

X-RAY STUDIES OF BL LACERTAE OBJECTS WITH THE *EINSTEIN OBSERVATORY*: CONFRONTATION WITH THE SYNCHROTRON SELF-COMPTON PREDICTIONS

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ABSTRACT

We present X-ray flux densities measured with the *Einstein Observatory* for a set of BL Lac objects with available VLBI angular sizes. We apply the static, single-component synchrotron self-Compton formalism to predict the X-ray flux densities. We find ratios of 10^{-6} – 10^{-8} for the observed to predicted flux densities and conclude that such a model, at least in its simplest form, does not explain the X-ray emission from these objects *as a class*. The hypothesis that the compact source is in relativistic motion allows a simple resolution of the discrepancy. The results agree qualitatively with a broad distribution of bulk Lorentz factors Γ with a fairly low typical value $\Gamma \approx 2$, and with a quasi-isotropic distribution of the direction of ejection relative to our line of sight.

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

I. INTRODUCTION

BL Lacertae objects as a class are known to be strong X-ray emitters (Schwartz *et al.* 1979; Ku 1980; Maccagni and Tarengi 1981*a, b*; Schwartz and Ku 1980, 1983). We use the *Einstein Observatory* data to study the X-ray emission mechanism of BL Lac objects. The observed nonthermal radio spectra and the polarization of these objects (see reviews by Stein, O'Dell, and Strittmatter 1976; Angel and Stockman 1980) demonstrate synchrotron radiation as the mechanism responsible for their radio emission. The size of the radio-emitting region (either inferred by the time variability or by VLBI) is typically less than 10^{18} cm, which requires a high radiation energy density compared to the energy density of the magnetic field. This suggests that inverse Compton scattering would be a primary and catastrophic electron energy loss mechanism, as originally pointed out by Hoyle, Burbidge, and Sargent (1966). Quantitative discussion by Jones, O'Dell, and Stein (1974*a, b*) considers a self-absorbed synchrotron source emitting X-rays by the inverse Compton process.

In this paper we consider the applicability of the Jones *et al.* formalism to a sample of 16 BL Lac objects for which radio VLBI sizes and flux densities are available in addition to the X-ray data. We use this formalism to predict the X-ray flux density at 1 keV as inferred from the radio data, and compare it to the *Einstein Observatory* measurements. We find a discrepancy of several orders of magnitude between the two, and conclude that the application of the static, single-component synchrotron self-Compton (SSC) formalism does not predict the observed X-ray flux densities of this class of objects. Such a conclusion has been

reached previously in studies of specific quasars and BL Lacs (see Hoyle, Burbidge, and Sargent 1966; Burbidge, Jones, and O'Dell 1974; Marscher *et al.* 1979; Marscher and Broderick 1981*a, b*; Urry and Mushotzky 1982).

To reconcile the discrepancy, we consider relativistic beaming of the radiation due to bulk motion of the emitting matter, and determine that the addition of one parameter, the bulk Lorentz factor Γ , can resolve the conflict. There is no previous work suggesting a functional form of the distribution of the Lorentz factors. Previous theoretical calculations have hypothesized values around 10 (Blandford and Königl 1979; Königl 1981) in order to explain the superluminal expansion and the polarization variability. Previous estimates of Γ based on X-ray fluxes have been derived from the X-ray time variability (Urry and Mushotzky 1982) or electron lifetime arguments (Worrall *et al.* 1982), and give values in the range of 20–165. In the present work we use the angular source radii measured by VLBI techniques since the regions of variable X-ray emission may not be coincident with the radio emission regions which are of interest here.

We estimate the values of Γ and find that reasonably small values are sufficient. In particular, we conclude that large (greater than 10) values of Γ do not apply to the BL Lac objects as a class.

II. SYNCHROTRON SELF-COMPTON PREDICTION OF THE X-RAY FLUX DENSITY

We employ the formalism derived by Jones, O'Dell, and Stein (1974*a, b*) to predict the X-ray flux density at 1 keV. The parameters needed are the synchrotron self-

absorption frequency f_m (in GHz); the radio flux density F_m (in Jy) at f_m ; the source angular radius θ (in milliarcsec); the redshift z ; the upper cutoff frequency f_b (in GHz); the spectral index α of the optically thin radio component, $F \approx f^{-\alpha}$; and the geometrical factors $\epsilon_{sc}, G_{sc}, f_{sa}$, which we set to unity.

The equation for the predicted first-order Compton scattering X-ray flux density F_{pred} in Jy at a frequency f is then:

$$F_{pred} = \theta^{-2(3+2\alpha)} F_m^{2(2+\alpha)} f^{-\alpha} f_m^{-(5+3\alpha)} (1+z)^{2(2+\alpha)} \times p(\alpha) \ln(f_b/f_m), \quad (1)$$

with $p(\alpha) = 6.6 \times 10^{-8} (5.5 \times 10^{-3})^\alpha (i_{a0})^{-2-2\alpha} e_{a0}^{sc}$, where i_{a0} and e_{a0}^{sc} are tabulated by Jones, O'Dell, and Stein (1974a). In particular, for $\alpha = 0.0, 0.25, 0.5$, and 0.7 , we have $p = 3.25 \times 10^{-8}$, $p = 2.7 \times 10^{-6}$, $p = 1.4 \times 10^{-4}$, and $p = 3.5 \times 10^{-3}$, respectively.

Weiler and Johnston (1980) carried out a systematic study of the radio structure of BL Lac objects. They present the equivalent Gaussian diameters and flux densities at 5 GHz measured using VLBI techniques on a single baseline. One must keep in mind that the Compton flux produced in compact objects is very strongly dependent on the size of the radio-emitting region (as the eighth power of θ for $\alpha = 0.5$), and great care must be employed in interpreting the radio diameters. Ideally, one would obtain VLBI hybrid maps at many frequencies. At 5 GHz, Bååth *et al.* (1981) have published hybrid maps of AO 0235+164 and PKS 0735+178. For AO 0235+164 they find that a circular Gaussian does fit a core, with a size and flux density consistent with Weiler and Johnston (1980), considering the observed variability in the 1 year between these two studies. On the other hand, for PKS 0735+178 Bååth *et al.* (1981) suggest that the diameter measured by Weiler and Johnston (1980) is 3 times larger because of the distortion by an additional compact component. In our calculations we adopt the equivalent Gaussian half-width at half-maximum from Weiler and Johnston (1980) as the source radius in equation (1) in order to treat all the sources uniformly. Furthermore, this is consistent with our hypothesis of the homogeneous, single-component case of the SSC formalism.

For 16 of the objects measured by Weiler and Johnston (1980) there are *Einstein* X-ray observations, including our own from the joint CFA and Columbia BL Lac survey (see Schwartz and Ku 1980, 1983) and those published by guest observers. Of these, 15 have detectable X-ray fluxes. This sample is not complete in any statistical sense, since no uniform definition or survey for BL Lac objects exists. Nevertheless, this is a substantial and quasi-random subset of all the objects commonly considered in this class. We shall keep this

limitation in mind in drawing the conclusions below. Table 1 lists the objects under study. The first column gives the coordinate names, with other commonly used names in column (2). The radii of the sources are listed in column (3), and the VLBI flux densities at 5 GHz in column (4).

The redshifts are given in column (5) where available. When the redshift cannot be determined, because of the lack of spectral features in BL Lac objects, we adopt $z = 0.4$, to give an intermediate value for the $(1+z)^{2(2+\alpha)}$ term in equation (1). The measurements of the high frequency cutoff of the spectrum generally do not exist, since they occur between the high frequency radio and the infrared regimes (Jones, O'Dell, and Stein 1974b; O'Dell *et al.* 1978). We adopt 10^4 GHz for f_b , and note that our prediction is sensitive to that value only through logarithmic dependence.

The synchrotron self-absorption frequency f_m is not measured in general. For the prediction to be unique, we must also assume that only one component contributes to X-ray flux. The highest reasonable value of f_m for this component must be the frequency of the VLBI measurements, 5 GHz. Calculations with this model (A) are given in Table 1, columns (7) and (9). As a lower limit to f_m , for that single component, we adopt the frequency at which the extrapolation from the VLBI flux density would exceed the single-dish measurements of Owen, Spangler, and Cotton (1980). (Note that this method is strictly valid only for quasi-simultaneous observations, which are not always available). In the few cases where the total flux density increases steeply with the decreasing frequency, we assume that this is due to an extended component and extrapolate from the single-dish measurements above 1 GHz. Calculations with this model (B) are given in Table 1, columns (8) and (10). Throughout this paper we assume a uniform spectral index $\alpha = 0.5$ for the optically thin component. Although single-dish spectra may often indicate $\alpha = 0.0$, theoretical considerations and multifrequency VLBI measurements, in a few cases (see Cotton *et al.* 1980), suggest that this does not represent the optically thin component of the Jones *et al.* formalism (see Kellerman and Pauliny-Toth 1981). We have repeated the calculations with $\alpha = 0.7$, the mean value observed for the X-ray spectra of quasars and Seyfert galaxies (Halpern and Grindlay 1983), and verified that the predicted X-ray flux densities change no more than by a factor of 6.

III. X-RAY DATA

The X-ray data were acquired by the imaging proportional counter (IPC) aboard the *Einstein Observatory* (Giacconi *et al.* 1979; Gorenstein, Harnden, and Fabricant 1981). The analysis was performed in a manner similar to that described by Zamorani *et al.* (1981). The

TABLE 1
X-RAY AND VLBI DATA FOR BL LACERTAE OBJECTS UNDER STUDY

COORDINATE NAME (1)	OTHER NAMES (2)	RADIO RADIUS ^a (marsec) (3)	RADIO FLUX DENSITY ^a (Jy) (4)	REDSHIFT (Reference) ^b (5)	X-RAY FLUX DENSITY AT 1 keV (Jy)			BEAMING FACTOR	
					Measured (Reference) ^b (6)	Predicted by		Model A ^c (7)	Model B ^c (8)
								Model A ^c (9)	Model B ^c (10)
0048-097	OB 081	0.2	0.71	...	6.5×10^{-8}	7.5×10^{-7}	1.7×10^{-2}	1.6	12.1
0219+428	3C 66A	0.75	0.2	0.444 (1)	1.6×10^{-7} (7,9,10)	4.0×10^{-14}	2.1×10^{-5}	0.048	2.6
0235+164	AO	0.25	1.75	0.852 (2)	1.7×10^{-7}	4.6×10^{-5}	3.1×10^{-4}	3.1	4.5
0735+178	OI 158	0.45	0.8	0.424 (3)	2.2×10^{-7}	2.3×10^{-9}	1.1×10^{-2}	0.40	8.7
0754+100	OI 090	0.3	0.53	...	1.7×10^{-7}	6.8×10^{-9}	1.2×10^{-7}	0.52	0.93
0818-128	OJ 131	0.4	0.47	...	$< 6.9 \times 10^{-8}$	3.7×10^{-10}	1.3×10^{-4}	> 0.35	> 4.5
0829+046	OJ 049	0.45	0.26	...	1.9×10^{-7} (8)	7.5×10^{-12}	2.3×10^{-9}	0.13	0.41
0851+202	OJ 287	0.45	1.44	0.306 (1)	1.2×10^{-6}	2.8×10^{-8}	1.8×10^{-5}	0.47	1.7
1101+384	Mkn 421	0.45	0.32	0.030 (4)	1.0×10^{-5} (11)	4.7×10^{-12}	2.0×10^{-7}	0.054	0.46
1219+285	ON 231	0.55	0.72	...	4.2×10^{-7}	2.5×10^{-10}	2.4×10^{-3}	0.23	5.7
1308+326	B2	0.25	1.97	0.964 (1)	2.8×10^{-7}	1.1×10^{-4}	6.2×10^{-4}	3.3	4.7
1400+162	MC3	0.7	0.08	0.244 (5)	1.0×10^{-7} (7,8)	3.4×10^{-16}	2.2×10^{-11}	0.020	0.19
1538+149	4C 14.60	0.4	0.7	...	1.5×10^{-7} (7,8)	2.7×10^{-9}	2.8×10^{-7}	0.45	1.1
1652+398	Mkn 501	0.55	0.39	0.033 (4)	1.1×10^{-5}	2.5×10^{-12}	1.7×10^{-1}	0.047	6.9
2201+044	PKS	0.35	0.16	0.028 (6)	2.1×10^{-7}	1.1×10^{-12}	9.7×10^{-10}	0.087	0.34
2254+074	OY 091	0.5	0.14	...	9.7×10^{-8} (7,8)	1.5×10^{-13}	4.1×10^{-6}	0.069	2.1

^aRadio data at 5 GHz from Weiler and Johnston 1980.

^bREFERENCES.—(1) Miller, French, and Hawley 1978. (2) Rieke *et al.* 1976. (3) Carswell *et al.* 1974. (4) Ulrich *et al.* 1975. (5) Baldwin *et al.* 1977. (6) Wills and Wills 1976. (7) Maccagni and Tarengi 1981a. (8) Maccagni and Tarengi 1981b. (9) Maccagni *et al.* 1982. (10) Feigelson and Berg 1983. (11) Hutter and Mufson 1982.

^cSee the text for the explanation of the models for calculating the predicted X-ray flux density.

background rate was determined in an annulus of inner radius 320'' and outer radius 520'', avoiding any obvious point sources. This was subtracted from the counting rate in a circle 200'' in radius around the centroid of the source. We assumed a power-law spectrum with energy index 0.5 and a galactic hydrogen column density $N_H = 4 \times 10^{20} \text{ cm}^{-2}$, consistent with the measurements of Heiles (1975) to convert the net IPC counting rate into an X-ray flux density at 1 keV. Note that this is near the logarithmic middle of the energy response of the telescope/detector system, and therefore the calculated flux density is not significantly sensitive to the assumed X-ray spectral index, given the measured broad-band X-ray counting rate. By permission we applied the same procedure to the raw data for five objects previously studied by Maccagni and Tarengi (1981a, b).

For several objects (0048-097, 3C 66A, 0235+164, 0735+178, OJ 287, 1400+162, 1538+149, and 2254+074) multiple observations were obtained. In general, the variation of the flux density was no more than a factor of a few between individual observations, and for these we calculated weighted averages. In the case of the highly variable 3C66A (Maccagni and Tarengi 1981a, b; Maccagni *et al.* 1982), we used the low state of the object (Feigelson and Berg 1983; Maccagni *et al.* 1982), assuming that it is the usual condition of the system. Column (6) in Table 1 gives the measured X-ray flux densities at 1 keV.

IV. COMPARISON WITH THE SSC PREDICTIONS

From Table 1, column (6) compared to column (7) or (8), there is a significant discrepancy between the measured X-ray flux density and that predicted by a single-component synchrotron self-Compton theory regardless of the model used. For some of the objects the prediction greatly exceeds the measurement, whereas for other objects the reverse is true. This conclusion holds for most of the sources, even allowing factors of 100 to 1000 uncertainty in the predicted flux density due to the factor of 2 uncertainty in interpreting the VLBI source size according to the uniform models of Jones, O'Dell, and Stein (1974a, b). For eight of the sources in Table 1 we could construct, ad hoc, a model with synchrotron self-absorption frequency, f_m , intermediate between models A and B which would force an agreement between the predicted and the measured flux densities. However, for eight of the 16, the nature of the prediction (too large vs. too small) does not change. Therefore, although the agreement can be considered satisfactory (within a factor of 100) for many individual sources, we conclude that the static, single-component SSC model for the X-ray emission mechanism is not sufficient to reconcile the radio and X-ray data for BL Lac objects as a class.

Strictly speaking, our calculation places only a lower limit to the predicted X-ray emission. The conflict can

be resolved, ad hoc, for the sources where the measured X-ray flux density exceeds the prediction by assuming an additional component of SSC X-ray emission. In addition, there possibly could exist another mechanism generating X-rays in those objects. However, we cannot easily reconcile the cases where the prediction greatly exceeds the measurement. Even when we use $f_m = 5$ GHz and the measured VLBI flux density for F_m , parameters yielding the lowest predicted X-ray flux, F_{pred} , allowed by the radio data, the conflict persists for AO 0235+164 and B2 1308+326.

V. BEAMING MODELS

We consider the possibility of a relativistic ejection of the emitting material. Such a scenario was first suggested by Shklovsky (1963, 1965), further developed by Rees (1966; Rees and Simon 1968), and discussed in more detail by Burbidge, Jones, and O'Dell (1974). (For a recent review, see Kellerman and Pauliny-Toth 1981). An attractive feature of this hypothesis is the ability to confront the data in a quantitative manner with the addition of one physical parameter. Relativistic beaming may also explain the apparent superluminal expansion inferred from VLBI techniques (e.g., Cohen *et al.* 1971; Marscher and Broderick 1981*a, b*), the polarization variability (Blandford and Königl 1979) of "blazar" objects, and the 200 s X-ray variability of the quasar 1525+227 (Matilsky, Shrader, and Tananbaum 1982). If the radiation from an isotropic source is beamed toward the observer, the source appears more luminous than in its rest frame. The calculated radiation density in the source is then an overestimate of the true radiation density, and therefore the calculated Compton flux is too large. If the bulk motion has the relativistic Lorentz factor Γ , the emitted radiation, as seen in the frame of the observer, will be concentrated in a cone having an opening angle $\sin^{-1}(1/\Gamma)$, which for a large Γ is $1/\Gamma$.

Let us assume that the source of radiation is moving with a velocity $\beta = (1 - \Gamma^{-2})^{1/2}$ at an angle ϕ with respect to the line of sight. The received frequency f of radiation emitted at the frequency f' in the source rest frame will be $f = \delta f'$ where

$$\delta = \Gamma^{-1}(1 - \beta \cos \phi)^{-1} \quad (2)$$

is an equivalent angle-convolved Lorentz factor, which we will call here the beaming factor.

If I_f is the specific intensity, then I_f/f^3 is a Lorentz invariant, and we can transform equation (1) to get

$$F_{\text{meas}} = F_{\text{pred}} \delta^{-2(2+\alpha)}, \quad \text{or} \quad \delta = (F_{\text{pred}}/F_{\text{meas}})^{1/(4+2\alpha)}, \quad (3)$$

where F_{meas} is the measured flux density while F_{pred} is

the value predicted by equation (1) for no beaming. It is instructive to see that $\delta = 1$ at the angle $\phi = \cos^{-1}[(\Gamma - 1)/\beta\Gamma]$, which for a large Γ gives $\phi \approx (2/\Gamma)^{1/2}$. Hence, for larger angles, one will see enhancement over the flux density predicted by the SSC formalism, whereas for smaller angles diminution will occur. It is important to note that while F_{pred} is very sensitive to θ and F_m as well as f_m , the dependence of δ on those parameters varies only as the 1 to 1.5 power for $\alpha \approx 0.5$.

VI. CONCLUSIONS

We conclude that the static, single-component synchrotron self-Compton emission mechanism does not apply to BL Lac objects *as a class*, since it predicts flux densities at 1 keV varying by 10^{-8} – 10^6 from those actually observed. One possibility is the existence of multiple, compact components making up the flat spectrum (see Kellerman and Pauliny-Toth 1969). Recent multifrequency observations of PKS 0735+178 (Cotton *et al.* 1980) do find multiple components "conspiring" to produce such a flat radio spectrum. Note from equation (1) that one could in general postulate θ , f_m , and F_m , ad hoc, to produce at least the observed X-ray flux. The confirmation of such a model could be only performed by multifrequency nearly simultaneous VLBI observations. However, the multiple components cannot reconcile the cases where the predicted flux density already exceeds that observed (see Table 1, col. [6] vs. col. [7] or [8]).

Introduction of relativistic beaming can guarantee an agreement between prediction and observation with the introduction of one parameter. The general plausibility of this explanation is supported by theories of superluminal expansion and time variability. Columns (9) and (10) of Table 1 give the beaming factors δ inferred from the models in columns (7) and (8), respectively. The distributions of δ are plotted as the histograms in Figure 1*a* and *b*, respectively for models A and B. The data presented here show that large (greater than 10) bulk Lorentz factors are not required in general in BL Lac objects as a class, although high values of Γ can exist in individual objects. Typical values of $\Gamma \approx 2$ –5 are consistent with the observations, as are power-law distributions of Γ with a negative exponent (see Schwartz, Madejski, and Ku 1982, eq. [2], for relating the observed δ values to a distribution of Γ and ϕ).

Although the above conclusion strictly applies to the compact radio/X-ray component, Schwartz and Ku (1983) show that the large number density of X-ray emitting BL Lac objects does not allow them to be only a subset of objects beamed toward us if their X-ray emission is isotropic, i.e., unbeamed. In such a case the ratio of recognized BL Lac objects to the parent population would be the relative solid angle of the beam, namely, $\pi\phi^2/4\pi \approx 1/4\Gamma^2$. For large Γ the parent popu-

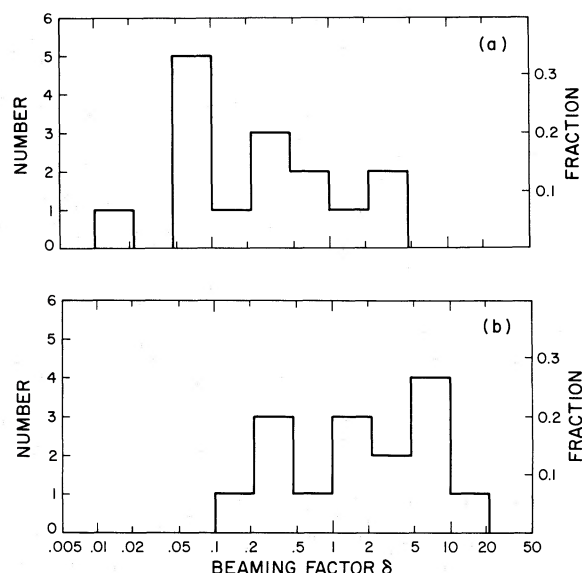


FIG. 1.—Histograms show the beaming factors derived using (a) model A or (b) model B as discussed in the text. Data are binned in equal logarithmic intervals of δ .

lation of (unrecognized) BL Lac objects would then be too numerous to be consistent with the diffuse X-ray background emissivity (Schwartz 1979) and with the *Einstein* medium survey source counts (Maccacaro *et al.* 1982). In addition, the high fraction of flat spectrum radio sources which are identified with optical counterparts (Condon *et al.* 1983) excludes the possibility that the observed optical emission is beamed with a much higher Γ than the radio/X-ray beam.

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