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ON THE SURFACE DENSITY OF X-RAY SELECTED BL LACERTAE OBJECTS[1]

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ABSTRACT

Only a handful of BL Lac objects have been found as a result of systematic optical identification of serendipitous *Einstein* X-ray sources. By combining the data from two flux-limited complete X-ray surveys (the *HEAO 1* A-2 and the *Einstein Observatory* Medium Sensitivity Survey) we have evaluated the surface density of X-ray emitting BL Lac objects as a function of their X-ray flux. We find that a single power law is not an acceptable representation of the BL Lac objects' X-ray log N–log S. The number-flux relationship is consistent with the Euclidean slope at "high" flux levels but shows a drastic flattening below fluxes of the order of 10^{-12} ergs cm^{-2} s^{-1}. We briefly discuss the implications of this result with respect to the luminosity function, the cosmological evolution, and the X-ray to optical flux ratio in BL Lac objects.

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

I. INTRODUCTION

BL Lac objects were identified as a class of strong X-ray emitters even prior to the launch of the *Einstein Observatory* (Schwartz *et al.* 1979), and early *Einstein* observations of known BL Lac objects have indeed confirmed that they are powerful X-ray sources (e.g., Maccagni and Tarenghi 1981; Schwartz, Madejski, and Ku 1982). The *HEAO 1* A-2 high galactic latitude sky survey (Piccinotti *et al.* 1982) has yielded four BL Lac objects with X-ray fluxes above the survey limit of about 3×10^{-11} ergs cm^{-2} s^{-1} in the 2–10 keV band. It was therefore expected that a large, statistically complete sample of BL Lac objects could have been gathered by searching for serendipitous X-ray sources in the many IPC images taken by the *Einstein Observatory* which are sensitive to sources more than a factor of 100 fainter than those detected in the *HEAO 1* A-2 survey.

Surprisingly only a handful of BL Lac objects (Maccacaro *et al.* 1982; Gioia *et al.* 1984) or BL Lac candidates (Chanan *et al.* 1982) have been found with this technique, despite the fact that about 200 active galactic nuclei (AGNs) have been thus far discovered (e.g., Margon, Chanan, and Downes 1982; Kriss and Canizares 1982; Reichert *et al.* 1982; Gioia *et al.* 1984). The lack of BL Lac objects among the serendipitous sources of the *Einstein* Medium Sensitivity Survey (MSS) was noted by Maccacaro *et al.* (1982) and by Stocke *et al.* (1982, hereafter Paper 1) who interpreted it as evidence that BL Lac objects do not show the same evolutionary properties shown by quasars. However, the extremely small statistics then available made this suggestion rather preliminary and called for a larger sample of X-ray sources with complete optical identification to increase the significance of the result.

Such a larger sample has become recently available; the Medium Sensitivity Survey has been updated (Gioia *et al.* 1984) and now consists of 112 X-ray sources. All but one of the sources have been identified, and the number of BL Lac objects has increased to four.[3]

We have combined these four objects with the four found in the Piccinotti survey to increase the size of the sample of X-ray selected BL Lac objects. In this *Letter* we derive an estimate of the X-ray number flux relation of BL Lac objects, and we discuss the implications of the results with respect to their luminosity function, cosmological evolution, and X-ray to optical flux ratio. A discussion of the X-ray, optical, and radio properties of these objects, and a comparison with the

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[3]1E 1207.9+3945 was originally classified by us (Maccacaro *et al.* 1982; Stocke *et al.* 1983) as an AGN on the ground that it was identified as a quasar at a redshift of 1.84 by De Ruiter, Willis, and Arp (1977). Subsequent spectra taken by us have raised doubts about the redshift of this object and its classification as a quasar, and we have excluded this object from the AGN sample (see Maccacaro *et al.* 1983 and Maccacaro, Gioia and Stocke 1984). Further spectroscopic observations have now convinced us that 1E 1207.9+3945 is a BL Lac object. 1E 0622.5−5256 is the only source with no identification yet, basically because of its projected proximity to Canopus (see Gioia *et al.* 1984). Although we could restrict ourselves, as we did in Paper 1, to the region of sky north of −25° declination, to eliminate the uncertainties due to this unidentified source, we have preferred to make full use of the statistics available since the basic result of this *Letter* would not be significantly affected by one more source being identified with a BL Lac object.

properties of a sample of BL Lac objects selected by other techniques, will be presented elsewhere.

II. THE DATA

The basic data for the four sources in the expanded Medium Sensitivity Survey (MSS) which are identified with BL Lac objects are summarized in Table 1. Of the 61 sources in the *HEAO 1* A-2 sample identified with extragalactic objects, only four have been associated with BL Lac objects (Piccinotti *et al.* 1982). Moreover, four of the seven unidentified *HEAO 1* sources have been recently identified and none with a BL Lac object (M. Elvis 1984, private communication). By restricting ourselves to the subsample of *HEAO 1* sources brighter than a limiting flux of about 3.5×10^{-11} ergs cm^{-2} s^{-1} (2–10 keV), we are dealing with a flux-limited, statistically complete sample of fully identified X-ray sources, since the three sources still unidentified have an X-ray flux below this limit. The basic data for the *HEAO 1* sample of BL Lac objects are also presented in Table 1. Columns are as follows: (1) source name; (2) redshift; (3) 0.3–3.5 keV flux (ergs cm^{-2} s^{-1}); (4) visual magnitude; (5) 0.3–3.5 keV luminosity (ergs s^{-1} in the source frame); and (6) logarithm of the X-ray to optical flux ratio.

The 0.3–3.5 keV flux for the *HEAO 1* BL Lac objects has been computed using, for each object, the measured X-ray spectrum (see, among others, Urry *et al.* 1982; Worrall *et al.* 1981; Mushotzky *et al.* 1978; Maccagni, Maccacaro, and Tarenghi 1983).

III. THE NUMBER-COUNT RELATIONSHIP

Figure 1 summarizes our present knowledge of the surface density of X-ray selected BL Lac objects. The point at the high flux end is derived from the detection of the four objects in the *HEAO 1* A-2 survey ($S > 3.5 \times 10^{-11}$ ergs cm^{-2} s^{-1}, corresponding to 5×10^{-11} ergs cm^{-2} s^{-1} in the 0.3–3.5 keV band for $\alpha_{ph} = 2.0$ and $N_H = 3.0 \times 10^{20}$ cm^{-2}; $\Omega = 2.7 \times 10^4$ deg^2). The point at the low flux end is derived from the detection of the four BL Lac objects in the *Einstein* MSS ($S > 10^{-12}$ ergs cm^{-2} s^{-1}; $\Omega = 89$ deg^2). The upper limit (95% confidence) reflects the fact that no BL Lac objects have been detected in the MSS at fluxes below 10^{-12} ergs cm^{-2} s^{-1}

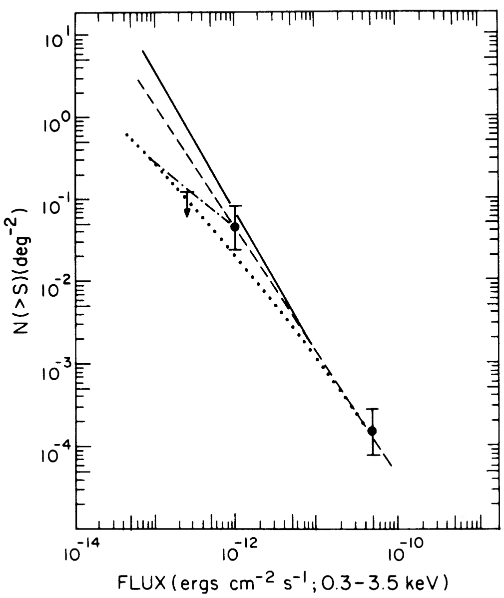

FIG. 1.—The surface density of X-ray selected BL Lac objects plotted as a function of their X-ray flux. The point at the high flux end of the figure is derived from the *HEAO 1* A-2 survey. The point and the upper limit (95% confidence) at lower fluxes are derived from the *Einstein Observatory* Medium Sensitivity Survey. Also shown are the AGN $\log N(>S)$–$\log S$ (*continuous line*), the Euclidean $\log N(>S)$–$\log S$ (*dashed line*), and a $\log N(>S)$–$\log S$ with slope 0.8 (*dashed dotted line*). The dotted line represents the $\log N(>S)$–$\log S$ of a class of sources characterized by a luminosity function with (integral) slope $\gamma = 1.25$ and no evolution. See the text for details.

TABLE 1

DATA ON X-RAY SELECTED BL LACERTAE OBJECTS

Source Name (1)	z (2)	X-Ray Flux 0.3–3.5 keV ($\times 10^{-13}$) (3)	m_v (4)	X-Ray Luminosity 0.3–3.5 keV ($\times 10^{44}$) (5)	log (f_x/f_v) (6)
1E 0317.0+1835 ...	0.19[a]	88.5[a]	18.12[a]	16.5	1.56
1E 1207.9+3945 ...	0.59[b]	14.9[c]	19.94[d]	37.4	1.52
1E 1235.4+6315 ...	0.297[a]	17.8[a]	18.52[a]	8.9	1.03
1E 1402.3+0416 ...	...	11.5[c]	16.82[d]	...	0.16
H0548−322	0.069[e]	637.0[f]	15.50[g]	14.0	1.37
H1219+305	0.13[h]	528.0[f]	16.30[i]	43.5	1.61
H1652+398	0.034[j]	592.0[f]	13.72[k]	3.0	0.63
H2154−304	0.117[l]	1520.0[f]	13.50[m]	100.3	0.95

[a] Gioia *et al.* 1984.
[b] Stocke *et al.* 1984, in preparation.
[c] Maccacaro *et al.* 1982.
[d] R. Schild 1983, private communication
[e] Fosbury and Disney 1976.
[f] Piccinotti *et al.* 1982.
[g] Disney 1974.
[h] Weistrop *et al.* 1981.
[i] Ledden *et al.* 1981.
[j] Ulrich *et al.* 1975.
[k] Puschell and Stein 1980.
[l] Bowyer *et al.* 1984.
[m] Miller and McAlister 1983.

even though they could have been detected. By comparison 87% of the AGNs found in the MSS have an X-ray flux fainter than 10^{-12}. We note that the AGN $\log N(>S)$–$\log S$ (Gioia *et al.* 1984), also shown in Figure 1 as the continuous line, indicates that AGNs and BL Lac objects are detected in similar numbers above fluxes of the order of 10^{-12} ergs cm^{-2} s^{-1}. It is evident from the data in Figure 1 that the number count relationship for BL Lac objects is consistent with a single power law only at fluxes brighter than about 10^{-12} ergs cm^{-2} s^{-1}, and that a flattening must occur at lower flux levels. We can further quantify this point by assuming a shape for the number flux relationship and then computing the expected number (and flux distribution) of BL Lac objects in the MSS. If we assume that the flux density distribution for X-ray selected BL Lac objects is well described by a single power law: $N(>S) = KS^{-\alpha}$, then, as we have shown in Paper 1, the number of sources expected in the survey is given by: $N = K\Sigma_i A_i(S_i^{-\alpha} - S_{i-1}^{-\alpha})$, where A_i is the area of sky surveyed to a limiting sensitivity S_i, ($A_i > A_{i+1}$, $S_0 = S_{\max}$; $S_n = S_{\min}$).

If BL Lac objects were characterized by the same slope which defines the AGN $\log N(>S)$–$\log S(\alpha = 1.71 \pm 0.15$; Gioia *et al.* 1984) we would expect a total of 33 BL Lac objects in the MSS, 29 of which should be detected at fluxes below 10^{-12}. For a slope $\alpha = 1.5$, 25 BL Lac objects should have been detected (21 with $S < 10^{-12}$ ergs cm^{-2} s^{-1}).[4]

A flatter $\log N(>S)$–$\log S$, ($\alpha = 1.25$, $K = 2.8 \times 10^{-17}$), would be marginally consistent with the eight detections but would still predict too many objects (eight) to be detected in the MSS below 10^{-12} ergs cm^{-2} s^{-1}. We can therefore rule out (at more than the 99% confidence level) the hypothesis that BL Lac objects are characterized by a single power law X-ray $\log N(>S)$–$\log S$, over the flux range sampled ($S > 7 \times 10^{-14}$ ergs cm^{-2} s^{-1}). We shall therefore assume that the flux density distribution of BL Lac objects is described by a model more complex. We consider here the simple case of two power laws: $N(>S_{\rm crit}) = K_1 S^{-\alpha_1}$ and $N(>S, <S_{\rm crit}) = K_2 S^{-\alpha_2}$, where $S_{\rm crit} = 10^{-12}$ ergs cm^{-2} s^{-1}.

α_1 and K_1 can be determined by the eight X-ray selected BL Lac objects. The value of α_1 is not very well determined, however, due to the poor statistics available. We shall assume $\alpha_1 = 1.5$. The obvious requirement of continuity in the number flux relationship at $S_{\rm crit}$ leads to the determination of K_2. Values of α_2 are thus constrained by the absence of BL Lac objects in the Medium Sensitivity Survey, at fluxes fainter than $S_{\rm crit}$. We find, at more than the 95% confidence level, that α_2 cannot be larger than 0.80.

IV. DISCUSSION

From the detection of eight BL Lac objects above a limiting X-ray flux of 10^{-12} ergs cm^{-2} s^{-1} and from the *non*-detection of BL Lac objects below such a flux level we have inferred that the $\log N(>S)$–$\log S$ of these objects shows a significant negative curvature. Within the approximation of two power laws, the $\log N(>S)$–$\log S$ is described by a slope $\alpha \approx 1.5$ at fluxes larger than 10^{-12} and by a much flatter slope ($\alpha \leq 0.8$) at fluxes smaller than 10^{-12} ergs cm^{-2} s^{-1}. Since the $\log N$–$\log S$ relation is mostly determined by the (local) luminosity function and by its evolution,[5] the present result can be used to set constraints on both these functions.

We have a redshift, and hence a luminosity determination, for seven out of the eight BL Lac objects in our composite sample. The four BL Lac objects in the *HEAO 1* A-2 survey (high fluxes) are all closer than the closest MSS BL Lac object. Should 1E 1402.3+0416 be at a redshift higher than 0.12 then the redshift distributions of these two samples would be significantly different, at more than the 95% confidence level. On the other hand, the X-ray luminosity distribution of the two samples largely overlaps. We have therefore evidence that, by moving to lower fluxes, we sample regions of higher redshifts more efficiently than regions of low luminosities. This is to be expected if the X-ray luminosity function is fairly flat. We have then considered different slopes γ for the BL Lac X-ray luminosity function (assumed to be a single power law) and we have integrated it within the framework of pure luminosity evolution to compute the resulting $\log N$–$\log S$ curves. We find that a marginal agreement with the observed data points and limits can be obtained if the BL Lac X-ray luminosity function has an (integral) slope $\gamma = 1.25$ and *no evolution* is assumed (see Fig. 1). This solution, however, is not unique. Although it is not possible to reconcile the data with the assumption that BL Lac objects evolve like AGNs do (if so we should detect BL Lac objects at much higher redshifts than observed), we cannot rule out steeper luminosity functions and an evolution opposite that required for quasars. It is worth noting that a slope $\gamma = 1.25$ is in agreement with the result of Schwartz and Ku (1983) on the local volume emissivity of BL Lac objects (see also Perez-Fournon and Biermann 1984).

The lack of BL Lac detections at very faint X-ray fluxes is supported by the results of two recent optical surveys (Impey and Brand 1982; Borra and Corriveau 1984). These two surveys, based upon optical polarization, though complete to 19 mag and 20 mag, respectively, failed to find any new BL Lac objects. Borra and Corriveau also interpreted their result by suggesting that BL Lac objects do not show the large increase in space density with cosmic time observed in quasars. Unfortunately the statistics are still too scanty to allow us to further constrain evolutionary models for BL Lac objects, and a much larger sample is needed to test whether these objects are characterized by a cosmological evolution opposite that required for quasars, or whether they do not show any evolution at all. We note that the former case is consistent with the prediction of a recent model of BL Lac object and quasar evolution (Stocke and Perrenod 1981), wherein quasars occur only in areas of space where the gas density is below a certain critical value; BL Lac objects, above that value. By this hypothesis, the strong dynamical evolution of bound groups and clusters of galaxies in the recent past (models of which

[4]In these computations the normalization K of the $\log N(>S)$–$\log S$ was such as to match the observed number of objects above a flux of 10^{-12} ergs cm^{-2} s^{-1}.

[5]The $\log N$–$\log S$ is also a function of the assumed geometry of the universe. For relatively low redshift, however, values of q_0 between 0 and 1 do not lead to large differences in the shape of the $\log N$–$\log S$.

were developed to investigate the evolution of cluster X-ray emission; Perrenod 1978), allows no sites for BL Lac objects beyond $z \approx 0.3$–0.5 and an increasing number of sites for quasars beyond those same epochs.

It is possible to imagine other effects which may be responsible for the lack of BL Lac detection at faint X-ray fluxes. If the energy spectrum of BL Lac objects were often characterized, in the X-ray domain, by two power laws, a very steep one at low energies and a flatter one at higher energies (cf. Riegler, Agrawal, and Mushotzky 1979), then, as the redshift increases, the steep soft component is redshifted outside the energy range of the IPC with a consequent significant decrease in X-ray luminosity. The measured X-ray flux will also decrease, and a percentage of the objects will fall below the minimum detectable flux. In this picture an inverse correlation of the ratio $L_x/L_{\rm opt}$ with redshift is expected (since is extremely unlikely that the *K*-correction in the optical band would play exactly the same role). However, in the sample of optically selected BL Lac objects observed by Schwartz and Ku (1983) there is no evidence of any decrease of $L_x/L_{\rm opt}$ with redshift, despite the fact that 11 of those BL Lac objects have $z > 0.5$, which is in the redshift range where the turn-off of X-ray BL Lac objects is expected to occur. The lack of simultaneous X-ray and optical flux measurements and the very small number of BL Lac objects for which a redshift determination is available, however, makes the search for such a dependence in the existing data rather difficult.

Finally it is worth noting that it has been suggested (Guilbert, Fabian, and McCray 1983) that in the framework of accretion models onto a central black hole, the presence of lines in the optical spectra of AGNs depends on the slope of the X-ray spectrum. The hard ($\alpha_{\rm ph} \approx 1.7$; Mushotzky 1982; Halpern 1982) X-ray spectrum of AGNs can heat the accreting gas by Compton scattering, thus creating the conditions for the existence of a broad-line region (BLR), while in objects with softer X-ray spectra like BL Lac objects, the existence of a BLR is inhibited by the fact that the gas does not reach temperatures in excess of 10^6 K. Furthermore, White, Fabian, and Mushotzky (1983) have compared the X-ray spectrum of Cyg X-1 in the high and low state with that of BL Lac objects and Seyfert galaxies, respectively. On the basis of a previous model for Cyg X-1 (Guilbert and Fabian 1982), they suggest that the transition between hard and soft spectra depends on the ratio of the X-ray luminosity to Eddington luminosity. If we accept this line of thought, mainly that AGNs and BL Lac objects are identical systems, and that the dichotomy is tied to a critical X-ray luminosity, we would expect that, at decreasing X-ray fluxes, given a unique mass and redshift distribution of the objects, BL Lac objects will progressively disappear from the survey because their X-ray luminosity will become too low with respect to their Eddington luminosity, the existence of a BLR will be favored and the object will be classified as AGN. Indeed, low-luminosity AGNs are commonly selected in X-ray surveys (Maccacaro and Gioia 1983 and references therein). We also note that the $f_x/f_{\rm opt}$ mean value for BL Lac objects is higher than for AGNs (Gioia *et al.* 1984), meaning that at the same redshift and for similar distribution in optical luminosities, X-ray selected BL Lac objects have higher X-ray fluxes, and therefore luminosities, than AGNs.

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