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COMPACT EXTRAGALACTIC NONTHERMAL SOURCES

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ABSTRACT

Results of photometry, polarimetry, spectroscopy, and direct photography at visual wavelengths of four additional objects of the BL Lacertae type are reported together with infrared observations to $\lambda = 10\ \mu$ of one of them (OJ 287). The data indicate that these objects are compact sources of nonthermal continuum radiation. They are likely to be extragalactic, and their possible relationship to QSOs is discussed.

I. INTRODUCTION

Recent investigations have suggested the existence of a new class of astronomical objects with the following characteristics: (1) rapid variations in intensity at radio, infrared, and visual wavelength; (2) energy distributions for which $F(\nu)$ in watts $m^{-2}\ Hz^{-1}$ rises through the visual and infrared regions in a manner such that most of the energy is emitted at infrared wavelengths; (3) absence of discrete features in low dispersion optical spectra; and (4) strong and rapidly varying polarization at visual and radio wavelengths.

The prototype object in this class is the variable BL Lac (VRO 42.22.01). A recent review of many of the previously published observations of this object has been given by MacLeod *et al.* (1971). Our purpose here is to describe new observations at optical and infrared wavelengths of four further members of this class, namely OJ 287 (VRO 20.08.01), ON 231 (W Com), ON 325 (B2 1215+30) and PKS 1514−24 (AP Lib). Some basic data for these objects are listed in table 1.

OJ 287 was identified by Blake (1970) with a stellar object of $m_v \approx 14.5$ and has subsequently been studied in some detail by Kinman and Conklin (1971) and by Andrew, Harvey, and Medd (1971). Recent photometry of this source has been published by Dyck *et al.* (1971). Identifications for ON 231 and B2 1215+30 were proposed by Browne (1971), who suggested from their radio properties that they may be objects of the BL Lacertae type. The radio source PKS 1514−24 has been identified by Bolton, Clark, and Ekers (1965) and by Westerlund and Wall (1969) with an object described as an N-type galaxy which corresponds to the optical variable AP Lib. Further data at radio frequencies have been discussed by Hunstead (1971). It has been reported to have a continuous spectrum (Searle and Bolton 1968; Rodgers 1971).

II. OPTICAL OBSERVATIONS

Spectroscopic observations of the four objects in this study have been made with the prime focus spectrograph at the 120-inch (305-cm) telescope of the Lick Observatory and with the Cassegrain image tube spectrograph of the Steward Observatory 90-inch (229-cm) telescope. No intrinsic emission or absorption lines could be found in the spectra of any of the four objects. It was immediately apparent that gross changes in

TABLE 1

DESCRIPTIVE AND PHOTOMETRIC DATA OF COMPACT NONTHERMAL SOURCES

Visual Object	Radio Source	Range of m_v	α (1950)	δ (1950)	l^{II}	b^{II}	U	B	V	R	I
... .	OJ 287, VRO 20.08.01	12–15	$08^h51^m57^s$	20°17′59″	207	+36	12.8	13.4	13.0	12.6	12.3
... .	ON 325, B2 1215+30	~14.5	$12^h15^m21^s$	30°23′39″	189	+82	15.6	16.1	15.6	15.1	14.8
W Com.....	ON 231, VRO 28.12.02	11.5–16.5	$12^h19^m01^s$	28°30′36″	202	+83	16.9	17.2	16.7	15.7	15.3
AP Lib......	OR−225, PKS 1514−24	14.5–16	$15^h14^m46^s$	−24°11′21″	341	+28	15.8	16.0	15.4	14.5	13.9
BL Lac.....	OY 401, VRO 42.22.01	12–15.5	$22^h00^m38^s$	42°02′01″	93	−10	...	...	...	...	...

NOTE.—The photometry was obtained 1972 April 9 UT. Errors on *UBV* photometry are approximately 0.1 and 0.2 mag, respectively, for *R* and *I*.

brightness had occurred in all objects except AP Lib since the Sky Survey plates were obtained. In particular ON 231 appeared to be at least 2 mag fainter ($m_v \approx 16.5$) than estimates ($m_v \approx 14$–14.5) made from the Sky Survey E print (Browne 1971). It has often been conjectured that the emission lines in BL Lacertae–type objects are overwhelmed by a strong (non-thermal) continuum but should become visible when the continuum source decreases in intensity. For this reason special attention was paid to ON 231, but no definite emission lines could be detected in its spectrum. This result does not augur well for the possibility of detecting emission lines in other lineless but variable radio sources even during their least luminous phases. It may, however, indicate that the violent activity in these objects in some way weakens or smears the lines. Why this should occur in objects such as AP Lib if this is indeed an N galaxy is not clear at all. Further spectroscopic monitoring of ON 231 is in progress.

In order to obtain the general shape of the energy distribution at optical wavelengths, broad-band photometric measures were made of the four objects under investigation on the night of 1972 April 8 using the *UBVRI* photometer at the Cassegrain focus of the Steward Observatory 90-inch telescope. The results are listed in table 1, together with published estimates of brightness from the Sky Survey (Blake 1970; Browne 1971; Bolton, Clark, and Ekers 1965). It is clear that both ON 231 and B2 1215+30 are substantially fainter than at the epoch of the Sky Survey plates whereas OJ 287 is rather brighter. Our measures for OJ 287 are consistent with those of Kinman and Conklin (1971) and slightly fainter than the measures given by Landolt (1972).

Polarization measures have been carried out on a number of occasions using the Steward Observatory 90-inch telescope and the 61-inch (155-cm) telescope of the Lunar and Planetary Laboratory on Mount Lemmon. The results are listed in table 2, where P and θ refer respectively to the percentage and position angle of linear polarization and superscripts refer to the wave bands[1] used (no subscript implies an unfiltered measurement with an S11 photocathode). Table 2 also contains approximate *UBV* data derived from the polarization measures. These photometric results, although not of high accuracy, agree reasonably well with the photometry listed in table 1.

From table 2 it is clear that all four objects are strongly polarized. There is evidence for a change in polarization in OJ 287 for which P^B increased by a factor of almost two between our February and March observations. This change was accompanied by a large (and highly significant) change in the plane of polarization. Note also the strong decrease in polarization from the values of 10 percent or more observed by Kinman and Conklin in 1971 April and May. By 1972 April the polarization had increased again to 10.8 percent while the flux from the object decreased. There appears to be no wavelength dependence of the plane of polarization. The March and April measures of polarization indicate that the degree of polarization is also wavelength independent. However, there is some suggestion of an increase in polarization in the R-band in the March results. For B2 1215+30 there is evidence for a change in P and θ between February and April. The measurements on this source again suggest that both P and θ are wavelength independent. The data for both ON 231 and AP Lib are somewhat less complete because they are fainter and AP Lib lies rather far south. No significant changes with time or wavelength dependence in P or θ were detected for AP Lib.

Direct photographs were obtained of OJ 287, B2 1215+30, ON 231, and AP Lib with an ITT image tube and a nightsky blue filter (4400–5400 Å) at the Cassegrain focus of the Steward Observatory 90-inch telescope. ON 231 and B2 1215+30 both appear stellar, although a faint galaxy or nebulosity is visible $\sim 10''$ SW of ON 231. In this respect OJ 287, B2 1215+30, and probably ON 231 differ from BL Lac and AP Lib which appear definitely nonstellar. This point may be especially significant for B2 1215+30 and ON 231, both of which are known to be well below their maximum brightness—a state in which any small-angular-size structure would be most likely to show up on photo-

[1] The R-band used for polarimetry is different from that of Johnson's system and has an effective wavelength of $\lambda_0 = 0.85\ \mu$.

TABLE 2

POLARIMETRY OF COMPACT NONTHERMAL SOURCES

Object	Date (1972 UT)	P	P^U	P^B	P^V	P^R	θ (deg.)	θ^U (deg.)	θ^B (deg.)	θ^V (deg.)	θ^R (deg.)	U	B	V
OJ 287	Feb. 18	. . .	. . .	2.9±0.1	. . .	. . .	. . .	. . .	39	. . .	. . .	. . .	12.8	12.7
	Mar. 17	. . .	5.2±1.0	5.0±0.3	5.0±0.4	7.0±0.6	. . .	91	92	93	92	12.7	13.2	12.8
	Apr. 16	. . .	11.0±0.8	10.3±0.4	10.2±0.5	10.4±0.9	. . .	83	87	87	83	13.3	13.9	13.5
	Apr. 17	. . .	. . .	10.8±0.3	10.4±0.4	11.2±0.9	. . .	. . .	87	88	85	. . .	. . .	. . .
ON 325 (B2 1215+30) . . .	Feb. 18	7.3±0.1	. . .	. . .	. . .	. . .	145	. . .	. . .	. . .	. . .	. . .	. . .	. . .
	Feb. 20	. . .	8.2±3.1	7.2±0.4	6.6±0.7	. . .	. . .	142	140	135	. . .	. . .	16.2	15.5
	Mar. 17	. . .	. . .	4.4±1.4	. . .	. . .	. . .	. . .	146	. . .	. . .	15.4	16.1	15.6
	Apr. 16	. . .	. . .	4.6±0.8	. . .	. . .	. . .	. . .	119	. . .	. . .	15.3	15.9	15.4
ON 231 (W Com) . .	Feb. 18	3.3±0.7	. . .	. . .	. . .	. . .	95	. . .	. . .	. . .	. . .	. . .	. . .	. . .
PKS 1514−24 (AP Lib)	Mar. 17	. . .	. . .	5.6±0.9	3.0±1.9	. . .	. . .	. . .	173	13	. . .	. . .	16.1	15.1
	Apr. 16	. . .	. . .	5.8±1.4	8.0±1.9	. . .	. . .	. . .	139	149	. . .	. . .	16.1	15.4

NOTE.—P and θ with superscript indicate unfiltered measurements.

graphic plates due to the reduced size of the stellar image. It is, of course, also necessary that the nebula material should not diminish in brightness on a timescale of the same order (or less) than that of the nucleus.

III. INFRARED OBSERVATIONS

Observations at 3.5 and 11 μ of BL Lac have been discussed by Stein, Gillett, and Knacke (1971). In recent months observations at 2.2, 3.5, and 10 μ have been made of OJ 287. The sources B2 1215+30, W Com (ON 231), and AP Lib (PKS 1514−24) have recently been too faint at visual wavelengths to allow guiding on these sources with the infrared photometer on the 60-inch Mount Lemmon telescope. Table 3 summarizes the infrared results obtained of OJ 287. The results indicate definite signs of variability on timescales of months 3.5 and 10 μ. This is consistent with the timescales derived from both the optical measures, in particular the polarization, and from the radio data (Andrew *et al.* 1971). The results obtained on OJ 287 show that the infrared energy distribution of this source is very similar to that of BL Lac.

IV. DISCUSSION

Figure 1 shows the energy distribution of each of the five sources in this study; their general characteristics are similar, although not enough information is available at high radio frequencies for AP Lib, B2 1215+30, and ON 231. The sources all appear to vary at radio wavelengths, thus complicating the task of deducing a spectral energy distribution. There is some indication that B2 1215+30 shows a typical nonthermal spectrum in contrast to the other compact sources, although it also appears to become flatter at the higher frequencies. The energy distribution of the quasi-stellar object 3C 273 is also shown in figure 1 for comparison. The energy distribution of the compact nonthermal

TABLE 3

OJ 287 SUMMARY

Date (UT)	λ (μ)	F_ν (W m^{-2} Hz^{-1})
1971 Nov. 14	10.8	$(1.0\pm0.16)\times10^{-26}$
1971 Nov. 18	3.5	$<0.24\times10^{-26}$*
1971 Nov. 20	3.5	$<0.32\times10^{-26}$*
	11	$(1.2\pm0.4)\times10^{-26}$
1972 Jan. 16	10.8	$<0.67\times10^{-26}$*
1972 Jan. 17	10.8	$<0.67\times10^{-26}$*
	3.5	$(3.4\pm0.8)\times10^{-27}$
1972 Jan. 19	3.5	$(2.1\pm0.6)\times10^{-27}$
1972 Jan. 20	10.8	$<0.75\times10^{-26}$*
January (average)	10.8	$(0.4\pm0.13)\times10^{-26}$
	3.5	$(0.25\pm0.05)\times10^{-26}$
1972 Feb. 13	3.5	$(0.12\pm0.02)\times10^{-26}$
	11	$(0.64\pm0.23)\times10^{-26}$
1972 Feb. 14	3.5	$(0.20\pm0.03)\times10^{-26}$
	11	$<0.73\times10^{-26}$*
1972 Feb. 18	10.8	$(0.43\pm0.08)\times10^{-26}$
1972 Mar. 13	3.5	$<0.22\times10^{-26}$*
	10.8	$<0.87\times10^{-26}$*
1972 Mar. 14	3.5	$(0.15\pm0.03)\times10^{-26}$
	2.2	$(0.074\pm0.020)\times10^{-26}$
1972 Mar. 16	3.5	$(0.21\pm0.03)\times10^{-26}$
	2.2	$(0.088\pm0.025)\times10^{-26}$
1972 Mar. 17	10.8	$(0.41\pm0.12)\times10^{-26}$

* Signifies a 3 σ upper limit.

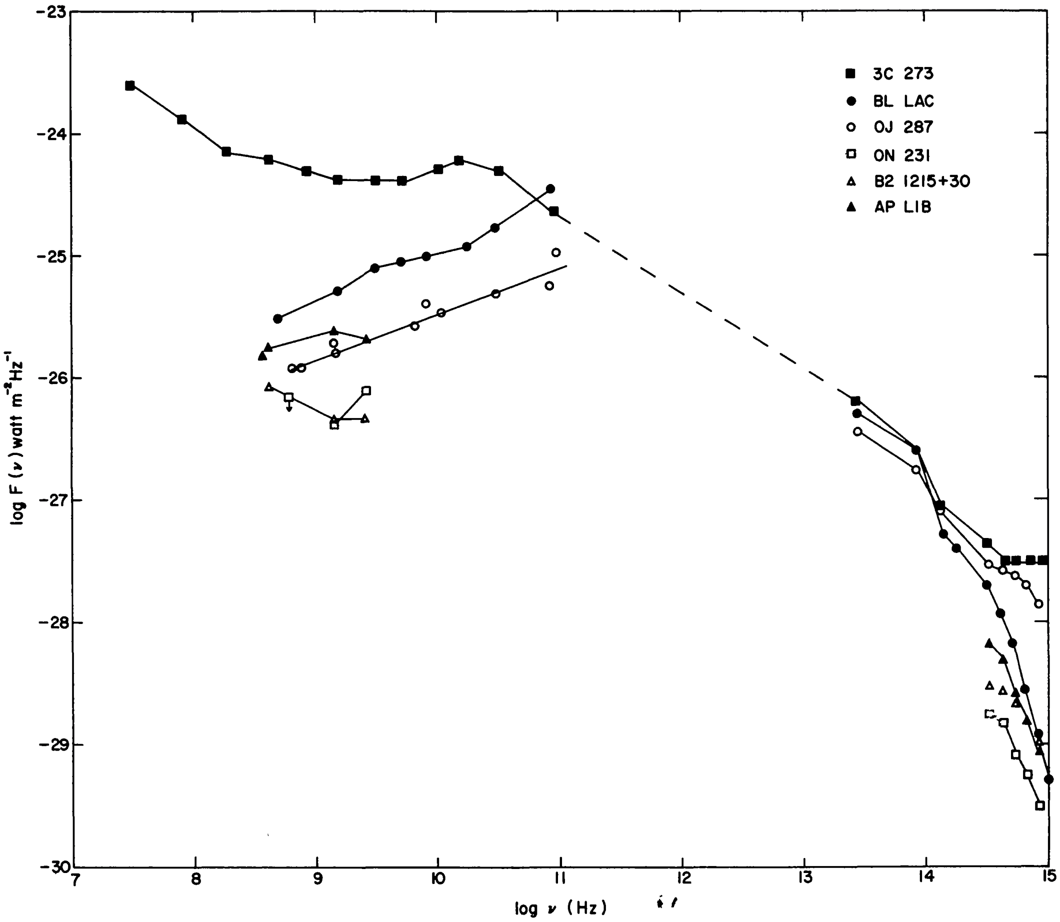

FIG. 1.—The energy distribution of the compact nonthermal sources compared with that of 3C 273

sources differs from that of 3C 273 in two respects. First, the radio spectrum of 3C 273 shows a component at low frequencies for which $F(\nu) \propto \nu^{-\alpha}$ $(\alpha > 0)$ indicative of a halo source whereas most of the data on the BL Lacertae–type objects indicate that these objects appear to consist primarily of a core source. Second, the visual wavelength spectrum of 3C 273 shows thermal continuum radiation from a hot gas which is fairly unusual among QSOs. It is certainly not present in the BL Lacertae–type objects, where the radiation appears, from the spectral shape and from the observed rapid variations in intensity and polarization, to be due to nonthermal processes. These variations also indicate that the radiation is emitted from a very small ($\leq 10^{17}$ cm) region.

It appears from the observations presented here that the BL Lacertae–type objects are exceedingly compact nonthermal objects. They are very similar to the QSOs except in that they have no spectral lines so that no redshifts can be measured. The distance of these objects remains unknown. It is clear from their distribution on the sky that they are not associated with the plane of our Galaxy. According to Pigg and Cohen (1971), 21-cm absorption in BL Lac indicates that this object is certainly at a distance exceeding 200 pc. It is consistent with a distance of 1 kpc or with an extragalactic location. This, together with the location of ON 231 and B2 1215+30 near the galactic pole, suggests that they are almost certainly extragalactic and probably objects of a similar nature to the QSOs. If OJ 287 were at a distance implied by the cosmological interpretation of a typical QSO redshift, it would be one of the most luminous objects in the Universe. It should also be noted that Burbidge and Burbidge (1967, p. 172) have discussed the expected optical properties of a blueshifted QSO. It is interesting that a blueshifted QSO might have many of the properties exhibited by the objects discussed in the present study.

The determination of the distance of these sources is clearly of considerable interest. A possible method of determining an upper limit to the distances of these objects from the observed properties of the nonthermal radiation has been discussed by Stein *et al.* (1971). This method is based partially on the arguments of Hoyle, Burbidge, and Sargent (1966), who pointed out the importance of Compton scattering in compact, highly luminous nonthermal sources. Simply summarized, it is hard to understand within any reasonable physical model how a very small source of radiation can produce such a large observed flux unless the objects are not far away. Further theoretical models of such sources are presently being investigated.

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