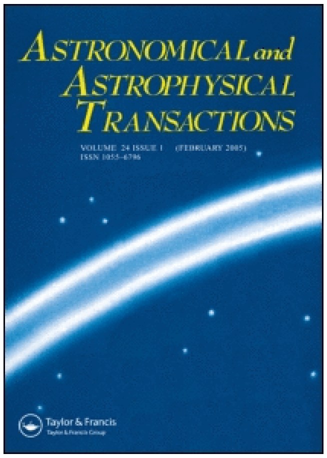

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LINE AND CONTINUUM EMISSION FROM HIGH REDSHIFT OBJECTS AND PROTO-OBJECTS

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We examine several processes which may allow us to study the state and distribution of matter during or just after the 'dark ages' of cosmic history in the redshift range $z \sim$ 5–1000. These include the Sunyaev–Zel'dovich effect from high-redshift clusters, line emission from molecules at very large z, and the continuum emission from star-forming objects. We also address the constraints present observational results place on some of these processes, and consider what planned facilities like SIRTF, ALMA or RATAN-600 will reveal about the evolution of structure at high redshifts.

KEY WORDS High redshift objects, line and continuum emission, cosmic microwave background radiation

1 INTRODUCTION

We begin by considering what 'high redshift' in the title means. It is well established, for instance by the work of Steidel *et al.* (1996) and of Chambers and his colleagues (e.g., Chambers *et al.*, 1996) that galaxies exist at redshifts of order 3–5. Present and future observations of the cosmic microwave background radiation (CMB) will give us quite precise information about the distribution of matter at redshifts of order 1000. The intermediate redshift range 5–1000 is sometimes referred to as the 'dark age' in cosmic history, and one of our aims will be to see whether there are observations that can reveal the properties of the Universe or its constituents in that range. Of course, 'dark age' is in some sense a misnomer: a comoving observer at $z \sim 100$, especially if its eyes operated in the IR (an owl, say, or a pit viper snake), would see a very bright sky everywhere because of the intense CMB. At $z = 100$, for instance, more CMB photons strike each square centimeter of a surface than solar photons strike the surface of the earth. The illumination from the CMB, however, is highly isotropic and as a consequence, our hypothetical owl couldn't see anything unless it is either moving or emitting radiation produced by some internal source of energy. Anisotropies in the CMB (or apparent 'discrete sources') will be produced only if the proto-objects have a peculiar velocity or if there is an internal source of energy. We will consider both possibilities below.

2 SECONDARY FLUCTUATIONS IN THE MICROWAVE BACKGROUND

Other papers here deal with anisotropies in the cosmic microwave background produced largely at the epoch of last scattering at $z \sim 1000$; these are generally referred to as *primary fluctuations*. As Silk showed in 1968, the power spectrum of such primary fluctuations is exponentially damped at angular scales below $\sim 7'$ (or somewhat larger if the epoch of last scattering is later, as might be the case if the Universe is reionized at $z \geq 10$). These primary fluctuations are extensively discussed by others here. What processes are responsible for fluctuations in the CMB on *smaller* angular scale (most are so-called *secondary fluctuations*), and what are the observational constraints on arcminute and arcsecond scale fluctuations? These are the questions we will examine in this section. Most result from the non-linear stage of evolution of proto-objects (at $z \leq 50$) which produces reheating and reionization of the baryon content of the Universe. Shocks produced by structure formation may also be present, resulting in temperature and density distributions quite different from the present Universe. In this paper, we concentrate on mechanisms which produce CMB fluctuations on scales below the $\sim 7'$ Silk cutoff. At least seven mechanisms have been suggested, some of which may in principle allow us to probe the 'dark age' at $z = 5$–1000. We will explore only two in detail.

2.1 Sources of CMB Fluctuations on Arcminute (and Arcsecond) Scales

1. At some point during the 'dark ages' the Universe was reionized (as shown by the Gunn–Peterson (1965) effect). If reionization occurred at a sufficiently early epoch, very roughly $z > 50$, Thomson scattering by free electrons will wash out the primary fluctuations on all but the largest scales. As first pointed out by Ostriker and Vishniac, however, if the reionization is inhomogeneous, secondary fluctuations will be introduced into the CMB (see Vishniac, 1987). At least some power is on arcminute and arcsecond scales. These are second-order effects, so the amplitude of $\delta T/T$ is relatively small.

2. Cosmic strings, if present, could introduce sharp discontinuities in the temperature of the microwave background and, consequently, non-Gaussian statistics in the amplitude of CMB fluctuations. These would be most prominent on the smallest angular scales. For a recent paper, see Moessner *et al.* (1994).

3. Loeb (1996) has pointed out that bremsstrahlung emission from Lyman-alpha clouds can also contribute to small angular scale fluctuations.

4. At high frequencies, the redshifted far infrared radiation from early star-forming galaxies is a potential source of fluctuations in the microwave sky,

though this mechanism is not directly related to the CMB itself. See Bond *et al.* (1991). Such models are better constrained by direct FIR observations (e.g., by SCUBA; Barger *et al.*, 1998).

5. One relatively well-explored mechanism for the production of arcminute and arcsecond scale fluctuations in the CMB is the Sunyaev–Zel'dovich effect produced by a background of clusters of galaxies at all redshifts. This mechanism has been explored, inter alia, by Markevitch *et al.* (1994) and Barbosa and his colleagues (1996). Here, we want to note that the rms amplitude of fluctuations (and to a lesser degree their angular scale) is strongly dependent on the epoch of formation of clusters of galaxies, and hence on the underlying cosmological model. Thus searches for small angular scale fluctuations produced by this mechanism provide useful tests of cosmological models and models for structure formation. We will return to this point later. It is worth noting, however, that these tests are separate from and complementary to determinations of the cosmological parameters obtained from measurements of the power spectrum of *primary* CMB fluctuations, discussed by others at this meeting.

6. Next, there is the Sunyaev–Zel'dovich signal from known, local clusters. As shown in 1978 by Gunn and also by Silk and White, the amplitude of the Sunyaev–Zel'dovich (S–Z) signal, combined with X-ray measurements of the intra-cluster gas, allow us to determine the distance to a given cluster, independent of all intermediate steps used by optical astronomers. Hence such measurements can provide a value for Hubble's constant. We will discuss some of the recent measurements, and values for H_0, below.

7. Finally, there are fluctuations introduced by spectral line processes, described in detail in the next section.

2.2 Fluctuations Introduced by Line Emission near Recombination

In listing mechanisms for the production of small-scale fluctuations in the CMB, we have so far neglected any consideration of their spectrum. It is very important to recognize, however, that some of the mechanisms listed above *are* wavelength dependent. That is not true of Thompson scattering or the fluctuations introduced by strings. Likewise, bremsstrahlung emission is only weakly frequency dependent. On the other hand, the Sunyaev–Zel'dovich effect has a very characteristic and well-studied spectral dependence, which is already being used to disentangle S–Z signals from other anisotropies (see the review by Rephaeli, 1995 and recent observational papers by Carlstrom et al., 2000, and Holzapfel *et al.*, 1997). The emission mechanisms in high redshift star-forming galaxies are very complicated, and will be treated briefly below. Thus the map of anisotropies in the CMB must truly be presented in technicolor, not in black and white. This is particularly true for mechanisms based on the interaction of the CMB and primordial molecules and ions. These mechanisms are strongly dependent on frequency – the difference in

Table 1. Parameters of relevant molecules.

	H_2	H_2^+	LiH	HD	HD^+	HeH^+	H_2D^+
D_e	4.48	2.65	2.43	4.51	2.67	1.85	4.3
z_r	355	210	195	357	210	150	340
$\lambda_r(\mu)$	84	170	676	112	227	149	1920
$\lambda_v(\mu)$	–	–	7.1	–	3.0	3.3	4.5

optical depth between the center of a molecular line and the nearby continuum may be as large as 10^{10}. This sharp spectral dependence may provide us a unique opportunity to study the CMB at extremely high angular resolution. These are the *spatial-spectral fluctuations* (SSFs).

We will now look at mechanisms involving the interaction of the CMB and molecules and ions, and assess the possibility that current observations may be able to constrain such models. The list of the most probable primordial molecules has been drawn up by several authors. Expected abundances of molecules in the early Universe are discussed by Dubrovich (1977, 1994, 1997), Lepp and Shull (1984), Puy *et al.* (1993), Palla *et al.* (1995), Maoli *et al.* (1996), and Stancil *et al.* (1996). The more probable molecules involve light elements we know to have been produced in the early minutes of the Big Bang: hydrogen, helium, deuterium and lithium. They are listed in Table 1, along with other parameters important for our study: the dissociation potential in eV, the redshift of recombination calculated from the Saha equation and the laboratory wavelengths of the first rotational and first vibrational transitions (these are taken from Dubrovich, 1997). We comment on several cases below.

LiH: An important molecule, because it contains primordial lithium. Hence its abundance is a good test of the epoch of nucleosynthesis in the early Universe. LiH has a large dipole moment and the relatively low frequency of the rotational and rovibrational transitions make it relatively easy to search for (de Bernardis *et al.*, 1993). But it is easily destroyed and hence not abundant.

HD^+: Also an important molecule since it contains the more abundant deuterium. The abundance of D is about 5 orders of magnitude larger than of Li. But HD^+ has a dipole moment about 10 times smaller and a cross-section, which is a hundred times smaller than LiH. In addition, we have to take account of the fact that the abundance of H^+ at redshifts might be 10^{-3}–10^{-4} of that of neutral hydrogen. Detecting this molecule will require high sensitivity.

HeH^+: Both components of this molecule are present in high abundance. There are only two factors leading to a low abundance: a high rate for the destruction of the molecule by electron recombination and collisions of neutral hydrogen compared to the rate of formation, and the small abundance of H^+ at high redshift. But it remains the most likely molecule to be found.

H_2D^+: This is the simplest triatomic molecule with a high dipole moment. Since it has very low frequency transitions, it can be searched for at centimeter wavelengths at relatively low redshifts. On the other hand, the redshift of formation of this molecule is very high so that in principle it would be possible to study the very early stages of proto-objects if measurements at appropriately long wavelengths could be made.

We now present some evidence supporting the argument that these primordial molecules will trace the initial large-scale distribution of matter.

1. The rate of formation of these molecules depends strongly on the number of cosmological parameters and is very sensitive to their variations. One such parameter is the electron density n_e. Free electrons play the role of catalyst in the formation of neutral molecules such as H_2. In turn the abundance of other molecules is strongly correlated with the concentration of H_2. Hence fluctuation in the density of matter (and n_e) leads to a nonlinear enhancement in the optical depth in molecular lines. Another important parameter is the kinetic temperature of matter, which again increases in over dense regions. Raising the kinetic temperature leads to an increase in the equilibrium ratio of H_2^+/H_2, HeH^+/H_2, LiH/H_2 and HD^+/H_2.
   Finally, there is the peculiar velocity of matter. Such velocities are introduced as a result of the hydrodynamic motions of matter caused by the density fluctuations.

2. There is an additional, specific cause for the correlation of perturbations in the matter density and distortions in the CBR: the effect first considered by Zel'dovich (1978) based on the dependence of optical depth on the gradient of the peculiar velocity. Consider first the passage of photons through a uniform medium undergoing cosmic expansion. Then the estimation of τ (Dubrovich, 1977) takes into account only the redshift of the propagating photon. Photons will stay resonant with a particular molecular line only over distances such that the cosmic expansion does not change their frequencies by more than the thermal width of the molecular line. However, if the molecules have a peculiar velocity in the proper direction, they will stay in resonance longer and the optical depth will increase (see Levshakov and Kegel, 1997, who consider such an effect in the intergalactic medium, for mathematical details). In our case, this situation arises at the moment when the Hubble expansion of a proto-object changes over to contraction due to self-gravitation. At this moment, photons may scatter in resonance along the entire length of the object, and τ is increased by as much as the ratio of the size of the object to the scale length determined by the thermal line width. Numerically, this may amount to an increase of 100–1000. The moment when self-gravitation stops expansion is determined by the mass of the object. For protoclusters of stars or protogalaxies, this moment lies in the range $300 > z > 10$. Further compression of a proto-object leads to an increase of τ due to the increase in density so it makes the epoch of turn-around the most interesting from

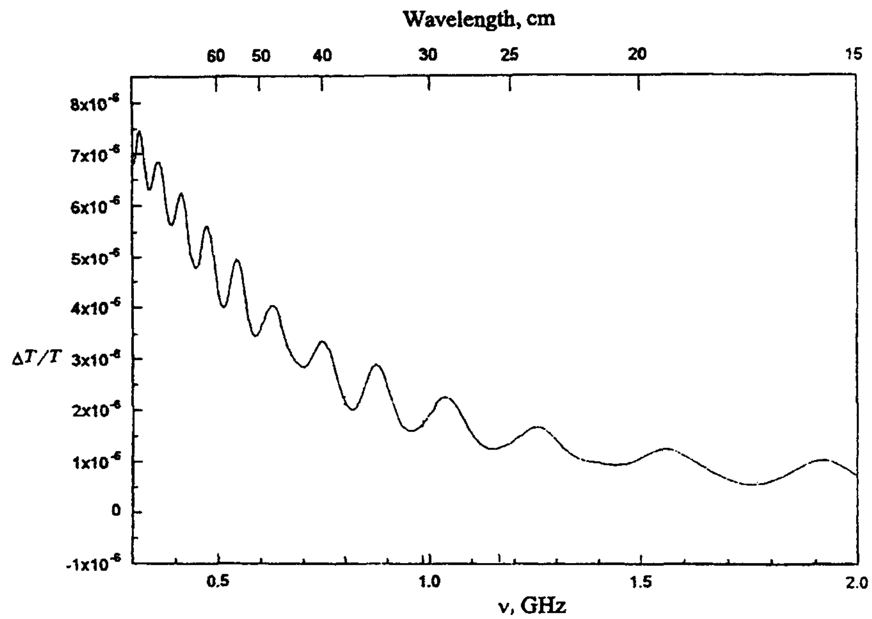

Figure 1 Summering spectrum of fossil recombination lines (HI + HeII + HeI).

the observational point of view. It may be that such strong increases in τ will allow us to detect molecules based on even heavier, and less abundant elements such as B, Be, etc.

So far, we have been discussing the period of linear evolution of density perturbations. Later, nonlinear stages of the evolution of proto-objects are characterized by the high temperature of matter and high ionization due to compression and shocks. This lies in the interval $50 > z > 5$. The UV photon flux may be sufficient to ionize hydrogen, but not strong enough to render the protogalaxies visible in the optical or the radio range. The Doppler mechanism still dominates, with the HeH^+ molecule playing a particularly important role. The rest wavelength of its first rotational transition of HeH^+ is 149μ, with other lines at 75μ and 50μ. At $z = 5$, these become 900μ, 450μ and 300μ, respectively, in the wavelength range of both COBE and future CMBR satellites. In addition, the CMBR is near its peak of emission in this range. Hence searches for SSF's may soon provide clues to the formation of structure and links to lower redshift observations.

We note that HeH^+ will be present wherever high temperature, compressed matter is present; i.e., in positive density perturbations. In addition, the fact that the effect on the CMBR is a resonant one with τ depending strongly on frequency means that observations at any fixed wavelength are strongly dependent on the redshift. Thus we can obtain a complete 3-dimensional picture of structural formation including the radial dimension, practically impossible to obtain in any other way.

The final stage of the evolution of matter is the formation of the first stars. The starburst phenomena will lead to the synthesis of heavy elements, especially C, N and O. This allows for the formation of molecules such as OH^+ OH, CH, CH^+, etc. At the same time, some matter will be accelerated to high speeds due to the expulsion of shells in the starburst phenomena. These conditions and molecules may also produce observable SSF effects.

2.3 Fluctuations Introduced by Line Emission Near Recombination

We also wish to mention spectral distortions and anisotropies in the CMBR produced at the recombination epoch itself. The recombination of both He and H produce broad emission lines in the CMB spectrum. These are highly isotropic, and hence will require spectral, rather than spatial-spectral methods to detect. In Figure 1, we display the summary of the CMBR spectrum produced by this mechanism. Small anisotropies, of amplitude up to 10^{-4}, may be produced by Rayleigh scattering of neutral hydrogen (Dubrovich, 1994). Since it is the Lyman-α line that scattered, the effect will be visible only at very high frequencies in the CMB spectrum at wavelengths below 0.3 mm.

3 RECENT MEASUREMENTS OF SMALL-SCALE CMB FLUCTUATIONS AND THEIR IMPLICATIONS

To probe angular scales below $1'$ at wavelengths accessible from the earth's surface (say $\lambda \geq 1$ mm) requires a substantial aperture. Hence most such measurements have been made using aperture synthesis or interferometry, rather than a single antenna (the exception is Kreysa and Chini, 1989). Two groups are pursuing such measurements, one using the Australia Compact Telescope Array (ACTA), the other the Very Large Array (VLA) in the US (see also Parijskij *et al.*, 1991). Upper limits on both total power and polarized fluctuations are provided in Table 2. Radio-frequency interferometry offers the advantage of virtually complete freedom from atmospheric emission and other systematic effects, as well as providing intrinsically a two-dimensional image of the sky. The disadvantage of current interferometers is that their bandwidths, and hence overall sensitivities, are restricted. Specially designed interferometers, like the Very Small Array in Cambridge, England, and the planned ALMA array will use much larger bandwidths, and are well suited to the detection of CMB fluctuations. Recent measurements from the Cambridge group and by John Carlstrom and his colleagues are very promising (see below).

The observations currently available on arcminute scales and below are already sufficient to establish one interesting result: the spectrum of CMB fluctuations does indeed fall off at small scales (or large spatial frequencies, ℓ), as Silk said it would. This statement is based on the fact that the upper limits at arcminute scales and below are factors of 2–3 below the peak amplitudes reported at the 0.5–2° scale. Thus the upper limits from the ACTA and VLA groups provide important constraints on *primary* fluctuations.

Table 2.

Resolution	λ *(cm)*	*Stokes Parameter*	$\Delta T/T \propto (10^{-5})^{\dagger}$	*Reference*
6δ	6.00	I	< 320	Knoke *et al.* (1984)
5.3δ	2.00	I	< 63	Hogan and Partridge (1989)
$30\delta^{*}$	0.13	I	< 26	Kreysa and Chini (1989)
10″	0.34	I	< 9	Radford(1993)
6″	3.60	I	< 12.8	Partridge *et al.* (1997)
10″	3.60	I	< 7.9	Partridge *et al.* (1997)
18″	3.60	I	< 4.8	Partridge *et al.* (1997)
30″	3.60	I	< 3.5	Partridge *et al.* (1997)
60″	3.60	I	< 2.0	Partridge *et al.* (1997)
80″	3.60	I	< 2.1	Partridge *et al.* (1997)
10″	3.60	V	< 5.3	Partridge *et al.* (1997)
30″	3.60	V	< 1.7	Partridge *et al.* (1997)
80″	3.60	V	< 1.8	Partridge *et al.* (1997)
10″	3.60	$\sqrt{U^2+Q^2}$	< 4.5	Partridge *et al.* (1997)
30″	3.60	$\sqrt{U^2+Q^2}$	< 1.6	Partridge *et al.* (1997)
80″	3.60	$\sqrt{U^2+Q^2}$	< 1.0	Partridge *et al.* (1997)
$\sim 120''$	3.50	I	< 0.9	Subrahmanyan *et al.* (1993)
20″	2.70	I	< 28	Parijskij *et al.* (1991)

†, at 95% confidence; *, beam-switch angle.

We turn now to the implications of these measurements for *secondary* fluctuations and the mechanisms listed above. The upper limits in Table 2 are not yet low enough to put serious constraints on the Vishniac effect except for low density, baryon-only models (Hu, Scott and Silk, 1994). On the other hand, they are able to place constraints on the amplitude of S–Z signals from background clusters.

In particular, if the modeling of Markevitch *et al.* (1992) is correct, available limits on 20″ and 60″ scale fluctuations rule out models with cluster formation occuring at $z > 5$ for low density $\Omega = 0.1$–0.3 models (see Figure 2, where the results from Partridge *et al.*, 1997, are indicated by shading). If instead we fix the epoch of cluster formation, the observations determine a lower limit on Ω (see Markevitch *et al.*, 1994); $\Omega \geq 1/2$ is favored, in agreement with results from measurements of the first Doppler peak in the power spectrum of primary fluctuations.

A relatively recent epoch of cluster formation, of course, is consistent with current CDM or ΛCDM models. Hence there was some excitement when two groups (at the VLA and in Cambridge) reported apparent evidence for discovery of S–Z signals from clusters of galaxies at high redshifts (Richards *et al.*, 1997; Jones *et al.*, 1997; Saunders *et al.*, 1997). In both cases, an extended negative feature in the CMB was discovered, of amplitude and extent consistent with the S–Z signal from a rich cluster of galaxies. In both cases, a pair of QSO was found near the apparent S–Z decrement, but no obvious optical galaxies were found in the immediate vicinity of the decrement. The absence of both optically detectable galaxies

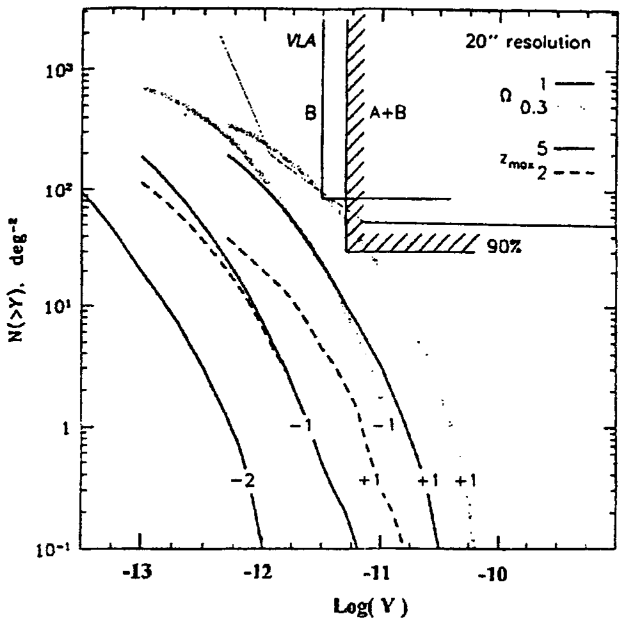

Figure 2 Curves: predicted counts of microwave decrements produced by the S–Z effect in background clusters for various values of the cosmological parameters Ω and n and two values for the redshift z_{max} of the first cluster formation (from Markevitch *et al.*, 1994). Boxes: Markevitch *et al.*'s estimate of limits set by our VLA work. Shaded: our estimates of limits set by additional, more recent, VLA observations (Partridge *et al.*, 1997), and corrected for the primary beam response of the VLA.

and detectable X-ray flux places a lower limit on the possible redshift of a cluster of galaxies capable of producing the observed S–Z signal. Richards, Partridge and their colleagues argued for the possible existence of a cluster of galaxies or protocluster containing ionized gas at the redshift of the quasar pair, $z = 2.56$. The Cambridge group, instead, argued for a cluster at a redshift between 1 and 2, which lenses a background quasar at $z = 3.8$.

The existence of clusters at such high redshifts would present real problems for standard or even modified cold dark matter theories, in which the formation of large bound systems occurs late. For that reason, there has been considerable interest in confirming the existence of these potential clusters. Deep searches at other wavelengths have been made to try to confirm the reality both of the apparent S–Z signal and to detect galaxies in the cluster. The results so far are discouraging.

On the other hand, the searches for S–Z signals from known, relatively local, clusters of galaxies have been a resounding success. Two groups are successfully applying aperture synthesis techniques to the detection of S–Z signals in a range of clusters, a group using interferometers in California and another group at Cambridge (Carlstrom *et al.*, 1996 and 2000; Saunders *et al.*, 1999; Grainge *et al.*, 1999). Figure 3 from Carlstrom *et al.* (1996) shows an early example of the detection of the

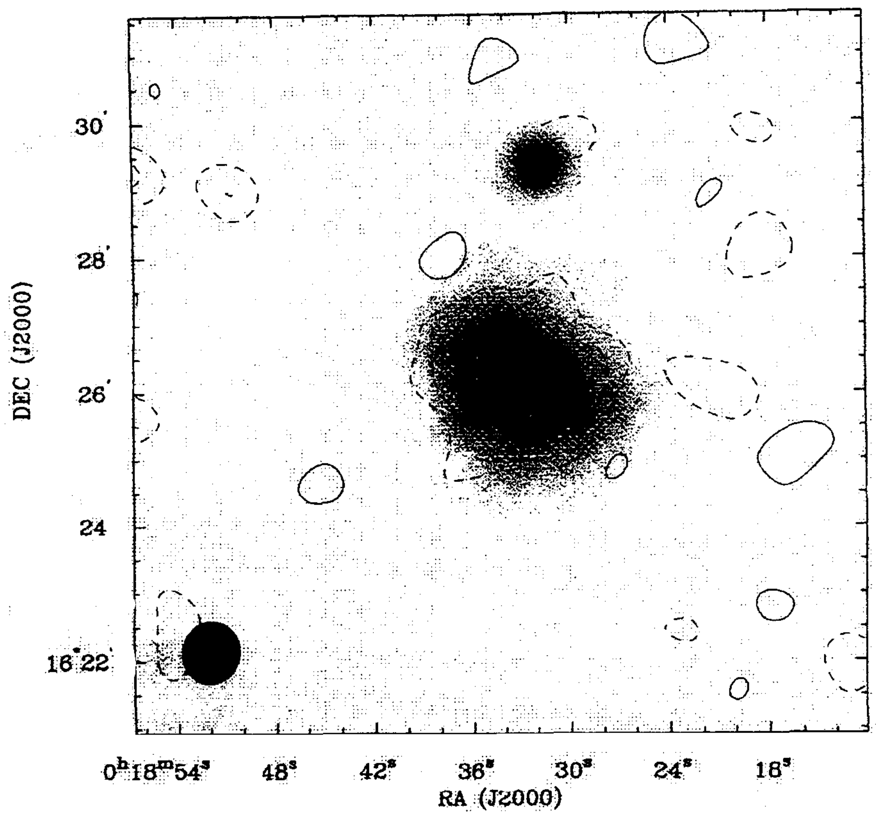

Figure 3 Overlay of Carlstrom *et al.* (1996) S–Z image of cluster CL0016 + 16 (contours) superimposed on a ROSAT X-ray image (grey scale).

S–Z signal in Abell 773. Carlstrom and his colleagues have continued their observational efforts, and now have robust S–Z signals for scores of clusters. Meanwhile, the Cambridge group have continued their work, and have good detections on a number of clusters as well. It is gratifying to see the predictions of Sunyaev and Zel'dovich now clearly realized, after a period of not always convincing claims for the detection of the effect. More importantly, now that we have results for a large number of clusters, we can begin to apply the distance estimator which depends on the magnitude of the S–Z signal and the X-ray luminosity (and temperature) in order to determine H_0. Concerns that the value of H_0 might be biased by the elongation of clusters employed in the measurement or other effects (Birkinshaw *et al.*, 1991) have been mitigated by the large sample now available. Values for H_0 derived from S–Z measurements are settling down around 60 km/sec per Mpc, with 10–20% error (Birkinshaw, 1999; Grainge *et al.*, 1999; Carlstrom, *et al.*, 2000). Recall that this method is entirely independent of all intermediate steps in the distance ladder, and thus is nicely complementary to determinations of H_0 derived from HST observations of Cepheid variables (the work of Freedman and her colleagues).

Finally, we note that upper limits on polarized fluctuations on arcminute scales and below are roughly as sensitive as the present upper limits on polarization on the quadrupole scale (Lubin *et al.*, 1985). There is considerable interest in polarized CMB fluctuations, as other speakers here will note. While the measurements available to date are not adequate to constrain any interesting models, the advent of both MAP and Planck (see also *Cosmological Gene*, this issue) offers the hope of detecting polarized fluctuations.

4 CONTINUUM EMISSION FROM HIGH REDSHIFT STAR-FORMING OBJECTS

Emission from high redshift star-forming objects reaching the earth in the radio and far infrared bands will be dominated by three emission mechanisms. First, there is synchrotron emission from the supernova of massive stars; second is free-free emission from HII regions and third is thermal reemission from warm dust. Synchrotron radiation has a characteristic spectrum with $S \propto \nu^{-0.7}$ typically, with some variation in the spectral index; the spectrum of free-free emission is much more precisely defined with $S \propto \nu^{-0.1}$. Note that both will produce a negative K-correction, in the sense that high redshift objects become increasingly difficult to detect as higher frequencies are shifted into the wavelength band of observation. Dust emission from dust of temperatures 20–40 K is quite different; redshift *increases* the observed flux. At submillimeter wavelengths, the emissivity is strongly frequency dependent, so the dust spectrum at long wavelengths is almost always steeper than the ν^2 Rayleigh–Jeans law, typically going as $\nu^3 - \nu^4$. As a consequence, as many have recognized, there is a very strong *positive* cosmological K-correction. As a consequence, FIR emission from warm dust is nearly as visible at a redshift of 10 as it is at a redshift of 1.

The combined radio-submillimeter spectrum for a dusty, star-forming galaxy (M82) is indicated in Figure 4. Note that there is a sort of 'valley of death' in the millimeter to centimeter range (this of course is the valley of life for microwave background observations, where searches for fluctuations in the microwave background are at least likely to be troubled by foreground sources). On the high frequency side of the valley, the K-correction is positive, and our best hope for the detection of high redshift, star-forming objects is found. Hence the intense excitement when deep surveys were made with the SCUBA instrument a year or so ago (Hughes *et al.*, 1998; Blain *et al.*, 1999). This and other current instruments lack angular resolution, making identifications difficult. However, the clearly detected SCUBA sources may be at substantially higher redshift than the radio-detected sources in the HDF. Unfortunately, those two issues are intertwined. There is some dispute (Richards, 1999; Downes *et al.*, 1999) over the optical and radio identifications of the SCUBA sources. The original claim by Hughes *et al.* (1998) that some were coincident with faint optical objects at $z \sim 3$ may in part have resulted from some misidentifications. These comments should not detract from the general enthusiasm we all feel for submillimeter observations – once angular resolution is improved on

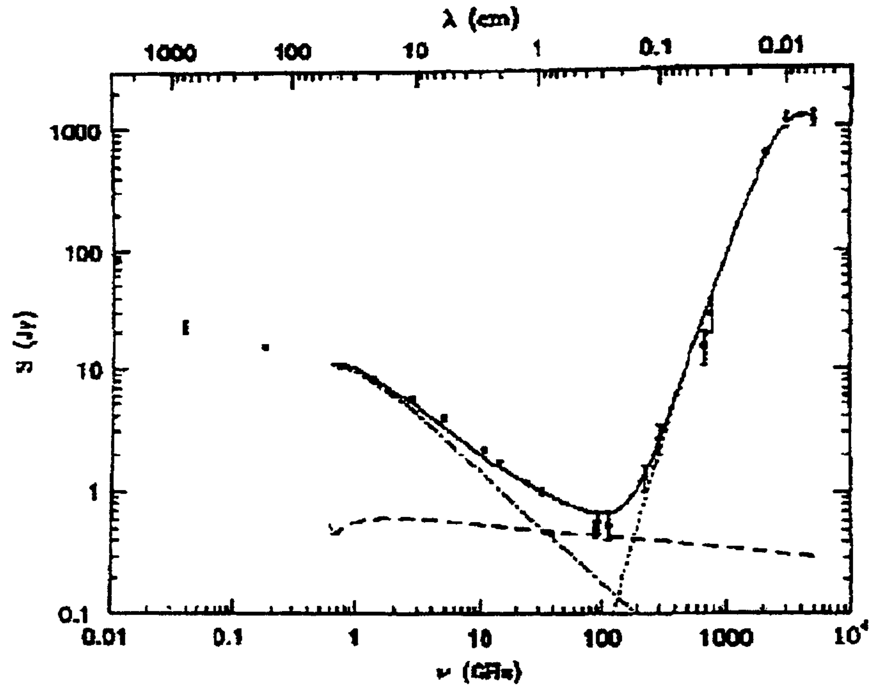

Figure 4 The rest-frame spectrum of a typical star-forming galaxy (M82). Synchrotron (dash-dot) free-free (dash) and dust (dots) emission are shown. From Condon (1992).

the high frequency side of the 'valley of death', we will have an immensely powerful tool for the detection of high redshift, star-forming objects. This is the promise of ALMA, to be completed in the next decade. It will be able to detect sources at 850μ, for instance, with the same angular resolution and sensitivity of the present VLA at cm wavelengths.

In addition, the characteristic profile of the valley of death can provide approximate redshift information (see Carilli and Yun, 1999). Redshift estimates depend on the differing behavior of the radio and FIR flux with redshift; the former decreases while the latter increases, hence the ratio $S_{\rm FIR}/S_{\rm radio}$ increases rapidly with z. We will describe more precise methods of determining redshifts below.

4.1 Centimeter Wave Flux and Star Formation

Allow us to add a brief coda to this section on the connection between radio flux, submillimeter flux and star formation. It has been known for nearly 15 years (Helou *et al.*, 1985) that radio flux and far infrared flux are strongly correlated. For instance, the ratio of 21 cm radio flux to 60μ far infrared emission is 0.00457 over a wide range of luminosities. Thus radio flux and far infrared flux can be used as proxies for one another, *provided* the redshift of the source is known to allow the Kcorrections which are radically different at the two wavelengths (see e.g., Haarsma and Partridge, 1998). In addition, both fluxes are proportional to the star formation rate (e.g., Condon, 1992). Since stellar emission warms the dust, the correlation between star formation rate (SFR) and FIR emission is fairly evident. But the less well understood radio/FIR correlation also allows us to argue (Condon, 1992) that radio flux, if not corrupted by unrelated AGN emission, is also proportional to the star formation rate.

4.2 ALMA

Let us return to look at the benefits ALMA will offer in a little more detail. A major ingredient in the planning for the US MMA and the European LSA instruments was high redshift studies. The two planned millimeter arrays have now been merged to form ALMA, an immensely promising instrument that combines high resolution, high sensitivity and good performance at submm wavelengths where star-forming systems are bright. It will operate in all the atmospheric windows from $\lambda = 1$ cm to $\sim 450\mu$ with a sensitivity that allows it easily to detect high-z galaxies. Simulations of ALMA deep surveys provide an estimate of the number of sources ALMA will detect ($\sim$ 100 arcmin^{-2}); our confidence in these simulations is bolstered by the promising early counts from SCUBA (Hughes *et al.*, 1998; Barger *et al.*, 1999).

4.3 Radio and Submm Measurements of Redshift

Not only will ALMA find high-z galaxies (and with much better positional accuracy than bolometer arrays), it will be able to measure their redshifts. Silk and Spaans (1997) have shown that even high-order rotational lines of CO (e.g., J = 6–5) will be strong enough in starburst galaxies to be detected at z = 10 or more in one or another of ALMA's frequency bands. The only difficulty will be in determining *which* CO line one has detected (and for that the approximate redshift given by the radio/submillimeter flux ratio may suffice). At high redshifts, the 158μ C^+ line may be a useful indicator as well. The molecule HeH^+ may be the most promising means of searching for early galaxies and determining their redshifts. Recall that it consists purely of primordial elements, unaffected by later CNO synthesis in protostars. To determine redshifts using HeH^+, one can use both rotational and vibrational transitions. The wavelength ratio is $\sim$ 50, so one could compare appropriate radio and submillimeter spectra of a proto-object. HeH^+ will also form a multi-line absorption spectrum in the continuum emission of proto-objects, like the Lyman-alpha forest in the optical spectra of QSO. This effect is due to HeH^+ in clouds along the line of sight to the proto-object (Dubrovich and Lipovka, 1995). There are also some high-level transitions in HeH^+ (Dalgarno, 1998), which could be used at radio wavelengths.

Finally, a wrinkle optical observers may not fully appreciate. Interferometers can produce 2-d images of arbitrary spectral resolution (no need for slits, fibers or masks). An excellent example is the J = 3–2 CO line seen in the redshift 2.8

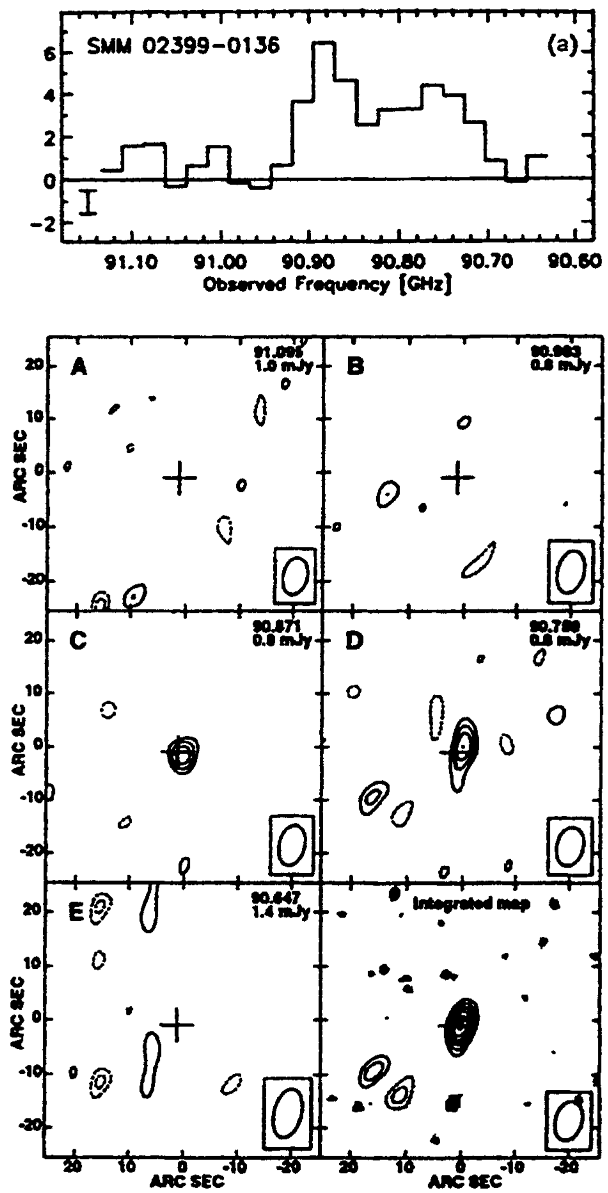

Figure 5 (a) Conventional spectrum of the CO ($3 \rightarrow 2$) line of a source at $z = 2.8$. (b) Frequency slices of the image of the source in $\sim$ 100 MHz steps around the observed frequency of the line. Both from Frayer *et al.* (1998).

galaxy SMM02399-0136 (Frayer *et al.*, 1998). Figure 5a shows a spectrum of this galaxy as spectra are usually shown. Figure 5b shows images at different frequency slices around (345 GHz)/$(z+1)$ – much more convincing and informative. Spectral images like this will pour out of ALMA. As we are about to see, the ability to determine redshifts without recourse to optical astronomy may be a key element in the characterization of high redshift, star-forming galaxies.

4.4 SIRTF

NASA's Space Infrared Telescope Facility (SIRTF) has as one of its major goals the detection of high-z galaxies. It has a cooled 85 cm mirror and detectors operating from 3μ to 180μ. Both spectrometers and photometers are planned; see SIRTF's home page at http://SIRTF jpl.nasa.gov. Estimated 5σ sensitivity in the mid-IR (8μ) is ~ 3 μJy; at 160μ, sensitivity will be limited by confusion to more like 20 mJy. The mid-IR detectors will provide useful data on the redshift of sources (Simpson and Einsenhardt, 1999) and on PAH emission – a useful test between AGN and starburst activity as shown by Genzel *et al.* (1998). However, the primary is small so that even at the shortest wavelengths resolution is only $\sim 2''$; FIRST, a 2007 ESA mission with a 3.5 m primary, will provide better resolution in the mid and far IR.

4.5 What Will These Instruments See?

We have emphasized the ability of ALMA (and other instruments) to detect continuum and even line sources to high redshifts. But there is little point in arguing that an instrument can detect a starburst galaxy at $z = 10$ if there are no galaxies at such high redshifts. We need to ask, for instance, what fraction of sources at radio and submillimeter wavelengths have we *already* detected? If the bulk of the FIR background has already been resolved, the scientific yield from the new instruments may be less than we hope. On the other hand, there is the equally important question: What fraction of the sources we may discover in the radio and submillimeter regime are essentially invisible at the optical?

How close have radio and submillimeter surveys come to seeing the bulk of all sources? More formally, at what flux density do the source counts begin to converge, that is to have dN/dS going slower than S^{-1}? That is a question one of us (BP) first asked in work with Rashid Sunyaev nearly 20 years ago. More recently Haarsma and Partridge (1998) argued that the convergence will be reached at $S \sim 1$ μJy at 8.5 GHz, corresponding to $S \sim 2$ mJy at 1.4 GHz in the radio band. The argument we use is that if the source counts converge at a much lower value of flux, the surface brightness of the radio sky would be too high. A similar argument can, of course, be made in the submillimeter regime. Haarsma and Partridge did so, suggesting that counts at a wavelength of $\sim 200\mu$ must converge by about 1 mJy. We based our argument on the correlation in flux between radio and FIR fluxes noted above. However, the same argument for convergence can be made directly from the submillimeter source counts (e.g., Puget *et al.*, 1999, who suggest convergence must set in by $S \sim 10$ μJy at $\lambda = 175\mu$, a stronger constraint).

Before we leave this topic, we want to emphasize that the statement that radio source counts converge at ~ 1 μJy does *not* mean that no interesting radio sources will be detected at lower flux values. The argument is a weaker one: that by the time we reach ~ 1 μJy, we will have essentially entirely resolved the radio background into discrete sources. It is worth asking what the areal density of sources at the convergence point will be. It is $\sim 3 \times 10^8$ per steradian, or an average separation of $\sim 14''$ if Haarsma and Partridge (1998) are right. The upgraded VLA now being planned by NRAO in the US will have the sensitivity and the angular resolution both to detect and to resolve radio sources down to this convergence limit.

To us, a more interesting question is whether there are a substantial number of radio and submillimeter sources essentially invisible in the optical with present technology. We know that some radio sources detected at 8.5 or 1.4 GHz are unidentified even in deep Hubble exposures (e.g., Waddington *et al.*, 1999; Richards *et al.*, 1999). As a salient example, the optical identification of the strongest SCUBA source in the HDF is still subject to some uncertainty (see Downes *et al.*, 1999). The SCUBA team (Hughes *et al.*, 1998) identified their source HDF 850.1 with a galaxy at redshift of 3.36, in part on the plausible basis that the ratio of fluxes at their two wavelengths, 850μ and 450μ suggested a high redshift. That identification was later disputed by Richards (1999) who suggested an ISO-VLA source at $z = 0.3$. Using IRAM, Downes *et al.* (1999) were able to pinpoint the position of HDF 850.1 and argued that it is associated with a faint arc-like pair of optical sources $0.8''$ away. In fact, as their image shows, even that identification could be questioned – is it possible that the single brightest 850μ source in the HDF remains optically unidentified?

Given the important role of dust obscuration, it is entirely plausible that some radio and submillimeter sources might not be visible in the optical. Two consequences follow. The first is that estimates of the star formation rate as a function of redshift (Madau *et al.*, 1996) based on optical measurements may well underestimate the total amount of star formation, particularly at high redshifts where rest-wavelength uv is being observed. This of course is a well-known issue, and attempts have been made to correct for dust obscuration (Calzetti *et al.*, 1994; Madau *et al.*, 1998; Steidel *et al.*, 1999). Here we want to point out the advantage of using radio observations, which are entirely unaffected by dust obscuration, to recalculate the Madau diagram; Debbie Haarsma and BP have done just that, using radio fluxes and redshifts for the HDF and other regions where sensitive radio surveys are available. Our results, at least for low redshifts, are shown in Figure 6. They agree well with other estimates of the star formation rate for $z < 2$, but tend to be somewhat higher, as we might expect from the argument given above (Haarsma *et al.*, 2000).

The second issue is that our normal reliance on optical astronomers to determine redshifts will not work if the sources are invisible or barely visible in the optical. In the future, it may be that radio astronomers will have to solve their own redshift problems, for instance by using CO or HeH^+ lines as noted above.

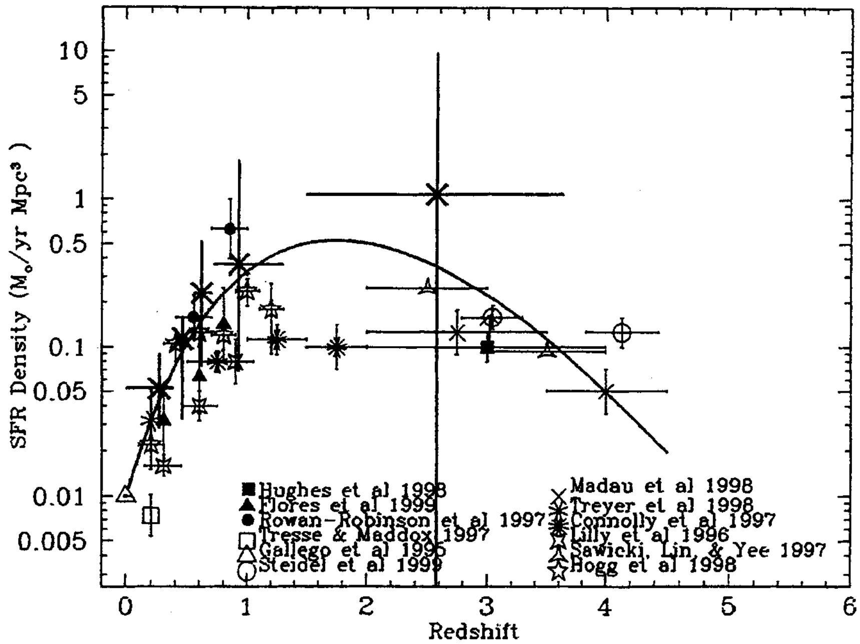

Figure 6 Star formation history. The heavy crosses and lines show the star formation rate derived purely from radio measurements, unaffected by dust extinction (Haarsma *et al.*, 2000). Other symbols show various optical/uv SFR's.

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