THE ASTROPHYSICAL JOURNAL, 234:810–817, 1979 December 15

OPTICAL AND X-RAY PROPERTIES OF THE NEWLY DISCOVERED BL LACERTAE OBJECT PKS 2155−304 (= H2155−304)

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Received 1979 April 18; accepted 1979 July 5

ABSTRACT

The soft X-ray source H2155−304 has been precisely located with the *HEAO 1* scanning modulation collimator, and identified with a $B_{mag} \sim 14$ object. The linear polarization, variability, spectrum, and diffuse image of the optical flux, together with the positional coincidence of the radio source PKS 2155−304, indicate that this object is a new member of the BL Lacertae class. Its characteristics are compared with those of other X-ray–emitting BL Lacertae objects, particularly Mrk 421.

Subject headings: BL Lacertae objects — galaxies: nuclei — radio sources: galaxies — X-rays: sources

I. INTRODUCTION

Over the past year or so, BL Lacertae objects have emerged as a new class of extragalactic X-ray sources. The initial suggestion that Mrk 421 was the optical counterpart of the flaring X-ray source 2A 1102+384 (Ricketts, Cooke, and Pounds 1976) was later confirmed by a more precise position from the modulation collimators on *SAS 3* (Hearn, Marshall, and Jernigan 1979). Similarly, the suggestion that Mrk 501 might be the optical counterpart for 4U 1651+39 (Forman *et al.* 1978) was confirmed by the *HEAO 1* modulation collimator (Schwartz *et al.* 1978). More recently, further BL Lacertae counterparts have been suggested for the X-ray sources 2A 1219+305 (Wilson *et al.* 1979) and H0548−32 (Mushotzky *et al.* 1978), both confirmed with the *HEAO 1* MC (Schwartz *et al.* 1979). Kinzer *et al.* (1978) have suggested three further BL Lacertae–type objects as counterparts for new X-ray sources found with the *HEAO 1* Large-Area Sky Survey experiment, and Marshall *et al.* (1978) have suggested 3C 371 as the counterpart for H1807+69 from *HEAO* A-2 observations, confirmed by a smaller error box from the *HEAO 1* LASS (Snyder *et al.* 1979), but these latter identifications do not yet have precise ($\lesssim 1'$) X-ray positions.

The soft X-ray source H2155−304 has been optically identified with an object of $B_{mag} \sim 14$ (Griffiths, Briel, and *HEAO* A-3 Group 1978, hereafter GB; Wade, Szkody, and Cordova 1978) which has been suggested to be of BL Lacertae class in a summary of observations of BL Lacertae objects with the *HEAO 1* modulation collimator (Schwartz *et al.* 1979). We present here our evidence supporting the discovery of the BL Lacertae nature of H2155−304 (= PKS 2155−304).

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II. X-RAY OBSERVATIONS

The *HEAO 1* scanning modulation collimator (MC) has been described by Gursky *et al.* (1978). A pointed observation of H2155−304 was made from 1978 November 8.67 to 8.92 UT, resulting in detection at a significance level of 18 σ in each of the two collimator systems. There is one resulting error box, of area 0.4 square arcmin (Table 1 and Fig. 1 [Pl. 10]), which falls within the *HEAO 1* LASS error box (Snyder *et al.* 1979). A preliminary version of this error box (of area 0.9 square arcmin) was obtained from the scanning data of 1977 November 12–14 and a $B_{mag} \sim 14$ object located within this error region was pointed out by GB. A preliminary optical spectrum taken by Wade, Szkody, and Cordova (1978) showed this object to be blue ($B - V < 0.1$) and featureless, but no conclusion could be drawn as to whether the object was galactic or extragalactic.

In the data from the pointed observation, the source was significantly detected in all three energy channels (0.9–2.6, 2.6–5.4, and 5.4–13.3 keV). A power-law photon spectrum

$$\frac{dN}{dE} = (0.06 \pm 0.01)E^{-2.0\pm0.4} \text{ photons cm}^{-2}\text{ s}^{-1}\text{ keV}^{-1}$$

(where the errors are standard deviations) gives a reasonable fit to the data, but with an excess of counts in the lowest energy channel (see Agrawal and Riegler's [1979] photon spectral index $\alpha = -2.4 \pm 0.3$ for data taken 1977 November 11–15). This spectral slope is steeper than the hard X-ray spectra measured for the BL Lacertae objects Mrk 421 and Mrk 501 (Mushotzky *et al.* 1978), but the latter objects were also observed to have a soft X-ray excess over the power-law fit.

Our data cannot be adequately fitted by the composite thermal spectrum of Agrawal and Riegler (1979), since neither the component at $kt = 0.14$ or that at $kt = 1.4$ keV gives a sufficient flux in our

TABLE 1

LOCATIONS OF PKS 2155−304

Wavelength Region	Position (equinox 1950.0)		Reference
		90% confidence error[a] region	
X-ray (2–12 keV)......	$21^h55^m58^s.0$, $-30°28'03''$	24W 10E 24E 10W 60N 8N 60S 8S	Figure 1*a*, this paper
Optical..............	21 55 58.2 ± 0.3, −30 27 54 ± 4		This paper (AAT setting position)
Radio................	21 55 57.9 ± 0.8, −30 27 24 ± 14		Parkes catalog (Shimmins and Bolton 1974)
	21 55 58.37 ± 0.07, −30 27 54 ± 3		Hjellming, Schnopper, and Moran 1978

[a] The corners of the error box are given as offsets in arcseconds from the most probable position.

highest energy channel. We therefore require a further higher-temperature component on the assumption of a thermal spectrum.

Our data are consistent with a point source: the formal upper limit on source size is 20″ for a 100% Gaussian.

From the scanning data of 1977 November 11–15, there is confirmation of the suggestion by Agrawal and Riegler (1979) that the source varies on the time scale of a day (this result has also been confirmed by Snyder *et al.* 1979, who observe variability on the time scale of ~6 hours). From the source fluxes given in Table 2, it is clear that the source was stronger during the 2 days (November 12 and 13) when it was scanned with high collimator transmission (the scan line is maintained at 90° from the Sun, and the source was observed with greatest efficiency on November 13.2). A search was made for variability on the time scale of 1.5 hours (one satellite orbit) during the 6 hour pointing on 1978 November 8, but no significant changes were observed.

We note that Agrawal and Riegler (1979) have presented evidence from the *HEAO* A-2 instrument for an X-ray flare lasting 1.28 s, which they associate with the soft X-ray flux from H2155−304. If this association is correct (see § V below), it would have extreme implications for an extragalactic object.

III. OPTICAL OBSERVATIONS

a) Polarization

Optical polarization measurements were made with the Minipol photopolarimeter (Frecker and Serkowski 1976) attached to the University of Arizona 1.54 m reflector in 1978 October and November, and with the same instrument attached to the 2.28 m reflector in 1978 December. The results are summarized in Table 1 and Figure 2. There is clearly a trend toward decreasing degree of the polarization over the ~3 month time scale of the observations. The average of the *B*, *V*, *R*, and *I* polarizations on the second night of observation, 1978 October 10, was 5.1 ± 0.2%, whereas the average of the *B* and *R* results on 1978 December 24 was 2.85 ± 0.2%. There is also indication of wavelength dependence, especially in the results for October 8, with the degree of the polarization being larger in the blue. There is little indication for such wavelength dependence on the nights of October 10 and December 24, however. The secular trend toward decreasing polarization is more prominent in the *B* than in the *R* or *I* bands; the polarization in the

TABLE 2

X-RAY VARIABILITY OF PKS 2155−304

Date	Average X-Ray Intensity[a]
1977 Nov 12.09–14.48 (scan)............	13 ± 2
1977 Nov 11.19–15.58 (scan)............	6 ± 2
1978 May 9.55–14.12 (scan)............	6 ± 4
1978 Nov 8.67– 8.92 (point)............	11 ± 1

[a] Unit = 10^{-11} ergs cm^{-2} s^{-1} (2–12 keV).

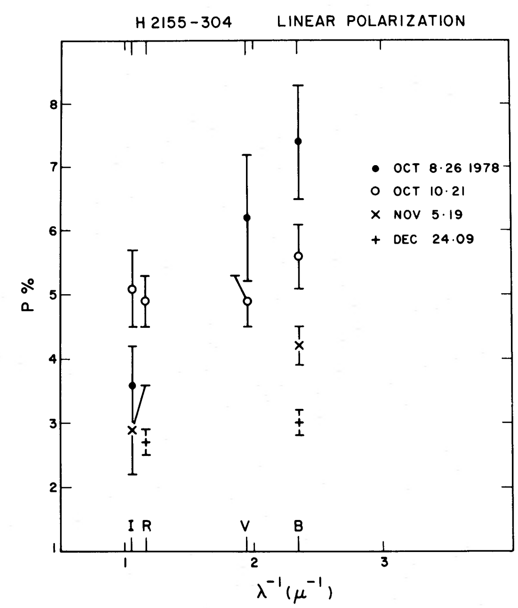

FIG. 2.—Optical polarization measurements made with the minipol photopolarimeter attached to the University of Arizona's 1.54 m reflector (1978 October and November) and the 2.28 m reflector (1978 December).

blue fell from 7% to 3% over the observational time span. There is thus a clear change in the wavelength dependence of the polarization, such that when the average level of polarization is greater, then the amplitude is larger in the blue than in the red.

There is also evidence for a possible rotation of the position angle of the polarization with time: the average for October 8 and 10 was 154° ± 4° and the averages for November 5 and December 24 were 169° ± 4° and 164° ± 3°, respectively.

Wavelength dependence of the polarization, in the same sense as that noted here—i.e., decreasing toward the red—has previously been noted in Mrk 501 and Mrk 421 (Tapia and Tarenghi 1975; Maza, Martin, and Angel 1978). These observations have been interpreted in terms of a BL Lacertae object embedded in the nucleus of an elliptical galaxy. The polarized optical flux originates in the nonthermal nuclear source, with intrinsic polarization, P_ν^N, independent of wavelength. However, the nonthermal radiation is diluted in a wavelength-dependent manner by the light from the surrounding elliptical galaxy. Following Maza, Martin, and Angel (1978), we can calculate the power-law spectral slope of the total nuclear flux, $F_\nu^N \propto \nu^{-n}$, to be $n = 1.2$ for the data of 1978 October 8. The corresponding intrinsic polarization of the nucleus is $P_\nu^N = 16 \pm 1$%, and the magnitude of the underlying galaxy, m_v(gal), is calculated as 14.9 ± 0.2, with a nuclear magnitude, $m_v^N = 14.1 \pm 0.2$; including the *K*-correction (Oke and Sandage 1968) of 0.4 mag for $Z = 0.17$ (see following section), m_v(gal) = 14.5 ± 0.2. For the observation of October 10, if the spectral index of the total nuclear flux remains constant at −1.2, then the intrinsic nuclear polarization is approximately 6%, and assuming m_v(gal, uncorrected) = 14.9 ± 0.2 as calculated above, then $m_v^N = 13.9 \pm 0.2$. We thus require a significant decrease in the intrinsic linear polarization of the BL Lacertae nucleus between observations only 2 days apart. Typically, intrinsic polarization of the nonthermal nucleus amounts to 3.6% for Mrk 421 and 7.1% for Mrk 501 (Maza, Martin, and Angel 1978). Variability in the polarization of Mrk 501, Mrk 421, and other BL Lacertae objects has previously been noted (Ulrich *et al.* 1975; Serkowski, Tapia, and Tarenghi 1975; Angel 1978). In Mrk 421, for example, the (wide passband) polarization has been observed to vary between 0.5% and 6% (Ulrich *et al.* 1975). This variability has also been observed to be wavelength-dependent for Mrk 501 and Mrk 421 (Serkowski, Tapia, and Tarenghi 1975) in the same sense as that reported here, i.e., the object becomes more polarized in the blue when the average level of polarization increases.

We note that the average level of polarization was less when the object was brightest (minimum polarization was observed on December 24, when the maximum *B* and *V* magnitudes were recorded). These data cannot be taken as evidence for generally correlated behavior, however, since similar trends sometimes seen in other BL Lacertae objects have been later followed by the inverse behavior pattern (e.g., PKS 0738+178 [Carswell *et al.* 1974] and B21308+326 [Puschell *et al.* 1979]).

b) *Optical Spectrum*

Spectra of the 14th mag stellar object were taken with the 3.9 m Anglo-Australian Telescope on the nights of 1978 December 2 and 3 UT (by A. S. Wilson, M. J. Ward, and R. E. G.). The spectra were taken using the RGO spectrograph at f/8, with the 25 cm camera and Image Photon Counting System (Boksenberg 1972) with a dispersion of 140 Å mm^{-1}. The resulting resolution was ~6 Å. No evidence was found for emission or absorption features in the spectrum, with upper limits on the equivalent widths of such features varying from about 1.5 Å at λ3600 through 1.0 Å at λ4700 to 1.5 Å at λ6000. The slope of the continuum was measured as

$$f(\nu) \propto \nu^{-0.95 \pm 0.15}$$

over the spectral range λλ4500–6700. This spectrum may be taken as evidence toward the BL Lacertae classification of the object. Spectra taken by Greenstein, Oke, and Wade (1979) using the Hale 5 m reflector and multichannel spectrophotometer similarly resulted in upper limits of 2 Å in the blue and 4 Å in the red on the equivalent widths of emission or absorption features. Charles, Thorstensen, and Bowyer (1979), however, using the Lick 3 m reflector, report the presence of weak emission lines, with equivalent widths of 0.56 and 0.96 Å, which are interpreted as [O III] at a redshift $z = 0.17$.

The *B* and *V* magnitudes reported in Table 3 represent evidence for a change in spectral slope. The colors on December 24 ($B - V = 13.1$) were similar to those reported by Wade *et al.*, i.e., $B - V < 0.1$, and are of spectral type A0 V (note that these colors are more typical of a QSO than of a BL Lacertae). The color index on October 8, however, $B - V = 0.5$, appeared considerably redder than A0 V. This variability is supported by the AAT spectrum of December 2, which gave $B - V = 0.35 \pm 0.05$.

Variation in spectral shape at visual wavelengths has also been observed in several BL Lacertae objects (Tapia, Craine, and Johnson 1976; O'Dell *et al.* 1977).

c) *Long-Term Optical Variability*

A search through the Harvard photographic collection has resulted in the long-term light curves shown in Figure 3*a*. Magnitude standards were established by measuring image diameters of stars on the blue prints of the Palomar Sky Survey and converting them to *B* magnitudes using the empirical formula derived by Liller and Liller (1975).

The *B* mag varies between 12.8 and 14.2 on time scales as short as a month. This is fairly typical of the behavior exhibited by many BL Lacertae objects (Stein, O'Dell, and Strittmatter 1976). The annual mean light curve (Fig. 3*b*) shows irregular activity

1979ApJ...234..810G

TABLE 3

Linear Polarization and Visual Magnitude of PKS 2155−304

Date 1978	JD 2,443,700.0+	P_B (%)	θ_B (deg)	P_V (%)	θ_V (deg)	P_R (%)	θ_R (deg)	P_I (%)	θ_I (deg)	B (mag)	V (mag)
Oct 8.26.........	89.76	7.4 ± 0.9	149	6.2 ± 1.0	156	...	...	3.6 ± 0.6	162	14.2 ± 0.1	13.7 ± 0.1
Oct 10.21.........	91.71	5.6 ± 0.5	153	4.9 ± 0.4	148	4.9 ± 0.4	154	5.1 ± 0.6	154	14.1	13.8
Nov 5.19.........	117.69	4.2 ± 0.3	169	...	...	...	...	3.9 ± 0.7	168	14.1	...
Dec 24.09.........	166.59	3.0 ± 0.2	160	...	...	2.7 ± 0.2	167	...	...	13.1	13.1

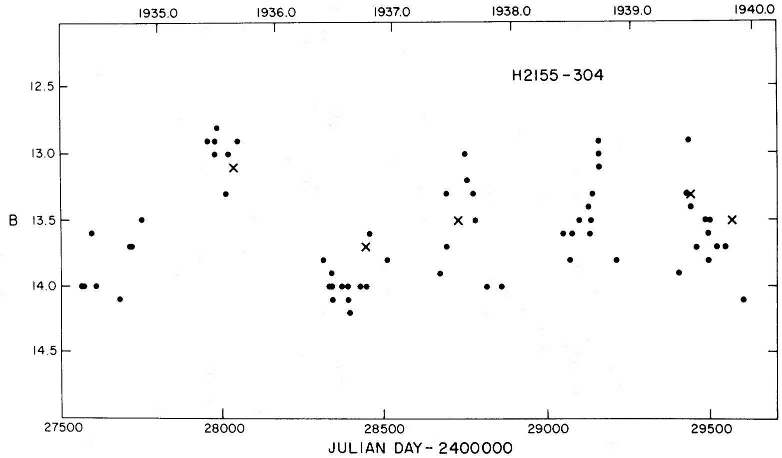

FIG. 3*a*

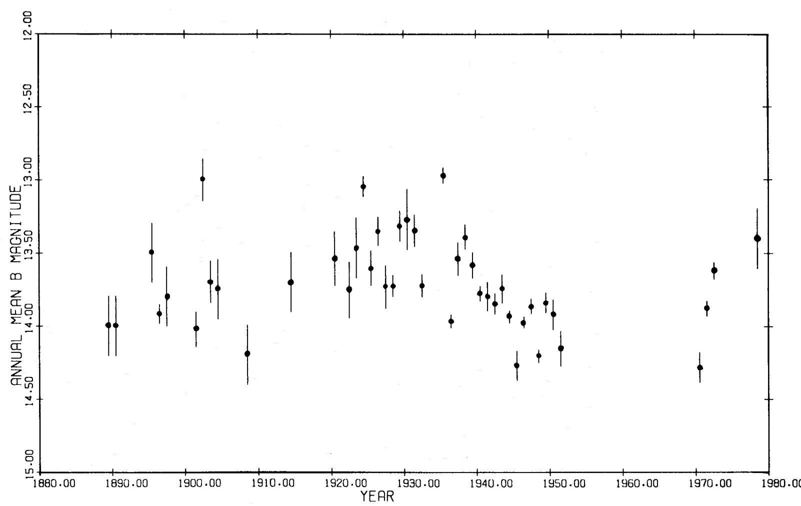

FIG. 3*b*

FIG. 3.—(*a*) Long-term *B* light curve of H2155−304, assembled from the Harvard photographic collection. Dots represent measurements with an error of ±0.1 mag, and crosses have an error of ±0.25 mag. (*b*) Presentation of the annual means of the magnitudes for H2155−304.

on the time scale of years, with the same limiting magnitudes.

d) *Photographic Plates*

In an attempt to establish the extragalactic nature of this object, we have examined plate material from (*a*) the UK SRC Schmidt sky survey, and (*b*) a far-red plate taken on the University of Arizona's 2.28 m reflector. The blue-sensitive UK Schmidt sky survey plate (III-aJ emulsion and GG295 filter) is shown in Figure 1 (left). The 80 minute exposure was made on 1978 July 16, and shows no evidence for any non-stellar components to the image of the H2155−304 object, on which the diffraction spikes are clearly visible.

A red plate of the object was exposed for 30 minutes using the 2.28 m reflector on 1978 November 19.15 UT (JD = 2,443,831.65). The broad spectral band was centered at 7500 Å, with a half-peak band-width of 2500 Å, defined by the combination of RG630 filter and the extended red spectral response of an image tube with multi-alkali photocathode. The plate is reproduced in Figure 1 (right), where it is clear that the candidate BL Lacertae object has an associated nebulosity, running approximately east-west. The nebulosity is asymmetric, with a longer and wider extension on the eastern side. From this plate alone, we cannot claim that the diffuse image is due to a galaxy. However, by analogy with some of the other X-ray–emitting BL Lacertae objects (e.g., Mrk 501 and Mrk 421), we conclude that the nebulosity is very likely the image of an elliptical galaxy. Better plate material and spectroscopy of the nebulosity are needed in order to confirm the nature of the diffuse image.

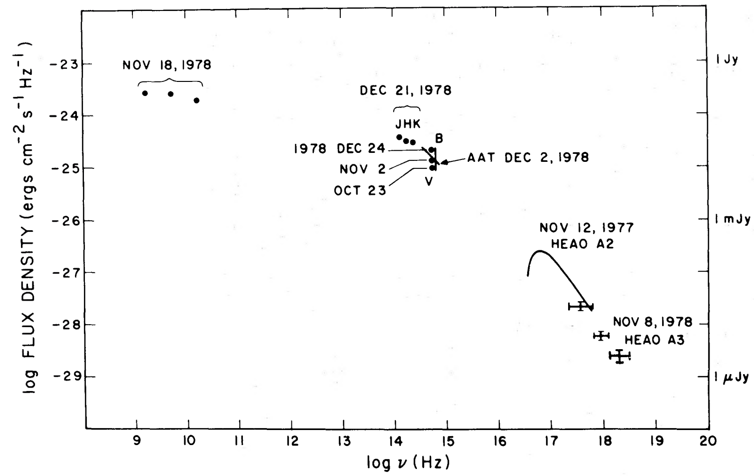

FIG. 4.—Overall spectrum of H2155−304. The radio points are from Hjellming *et al.*, the infrared points from Persson. The optical spectrum was obtained at the AAT, and the Greenstein, Oke, and Wade (1979) visual magnitudes are also shown. The vertical line marked *B* shows the total range of *B* magnitudes from the long-term light curve (see Fig. 3). The *HEAO* A-2 soft X-ray flux is from Agrawal and Riegler (1979), and the *HEAO* A-3 points are from the pointed observation (this paper).

IV. RADIO EMISSION

The 300 mJy radio source PKS 2155−304 (Shimmins and Bolton 1974) is cataloged at the position given in Table 1, some 30″ north of the optical object under discussion, but with an rms error of 14″. At our request, a more accurate position for the 300 mJy radio source has recently been obtained at the Very Large Array (Hjellming, Schnopper, and Moran 1978) with the result also shown in Table 1, i.e., consistent, within the errors, with the optical candidate. The radio spectrum of the object was found to be flat (Hjellming *et al.*; see also Fig. 4), similar to that of Mrk 421 and other BL Lacertae objects (O'Dell *et al.* 1978). The size of the radio source was found to be less than 0″.3.

V. DISCUSSION AND CONCLUSIONS

On the basis of our X-ray position, the optical properties of the stellar object, and its coincidence with the new radio position of PKS 2155−304, we identify the X-ray source H2155−304 with a new BL Lacertae object.

The overall spectrum of the object is shown in Figure 4, where the different spectral regions were not observed simultaneously. Since it is known that the object is variable at least at optical and X-ray wavelengths, we can discuss the overall spectrum only in a qualitative way. We note its resemblance to the overall spectrum of Mrk 421 (Ulrich *et al.* 1975; Schwartz *et al.* 1979). Furthermore, the spectrum at radio, infrared, and optical frequencies resembles those of several other objects in the BL Lacertae class (O'Dell *et al.* 1978), being flat in the radio region and steepening through the infrared-optical region. The X-ray spectral index (this paper; Agrawal and Riegler 1979) is considerably steeper than the radio spectral index. This is the first demonstration of such a disagreement between radio and X-ray spectral indices in a BL Lacertae object (cf. Mushotzky *et al.* 1978), and contradicts the prediction of the synchrotron self-Compton mechanism (Jones, O'Dell, and Stein 1974) which has been commonly invoked to explain or predict the X-ray emission from these objects (Margon *et al.* 1976; Mushotzky 1977; Margon, Jones, and Wardle 1978; Schwartz *et al.* 1978). The self-Compton mechanism, when applied to a relativistic Maxwellian synchrotron source, may, however, be able to satisfy the steepening in spectral slope toward higher frequencies (Jones and Hardee 1979). Alternatively, the X-ray flux may be thermal, as in the model of Colgate and Petschek (1978).

The infrared fluxes measured by Persson (1979) on 1978 December 21 lie close to an extrapolation of the power-law continuum determined by Greenstein *et al.* only 3 days later. A fit to both data sets yields a spectral index $\alpha \sim 0.44 \pm 0.07$. Comparing this index with that measured on 1978 December 2 (see § III*b* above), i.e., $\alpha = -0.95 \pm 0.15$, we have further evidence for a change in spectral slope in the optical region.

If the optical features observed by Charles *et al.* are confirmed as [O III] lines at a redshift $z = 0.17$, then the peak X-ray luminosity of the source as measured by our instrument was L_x(2–10 keV) $\sim 1.7 \times 10^{46}$ ergs s^{-1}. From the observed peak intensity of the soft X-ray flux (Agrawal and Riegler 1979), i.e., $F_x = 4.10^{-10}$ ergs cm^{-2} s^{-1} (0.15–2.2 keV), we can similarly calculate $L_{x\,\mathrm{soft}} \sim 5.10^{46}$ ergs s^{-1}. We note that this luminosity is 4 times greater than that of the maximum previously reported X-ray luminosity of a BL Lacertae object, viz., that of Mrk 421 in a flaring state (Ricketts, Cooke, and Pounds 1976), but is still less than the optical-infrared luminosity of B21308+326 in outburst, viz., $\sim 10^{48}$ ergs s^{-1} (Puschell *et al.* 1979). At a distance of 1000 Mpc ($H_0 = 50$ km s^{-1} Mpc^{-1}), the diffuse image of $\sim 10''$ extent (see Fig. 1) corresponds to ~ 40 kpc, compared with 26 × 35 kpc reported for Mrk 421 (Ulrich *et al.* 1975). From our estimates of the magnitude of the underlying galaxy, the absolute luminosity is calculated to be at the top of the luminosity function for elliptical galaxies (Schechter 1976), i.e., $M_B \sim -24$.

The *HEAO* A-2 low energy detector (LED) recorded an increase in counting rate for 1.3 s while scanning the vicinity of the BL Lacertae object (Agrawal and Riegler 1979), and this flare, if statistically significant, must therefore have come from a region of size $\leq 4 \times 10^{10}$ cm. The total blackbody emission from a region of this size at a temperature $kT \sim 0.3$ keV (with a spectral peak near 1 keV, in the *HEAO* A-2 LED energy band) amounts to $\sim 10^{43}$ ergs s^{-1}. If the flare is indeed associated with the BL Lacertae object, as Agrawal and Riegler suggest, then it represents an increase of at least $\sim 50\%$ of the steady flux, i.e., $2\text{–}5 \times 10^{46}$ ergs s^{-1}, several orders of magnitude greater than the above blackbody limit of thermodynamic equilibrium. This implies, therefore, that the flare and perhaps most of the persistent X-ray flux are of nonthermal origin. Furthermore, it has been shown, from considerations of electron scattering and the conversion efficiency from matter into energy (Fabian 1979), that such a flare implies the presence of relativistic outflow from a massive black hole, possibly coupled with beaming effects. The field of view of the *HEAO* A-2 LED (defined by a combination of 1°.5 × 3° and 3 × 3° FWHM collimators) is such, however, that the flare could have come from the nearby cataloged source H2158−321 (Marshall *et al.* 1979), which has no identification (area 4 square degrees) and may be galactic. The center of the error box for H2158−321 is only ~1°.5 away from the BL Lacertae object.

PKS 2155−304 is the second example of a BL Lacertae object found as a result of its X-ray emission (note that 2A 1219+305 was tentatively identified with a new BL Lacertae object by Wilson *et al.* 1979 from an *Ariel 5* 0.03 square degree error box, before confirmation by the *HEAO 1* MC). It can be expected that the *Einstein* observatory will lead to the discovery of significant numbers of new BL Lacertae objects as a result of their X-ray emission.

We thank the staffs of the Harvard-Smithsonian Center for Astrophysics and of the Center for Space Research of Massachusetts Institute of Technology, especially other members of the *HEAO* MC team. In particular, we would like to express our appreciation to M. Conroy, M. Garcia, E. Ralph, and W. Roberts for help with the X-ray data analysis.

We are grateful to Mrs. Sue Tritton for providing the print from the UK Schmidt sky survey plate.

This work was supported in part by NASA grants NAS8-30543 and NAS8-27972, and NSF grants AST 76-00527 and AST 76-07685.

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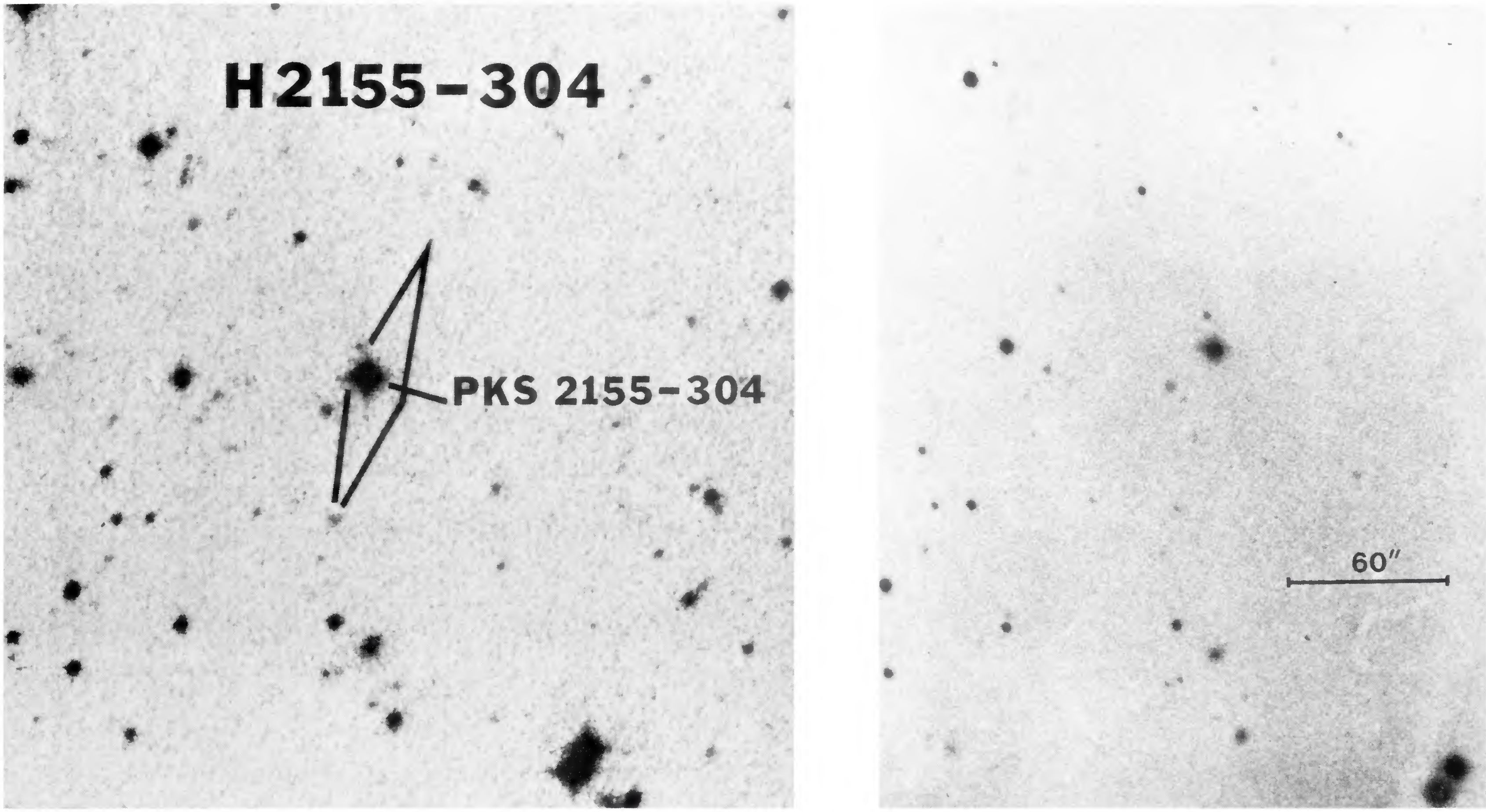

FIG. 1.—*Left*, *HEAO 1* MC error box for H2155−304 superposed on the blue-sensitive UK Schmidt sky survey plate. The 14th mag stellar object is positionally coincident with PKS 2155−304 (see Table 1). *Right*, red plate of the region around H2155−304 taken at the University of Arizona, with the 2.28 m reflector with a 2500 Å half-peak bandwidth centered at 7500 Å. The BL Lacertae object is slightly east and north of center. Note the fuzzy extensions running east and west of the starlike image. These extensions are far more pronounced than the diffraction spikes seen on the brighter objects in the southeast corner of the plate.

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