass density of quasar remnants today

$$\rho_{\text{BH}} = 3 \pm 2 \times 10^6 h \text{ M}_{\odot} \text{ Mpc}^{-3}. \quad (2)$$

Since the observed energy density from all quasars is equal to the emitted energy divided by the average quasar redshift, the total contribution to the EBL from accretion onto black holes is

$$I_{\text{BH}} = \frac{c^3}{4\pi} \frac{\eta \rho_{\text{BH}}}{\langle 1+z \rangle} \approx 4 \pm 2.5 \text{ nW m}^{-2} \text{ sr}^{-1} \eta_{0.05} \frac{2.5}{\langle 1+z \rangle} \quad (3)$$

($h = 0.5$), where $\eta_{0.05}$ is the efficiency of accreted mass to radiation conversion (in units of 5%). Therefore, unless dust-obscured accretion onto supermassive black holes is a very efficient process ($\eta \gg 0.05$), a population of quasars peaking at $z \sim 1.5 - 2$ is expected to make a contribution to the brightness of the night sky not exceeding 10–20% [14], [21].

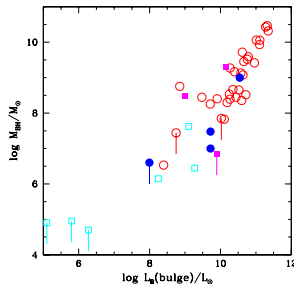


Fig. 3. Black hole mass distribution against the bulge luminosity of their host galaxies [23]. Arrows indicate upper limits on M_{BH} . The symbols denote different galaxy types: *empty circles* (E), *filled squares* (S0), *filled circles* (Sab), and *empty squares* (Sbc-Scd).

5 The stellar mass density today

With the help of some simple stellar population synthesis tools we can now set a lower limit to the total stellar mass density that produced the observed sky brightness and constrain the cosmic history of star birth in galaxies. One of the most serious uncertainties in this calculation has always been the lower cutoff (usually treated as a free parameter) of the initial mass function (IMF). Observations of M subdwarfs stars with the *HST* have recently shed some light on this issue, showing that the IMF in the Galactic disk can be represented analytically over the mass range $0.1 < m < 1.6$ (here m is in solar units) by $\log \phi(m) = \text{const} - 2.33 \log m - 1.82(\log m)^2$ ([17], hereafter GBF). For $m > 1$ this mass distribution agrees well with a Salpeter function. Observations of normal Galactic star-forming regions also show some convergence in the basic form of the IMF at intermediate and high masses, a power-law slope that is consistent with the Salpeter value [13]. In the following I will use a ‘universal’ IMF with the GBF form for $m < 1$, matched to a Salpeter slope for $m \geq 1$; the mass integral of this function is 0.6 times that obtained extrapolating a Salpeter function down to $0.1 M_{\odot}$.¹

As shown in Figure 4, the *bolometric* luminosity as a function of age τ of a simple stellar population (a single generation of coeval, chemically homogeneous stars having total mass M , solar metallicity, and the above

¹ The bolometric light contributed by stars less massive than $1 M_{\odot}$ is quite small for a ‘typical’ IMF. The use of the GBF mass function at low masses instead of Salpeter leaves then the total radiated luminosity of the stellar population virtually unaffected.

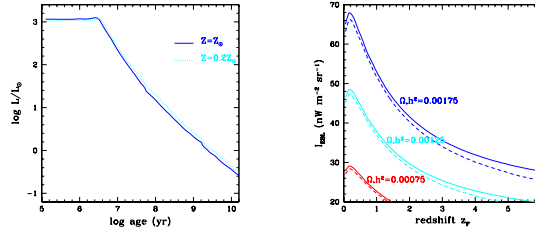


Fig. 4. *Left:* Synthetic [4] bolometric luminosity versus age of a simple stellar population having total mass $M = 1 M_{\odot}$, metallicity $Z = Z_{\odot}$ (solid line) and $Z = 0.2 Z_{\odot}$ (dotted line), and a GBF+Salpeter IMF (see text for details). *Right:* EBL observed at Earth from the instantaneous formation at redshift z_F of a stellar population having the same IMF, solar metallicity, and mass density $\Omega_* h^2 = 0.00175, 0.00125,$ and $0.00075,$ as a function of z_F . *Solid curves:* EdS universe with $h = 0.5$. *Dashed curves:* Λ -dominated universe with $\Omega_M = 0.3, \Omega_{\Lambda} = 0.7,$ and $h = 0.65$.

IMF) can be well approximated by

$$L(\tau) = \begin{cases} 1200 L_{\odot} \frac{M}{M_{\odot}} & \tau \leq 2.6 \text{ Myr}; \\ 0.7 L_{\odot} \frac{M}{M_{\odot}} \left(\frac{\tau}{1 \text{ Gyr}} \right)^{-1.25} & 2.6 \leq \tau \leq 100 \text{ Myr}; \\ 2.0 L_{\odot} \frac{M}{M_{\odot}} \left(\frac{\tau}{1 \text{ Gyr}} \right)^{-0.8} & \tau > 100 \text{ Myr} \end{cases} \quad (4)$$

(cf [6]). Over a timescale of 13 Gyr (the age of the universe for an EdS cosmology with $h = 0.5$), about 1.3 MeV per stellar baryon are radiated away. This number depends only weakly on the assumed metallicity of stars. In a stellar system with arbitrary star formation rate per comoving cosmological volume, $\dot{\rho}_*$, and formation epoch t_F , the comoving bolometric emissivity at time t is given by the convolution integral

$$\rho_{\text{bol}}(t) = \int_0^t L(\tau) \dot{\rho}_*(t - \tau) d\tau. \quad (5)$$

The total background light observed at Earth ($t = t_H$) is

$$I_{\text{EBL}} = \frac{c}{4\pi} \int_{t_F}^{t_H} \frac{\rho_{\text{bol}}(t)}{1+z} dt, \quad (6)$$

where the factor $(1+z)$ at the denominator is lost to cosmic expansion when converting from observed to radiated (comoving) luminosity density. To set a lower limit to the present-day mass density, Ω_* , of processed gas + stars (in units of the critical density $\rho_{\text{crit}} = 2.77 \times 10^{11} h^2 M_{\odot} \text{ Mpc}^{-3}$), consider now a scenario where all stars are formed instantaneously at redshift z_F .

The background light that would be observed at Earth from such an event is shown in Figure 4 as a function of z_F for $\Omega_* h^2 = 0.00075, 0.00125, 0.00175$ (corresponding to 9, 6.5, and 4 percent of the nucleosynthetic baryon density, $\Omega_b h^2 = 0.0193 \pm 0.0014$ [5]), and two different cosmologies. A couple of points are worth noting here: (1) the time evolution of the luminosity radiated by a simple stellar population makes the dependence of the observed EBL from z_F much shallower than the $(1 + z_F)^{-1}$ lost to cosmic expansion, as the energy output from stars is spread over their respective lifetimes; and (2) in order to generate an EBL at a level of $50 I_{50} \text{ nW m}^{-2} \text{ sr}^{-1}$, one requires $\Omega_* h^2 > 0.00125 I_{50}$ (for an EdS universe with $h = 0.5$), hence a mean mass-to-blue light ratio today of $\langle M/L_B \rangle_* > 3.5 I_{50}$ for a present-day blue luminosity density of $\rho_B = 2.0 \times 10^8 h L_\odot \text{ Mpc}^{-3}$ [11]. As shown in Figure 4, the dependence of these estimates on the cosmological model is rather weak. With the adopted IMF, about 30% of this mass will be returned to the interstellar medium in 10^8 yr after intermediate-mass stars eject their envelopes and massive stars explode as supernovae. This ‘return fraction’, R , becomes 50% after about 10 Gyr.

A visible mass density at the level of the above lower limit, $0.00125 h^{-2} I_{50}$, while able to explain the measured sky brightness, requires all the stars that give origin to the observed light to have formed at $z_F \approx 0.2$, and is, as such, rather implausible. A more realistic scenario appears to be one where the star formation density evolves as

$$\dot{\rho}_*(z) = 0.23 \frac{e^{3.4z}}{e^{3.8z} + 44.7} \text{ M}_\odot \text{ yr}^{-1} \text{ Mpc}^{-3}. \quad (7)$$

This model fits reasonably well all measurements of the UV-continuum and $\text{H}\alpha$ luminosity densities from the present-epoch to $z = 4$ after an extinction correction of $A_{1500} = 1.2 \text{ mag}$ ($A_{2800} = 0.55 \text{ mag}$) is applied to the data [21], and produce a total EBL of the right magnitude ($I_{50} = 1$). Since about half of the present-day stars are formed at $z > 1.3$ (hence their contribution to the EBL is redshifted away), the resulting visible mass density is $\Omega_* h^2 = 0.0031 I_{50}$ ($\langle M/L_B \rangle_* = 8.6 I_{50}$). Note that this estimate ignores the recycling of returned gas into new stars.

The observed EBL therefore requires that between 7% and 16% of the nucleosynthetic baryons are today in the forms of stars, processed gas, and their remnants. According to the most recent census of cosmic baryons, the mass density in stars and their remnants observed today is $\Omega_s h = 0.00245_{-0.00088}^{+0.00125}$ [16], corresponding to a mean visible mass-to-blue light ratio of $\langle M/L_B \rangle_s = 3.4_{-1.3}^{+1.7}$ ($h = 0.5$) (about 70% of this mass is found in old spheroidal populations). While this is about a factor of 2.5 smaller than the visible mass density predicted by equation (7), efficient recycling of ejected material into new star formation would tend to reduce the apparent discrepancy in the budget. Alternatively, the gas returned by stars may be ejected into the intergalactic

medium. With an IMF-averaged yield of returned metals of $y \approx 1.5 Z_{\odot}$,² the predicted mean metallicity at the present epoch is $y\Omega_*/\Omega_b = 0.25 Z_{\odot}$, in good agreement with the values inferred from cluster abundances [26].

References

1. Armand, C., Milliard, B., & Deharveng, J.-M. 1994, *A&A*, 284, 12
2. Baugh, C. M., Cole, S., Frenk, C. S., & Lacey, C. G. 1998, *ApJ*, 498, 504
3. Bernstein, R. A., Freedman, W. L., & Madore, B. F. 1999, in preparation
4. Bruzual, A. C., & Charlot, S. 1993, *ApJ*, 405, 538
5. Burles, S., & Tytler, D. 1998, *ApJ*, 499, 699
6. Buzzoni, A. 1995, *ApJS*, 98, 69
7. Dwek, E., & Arendt, R. G. 1999, *ApJ*, in press
8. Dwek, E., et al. 1998, *ApJ*, 508, 106
9. Eales, S., et al. 1999, *ApJ*, 515, 518
10. Elbaz, D., et al. 1998, in *The Universe as seen by ISO*, ed. P. Cox & M. F. Kessler (Noordwijk: ESA Pub.), in press
11. Ellis, R. S., et al. 1996, *MNRAS*, 280, 235
12. Ellis, R. S. 1997, *ARA&A*, 35, 389
13. Elmegreen, B. G. 1998, in *Unsolved Problems in Stellar Evolution*, ed. M. Livio (Cambridge: Cambridge University Press), in press
14. Fabian, A. C., & Iwasawa, K. 1999, *MNRAS*, in press
15. Fixsen, D. J., et al. 1998, *ApJ*, 508, 123
16. Fukugita, M., Hogan, C. J., & Peebles, P. J. E. 1998, *ApJ*, 503, 518
17. Gould, A., Bahcall, J. N., & Flynn, C. 1996, *ApJ*, 465, 759 (GBF)
18. Guiderdoni, B., et al. 1997, *Nature*, 390, 257
19. Hauser, M. G., et al. 1998, *ApJ*, 508, 25
20. Lagache, G., et al. 1999, *A&A*, 344, 322
21. Madau, P. 1999, in *Proceedings of the Nobel Symposium on Particle Physics and the Universe*, *Physica Scripta*, in press
22. Madau, P., & Pozzetti, L. 1999, in preparation
23. Magorrian, G., et al. 1998, *AJ*, 115, 2285
24. Nagamine, K., Cen, R., & Ostriker, J. P. 1999, *ApJ*, submitted
25. Pozzetti, L., et al. 1998, *MNRAS*, 298, 1133
26. Renzini, A. 1997, *ApJ*, 488, 35
27. Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, *ApJ*, 500, 525
28. Smail, I., Ivison, R. J., & Blain, A. W. 1997, *ApJ*, 490, L5
29. Soltan, A. 1982, *MNRAS*, 200, 115
30. Somerville, R. S., Primack, J. R., & Faber, S. M. 1999, *MNRAS*, in press
31. Steidel, C. C., et al. 1998, in *The Birth of Galaxies*, ed. B. Guiderdoni, F. R. Bouchet, Trinh X. Thuan, & Tran Thanh Van (Gif-sur-Yvette: Edition Frontieres), in press
32. Steidel, C. C., et al. 1996, *ApJ*, 462, L17
33. Tsujimoto, T., et al. 1995, *MNRAS*, 277, 945

² Here we have taken $y \equiv \int m p_{\text{zm}} \phi(m) dm \times [\int m \phi(m) dm]^{-1}$, the stellar yields p_{zm} of [33], and a GBF+Salpeter IMF.