Published in "Extragalactic Background Radiation", Space Telescope Science Institute Symposium Series 7, 1995, eds. D. Calzetti, M. Livio and P. Madau

# THE RADIO BACKGROUND EMISSION - THE LONG AND SHORT OF IT

## M. S. Longair

Cavendish Laboratory, Madingley Road, Cambridge CB3 0HE, England

**Abstract.** A brief survey is presented of the extragalactic background radiation in the radio, centimeter and millimeter wavebands, excluding the Cosmic Microwave Background Radiation. Little progress has been made in the study of the long wavelength radio background radiation over recent years. At millimeter wavelengths, the possibility of searching for the strongly redshifted far-infrared luminosity associated with the first generations of star formation in young galaxies is discussed.

**Table of Contents**



Next

# 1. SALUTATIONS

Let me begin with two items which are the source of great pleasure in attending this symposium in honor of Riccardo Giacconi. The first is the obvious one that we should celebrate Riccardo's enormous contributions to the undoubted success of the Space Telescope Science Institute. This has been a complex and difficult task but one which is now showing the just rewards for a really huge effort on the part of many people.

The second great pleasure is the fact that Rashid Sunyaev has been able to attend this symposium. It was more than 20 years ago that Rashid and I produced our spectrum of the extragalactic background radiation at all accessible electromagnetic wavelengths and I reproduce our spectrum in Fig. 1. The remarkable thing about Fig. 1 is that it is still a reasonably accurate representation of the overall spectrum of the background radiation. The reason for this is that in those wavebands in which the background is reasonably easy to detect, background radiation was amongst the earliest observations to be made by telescopes with low angular resolution. In contrast, in those wavebands in which the background was swamped by the contribution of discrete sources, this has by and large remained the same.

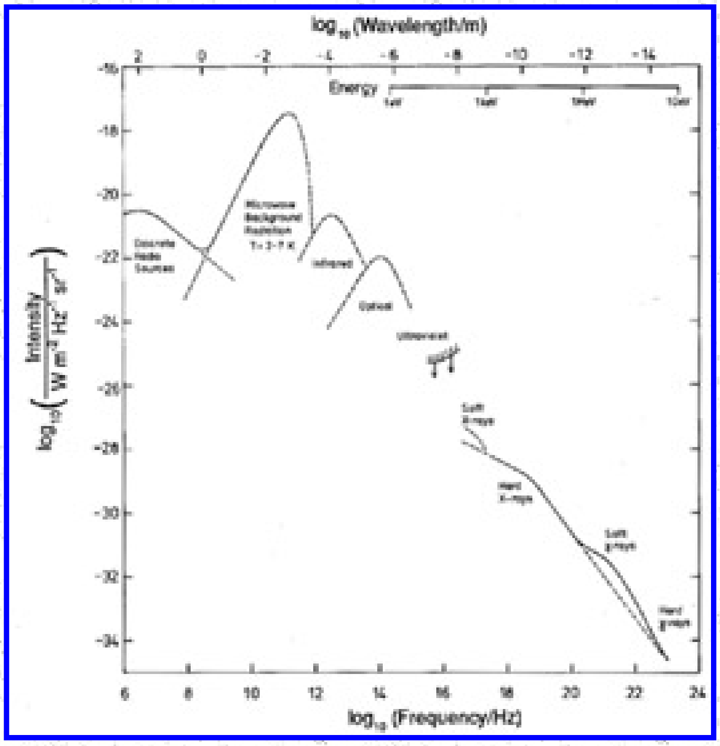

**FIgure 1.** The spectrum of the extragalactic background radiation as is was known in 1969 (Longair and Sunyaev 1971). The solid lines indicate regions of the electromagnetic spectrum in which extragalactic background radiation had been measured. The dashed lines are theoretical estimates of the background radiation due to discrete sources and should not be taken very seriously.

I must confess that my heart sank somewhat when I saw that the topic I have been asked to discuss is one of the least popular and exciting aspects of the background radiation - *The Radio Background - Observations*. Essentially nothing has happened in this area for about 25 years and most of the exciting topics will be covered by John Peacock who will discuss the interpretation of the background radiation and, in particular, what we can learn about the cosmological evolution of the radio source and quasar populations.

I will therefore do two things. First, I will talk about what I am meant to talk about - the classical extragalactic radio background radiation and then I will turn to some new work which Andrew Blain and I have been doing concerning the millimeter and sub-millimeter background radiation which we believe can tell us a lot about the early evolution of galaxies.

Next Contents

## 2. THE RADIO BACKGROUND RADIATION

The story begins in 1933 with Jansky's discovery of the radio emission from the Galaxy. It was immediately apparent that, on large angular scales, the radio sky is dominated by diffuse Galactic emission. As is well known, this great discovery caused little stir in the astronomical community and it was only after the Second World War that the nature and origin of the radio background emission became the object of astronomical interest. By the late 1940s, the emission mechanism was identified as synchrotron radiation and, at about the same time, the first of the discrete radio sources was identified.

At that period, one of the principal motivations for attempting to extract the diffuse extragalactic component of the radio background radiation was related to the question of the distances and luminosities of the discrete radio sources which continued to be discovered as the sky surveys discovered more and more faint sources. The argument is a well-known one and goes as follows. Suppose the sources have typical luminosities $L_\nu$ and space densities $\rho_L$. Then the diffuse background emission due to a uniform cosmological distribution of these sources is

$$I_\nu \propto \rho_{\rm L} L_\nu$$

On the other hand, if we also measure the number of sources brighter that a given flux density $S$, $N(\geq S)$, that number is given by

$$N(\geq S) \propto \rho_{\rm L} L_\nu^{3/2}$$

Since the observed background intensity $I_\nu$ is an upper limit to the integrated intensity, and $N(\geq S)$ is fixed, we can find a lower limit to $L_\nu$. This was the argument used by Martin Ryle to demonstrate reasonably convincingly that the bulk of the discrete radio sources had to be distant extragalactic objects. It was also the motivation for attempting to disentangle the intensity of the isotropic radio background emission from the anisotropic Galactic radio emission which was much more intense. This was a very difficult observational programme and several generations of Cambridge research students were almost broken in attempting to find a credible result.

The problem is that the radio sky is dominated by the synchrotron emission of our own Galaxy as is beautifully demonstrated by the map of the whole sky due to Glyn Haslam and his colleagues at the Max Planck Institute for Radio Astronomy at Bonn. As a result, wherever one looks in the sky, there is always intense radiation in the far out sidelobes of the radio telescope. The best one can do is to map the sky at different wavelengths with *geometrically scaled antennae* so that although the sidelobe problem is not eliminated, at least it should be the same at different frequencies. What one observes on the sky is

$$I_\nu(\alpha, \delta) = I_{\rm gal}(\alpha, \delta) + I_0(\nu)$$

where the first term on the right-hand side represents the anisotropic component associated with the Galaxy and the term $I_0(v)$ represents the isotropic extragalactic component. The procedure is then to map the sky at different frequencies, assume that the anisotropic component has the same radio spectrum in all directions and then find $I_0(\nu)$. The procedure only works because the Galactic continuum spectrum is different from that of the diffuse extragalactic component, specifically, the spectrum of our Galaxy having the form $I\nu \propto \nu^{-0.4}$ at frequencies less than about 200 MHz whereas the extragalactic sources have much steeper spectra.

The best results are still those presented by Bridle (1967). It is convenient to express the results in terms of the brightness temperature of the radiation $T_b = (\lambda^2 / 2k) I\nu$. At the traditional wavelength of 178 MHz, the frequency of the revised 3C Catalogue, the results are a follows. The minimum sky temperature at 178 MHz is about 80 K and includes both the minimum Galactic component as well as the isotropic component. As the errors build up, it is not possible to determine both the intensity and spectrum of the extragalactic component and so the isotropic component is extracted assuming different values for the radio spectral index. If $\alpha$ = 0.75, the isotropic background temperature is 30 ± 7 K; if $\alpha$ = 0.9, the intensity corresponds to 15 ± 3 K. The typical spectral index of radio sources at 178 MHz is about $\alpha$ = 0.8.

These figures should be compared with the brightness temperature found when the source counts are integrated to the lowest flux densities observed. The integrated background emission to sub-millijansky levels corresponds to about 20 K. It is interesting to identify the principal contributors to the discrete source background on the basis of modeling the source counts. If we simply adopt the local radio luminosity function for extragalactic radio sources and assume that there was no evolution of the population with cosmic epoch, we would expect a radio background at 178 MHz of only about 1-2 K. When the effects of strong evolution of the source population is taken into account, the background emission from the evolving component of the population increases to about 16-19 K. To these components we have to add the contribution of normal galaxies which amounts to about 4 K and the low luminosity `starburst' galaxies which probably contribute a further few K to the total background.

Thus, it seems that virtually all the radio background emission can be attributed to discrete sources and there is not much room left for any other contribution to the background radio emission at low frequencies. One contribution of possible cosmological interest is the upper limit to the intensity of intergalactic bremsstrahlung which would have a flat radio spectrum, $I\nu \propto \nu^0$. As a result, the best limit comes from observations at about the minimum of the radio background emission which occurs at about 400 MHz because at higher frequencies, the Cosmic Microwave Background Radiation becomes the dominant component. Once the discrete source component of the background and the Cosmic Microwave Background Radiation are removed, the upper limit to any residual diffuse component would amount to about $T_{400\ \mathrm{MHz}} \leq 0.1$ K.

What all of this means is not my job - John Peacock will take up the story of the astrophysical and cosmological implications of these observations. I will end this story with two footnotes. The first is the touching story reported by Jasper Wall at the 1989 Heidelburg meeting on the Galactic and Extragalactic Background Radiation (Wall 1990). In 1964, Jasper and Donald Chu were attempting to measure the background radiation at a frequencies of 320 and 707 MHz. They found to their distress that they could not obtain the `right' answer - their background spectrum was too flat (Wall, Chu and Yen 1970). As research students, the tacit assumption was made that they had simply made some error in the calibration of their experiment. Only in the next year was the discovery of the Cosmic Microwave Background Radiation reported which accounted for their excess antenna temperature.

The second footnote concerns the extragalactic background emission at very long wavelengths, 1 - 10 MHz. This is an even more unfashionable waveband because the observations are very difficult to make because of ionospheric absorption and refraction. However, at certain locations in the auroral zone, it is possible to observe the sky at 10 MHz. In the 1960s Chris Purton and Alan Bridle did as good a job as could be done at that time at these very low frequencies from the Penticton Radio Observatory (Bridle and Purton 1968). The sky is still dominated by the synchrotron emission of the Galaxy but, because of the differences in spectral indices, the extragalactic component is relatively more important. The process which becomes important at these low frequencies is bremsstrahlung absorption so that, at 10 MHz, the Galactic plane is observed in absorption (Purton 1966). As observations are made at frequencies less than 10 MHz, the distance at which the bremsstrahlung optical depth becomes unity decreases. The spectrum of the background radiation in the region of the Galactic pole has, however, been determined from the Canadian RAE1 satellite and the shape of the extragalactic component of the background was determined (Clark et al. 1970). Evidence was found that the extragalactic spectrum showed a cut-off at low frequencies, $\nu \leq < 3$ MHz (Fig. 2).

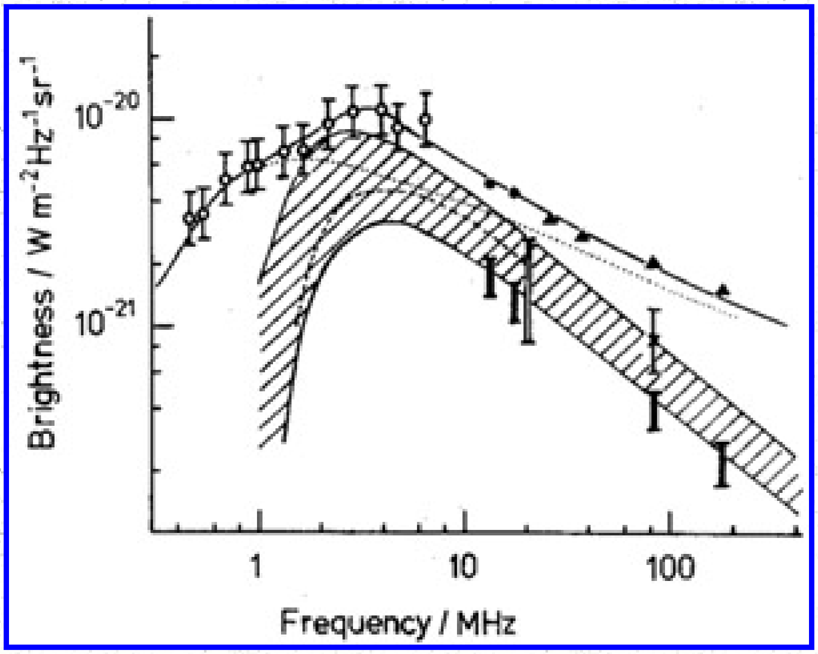

**Figure 2.** The spectrum of the radio sky in the direction of the `north halo minimum'. The solid line shows the best fit to the total background. The dotted line shows the Galactic contribution and the dashed line the estimated extragalactic contribution, the shaded region indicating the uncertainties in the latter estimate. Independent estimates of the extragalactic background are also shown. (From Simon 1977).

The origin of this behavior was discussed by Simon (1977). The obvious interpretation of the cut-off is that it is associated with synchrotron self-absorption in the discrete sources which make up the background. She studied the predicted spectra of a complete sample of 3CR radio sources to very low frequencies for which detailed radio structural information was available. Compact components and hot spots become synchrotron self-absorbed at frequencies $\nu \geq$ 100 MHz and the only components which contribute to the 1 - 10 MHz background radiation are the most diffuse components. Because of the strong inverse correlation between diffuse structure and radio luminosity, the greatest contributions to the background in the 1-10 MHz waveband come from relatively low luminosity sources (Fig. 3). Simon evaluated the predicted background spectrum when account was taken of the cosmological evolution of these sources and found that she could account quite naturally for the inferred turn-over in the isotropic radio background spectrum.

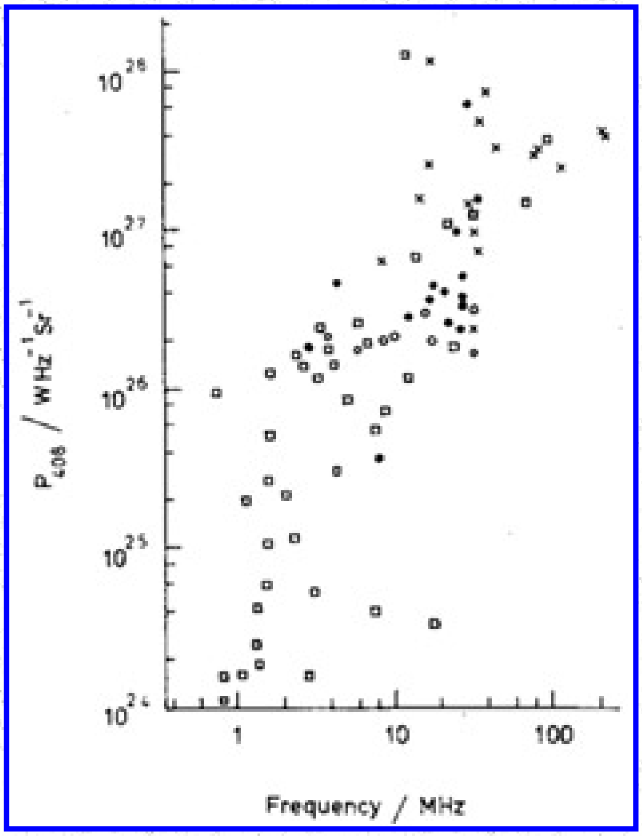

**Figure 3.** The relation between radio luminosity at 408 MHz and the frequency at which the radio source is expected to exhibit synchrotron self-absorption. The radio sources form a representative sample of the radio sources in the 3CR catalogue. (From Simon 1977).

Next Contents Previous

# 3. THE BACKGROUND RADIATION AND GALAXY FORMATION REVISITED

I will now change tack completely and look at some aspects of galaxy evolution and in particular at the very beautiful analysis by Lilly and Cowie (1987) of the constraints on metal production in large redshift galaxies. Let me first repeat their argument.

The analysis begins with the observation that a prolonged burst of star formation in a galaxy has a remarkably flat emission spectrum out to the Lyman limit at 91.2 nm. This is nicely illustrated by the model star-bursts synthesized by Bruzual and presented by White (1989) (Fig. 4). These spectra show the integrated spectra of the starburst galaxy at different ages assuming that the star formation rate is a constant and that the stars are formed with the same Salpeter mass function. The flatness of the spectrum is due to the fact that, although the most luminous blue stars have short lifetimes, they are constantly being replenished by new stars. Furthermore, the intensity of the flat part of the spectrum is directly proportional to the rate of formation of heavy elements since their energy is primarily derived from the conversion of hydrogen into helium which is the first stage in the formation of the heavy elements - these are only formed in stars with mass greater than about 4 $M_{\odot}$. From the model starbursts and from simple physical arguments, it can be shown that the intensity of the flat spectrum region of the spectrum is related to the mass of heavy elements produced by the simple relation

$$L_{\nu} = 2 \times 10^{22} \left( \frac{\dot{M}}{1 M_{\odot}\ \mathrm{year}^{-1}} \right)\ \mathrm{W\ Hz^{-1}}$$

at all wavelengths longer than the Lyman continuum edge at 91.2 nm. $\dot{M} Z$ is the rate of formation of heavy elements. It is a simple calculation to work out the background intensity due to such sources and, provided the Lyman limit is not redshifted into the observing waveband, Lilly and Cowie show that the intensity expected for a given amount of element formation is independent of the cosmological model. Specifically, the background intensity due to the formation of a density of the heavy elements $\rho_m$ is

$$I_{\nu} = 7.5 \times 10^{-25} \left( \frac{\rho_m}{10^{-31}\ \mathrm{kg\ m^{-3}}} \right)\ \mathrm{W\ m^{-2}\ Hz^{-1}\ sr^{-1}}$$

Notice that the density used in this relation is the density of heavy elements observed at the present epoch and that a density of $10^{-31}$ kg m$^{-3}$ of heavy elements would correspond roughly to $Z = 0.01$ in an $\omega = 0.01$ Universe. The beautiful thing about this relation is that, by inserting the intensity of the background radiation originating in a particular redshift interval $\delta z$, we can immediately read off the density of metals synthesized in that interval.

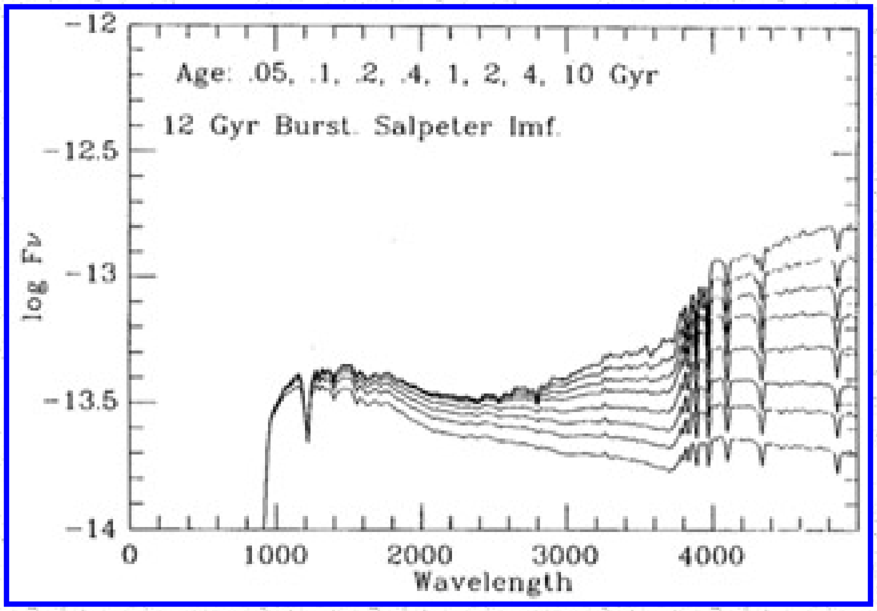


**Figure 4.** Synthetic spectra for a region with constant star formation rate at the ages indicated. A Salpeter initial mass function has been assumed with cut-offs at 75 and 0.08 $M_\odot$. The spectra were generated by Gustavo Bruzual from a recent version of his evolutionary synthesis programmes (from White (1989)).

Cowie and Lilly have observed a class of flat spectrum objects in their very deep optical surveys. Originally, it was though that these objects lay at large redshifts but it is now believed that they have redshifts roughly one. The background intensity due to such objects amounted to about 6.6 x $10^{-25}$ W $m^{-2}$ $Hz^{-1}$ $sr^{-1}$. Lilly and Cowie interpret this result as meaning that a significant fraction of the heavy elements must have been produced about a redshift of one. In fact, this heavy element abundance is significantly less than the maximum permissible. If we were to assume that $H_0$ = 50 km $s^{-1}$ $Mpc^{-1}$, the upper limit to the baryon density in the Universe as determined by the need to produce at least the observed abundance of deuterium is about 0.1. If a maximum metal abundance of $Z$ = 0.03 is adopted, the total background intensity due to metal formation could be up to about 30 or 40 times the intensity already detected by Lilly and Cowie. In fact such an intensity would exceed the upper limit to the background intensity reported by Toller (1990).

Now, it is well known that galaxies undergoing bursts of star formation are not only sources of ultraviolet continuum radiation but also are strong emitters in the far infrared waveband because of the presence of dust in the star forming regions. According to Weedman (1993), in a sample of star forming galaxies studied by the IUE, most of the galaxies emit much more of their luminosities in the far infrared rather than in the ultraviolet region of the spectrum. As a result, it is quite possible that most of the radiation associated with the formation of the heavy elements is not radiated in the ultraviolet-optical region of the spectrum but in the far infrared region and would permit a higher abundance of the elements as compared with the existing optical and ultraviolet limits.

This was one of the motivations for undertaking a study of the feasibility of detecting the far-infrared emission from star-forming galaxies at large redshifts in the submillimeter waveband.

Next Contents Previous

# 4. SUBMILLIMETRE COSMOLOGY

Andrew Blain and I have been carrying out some computations of the expected source counts and background emission expected from star-forming galaxies at large redshifts in the submillimeter and millimeter wavebands (Blain and Longair 1993). Until recently, the prospects for making surveys of sources in the submillimeter waveband have not been very encouraging because of the lack of array detectors which would allow a significant region of sky to be surveyed. The situation will change dramatically in the near future with the introduction of submillimeter bolometer array detectors on telescopes such as the James Clerk Maxwell Telescope. Specifically, the Submillimeter Common User Bolometer Array (SCUBA) currently being completed for that telescope will enable the mapping of regions of the sky in these wavebands to be carried out about 10,000 times faster than is possible with the current generation of single element detectors.

It might be thought that the detection of star-forming galaxies at cosmologically interesting distances would be very difficult because nearby examples of these types of galaxy are only weak submillimeter emitters. This problem is, however, more than offset by the enormous far infrared luminosities of these galaxies which are redshifted into the submillimeter waveband at redshifts greater than about 1. Specifically, the far infrared spectra of IRAS galaxies peak about 100 $\mu$m and have very steep spectra, $I_{\nu} \propto \nu^{\alpha}$ where $\alpha$ is about 3-4. As a consequence, the `K-corrections' are very large and negative at submillimeter wavelengths. The result is that, at redshifts greater than 1, the flux density of a standard IRAS galaxy is more or less independent of redshift until the far infrared maximum is redshifted through the submillimeter wavebands. This is illustrated in Fig. 4 which shows the expected flux density-redshift relations for a galaxy emitting $10^{13}$ $L_{\odot}$ with a standard dust emission spectrum at temperatures of 30 and 60 K as observed at 450 and 1100 $\mu$m. Correspondingly, the counts of submillimeter sources show a remarkable behavior at those flux densities at which the `coasting phase' in the flux density-redshift relation is reached. The predicted differential number counts for a single luminosity class of source at different wavelengths and for different assumed temperatures of the dust grains are shown in Fig. 5. These differential counts have to be convolved with the luminosity function of the sources and this can be found from the IRAS luminosity function derived by Saunders et al. (1990). The differential source counts for a uniform population of sources is shown in Fig. 6 in which it can be seen that there is an enormous excess over the expectations of a `Euclidean' model. It must be emphasized that these computations are carried out for a *uniform* world model and that the apparent `excess' is entirely due to the large and negative K-corrections. If the effects of cosmological evolution are included, an even more remarkable excess of faint sources and extraordinarily steep source counts are predicted. Fig. 7 shows the results of incorporating the effects of luminosity evolution of the form $L \propto (1 + z)^3$ in the redshift interval $0 \leq z \leq 2$ and a constant value at larger redshifts, $L = 27\ L_0$ where $L_0$ is the luminosity of sources at zero redshift; according to Peacock (1993), this form of evolution can account not only for the radio and optical counts of quasars and radio sources but also for the counts of IRAS galaxies. In this case, there would be very large surface densities of submillimeter sources at flux densities which will be accessible to instruments such as SCUBA.

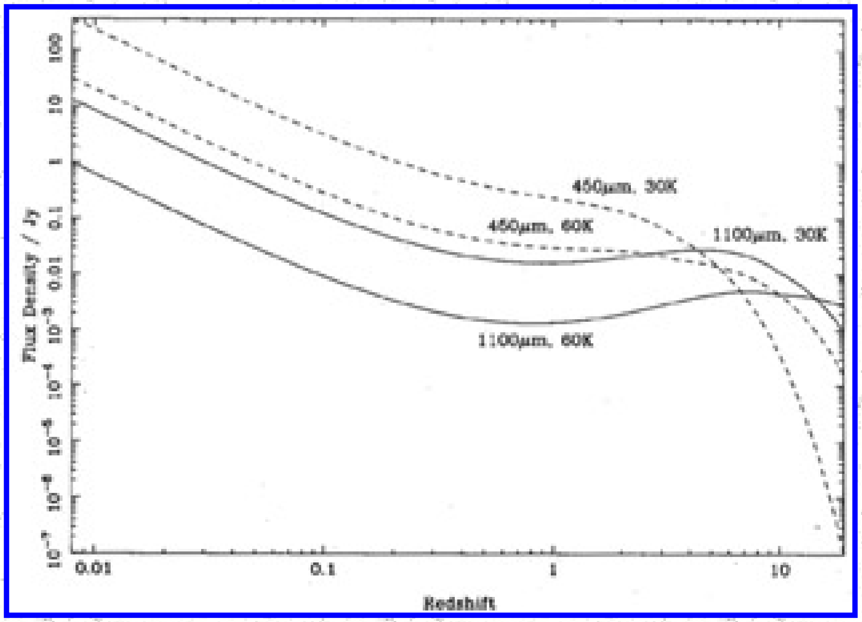


**Figure 5.** The flux density-redshift relations for a standard dust emission spectrum from a source of far infrared luminosity $10^{13}$ $L_{\odot}$ evaluated for dust temperatures of 30 and 60 K and for wavelengths of 450 and 1100 $\mu$m (Blain and Longair 1993).

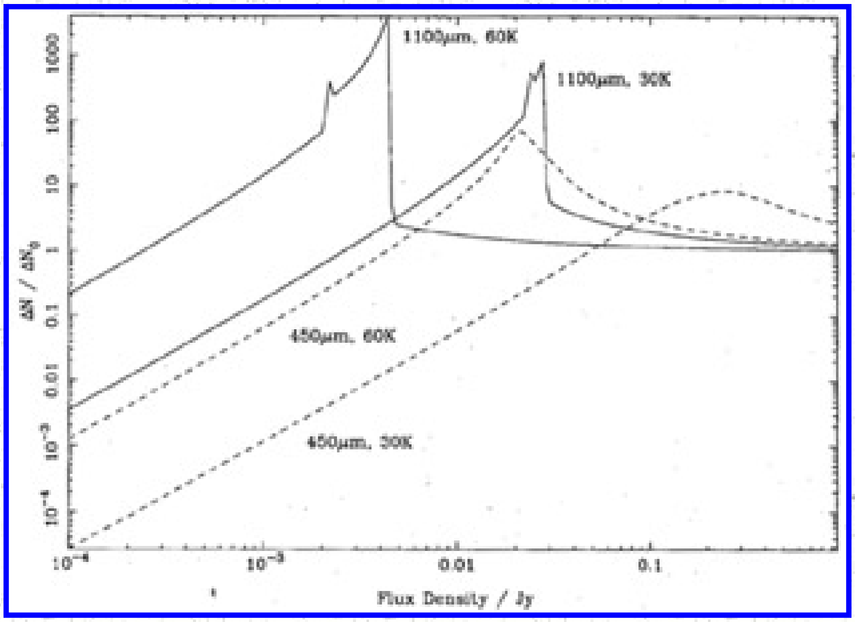

**Figure 6.** Differential source counts normalized to the expectations of a Euclidean world model for a uniform distribution of standard dust sources at temperatures of 30 and 60 K as observed at wavelengths of 450 and 1100 $\mu$m. The bolometric luminosity of the dust source is assumed to be $10^{13}$ $L_\odot$ (Blain and Longair 1993).

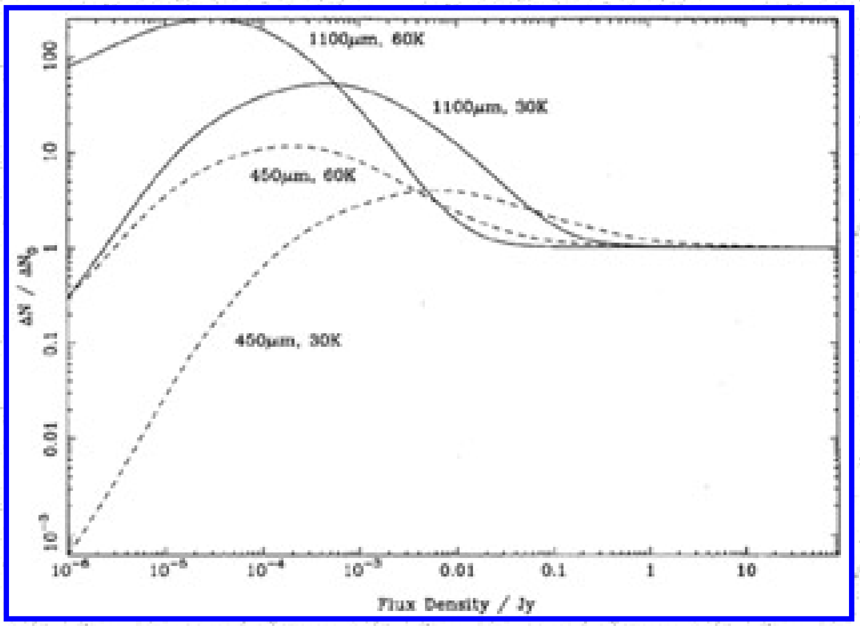


**Figure 7.** The normalized differential source counts of all IRAS galaxies at wavelengths of 450 and 1100 $\mu$m for assumed dust temperatures of 30 and 60 K. It is assumed that the comoving number densities and luminosities of the sources are unchanged with cosmic epoch. (Blain and Longair 1993).

Next Contents Previous

# 5. THE BACKGROUND RADIATION AND GALAXY FORMATION

As part of our analysis, we have investigated the feasibility of distinguishing different models of galaxy formation by submillimeter observations. The expectations of Hot Dark Matter or "pancake" models in which large scale structures form first at relatively late epochs can be well approximated by the evolution models described at the end of the last section and result in very steep number counts of submillimeter sources. In fact, it is a quite general result that any model in which the bulk of the star and galaxy formation takes place at redshifts of the order 2-5 results in large number densities of sources at accessible submillimeter flux densities. The background radiation from such populations are strongly constrained by the fact that the spectrum of the Cosmic Microwave Background Radiation is known to be very precisely of black-body form in the wavelength interval 2500 to 500 $\mu$m. The problem can be alleviated if it is assumed that the dust grains in the large redshift star-forming galaxies are at a higher temperature, say, 60-80 K.

The currently favored picture of galaxy formation involving Cold Dark Matter and hierarchical clustering of galaxies can be modeled using the Press-Schechter formulation for the mass function of galaxies as a function of cosmic epoch (Press and Schechter 1974). We have converted this function into a rate of coalescence of small galaxies into larger ones and assumed that each time this occurs a fixed fraction of the mass involved in the collision results in star formation with the standard dust emission spectrum. As expected, the number counts in these models are not nearly as remarkable at those expected in the strong evolution models because the galaxies are built up gradually over a long time period and become more rather than less luminous at later epochs. The number densities of submillimeter sources are expected to be much smaller in these models at the same flux density.

The millimeter background radiation from these models is, however, of considerable interest. The results of computations of the background intensity expected from these models is shown in Fig. 8 and compared with the current upper limits to the deviations of the spectrum of the Cosmic Microwave Background Radiation from a pure black-body spectrum. It can be seen that the upper limits are precisely parallel to the upper limits to the contribution which such sources could make to the background radiation. It can be seen that these models are already constrained by the remarkable precision with which the spectrum of the Cosmic Microwave Background Radiation is known to be of black body form. The point of special interest is the fact that the predicted background radiation spectrum extends well into the millimeter waveband. This background is associated with star formation in coalescing galaxies at redshifts of the order of 10 or more. The intriguing point is that these galaxies must be far infrared emitters due to the star formation which must occur as the small galaxies collide to form larger ones. It is apparent that the precise spectrum is sensitive to the exact assumptions made about the amount of star formation associated with each coalescence but, quite independent of these predictions, the millimeter and submillimeter background radiation provide a direct measure of the rates of star formation as a function of cosmic epoch.

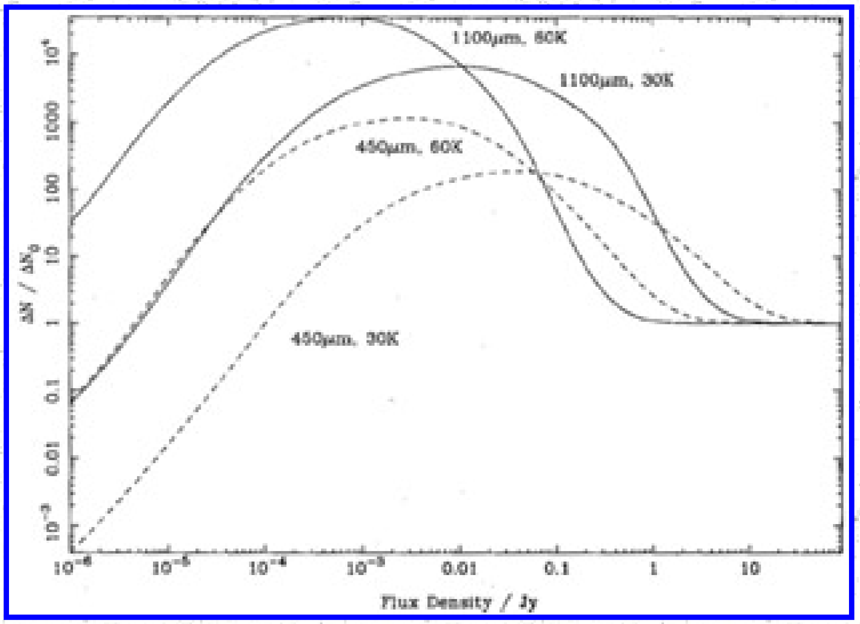


**Figure 8.** The normalized differential source counts of all IRAS galaxies at wavelengths of 450 and 1100 $\mu$m for assumed dust temperatures of 30 and 60 K. It is assumed that the comoving number densities are unchanged with cosmic epoch but that the luminosities of the sources evolve as $(1 + z)^3$ in the redshift interval $0 < z < 2$ and remain constant at 27 times the local luminosity at all redshifts greater than 2. (Blain and Longair 1993).

The prediction of this analysis is that, at some sensitivity level, it must be possible to detect the integrated emission from star formation in young galaxies and that by measuring precisely the spectrum of the background due to these galaxies in the millimeter and submillimeter wavebands, the rate of star formation at very large redshifts can be read off directly. These observations would be of the utmost cosmological importance. The magnificent COBE spectrum of the background is already constraining these models but with further increase in sensitivity, the young galaxies must make their presence known.

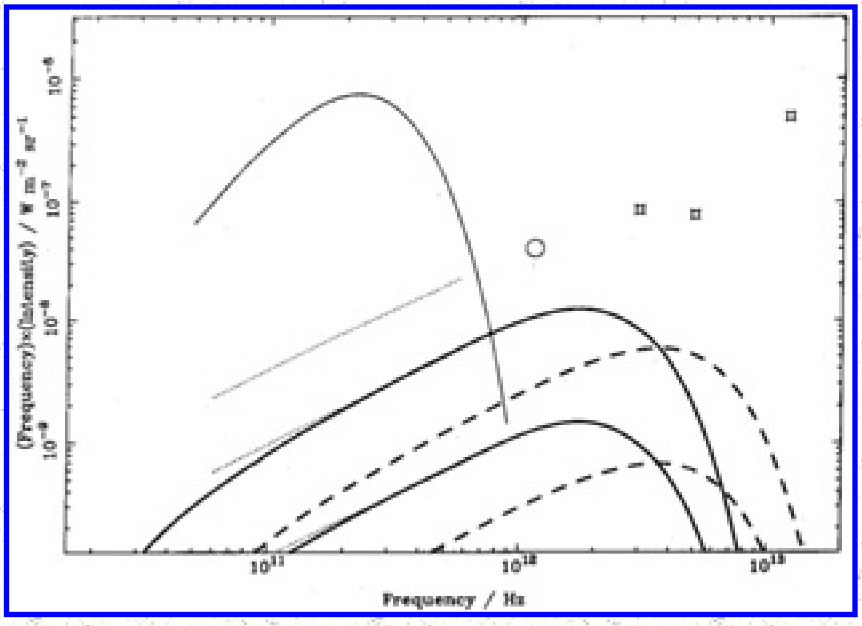

**Figure 9.** Comparison of the integrated background emission expected from dusty merging galaxies with the intensity of the Cosmic Microwave Background Radiation and upper limits to the far infrared background radiation from the IRAS survey. The assumed temperatures of the dust grains are 30 K (solid lines) and 60 K (dashed lines). In each case, the upper curve has been normalized to the maximum allowable density of metals at the present epoch. The lower curve corresponds to about one tenth that density of metals. The dotted lines correspond to 1%, 0.25% and 0.1% of the maximum intensity of the Cosmic Microwave Background Radiation. (Blain and Longair 1993).

Next Contents Previous

# REFERENCES


1. Blain, A. W. and Longair, M. S. (1993). *Mon. Not. R. astr. Soc.*, (in press).
2. Bridle, A. H. (1967). *Mon. Not. R. astr. Soc.*, 136, 219.
3. Bridle, A. H. and Purton, C. (1968). *Astron. J.*, 73, 717.
4. Clark, T. A., Brown, L. W. and Alexander, J. K. (1970). *Nature*, 228, 847.
5. Cowie, L. (1988). In The Post-Recombination Universe, (eds N. Kaiser and A. N. Lasenby), 1. Dordrecht: Kluwer Academic Publishers.
6. Lilly, S. J. and Cowie, L. L. (1987). In *Infrared Astronomy with Arrays*, (eds. C. G. Wynn-Williams and E. E. Becklin), 473. Honolulu: Institute for Astronomy, University of Hawaii Publications.
7. Longair, M. S. and Sunyaev, R. A. (1971). *Uspekhi Fiz. Nauk*, 105, 41.
8. Peacock, J. A. (1993). In *The Nature of Compact Objects in Active Galactic Nuclei*, NATO Advanced Study Institute, Cambridge 1992 (in press).
9. Press, W. and Schechter, P. (1974). *Astrophys. J.*, 187, 425.
10. Purton, C. (1966). Ph.D. Dissertation, Cambridge University.
11. Saunders, W., Rowan-Robinson, M., Lawrence, A., Efstathiou, G., Kaiser, N., Ellis, R. S. and Frenk, C. S. (1990). *Mon. Not. R. astr. Soc.*, 242, 318.
12. Simon, A. C. (1977). *Mon. Not. R. astr. Soc.*, 180, 429.
13. Toller, G. N. (1990). In *The Galactic and Extragalactic Background Radiation*, (eds. S. Bowyer and C. Leinert), 21. Dordrecht: Kluwer Academic Publishers.
14. Wall, J. V. (1990). In *The Galactic and Extragalactic Background Radiation*, (eds. S. Bowyer and C. Leinert), 327. Dordrecht: Kluwer Academic Publishers.
15. Wall, J. V., Chu, T. Y. and Yen, J. L. (1970). *Aust. J. Phys.*, 23, 45.
16. Weedman, D. (1993). *The Physics of Active Galaxies*, (ed. G. Bicknell), First Stromlo Symposium, Canberra, (in press).
17. White, S. D. (1989). In *The Epoch of Galaxy Formation*, (eds. C. S. Frenk, R. S. Ellis, T. Shanks, A. F. Heavens and J. A. Peacock), 1. Dordrecht: Kluwer Academic Publishers.