NICMOS IMAGING OF THE DUSTY MICROJANSKY RADIO SOURCE VLA J123642+621331 AT \( z = 4.424 \)

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ABSTRACT

We present the discovery of a radio galaxy at a likely redshift of \( z = 4.424 \) in one of the flanking fields of the Hubble Deep Field (HDF). Radio observations with the Very Large Array and MERLIN centered on the HDF yielded a complete sample of microjansky radio sources, of which about 20% have no optical counterpart to \( I \leq 25 \) mag. In this Letter, we address the possible nature of one of these sources through deep *Hubble Space Telescope* near-infrared camera and multiobject spectrometer (NICMOS) images in the F110W \((J_{110})\) and F160W \((H_{160})\) filters. VLA J123642+621331 has a single emission line at 6595 Å, which we identify with Ly\( \alpha \) at \( z = 4.424 \). We argue that this faint \((H_{160} = 23.9 \text{ mag})\), compact \((r = 0.2 \text{ arcsec})\), red \((J_{814} - K = 2.0)\) object is most likely a dusty, star-forming galaxy with an embedded active nucleus.

Subject headings: galaxies: active — galaxies: evolution — galaxies: individual (VLA J123642+621331) — galaxies: starburst

1. INTRODUCTION

One of the contemporary topics of interest in extragalactic astronomy is the measurement of the star formation history of the universe (Madau et al. 1996). However, the effect of dust obscuration is a major uncertainty in calculating the star formation rate (SFR), particularly for measurements in the ultraviolet and at high redshifts. For example, Calzetti & Heckman (1999) found that at \( z \approx 3 \), even a modest amount of dust can reduce the 1500 Å flux of a galaxy by a factor of 5. This is of particular significance for the high-\( z \) evolution of the SFR: does the SFR turn over at \( z \approx 1.5 \) as Madau et al. (1996) suggested, or is it constant (or even increasing) for \( z \approx 1.5 \) (e.g., Pascarelle, Lanzetta, & Fernández-Soto 1998; Steidel et al. 1999)? If a high-redshift starburst is significantly reddened by dust, then its ultraviolet flux will be so obscured that it will have a negligible Lyman-limit break. Such sources would not have been detected by Steidel et al. (1999), and their measurements of the SFR could still be underestimating the actual amount of star formation at high \( z \).

A powerful technique for avoiding the problem of dust obscuration is to use radio-selected galaxies as probes of the star formation history (Cram 1998). The most important advantage of this technique is that radio emission is not attenuated by dust and thus a radio-selected sample is unbiased with respect to dust, unlike the optical/infrared selection techniques that are widely used. D. B. Haarsma et al. (1999, in preparation) conclude from their study that the radio-selected SFR is somewhat higher than the Madau et al. (1996) results for \( z < 1 \), even when the latter have been corrected for dust. At higher redshifts, the “radio Madau diagram” is poorly constrained but is consistent with a relatively constant or increasing SFR. This suggests that a significant fraction of the star formation in the universe may be obscured by dust.

Radio-selected samples thus provide an essential tool for understanding the cosmic history of dust as well as that of the SFR. In particular, radio sources that are heavily reddened in the optical (rest-frame ultraviolet at redshifts of interest) can be used to constrain the dust content of high-\( z \) galaxies. We present in this Letter deep *HST* NICMOS images of the microjansky radio source VLA J123642+621331. At a probable redshift of \( 4.424 \), this is the second highest redshift radio-selected galaxy currently known. It was barely detected in the reddest optical wave bands and is an excellent candidate for a dusty high-\( z \) galaxy.

We use a cosmology with \( H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1} \), \( \Omega_m = 0.2 \), and \( \Omega_{\Lambda} = 0 \) throughout. All magnitudes are in the AB system, unless noted otherwise. For comparison, Vega-based magnitudes are approximately given by \( I_{814} - 0.4, J_{110} - 0.7, H_{160} - 1.3, K - 1.9, \) and \( (I_{814} - K) + 1.5 \).

2. VLA J123642+621331

Two of the deepest high-frequency radio surveys available are those centered on the Hubble Deep Field (HDF; Richards et al. 1998; Richards 1999) and the Small Selected Area 13 (SSA 13; Windhorst et al. 1995). These surveys reach \( 5 \sigma \) detection limits of \( 8 \mu Jy \) at 8.5 GHz (HDF and SSA 13) and \( 40 \mu Jy \) at 1.4 GHz (HDF). Optical identifications of the sources were made on deep *Hubble Space Telescope* and ground-based images, primarily in the \( I \) band. Approximately 20% of the 1.4 GHz sources were not identified, although a few of them show faint optical emission below the formal completeness limit of the \( I \)-band images. The full sample is discussed by Richards et al. (1999); in this Letter we investigate in detail one of these “unidentified” sources.

VLA J123642+621331 is a steep-spectrum radio source \((\alpha = 0.94 \pm 0.06, S_{\nu} \propto \nu^{-\alpha})\) with flux densities of \( 70 \mu Jy \) at 8.5 GHz and \( 470 \mu Jy \) at 1.4 GHz (Richards et al. 1998; Richards...
1999). Approximately 10% of its radio flux density is extended in an eastward jet in 0:15 MERLIN observations, with the remainder in a resolved compact core (T. Muxlow et al. 1999, in preparation). The source was identified with a faint object below the formal completeness limit of the HDF flanking field I-band image (IW3), with a magnitude of $I_{64}=25.3\pm0.2$ (Fig. 1a). The object was also identified in the K-band image of Dickinson (1998) from the KPNO 4 m telescope and has a magnitude of $K=23.25\pm0.05$ (Fig. 1d). The KPNO images do not detect the object in either the J or H bands. Aussel et al. (1999) identify VLA J123642+621331 in their supplementary list of sources detected by ISOcam on the Infrared Space Observatory (ISO). It has a flux of $23^{+10}_{-12}$ mJy in the LW3 filter at 15 $\mu$m, corresponding to an AB magnitude of $20.5\pm0.5$. The source lies at the edge of the SCUBA submillimeter map of Hughes et al. (1998) and was not detected, giving a conservative upper limit of 5 mJy to its 850 $\mu$m flux.

3. NICMOS OBSERVATIONS AND PROCESSING

In 1997 December, we observed VLA J123642+621331 with the Hubble Space Telescope NICMOS camera 2 for three orbits in F110W (close to the J band) and six in F160W (essentially the H band), in the continuous viewing zone. In each orbit, five 1024 s exposures were taken using a spiral dither pattern with 1'3 offsets. We reduced the images using a two-stage process: first we ran them through the standard pipeline CALNICA, using the most recent calibration files, and then we applied a further flat-field correction to the data, adapted from standard ground-based infrared imaging methods.

Following CALNICA processing, additional bad pixels were flagged after a visual inspection of the data—these consisted of a dead column, the coronograph hole, and other insensitive pixels (also known as the “grot”). Since the NICMOS camera actually consists of four physically separate subarrays, we obtained better results by dividing each partially reduced image into four separate quadrants. For each filter, all the exposures of each quadrant were stacked and a median image calculated. Given that the exposures were dithered by 1'3, this produced a map of the residual instrumental features, devoid of any astronomical objects—a “supersky.” The supersky images for each quadrant were normalized to the mean of all four quadrants in order to preserve the quadrant-to-quadrant photometric accuracy. Each exposure was then divided by this normalized supersky. We also tested the results of subtracting a scaled copy of the supersky from each exposure and found that the results were not significantly different (the standard deviation of an empty sky region varied randomly by less than 3% between the two methods). The success of this supersky division suggests that the instrumental features left after CALNICA processing were most likely due to differences between the sky and the calibration flat fields, rather than poor subtraction of the bias or dark current. Finally, all the quadrants were combined to produce F110W and F160W mosaics. By ensuring that the mean of our supersky was unity, the overall sensitivity of the images was unchanged by the additional processing, and they were calibrated using the most recent photometric calibration parameters from STScI.

Figure 1c shows the six-orbit NICMOS image in F160W. The counterpart to the radio source is clearly detected at 1.6 $\mu$m, with an AB magnitude of $H_{60}=23.87\pm0.04$ in a 1'5 diameter circular aperture. The three-orbit NICMOS image in F110W provided a marginal detection of $J_{110}=25.2\pm0.4$ (Fig. 1b). Thus, the object is red with $(I_{64}-K)=2.0\pm0.2$, $(J_{110}-H_{60})=1.3\pm0.4$, and $(H_{160}-K)=0.6\pm0.1$.  

Fig. 1.—Multiband images of VLA J123642+621331. (a) WFPC2 F814W (J-band) gray-scale image, overlaid with the 1.4 GHz combined (uniform-weighted) MERLIN/VLA radio image of T. Muxlow et al. (1999, in preparation) at a resolution of approximately 0'15. Contour levels are at flux densities of 8, 16, 32, and 128 $\mu$Jy ($\sigma=4$ $\mu$Jy). (b) The source is barely detected in a three-orbit NICMOS F110W (J-band) image. (c) The six-orbit NICMOS F160W (H-band) image shows a red object at the radio position. (d) Ground-based K-band image with the KPNO 4 m (170 seeing). Each image is 4' on a side and has been smoothed with a 2 pixel-wide Gaussian.

Fig. 2.—Keck spectra of VLA J123642+621331. The single emission line is detected in two independent observations over a period of more than 1 yr and is identified as Ly$\alpha$ at $z=4.424$. The 1998 spectrum is smoothed with a 3 pixel boxcar filter.
4. KECK OBSERVATIONS

We obtained spectra of VLA J123642+621331 through 1′5 wide, ≈30′ long slits using the Low-Resolution Imaging Spectrograph (Oke et al. 1995) at the Keck II telescope in slitmask mode. On UT 1998 February 19, with 0′8 seeing and photometric conditions, we observed VLA J123642+621331 for 1.9 hr (position angle 103°) with the 400 line mm⁻¹ grating, sampling the wavelength range 5700−9400 Å, at ΔΛFWHM ≈ 11 Å. On UT 1999 May 10, with 0′6 seeing and thin cirrus, we observed the source for 2 hr (position angle −67°) with the 150 line mm⁻¹ grating, with ΔΛFWHM ≈ 17 Å resolution over the wavelength range 4000 Å to 1 μm. Between each 1800 s exposure, we performed a ∼4″ spatial shift along the slit to facilitate removal of fringing in the reddest regions of the spectra. The final wavelength calibration is accurate to better than 1 Å.

There is a single emission line at λ ≈ 6595 Å in both data sets, which we identify with Lyα at a redshift of 4.424 ± 0.003 (Fig. 2; Table 1). The line shifts by ≈7 Å between the two observations, which corresponds to a velocity difference of 320 km s⁻¹ if it is due to a Doppler shift. In the data for both years, the line was offset by ≈1″ to the northwest of the (marginal) I-band detection. Emission-line regions of high-redshift radio galaxies are known to be kinematically complex (Chambers, Miley, & van Breugel 1990; van Ojik et al. 1997); thus, slight pointing changes between the two observations may have caused the slit to sample different regions of spatially extended, line-emitting gas.

5. DISCUSSION

The only two reasonable identifications for the single emission line are Lyα or [O ii] λ3727. We argue that it is unlikely to be [O ii] at z = 0.77 for the following reasons. The faint K magnitude of 23.3 argues strongly against the source being at low z when it is compared to the K-z relation of radio galaxies (see van Breugel et al. 1999 for a recent version). If VLA J123642+621331 were at z = 0.77, it would be 3−4 mag underluminous in K compared with all other known radio galaxies at that redshift. The rest-frame equivalent width if the line were [O ii] would be W[O II] > 207 Å, which is very large for [O ii]. The absence of a redshifted [O ii] doublet at ~8860 Å further argues against z = 0.77, although this argument is not completely satisfying since galaxies show a wide range in [O iii]/[O ii] ratios and our flux limits are not particularly strong.

The alternative is to identify the emission line with Lyα at z = 4.424. We compared the observed spectral energy distribution (SED) from 0.8 to 15 μm with the 1996 revision of the spectral evolution models of Bruzual & Charlot (1993). We used a single-burst model of solar metallicity and added a foreground screen of dust, modeling the effects of dust ob-

![Fig. 3.—Optical/infrared spectral energy distribution of the radio galaxy. The three spectra are the best-fitting model (solid line), the oldest and least dusty model (dot-dash line), and youngest and most dusty model (dotted line), both at the 3 σ confidence limits.](image-url)
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Fig. 4.—NICMOS F160W surface brightness profile of VLA J123642+621331. Triangles denote 1σ upper limits. The best-fitting model (solid line) is an exponential with scale length 0′′.17 (1.4 kpc), convolved with the appropriate PSF (dotted line) from Tiny Tim.