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A cluster or filament of galaxies at redshift z = 2.5?

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ABSTRACT

We report the discovery of 56 new Lyα-emitting candidates (LECs) at redshift $z \approx 2.5$ in a field of $8' \times 14'$ around two previously known weak radio QSOs and a cosmic microwave background decrement (CMBD) that is plausibly due to the Sunyaev-Zel'dovich effect. Broad-band and medium-band imaging at the redshifted Lyα wavelength have allowed us to identify the LECs at the redshift of the QSOs. Three of the brightest LECs have been confirmed spectroscopically, with redshifts between $z = 2.501$ and $z = 2.557$; one of them is another QSO. Excluding the third QSO, the four spectroscopically confirmed objects form a $3'$ filament with a rest-frame velocity dispersion of 1000 km s^{-1} lying adjacent to the CMBD, and there is a significant concentration of LECs at the NW end of the filament around the brightest QSO. If confirmed, a velocity dispersion ~ 1000 km s^{-1} on a proper scale ~ 1 Mpc at redshift $z = 2.5$ would, in and of itself, constrain the cosmological model to low Ω.

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1. INTRODUCTION

The abundance of clusters of galaxies is known to evolve at redshifts $z \lesssim 1$, and this time dependence can be used to constrain cosmological models (e.g., Carlberg et al. 1997; Bahcall, Fan, & Cen 1997; Bartelmann et al. 1998). But the nature of clustering at redshifts $z \gtrsim 1$, where the contrast between model predictions is much more pronounced, is largely unknown. While QSO absorption systems show clustering (e.g., Heisler, Hogan & White 1989; Lanzetta, Webb, & Barcons 1995; Fernández-Soto et al. 1996), and while there is recent indication of large-scale structure at high redshift (Steidel et al. 1998; Adelberger et al. 1998; Giavalisco et al. 1998), the identification of specific groups and clusters is rather tentative (Dressler et al. 1993; Giavalisco, Steidel & Szalay 1994; Pascarelle et al. 1996a; Hu & MacMahon 1996; Francis et al. 1996; LeFèvre et al. 1996; Warren & Møller 1996; Malkan, Teplitz, & McLean 1996; Dickinson 1997; Stanford et al. 1997), and to date no rich cluster has been definitively detected at redshift $z > 1.3$.

One tracer of a possible distant cluster is a cosmic microwave background decrement (CMBD), which is most plausibly due to inverse Compton scattering by intracluster plasma (Sunyaev and Zel'dovich 1972). Two such CMBDs without identified optical clusters have recently been reported at 1312+4237 (Richards et al. 1997) and 1643+4631 (Jones et al. 1997). The absence of X-ray flux detection in deep ROSAT images can be used to set lower limits for the redshifts of intervening clusters. Kneissl, Sunyaev, & White (1998) found $z \geq 0.7$ and $z \geq 2.8$ at the 95% confidence level for the redshifts of 10-keV isothermal objects of any size along the lines of sight to 1312+4237 and 1643+4631, respectively.

Intriguingly, both CMBDs are in the direction of QSO pairs at redshifts $z = 2.561$ for 1312+4237 (Windhorst et al. 1995) and $z = 3.790$ and $z = 3.831$ for 1643+4631 (Schneider, Schmidt, & Gunn 1991). The differing redshifts for the 1643+4631 QSOs (corresponding to a rest-frame velocity difference of 2500 km s^{-1}) and the large separations ($90''$ and $200''$ for 1312+4237 and 1643+4631, respectively) argue against gravitational lensing by intervening clusters, so it is possible that the clusters are at the redshifts of the QSOs.

With this in mind, we searched a field of $8' \times 14'$ around 1312+4237 for objects whose medium-band imaging shows enhanced emission centered at 4350Å. We found 56 such objects (in addition to the two previously known QSOs) and interpret them as Lyα-emitting candidates (LECs) at redshift $z \approx 2.5$. We have confirmed the redshifts of three of the brightest new LECs (one of which is a QSO), with redshifts between $z = 2.501$ and $z = 2.557$. A grey-scale image of the 1312+4237 field, with all the LECs and the CMBD marked, is shown in Figure 1. Data for all the objects with existing spectroscopy are given in Table 1.

2. OBSERVATIONS

Images of 1312+4237 in the B and I bands (Harris set) were obtained in 1997 April with the prime focus camera of the KPNO 4m telescope (FOV $16' \times 16'$, pixel size $0\farcs47$). Five dithered exposures of 15 minutes each were taken in each band under photometric conditions with an average seeing of $1\farcs2$. In order to select the LECs, the field was also imaged using a medium-band filter, $\Delta\lambda = 130$Å, centered at 4350Å. (Hereafter we use B_M to designate both the filter and the associated magnitude.) A total of sixteen dithered 30-minute exposures were obtained, giving continuum depth comparable to the B images. All images were reduced using standard IRAF procedures, with magnitudes measured by the *phot* routine in apertures of 6-pixel radius. In order to reduce photometric color errors, the B and the B_M magnitudes were both calibrated against the same exposures of Landolt (1992) standards in B. The zero-point difference between the magnitudes, calibrated separately with the Landolt standards, showed a perfectly linear relation, with an *rms* calibration error of 0.04 mag. Color errors were determined by adding in quadrature magnitude errors.

The SExtractor program (Bertin & Arnouts 1996) was used for automatic source identification; source confusion is not a problem at these magnitudes. The presence of a bright star at the east of the field forced the removal of around 30% of the image. A total of 3772 objects with $B \leq 26$ were detected in the remaining field of about $8' \times 14'$. We determined the galaxy catalogue to be complete to $B = 25$ and $I = 23.5$ by comparing with published galaxy counts (e.g., Metcalfe et al. 1996).

The color-magnitude diagram, $B - B_M$ (IRAF aperture photometry) versus B_{tot} (SExtractor "best"-magnitude), is shown in Figure 2 for all the galaxies detected in the image with magnitudes $B \leq 26$ and photometric color errors $\Delta(B - B_M) < 0.2$ mag. The most noticeable feature of the diagram is the number of galaxies with excess color $B - B_M$.

The traditional method of identifying emission-line candidates has been to seek objects with color excesses exceeding 2σ or 3σ, where the standard deviation includes both the intrinsic spread and the observational errors (Pascarelle et al. 1996b; Cowie & Hu 1998). But the distribution of observed colors is not Gaussian: *intrinsic* colors are skewed toward negative $B - B_M$, as can be seen in Figure 2 for galaxies with $B < 23$, for which the sample is complete and observational errors are negligible, and incompleteness at faint magnitudes affects negative $B - B_M$ first, since the sample was selected in B. In order to avoid a complicated selection criterion, we apply a fixed color cut and designate as LECs all objects with $B - B_M > 0.6$ and color errors $\Delta(B - B_M) < 0.2$. (The median color errors, after eliminating those exceeding 0.2, are 0.11 and 0.16 mag for $24 \leq B < 25$ and $25 \leq B < 26$, respectively.) To verify the effectiveness of this cut, we used a variety of evolutionary models (Campos 1997), convolved with the actual photometric color errors, to show that, without excess line emission, the number of galaxies expected to have color excess $B - B_M > 0.6$ is very small compared with the number observed. As an example, the expectation in an $\Omega_0 = 0.1$ $\Lambda = 0$ model is for less than one galaxy in the magnitude range $24 \leq B < 25$ to satisfy the color cutoff, $B - B_M > 0.6$, and for only 3 galaxies to do so for $25 \leq B < 26$, while we found 16 and 39 objects, respectively, with colors exceeding that limit. Our color criterion, $B - B_M > 0.6$, corresponds to an observed equivalent width over a flat spectrum exceeding 120Å. At the $B = 25$ completeness limit of our catalogue this translates to a line flux of 6×10^{-17} erg cm^{-2} s^{-1} and $B_M = 24.4$. There are 37 LECs above this limit, or a surface density of $0.33/\Box'$. This LEC surface density is similar to that found by Steidel et al. (1996) for normal star-forming galaxies at redshifts $z > 3$.

There are 3 objects in the field with magnitudes $B < 21.5$ and a clear excess of emission in the B_M band (see Figure 2). Two of the objects, Q1 and Q2, are the previously known μJy QSOs (Windhorst et al. 1995). The third object, with similar $B - B_M$ and intermediate B magnitude, was observed at the MMT in 1998 February with a dispersion of 1.95Å/pixel and nominal resolution of 7.1Å and found to be another QSO at redshift $z = 2.501$. Its spectrum is shown in Figure 3.

The other LECs are all fainter, $B > 24$. We tried to confirm their redshifts in another spectroscopic follow-up in 1998 March, using the LDSS-2 multi-slit spectrograph at the WHT 4m telescope at La Palma Observatory with a dispersion of 5.3Å/pixel and nominal resolution of 13.3Å. Inclement weather allowed us to obtain workable spectra for only 2 objects, G1 and G2. Both of them show lines in their spectra that, if identified with Lyα, imply redshifts of $z = 2.557$ and $z = 2.536$, respectively. Their spectra are plotted in Figure 4. Note that both galaxies show little or no emission shortward of the putative Lyα line and continuum longward of the line, consistent with a Lyα-forest interpretation. With our signal-to-noise ratio and resolution we cannot exclude the possibility that they are also active galaxies. In three other objects with $0.60 < B - B_M < 0.65$ we could barely detect continua but no lines. One object close to G1 in the color-magnitude diagram, Figure 2, but with $B - I = 1.9$, was not detected at all. The spectroscopic confirmation rate is similar to the one in the 53W002 field of Pascarelle et al. (1996b).

3. DISCUSSION

In the 1312+4237 field under analysis—$8' \times 14'$ around two known QSOs at redshift $z = 2.561$ and a cosmic microwave background decrement (CMBD)—we have found 56 new Lyα-emitting candidates (LECs) at redshift $z \approx 2.5$. Three of the new LECs now have confirmed redshifts ranging from $z = 2.501$ to $z = 2.557$; one of them is another QSO at $z = 2.5$.

It is unlikely that the excess emission in the as yet unconfirmed LECs is due to another line, for example [OII]λ3727 at redshift $z = 0.16$. First, Hβ was not observed at the expected wavelengths in the spectra of G1 and G2 (dotted lines in Figure 4). Second, at redshift $z = 0.16$ the galaxies would be starbursting dwarfs with $M_B \sim -15$, W[OII]$\gtrsim$ 80Å, and density $\sim 6 \times 10^{-2}\ h_{50}^3$ Mpc^{-3}. For any cosmology, the space density of such a population implied by our observation would far exceed that observed heretofore (e.g., Campos 1997). Moreover, many of the LECs are red (31 with colors $B - I \geq 1$), while starbursting dwarfs are expected to be blue, $0 \lesssim B - I \lesssim 0.5$.

The LECs are scattered throughout the observed field of $8' \times 14'$, corresponding to proper lengths of $6 \times 10\ h_{50}^{-1}$ Mpc for $\Omega_0 = 0.1$ and $\Lambda = 0$ and a factor of 1.5 smaller if $\Omega_0 = 1$. Virialized clusters at the present epoch are somewhat smaller, but some of the LECs may also belong to a surrounding supercluster and not be part of a virialized cluster. For non-virialized objects, such as protoclusters and filaments, the relevant scales can be as high as the comoving dimensions of the field, $20 \times 35\ h_{50}^{-1}$ Mpc, corresponding to present-day large-scale structure. Using the same medium-band imaging technique at 4100Å, Pascarelle, Windhorst, & Keel (1998) find densities ranging from $0.2 - 2/\Box'$ in four fields complete to a depth of 25 mag, three of which were randomly chosen. Multiplying our surface density of $0.33/\Box'$ by a factor of 1.4 to bring it to the same completeness level, we find it to be in mid-range. The galaxian density may not reflect the underlying mass density, however. Reported biasing factors at high redshifts range from high (Adelberger et al. 1998) to extreme (Mannucci et al. 1998).

Four of the five spectroscopically confirmed objects actually form a $3'$ filament with a rest-frame velocity dispersion of 1000 km s^{-1} located near the CMBD, and the CMBD possibly extends NE across it (Windhorst et al. 1995, Figure 1). (Q3 is $10'$ away and has a relative velocity of 4500 km s^{-1}.) Moreover, five LECs with $0.75 \pm 0.11 < B - B_M < 1.63 \pm 0.12$, including G2, are within $0.7'$ of Q1 at the NW end of the filament. Since only half the LECs have $B - B_M > 0.75$, their mean surface density in the field is $0.25/\Box'$, and the probability for such a clustering to be random is 5×10^{-5}. This probability need not be viewed as completely *a posteriori*, since Q1 is by far the brightest LEC in the field and may well point to the location of the cluster (but note that some of the LECs may be due to the

QSO itself, cf., Natarajan, Sigurdsson, & Silk 1998).

Deeper imaging might reveal more structure, but spectroscopy is the critical confirmatory observation. While cluster evolution is usually stated in terms of the abundances of properly identified clusters, velocity dispersion is a dynamical measure of mass in its own right and can be compared directly with numerical simulations. A velocity dispersion ~ 1000 km s^{-1} on a proper scale ~ 1 Mpc at redshift $z = 2.5$ would, in and of itself, constrain cosmological models to low Ω (Eke, Cole, & Frenk 1996), as would a definitive association of the CMBD with this redshift (Bartlett, Blanchard, & Barbosa 1998). If confirmed, the 1312+4237 cluster would therefore be a "smoking-gun" measure of Ω.

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FIGURE CAPTIONS

Fig. 1.— Grey-scale $15' \times 14'$ image of 1312+4237 in the medium band, B_M, with north and east to the top and left as usual. Circles mark the position of the two previously known QSOs, Q1 and Q2, and the new one, Q3. Squares and triangles mark the other LECs with $B - I$ color ≥ 1 and < 1, respectively, with the two spectroscopically confirmed galaxies identified as G1 and G2. The ellipse is at the position of the cosmic microwave background decrement.

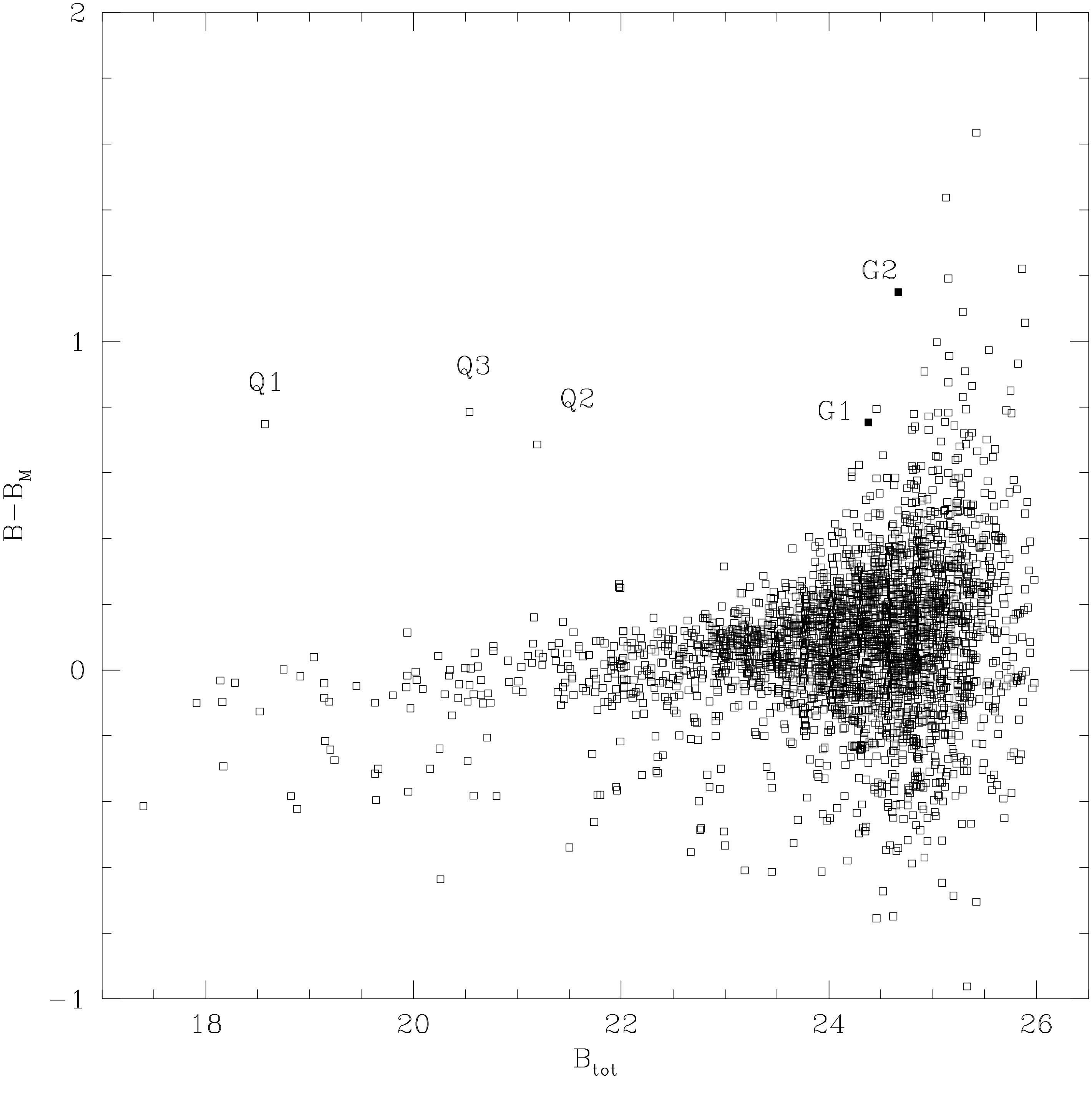
Fig. 2.— $B - B_M$ versus B color-magnitude diagram for all the galaxies detected with magnitude $B \leq 26$ and color photometric error $\Delta(B - B_M) < 0.2$. The objects marked as Q1 and Q2 are the two known μJy QSOs. Q3, G1 and G2 denote the newly confirmed QSO and two galaxies.

Fig. 3.— Spectrum of the newly confirmed QSO, Q3.

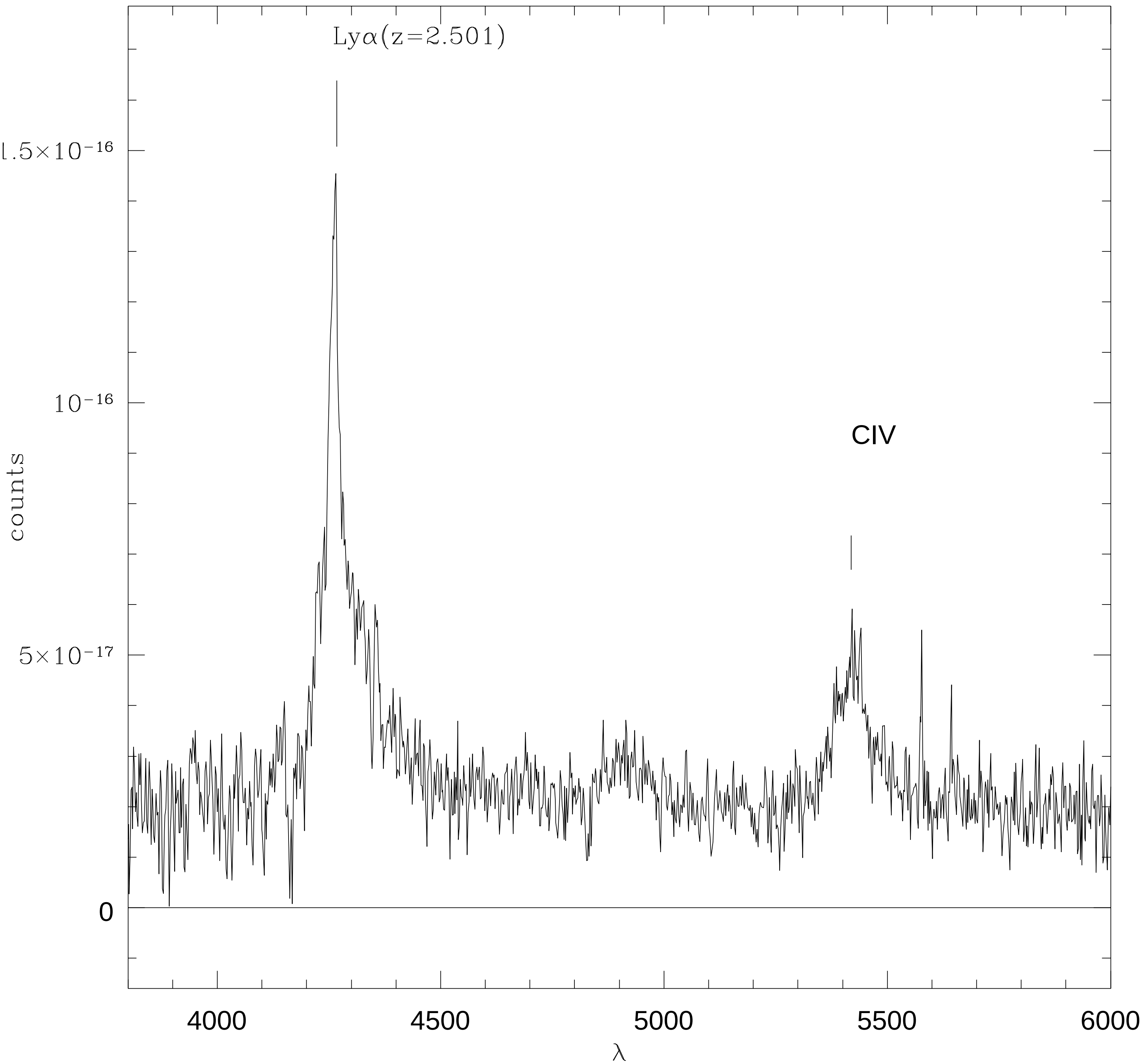
Fig. 4.— Spectrum of the newly confirmed galaxies, G1 and G2. Note that if the emission lines are O[II]λ3727 at redshift $z = 0.16$, then Hβ emission is expected at the positions of the dotted lines but is not seen.

Table 1. Spectroscopically Confirmed Lyα-Emitting Objects

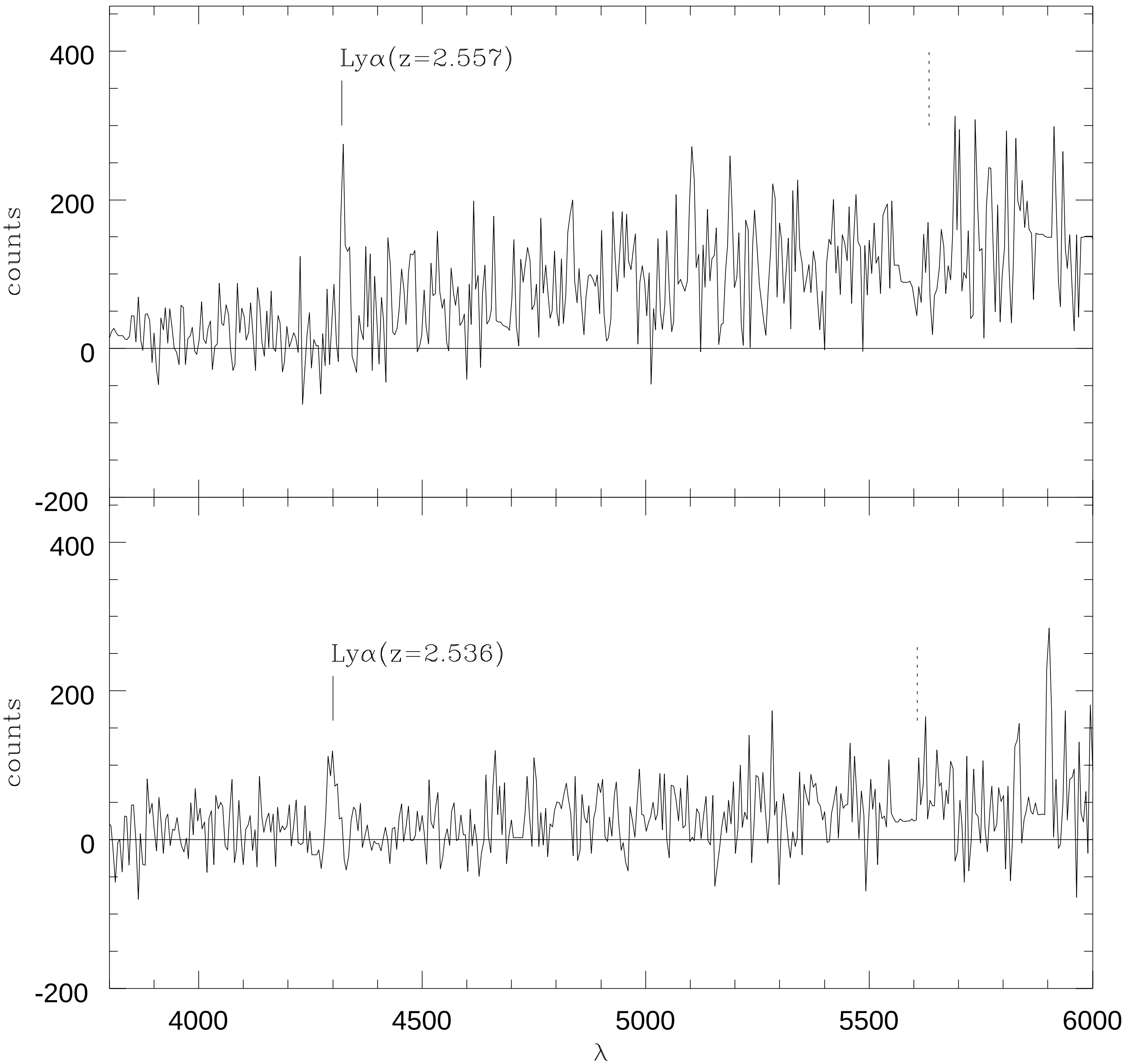
Object	α (J2000)	δ (J2000)	B	$B - B_M$	$B - I$	z
Q1	13 12 15.3	42 39 00	18.57	0.75±0.01	0.66±0.01	2.561
Q2	13 12 22.4	42 38 14	21.19	0.69±0.01	1.57±0.01	2.561
Q3	13 12 39.4	42 29 40	20.54	0.79±0.01	0.73±0.01	2.501
G1	13 12 25.1	42 37 23	24.38	0.75±0.09	0.28±0.33	2.557
G2	13 12 11.6	42 39 06	24.67	1.15±0.10	1.00±0.21	2.536



2
1
0
−1
B−B_M
Q1
Q3
Q2
G2
G1
18
20
22
24
26
B_tot



Lyα(z=2.501)
CIV
1.5×10⁻¹⁶
10⁻¹⁶
5×10⁻¹⁷
0
counts
4000
4500
5000
5500
6000
λ



Lyα(z=2.557)
400
200
0
-200
counts
Lyα(z=2.536)
400
200
0
-200
counts
4000
4500
5000
5500
6000
λ