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OPTICAL AND RADIO OBSERVATIONS FOR THE BL LACERTAE OBJECTS 1219+28, 0851+202, AND 1400+162

DONNA WEISTROP[1]
Laboratory for Astronomy and Solar Physics, NASA/Goddard Space Flight Center
DAVID B. SHAFFER
Interferometrics Inc., Vienna, Virginia
AND
PAUL HINTZEN[1] AND W. ROMANISHIN[2]
Laboratory for Astronomy and Solar Physics, NASA/Goddard Space Flight Center
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ABSTRACT

Radio and visible wavelength observations have been obtained for the BL Lacertae objects 0851+202 (OJ 287), 1219+28 (ON 231, W Com), and 1400+162 (4C 16.39, OQ 100). Spectra of 1219+28 show two emission features which give a redshift $z = 0.102$. No observations of emission or absorption lines have been reported previously for this object. Deep imaging of 1219+28 indicates the presence of an elliptical nebulosity underlying the point source. The observations are consistent with the nebulosity being an associated elliptical galaxy, while use of a spiral galaxy model for the nebulosity does *not* produce an acceptable fit to the luminosity profile. VLBI maps of 1219+28 at 2.3 GHz, 5.0 GHz, and 8.3 GHz show a central source plus a jet with at least three components. There is no obvious relationship between the orientations of the radio jet and the visible-wavelength nebulosity underlying the point source. Radio observations of 1400+162 were also obtained using the VLBI network. The map shows a nearly unresolved source, unaligned with the extended radio source seen in VLA maps. Imaging and photometry of 0851+202 (OJ 287) are also reported. The observations show no evidence of an underlying nebulosity.

Subject heading: BL Lacertae objects

I. INTRODUCTION

The study of BL Lacertae objects has been of interest for several years, to determine their nature and relationship to quasars and to galaxy evolution. Investigation of these objects has been hampered by one of their most marked identifying characteristics, the absence of strong lines in the spectrum. Without such features, it has been impossible to estimate the distance to these objects. With systematic investigation, several BL Lac objects have been found to show weak emission lines (Miller, French, and Hawley 1978*b*; see Hewitt and Burbidge 1980 for additional references), permitting an estimate of their distances, assuming the cosmological nature of the redshifts. Deep images of BL Lac objects, obtained with both photographic plates and electronic detectors, have revealed several of them to be superposed on elliptical nebulosities which often have the characteristics of galaxies (Miller 1981; Weistrop *et al.* 1981, hereafter W81; see also references in Weistrop, Smith, and Reitsema 1979).

Until recently, no classical double radio sources had been observed among BL Lac objects, consistent with the suggestion that the radio emission is due to a relativistic jet with the beam aimed almost directly toward the observer (Blandford and Rees 1978; Blandford and Königl 1979). Such a model explains many of the observations, including the extreme variability, changes in polarization, and shape of the radio and optical spectra. Browne has suggested that BL Lac objects occur in aligned elliptical radio galaxies (1983).

Based on the relativistic beaming model, any extensive radio structure in BL Lac objects should consist of a halo surrounding the radio core (Antonucci and Ulvestad 1984; Wardle, Moore, and Angel 1984). However, Very Large Array (VLA) observations have demonstrated that the BL Lac object 1400+162 is a fairly large (17″), bent triple radio source (Hintzen and Owen 1981; Wardle, Moore, and Angel 1984), while Antonucci and Ulvestad (1984) found at least two classical triple sources (1522+155 and 2208−137) and one radio-tail object (0548−322) in their survey of BL Lacertae objects. Such cases may strain the relativistic beaming model for the BL Lac objects *if* the particular objects involved exhibit the traits which the beaming model was invoked to explain. Light from the optical counterparts of 1522+155 and 2208−137 has been observed to be variably polarized, but neither object has been monitored for optical photometric variations (Antonucci and Ulvestad 1984). 1400+162 is strongly polarized (Angel and Stockman 1980) and may vary at optical wavelengths (Weistrop *et al.* 1983).

In this paper we report radio- and visible-wavelength observations for the BL Lac object 1219+28 (ON 231, W Com), optical observations of 0851+202 (OJ 287), and radio data for 1400+162 (4C 16.39, OQ 100). The data consist of imaging and surface photometry for both 1219+28 and 0851+202, as well as spectra for 1219+28 and Very Long Baseline Interferometry (VLBI) observations for 1219+28 and 1400+162. Two emission features have been observed in the spectrum of 1219+28. Radio observations of 1219+28 in three frequencies reveal the presence of a radio jet with at least three com-

[1] Visiting Astronomer, Kitt Peak National Observatory, National Optical Astronomy Observatories, operated by the Association of Universities for Research in Astronomy, Inc. under contract with the National Science Foundation.

[2] NAS/NRC Research Associate.

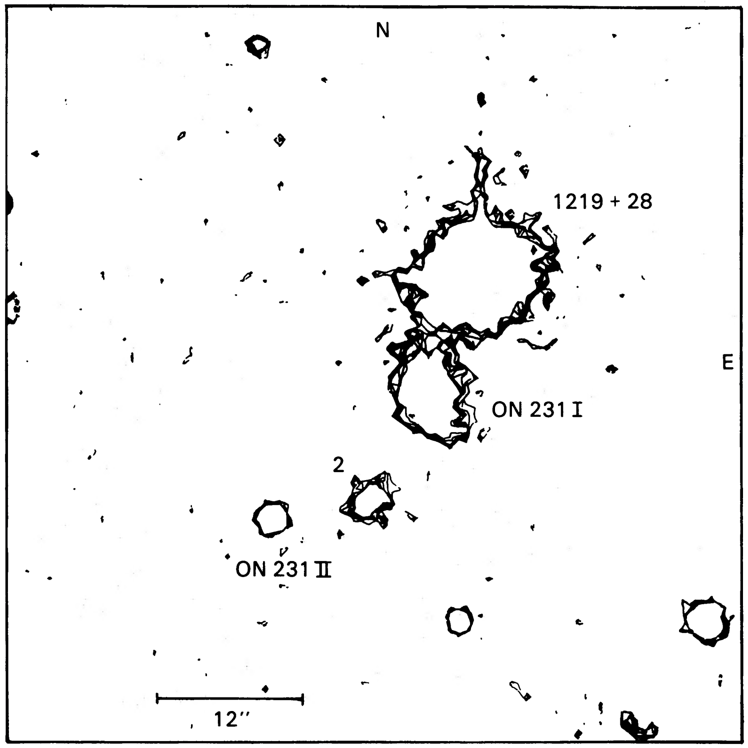

FIG. 1.—Contour map of a 1 arcmin^2 area surrounding 1219+28, taken from a 300 s red frame. Low-level contours are shown to illustrate the faint structure associated with the BL Lac object. Objects discussed in the text are labeled. There are several stars in the field, including ON 231 II, for comparison with the extended objects. Note that east is to the right.

ponents. At visible wavelengths we have resolved an elliptical structure underlying the bright point source. A preliminary report of the 1219+28 observations was given previously (Weistrop, Shaffer, and Hintzen 1984). The object 0851+202 is unresolved in our optical observations. At radio wavelengths 1400+162 has a compact core source which we find to be nearly unresolved.

II. SPECTROSCOPY

Three 30 minute spectra of 1219+28 were obtained on 1982 May 16 on the 4 m telescope at Kitt Peak National Observatory (KPNO) using the cryogenic camera with the 300 lines mm^{-1} grating (DeVeny 1982). A single long slit was placed so that spectra of both the BL Lac object and the nearby object ON 231 I (see Fig. 1) were obtained. The frames were corrected for bias, dark count, and pixel-to-pixel sensitivity variations using standard KPNO programs. The sum of the three spectra is shown in Figure 2, with the sky subtracted. The internal accuracy of the third-order fit of wavelength to pixel number is ± 1.6 Å, with a scale of approximately 4.3 Å pixel^{-1} and resolution of 14 Å FWHM. Several features in the spectrum are identified in Table 1, including remnants of strong night-sky lines which remained after the sky subtraction. The feature at 5890 Å may be a combination of remnant night-sky Na I emission and interstellar absorption. There are emission features at wavelengths 5519 and 7226 Å. The latter feature is located within an atmospheric OH band but appears to have significant flux after the sky subtraction has been performed. From the ratio of the observed wavelengths and lists of lines previously observed in BL Lac objects (Miller, French, and Hawley 1978*a*), the most probable identifications are [O III] $\lambda 5007$ and Hα $\lambda 6563$, giving a redshift of $z = 0.102 \pm 0.001$. The line at 5519 Å is narrow, while the feature identified as Hα is broad, as would be expected for these lines. The [N II] $\lambda 6584$ line has been observed in BL Lac (Miller and Hawley 1977), but our spectral resolution is insufficient to separate it from Hα if it is present. At $z = 0.102$, the [O III] $\lambda 4959$ line is blended with the Hg $\lambda 5460.7$ night-sky line. The small bump in the sky-subtracted spectrum could be due to remnant night-sky emission. There is no significant feature at the wavelength of redshifted Hβ, but this is not surprising in view of the weakness of Hα. The spectrum for ON 231 I is a very faint continuum with no obvious features.

If the 7226 Å emission feature is due to poor sky subtraction, we cannot rule out other possible identifications for the 5007 Å line. However, it is unlikely that the redshift is greater than $z = 0.45$, because of the presence of the extended underlying nebulosity (Malkan, Margon, and Chanan 1984). The observed

TABLE 1

FEATURES IN 1219+28 SPECTRUM

Identification	λ (Å)	λ_0 (Å)
Hg night sky	5460	5461
O III	5519	5007
O I night sky	5574	5577
Na I night sky / interstellar	5890	5892
Interstellar	6278	6283
Atmospheric B	6873	...
Hα	7226	6563
Atmospheric A	7606	...

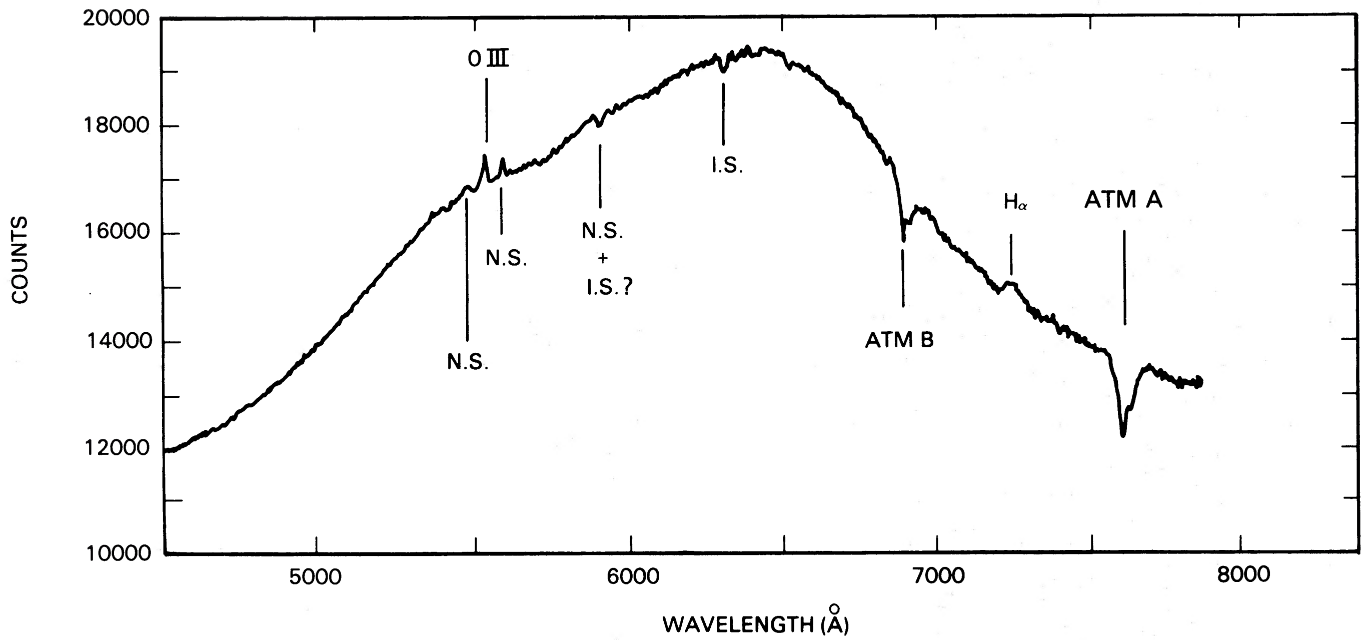

FIG. 2.—Spectrum of 1219+28. Counts shown are the sum of three pixel rows, co-added in each of three spectra. The scale is 4.3 Å pixel^{-1}. The features are identified in Table 2.

redshift is consistent with the lower limit of $z = 0.10 \pm 0.03$ for 1219+28 estimated previously (Usher 1978; W81).

III. IMAGING AND SURFACE PHOTOMETRY

Brief observations of 1219+28 with a charge-coupled device (CCD) camera were reported previously (W81). 1219+28 was not resolved in those observations, but color information for it and ON 231 I and ON 231 II was derived. The observations reported here follow up those preliminary results.

Imaging data for 0851+202 and 1219+28 were obtained with the 4 m telescope at KPNO during an observing run with the prime focus CCD camera (1982 Nov. 12–14 UT). Images were taken through *B*, *V*, and an RG 695 (red) filter (Table 2).

TABLE 2

CCD OBSERVATIONS

Filter	Integration Time	Number of Frames
	0851+202	
B...........	10^s	1
	100	1
V...........	5	1
	25	1
r............	10	1
	50	1
	100	1
	1219+28	
B...........	5	1
	15	1
V...........	5	1
	10	1
r............	5	1
	10	2
	300	3
	600	2

The active area of the chip corresponds to an area of 5′ × 3′ on the sky in a 512 × 320 pixel format. The scale on the CCD is 0″.6 pixel^{-1}. Each frame was corrected for a bias level and variations in pixel-to-pixel sensitivity ("flat-field" corrections), which are wavelength-dependent. At the temperature at which the camera was operated, typically −109°C, dark count was negligible for the integration times of 300 s or less.

Figure 1 shows a 60″ × 60″ area from a 300 s red integration of 1219+28. Not only is there clearly an elliptical nebulosity underlying 1219+28, but objects ON 231 I and 2 southwest of 1219+28 are also obviously extended. There is a suggestion of a spiral arm on the southeast side of ON 231 I, but this feature requires verification. Object 2, which is very faint, has not been previously reported. ON 231 II is clearly stellar, which agrees with previous discussion of this object (W81). The 10 s *V* frame also shows an elliptical nebulosity underlying 1219+28, in approximately the same orientation as seen in Figure 1.

The *B* and *V* images were calibrated using stars A and D of Wing's photoelectric sequence (Wing 1973), which appear on the CCD frames. The photometry for the objects identified in Figure 1 is given in Table 3. Except for object 2, the *V* magnitudes are the averaged values from two frames, weighted by the integration times. Only 1219+28 was detected on the two *B* frames. The errors represent the internal agreement of the observations, and do not include systematic effects. In particu-

TABLE 3

PHOTOMETRY

Object	*V*	*B*−*V*
0851+202	13.90 ± 0.13	0.71 ± 0.03
1219+28	15.56 ± 0.09	0.57 ± 0.06
ON 231 I	19.05 ± 0.05	
ON 231 II	19.08 ± 0.04	
1219+28, 2	21[a]	

[a] See text.

lar, the linearity of the CCD response is assumed, since the calibration stars are brighter than the program objects. Object 2 is too faint to be detected on the V frames. Its V magnitude is estimated by comparing its red magnitude to the red magnitudes of brighter objects for which V is known. Since we have no color information for this object, the result is very uncertain.

The $(B-V)$ color of 1219+28 agrees with previous observations (Tapia, Craine, and Johnson 1976; Kinman 1976). The magnitude is about 0.3 mag fainter than a previous result (W81), but the difference may be within the uncertainties of the two determinations. There is considerable evidence for the variability of 1219+28 (Strittmatter *et al.* 1972; Pollock *et al.* 1974, 1979; McGimsey *et al.* 1975; Tapia, Craine, and Johnson 1976). The V magnitudes for ON 231 I and II are similar to previous results within the uncertainty (W81).

Using techniques described previously (W81), we have modeled the V and red images of 1219+28 to determine whether the light distribution can be reproduced by a bright point source plus associated elliptical galaxy. The point-spread function was in each case represented by a star on the CCD frame in question, to eliminate problems due to seeing changes between frames. Modeling was carried out for three red (5, 10, 300 s) and one V (10 s) frames. There was no indication of any underlying nebulosity on the B frame. For the four images the best fit to the observations is a model with about 20% of the total observed light due to the underlying nebulosity.

As an independent check on the modeling technique, one of us (W. R.) applied a different profile-fitting method to the 300 s red frame. A description of this method will be published elsewhere (Romanishin, in preparation). This second method has an advantage over the one used previously, in that the morphology of the underlying galaxy is not assumed. The results indicate that a spiral galaxy plus point source does not give an acceptable match to the shape of the observed profile. An elliptical galaxy plus point source does give a good match with the best fit for 21% ± 3% (90% confidence level) of the observed light being in the associated galaxy. These results are in good agreement with those described above. The value for r_e, the radius containing half the light in the galaxy assuming a de Vaucouleurs intensity distribution (1953), is $r_e = 2''.6$ $(+1''.2, -0''.6)$ from the Romanishin analysis.

Using the flux calibration given by O'Dell *et al.* (1978*b*) we calculate the spectral index α from the $B-V$ color observed for 1219+28. We assume no interstellar reddening or absorption at the galactic latitude of this object ($b = +83°$). For the point source alone, we find $\alpha = 1.6 \pm 0.3$, where the uncertainty reflects the range of acceptable models for this object. This result agrees with the spectral index $\alpha = 1.7 \pm 0.2$ previously found for 1219+28 (W81).

Assuming 17% of the light observed in V is due to an elliptical galaxy, $z = 0.102$, and the continuum of the point source can be represented by a power law $F_\nu \approx \nu^{-\alpha}$, $\alpha = 1.6$, the absolute magnitude of the point source is $M_V = -23.4 \pm 0.1$ mag. The uncertainty represents the range of models which give acceptable fits to the data. We assume $q_0 = +0.1$ and $H_0 = 50$ km s^{-1} Mpc^{-1} throughout this paper. The corresponding absolute magnitude of the galaxy, out to the Sandage standard diameter (Sandage 1972), is $M_V = -22.1$ $(+0.7, -0.4)$ mag. The absolute magnitudes of the point source and galaxy are typical of values found for BL Lac objects (Fosbury and Disney 1976; Kinman 1978; Miller, French, and Hawley 1978*a*, *b*; Oke 1978; Weistrop, Smith, and Reitsema 1979; W81). If the underlying galaxy is an ordinary elliptical, its effective radius and absolute magnitude should be related by the standard elliptical log r_e–M_B relation. Assuming $B-V = 0.9$ mag, the underlying galaxy lies close to the mean line in the log r_e–M_B plot given by Davies *et al.* (1983).

The low light level contours of the 300 s red frame of 1219+28 were fit with an ellipse. The best fit has a semimajor axis with position angle (p.a.) 65° ± 10°.

B, V, and broadband red observations of 0851+202 were obtained during the same observing run (Tables 2, 3). The observations were calibrated using stars 4, 10, and 11 in the Penston and Wing sequence (1973), which are on the same CCD frames as the object. The mean errors for 0851+202 were calculated from the residuals of the calibration stars. The BL Lac object appears stellar on all frames. Our $B-V$ color is the reddest yet reported for this object (Dyck *et al.* 1971; Epstein *et al.* 1972; Wing 1973; Frohlich, Goldsmith, and Weistrop 1974; O'Dell *et al.* 1978*a*, *b*; Puschell and Stein 1980; Sitko *et al.* 1983). The value is internally consistent; $B-V = 0.70$ using the 5 s V and 10 s B, and $B-V = 0.72$ from the 25 s V and 100 s B. (The value in Table 3 is the average weighted by the integration time.) However, we cannot rule out the presence of systematic errors. The B magnitude is brighter than that reported for 1980–1981 (Sitko *et al.* 1983) and similar to values for the latter part of 1978, when 0851+202 may have been at the onset of a burst (Pollock *et al.* 1979). The short time-scale variations are so large, however (McGimsey *et al.* 1975; Pollock *et al.* 1979), that we cannot relate our single observation to any long-term variability.

IV. RADIO OBSERVATIONS

VLBI observations of 1219+28 were made at 2.3, 5.0, and 8.3 GHz. The 5 GHz observations were part of a US VLBI Network session during 1982 April 3–5. A 2 MHz band centered on 4989 MHz sensitive to left circular polarization was recorded and processed with the Mk II VLBI system (Clark 1973). Data were recorded successfully from the 100 m Max Planck Institut für Radioastronomie (MPIfR) antenna near Bonn, West Germany; the 37 m Haystack antenna (Westford, MA); the 43 m National Radio Astronomy Observatory (NRAO) antenna (Green Bank, WV); the 26 m Harvard Radio Astronomy Station (HRAS) antenna (Fort Davis, TX); and the 40 m Owens Valley Radio Observatory (OVRO) antenna (Big Pine, CA). The 2.3 and 8.4 GHz observations were part of a NASA Crustal Dynamics Project geodesy observing session on 1980 July 26. The Mk III VLBI system (Rogers *et al.* 1983) was used to record six and eight 2 MHz channels near 2.3 and 8.4 GHz respectively of right circularly polarized radiation from the antennas at MPIfR, Haystack, HRAS, and OVRO as well as the 26 m (2.3 GHz) and 20 m (8.4 GHz) antennas of the Onsala Space Observatory near Onsala, Sweden.

The data were hybrid mapped and CLEANed using techniques described by Readhead and Wilkinson (1978) and Cornwell and Wilkinson (1981). The 2.3 and 8.4 GHz maps have uncertain amplitudes because no calibration data are available, but at all three frequencies, the bulk of the radio emission ($\gtrsim$90%) comes from the compact source. At all three frequencies there is a central source, unresolved at 5 and 8 GHz (less than 0.5 milli-arcsec [mas] in extent), with a jet at p.a. ≈ 110°. The jet has at least three components. Two are visible in the 5 GHz map, at distances of 3.4 mas and 6.2 mas from the core source (Fig. 3), corresponding to 10 and 18 pc. A third component is visible in the 8 GHz map, only 0.74 mas (2

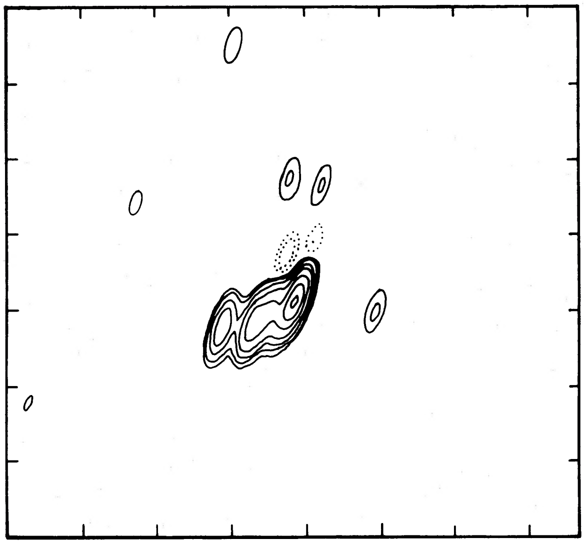

FIG. 3.—5.0 GHz map of 1219 + 28. North is to the top and east to the left. The field is 45 mas × 41 mas; the tick marks are at intervals of 5.9 mas. Contour intervals are −2%, −1%, +1%, 2%, 5%, 10%, 25%, 50%, and 90% of the peak brightness temperature, which is 9.5 × 10^9 K.

pc) from the core. A component 4.0 mas from the core in the 2.3 GHz map is probably the same as the 3.4 mas component in the 5 GHz map. The different epochs and frequencies do not allow us to determine if component motion has occurred. The jet shows some curvature which does not increase close to the core. Observations at 5 GHz with the Westerbork Synthesis Radio Telescope (WSRT) indicate that there are no discrete features a few arc seconds or larger in size coincident with 1219 + 28 (de Bruyn 1983, private communication).

As noted earlier, 1400 + 162 is a moderately bent triple radio source. Detailed analysis of Wardle, Moore, and Angel's data (1984) shows that a compact "hot spot" lies about 3″ east of the central source, directly on the axis connecting the central source with the eastern outer lobe (Antonucci and Ulvestad, private communication). The arc second–resolution observations reported by Stannard and McIlwrath (1982) suggest the presence of a jet, possibly curved, extending from the central component toward the eastern hot spot.

If the distorted radio structure observed in 1400 + 162 is due to interaction with an external medium, one might expect that the orientation of the jet at milli–arc second resolution (i.e., within the parent galaxy) would differ from that observed on scales of 2″ or 3″ (Jones and Owen 1979; Hintzen, Ulvestad, and Owen 1983). We observed 1400 + 162 on 1983 April 1 in a Mk III VLBI experiment during a US VLBI Network session. Left circular polarization in a 28 MHz band of frequencies, centered on 4986 MHz, was processed and hybrid mapped. Participating stations were MPIfR, Haystack, NRAO, HRAS, one 25 m antenna of the VLA, and OVRO.

The total flux density of the source was 0.45 ± 0.04 Jy as measured at MPIfR. About 0.15 Jy comes from the compact core. The source is nearly unresolved, but appears to be slightly extended northward from the core. The extension is approximately orthogonal to the extended emission seen by Hintzen and Owen (1981). The observations suggest strong bending between the compact and extended sources, as seen in some of the active compact sources (see, e.g. Barthel and Lonsdale 1983; Benson *et al.* 1984; Muxlow, Jullian, and Linfield 1984; Unwin and Biretta 1984; Wilkinson *et al.* 1984). Such morphology is consistent with interactions between the jet and an external medium. Any compact emission in 1400 + 162 more than 1 mas from the core and less than 1 mas in size is weaker than ~15 mJy.

V. DISCUSSION AND SUMMARY

We have observed two emission features in the spectrum of 1219 + 28. Previous observations revealed no emission lines (Strittmatter *et al.* 1972). At the time of the observations by Strittmatter *et al.*, the magnitude of 1219 + 28 was $m_V \approx 16.5$ mag. We report here a magnitude of $V = 15.56$ mag observed six months after our spectra were obtained and similar to the $V = 15.25$ mag obtained in 1979 May. If 1219 + 28 has not varied significantly between those two observations, it was considerably brighter when the emission lines were observed than when they were not detected. However, the line identified with [O III] λ5007 peaks only 3% above the continuum. Therefore, even if the line flux has not changed since the observations reported by Strittmatter *et al.* (1972), one would probably not expect the [O III] line to be detectable in their image-tube photographic spectra.

Our results for 1219 + 28 support previous conclusions that at least some BL Lac objects are located at the center of elliptical galaxies. In this regard it is encouraging that two different methods of profile fitting give the same result for the fraction of observed light in the associated nebulosity. The negative result for nebulosity associated with 0851 + 202 is not necessarily significant. If the redshift is $z = 0.306$ (Miller, French, and Hawley 1978*a*), any associated nebulosity might not be distinguishable from the bright point source.

Stockton (1982) and Hutchings and Campbell (1983) have recently suggested that many quasars appear to be interacting with other galaxies and that such interactions may activate the quasar. If objects ON 231 I and 2 are at the same redshift as 1219 + 28, their distances from 1219 + 28 are 27 kpc and 53 kpc respectively. The presence of these extended objects close to 1219 + 28 would be consistent with the interaction hypothesis. However, no definite conclusions can be drawn until redshift data have been obtained.

There is no obvious relationship between the orientation of the radio jet and the nebulosity underlying 1219 + 28. The position angle of the apparent major axis of the nebulosity is about 65°, while the jet has p.a. ≈ 110°. The difference in the position angles indicates the radio jet is not being emitted along the rotation axis of the nebulosity, if the rotation axis defines the minor axis. This result puts 1219 + 28 in the category of galaxies like NGC 1052 and NGC 4278, which also have radio structure that is not aligned with either the major or minor isophotal axis (Jones, Wrobel, and Shaffer 1984). We cannot rule out the possibility that the jet is emitted in the plane of the nebulosity.

Madejski and Schwartz (1983) have reported an X-ray flux of 4.2 × 10^{-7} Jy for 1219 + 28. This value is consistent with an extrapolation of the optical spectral index, similar to previous results for several other BL Lac objects (Snyder 1982; Cruz-Gonzalez and Huchra 1984). Extrapolation of the visible wavelength observations of 0851 + 202 predict a smaller X-ray flux than is observed (Worrall *et al.* 1982; Madejski and Schwartz 1983). There are other BL Lac objects which exhibit similar behavior (Cruz-Gonzalez and Huchra 1984). As noted previously, both 1219 + 28 and 0851 + 202 are known to be variable, so that conclusions drawn by comparing observations from different epochs must be treated with care.

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P. Hintzen and D. Weistrop: Code 681, NASA/Goddard Space Flight Center, Greenbelt, MD 20771

W. Romanishin: Dept. of Physics, Arizona State University, Tempe, AZ 85281

D. B. Shaffer: Interferometrics Inc., 8150 Leesburg Pike, Vienna, VA 22180