An infrared search for primeval galaxies

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Summary. For galaxy formation epochs now considered to be most likely, primeval galaxies will be infrared objects. We have therefore undertaken a deep survey of two ‘blank’ fields at J and K (1.2 and 2.2μm) to search for primeval galaxies. The one object discovered has infrared colours indicating that it is a faint foreground galaxy. The flux density of the brightest primeval galaxy which could have escaped detection, to 90 per cent confidence, in our survey of ~1300 arcsec^2 is ~33 μJy at K. This limit constrains models of primeval galaxies by up to an order of magnitude over previous optical searches, for galaxy formation redshifts 5<z<10.

1 Introduction

One of the outstanding problems of observational cosmology is to explain the existence of galaxies and to determine the epoch of galaxy formation. In the gravitational instability picture, overdensities δ ρ/ρ in the matter distribution grow at a rate ∝ (1+z)^-1 after the matter and radiation have decoupled, until δ ρ/ρ ~ 1. At about this stage the growth rate becomes non-linear, and the first generation of bound objects appears shortly thereafter. The redshift at which these objects form, and their properties, depend critically on the amplitude of the mass fluctuation spectrum prior to decoupling and the detailed way in which both the baryonic and non-baryonic components of the matter are perturbed (Peebles 1980). There is a vast body of theoretical literature on this subject and no shortage of speculation on the wide range of possible formation models. At one extreme, bound structures ~10^5 M_☉ could have formed as early as z~100 (Press & Schechter 1974). At the other extreme, galaxies may form from the fragmentation of planar or pancake-like structures, of size ~10^{13} M_☉. In this case the predicted strength of clustering on large scales can only be reconciled with observation if galaxies form at very late epochs, i.e. z~1–4.

Recently, there has been active interest in biased galaxy formation, in which the efficiency of galaxy formation in a region is a strong function of the local density (Dekel & Rees 1987). The

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earliest galaxies then form near the peaks of the density field (assumed to be Gaussian) with formation in less dense regions extended over a long time-scale. In this picture there is no unique epoch of formation; indeed galaxies may still be being born today in underdense regions.

In contrast to the theoretical situation, there are very few observational constraints directly addressing the question of galaxy formation. The different predictions for the epoch of galaxy formation made by various theories make the search for young galaxies a particularly worthwhile undertaking. Despite the wide variety of plausible models for the formation of galaxies, nearly all of them incorporate a highly luminous phase resulting from a very high initial rate of star formation, making them detectable with modern instrumentation.

There have been two general approaches taken to search for primeval galaxies. One has been to detect them directly by deep searches in blank areas of sky, using broadband or spectroscopic techniques. Perhaps the earliest search was that carried out by Partridge (1974), who used both photoelectric photometry and photographic plates to search for primeval galaxies of angular size consistent with the Partridge & Peebles (1967a, b, hereafter P&P) models, i.e. >10 arcsec. Davis & Wilkinson (1974) also looked for P&P-type objects of angular size 10–30 arcsec. They searched an area of 20000 arcsec$^2$ in the red (6200–8900 Å). The result of both searches was negative, with a sensitivity limit for a single object of ∼40 μJy. While these two searches are sufficiently sensitive to test the P&P models out to z∼6, they do not constrain more recent collapse models which predict smaller angular sizes and luminosities. In addition, their passbands are too blue for epochs of galaxy formation z>6. Indeed P&P conclude that young galaxies in their model would have peak luminosities in the 1–3μm wavelength region, as a result of the high redshift of formation.

More recently the quest for primeval galaxies has been extended using narrow-band filters and CCD detectors. As pointed out by P&P, a young galaxy could radiate a substantial fraction of its light, ∼10 per cent, in the Lyman α line. The pioneering Lyα survey was carried out by Koo & Kron (1980), who searched between z∼4–6, using slitless spectroscopy with a CCD detector and hypersensitized photographic IV-N plates (6000–9000 Å). The limits achieved, ∼4μJy, are considerably stronger than the earlier results of Partridge (1974) and Davis & Wilkinson (1974) for this redshift region. Other spectroscopic searches of both blank sky and faint galaxies detected in photometric surveys have been pursued but with no confirmed detections of primeval galaxies (cf. Koo 1986 and references therein).

The other approach has been to measure the integrated light due to primeval galaxies on the sky. Matilla (1976) employed a novel method to achieve an apparent detection of an optical background, but this report was not confirmed (Dube, Wickes & Wilkinson 1979; Spinrad & Stone 1978; Toller 1983). These later experiments reached an upper limit of ∼3×10$^{-8}$W. This limit is below the predictions of most formation models with epochs of formation z<5 (Toller 1983) but, for galaxies forming at higher redshifts, the limit is larger than the predicted background.

These experiments were all carried out at wavelengths <1μm and the results demonstrate the limitations of optical techniques. As Koo (1986) concluded in his review of optical searches, the lack of detection using a wide range of broadband and spectroscopic techniques suggests that galaxies form at z≥5. Indeed, from his recent CCD multi-colour imaging of faint galaxies, Tyson (1988) concludes that the number count and colour data imply the earliest epoch of massive star formation at z∼6–7. For formation redshifts z>5, primeval galaxies, and the extragalactic background from them, will have redshifted into the near-IR. It therefore seems particularly worthwhile to carry out a near-IR search for primeval galaxies.

Concurrently to our IR survey, a very similar survey at K was carried out by Boughn, Saulson & Uson (1986). They surveyed two areas of blank sky. Their most sensitive search, with an 11-arcsec aperture, covered an area ∼1700 arcsec$^2$. The upper limits they set are at an almost identical sensitivity to ours, as discussed in Section 5.
2 Observational parameters of a primeval galaxy

The objects we seek are the progenitors of present-day galaxies at high redshift, undergoing the first stage of star formation. To define an observational search for such objects one must adopt a plausible model for their physical properties. In the following we summarize the theoretical ideas on the parameters expected for primeval galaxies.

2.1 Luminosity

Virtually all models for the formation of galaxies incorporate an initial phase of high luminosity due to a very high rate of star formation. Evidence for this comes from the fact that the oldest disc stars are not particularly metal-poor. Such stars have metallicities $Z \sim 1-2$ per cent (P&P). The starburst producing these heavy elements would have had a luminosity:

$$L_{\text{pg}} \sim 0.007 Z M c^2 / \Delta t,$$

(1)

where $M$ is the mass of the galaxy and $\Delta t$ is the duration of the starburst. The major uncertainty in this equation is the duration, $\Delta t$. P&P, in their classic study, assumed that the starburst would last $\sim 3 \times 10^7$ yr. Similar time-scales are predicted in the dissipationless collapse models of Gott (1975) and Gott & Thuan (1976), who also predict that the star formation will be completed by the time the disc forms. More recently, this picture of the bright phase has been modified. Larson’s (1969, 1974, 1975, 1976) collapse models involve both stellar and gas dynamics, with slow gas-infall through a background of already-formed stars. In these models the collapse time-scale is $\sim 10^5 - 10^{10}$ yr. These estimates of the starburst duration imply luminosities of $L_{\text{pg}} \sim 10^{38} - 10^{40}$ W for the bright phase of a primeval galaxy of mass $\sim 10^{11} M_\odot$.

The feasibility of searching for objects at high redshift is determined partly by the expected flux density:

$$S_\nu = \frac{L_{\text{pg}} \varepsilon(T_{\text{pg}})}{4 \pi d_\lambda^2 (1+z)^4 \Delta \nu}$$

(2)

(Weinberg 1972). Here $L_{\text{pg}}$ is the bolometric luminosity, $T_{\text{pg}}$ is the temperature of the redshifted spectrum, $\varepsilon$ is the fraction of this radiation falling in the observed frequency band $\Delta \nu$, and $d_\lambda$ is the angular diameter distance defined in equation (3). Taking $T_{\text{pg}} \sim 10^4 K$, $z=7$, $\Omega_0=1$, $h=1$ (where $\Omega_0$ is the density parameter and the Hubble constant $H_0=100h$ km s$^{-1}$ Mpc$^{-1}$) and using the results obtained from equation (1), the expected flux requires integration times $\sim 10$ min pixel$^{-1}$, for a 5$\sigma$ detection using UKIRT at $K$, with an 8-arcsec aperture.

2.2 Spectrum

If the bright phase of a primeval galaxy is powered by such a spectacular starburst, its spectrum is expected to resemble that of a giant, dust-free HII region full of OB-type stars. The strongest features would then be the Lyman $\alpha$ line at 1215 Å and the break at the Lyman limit, 912 Å. As much as 15 per cent of the bolometric luminosity could be in the Lyman $\alpha$ line (P&P). Whether the primeval galaxy will be dust-free in the bright phase is not certain, although it seems eminently plausible. The fact that quasars are relatively unobscured, emitting strongly in the UV and optical bands, provides some evidence for relatively little dust at high redshift. Evidence is continuing to accumulate for strong Lyman $\alpha$ emission from different types of galaxies at $z>2$ (cf. review by Djorgovski 1988). In particular, Djorgovski et al. (1985, 1987) have found a galaxy at $z=3.215$ which emits strong Lyman $\alpha$ and shows little or no evidence for dust. The strong blueing trend found by Tyson (1988) in his CCD multi-colour imaging of faint galaxies provides further
observational evidence for massive star formation at early epochs. Thus we conclude it is reasonable to expect the spectrum of a primeval galaxy to resemble a bright H\textsc{ii} region.

2.3 ANGULAR DIAMETER

Angular diameters are given by $\theta = D/d_\Lambda$, where $D$ is the linear diameter and $d_\Lambda$ is the angular diameter distance given by (Weinberg 1972):

$$d_\Lambda = \left[ c / H_0 (1 + z)^2 \right] \left[ (q_0 z + (q_0 - 1) (1 + 2q_0 z)^{1/2} - 1) / q_0^2 \right].$$

(3)

The linear diameter of a primeval galaxy will depend on the star formation rate during the bright phase. In the models by Partridge & Peebles (1967a, b), Gott (1975), and Gott & Thuan (1976), the brightest phase occurs while the young galaxy is extended $\sim 30 \text{kpc}$, whereas in Larson’s (1975, 1976) models the star formation rate is at its fastest stage after the galaxy has collapsed to $\sim 10 \text{kpc}$. Thus, depending on the Hubble constant, $H_0$, and the density parameter, $\Omega_0$, we expect the angular diameter of a primeval galaxy to be in the range $\sim 1 - 10 \text{arcsec}$ for redshifts of $3 - 10$.

2.4 AREAL DENSITY

The expected number of primeval galaxies per steradian is given by:

$$N = (1 + z)^3 c \Delta t d_\Lambda^2 \eta_0,$$

(4)

where $\eta_0$ is the local number density of galaxies. For $\eta_0 \sim 0.01 h^3 \text{Mpc}^{-3}$ (cf. Davis & Huchra 1982), and $\Delta t \sim 10^8 \text{yr}$, we find $N \sim 2 \times 10^4 h \text{deg}^{-2}$ for $z = 5$, and $N \sim 10^4 h \text{deg}^{-2}$ for $z = 10$. Thus primeval galaxies are not rare.

The minimum area, $A$, needed to be searched in order that at least one primeval galaxy be in the beam at some time, if the distribution is represented by Poisson statistics, is given by:

$$1 - \exp \left( - N A \right) > 0.9.$$ 

(5)

At the redshifts of formation tested by this experiment it is most likely that galaxies formed in independent regions of space, with clustering developing after the bright phase, so the assumption of Poisson statistics is probably not unreasonable. For areal densities $N \sim 10^4 h \text{deg}^{-2}$, the area required to be covered $\sim 1500 \text{arcsec}^2$.

3 Observations

Using UKIRT, we have carried out a deep survey of several blank fields in the $J$ and $K$ bands (1.2 and 2.2 $\mu$m) to search for primeval galaxies. The blank fields selected were those surveyed in the visible by Davis & Wilkinson (1974). All observations were made with an 8-arcsec aperture. Photometric standard stars were HD 105601, 162208, 201941 and 106965. Chopping and nodding amplitudes were 16 arcsec, all in the hour angle direction. This value was adopted in order to maximize the contrast of signals in the object and reference beams, based on the likely separation of primeval galaxies at $z \sim 10$, i.e. $>20 h^{-1} \text{arcsec}$.

Two observing runs were devoted to this project. On the first run we used the UKIRT two-channel photometer, observing simultaneously at $J$ and $K$. The object in using $J$ was to search for Lyman $\alpha$ from redshift $8 < z < 10.5$. The search pattern on the sky for the two blank fields is shown in Fig. 1. The positions of these pixels were determined by offsetting from nearby guide stars. The procedure adopted was to integrate on a given pixel for a fixed time of 10 min, then to move 8 arcsec in hour angle to the next pixel. We could then repeat observations of each pixel on another night, as weather permitted, to increase the total integration time. As it turned out, only
two nights were photometric, but we were able to search two areas, totalling \( \sim 1300 \text{arcsec}^2 \), simultaneously at \( J \) and \( K \). All pixels were observed with a minimum integration time of 23 min. With this integration time, the rms noise on each pixel is \( \sim 16 \mu\text{Jy} \) at \( K \) and \( 21 \mu\text{Jy} \) at \( J \).

Analysis of these data showed that there were four pixels with signal-to-noise in excess of 2.5. We then re-observed all these candidates about 13 months later, again at UKIRT. On this run we used the UKIRT single-channel photometer, but with the same 8-arcsec aperture. Only one of these candidates, pixel 23b, was confirmed as a genuine source. We carried out photometry on this source at \( JHK \) to measure its colours, to discriminate between a redshifted primeval galaxy and a faint foreground galaxy or star. The observations of 23b have been made at two positions \( A \) and \( B \) indicated in Fig. 1. Both positions \( A \) and \( B \) were observed extensively on this run, using either an 8- or 12-arcsec aperture and with chopper throws of either 16 or 60 arcsec. Experiment showed no detectable difference in signal between these combinations. A discussion of the detections of this candidate is given in Section 5.

4 Results

The data at \( J \) and \( K \) for the survey are shown in Fig. 2(a) and (b), where the signals and standard errors are given for each pixel. In every case the signals represent the weighted average of two integrations of 10 and 13 min. The data were collected in blocks of 1-min integration. To eliminate the spikes which appeared occasionally, each point shown in Fig. 2 has had each block with signal \( > \pm 2 \) times the mean standard deviation removed. The number of blocks discarded in this way is small, \(< 10 \) per cent.

Fig. 3(a) and (b) display the distribution of signal to noise for all the candidates (except 23b) after the first observing run, at both \( J \) and \( K \). Also plotted are the theoretical curves for the distribution of signal-to-noise ratio if all pixel signals are drawn from the same Gaussian noise distribution. The distribution at \( J \) is Gaussian, and has a reduced \( \chi^2 \) for 14 degrees of freedom of 0.64. For \( K \), on the other hand, the distribution is clearly non-Gaussian. To investigate the origin of this effect we measured the distribution of signal-to-noise ratio for the two-channel instrument with the detectors blanked off inside the cryostat. The distribution is similar at \( J \). However, at \( K \) this distribution is Gaussian, with an rms noise that is \( \sim 0.5 \) that of the distribution on the sky. Thus we conclude that there is a significant non-Gaussian contribution to the noise at \( K \).

To investigate a possible astronomical origin for this non-Gaussian component we re-observed...
Figure 2. Signals and standard errors for each pixel after both observing runs. The bars indicate ± the standard error for the mean of each pixel. The dashed lines indicate the standard deviation of all pixels. (a) J waveband; (b) K waveband.

Each pixel in which the signal-to-noise ratio was >2.0 in our second observing run. Aside from using the single channel photometer in this run, our observational technique was identical to that used on the first run. In no case, with the exception of pixel 23b, did we reproduce the signal found in the first run, despite integrating to a noise level ~60 per cent smaller than that obtained originally. We conclude that the non-Gaussian character of the data obtained at K with the two-channel instrument is not of astronomical origin, nor is it merely an internal instrumental effect.
Figure 3. The distribution of signal-to-noise ratio for all pixels after both observing runs. A best-fit Gaussian with zero mean is shown for comparison. (a) $J$ waveband; (b) $K$ waveband.

for that should have appeared in the blanked-off test. It is clear that in observations of this type one cannot assume that the noise distribution is Gaussian, and an observing strategy with built-in redundancy is mandatory.

5 Interpretation

To use our null result to place limits on galaxy formation models, it is necessary to decide on the maximum signal which could have escaped detection in this search. The pixels searched to the least sensitivity were those with only 23-min integrations. Of these the highest signal was recorded at $K$ in pixel 15, 17 $\mu$Jy. Therefore the most conservative assumption is that there is a primeval galaxy, which we did not recognize, in this pixel. The largest flux density such a primeval galaxy could have, to 90 per cent confidence, is then 17 $\mu$Jy + $1\sigma$, where $\sigma$ is the standard deviation for all
the pixels shown in Fig. 2, viz. $\sim 16 \mu$Jy. The limit adopted for the complete search at $K$ is thus $33 \mu$Jy. At $J$ the highest signal obtained, $22 \mu$Jy, was in pixel 13. In a similar manner to $K$, an upper limit of $22+1\sigma$ or $43 \mu$Jy has been adopted at $J$. Another way to look at these limits is that they correspond to upper limits of $\sim 2\sigma$ if they are assumed to be drawn from parent populations of Gaussian noise.

Interpretation of these limits in terms of primeval galaxy models is complicated since there are several interrelated parameters involved in any model. For clarity we will adopt a cosmology in which $\Omega_0 = h = 1$, and investigate the range of primeval galaxy luminosity and temperature for various formation redshifts that are excluded by the results of this survey.

Constraints on primeval galaxy models are limited by the finite search area, $1300$ arcsec$^2$. If Poisson statistics is assumed for the distribution of primeval galaxies, equation (5) shows that the areal density of primeval galaxies, $N_i$, must be $>2 \times 10^4$ deg$^{-2}$ in order to ensure that at least one primeval galaxy was in the beam during the search. For this search to be able to place limits on models it is essential that the luminosity limits set do not imply a bright phase duration shorter than that necessary to ensure with $90\%$ confidence that a primeval galaxy was in the beam. Moreover, a luminosity limit at a given wavelength implies a limit on the temperature of the primeval galaxy, $T_{pg}$. For redshifts of interest, a primeval galaxy was in our survey area to $90\%$ confidence for $T_{pg} < 3 \times 10^4$ K, in an $\Omega_0 = 1, h = 1$ cosmology. If $h$ were $\sim 0.5$, $T_{pg}$ would have to be implausibly cool, and the search would therefore be inconclusive.

The upper limit on the luminosity ($L_{pg}$) of primeval galaxies versus redshift is shown in Fig. 4. The luminosity has been calculated assuming the model parameters listed and using equation (4). For comparison the best available optical limits from the search by Davis & Wilkinson (1974) are shown. This IR search extends the upper limits on primeval galaxy detection below the Davis & Wilkinson (1974) search for redshifts $z > 6$. The dependence of the limits on assumed intrinsic temperature is shown in Fig. 5. Here the excluded intrinsic temperature $T_{pg}$ versus $L_{pg}$ is shown for the redshifts of $z = 5$ and $z = 9$, in a cosmology with $\Omega_0 = 1, h = 1$. This figure indicates that for
reasonable estimates of the intrinsic primeval galaxy temperature, this experiment improves constraints on realistic luminosities of galaxies at high redshift by about an order of magnitude. These limits are essentially identical to those of the Boughe et al. (1986) search. Their most sensitive search region, totalling $\sim 1728$ arcsec$^2$, and carried out at CTIO with an 11-arcsec aperture, contains a pixel with a signal $\sim 2.4$ times the standard deviation, or $\sim 24 \mu$Jy. Therefore
the maximum signal which could have escaped detection is smaller than $24 \mu Jy + 1 \sigma \approx 34 \mu Jy$, at the 90 per cent confidence level. This compares with our upper limit at $K$ of $33 \mu Jy$. Their second search of a larger area (88 500 arcsec$^2$), carried out at Kitt Peak with a 70-arcsec aperture, is an order of magnitude less sensitive than this.

We can slightly strengthen these constraints by combining our results with those of Boughn et al. (1986), since their CTIO survey is of virtually identical sensitivity and area covered. In this case we can exclude primeval galaxies of temperature $T_{pe} < 3 \times 10^4$ K for $h = 0.75$. To exclude any physically reasonable primeval galaxy model in an $h \sim 0.5$ cosmology requires an order of magnitude larger area to be surveyed.

The photometry at $J$ can be used to place useful limits on the possible Lyman $\alpha$ emission from primeval galaxies in the redshift interval $8 < z < 10.5$. For the adopted $2 \sigma$ flux limit of $43 \mu Jy$ at $J$, the limit on the Lyman $\alpha$ luminosity is $\sim 4.5 \times 10^{48} \left( h^2 \Omega_{0} \right)^{-1}$ W. Koo & Kron (1980) derive a practical detection limit of $3.5 \times 10^{-19}$ W m$^{-2}$ for the Lyman $\alpha$ line redshifted to $z \sim 5$. The limit obtained in this IR search falls below the limit of the Koo & Kron (1980) $\alpha$ search if the assumed diameter of a primeval galaxy is $> 5$ arcsec, which is likely to be true for the redshift range of interest.

The only confirmed infrared source discovered in this search is that in pixel 23b. It was detected repeatedly at times more than a year apart, which rules out its identification as a solar system object, such as an asteroid, whose proper motion would easily exceed $\sim 8$ arcsec yr$^{-1}$. There is no optical object near this position on the best UK Schmidt plate available. However, the near-infrared colours can be used to distinguish a primeval galaxy from a faint foreground galaxy or

![Figure 6. The infrared colours of a dust-free primeval galaxy with a blackbody temperature $\sim 3 \times 10^4$ K at various redshifts. The discontinuity at $z \sim 8$ is due to Lyman $\alpha$. The colours of common foreground objects are also shown. The infrared colours of pixel 23b are shown for comparison.](https://academic.oup.com/mnras/article-abstract/235/1/209/991877)
star. The infrared colours of 23b are: $J-H=0.76\pm0.32$, $H-K=0.27\pm0.3$. As is indicated in Fig. 6, these colours are characteristic of a normal spiral galaxy. Thus we conclude that this object is a faint foreground galaxy.

6 Discussion

There are several possible reasons why this search for primeval galaxies has yielded a null result. The most probable explanations are:

1. The pre-dust phase of the initial burst of star formation is not long enough for primeval galaxies to be detectable in the optical or near-infrared with present instrumental limitations. Dust will be particularly relevant for the slower infall models since, in that case, the bright phase occurs after many enrichment times.

2. Primeval galaxies are intrinsically fainter than the models tested by either the optical or IR searches, i.e. $T_{pe}<10^4$K. Young galaxies may not resemble giant HI regions at all, but perhaps are like star-forming regions suggested to occur at the centres of cooling flows in dense galaxy clusters (Fabian, Nulsen & Canizares 1984). The initial mass function is then biased towards the formation of low-mass stars.

3. Perhaps not all morphological types of galaxies go through a highly luminous phase of star formation. Tinsley (1978) suggests that only early-type galaxies were conspicuously brighter as primeval objects, since any past enhancement in the star formation rate would lead to excessively red colours. Since spirals constitute about 80 per cent of the total number of galaxies in the Universe, the number density $\eta_0 \sim 0.01 h^3$ Mpc$^{-3}$ may be an overestimate.

4. The areal density of primeval galaxies will be reduced to a level untested at 90 per cent confidence by this experiment if $h<0.75$, or $\Omega_0>2$. Further constraints for these cosmologies will require a survey to a similar sensitivity for an order of magnitude larger area of sky.

5. If the universe is very open ($\Omega_0<0.1$) then the upper limits on flux eliminate only those models with unrealistically large luminosities.

In conclusion, it is important to note that one is unlikely to be able to improve significantly on these constraints on primeval galaxies by further infrared searches of this type. However, with the advent of IR detector arrays, cameras such as IRCAM on UKIRT will be an excellent tool for future IR searches at high redshift. Using the maximum pixel size of 2.3-arcsec diameter and the same integration time per frame as used in this survey, it will be possible to search more than order of magnitude more area to greater depth. This will permit significant tests of galaxy formation models with smaller assumed galaxy densities $\eta_0$ and with values of $h\sim0.5$.

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References

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