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THE DISTANCE OF BL LACERTAE

J. B. OKE AND J. E. GUNN*
Hale Observatories, California Institute of Technology, Carnegie Institution of Washington
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ABSTRACT

The extended object around BL Lacertae has been observed spectrophotometrically, with the use of both an annulus and round apertures. The annulus spectrum shows the absorption lines normally seen in spectra of ordinary giant galaxies; these lines yield a redshift $z = 0.07$. It is also shown that (1) the central source is a power-law spectrum with $\alpha = -1.55$; (2) the underlying galaxy energy distribution is consistent with that of a normal giant elliptical galaxy; (3) the interstellar extinction corresponds to $E_{B-V} = 0.28$; (4) if $H_0 = 60$ km s^{-1} Mpc^{-1} is used, the absolute visual magnitude of the galaxy is -22.9 and the distance is 350 Mpc (the central source at the brightest we have observed it is 7 times as bright as the galaxy); (5) on the assumption that the redshift $z = 0.07$, the central source is similar in spectral index and luminosity to quasars such as 3C 48, 3C 279, and 3C 345, provided a cosmological distance is assumed for these latter quasars.

Subject headings: quasi-stellar sources — spectrophotometry — redshifts

I. INTRODUCTION

The radio source VRO 42.22.01, which is unusual because of its peculiar radio spectrum and its rapid radio variability, has been identified with the variable object BL Lacertae (MacLeod and Andrew 1968; Schmitt 1968). The radio variations occur in time scales of 1 month (Andrew *et al.* 1969; MacLeod *et al.* 1971; Andrew 1973). Optical variations from night to night have been measured (DuPuy *et al.* 1969; Bertaud *et al.* 1969; Tritton and Brett 1970), and small flickers in times of about 2 minutes have been reported by Racine (1970).

The spectrum from 0.32 to 11 μ (Oke, Neugebauer, and Becklin 1969; Stein, Gillett, and Knacke 1971) suggests that the bulk of the radiation may be non-thermal; this is supported by the discovery of strong optical polarization (Visvanathan 1969). No spectral features have ever been seen. The object, on the other hand, is extended, and its appearance is compatible with its being a galaxy. Photographs have been published by Arp (MacLeod *et al.* 1971) and by Penston and Penston (1973).

Since BL Lac is peculiar and its distance has remained a mystery, we have been monitoring the object during the last 4 years by obtaining spectral energy distributions. Since none of the material yielded a redshift, a different approach, described below, was made.

II. OBSERVATIONS

All of the observations reported here were made with the multichannel spectrometer attached to the 200-inch (5 m) Hale telescope. These observations are described in table 1 and are plotted in the upper part of figure 1, where the absolute fluxes f_ν (ergs s^{-1} cm^{-2} Hz^{-1}) are plotted against the observed frequency ν. The energy distributions are based on the calibration of α Lyr given by Oke and Schild (1970). Since spectral features are either absent or very broad, we have shown only the smoothed data, not individual measures. Observations marked (1)–(8) are all made with a circular aperture with the diameter noted in table 1.

TABLE 1

OBSERVATIONS

Energy Distribution No.	Date	Aperture (arc sec)	V	Bandpasses (Å)
1..........	1970 Jan. 10–11	14	13.3	80/160
2..........	1969 Aug. 14–15	10	13.4	40/80
3..........	1970 Nov. 18–19	10	13.7	40/80
4..........	1973 June 29–30	7	14.0	40/80
5..........	1970 Apr. 25–26	14	14.3	80/160
6..........	1971 June 19–20	7	14.8	80/160
7..........	1971 Nov. 12–13	14	15.1	40/80
8..........	1973 Oct. 2–3	7	15.6	80/160
Annulus.....	1973 Oct. 4–5	5–10	16.9	80/160

Because it is apparent from the photographs that BL Lac is extended, it was decided to make observations in an annulus, in which the bright central source was largely obscured. These apertures were constructed, and observations of BL Lac were made with an outer diameter of 10″ and an inner obscuring disk of 5″. The result is the energy distribution shown in figure 1 and marked "Annulus." By good fortune it is probable that the central source was abnormally weak at the time, since two days previously (energy distribution [8]) it was fainter than on any previous occasion when we had observed it.

III. ANALYSIS

It is clear from figure 1 that the energy distribution of the annulus does indeed have features; note also that

* Alfred P. Sloan Foundation Fellow.

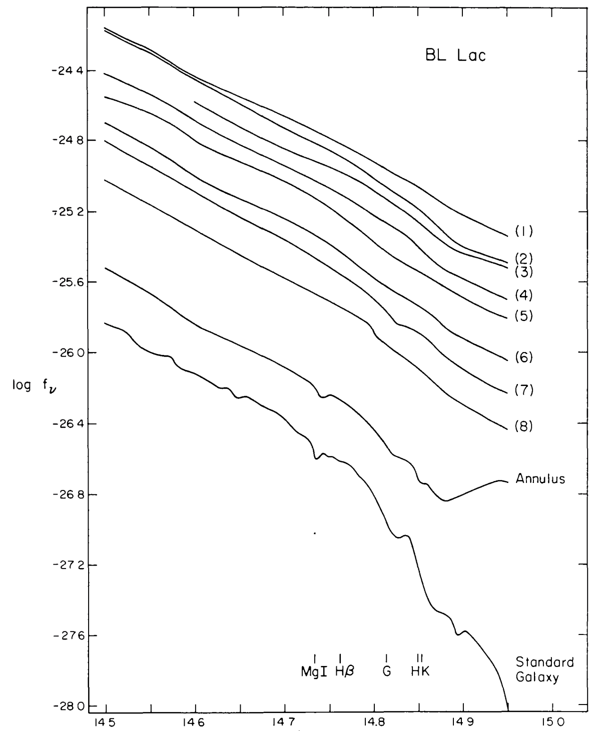

FIG. 1.—Absolute spectral energy distributions for BL Lac. The flux f_ν is in ergs s^{-1} cm^{-2} Hz^{-1}, and the observed frequency ν is in Hz. Observations (1)–(8) and the annulus observation are described in table 1. The lowest curve is a standard galaxy energy distribution reddened by an amount corresponding to $E_{B-V} = 0.28$ and redshifted by 0.029 in log ν. Several redshifted absorption features are marked.

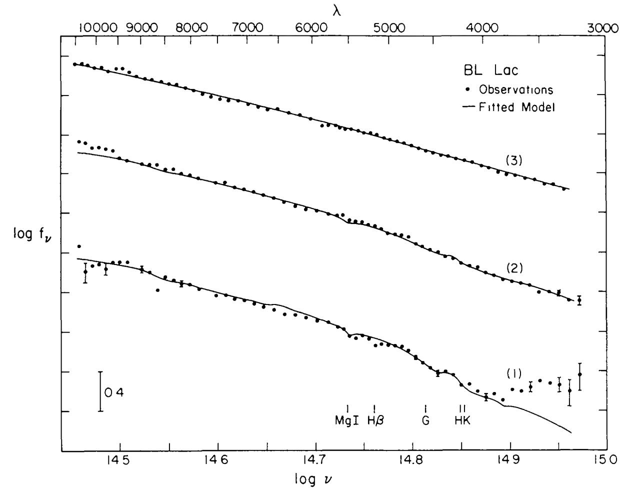

FIG. 2.—Detailed absolute spectral energy distributions for BL Lac are shown by dots. Synthesized spectra are represented by the curves. (1) is the annulus observation, (2) is the observation of 1973 Oct. 2–3 and corresponds to (8) in fig. 1. (3) is the observation of 1970 Jan. 10–11, and corresponds to (1) in fig. 1. Several redshifted absorption features are marked. Representative standard-deviation bars are shown if the deviation is appreciably larger than the plotted point.

energy distribution (8), which was reduced in exactly the same way with the same standard stars, does not. A comparison of the annulus energy distribution with that of a normal galaxy leaves no doubt that the features are due to the Mg I *b*-band, the G-band, and H and K of Ca II. In addition, the detailed plotted points shown as (1) in figure 2 also suggest the presence of Hβ in absorption. The redshift is $z = 0.07$. Further evidence that this redshift is correct is given below where the observed spectra are synthesized.

The above redshift and, of course, the appearance on direct photographs confirm that there is an underlying galaxy. We assume that this galaxy has the same spectral energy distribution as a typical galaxy but reddened in our own Galaxy by Whitford's (1958) interstellar extinction law by an amount corresponding to $E_{B-V} = 0.28$ (see below). The "typical" unreddened galaxy energy distribution used is that of NGC 4889 in the Coma cluster (it is essentially the same as that published by Oke and Schild 1971). We also redshift the energy distribution by an amount corresponding to $z = 0.07$. The result is the lowest curve in figure 1.

The energy distributions (1)–(8) shown in figure 1 are now assumed to be combinations of the energy distributions of the typical galaxy and a nonthermal source. Since the slopes of the energy distributions (1)–(8) vary smoothly with brightness ([2] being the only exception), it is found that energy distribution (1), obtained when the nonthermal source was very bright, is a close representation of this nonthermal source, assuming its spectral index is independent of brightness. We have chosen therefore to represent the nonthermal source by a power law $f_\nu \propto \nu^{-1.55}$ reddened by the same amount as the galaxy.

We are now in a position to fit the various observed energy distributions by the sum of the reddened power law and the reddened standard galaxy. The only unknowns are the relative contributions of each. We must also justify the amount of interstellar extinction assumed above.

a) Fitting the Energy Distribution of the Annulus

This was done for a range of interstellar absorption values and for various contributions from the two sources. The best result was obtained with a total extinction at V of 0.85 mag ($E_{B-V} = 0.28$). The partition of the energy between the galaxy and power-law source is listed in table 2 at several wavelengths. Decreasing the interstellar extinction at V to 0.57 mag or increasing it to 1.14 mag produced significantly worse overall fits. The final fit is shown in curve (1) of figure 2. The excellent fit reinforces our conclusion that the redshift is 0.07, since it is not possible to fit a typical curved galaxy continuum energy distribution with more than one value of z. The apparent surplus of radiation in the far-violet is caused by atmospheric

TABLE 2

SYNTHESIZED SPECTRA

		Flux (10^{-27} ergs cm^{-2} s^{-1})					
		Annulus		Energy Dist. (8)		Energy Dist. (1)	
λ_{obs}	λ_{em}	Std. Gal.	Power Law	Std. Gal.	Power Law	Std. Gal.	Power Law
4000..........	3738	0.52	0.82	1.06	5.33	1.5	71.5
4226..........	3950	0.90	0.94	1.84	6.10	2.8	81.8
4326..........	4043	1.34	0.99	2.75	6.48	4.1	87.0
5600..........	5232	4.68	1.97	9.57	12.82	14.3	171.9
7400..........	6914	11.29	3.89	23.12	25.35	34.4	339.9
9956..........	9305	24.59	7.54	50.34	49.20	74.9	659.7

refraction, which makes the image of the central source spill outside of the occulting disk. The adopted interstellar absorption of 0.85 mag at V is much larger than the value of 0.31 mag determined by Crawford (1961) for the I Lacertae association. It agrees quite well, however, with $E_{B-V} = 0.31$ determined by DuPuy *et al.* (1969) from a star only 20″ from BL Lac.

b) Fit of Energy Distribution (8)

As noted above, observation (8) was made when the nonthermal component of BL Lac was particularly faint. If one uses the interstellar absorption derived above, the best fit is shown in curve (2) of figure 2 and also listed for several wavelengths in table 2. The uncertainty in the galaxy contribution is about 25 percent. The galaxy contribution is small enough that spectral features are almost obliterated.

c) Fit of Energy Distribution (1)

This is the brightest magnitude of BL Lac for which we have observations. The best fit is shown in curve (3) of figure 2 and in table 2. The galaxy contributes 10 percent or less of the observed light at all wavelengths.

d) The Background Galaxy in BL Lacertae

Using the Hubble law which best fits the luminosity-radius relation for giant ellipticals (see e.g., Sandage 1972*a*), we find that the brightness of the galaxy in the annulus should be lower than that in the 7″ aperture by a factor of 1.4. The observations and our supposition that the spectral index does not change yield a fitted value of this ratio of 2.0 ± 0.5. If this small discrepancy is real, it means that the galaxy associated with BL Lac is rather more compact than ordinary ellipticals; if the shapes are the same, the radial scale is smaller by about a factor of 3. If one uses $H_0 = 60$ km s^{-1} Mpc^{-1} and $q_0 = 0.0$, the integrated absolute visual magnitude inside a circle of radius 16 kpc is −22.86, compared with −22.4 inside this radius for the mean brightest cluster elliptical (Sandage 1972*b*).

If instead we suppose that the galaxy is normal and that the central fit is influenced by real changes in the spectral index of the nonthermal source, then the total luminosity obtained from the annulus alone and the standard galaxy growth curve is −22.81, again referred to a 16-kpc radius circle. Thus the derived luminosity of the background galaxy is almost entirely independent of assumptions about its concentration, and depends little on the assumption of constant spectral index for the nonthermal source. The galaxy is at all events a very luminous object, comparable to the brightest galaxies known.

e) The Nonthermal Source

We make use of the results in § III*c* above when the nonthermal source is very bright. The value of $\log f_\nu$ at $\log \nu = 14.97$ (redshifted from 15.00) is −24.80 after correction for contamination and interstellar extinction. Using $H_0 = 100$ km s^{-1} Mpc^{-1}, for which most quasar fluxes in the literature are calculated, we find for $q_0 = 0.0$ an absolute emitted flux at a rest frequency of 10^{15} Hz corresponding to $\log F_\nu$ (10^{15} Hz) = 29.92. It should also be recalled that the spectral index α is −1.55. For comparison we have similar data for quasars (Oke, Neugebauer, and Becklin 1970). For 3C 48, $\log F_\nu$ (10^{15} Hz) = 29.90 and $\alpha = -1.38$. For 3C 279 (variable), $\log F_\nu$ (10^{15} Hz) = 29.76 and $\alpha = -1.51$. For 3C 345 (variable), $\log F_\nu$ (10^{15} Hz) = 30.06 and $\alpha = -1.50$ (in the above reference the values of $\log F_\nu$ [10^{15} Hz] in table 1 should all be increased by 3 to give the flux in units of ergs s^{-1} Hz^{-1}). In these respects BL Lac appears to be a typical quasar.

f) Infrared Fluxes

Between 3 and 10 μ the nonthermal power-law source should dominate over the galaxy flux, and we would expect the fluxes to follow a power law with $\alpha = -1.55$. The observations of Stein *et al.* (1971) at 3.5 and 11.0 μ yield $\alpha = -0.6$ with an uncertainty of at least 0.4. This discrepancy is probably not significant. Their absolute flux levels are also compatible with our predictions, although this is not highly significant in view of the variability of BL Lac. Between 1.0 and 2.2 μ the power-law source and the galaxy both contribute, and a model which fits the visual energy distribution also fits the infrared observations at 1.65 and 2.2 μ (Oke *et al.* 1969).

IV. THE ABSENCE OF EMISSION LINES

In most models for quasars, it is usual to divorce the nonthermal source from the emission-line emitting region. There are numerous arguments for doing so. If such arguments are valid, then the lack of emission lines in BL Lac is of no particular relevance, particularly since the quasar in the object appears to be quite representative. We postulate that the lack of emission lines, particularly Balmer lines, arises either (*a*) because there is no radiation generated below the Lyman limit, or (*b*) because there is insufficient gas around the central object to convert Lyman continuum radiation to Balmer-line radiation. Extrapolating the power-law spectrum to the far-ultraviolet and integrating the total number of Lyman photons, one predicts an equivalent width for Hα of about 200 Å. This equivalent width is near that usually observed in objects such as 3C 48. Since we would readily detect an emission line 10 times fainter than this, then, if our postulate (*a*) is correct, the radiation below the Lyman limit must be 10 times less than that predicted by the power law. There is no way to test this possibility at present.

Next suppose that there is radiation beyond the Lyman limit as predicted by the observed power law, but that there is little gas around the source. We now find for this gas that $N_e^2 V \leq 1 \times 10^{66}$ cm^{-3}, where N_e is the electron density and V is the volume in cm^3. An electron temperature of 20,000° K is assumed. If a uniform spherical mass of gas with $N_e = 10^5$ is assumed, then the radius is no more than 1 pc and the mass no more than 8200 $M_\odot$. The optical depth for electron scattering is 0.4. If, on the other hand, $N_e = 1$, then the radius is less than or equal to 2000 pc, the mass less than or equal to 0.8×10^9 $M_\odot$, and electron scattering is negligible. Minkowski and Osterbrock (1959), from a study of the $\lambda\lambda$3727, 3729 lines of [O II] in the elliptical galaxy NGC 1052, find $N_e^2 V = 5.6 \times 10^{61}$ cm^{-3}, which is over four orders of magnitude less than our limit for BL Lac. Thus the absence of emission lines in BL Lac is compatible with the amounts of gas typically found in elliptical galaxies. Our limit is also consistent with an estimated mass loss due to stellar evolution of 0.2 M$_\odot$ per year from the stars in the galaxy provided this mass does not accumulate for more thar 10^8–10^9 years and the density of gas remains less thar 10^2 cm^{-3}. Therefore, our second postulate appears tc be a viable one.

V. STRUCTURE AND VARIABILITY

Recent models of the VLBI structure of VRC 42.22.01 by Andrew (1973) show structure and change highly reminiscent of those of some active quasi stellar sources, such as 3C 279. Andrew's model o expanding double sources requires expansion velocitie of 10^{-3} arc seconds per year, and changes in size of thi order are apparent from the VLBI data even in th absence of a model. At our distance for BL Lac, 35(Mpc, this angular velocity corresponds to a linea velocity of separation of 1.7×10^{11} cm s^{-1}, or 5.7 time the velocity of light; nearly 3c even if both blobs ar moving at the same speed. It is of course possible tha there is no source motion in this source as in others, bu that instead there are several temporally variable spatially fixed but separated sources (the so-calle Christmas-tree model). It has also been apparent fo some time that BL Lac displays the same inverse Compton difficulty as do active quasars if the distanc is greater than a few hundred kiloparsecs (Hoyle Burbidge, and Sargent 1966; Stein *et al.* 1971). In thi case there may be a resolution via small electron pitcl angles about an essentially radial field (Woltjer 1966) or the optical radiation may not be synchrotron. It i interesting, however, that the same phenomena a approximately the same level of outrageousness exis for BL Lac as for higher-redshift QSOs if they are place at the distances suggested by their redshifts.

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REFERENCES

Andrew, B. H. 1973, *Ap. J.* (*Letters*), **186**, L3.
Andrew, B. H., MacLeod, J. M., Locke, J. L., Medd, W. J., and Purton, C. R. 1969, *Nature*, **223**, 598.
Bertaud, Ch., Dumortier, B., Véron, P., and Wlérick, G. 1969, *Astr. and Ap.*, **3**, 436.
Crawford, D. L. 1961, *Ap. J.*, **133**, 860.
DuPuy, D., Schmitt, J. L., McClure, R., van den Bergh, S., and Racine, R. 1969, *Ap. J.* (*Letters*), **156**, L135.
Hoyle, F., Burbidge, G. R., and Sargent, W. L. W. 1966, *Nature*, **209**, 751.
MacLeod, J. M., and Andrew, B. H. 1968, *Ap. Letters*, **1**, 243.
MacLeod, J. M., Andrew, B. H., Medd, W. J., and Olsen, E. T. 1971, *Ap. Letters*, **9**, 19.
Minkowski, R., and Osterbrock, D. 1959, *Ap. J.* **129**, 583.
Oke, J. B., Neugebauer, G., and Becklin, E. E. 1969, *Ap. J.* (*Letters*), **156**, L41.
———. 1970, *Ap. J.*, **159**, 341.
Oke, J. B., and Schild, R. E. 1970, *Ap. J.*, **161**, 1015.
Penston, M. V., and Penston, M. J. 1973, *M.N.R.A.S.*, **162**, 10
Racine, R. 1970, *Ap. J.* (*Letters*), **159**, L99.
Schild, R., and Oke, J. B. 1971, *Ap. J.*, **169**, 209.
Schmitt, J. L. 1968, *Nature*, **218**, 663.
Sandage, A. 1972*a*, *Ap. J.*, **173**, 485.
———. 1972*b*, *ibid.*, **178**, 1.
Stein, W. A., Gillett, F. C., and Knacke, R. F. 1971, *Natur* **231**, 254.
Tritton, K. P., and Brett, R. A. 1970, *Observatory*, **90**, 110.
Visvanathan, N. 1969, *Ap. J.* (*Letters*), **155**, L133.
Whitford, A. E. 1958, *A.J.*, **63**, 201.
Woltjer, L. 1966, *Ap. J.*, **146**, 597.