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DISCOVERY OF A NORMAL GALAXY AT $z = 1.018$

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ABSTRACT

We report on the discovery of an apparently normal galaxy at $z = 1.018$, designated G0333+3208, found during a long-slit search for faint emission-line objects. One strong emission line has been detected in the wavelength range 3800–8500 Å, which we attribute to [O II] λ3727. The object is a $\sim$24 mag galaxy with a relatively flat optical spectrum. There are no morphological or spectroscopic signs of an active nucleus in the object, or in its vicinity, and no radio flux from the object down to 200 μJy rms at $\lambda = 20$ cm. From the emission-line flux, assuming photoionization by young stars and a normal IMF, we estimate a star formation rate of $\sim 3.5h^{-2}\ M_{\odot}\ \mathrm{yr}^{-1}$ (for $\Omega_0 = 1$). This object would thus be among the most distant of normal galaxies now known. It may be representative of the faint blue or flat-spectrum population, which dominates deep galaxy counts.

Subject headings: cosmology — galaxies: evolution — galaxies: formation — galaxies: redshifts

1. INTRODUCTION

Study of galaxy evolution at large look-back times is one of the principal tasks of modern observational cosmology. However, normal galaxies at large redshifts are notoriously difficult to find. Many examples of powerful radio galaxies and emission-line galaxies near quasars are now known at high redshifts, but the presence of active nuclei in or near them makes the interpretation of their properties in terms of "normal" galaxies somewhat uncertain (see, e.g., Djorgovski et al. 1987; McCarthy et al. 1987; Steidel, Sargent, & Dickinson 1991, etc.; or the reviews by Spinrad 1987 and Djorgovski 1988). On the other hand, deep imaging surveys (e.g., Tyson 1988; Cowie et al. 1988; Lilly, Cowie, & Gardner 1991; see also the reviews by Tyson 1990 and Cowie & Lilly 1990) have certainly detected galaxies at large redshifts, but to date unambiguous redshifts greater than a few tenths have not been obtained for any of them.

In this *Letter*, we report on the discovery of an apparently normal field galaxy at $z = 1.018$, found in the course of an unbiased long-slit survey for high-redshift objects. This galaxy, designated G0333+3208, is one of the first examples of galaxies at $z > 1$ which are not associated in any way with an active nucleus. It may be representative of an actively evolving, normal galaxy population at a look-back time of about one-half of the present epoch. Other possible examples of such objects include some recently found galaxies, associated with quasar absorption-line systems (Bergeron 1990; A. Wolfe et al. in preparation).

2. DATA AND RESULTS

A long-slit spectrum of the quasar NRAO 140 (0333+321) and its stellar companion at PA = 100° was obtained on UT 1988 September 8 as part of a program to search for possible gravitational lens candidates. The Four-Shooter spectrograph at the Cassegrain focus of the Palomar Observatory Hale 200 inch (5 m) telescope was used with a 300 lines mm^{-1} grism and a TI 800 × 800 CCD detector, giving a dispersion of 4.09 Å pixel^{-1} and a resolution of $\sim$15 Å. The exposure time was 1200 s and covered the wavelength range 4760–8010 Å. After bias subtraction and flat-fielding using standard procedures, the CCD frame was cleaned of cosmic-ray hits, and the night sky emission lines were straightened and subtracted so that it could be checked as part of an ongoing serendipitous long-slit survey for faint emission-line objects.

A possible emission line was detected at 7523 Å at a separation of 32″ from the quasar. A deeper, confirming spectrum of 3000 s duration was obtained on UT 1990 September 19, again with the Four-Shooter, and with a similar set-up, covering the wavelength range 4790–8450 Å. The emission line was again detected. A third spectrum of the emission-line object was obtained on UT 1990 October 18 with the Double Spectrograph (Oke & Gunn 1982) at the Hale 200 inch (5 m) telescope, looking for other emission lines at the blue end. The slit was set to the optimum parallactic angle, but since all three spectra were taken at low air mass, atmospheric dispersion should not be significant. A 300 lines mm^{-1} grating gave a dispersion of 2.05 Å per pixel, resolution of $\sim$10 Å, and a wavelength coverage of 3950–5580 Å. An exposure time of 4000 s failed to detect any other convincing emission lines, but does show a weak continuum extending down to approximately 4000 Å. Exposures of standard stars from Oke & Gunn (1983) were used for the flux calibration. A coaveraged spectrum of G0333+3208 is shown in Figure 1.

Imaging in the Gunn-Thuan g, r, and i bands was done on the night of UT 1990 October 17 with the Four-Shooter on the Hale 200 inch (5 m) telescope. Exposure times totalled 700 s each in r and i and 400 s in the g band. The images were flux-calibrated with the standard star BD +28°4211 (Kent 1985). Magnitudes of the object are $g = 23.5 \pm 0.2$, $r = 23.5 \pm 0.2$, and $i = 22.6 \pm 0.2$. The i band magnitude is undoubtedly affected by the strong emission line, which falls at the peak of the i filter transmission curve. A co-added contour plot of the region is shown in Figure 2.

Assuming the radio position for NRAO 140 from Perley (1982) and the offsets from the quasar in our CCD images, we obtain for the position of G0333+3208:

$$\alpha_{1950} = 03^{\mathrm{h}}33^{\mathrm{m}}24^{\mathrm{s}}.89\ ,\quad \delta_{1950} = +32°08'31''.3\ ,$$

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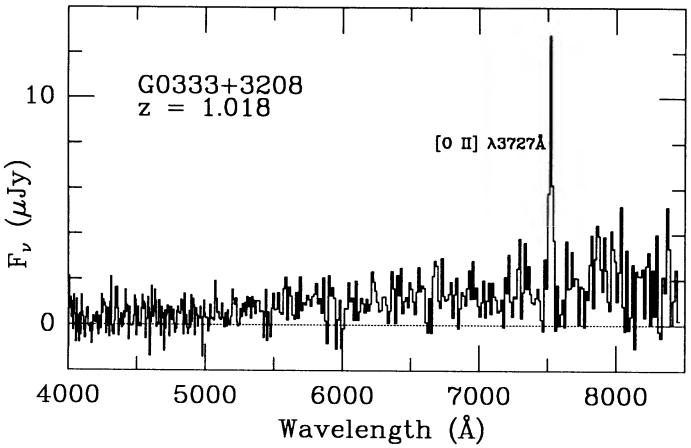

FIG. 1.—Spectrum of G0333+3208, coaveraged from all three of our observations. The absolute flux calibration is accurate to about 30%, based on a comparison with the broad-band magnitudes. The strong emission line at 7523 Å is interpreted as [O II] λ3727 at $z = 1.018$.

with the net estimated uncertainties of about 0".5 in each coordinate.

3. DISCUSSION

There is only a single emission line in the optical spectrum of G0333+3208, which we interpret as [O II] λ3727 at $z = 1.018 \pm 0.001$. This line is commonly seen in high-redshift galaxies and is one of the strongest. Other possibilities are much less likely: Hα and [O III] λ5007 can be ruled out due to the absence of other expected strong emission lines, e.g., Hβ or [O II] λ3727. If the detected line were Mg II λ2798, it would have an unusually large equivalent width, and we would expect to see either C II] λ2326 or C III] λ1909. Lyα at $z = 5.2$ is ruled out both from the lack of continuum depression across the line, which at that redshift may be as much as a factor of 5, extrapolating from the known quasars at $z > 4$ (Schneider, Schmidt, & Gunn 1989), and by the presence of a detectable continuum blueward of the corresponding Lyman limit at 5641 Å.

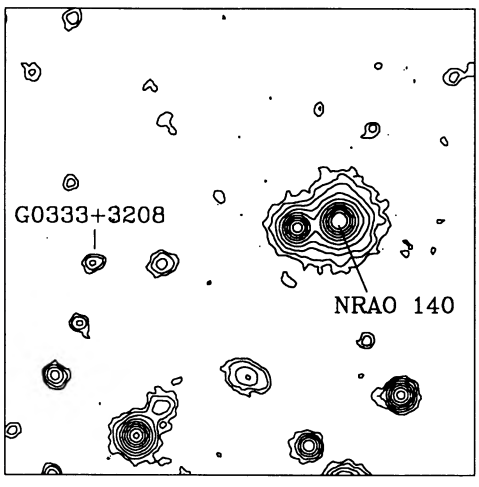

FIG. 2.—Co-added Gunn g, r, and i CCD frames of the field of G0333+3208, obtained at Palomar. North is at the top, east to the left, and the field size is 60" × 60". The emission-line object and the quasar are indicated. The object just east from the quasar is a foreground Galactic star. Contours have an arbitrary zero point and are spaced by a factor of 2 in intensity.

No absorption lines due to Mg II λ2798 at the galaxy redshift are detected in the spectrum of the quasar NRAO 140 ($z = 1.258$), though this is not surprising since the narrow absorption lines would perhaps be lost in our low-resolution spectrum, and at $z = 1.018$ the separation of 32" on the sky represents a projected comoving separation of $\sim 300h^{-1}$ kpc, for a reasonable range of Ω_0.

Assuming the redshift $z = 1.018$, the distance modulus in a standard $\Lambda_0 = 0$ Friedmann cosmology, for $H_0 = 100$ km s^{-1} Mpc^{-1} is in the range of 42.8 ($\Omega_0 = 1$) to 43.3 ($\Omega_0 = 0$). Thus, the inferred luminosity of G0333+3208 is consistent with that of an approximately L_* galaxy, undergoing a relatively mild evolution.

There is no morphological or spectroscopic sign of an active nucleus in this object. The velocity dispersion of the emission line is 160 ± 30 km s^{-1}, typical for normal galaxies. The emission is also marginally extended (spatially resolved) on the slit, suggesting an *in situ* ionization mechanism, such as the young stars. If the line is indeed [O II] λ3727, then the ionization is fairly low; witness, e.g., the complete absence of the Mg II λ2798 line. There is no radio emission detected from this object to 200 μJy rms at $\lambda = 20$ cm (R. Perley & D. Murphy, private communication). We thus conclude that G0333+3208 does not contain an active nucleus and that the line emission is probably powered by star formation.

The integrated emission line flux is 1.5×10^{-16} ergs cm^{-2} s^{-1}. In the models by Stasinska (1982), the [O II] λ3727/Hβ flux ratio is constant to within a factor of 2 or so over three orders of magnitude in density, over the range 30,000–53,000 K in the temperature of the exciting star, and the metallicity range of 0.1–1.0 times solar. Adopting the value of 1.65 for this ratio and using the theoretical value of 2.87 for the Hα/Hβ flux ratio gives us a conversion to Hα flux of $L(\mathrm{H}\alpha) = 1.74 \times L([\mathrm{O\ II}])$. Kennicutt (1983), using a nearly Salpeter IMF, gives a conversion to the integrated star formation rate as SFR $= L(\mathrm{H}\alpha)/(1.12 \times 10^{41}$ ergs s$^{-1}) M_\odot$ yr^{-1}. From this we derive the estimate for the star formation rate in G0333+3208 of about $3.5h^{-2} M_\odot$ yr^{-1}. An independent estimate by N. Scoville (private communication), using a somewhat different approach, gives nearly the same result. This SFR is comparable to that of actively star-forming, normal galaxies at low redshifts, and it is at least an order of magnitude smaller than the rates inferred (using similar reasoning) for the powerful radio galaxies at comparable or larger redshifts, or to the ultraluminous *IRAS* galaxies at low redshifts.

The [O II] restframe equivalent width in G0333+3208 is $W_\lambda = 106 \pm 10$ Å, which is several times smaller than the values typically found in powerful radio galaxies at similar or larger redshifts (McCarthy 1988, and references therein). It is also at the high end of the distribution found for the field galaxies from the field surveys with typical limiting magnitudes of $B \sim 21$–22, and median redshifts of $z \sim 0.2$–0.4 (Ellis 1988; Colless et al. 1990). This difference may be indicative of an evolution of the average SFR in galaxies over the corresponding time interval.

The optical continuum shape in G0333+3208 is broadly similar to the flat spectrum or blue galaxies found in large numbers at comparable magnitude levels in the deep field surveys by Tyson (1988), Cowie et al. (1988), Lilly et al. (1991), etc. This population is generally interpreted as actively evolving normal galaxies at $z > 1$, which may be responsible for a substantial part of the energy and metals generation in the universe. The only constraint on the typical redshift of these

galaxies is the absence of the Lyman limit in the U and B bands, suggesting that most of them are at $z < 3$ (Guhathakurta, Tyson, & Majewski 1990). G0333+3208 may be a representative member of this faint galaxy population.

Finally, we note that there are several other galaxies in the field, which have blue or neutral colors similar to G0333+3208, possibly signifying the presence of a loose cluster. We will be following these up with spectroscopic observations in the future.

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