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NONTHERMAL CONTINUUM RADIATION IN THREE ELLIPTICAL GALAXIES

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ABSTRACT

Optical, infrared, and radio observations are presented for three elliptical galaxies (NGC 6454, B2 1652+39, and B2 1101+38) which have flat high-frequency radio spectra. Two of these galaxies emit optical nonthermal continuum radiation, as evidenced by linear polarization of the ultraviolet radiation of the nuclei. No emission lines were detected in the optical spectra of the galaxies, and in that respect they may be related to the BL Lacertae class. The redshifts were obtained from the Ca II H- and K-lines and the G-band in absorption. These galaxies appear to form a sequence by order of increasing contribution of a nonthermal source to the luminosity of the nuclear regions, and their optical properties appear to be intermediate between those of ordinary ellipticals and those of objects like BL Lacertae.

Subject headings: BL Lacertae objects — galactic nuclei — galaxies, photometry of — infrared sources

I. INTRODUCTION

The objects BL Lac and AP Lib are members of a group of luminous galaxies which contain strongly variable nonthermal sources in their nuclei. In addition to their rapid variability, these sources have been set apart from other luminous, active galaxies because of the lack of bright emission lines in their spectra, their strong and variable polarization, their infrared emission, and their flat high-frequency radio spectra (Strittmatter *et al.* 1972). Other sources, such as OJ 287 and 0735+178, are similar except for the lack of a detectable galactic component surrounding the compact nonthermal source. This apparent difference may simply be a consequence of these objects having relatively stronger nonthermal sources and being at greater distances.

We have observed three galaxies, NGC 6454, B2 1652+39, and B2 1101+38, which appear to be related to members of this group. These sources were selected because they have flat high-frequency radio spectra, highly condensed nuclei in the optical, and no bright emission lines. B2 1101+38 and B2 1652+39 were noticed in the course of a spectrographic study of a complete sample of 57 elliptical galaxies identified with radio sources in the second Bologna catalog of radio sources (Colla *et al.* 1972). The flat high-frequency radio spectra of NGC 6454 and B2 1652+39 were discovered in a program of observations of low-luminosity radio galaxies. We find evidence for nonthermal optical emission from B2 1652+39 and B2 1101+38, and for variable polarization in the latter source. However, even for this object the luminosity of the nonthermal flux in the optical range is smaller than the luminosity of the galactic (stellar) component. Our measurements and the detection of transient emission lines from AP Lib by Disney, Peterson, and Rodgers (1974) show that these sources related to BL Lac exhibit a wide range of properties.

II. SPECTROGRAPHIC OBSERVATIONS

The three galaxies we have observed have very concentrated nuclei, and through the 2.1-m telescope the visual appearance of the nuclei of B2 1101+38 and B2 1652+39 was essentially stellar to within the seeing limit of 1″ to 2″.

On the *National Geographic Society–Palomar Observatory Sky Survey*, all three galaxies show rather smooth elliptical images having angular dimensions of about 30″ × 40″. Mayall telescope prime-focus photographs of B2 1652+39 show the extranuclear regions of the galaxy to be perfectly smooth and to resemble qualitatively those of a typical E galaxy.

Our spectrographic material was obtained in 1973 and 1974 with two different image-tube spectrographs on the Kitt Peak National Observatory 2.1-m telescope. The two image tubes were RCA cascaded tubes of two and three stages. The useful spectral region was generally from 3600 to 6000 Å, and the dispersions employed were roughly 100, 200, and 400 Å mm^{-1}.

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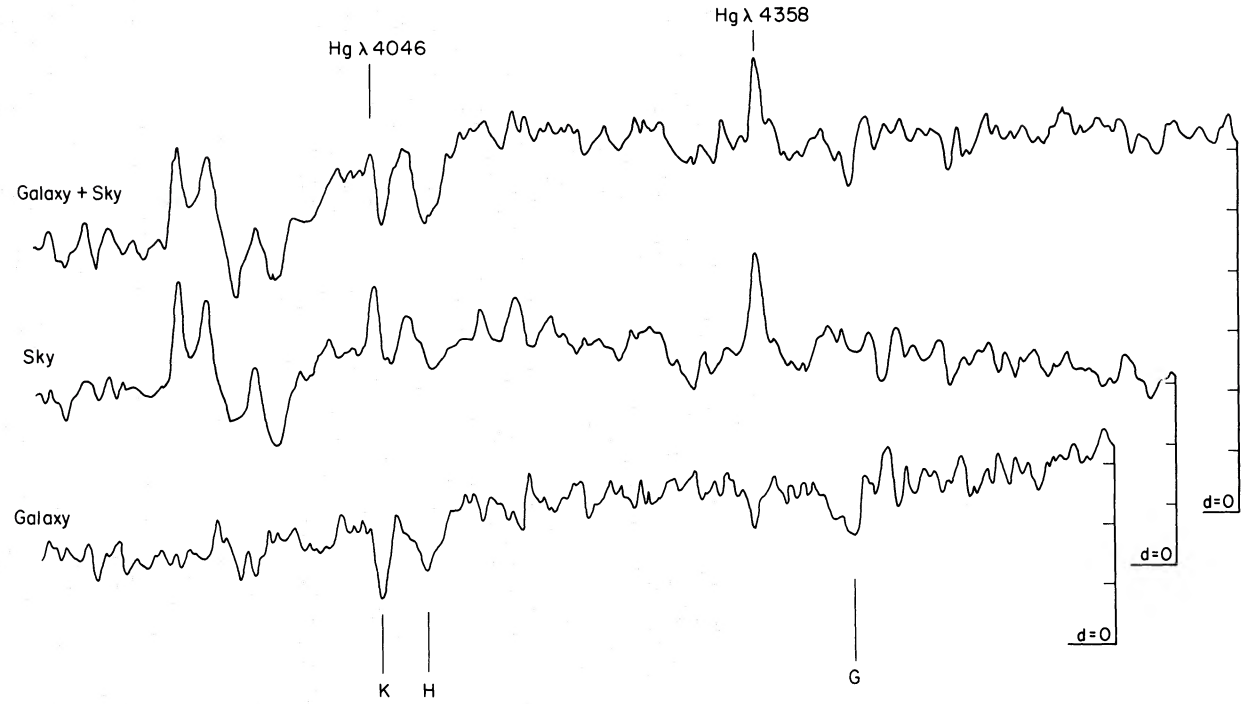

FIG. 1.—Density tracings made on one of the untrailed spectra of B2 1101+38 taken with the slit set 4″ away from the nucleus. "Galaxy + sky" is the average of five adjacent tracings made along the spectrum of the object. "Sky" is the average of five adjacent tracings of the nightsky spectrum. "Galaxy" is the difference of the two density distributions. The density scales are graduated in intervals of 0.2.

The spectrograms of none of the objects show clear evidence for the presence of emission lines.[1] There was no difficulty in obtaining the redshift of NGC 6454 from the H- and K-lines of Ca II and the G-band in absorption by setting the spectrograph slit directly through the nucleus; the redshift is 0.0306 (also see Tritton 1972). A spectrogram of B2 1652+39 obtained with the slit passing through the nucleus of the galaxy is dominated by a featureless blue spectrum of the small, bright nucleus. However, spectrograms obtained with the slit positioned a few arc seconds south of the nucleus show the H- and K-lines and the G-band at a redshift of 0.0337 (Ulrich 1974; Wills and Wills 1974).

The redshift of the third galaxy, B2 1101+38, is more difficult to determine because the nucleus is substantially brighter relative to the surrounding galaxy than is the case for the other two objects. The surface brightness of the galaxy is so low that spectrograms obtained several arc seconds from the nucleus are seriously contaminated by the airglow spectrum and possibly also by the featureless spectrum of the intense nucleus (scattered into the slit of the spectrograph). In an effort to separate any spectroscopic features of the galaxy from those contributed by the airglow, the best-exposed spectrogram was scanned

[1] However, from objective prism plates taken at an earlier epoch, Markarian (Markarian and Lipovetski 1974) reports the presence of Hα emission in the spectra of B2 1101+38 (=Markarian 421) and B2 1652+39 (=Markarian 501).

TABLE 1

DISTANCES, MAGNITUDES, AND RADIO DATA AT 5 GHZ

OBJECT*	REDSHIFT	DISTANCE (Mpc)	m_p†	M_p	FLUX DENSITY (10^{-26} W m^{-2} Hz^{-1})	DIAMETER arcsec	DIAMETER kpc
B2 1101+38.....	0.0308	90	13.1	−21.6	0.64‡	$\lesssim 1$	$\lesssim 0.5$
B2 1652+39.....	0.0337	100	13.7	−21.4	1.0	< 3	< 1.4
NGC 6454.....	0.0306	90	14.6	−20.1	0.45	~ 5	~ 2.2

* Other names: B2 1101+38 = Markarian 421; B2 1652+39 = 4C 39.49 or VV 7-35-2 or Markarian 501; NGC 6454 = 4C 55.33.1.

† From the CGCG (Zwicky and Herzog 1963, 1966; Zwicky and Kowal 1969).

‡ Colla *et al.* 1974.

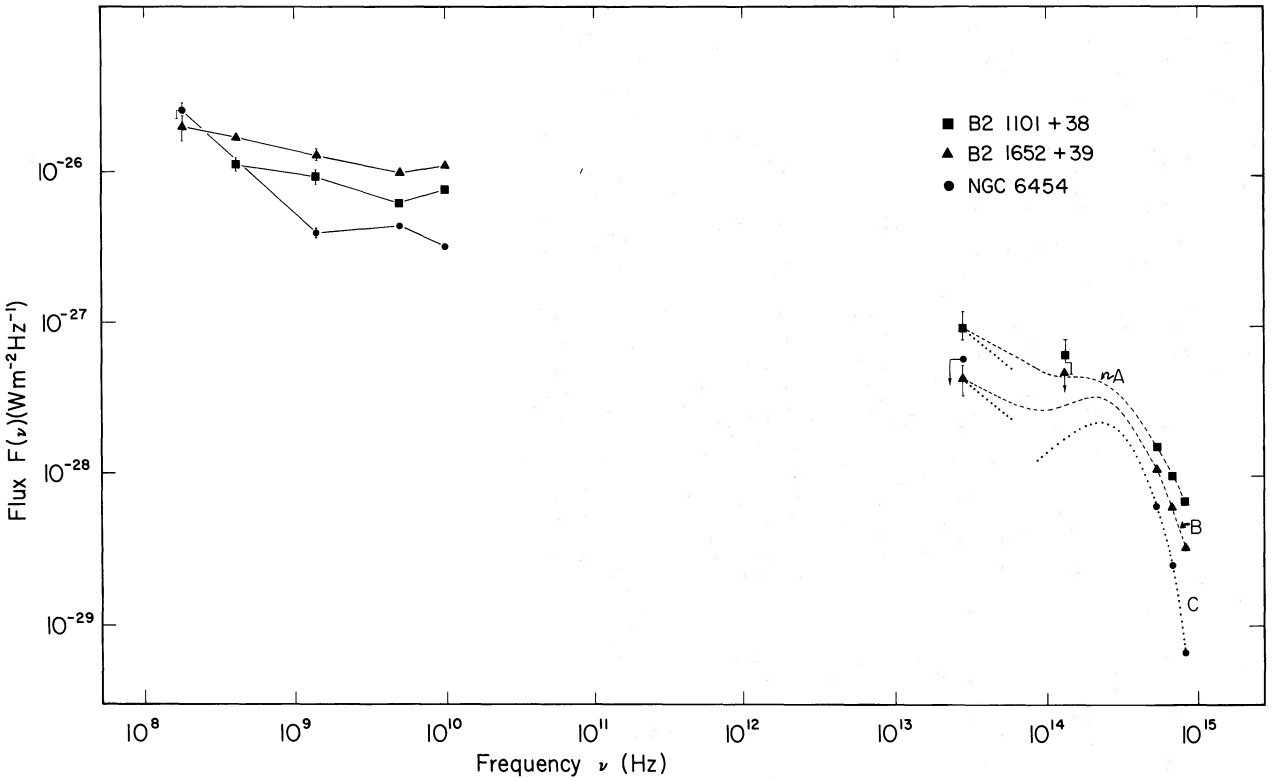

FIG. 2.—Energy distributions of B2 1101+38, B2 1652+39, and NGC 6454. Fluxes at 178 MHz, Caswell and Wills (1967); fluxes at 408 MHz, Colla *et al.* (1972); B2 1101+38 flux at 5000 MHz, Colla *et al.* (1974); all other data, this paper. Infrared and *UBV* measurements were made through 6″ and 10″.6 diameter diaphragms, respectively. The energy distribution represented by curve C has the *UBV* fluxes of NGC 6454 and the infrared colors of a giant elliptical galaxy as given by Johnson (1966). *Straight dotted lines*, energy distributions $S(\nu) \propto \nu^{-0.82}$ contributing 100 percent of the 10.6 μ fluxes of B2 1101+38 and B2 1652+39. *Curves A and B*, see text. Error bars which are not shown are smaller than the symbols.

on a microdensitometer, and the sky spectrum was subtracted from the combined galaxy-sky spectrum. The tracings and the difference between them are reproduced in Figure 1, where it will be noted that the three most prominent absorption features remaining in the difference spectrum coincide closely with the expected positions of the H- and K-lines and G-band for a redshift of 0.0308. Even though the subtraction of the spectra was performed in density units, the only indication that the subtraction was less than satisfactory is the small depression at the position of the Hg line λ4358, which also, perhaps coincidentally, is the redshifted position of Ca I λ4226. In addition, the spectrum of the faint galaxy located approximately 20″ northeast of the nucleus of B2 1101+38 clearly shows an absorption-line spectrum at a redshift of 0.0316. Nevertheless, the proposed redshift for B2 1101+38 should not be regarded as beyond question.

Table 1 summarizes the redshifts, distances based on a Hubble parameter of 100 km s^{-1} Mpc^{-1}, apparent photographic magnitudes (probably not reflecting adequately the brightness of the nuclei, especially in the case of B2 1101+38), absolute photographic magnitudes, and 5 GHz flux densities.

III. RADIO OBSERVATIONS

The radio spectra for these three sources are shown in Figure 2. All have flat high-frequency spectra, and were first thought to be the same type of compact radio sources now known to occur in the nuclei of many elliptical galaxies (see, e.g., Ekers 1974). However, NGC 6454 is partially resolved with the Westerbork interferometer at 5 GHz with an equivalent diameter of about 5″ (Table 1). B2 1101+38 may also be slightly resolved with diameter ~1″. Most nuclear radio sources with flat high-frequency radio spectra have been found to be extremely small; both NGC 1052 and the core in M87 are ≤0″.001. With the available resolution it is not possible to say anything about the distribution of the radio brightness, so, for example, NGC 6454 could be a double with unresolved components. Unless a small component is found in its nucleus, the radio source in NGC 6454 differs significantly from those in very compact sources like BL Lac and OJ 287.

At present all three objects have been observed at only one epoch, so we have no information on variability.

At 5 GHz the observations have been made in all polarizations, but no polarized emission is detected;

TABLE 2

PHOTOMETRIC DATA

OBJECT	DATE (UT)	DIAPHRAGM DIAMETER	V	B	$B-V$	$U-B$	FLUX ($\times 10^{-26}$ W m^{-2} Hz^{-1}) 2.2 μ	10.6 μ
B2 1101+38.....	1972 Apr. 28	10″.6	...	13.99 ±0.05	...	...	...	...
	1974 Feb. 21	10″.6	13.51	14.07	+0.56	−0.47	...	...
		6″	...	...	...	...	0.064 ± 0.016	0.097 ± 0.016
B2 1652+39.....	1973 Apr. 26	7″.0	...	14.74 ±0.05	...	...	...	...
	1973 May 31	10″.6	...	14.65 ±0.1	...	...	...	...
	1973 July 26	10″.6	13.83	14.56	+0.73	...	...	...
	1973 Sept. 1	10″.6	13.84	14.60	+0.76	−0.22	...	...
	1973 Oct. 24*	10″.1	13.88	14.60	+0.72	−0.28	...	...
		6″	...	...	...	...	≤0.05	0.044 ± 0.01
NGC 6454.....	1974 Apr. 14	10″.6	14.46	15.55	+1.09	+0.54	...	...
	1974 Apr. 16	7″.0	14.94	16.06	+1.12	+0.65	...	...
		6″	...	...	...	...	...	≤0.06

* E. Ye. Khachikian and D. W. Weedman 1974.

the limits (3 σ) are, for NGC 6454, less than 6 percent; for B2 1652+39, less than 3 percent; and for B2 1101+38, less than 5 percent.

IV. PHOTOMETRY AND POLARIMETRY

UBV colors and magnitudes for the three galaxies were obtained with the Kitt Peak 2.1-m and 4-m telescopes, and are given in Table 2. Infrared fluxes at 2.2 μ and 10.6 μ were measured with the Steward 2.25-m and NASA 1.52-m telescopes, and are also given in this table. The linear polarizations of these objects are given in Table 3; they were obtained with the Kitt Peak telescopes using an unfiltered ITT type FW129 photomultiplier with an S11 response. From 1973 July, the *UBV* photometry and the polarimetry were obtained with the photometer-polarimeter described by Kinman and Mahaffey (1974), while before that the instrument described by Dyck and Sandford (1971) was used.

The photometry gives no evidence that the fluxes from any of these objects are variable. Significant polarization was found in both B2 1101+38 and B2 1652+39, and it is clear that the polarization in B2 1101+38 is variable; it may well be that the flux from B2 1652+39 does vary, but we do not have enough observations to show it. There is no evidence for any intrinsic polarization in NGC 6454, and its *UBV* colors are comparable with those of a giant elliptical galaxy with its redshift (Schild and Oke 1971). Its colors redden with decreasing size of measuring aperture, as is found with normal E galaxies (de Vaucouleurs 1961); although it has a strong central concentration, it did not show a stellar nucleus at the

TABLE 3

POLARIZATION DATA

Object	Date (UT)	P (%)	θ Position Angle	Diaphragm Diameter
B2 1101+38.....	1973 Apr. 25	3.1 ± 0.1	174°	10″.2
	1973 Apr. 27	5.6 ± 0.1	6°	6″.4
	1973 Apr. 28	4.4 ± 0.2	4°	10″.2
	1973 May 29	1.6 ± 0.1	150°	10″.2
	1973 Nov. 21	2.5 ± 0.2	174°	10″.6
	1974 Feb. 22	0.5 ± 0.2	174°	10″.6
	1974 Mar. 26	4.0 ± 0.1	167°	10″.3
	1974 May 17	5.9 ± 0.1	155°	10″.3
	1974 June 18	1.3 ± 0.2	148°	10″.6
B2 1652+39.....	1973 Apr. 25	2.1 ± 0.2	140°	6″.4
	1973 Apr. 27	1.8 ± 0.1	145°	10″.2
	1973 Apr. 28	2.7 ± 0.1	143°	7″.0
	1973 Aug. 30	3.0 ± 0.1	146°	10″.6
	1974 May 17	2.6 ± 0.1	145°	10″.3
	1974 June 18	2.4 ± 0.2	143°	10″.6
NGC 6454.....	1974 May 17	0.5 ± 0.2	65°	10″.3
	1974 June 18	1.1 ± 0.3	145°	10″.6
Mean.....		0.3 ± 0.2	138°	...
Star ~1′ north of NGC 6454.....	1974 June 18	0.7 ± 0.3	1°	10″.6

f/45 focus of the NASA telescope—unlike the other two galaxies. We therefore found no optical evidence for a nonthermal component in NGC 6454.

The infrared luminosities of B2 1101+38 and B2 1652+39 are high; however, unlike most known high-luminosity extragalactic infrared sources, the infrared flux does not appear to dominate the total emission from the nuclei of these galaxies. Rieke and Kinman (1974) have summarized the evidence that the infrared and optical fluxes of the variable radio sources such as BL Lac and OJ 287 are strongly correlated. These sources, particularly OJ 287, have a low ratio of infrared to total luminosity when compared with other luminous extragalactic objects; the infrared data are therefore consistent with the hypothesis that B2 1101+38 and B2 1652+39 contain similar, presumably nonthermal, sources.

The optical and infrared fluxes (measured through 10".6 and 6" apertures, respectively) of B2 1101+38 and B2 1652+39 are reasonably consistent with the notion that these objects are composed of a normal elliptical galaxy containing a central compact nonthermal source having a power spectrum with spectral index -0.82 and contributing 100 percent of the flux at 10.6 μ. The composite energy distributions are represented by curves A and B of Figure 2. The flux for the galaxy component in B2 1101+38 was taken to be the same as for NGC 6454 (which has the same redshift, $z \simeq 0.031$) in the visible; infrared fluxes, neglecting K-corrections, were deduced using the mean infrared colors of giant elliptical galaxies given by Johnson (1966). In the case of B2 1652+39, a flux for the galaxy component 1.14 times that used for B2 1101+38 was needed to obtain a good fit (Figure 2). At the larger redshift (0.0337) of B2 1652+39, and taking into account the aperture correction (Sandage 1972), we would expect NGC 6454 to have 0.89 times the flux actually measured through a 10".6 diaphragm. Our model therefore assumes that the galaxy component in B2 1652+39 is 1.28 times brighter than NGC 6454 if the radial distribution of light in these objects is similar to that in a normal bright elliptical: this latter point requires checking. No correction for interstellar reddening was made, since all these objects are at galactic latitudes greater than 30°.

It seems reasonable to compare the objects studied here with 3C 371 and with BL Lac. The estimated fluxes in the V passband of the nonthermal components in B2 1101+38 and B2 1652+39 are 8.7×10^{-29} and 4.1×10^{-29} W m^{-2} Hz^{-1}, respectively. These may be compared with V passband fluxes of 2.4 to 7.0×10^{-29} W m^{-2} Hz^{-1} estimated for the variable nonthermal component of 3C 371, which has a spectral index of ~ -1.25 shortward of 1 μ (Oke 1967). If distances are assumed to be proportional to redshifts, then the nonthermal V fluxes of B2 1101+38 and B2 1652+39 would be 3.3×10^{-29} and 1.9×10^{-29} W m^{-2} Hz^{-1}, respectively, at the distance of 3C 371, which has a redshift of 0.05. It must be stressed that a comparison of fluxes at one passband of objects with differing relative energy distributions has only limited significance; nevertheless, the nonthermal fluxes from these objects are clearly comparable.

In both B2 1101+38 and B2 1652+39, the luminosity of the nonthermal flux in the optical range is smaller than the luminosity of the whole galaxy component. For comparison, in BL Lac, the nonthermal component at the brightest at which it was observed by Oke and Gunn (1974) was seven times as bright as the galaxy component.

The spectral index (-0.82) found here for B2 1101+38 and B2 1652+39 between 0.44 and 10.6 μ is similar to that found by Rieke and Kinman (1974) for OJ 287: in this and in related sources, however, there is evidence that the spectral index gets steeper toward higher frequencies. More observations, particularly in the infrared, are required if one is to check for the same effect in B2 1101+38 and B2 1652+39: the discrepancy between the predicted and measured flux in B2 1101+38 at 2.2 μ suggests this effect.

V. CONCLUSIONS

From spectrographic, photometric, polarimetric, and radio observations, we conclude that NGC 6454, B2 1652+39, and B2 1101+38 are elliptical galaxies which form a sequence ordered by increasing brightness of a centrally located, compact, nonthermal source. B2 1101+38, which has the brightest nonthermal source, also exhibits variable polarization. Although they have relatively low luminosities, in many respects these sources resemble those found in a class of very luminous objects which include BL Lac, AP Lib, and 0735+178. This resemblance suggests that the class is more diverse than was known previously, and that the division between it and other kinds of high-luminosity galaxies is not distinct.

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