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THE EXTENT OF NEBULAR EMISSION ASSOCIATED WITH THE $z = 0.525$ ABSORBER NEAR AO 0235+164

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ABSTRACT

Direct imaging results with V, R, and [O II] (FWHM = 15.6 Å) filters in good seeing ($\sim 0\farcs8$) are reported for a $80'' \times 80''$ field centered on AO 0235+164. Redshifted [O II] λ3727 emission ($z = 0.525$) totaling $9.2 \pm 0.6 \times 10^{-16}$ ergs cm^{-2} s^{-1} ($4 \times 10^{41} h^{-2}$ ergs s^{-1}, $H_0 = 100h$ km s^{-1} Mpc^{-1}) extends over an oval region $\sim 6'' \times 4'' \approx (20h^{-1}$ kpc$)^2$. The light distribution in all filters appears to have at least two distinct peaks, one near the previously known $V = 21$ object 2″ south in projection from AO 0235+164, the second $1\farcs3$ E of AO 0235. We report the detection of 1.4×10^{-16} ergs cm^{-2} s^{-1} in emission at the same wavelength 26″ ($100h^{-1}$ kpc) SW of the BL Lac in projection. Assuming the BL Lac itself is cosmologically distant, we consider emission from an active galactic nucleus, shock heating, and emission from large associations of hot young stars to be possible ionization mechanisms, the latter two more likely than the former based on Cohen *et al.*'s measurement of a relatively low [O III]/Hβ($\sim$3) combined with the large extent of the [O II] region. We note that an interacting system is consistent with the data on the $6'' \times 4''$ object.

Subject headings: BL Lacertae objects — galaxies: interactions — galaxies: nuclei — galaxies: structure — quasars

I. INTRODUCTION

A survey of [O II]λ3727 emission associated with moderate redshift ($0.4 < z_{\rm abs} < 1.2$) quasar and BL Lac absorption systems is underway. Motivation for the survey is the idea that the large velocity spreads seen in many Mg II and C IV absorption systems, which are difficult to explain with lines of sight through rich clusters or quiescent galaxy haloes, may be related to star-forming activity (York *et al.* 1986). If [O II] is not found, limits on [O II] surface brightness at $0.4 < z < 1.2$ imply limits on high-mass star formation at moderate redshift, with methods similar to the high z Lyα searches (Koo 1986; Pritchet and Hartwick 1987). Low surface brightness limits are important for cold dark matter models which predict galaxy formation to occur quite recently or to be on-going (Baron and White 1987; Silk and Szalay 1987). Oxygen line emission is not directly indicative of primordial metallicity in the interstellar medium. In regions where star formation is on-going, however, enrichment is inevitable on time scales of 3×10^7 yr through supernovae of massive stars followed by cooling and mixing of the processed gas. The survey therefore amounts to a search for galaxy formation at $0.4 < z < 1.2$.

Objects for the survey are selected based on the existence of a well established quasar or BL Lac metal line absorption system (usually Mg II $\lambda\lambda$2796, 2803 plus at least one other line). There are only $\sim$40 such systems in the correct z-range for ground-based [O II] observation known (Hewitt and Burbidge 1987), although the number is growing. A QSO field with radius $\sim 1'$($250h^{-1}$ kpc at $z = 0.5$; $H_0 = 100h$ km s^{-1} Mpc^{-1}, $q_0 = 0$ used throughout) is imaged in [O II] at the absorber redshift using narrow-band imaging techniques. Fabry-Perot interferometry (York *et al.* 1989), an array of packed optical fibers (Yanny *et al.* 1989), and 7–15 Å narrow band interference filters (Yanny *et al.* 1987) have all been tried; the best results were obtained with the latter. Once emission patches are found, the redshifts must be confirmed spectroscopically.

The heavily studied BL Lac object AO 0235+164 met the criteria for study. It is especially interesting since previous work (Smith, Burbidge, and Junkkarinen 1977, hereafter SBJ) revealed the presence of emission in a nearby galaxy with $z_{\rm em} = z_{\rm abs} = 0.525$. The BL Lac object itself recently revealed faint emission lines at $z = 0.95$ (Cohen *et al.* 1987), and in the following discussion we assume the BL Lac is cosmologically distant from the system at $z = 0.525$. The same paper also showed [O II] and [O III]λ5007 at $z = 0.525$ in a slit 2″ away from the small galaxy, from which the authors concluded the [O II] emission might be an extended patch, more than 3″ in size.

We present here the full spatial extent of the [O II] emission down to $S([\text{O II}]) \gtrsim 3 \times 10^{-17}$ ergs cm^{-2} s^{-1} arcsec^{-2} in sub–arc second seeing as well as deep V and R frames of the $80'' \times 80''$ field. A subsequent paper on a larger sample of objects will discuss other detections, limits on [O II] point sources, as well as large-scale diffuse, low surface brightness limits in the context of the galaxy formation (Yanny 1989).

II. OBSERVATIONS

Images of the field centered on AO 0235+164 were recorded on the nights of 1987 October 25–27 (UT) using a Texas Instruments 800 × 800 CCD (TI3) mounted at the Ritchey-Chretien (RC) focus of the Mayall 4 m telescope at Kitt Peak National Observatory. The CCD was mounted to the structure originally used for the Video Camera instrument. V, R, and

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narrow-band circular filters ($d = 5$ cm) were loaded into one of two filter wheels located 8 and 13 cm above the CCD. The narrow-band filter was at 5684 Å with a FWHM of 15.6 Å, corresponding to a reasonable search width for an [O II] line at 3727 Å $(1 - z)$, $z = 0.525$. The FWHM of the [O II] filter was chosen to allow for possible uncertainty in the redshift of the [O II] ($\Delta z = 0.001$) and possible velocity spreading of the doublet ($\lambda\lambda$3726.1, 3728.8). We used the detector TI3 in 400 × 400 pixel format (1 pixel = 30 μm) at the RC focus of the 4 m, yielding a scale of 0″.196 arcsec pixel^{-1}. In the best seeing images were $\lesssim$0″.8 FWHM. Seeing varied from 0″.75–1″.4.

Six exposures of 300–900 s in *R*, two of 300 s in *V*, five of 3600 s in [O II] were taken along with bias, dark, flat, and flux standard frames. Listed in Table 1 for each exposure of the AO 0235+164 field are the image index, filter used, exposure time, zenith distance in degrees, FWHM of field object S1 (see Fig. 1) as an indicator of seeing, estimated extinction due to clouds, date of exposure, and median actual detected units (ADUs), with 1 σ deviations, read out of the CCD per sky pixel.

Exposure times for the [O II] frames were determined by requiring sky counts to be above ~200 photoelectrons (e^-/ADU = 4) to avoid charge transfer problems upon readout. No preflashing was done. Overall system throughput for all filters is estimated at 16%. This is lower than the ~25% efficiency expected with only four elements (primary, secondary, filter, and CCD) in the optical system.

To aid in further discussion, objects noted below and in Table 2 are labeled in Figure 1, which shows the median of three 300 s *R* band exposures in 0″.8 FWHM seeing, reaching $R \sim 24$. Objects are denoted as follows: AO, the BL Lac object; A, the bright object 2″S of AO; A1 (not marked in figure), a new feature ~1″.3E of AO; B, red object ~6″ from AO; C, extended object with strong emission line; and D, D1, E, S1, and S2. D1, 18″ East of D, is not marked on Figure 1.

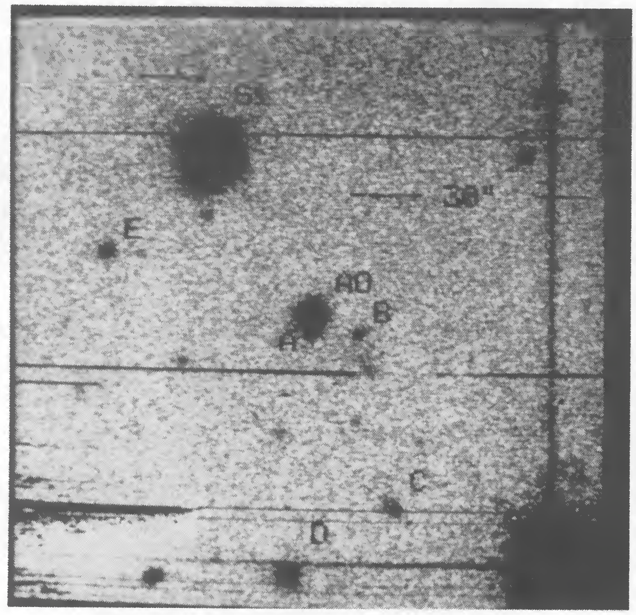

FIG. 1.—AO 0235+164 field. North is up, and east is to the left. Fig. 1 shows the median of three 300 s *R* band exposures. Limiting mag is ~24. Contrast is enhanced to bring up faint objects, which blurs distinction between AO and A, although seeing is good enough to clearly resolve objects and is apparent on a lower contrast print. Labeled objects are referred to in the text and Table 2. A1 is 1″.3E of AO, D1 is the object 18″E of D.

III. REDUCTIONS

a) *Photometry*

Our goal in reducing the data was to average the individual frames of AO 0235+164 taken with the [O II], *V*, and *R* filters, then to take properly normalized differences, [O II] − continuum, which would highlight the line emitting regions. The method of choice is to take multiple shorter exposures (limited by read noise), shifted by a few arcseconds between frames, which can then be registered and medianed to clean cosmetic defects and increase signal to noise. Several problems prevented us from carrying out reductions in this straightforward manner.

The primary difficulties encountered were highly variable observing conditions due to passing clouds. Extinction, assumed to be uniform across the 1′ field, ranged from 0 to 1 magnitudes. Sky brightness, apparently due to reflected light from the clouds, varied by ~20%. Estimates of these effects are listed for each frame in Table 1. Of the several standard star

TABLE 1

EXPOSURES OF THE AO 0235+164 FIELD

Index	Filter	Exposure Time (s)	Zenith Distance	FWHM S1[a]	Extinction Clouds[b] (mag)	Time (1987 October UT)	Sky ADU e^-/ADU = 4
a	V	300	24°	0″.76	0.3	27.378	319 ± 7
b	V	300	27	0.73	0.0	27.391	318 ± 7
c	R	900	16	2.1:	0:	26.311	1706 ± 16
d	R	400	29	1.3	0.1	26.398	721 ± 11
e	R	400	30	1.4	0.3	26.403	734 ± 8
f	R	300	15	0.81	0.0	27.324	544 ± 9
g	R	300	16	0.78	0.1	27.327	541 ± 8
h	R	300	16	0.77	0.3	27.331	546 ± 9
i	5684/15	3600	21	0.93	0.6	25.357	59 ± 6
j	5684/15	3600	25	1.4	0.5	26.266	60 ± 4
k	5684/15	3600	16	1.0	0.5	26.338	61 ± 3
l	5684/15	3600	20	0.84	0.0	27.281	48 ± 3
m	5684/15	3600	16	0.81	0.8	27.336	57 ± 5

[a] A measure of seeing quality.

[b] Estimate assuming most counts from object S1 implies minimal clouds for each filter.

TABLE 2

OBJECTS IN THE AO 0235+164 FIELD

Identifying Object Name (1)	$\Delta\alpha$[a] (2)	$\Delta\delta$ (3)	[O II] mag k/l/m[b] (4)	V mag ND/a/b[b] (5)	R mag e/g/h[b] (6)	$V-R$[c] (7)	Flux [O II][d] (8)	Shape (9)
AO	0″	0″	17.81/18.15/18.15	ND[e]/18.56/18.56	18.04/18.53/18.57	+0.0	9.2 ± 0.6[f]	...
A	0.2	−1.9	19.9/19.7/19.8[g]	ND/21.0/20.9[g]	21.4/21.2/21.2[g]	−0.3	4.5[g]	V, point-line R, extended
A1	1.3	−0.5	20.5/20.8/20.8[h]	ND/22.2/22.4[h]	ND/22.5/22.6[h]	−0.2:	2[h]	extended: EW
B	−5.9	−2.4	22.4/22.4/23.0:	ND/23.1/23.2	22.5/22.4/22.2:	+0.8	0.3 ± 0.6	extended
C	−10.3	−23.4[i]	21.0/21.3/20.9[j]	ND/22.2/22.1	22.2/22.2/22.2	−0.1	1.4 ± 0.6	elongated: NE
D	1.7	−33.3	20.4/20.5/20.4	ND/20.5/20.5	20.6/20.4/20.3	+0.1	0.2	extended
D1	18.7	−34.4	ND/21.1/21.3[k]	ND/20.7/21.0	21.1/21.1/21.1	−0.2	−0.6[k]	point-like
E	26.2	6.5	21.6/21.1/21.1[k]	ND/21.5/21.4	21.4/21.1/21.3	+0.3	0.6[k]	point-line
S1	13.5	19.5	14.96/14.96/14.96	ND/14.96/14.96	15.00/15.00/15.00	−0.04	0[l]	point-like

[a] BL Lac R.A. $02^h37^m58^s$, Decl. 16°33′48″ epoch 1987.8; positional errors: ±0″.2.
[b] Image index in Table 1.
[c] Add +0.2 for Johnson system colors.
[d] Flux units: 10^{-16} ergs cm^{-2} s^{-1}.
[e] ND: No data taken or magnitude unmeasurable.
[f] Includes all [O II] flux within 4″.8 of AO.
[g] Flux within 1″.8 of object A, excludes flux directly over BL Lac—see text.
[h] Flux within 1″.5 of object A1, excludes flux directly over BL Lac—see text.
[i] Position of [O II] centroid; V offsets are −11″.1, −24″.3.
[j] Bad CCD column makes measurement difficult.
[k] [O II] mags affected by dark leak (*see text*).
[l] [O II] flux is normalized to V flux.

frames obtained through the [O II] filter, clouds prevented the use of any for photometric calibration of the [O II] frames independent of the V band exposures. Since the BL Lac object itself is highly variable, we could not use its continuum flux to normalize individual frames.

Additionally, the TI3 chip suffered from several cosmetic defects (bad columns) and had a dark current "leak," perhaps due to light from an amplifier LED (G. Jacoby, private communication) which affected the leftmost 75 rows and especially the SE corner of the chip. This is most apparent on the 3600 s [O II] exposures, but can also be seen in the R band exposure in Figure 1. These were only partially compensated for by subtraction of dark exposures of the same length. This increases the uncertainty in the photometry of D1 and E.

Aware of these problems, we proceeded as follows: all frames were bias subtracted and flat fielded. A scaled dark exposure was subtracted from each [O II] frame before flat fielding. Viewing each frame by eye, we marked all objects that appeared to be significantly above sky noise. There were ∼15 objects on the best [O II] exposures and ∼30 objects on any V or R band frame. The images of point sources corresponded to at least 4 pixels linearly, making it easy to identify 1–2 pixel radiation events, which were removed near objects of interest by interpolation with nearby sky pixels. All reductions were done with IRAF.[3]

Magnitudes of faint objects ($V > 20$) were then measured by first subtracting a single sky value determined by a modal average in a 2″ annulus with an inner radius of 2″–3″ centered on the object. Counts were then summed within a circular aperture of radius 1″.2–2″.0 again centered on the object. Judging from the point spread profiles in row 1 of Figure 2 (central contour shows approximate FWHM), the small apertures underestimate total flux by less than 10% for point sources. For the bright objects (AO and S1), an aperture of radius 4″.8 was used with an appropriate sky annulus.

Observations of the standard star Feige 25 taken through the V and R filters during reasonably photometric conditions on 1987 October 27 were used to absolutely calibrate the two V and R frames listed as b and f, respectively, in Table 1. Frames b and f were also taken during reasonably photometric conditions. The bright field star, S1, assumed not to vary in magnitude, was used to relate all other V and R frames to this standard. This normalization was done independently for the V and R filters. Since the center of the redshifted [O II] filter at 5684 Å is near the center of the V band at 5556 Å and since no good (cloudless) standard star frame through the [O II] filter was recorded, we normalized the [O II] magnitude of S1 to the V magnitude, which should be a reasonable approximation unless the bright star has a strong absorption or emission feature at 5684 ± 8 Å. Other $V = 20$–22 objects in the field were used to verify this relative normalization.

Objects which appeared in more than one [O II] exposure and had a repeatable [O II] magnitude significantly greater than sky noise ($>5\ \sigma$) are listed in Table 2. Table 2 lists in column (1), identifying object name corresponding to the labels in Figure 1; columns (2) and (3) positions relative to the BL Lac; in columns (4)–(6) [O II], V and R magnitudes (on the system described in Oke and Gunn 1983) in good seeing on October 26 and for two independent exposures on October 27 to indicate possible photometry problems and measurement errors. Column (7) lists $V-R$ colors ($V-R$[Vega] $= -0.2$ in this system); column (8), excess [O II] flux determined by magnitude difference relative to V (using an [O II] bandpass of 15.6 Å); and column (9) the shape of the objects (point-like, extended, or elongated). The small positive (negative) fluxes for objects D, D1, and E, if we assume they are without emission, indicate the accuracy of our normalization to S1 and limit our sensitivity to [O II] emission from point sources to $F([\mathrm{O\ II}]) > 6 \times 10^{-17}$ ergs cm^{-2} s^{-1}. We note that the errors were only this great for objects D1 and E, both located in the

[3] IRAF is distributed by National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract to the National Science Foundation.

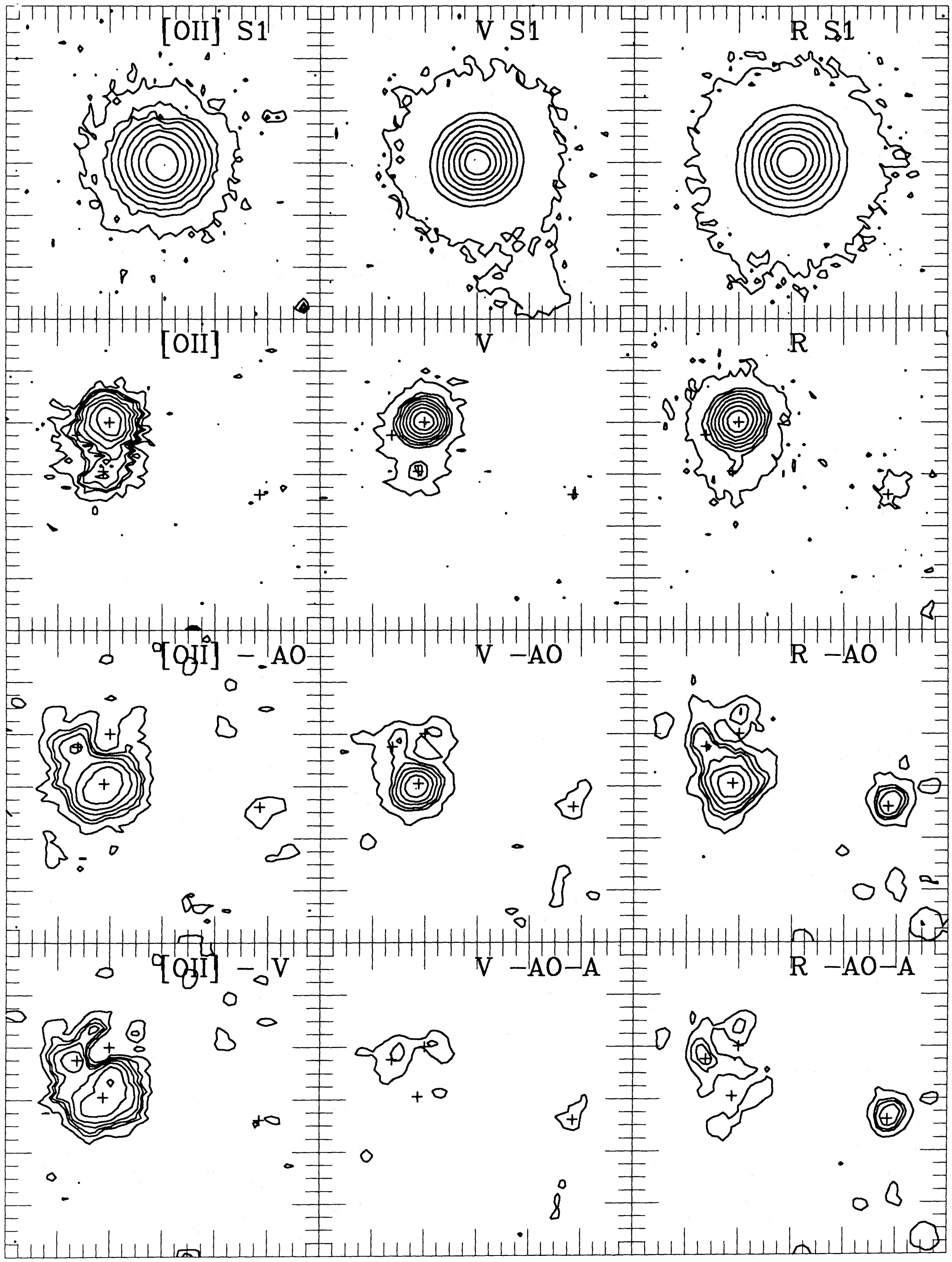

FIG. 2.—North is up, and east to the left in each 12″ × 12″ cell. Column one is [O II] data. Columns two and three are V and R, respectively. Row one is object S1, a $V = 15$ field star used for profile subtraction. Central contours indicate FWHM. The extension SW of the V image is a $<1\%$ ghost. Row two shows AO 0235+164 and the object 2″S before subtraction. In row three the BL Lac has been subtracted off using S1 and normalizing to peak flux (*see text for details*). Total excess [O II] flux is $9.2 \pm 0.6 \times 10^{-16}$ ergs cm^{-2} s^{-1}. Note the appearance of the third object, A1, 1″.3E of AO 0235 and the oval distortion of the [O II] at A. In row four, a stellar profile has been subtracted from A, except in the [O II] case where all the V (continuum) light has been removed. Rows 3 and 4 have been boxcar average smoothed 4 × 4 pixels (0″.8). Crosses fix positions of AO, A, A1, and B in the last three rows for reference. Outer contours are at sky $+2.5\ \sigma$ (sky noise). Contours are plotted in 50% increments except for row one, where the increment is 100%.

region of the chip affected by poor dark subtraction; for other objects, the errors are considerably less. Since this error is greater than the random error on the individual magnitudes, we adopt this as our conservative error bar on total [O II] flux.

As is apparent from frames k and l and e and g in the first row of Table 2, we observed a ~0.4 mag drop in the [O II](V) and R continuum flux from AO 0235+164 between 1987 October 26.4 and October 27.3 (UT). Lower quality October 26 magnitudes are listed in Table 2 for [O II] and R exposures (no V were taken that night) only to demonstrate that AO 0235+164 varied in magnitude during this 24 hr period; [O II] flux measurements made on October 27 do not depend crucially on these earlier exposures.

b) Profile Subtraction

In order to look for structure less than 2″ from the $V \sim 18.5$ BL Lac (object AO), the field star S1 ($V = 15$) served as our point spread function model. It was normalized so that its peak surface brightness matched the peak of the BL Lac after sky subtraction. Assuming the BL Lac to be a point-source, this normalization procedure is conservative, tending toward over-subtraction if there is an underlying galaxy at $z < z_{\rm BL\ Lac}$. If the BL Lac was not point-like, then a rim would have been left following the subtraction. Using a fractional pixel shifting algorithm, we aligned S1 to the centroid of the BL Lac in each case ([O II], V, and R) and subtracted the former from the latter frame by frame. As a test of the procedure, object S1 was also peak fitted to object E ($V = 20$) and subtracted with the resulting residuals insignificantly above sky noise. The deep linear wells of the CCD make such a good subtraction between two stars of differing magnitude possible. Object S2 could not be used as a profile star as it was saturated on the V and R frames. Peak count levels of object S1 suggest that nonlinearities may affect the central 1″ on V and R frames (resulting in oversubtraction of the BL Lac wings), although the effect is not noticeable when removing object E. Objects D, D1, and E, at $V \geq 20$ have too low a signal-to-noise ratio to use as a point-spread profile. A filter ghost, apparent in the V image of S1 (see Fig. 2), is at the 1% level and does not affect any of the subtractions. A good centroid is crucial, and a misshift by as little as 0.5 pixel (0″.1) resulted in the familiar hill and ditch residual. We also subtracted a stellar profile from object A, 2″S of AO.

Figure 2 shows the results of the various subtractions. The size of each box is 12″ × 12″. The top row shows S1, the field star, for the best-seeing, lowest extinction frames of [O II], V and R. These correspond to Table 1 images indices l, b, and g, respectively. The contours are in steps of factors of 2 with the outer contour at sky + 2.5 σ (sky noise) and the inner contour at approximately FWHM. The second row shows AO 0235+164, unsmoothed. The third row shows the 0″.8 × 0″.8 smoothed residual after S1 has been subtracted from the BL Lac. The crosses mark the positions of AO, A, A1, and B, and are fixed from cell to cell for reference. In each cell in rows two through four the outermost contour is at mean sky + 2.5 σ, the remaining contours are spaced so that there is an equal number of contours in the cells across any given row from sky to peak with a 50% surface brightness increment between successive contours. In the fourth row, the V and R cells show the residual after object A has additionally been subtracted from the box above using the same technique of scaling the point-source profile of object S1 to that of object A and subtracting. After the subtraction, these images are smoothed 0″.8 × 0″.8 as well. In these two cells, since a peak is poorly defined, contour levels are identical to those in the cell directly above.

The lower left-hand cell labeled "[O II] − V" was processed differently. In this case, the V band image of AO 0235+164 (row two, column two) was convolved with various Gaussian profiles until the FWHM of the V band approximately matched that of the [O II] band (row two, column one). Then the V was normalized to the [O II] based on exposure times and filter widths and subtracted from the [O II] image. The smoothed result is shown, with contours plotted as in row three. This is perhaps the simplest way to see the extent of the excess [O II] flux. We performed two checks on this alternate subtraction procedure. First, we subtracted S1 (V band) from S1 ([O II] band) with the same normalizations and Gaussian profiles and achieved residuals of 5% of S1 flux, indicating our subtraction is good on the BL Lac to magnitudes ~22. Second, we subtracted an [O II] profile point source (S1) from A and A1 (marked by crosses in row three, column one), normalized to the V continuum flux present in row three, column two. That is, we subtract most of the remaining continuum light off of the cell shown in column one. The contour map for this operation (*not shown*) is nearly identical to that shown in the lower left-hand corner of Figure 2, as one would expect.

The [O II] − V technique has the advantage of correcting for all continuum light from both point source and extended objects, provided the point-spread profiles of the respective frames can be properly matched. On the other hand, since a suitable profile star, S1, was available in the same field as AO 0235+164, the method of subtracting off point sources using S1 avoided the need to accurately model the point spread function.

It is apparent from the lower left-hand cell of Figure 2 that there is an extended source of [O II] emission. At our resolution, the [O II] has at least two distinct peaks: the first is near A, but does not exactly coincide with it as is apparent from the oval distortion of the [O II] in cell [O II] − AO. The second is at A1. This object is certainly real, as it appears in independent subtractions where a systematic centroiding error is unlikely. As we may have slightly oversubtracted AO by normalizing to the peak, A1 could actually be the Eastern extent of a large object extended completely over the BL Lac.

We attempted a subtraction of the V image from the [O II] image with the normalization set so that all the excess [O II] flux (as measured from the unsubtracted [O II] and V images) remained on the subtracted images, eliminating over-subtraction, but less conservative because of the variability of AO. The contour map from this procedure, not shown, closed the contours just NW of AO smoothly, but left A1 as a distinct peak in [O II] surface brightness. That is, in the contour maps shown, A1 is not an artifact of the oversubtraction of AO.

At our resolution, [O II] surface brightness at A and A1 is $\sim 3\text{–}8 \times 10^{-17}$ ergs cm^{-2} s^{-1} arcsec^{-2} over a region ~6″ × 4″. The rest frame [O II] equivalent widths at A and A1 are 20 ± 5 Å and 30 ± 10 Å, respectively. Object B is included in Figure 2 and Table 2, because of its proximity to AO and its very red color compared to the rest of the field. Its [O II] excess is below our stated detection limit.

Figure 3 shows the patch (object C) 26″SW in the V, R, and narrow-band filters, smoothed to 0″.8. The centroid of the emission is ~1″NE of the V centroid. Contamination by a bad column (running E–W) is most apparent in the R band frame and makes estimated fluxes uncertain. No spectroscopic data is yet available to confirm that the excess in the 5684 Å exposure

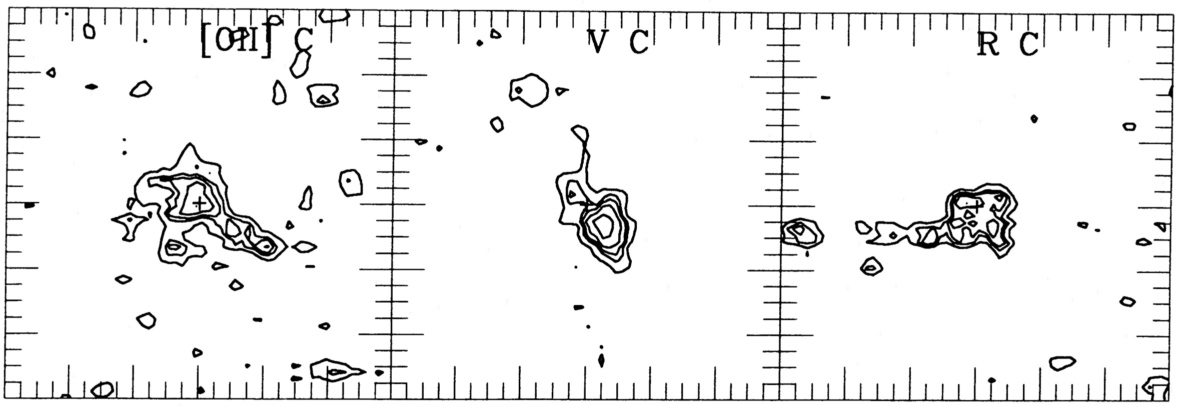

FIG. 3.—North is up, east left in this 12" × 12" view. This shows 5684 Å, V, and R (with obvious bad column running E–W) contour maps of the claimed emission object C, 26"SW of AO 0235+164. Maps have been boxcar average smoothed 4 × 4 pixels (0".8). Total excess emission is $1.4 \pm 0.6 \times 10^{-16}$ ergs cm^{-2} s^{-1}. Note emission and continuum (V) centers do not exactly coincide. The cross is a registration mark.

is really [O II], though the chance of accidently finding an emission line at 5684 Å in a 15 Å filter from a redshift other than $z = 0.525$ is extremely small, as discussed below.

IV. DISCUSSION

a) *The Object at z = 0.525*

The main result of this work is the delineation of a $(20h^{-1}$ kpc$)^2$ region of [O II] emission at $z = 0.525$ with total line flux of $9.2 \pm 0.6 \times 10^{-16}$ ergs cm^{-2} s^{-1} (L[O II] $= 4 \times 10^{41}h^{-2}$ ergs s^{-1}), in rough agreement in shape and in total flux with that inferred by Cohen *et al.* (1987), based on their independent slit spectra (E–W oriented) at AO and at A. Subtraction of a point-source profile from the BL Lac reveals a previously unnoticed galaxy, A1, with $V \sim 22.4$, located 1".3E and 0".5S of AO. This could be the galaxy responsible for the BL Lac absorption system at $z = 0.851$ (Burbidge *et al.* 1976). The fact that the [O II] $z = 0.525$ emission has a local peak at approximately the same spot suggests, however, that A1 is at $z = 0.525$. Since our subtraction of the BL Lac profile was conservative in the sense of slight oversubtraction, galaxy A1 probably extends to the west, directly overlapping the BL Lac (as it must if it is responsible for the 21 cm and metal line absorption features seen). Some [O II]λ3727 flux is directly over the BL Lac, and some exists in the region beyond the apertures used in measuring magnitudes near A and A1. This accounts for $\sim 3 \times 10^{-16}$ ergs cm^{-2} s^{-1} in [O II] that is seen in the AO entry in Table 2, but is not seen when the Table 2 fluxes for A and A1 are added.

An important issue is the nature of object A. It is an unresolved point source ($V = 21$, $V - R = -0.3$) in the V band image with best seeing 0".75, although Figure 2, cell $R - \mathrm{AO} - \mathrm{A}$, shows evidence for an underlying galaxy. Is the point source an AGN? Cohen *et al.* (1987) measure an [O III]/Hβ ratio of ~3–4, which, when combined with a low [O III]/[O II] ratio ~3 right at object A (SBJ) and an even lower ratio 2" north, [O III]/[O II] ~ 0.6, suggests photoionization by OB stars rather than a hard power-law continuum source (Baldwin, Phillips, and Terlevich 1981).

Shuder and Osterbrock (1981) list emission-line fluxes for galaxies with active nuclei. Their Seyfert 1 and narrow emission line galaxies, with [O III]/H$\beta \lesssim 3$ and emission line FWHM $\lesssim 300$ km s^{-1}, have [O II] luminosities 5–10 times smaller than the total [O II] luminosity observed at objects A and A1. Comparing the line ratios and fluxes as measured by SBJ at object A with galaxies listed in Table 2 of Shuder and Osterbrock (1981), the closest match is with Markarian 833. We cannot exclude the possibility that object A is a luminous AGN. We doubt, however, that the Strömgren sphere of such an AGN ($M_B = -22$ for $h = 0.5$) could photoionize all the [O II] seen in the $(20h^{-1}$ kpc$)^2$ region, especially toward A1, given reasonable assumptions about the electron density distribution.

Spinrad (1982), has found optical counterparts to several distant radio galaxies which show huge [O II] luminosities, up to $\sim 1.5 \times 10^{43}h^{-2}$ ergs s^{-1}. These [O II] lines are quite broad, however, ~800 km s^{-1}, compared with 300 km s^{-1} seen by Cohen *et al.* (1987) near A and AO at $z = 0.525$. We do not know of any radio emission from the objects at $z = 0.525$. It is, of course, difficult to distinguish it from radio emission from the BL Lac itself.

Gallagher, Bushouse, and Hunter (1989) have calibrated [O II] in terms of Hβ in nearby luminous blue galaxies. If the [O II] flux is due entirely to "H II regions" we can estimate an Hα flux, $f(\mathrm{H}\alpha) \sim 1.1 \times f([\mathrm{O\ II}])$, assuming photoionization and little reddening. The number of recombining photons then implies a star formation rate for massive stars ($M > 10\ M_\odot$) which can be extended to a global star formation rate by assuming an initial mass function. For a Salpeter IMF, this yields a SFR of $3h^{-2}\ M_\odot$ yr^{-1}. This compares with 1–$2h^{-2}$ $M_\odot$ yr^{-1} on the same system for Sc galaxies (Kennicutt 1983; Hunter and Gallagher 1986). The rest frame equivalent widths of [O II], 20–30 Å at A and A1, are comparable to those of blue $[(B-V)_{\rm rest} < 0.5]$ spirals (Dressler and Gunn 1982).

We would like to use the V and R colors near A and A1, which appear to be at least as blue as A stars (uncorrected for reddening), to indicate what stellar population may be present. The V band is contaminated by the redshifted [O II] line, but our [O II]$-V$ magnitude difference would have to be ~2 (W_λ[O II] ~ 80 Å) before a line correction would be significant at the ~10% level since the V band is ~60 times broader than the [O II] band. Since that is not the case for our objects here, we have made no line corrections. As [O III]+Hβ could be several times the strength of [O II], the situation in the R band is slightly more uncertain. As has been noted several times, reddening is also probably important given the large H I mass and the red color of AO itself (Snijders *et al.* 1982); this makes it difficult to infer stellar populations. The colors of A and A1 are blue, spectral types A0V, and if reddened, even bluer. Based on $M_B = -21 + 5 \log h$, objects A and A1 could contain $10^9\ M_\odot$ in hot young stars ($M \gtrsim 2.5\ M_\odot$) and have total stellar mass greater than $10^{11}\ M_\odot$. Koo (1985) predicts colors of spiral-type galaxies to be no bluer than $V-R = +0.4$ at $z = 0.5$. If A+A1 is a galaxy forming stars, and there is no AGN present, then few stars have had time to evolve into red giants.

AO 0235+164 shows 21 cm absorption, $N(\text{H I}) = 3 \times 10^{21}$ cm^{-2} (Roberts *et al.* 1976; Wolfe, Davis, and Briggs 1982). If we assume the extent of the H I is as great as that of the [O II] $(20h^{-1}$ kpc$)^2$, the estimated H I mass is $\sim 10^{10}h^{-2}\ M_\odot$ or greater.

Could A and A1 be a galaxy-galaxy interaction? Bushouse (1987) lists global properties of interacting galaxies. The shape and size are not inconsistent. Interacting galaxies show large IR fluxes. AO 0235+164 itself is a continuum source over a wide range of frequencies, including the IR. Although it is not listed in the IRAS Point Source Catalog (1985), careful inspection of the *IRAS* sky plates shows a IR flux of ~ 0.1 Jy at 60 μm. Although we can't distinguish between the IR flux of AO and that of A+A1 at $z = 0.525$, if even 10% of it were due to A or A1 the inferred $L_{\rm IR} = 10^{44}h^{-2}$ ergs s^{-1} is typical of an interacting region (Bushouse 1987).

Takahara *et al.* (1987) have searched for CO $J = 1$–0 absorption at $z = 0.525$. They place an upper limit on $N(\text{CO})/N(\text{H I}) < 3 \times 10^{-7}$, or 1/10 the galactic value. This would argue against large star-forming molecular clouds, but only over the projected area ($\lesssim 10^{-4}h^{-2}$ kpc^2) intercepted at $z = 0.525$ by the compact radio continuum source AO 0235+164 at $z = 0.95$ (Wolfe, Davis, and Briggs 1982).

Certainly better spectra, which permit separating the [O II] doublet, and measuring [O III]λ4363 to get temperatures and densities could help to resolve the nature of the $z = 0.525$ system. Most useful would be data on a line sensitive to shock ionization mechanisms, such as [S II] $\lambda\lambda$6713, 6731 or Hα+[N II], but these unfortunately are redshifted, with the exception of [O I]6300, longward of $\lambda = 1$ μm. The low [O III]/[O II] ratio ~ 0.6 in the spectrum of Cohen *et al.* (1987) at the AO position suggests that [O I]6300 might be detectable.

Although 21 cm emission at $z = 0.525$ is probably not detectable (or would be swamped by signal from AO 0235 itself), recently, Bothun *et al.* (1987) have detected a large, low surface brightness galaxy with $M(\text{H I}) = 10^{11}\ M_\odot$ and (only nuclear) [O II] emission at $z = 0.083$. The optical disk of this galaxy is extended over $100h^{-1}$ kpc and would be lost in the sky noise at a redshift of 0.525. A search for extended H I, and deeper searches for emission line gas seem warranted in order to define the limits of star formation in an object of moderate redshift.

b) Speculation

Could [O II] emission regions such as the one examined here be common at high redshift? Koo and Kron (1988), in a spectroscopic sample of point-like objects with nonstellar colors complete to $J = 21$, find 15 narrow-line emission galaxies ([O II] or [O III]) at redshifts of $0.4 < z < 0.65$ in 0.3 deg^2, or 0.014 objects arcmin^{-2}. Extending this sample to resolved objects could increase the number of strong emission line galaxies by a factor of 10 (Kron 1980). Thus the chance (P_3) of finding an object with [O II] emission of $\sim 10^{-16}$ ergs cm^{-2} s^{-1} within 3″ of any given QSO or BL Lac can be as high as 1×10^{-3}. One needs a probability close to 1, certainly greater than 0.1, to explain the observed frequency of QSO absorption systems. Thus small point-like bright emission line objects such as those in the Koo and Kron sample and discussed here and in Yanny *et al.* (1987), then, could not by themselves explain the absorbers.

Object C is interesting because of its line emission, elongated morphology, and noncoincidence of V and narrow-line centroids. Spectroscopic confirmation must be made of the emission line at 5684 Å, but if it is [O II] produced by young hot stars, then one has to consider the possibility of large areas more than $(100h^{-1}$ kpc$)^2$ over which low-surface brightness star formation may be occurring at redshift < 1 as suggested by York *et al.* (1986) from absorption-line properties. The chance of finding an accidental emitting object (C) at some other redshift, 30″ from a known redshift object, is higher only by a factor of ~ 4 from that given above for P_3, or 4×10^{-3}, since one multiplies P_3 by a factor of 100 for relative area, $(30/3)^2$, by a factor of 5 because several emission lines ([O III], Hβ, and so on) might be detectable if accidently shifted to $\lambda = 5684$ Å, and by a factor of $1/125 = 0.002/0.25$ since the prescribed bandwidth (15 Å) corresponds to $\Delta z = \pm 0.001$. Therefore, object C is most likely to be [O II] as suggested above. If object C is spectroscopically confirmed to be at $z = 0.525$, it would be particularly valuable to measure QSO absorption lines within 30″ of AO but outside the emission patches, to look for gas of low metallicity at $z = 0.525$ yet uncollapsed into the main object (presumably A+A1). Unfortunately, from our broad-band images of the field, no QSO candidates with $V < 22$ are apparent.

Baron and White (1987) model a supposed primeval galaxy at $z = 1.8$, showing it to be 10″ × 25″ in extent containing several peaks with B surface brightness = 28 mag arcsec^{-2} surround by more diffuse regions at ~ 31 mag arcsec^{-2}. Although we have not worked out what these objects would look like in detail at redshifts as low as $z = 0.5$, a crude scaling yields objects of similar angular extent with V surface brightness of 25–28 mag arcsec^{-2}. Our broad-band exposures reached V and R limits of ~ 25 mag arcsec^{-2}, and only the brightest peaks would show up if a diffuse region such as this existed, extending over the ~ 30″ from A to C.

Does the existence of A, A1, and C at the same redshift indicate a large $\sim 100h^{-1}$ kpc galaxy coming together or separate systems, such as multiple AGNs in the same cluster? If there is an extended object 30″ between C and A+A1 and such objects are common then $P_{30} = 100P_3 \sim 0.1$ and such large objects may then be able to account for the QSO absorbers.

Note: While this paper was being refereed, an additional paper on the AO 0235+164 field has appeared (Stickel, Fried, and Kühr 1988, hereafter SFK) which is relevant to the present paper. SFK obtained a deep R band of the field and spectra of objects B and D1, among others. Their spectra detect [O II]λ3727 in object B at the level of $0.4 \pm 0.2 \times 10^{-16}$ ergs cm^{-2} s^{-1} (estimate from SFK, Fig. 3). This demonstrates that our error limits of 0.6×10^{-16} ergs cm^{-2} s^{-1} are quite conservative. The spectrum of object B is shown to be rising in the red and notably missing a 4000 Å break. This agreement, then, increases our confidence in the reality of the emission in object C, with 5 times the emission flux of object B.

SFK show an extended object with $R = 20.1$ superposed over the BL Lac at $z = 0.525$ (redshift based on Cohen *et al.* 1987) centered only 0″.5E of AO 0235+164. We measure A1 to have $R = 22.5$ within 1″.5 of its center, 1″.3 from AO 0235+164.

We point out that before subtraction of the BL Lac point source, AO 0235+164 showed a clear elongation to the East, and it is not obvious to us that, after subtraction, the "galaxy" should be so nearly centered on AO 0235+164, as SFK, Figure 2*c*, shows. The residual contours 3″NE of object A in SFK, Figure 2*d*, also suggest a nucleus at the position of object A1. We consider the subtraction operation difficult and sensitive to the profile normalization. We acknowledge that our subtraction procedure, normalizing to an object's peak, will oversubtract. If we sum the flux in the [O II], *V*, and *R* bands within 4″.8 of the location of A1 after subtraction of AO and A we measure magnitudes of 19.5, 21.4, and 21.3, respectively. SFK point out that object D1 is a galaxy at $z = 0.065$, and not a point source as we suggest in Table 2. We believe our measurement of D1 to be uncertain due to the CCD leak, as noted above.

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Note added in proof.—Medium resolution (2 Å) spectra taken with the KPNO 4 m on 1988 December 13–14 confirm the fact that object C is an emission-line object at $z = 0.525$. Redshifted ($z = 0.5248$) [O II] $\lambda 3727$ is detected 10″W and 25″S of AO0235+164 at a level of $6 \pm 1 \times 10^{-17}$ ergs cm^{-2} s^{-1} in a 1″ slit. The redshift is certain since Hβ $\lambda 4861$ was detected at 7413.3 Å ($z = 0.5251$) at a level of $2.6 \pm 0.4 \times 10^{-17}$ ergs cm^{-2} s^{-1} in a 2″ slit at the position of C.

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