THE ASTROPHYSICAL JOURNAL, 270:L1–L5, 1983 July 1

THE DISCOVERY OF AN X-RAY BRIGHT BL LACERTAE OBJECT: 0414+009

M. P. ULMER,[1,2,3,4] ROBERT L. BROWN,[5] D. A. SCHWARTZ,[6] J. PATTERSON,[2,6] AND R. G. CRUDDACE[7]
Received 1982 November 9; accepted 1983 March 16

ABSTRACT

We have made X-ray, optical, and radio observations of an X-ray source originally discovered by Ulmer *et al.* in a survey of Abell clusters of galaxies. The relatively flat radio spectrum, the featureless optical spectrum, and the shape of the X-ray spectrum lead us to classify the source as a BL Lacertae object. The source has one of the highest X-ray flux density ratios to both the optical and radio flux densities, and its strength at all these wavelengths warrants further multiwavelength studies. The radio, optical, and X-ray flux densities for our observations were ~ 100 mJy, $V \sim 16.4$ (~ 1 mJy), and ~ 1 UFU (~ 1.6 μJy). The X-ray flux varied by a factor of 2 over a 1 year period, but no 100 s time scale variations were seen. A search of the Harvard plate stacks did not reveal any optical variations. A model for the source is presented, and the implications of this object with respect to X-ray surveys are briefly discussed.

Subject headings: BL Lacertae objects — X-rays: sources

I. INTRODUCTION

We report the optical and radio identification of an X-ray source, 1H 0414+009, that was originally associated with a rich cluster of galaxies (Ulmer *et al.* 1980). A refined X-ray position from *HEAO 1* A-3 (Gursky *et al.* 1978) and *HEAO 2* (the *Einstein Observatory*, Giacconi *et al.* 1979) led to optical and radio observations. The optical and radio work revealed a starlike object with a flat, nonthermal radio spectrum and a featureless optical spectrum. The uncommonly high ratio of X-ray flux density to the radio and to the optical flux density (S [1.4 GHz] ≈ 100 mJy, $V \approx 16.4$ and S [2–6 keV] ≈ 1.6 μJy) provides an opportunity to study this object over a wide wavelength range. We first describe our observations and results, and then we discuss the nature of this object and present a model for the source.

[1] Department of Physics and Astronomy, Northwestern University.

[2] Visiting Astronomer at Kitt Peak National Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

[3] Visiting Astronomer at the National Radio Astronomy Observatory VLA; NRAO is operated by Associated Universities, Inc., under contract with the National Science Foundation.

[4] *Einstein Observatory* Guest Observer.

[5] National Radio Astronomy Observatory, Charlottesville, Virginia.

[6] Harvard-Smithsonian Center for Astrophysics.

[7] E. O. Hulburt Center for Space Research, Naval Research Laboratory.

II. OBSERVATIONS

a) *X-Ray*

The X-ray discovery (Ulmer *et al.* 1980) was made using the Naval Research Laboratory (NRL) *HEAO 1* A-1 Large Area Sky Survey (LASS). The position and intensity were determined by applying interactive fitting routines to each day's superposed data. No spectral information was available for this observation. This object is also reported in the NRL sky survey catalog (Wood *et al.* 1982). The conversion of flux to ergs cm^{-2} s^{-1} is dependent on the spectral shape. For simplicity, we have followed Ulmer *et al.* (1981) and used a conversion appropriate for clusters of galaxies: 10^{-3} counts cm^{-2} = 3.4×10^{-12} ergs cm^{-2} s^{-1}. The uncertainty extant in this conversion of counts to energy is ~ 50%. The *HEAO 1* A-3 experiment (Gursky *et al.* 1978) detected a 3.3 σ flux in the 0.9–2.5 keV channel with the 2′ modulation collimator (MC2) consistent with the A-1 flux. The location derived from the MC2 is shown in Figure 1 (Plate L1).

We obtained two follow-up observations of this source—one with the *HEAO 2* IPC, the other with the HRI (Giacconi *et al.* 1979; Gorenstein, Harnden, and Fabricant 1981). The IPC observation revealed that the source was not Abell 480 as originally hypothesized by Ulmer *et al.* (1980); and the HRI showed the source to be pointlike (< 3″) and have a position of

$$\alpha(1980) = 04^h14^m17^s.81, \quad \delta(1950) = 00°58'02''.4,$$

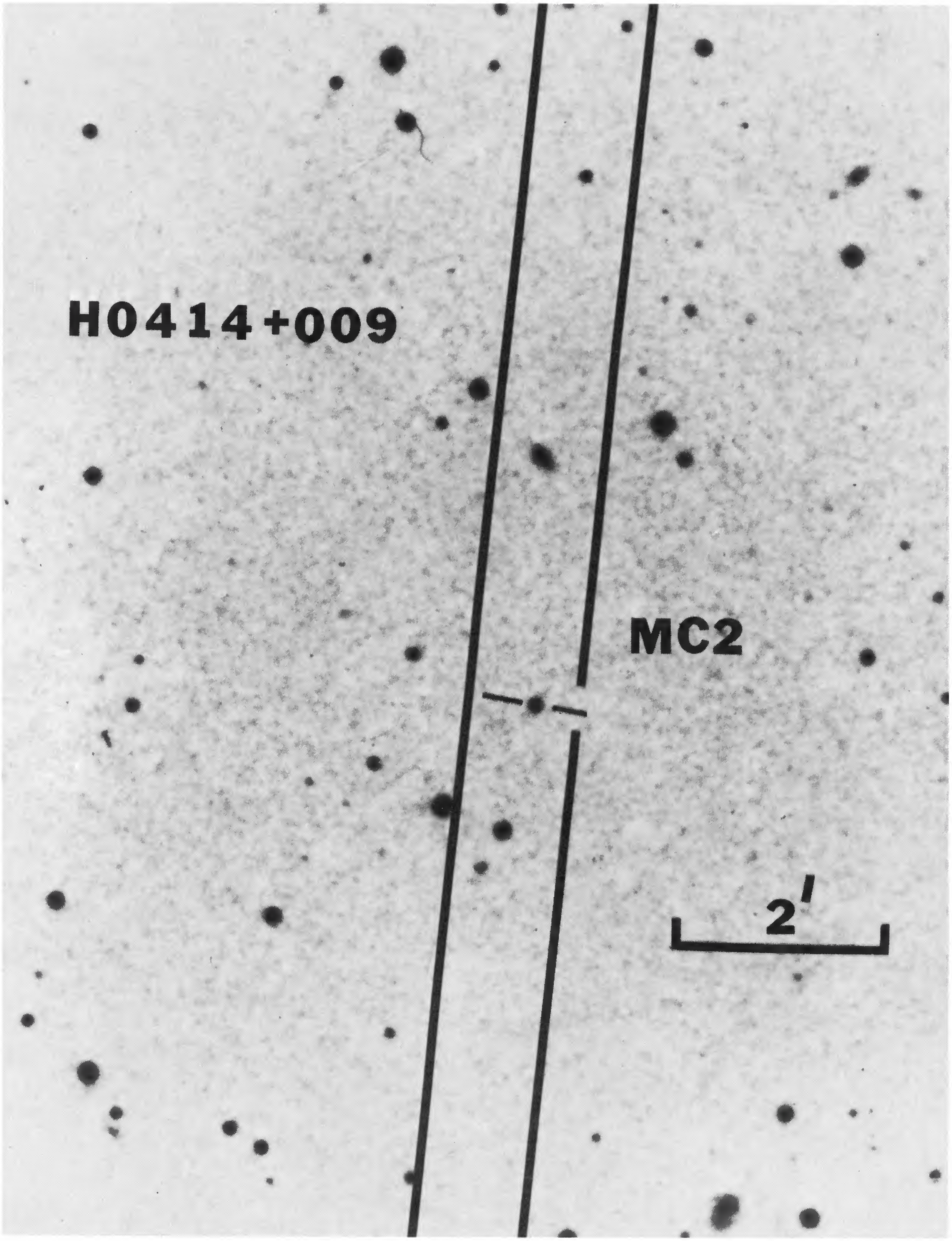

FIG. 1.—Reproduction of a portion of the POSS print with a portion of the position allowed by the *HEAO 1* A-3 MC2 (*parallel lines*). The stellar object identified with the HRI X-ray and VLA radio positions is also marked.

ULMER *et al.* (*see* page L1)

TABLE 1
BEST FIT VALUES

Year	γ	E_a (keV)	A
1980	2.4 ± 0.3	$0.9^{+0.3}_{-0.9}$	1.6×10^{-2}
1981	2.6 ± 0.2	$0.3^{+0.9}_{-0.3}$	1.17×10^{-2}

with a nominal 90% error radius of 5″. During both *HEAO 2* measurements, the source was strong enough to use the monitor proportional counter (MPC) to determine fluxes and spectral shapes. Using the form

$$F = AE^{-\gamma}/\exp\,(E_a/E)^{8/3} \text{ photons cm}^{-2}\text{ s}^{-1}\text{ keV}^{-1},$$

we found the best fit values given in Table 1. The fits were good. The values of χ^2 were 1.5 and 5.8 with 3 degrees of freedom. The fits are shown with the data in Figure 2 for the 1980 and 1981 observations respectively. The N_H in the Galaxy (Heiles 1975) along the line of sight to 0414+009 corresponds to an E_a of ~ 0.34 keV. The average flux history and observation dates are given in Table 2. Systematic effects prevent a search for variability by comparing the *HEAO 1* and *HEAO 2* results, but the MPC values alone indicate that 0414+009 has varied by a factor of 2 on the time scale of a year (see Grindlay *et al.* 1980 for a description of the MPC analysis). This result is confirmed by the coincident IPC and HRI results, which give fluxes consistent with the MPC data. The HRI data can also be used to delimit the range of photoelectric absorption values allowed if we assume the X-ray spectral shape derived by the MPC. Under this assumption, the 90% confidence E_a must have been between 0.4 keV and 0.6 keV for the 1981 observation.

We used the IPC data to search for rapid variability. This was done by sorting the data into 11 bins, each nominally 100 s long. There was no evidence for variability, with $\chi^2 = 10.5$ for 10 degrees of freedom. At the 95% confidence level, we can state that the intrinsic source variability is less than 17% on a 100 s time scale during this IPC observation.

b) *Optical*

The HRI X-ray position provided an optical identification. We then made observations to produce spectra and broad-band photometry. We also searched the Harvard plate stacks.

The high-resolution sky-subtracted spectrum taken with the 4 m telescope at Kitt Peak National Observatory (KPNO) using the high gain video spectrometer (HGVS), is shown in Figure 3. The resolution is ~ 1.5 Å per pixel, the bandpass is ~ 3900–5300 Å, and the integration time is 26 minutes. The observation was made on the night of 1981 November 18.

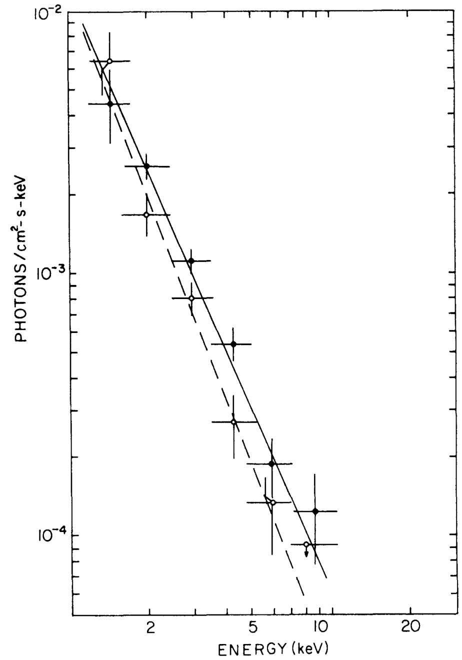

FIG. 2.—The MPC X-ray observations from 1980 (*solid circles*) and 1981 (*open circles*) and the fit power laws (see text).

Photometric work was done with the Mark II photometer on the KPNO 1.3 m telescope on 1981 September 26 and 29. Both observations are consistent with $V = 16.38$, $B - V = 0.48$, $U - B = -0.70$, within an uncertainty of 0.02 mag. For this galactic position, $l = 192°$, $b = -33°$, we derive $(B - V)_0 = 0.38$ using the reddening given by Burstein and Heiles (1982), and $(U - B)_0 = -0.78$ using $E(U - B)/E(B - V) \approx 0.75 + 0.05E(B - V)$ (cf. Allen 1976).

We searched the Harvard plate stacks to see whether the object might have had a large optical outburst in the past. There are about 300 plates between 1921 and 1949, and about 25 more extending back to 1890. The object is invisible on almost all these plates, whose faint limits

TABLE 2
X-RAY FLUX HISTORY

Satellite	Date (year, day)	Flux[a]
HEAO 1 ...	1977, 234–238	0.68 ± 0.08[b]
HEAO 2 ...	1980, 40.5	0.98 ± 0.08[c]
	1981, 23.6	0.55 ± 0.06[c]

[a]Flux in Uhuru flux units (UFU) = 1.7×10^{-11} ergs cm^{-2} s^{-1} 2–6 keV ≈ 1.6 μJy at 3.6 keV. Only the statistical uncertainties are shown.
[b]Ulmer *et al.* 1980; Ulmer *et al.* 1981.
[c]From MPC.

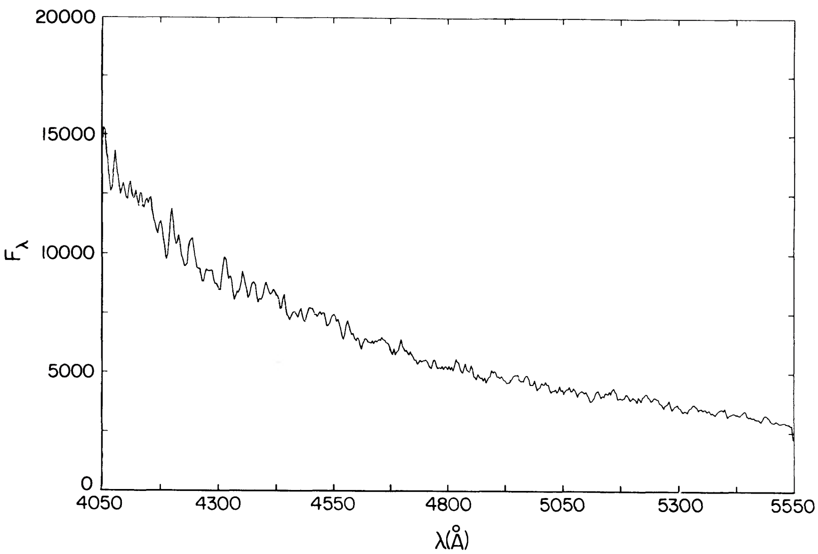

FIG. 3.—The optical spectrum taken with the KPNO 4 m telescope HGVS system in counts per pixel, where 1 pixel = 1.5 Å

ranged from ~ 14 to 16 mag. On a few plates where it is visible, it is within half a magnitude of its expected brightness as compared with neighboring stars on the plates. We also searched the Kukarkin *et al.* (1970) variable star catalog and the Ohio State radio source catalog, but we found no object at the position of 0414+009.

Astrometry on the Palomar Observatory Sky Survey (POSS) prints yields a position of $\alpha(1950) = 04^h14^m17^s.58$, $\delta = 0°58'03''.4$ with a 1''.5 rms error.

c) *Radio*

We observed the source 0414+009 with the VLA on 1981 October 26 at both 1446 and 4866 MHz. The observations were made in the C array which provided us with synthesized beam (full width at half-maximum) of 8''.4 and 2''.6 at 1446 and 4866 MHz respectively. We mapped a region 10' in diameter centered on the X-ray position, and we found a strong point source very near the map center at each frequency. We determine the radio source position to be $\alpha(1950) = 04^h14^m17^s.692 \pm 0^s.013$, $\delta(1950) = 00°58'03''.2 \pm 0''.2$, and the corresponding flux densities are $S(1446\ \mathrm{MHz}) = 101$ mJy, $S(4886\ \mathrm{MHz}) = 83$ mJy. Over this restricted range, $\alpha = 0.16$ where α is defined by $S \propto \nu^{-\alpha}$.

III. DISCUSSION

The X-ray, optical, and radio positions all agree within the uncertainty of the measurements, and there is no doubt that the X-ray source is the same as the optical and radio objects. The spectral shape from the radio to the X-ray is similar to the BL Lac object PKS 2155−304 (see Urry and Mushotzky 1982), and the optical spectrum is featureless. If optical polarization measurements showed high polarization, this would confirm the classification of 0414+009 as a BL Lac object. Without this measurement, we conclude that 0414+009 is probably a BL Lac object, and we assume this is true in the discussion that follows.[8]

With the proviso that the X-ray, optical, and radio measurements were not made simultaneously, we summarize the energy spectrum of 0414+009 as follows: (1) $\alpha_r = 0.16$, 1446–4886 MHz; (2) $\alpha_{ro} \sim 0.37$, 2.5×10^9 Hz to 6×10^{14} Hz; (3) $\alpha_o \approx 0.71$ from the *UBV* colors we measure (Mathews and Sandage 1963); (4) $\alpha_{ox} = 0.82$, 6×10^{14} Hz to 4.9×10^{17} Hz; (5) $\alpha_x \approx 1.5$, 2.4×10^{17} to 2.4×10^{18} Hz. Thus, 0414+009 has a relatively high ratio of X-ray flux to optical and optical to radio flux in comparison with other BL Lac objects which have $\alpha_{ox} \sim 1$–1.3 and $\alpha_{ro} \sim 0.55$ (Condon, Jauncey, and Wright 1978; Stein, O'Dell, and Strittmatter 1976; Kuhr *et al.* 1979; and Schwartz *et al.* 1979). The 0414+009 X-ray to optical ratio is also high in comparison with QSOs and "blazers," which have $\alpha_{ox} \sim 1.3$–1.5 (see Tananbaum *et al.* 1979; Ku 1980; Zamorani *et al.* 1981); however, the α_{ox} value of 0414+009 is similar to other X-ray selected BL Lac objects.

Compact nonthermal objects that are similar to 0414+009, in that they have large ratios of X-ray to optical emission, have been interpreted as relativistically beamed sources. In these models, the Doppler boost is so large that most of the observed emission, radio through X-ray,

[8]Rather than being identified as a BL Lac object, there is a chance that 0414+009 might prove to be like H0323+022 (Doxsey *et al.* 1983); however, the X-ray characteristics of 0414+009 are significantly different from those of H0323+022.

is dominated by the nonthermal jet (Blandford and Rees 1978; Blandford and Königl 1979; Königl 1981). This is *not* a unique interpretation of our data, but this description has been partly applied to the BL Lac object 2155 − 304 (Urry and Mushotzky 1982). Since 0414 + 009 and 2155 − 304 have two of the highest X-ray to optical ratios of extragalactic compact nonthermal sources, we apply this type of analysis here to 0414 + 009.

Following the formalism developed by Königl (1981), we can reproduce the source spectrum by describing the emission region as being an inhomogeneous jet where the (power-law) radial dependence of the magnetic field and the relativistic electron distribution follow $B = B_o r^{-1.2}$ and $K = K_o r^{-1.5}$ respectively. Here we interpret the observed spectral indices at radio and optical frequencies as indicative of optically thick and optically thin synchrotron emission, respectively, while that at X-ray energies is synchrotron radiation from an electron distribution that has been affected by radiation losses. Thus, in Königl's notation, $\alpha_{s1} = 0.16$, $\alpha_{s2} = 0.71$, $\alpha_{s3} = 1.4$, from which the power-law indices (m and n in Königl's notation) for the radial electron and magnetic field distribution may be derived. The frequency at which the synchrotron optical depth becomes appreciable is determined from the intersection of the extrapolated radio spectrum with an extrapolation of the optical spectrum assuming that the latter arises wholly from optically thin synchrotron radiation: this frequency is approximately $\nu_s = 6000$ GHz. The uncertainties in α_{s1}, α_{s2}, and α_{s3} are all $\leq 30\%$; this leads to uncertainties of the same order in the values of m and n, and to an uncertainty of ~ 2 in the value of ν_s. These uncertainties do not affect the conclusions we draw below within the context of Königl's model.

Continuing with this relativistic beaming model, we note that the X-ray spectra of BL Lac objects are usually soft ($\alpha > 1$) as is the case with 0414 + 009, but a few objects also exhibit a hard ($\alpha < 0.7$) spectrum at X-ray energies greater than 5 keV (Mushotzky *et al.* 1978; Schwartz *et al.* 1979). One identifies these two components as a continuation of the synchrotron spectrum and once-scattered Compton radiation respectively (e.g., Margon, Jones, and Wardle 1978). Since we see no convincing sign of a flattening of the high-energy X-ray spectrum of 0414 + 009, we infer that the observed soft X-ray emission is (mostly) synchrotron emission. Then, by assuming the X-ray variability (Table 1) was due to synchrotron radiation losses, we estimate the magnetic field $B_0 = 1040\ \nu_x^{-1/3} t_y^{-2/3} \approx 1.1 \times 10^{-3}$ gauss, where t_y is the variability time scale in years. Further, the limit on the Compton-scattered X-ray emission to the radio flux density at $\nu = \nu_s$ can be expressed (Königl 1981) in terms of the inner source radius, r_m, and the normalization of the electron spectrum K_o as

$$S_c/S_s = 1.6 \times 10^{-7} r_m^{-0.54} \phi K_o < 10^{-5},$$

where ϕ is the jet opening semiangle.

This expression allows us to place a limit on r_m which we use in conjunction with Königl's (1981) equations (5) and (6) and our estimate of ν_s above to conclude that

$$D^{4/5} (\gamma\beta)^{2/3} \csc^{1/5}\theta \geqslant 3.$$

Here $D = \gamma^{-1} (1 - \beta \cos\theta)^{-1}$, $\gamma = (1 - \beta^2)^{-1/2}$, β is the ejection velocity (in units of the speed of light), θ is the viewing angle, and we have assumed that the redshift of the object is not large, $(1 + z) \approx 1$.

If the velocity of the jet is not relativistic, $\beta \ll 1$, $\gamma \approx 1$, and $D \approx 1$, then we must be viewing the jet precisely down the jet axis, $\theta \ll 24''$. Since we regard this as extremely unlikely, we see that, in order to satisfy the above equation, we require that $\beta \approx 1$, that is, that the ejection velocity be relativistic. Then, since $\gamma > 1.5$, we only require that $\theta < 40°$, which is not particularly restrictive. The lack of noticeable X-ray absorption is also consistent with this picture (see Wolfe 1978). In fact, as Königl (1981) noted, we can expect relativistic jets whenever the ratio of X-ray flux density to radio flux density is as high as 10^{-5} (as it is here) and the source is very compact.

Thus, we conclude that 0414+009 is a BL Lac object whose spectrum, radio through X-ray, is adequately (not uniquely) described by a model involving beamed synchrotron radiation wherein the velocity of the beam or jet is mildly relativistic. Further, the inference noted here, that both the X-ray and optical emission are optically thin synchrotron radiation, suggests that correlated variability studies and related investigations would be particularly illuminating.

The relatively steep X-ray spectrum of 0414+009 yields a source that was readily detected by the *Einstein Observatory*. X-ray sources with 100 times lower fluxes and with α_{ox} values similar to that of 0414+009 would be barely visible (if at all) on the POSS, but such sources would be detected by the *Einstein Observatory* deep sky survey (see Murray 1981). Taken at face value, this leads us to propose that many of the unidentified *Einstein Observatory* deep sky survey sources are similar to 0414 +009. A comparison of *HEAO 1* with *Einstein Observatory* medium survey results (Stocke *et al.* 1982) suggests, however, that the fraction of BL Lac objects among extragalactic X-ray sources decreases as the apparent X-ray brightness decreases from ~ 1.5 UFU to ~ 0.01 UFU. This implies that most of the unidentified deep sky survey sources are *not* similar to 0414+009. The total number of known X-ray emitting BL Lac objects $\geqslant$ 1.0 UFU is only ~ 10, however, and the continued analysis of the NRL LASS data and the *Einstein Observatory* data banks will be needed to clarify the situation.

This work could not have been done without the help of the following people: P. Perley, who made and edited the VLA observations for us; C. Anderson, who reduced the KPNO spectral data at the Midwestern Astronomical Data Reduction and Analysis Facility (MADRAF); J. Halpern and J. Grindlay, who reduced the *Einstein Observatory* MPC data for us; and, of course, the staff at the VLA, KPNO, and SAO, who made their instruments and data available to us. We thank W. Roberts and E. Rosenthal for performing the optical astrometry and plate stack search. This work was supported, in part, by NASA contract NAS 8-30543 at SAO, and NASA grants NAG-8367, NAG-8368, NAG-8416 at Northwestern University.

REFERENCES

Allen, C. W. 1976, *Astrophysical Quantities* (3d ed.; London: Athlone), p. 264.
Blandford, R. D., and Königl, A. 1979, *Ap. J.*, **232**, 34.
Blandford, R. D., and Rees, M. J. 1978, in *Pittsburgh Conference on BL LAC Objects*, ed. A. M. Wolfe (Pittsburgh: University of Pittsburgh), p. 238.
Condon, J. J., Jauncey, D. L., and Wright, A. E. 1978, *A.J.*, **83**, 1036.
Burstein, D., and Heiles, C. 1982, *A.J.*, **87**, 1165.
Doxsey, R., Bradt, H. McClintock, J., Petro, L., Remillard, R., Ricker, G., Schwartz, D., and Wood, K. 1983, *Ap. J. (Letters)*, **264**, L43.
Giacconi, R., *et al.* 1979, *Ap. J.*, **230**, 540.
Grindlay, J. E. *et al. Ap. J. (Letters)*, **240**, L121.
Gorenstein, P., Harnden, F. R., Jr., and Fabricant, D. G. 1981, *IEEE Trans. Nucl. Sci.*, NS-28.
Gursky, H., *et al.* 1978, *Ap. J.*, **223**, 973.
Heiles, C. 1975, *Astr. Ap. Suppl.*, **20**, 37.
Königl, A. 1981, *Ap. J.*, **243**, 700.
Ku, W. H-M 1980, *Highlights Astr.*, **5**, 667.
Kukarkin, B. V., *et al.* 1970, *General Catalog of Variable Stars* (3d ed.; Moscow: Academy of Sciences).
Kuhr, H., Nauber, U., Pauliny-Toth, I. I. K., and Witzel, A. 1979, Max-Planck Institute für Radio Astronomie, Preprint No. 55.
Margon, B., Jones, T. W., and Wardle, J. F. C. 1978, *Ap. J.*, **83**, 1021.
Marsher, A. P. 1977, *Ap. J.*, **216**, 244.
Mathews, T. A., and Sandage, A. R. 1963, *Ap. J.*, **138**, 30.
Murray, S. S. 1981, in *X-Ray Astronomy with the Einstein Satellite*, ed. R. A. Giacconi (Dordrecht: Reidel), p. 281.
Mushotzky, R. F., Boldt, E. A., Holt, S. S., Pravdo, S. H., Serlemitsos, P. J., Swank, J. H., and Rothschild, R. E. 1978, *Ap. J. (Letters)*, **226**, L65.
Stein, W. A., O'Dell, S. L., and Strittmatter, P. A. 1976, *Ann. Rev. Astr. Ap.*, **14**, 173.
Schwartz, D. A., Doxsey, R. E., Griffiths, R. E., Johnston, M. D., and Schwartz, J. 1979, *Ap. J.*, *(Letters)*, **229** L53.
Stocke, J., Liebert, J., Stockman, H., Danziger, J., Lub, J. Maccacaro, T., Griffiths, R., and Giommi, P. 1982, *M.N.R.A.S.*, **200**, 27.
Tananbaum, H., *et al.* 1979, *Ap. J. (Letters)*, **234**, L9.
Ulmer, M. P., *et al.* 1981, *Ap. J.*, **243**, 681.
Ulmer, M. P., *et al.* 1980, *Ap. J.*, **235**, 351.
Urry, C. M., and Mushotzky, R. F. 1982, *Ap. J.*, **253**, 38.
Wolfe, A. M. 1978, in *Pittsburgh Conference on BL LAC Objects*, ed. A. M. Wolfe (Pittsburgh: University of Pittsburgh).
Wood, K., *et al.* 1982, preprint.
Zamorani, G., *et al.* 1981, *Ap. J.*, **245**, 357.

R. L. BROWN: National Radio Astronomy Observatory, Edgemont Road, Charlottesville, VA

R. G. CRUDDACE: Naval Research Laboratory, Code 4129, Washington, D.C. 20375

J. PATTERSON: Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

D. A. SCHWARTZ: Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

M. P. ULMER: Northwestern University, Dearborn Observatory, Evanston, IL 60201