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# DEEP IMAGING SEARCH FOR LYMAN-ALPHA EMISSION ASSOCIATED WITH AN H I CLOUD AT $z = 3.4$

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## ABSTRACT

We have carried out deep broad- and narrow-band imaging of a field reported to contain a possible Zel'dovich pancake at $z = 3.4$ in order to search for Ly$\alpha$ emission from galaxies or protogalaxies associated with the cloud. We are sensitive to objects with sizes less than 5" but do not detect any Ly$\alpha$ emission-line objects down to a limiting flux level of $3.8 \times 10^{-30}$ ergs s$^{-1}$ cm$^2$ Hz$^{-1}$, or an integrated line flux of $4.4 \times 10^{-17}$ ergs s$^{-1}$ cm$^{-2}$. This limit is some 25 to 50 times fainter than the Ly$\alpha$ emission detected from a nearby radio galaxy at the same redshift.

*Subject headings:* cosmology: observations — galaxies: formation — galaxies: photometry

## 1. INTRODUCTION

The "top-down" theory of galaxy formation (Zel'dovich 1970) predicts the existence of massive protoclusters of galaxies at large redshifts. In order to develop into modern-day clusters these protoclusters would have had to consist, at some point, of $10^{13}$–$10^{15}$ $M_\odot$ of neutral hydrogen gas. Extrapolating backwards in time from present-day cluster dimensions, one concludes (e.g., Sunyaev & Zel'dovich 1974) that these clouds must have formed at $z \leq 10$. A gravitational instability causes these clouds to collapse along one dimension to become "pancakes" (Sunyaev & Zel'dovich 1972) which could then fragment into galaxy-sized masses. Recently, the collapse, cooling, and fragmentation of a massive cloud composed of baryons and collisionless dark matter has been numerically simulated in two dimensions by Yuan, Centrella, & Norman (1991). Their simulation follows a gas cloud which is perturbed at $z = 50$, collapses to a pancake at $z = 5$, and then fragments due to cooling and gravitational instabilities. Fragmentation into protogalactic objects of size (17–9) $h_{100}^{-1}$ kpc (for $0.05 \leq q_0 \leq 0.5$) occurs by $z = 3.88$ and by $z = 2.4$ the dominant mode is (33–19) $h_{100}^{-1}$ kpc (same range of $q_0$) as the fragments begin to merge into larger and larger structures. Sunyaev & Zel'dovich (1972, 1974) pointed out that it should be possible to detect H I and Ly$\alpha$ emission from these objects.

The first search for neutral hydrogen emission from protoclusters was reported by Davies, Pedlar, & Mirabel (1978). The authors searched a range of frequencies corresponding to emission at $3.33 \leq z \leq 4.92$ and constrained the Sunyaev & Zel'dovich (1972, 1974) protoclusters to either have masses $\leq 3 \times 10^{15}$ $M_\odot$ or to a number $\leq 10^6$. Bebington (1986) found no emission at 200 cm (corrsponding to H I emission at $z \sim 8.4$) and thereby constrained some galaxy-formation scenarious in certain cosmologies. The null results of Noreau & Hardy (1988) and Hardy & Noreau (1987), using VLA observations at 90 cm (corresponding to $z \sim 3.3$), put upper limits of $M \leq 10^{15}$ $M_\odot$ for any H I clouds. De Bruyn et al. (1988) searched for emission at $z = 3.35$ and concluded, depending on the angular resolution and value of $\Omega$, that H I masses at this redshift are $\leq$(0.5–12) $\times 10^{14}$ $M_\odot$. The Ooty radio telescope was used by Subrahmanyan & Swarup (1990) to search for emission from protosuperclusters at $z = 3.35$, while a complementary survey with the VLA was used to search for protoclusters at the same redshift (Subrahmanyan & Anantharamaiah 1990).

The only reported detection of neutral hydrogen emission which has appeared in the literature is that of Uson, Bagri, & Cornwell (1991). The authors used the VLA to search for neutral hydrogen absorption and emission at $z = 3.4$. The search field was centered on the radio source 0902+34 which has been identified optically as a galaxy at $z = 3.395$ (Lilly 1988). Twenty-one cm absorption was detected against the radio galaxy at a redshift of $z = 3.3968 \pm 0.0004$. More interestingly, H I emission from $z = 3.3970 \pm 0.0003$ was detected 33' away from the absorption signal position. The emission has a velocity dispersion of $180 \pm 40$ km s$^{-1}$ and a transverse dimension of $\sim 300"$. Though the emission and absorption redshifts agree, Uson et al. (1991) argue that they are not physically associated as the projected proper separation between the signals is 7–24 Mpc (depending on the values used for $H_0$ and $\Omega$). The emission signal was interpreted as being due to an H I mass of (1.3–0.4) $\times 10^{14}$ $h_{100}^{-2}$ $M_\odot$ for $0.05 \leq q_0 \leq 0.5$. The angular size of the emission corresponds to a linear dimension of (1.0–1.8) $h_{100}^{-1}$ Mpc for the same range of $q_0$.

Closely associated with the searches for protocluster H I emission are the optical searches for primeval galaxies (Koo 1986; Djorgovski & Thompson 1992). Primeval galaxies undergoing their first burst of star formation are expected to radiate substantial amounts of Ly$\alpha$ (e.g, Cox 1985). However, Ly$\alpha$ emission is also expected from clouds ionized in the vicinity of QSOs and from the hydrogen cloud population responsible for the "Ly$\alpha$ forest" observed in QSO spectra (Hogan & Weymann 1987). Thus, strong Ly$\alpha$ emission has been detected from, and in the vicinity of, most high-redshift radio galaxies (e.g., Djorgovski 1988; Chambers, Miley, & van Breugel 1990; Lowenthal et al. 1991) and QSOs (e.g., Heckman et al. 1991) with typical Ly$\alpha$ luminosities of $10^{44}$–$10^{45}$ ergs s$^{-1}$.

Blank regions of sky have been searched for Ly$\alpha$ emission using both narrow-band imaging and spectroscopic techniques (e.g., Koo 1986; Thompson, Djorgovski & Trauger 1991). The tightest limits on emission come from Lowenthal et al. (1990) who find no unresolved emission objects down to a limiting line surface brightness of 1–4 $\times 10^{-18}$ ergs s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$. Similar sensitivities have been reached by Thompson, Djorgovski, & Trauger (1991).

We have searched for Ly$\alpha$ emission from the area in which Uson et al. (1991) have reported detecting a high-redshift H I cloud. The observations and data reduction techniques are detailed in § 2, and the conclusions are presented in § 3.

## 2. OBSERVATIONS

The observations were carried out at the Canada-France-Hawaii telescope on the night of 1992 March 10. We used the MARLIN imaging spectrograph with the SAIC1 CCD. The scale was 0.34 arcsec pixel$^{-1}$ for a field view of 5 × 5 arcmin and the CCD readout noise was 9 e$^{-}$ pixel$^{-1}$. Images were taken in broad-band $V$ and using a narrow-filter band filter centered on 5340 Å ($z = 3.39$ for Ly$\alpha$ emission) with a width of 111 Å. The images were centered on the position $\alpha_{1950} = 09^h03^m48^s.10$, $\delta_{1950} = 33''52'01''.00$. This is the position at which neutral hydrogen emission was detected by Uson et al. (1991).

Seven 1200 s exposures were taken with the narrow-band filter and one 900 s with the broad-band filter. An exposure of the star BD +26°2606 was taken in the narrow band as a calibrator. The data were reduced using the NOAO IRAF package. Each of the seven Ly$\alpha$ images was bias-subtracted. A normalized sky flat was constructed using a median of five of the images. The images were then flat-fielded using the normalized sky flat and corrected for bad columns. The images were then coregistered and a median of the seven images was made. This is the image on which the analysis was performed (the effective exposure time is 8400 s). The 900 s $V$ band image was bias-subtracted and divided by a normalized dome flat (constructed by median filtering 10 dome flats). The image quality was measured on stars to be 1''.1 in $V$, and 1''.2 on the composite Ly$\alpha$ image. A bright star at the top of the image produced some internal reflections. To eliminate these we computed a median using the final narrow-band image. The median consists of a sliding rectangular window (20 × 20 pixels) in which the center pixel of the window is replaced by the median of all the pixels in that window. This median-filtered image is subtracted from the original image to yield an image that is background-subtracted with the large-scale fluctuations removed.

The images have been reduced using DAOPHOT running in the IRAF environment. The program DAOFIND was used to search for local density maxima greater than 5 $\sigma$ above the local background in the narrow band. The magnitude zero point was set in the narrow band using the star BD +26°2606. The $V$-band magnitude zero point was set by requiring that several stars have the same magnitude in the broad and narrow band.

Magnitudes were measured with the program PHOT. This program computes accurate centers, sky values and magnitudes for each object. The sky for each object was determined by taking the mode of counts within an annulus centered on each object. The magnitude of each object was estimated using a circular aperture 8 pixels in radius (2''.7). The projected size of our 5''.4 aperture is (33–19) $h_{100}^{-1}$ kpc for $0.05 \leq q_0 \leq 0.5$.

Magnitudes for all objects found down to the 5 $\sigma$ level in the narrow band were determined in the broad and narrow band.

Lilly (1988) lists the $V$ magnitude in the continuum ($V_c$) and the total $V$ magnitude ($V_t$) for the nearby radio galaxy, 0902+34, at $z = 3.395$. For a 3.5 × 3.5 arcsec$^2$ aperture centered on the galaxy, he finds $V_c = 23.8$ and $V_t = 23.0$, while for the entire area of the galaxy (7 × 4 arcsec$^2$) the values are $V_c = 23.5$ and $V_t = 22.5$. The Ly$\alpha$ fluxes from these same two areas are 1.1 $\times 10^{-15}$ ergs s$^{-1}$ cm$^{-2}$ and 2.1 $\times 10^{-15}$ ergs s$^{-1}$ cm$^{-2}$, respectively. The observed FWHM of the Ly$\alpha$ line is about 1000 km s$^{-1}$ or 18 Å.

Using the continuum and total $V$ magnitudes of Lilly (1988) as a guide, we have searched for objects having $V-N$ ($V$ is the $V$-band magnitude and $N$ is the narrow-band magnitude) $\geqslant 0.8$. Since we have normalized the narrow-band zero point to give the same magnitude as the $V$-band magnitude for stars, any Ly$\alpha$ emitting objects should stand out clearly with our selection criterion. We do not find any such objects. The flux limit we derive is a magnitude of 25 in the narrow band which corresponds to a flux limit of 3.8 $\times 10^{-30}$ ergs s$^{-1}$ cm$^{-2}$ Hz$^{-1}$ within a 2''.7 radius.

## 3. DISCUSSION

We find no Ly$\alpha$ emitting objects of size less than 5''.4 in the direction of H I cloud reported by Uson et al. (1991). The flux limit we derive is a magnitude of 25 in the narrow band which corresponds to a flux limit of 3.8 $\times 10^{-30}$ ergs s$^{-1}$ cm$^{-2}$ Hz$^{-1}$, or an integrated line flux of 4.4 $\times 10^{-17}$ ergs s$^{-1}$ cm$^{-2}$. This is a factor of 25 times fainter than the Ly$\alpha$ flux detected by Lilly (1981) from the central region of the nearby radio galaxy 0902+34 and a factor of 50 fainter than the Ly$\alpha$ flux from the area surrounding the entire radio galaxy (which is comparable in size to our search area). Therefore, any unobscured Ly$\alpha$ emission objects in the putative H I cloud would have to emit Ly$\alpha$ radiation at a level more than 4 mag fainter than the nearby radio galaxy located at the same redshift.

Our upper limit on the Ly$\alpha$ flux may be used to estimate an upper limit on the total star-formation rate in regions of radius less than 2''.7 within the reported H I cloud (see, e.g., Lowenthal et al. 1991). Assuming a negligible dust and case B recombination (e.g., Brocklehurst 1971), our observed Ly$\alpha$ flux is roughly 10 times greater than the flux of ionizing UV photons. Assuming that these photons all come from hot stars, we use Kennicutt's (1983) parameterization of the star-formation rate (SFR) in terms of total observed H$\alpha$ emission for an "extended" Miller-Scalo initial mass function. We find that the SFR is less than (3–0.9) $h_{100}^{-2}$ $M_\odot$ yr$^{-1}$, where the limits correspond to $q_0 = 0.05$ and $q_0 = 0.5$, respectively.

Due to the problem of eliminating internal reflections from the bright star we have not searched for extended emission over scales in excess of 5''. We hope to do this in the near future, as well as reducing our upper limit on the Ly$\alpha$ flux, with improved data.

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