1983ApJ...273...70M

THE ASTROPHYSICAL JOURNAL, 273:70–74, 1983 October 1
© 1983. The American Astronomical Society. All rights reserved. Printed in U.S.A.

THE X-RAY SPECTRA OF THE BL LACERTAE OBJECTS PKS 0548−322 AND 3C 66A

DARIO MACCAGNI[1]
CNR, Istituto di Fisica Cosmica, Milano, Italy

TOMMASO MACCACARO[2]
Harvard-Smithsonian Center for Astrophysics

AND

MASSIMO TARENGHI[1]
European Southern Observatory, Garching bei München, West Germany

Received 1982 December 27; accepted 1983 March 14

ABSTRACT

We have observed two BL Lac objects, PKS 0548−322 and 3C 66A, on several occasions with the *Einstein Observatory*. We combine the simultaneous imaging proportional counter and monitor proportional counter data to derive the energy spectra of the two sources between 0.2 and 10 keV. 3C 66A is found to be variable, both in intensity and spectral shape, within our data set. PKS 0548−322, which shows a constant behavior in our data, is inferred to have experienced a variation in its spectrum by comparison with results from other experiments. We discuss the implications of flux and spectral variability in BL Lac objects for models of X-ray emission mechanisms, and we find plausible that the wide spread in the spectral index distribution is due to the detection of the highly variable synchrotron-produced X-rays generally undetected in QSOs.

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

I. INTRODUCTION

Many experimental data on single objects can be accounted for by relativistic jet models (Königl 1981; Marscher 1980), which were originally invoked to explain the superluminal expansion of some radio sources (Blandford and Rees 1978). These models generally imply that BL Lac objects are intrinsically the same physical objects as QSOs, some properties like polarization and avoidance of the so-called Compton catastrophe being either enhanced or naturally explained by the relativistic effects due to the bulk motion of the plasma constituting the jet and by the geometry of the system observer-object. A description of active galactic nuclei (AGNs) (Seyfert galaxies and QSOs) where the geometry is the main differentiating feature between QSOs and BL Lac objects is very attractive, but its validity has been questioned by recent results. Madejski and Schwartz (1983), for instance, have analyzed a set of X-ray emitting BL Lac objects with available VLBI angular sizes and concluded that the synchrotron self-Compton formalism can explain the X-ray emission provided the sources are in relativistic motion, but the distribution of the bulk motion directions relative to our line of sight must be quasi-isotropic. There are other differences in the properties of QSOs and BL Lac objects that can be considered as evidence that they belong to two different populations. Schwartz and Ku (1983) conclude from the analysis of the absolute volume density of BL Lac objects that it is unlikely that the difference between these objects and quasars is solely due to the orientation of a relativistic beam. Moreover, BL Lac objects do not show the same amount of cosmological evolution shown by quasars either in the optical (Setti 1978; Woltjer and Setti 1982) or in the X-rays (Maccacaro *et al.* 1982; Stocke *et al.* 1982).

The knowledge of the energy spectra of this class of objects is a powerful tool for further investigation of the nature of BL Lac objects and their relationship with other AGNs. During 1979 and 1980, we have therefore observed several BL Lac objects with the *Einstein Observatory*. Preliminary data obtained with the imaging proportional Counter (IPC) have already been published (Maccagni and Tarenghi 1981*a*, *b*). In this paper we present the observations of the two X-ray brightest BL Lac objects in our sample, PKS 0548−322 and 3C 66A, for which we have data also from the monitor proportional counter (MPC). The detection of these two sources by the MPC, which is sensitive in the range from 1.2 to 20.0 keV, allows us to overcome the difficulties in determining the energy spectrum brought about by the varying and still poorly known gain of the IPC.

II. OBSERVATIONS

a) PKS 0548−322

We observed PKS 0548−322 three times, in 1979 on February 28 and March 26, and in 1980 on March 3.

[1] Guest Observer with the *Einstein Observatory*.
[2] Also CNR, Istituto di Radioastronomia, Bologna, Italy.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1983ApJ...273...70M

The IPC field contains only this source, which is also detected by the MPC on all three occasions (for a description of the instruments, see Giacconi *et al.* 1979 and Halpern 1982). We consider only the MPC data in the first six energy channels (range 1.2–10 keV) since the two channels at higher energy (10–20 keV) are often significantly contaminated by large uncertainties in the background subtraction. In the energy range used, the MPC has an energy resolution of $\sim 30\%$ (0.5 keV at 1.25 keV and 1.2 keV at 5.9 keV). Since for all the observations, the pulse-height analyzer (PHA) distributions of the MPC counts can be ascribed to the same parent distribution, we summed all the data together, to maximize the signal-to-noise ratio, and then tried a best fit with a power-law spectrum with low-energy cut-off due to photoelectric absorption. We derived a best fit energy slope α of 1.1 with an associated 95% confidence error of ± 0.2 and an upper limit of $N_{\rm H} < 5 \times 10^{21}$ cm^{-2} for the amount of the absorber.

The derivation of the spectral parameters from the IPC pulse-height spectrum depends on the detector gain which is a function of the position within the counter and of the time of the observation. Until the data are reprocessed, the correction for the position dependence cannot be made but the time dependence is easily accounted for. The resultant gain value is at present uncertain by about $\pm 10\%$ for sources detected in the central region ($2' \times 2'$) of the IPC. We have thus checked how well the spectral parameters derived from the MPC data fit the IPC data for each observation. To do so, we have tried a best fit to the IPC data with a power-law spectrum of slope $\alpha = 1.1$ as determined by the MPC. We have left as free parameters the amount of photoelectric absorption as well as the normalization of the spectrum. We have restricted our analysis to the inner 10 of the 15 IPC energy channels, corresponding approximately to 0.2–4 keV, where the signal-to-noise ratio is optimized.

In all cases we have derived the same best fit value of about 4.5×10^{20} cm^{-2} for the amount of photoelectric absorption, and we have found an excellent agreement between the distribution of the observed counts and the one implied by the MPC slope of $\alpha = 1.1$ (see Fig. 1). A slight difference ($\sim 30\%$) in the normalization between IPC and MPC data is considered acceptable, given the uncertainties due to the combined systematic errors of the two instruments. All this provides independent support to the MPC fit. In Figure 2, the derived energy spectrum of PKS 0548 − 322 is shown. IPC data points are from the observation of 1979 February and have been normalized (at 2 keV) with the MPC data (sum of three observations). We note that we have allowed the IPC gain to vary within the suggested $\pm 10\%$ limits and that best fits were always obtained for a gain very close to the nominal value.

The results of our observations of PKS 0548 − 322 can be summarized as follows (see also Table 1). (1) No intensity variability is apparent in our data, nor is there evidence of variation in the spectral shape (slope or photoelectric absorption). (2) The X-ray spectrum in the range from 0.2 to 10.0 keV is well described by a single power law with energy index 1.1 and a low-energy cut-off given by a hydrogen column density of 4.5×10^{20} cm^{-2}. This value is entirely accounted for by the neutral hydrogen in our own Galaxy in the direction of PKS 0548 − 322 ($l = 237.6$, $b = -26.1$) (Heiles 1975).

In addition to these measurements, there are several other determinations of the X-ray spectral index of

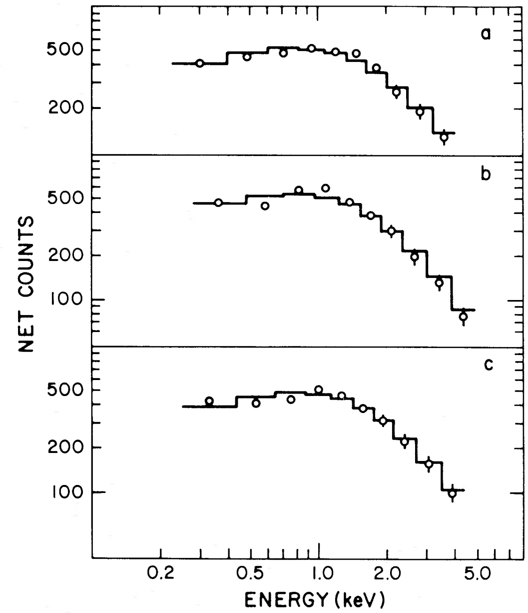

FIG. 1.—The observed IPC pulse-height distributions (○) for the observations of PKS 0548 − 322 on (*a*) 1979 February 28; (*b*) 1979 March 26; and (*c*) 1980 March 3 vs. the distribution predicted from a power-law energy spectrum, of slope $\alpha = 1.1$. with low-energy cut-off (see text for details).

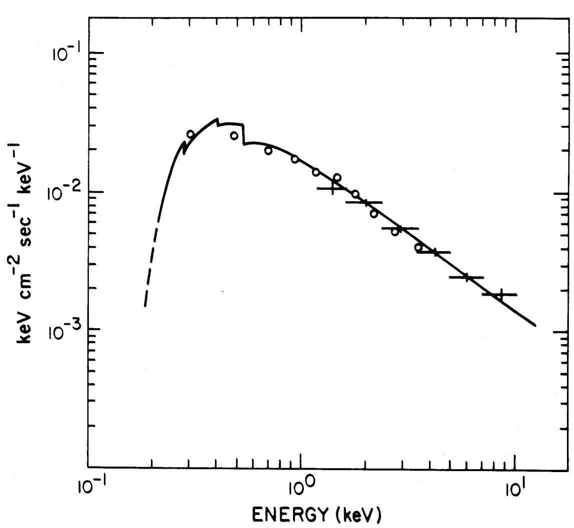

FIG. 2.—The derived 0.2–10 keV energy spectrum of PKS 0548 − 322. IPC data points (○) are from the observation of 1979 February and have been normalized at 2 keV with the MPC (+) data (sum of the three observations).

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1983ApJ...273...70M

TABLE 1

RESULTS OF X-RAY OBSERVATIONS

		MPC				IPC		
SOURCE	DATE (year/month/day)	Exposure (s)	Flux[a] (1.2–10 keV) (ergs cm^{-2} s^{-1})	N_H (cm^{-2})	α	N_H (cm^{-2})	Flux[a] (0.2–4 keV) (ergs cm^{-2} s^{-1})	Exposure (s)
PKS 0548−322 ...	1979/2/28	2294	$(5.42 \pm 0.12) \times 10^{-11}$	$<5 \times 10^{21}$	1.1 ± 0.2	4.5×10^{20}	$(5.25 \pm 0.10) \times 10^{-11}$	2314
	1979/3/26	1475				4.4×10^{20}	$(5.35 \pm 0.10) \times 10^{-11}$	2232
	1980/3/03	2294				4.8×10^{20}	$(5.07 \pm 0.10) \times 10^{-11}$	2236
3C 66A	1979/7/29	1532	$(1.32 \pm 0.12) \times 10^{-11}$	$<1 \times 10^{22}$	2.1 ± 0.6	2.9×10^{21}	$(1.42 \pm 0.06) \times 10^{-11}$	1567
	1979/8/25	1475				1.7×10^{21}	$(1.19 \pm 0.08) \times 10^{-11}$	732
						2.2×10^{21}	$(1.33 \pm 0.05) \times 10^{-11}$	1580
	1979/8/27	1475	...	...	[b]	[b]	$(0.97 \pm 0.04) \times 10^{-11}$	2379

[a] Calculated from best fit parameters. Errors are from photon counting statistic only.
[b] A slope $\alpha = 4.2$ is derived from the IPC data ($N_H = 10^{21}$ cm^{-2}).

PKS 0548−322. For 1977 September 19–21, Riegler, Agrawal, and Mushotzky (1979) report a two-component spectrum with indexes 2.2 ± 0.4 below 2 keV and $0.3^{+0.4}_{-0.3}$ above 2 keV. Worrall *et al.* (1981) give $4.0^{+3.0}_{-1.5}$ (2–10 keV) for 1978 March 12–22 and $1.75^{+0.4}_{-0.3}$ (2–15 keV) for September 30. Between 0.6 and 4.5 keV, Urry *et al.* (1982) find 1.2 ± 0.3 on 1979 March 10 and 1.1 ± 0.3 on 1979 April 6. The spectral slope we obtain here is in excellent agreement with the solid state spectrometer (SSS) measurement of Urry *et al.* and probably is not different from the one of 1978 September 30. The comparison of all these measurements indicates that the X-ray spectrum of PKS 0548−322 has undergone a change over the period from 1977 to 1979. In particular, our measurements and that of Riegler, Agrawal, and Mushotzky differ mainly because of the soft X-ray excess these authors find, which is not present in our data, thus making unnecessary a two-component fit. As for the source intensity, our measurements agree with the 1979 March 10 measurement of Urry *et al.*, but indicate a higher intensity than on 1979 April 6. As they remarked, flux comparisons between two different instruments are not straightforward: however, if their two SSS measurements are significantly different, then this would imply a small variation in the flux of PKS 0548−322 on a time scale of 11 days between 1979 March 26 and April 6.

b) 3C 66A

3C 66A has been observed on four different occasions: on 1979 July 29, August 25 and 27, and on 1980 July 23. We have already reported on the flux variability of this object, from the analysis of the IPC data (Maccagni and Tarenghi 1981*a*, *b*). Evidence for variability is present also in the MPC data. Although much weaker than PKS 0548−322, 3C 66A is in fact detected by the MPC in the first two occasions, marginally detected in the third one. In the last observation, its low absolute flux and the fact that other sources of consequently comparable intensity are present in the field of view make it impossible to use the MPC data. These other sources (3C 66B, a diffuse emission associated with a concentration of galaxies in the cluster Abell 347, and a third unidentified source) do not affect the MPC data when 3C 66A is in its "high" state, i.e., during our 1979 observations. At that epoch, in fact, their combined emission accounts for no more than 10% of the IPC flux of 3C 66A (Maccagni and Tarenghi 1981*a*). In the optical, Pica *et al.* (1980) report a maximum variation of 1.2 mag during their 5 year monitoring of the object (1974–1979). During the period in which we have X-ray data, the partially overlapping monitoring of both Pica *et al.* and Barbieri, Cristiani, and Romano (1982) do not show variations of comparable magnitude with the X-rays.

In order to obtain spectral information on 3C 66A, we adopted the same procedure we followed in the case of PKS 0548−322. The MPC data for 1979 July 29 and August 25, at constant source intensity and consistent PHA distribution, were summed together to increase the signal-to-noise ratio. A power-law spectrum fits the data with $\alpha = 2.1 \pm 0.6$ (95% confidence level) and $N_H < 10^{22}$ cm^{-2}. As we did for PKS 0548−322, we have checked for consistency between the IPC and the MPC data. First, we have analyzed the IPC data obtained simultaneously to the MPC data used to derive the spectral fit. Since the IPC observation of August 25 experienced a gain variation, we have divided it in two pieces for a more accurate analysis. In all of the three above cases we have derived consistent best fit values of about 2.5×10^{21} cm^{-2} for the amount of photoelectric absorption, and we have found, once again, an excellent agreement between the distribution of the observed counts and the one implied by the slope $\alpha = 2.1$ derived from the MPC (see Fig. 3). We have then analyzed the IPC count distribution from the August 27 observation and found it inconsistent with a spectral slope of 2.1 and $N_H = 2.5 \times 10^{21}$ cm^{-2} (see Fig. 4). Lowering the value of the absorption to 7×10^{20} cm^{-2} (the amount of hydrogen in our own Galaxy measured by Heiles 1975 at $l = 140.1$, $b = -16.8$, the direction of 3C 66) does not eliminate the disagreement, and it is necessary to assume a slope $\alpha = 4.2 \pm 0.3$ at $N_H = 1 \times 10^{21}$ to fit the observed count distribution.

It is unfortunate that, in the simultaneous MPC

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1983ApJ...273...70M

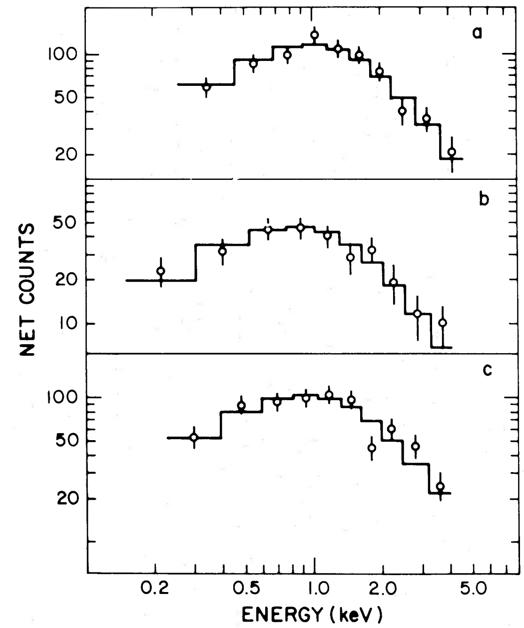

FIG. 3.—The observed IPC pulse-height distribution (○) for the observations of 3C 66A on (*a*) July 29; (*b*) August 25 low gain; and (*c*) August 25 high gain vs. the distribution implied by a power-law energy spectrum, of slope $\alpha = 2.1$ with low-energy cut-off (see text for details).

observation, the source is only marginally detected and consequently it is not possible to use these data to support this finding. However, the excellent agreement between IPC and MPC data we have found so far is convincing evidence of the reliability of our IPC spectral analysis, and we are therefore convinced that a spectral steepening did indeed occur contemporaneously with the intensity decrease.

Finally, in the 1980 observation, the statistics are too poor, even in the IPC, to attempt to determine the spectral shape. Nonetheless, a slope of the same steepness of the August 27 one is suggested by the pulse-height distribution of the counts. These results are summarized in Table 1. In Figure 5, the derived energy spectrum of 3C 66A is shown. IPC data points are from the observation of 1979 July and have been normalized (at 2 keV) with the MPC data (sum of the first two observations).

III. DISCUSSION AND CONCLUSIONS

The results we obtained put forward, once more, the variability characteristics of BL Lac objects.

PKS 0548 − 322 shows a rather flat spectrum which has probably changed since 1977 September. 3C 66A has an X-ray spectrum which is already steeper during the intensity peak of 1979 July–August and further steepens when the intensity begins to drop. In the two cases we have discussed, the X-rays are probably the tail of the synchrotron emission detected in the infrared and optical bands. This has already been pointed out by Urry *et al.* (1982) for PKS 0548 − 322 and is probably true also for 3C 66A where the spectral steepening is most readily interpreted as the effect of aging of the electron population losing energy via the synchrotron mechanism.

Recently, Halpern and Grindlay (1983) have pointed out that the X-ray spectral index distribution of Seyfert galaxies and QSOs is narrowly peaked around 0.7 and pointed out the ubiquity, in AGNs, of such slope. Although their sample of AGNs, being entirely made up of objects detected by the MPC, favors sources with flat spectra, this matter deserves further investigation. On the other hand, the distribution of X-ray spectral indexes of BL Lac objects collected by Maccacaro and

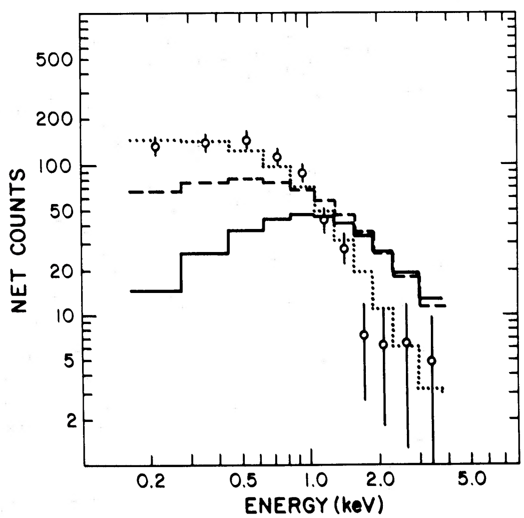

FIG. 4

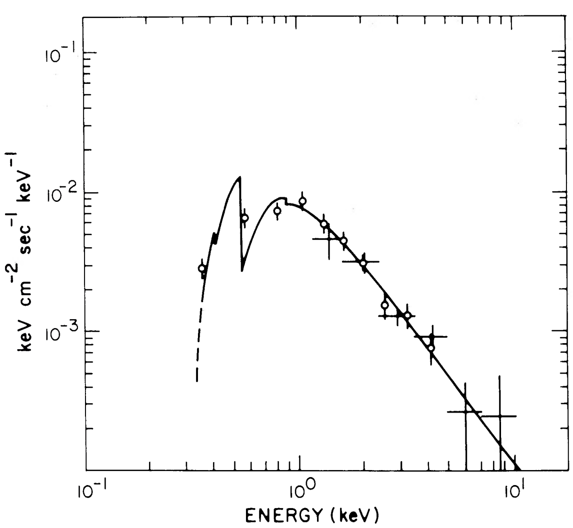

FIG. 5

FIG. 4.—The observed IPC pulse-height distribution (○) for the observation of 1979 August 27 vs. the distribution predicted by a power-law spectra with low-energy cut-off of slope $\alpha = 2.1$ and $N_H = 2.5 \times 10^{21}$ cm^{-2} (*solid line*), $\alpha = 2.1$ and $N_H = 7 \times 10^{20}$ cm^{-2} (*dashed line*), and $\alpha = 4.2$ and $N_H = 10^{21}$ cm^{-2} (*dotted line*).

FIG. 5.—The 0.2–10 keV energy spectrum of 3C 66A. IPC data points (○) are from the observation of 1979 July 29 and have been normalized at 2 keV with the MPC (+) data (sum of July 29 and August 25 observations).

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1983ApJ...273...70M

Gioia (1983) is indicative, for these objects, of an extremely varied situation. Apart from the two objects we have presented in this paper, whose spectral indexes are both different and variable in time, we have also marginal evidence that in the IPC range (0.2–4 keV) the BL Lac object 4C 14.60 has a spectral slope of ~ 0.1 (our data, unpublished). It seems to us that such a spread in X-ray spectral indexes has to be understood in terms of the variability of the objects, which becomes once more the distinguishing feature of BL Lac objects.

The spread in spectral indexes can be due to the combined effects of the sporadic nature of the observations with the irregularities in the acceleration processes of the particles responsible for the emission. If higher energy electrons are injected or accelerated from time to time, we sample synchrotron-produced X-rays and the spectral slope tends to be steeper and eventually to steepen further as time from injection elapses; in more "stable" conditions, we detect X-rays which are produced by inverse Compton and tend to have a flatter spectrum like the radio emission. In this type of picture, the largest amount of spectral variability would occur at high frequencies, where it is possible to sample the two different production regimes. If indeed QSOs are characterized by a "universal" power-law spectrum with slope 0.7, and if new, more accurate and systematic measurements of the X-ray spectral indexes of BL Lac objects confirm both the wide distribution and the interpretation of the double production regime, relativistic beaming models may provide a natural explanation once it is assumed that the preferential orientation of the beam determines the detectable spectral behavior. In this respect, it seems very interesting to verify the X-ray properties of what are thought to be intermediate objects between QSOs and BL Lac objects, such as the highly polarized quasars (HPQs) described by Moore and Stockman (1981).

We thank I. M. Gioia for a careful reading of the manuscript, J. Halpern for assistance in the analysis of the MPC data, and D. A. Schwartz and E. G. Tanzi for several useful comments. We also thank P. Wilbur for her care in typing the manuscript. This work, done as part of a guest observing program with the *Einstein Observatory*, has received partial financial support from the Italian PSN (Piano Spaziale Nazionale) and from NASA contract NAS 8-30751.

REFERENCES

Barbieri, C., Cristiani, S., and Romano, G. 1982, *A.J.*, **87**, 616.
Blandford, R. D., and Rees, M. H. 1978, in *Pittsburgh Conference on BL Lac Objects*, ed. A. M. Wolfe (Pittsburgh: University of Pittsburgh), p. 328.
Giacconi, R., *et al.* 1979, *Ap. J.*, **230**, 540.
Halpern, J. 1982, Ph.D. thesis, Harvard University.
Halpern, H., and Grindlay, H. E. 1983, *Ap. J.*, submitted.
Heiles, C. 1975, *Astr. Ap. Suppl.*, **20**, 37.
Königl, A. 1981, *Ap. J.*, **243**, 700.
Maccacaro, T., *et al.* 1982, *Ap. J.*, **253**, 504.
Maccacaro, T., and Gioia, I. M. 1983, in *IAU Symposium 104, Early Evolution of the Universe and Its Present Structure*, ed. G. Abell and G. Chincarini (Dordrecht: Reidel), in press.
Maccagni, D., and Tarenghi, M. 1981*a*, *Ap. J.*, **243**, 42.
———. 1981*b*, *Space Sci. Rev.*, **30**, 55.
Madejski, G. M., and Schwartz, D. A. 1983, *Ap. J.*, submitted.
Marscher, A. P. 1980, *Ap. J.*, **235**, 386.
Moore, R. L., and Stockman, H. S. 1981, *Ap. J.*, **243**, 60.
Pica, A. J., Pollock, J. T., Smith, A. G., Leacock, R. J., Edwards, P. L., and Scott, R. L. 1980, *A.J.*, **85**, 1442.
Riegler, G. R., Agrawal, P. C., and Mushotzky, R. F. 1979, *Ap. J. (Letters)*, **233**, L47.
Schwartz, D. A., and Ku, W. H.-M. 1983, *Ap. J.*, **266**, 459.
Setti, G. 1978, in *Pittsburgh Conference on BL Lac Objects*, ed. A. M. Wolfe (Pittsburgh: University of Pittsburgh), p. 385.
Stocke, J., Liebert, J., Stockman, J., Danziger, J., Lub, J., Maccacaro, T., Griffiths, R. E., and Giommi, P. 1982, *M.N.R.A.S.*, **200**, 27P.
Urry, C. M., Mushotzky, R. F., Kondo, Y., Hackney, K. R. H., and Hackney, R. L. 1982, *Ap. J.*, **261**, 12.
Woltjer, L., and Setti, G. 1982, in *Astrophysical Cosmology: Proceedings of the Vatican Study Week on Cosmology and Fundamental Physics*, ed. H. A. Bruck, G. V. Coyne, and M. S. Longair (Vatican City: Pontifical Scientific Academy), p. 293.
Worrall, D. M., Boldt, E. A., Holt, S. S., Mushotzky, R. F., and Serlemitsos, P. J. 1981, *Ap. J.*, **243**, 53.

T. Maccacaro: Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

D. Maccagni: CNR, Istituto di Fisica Cosmica, via Bassini 15, 20133 Milano, Italy

M. Tarenghi: European Southern Observatory, K. Scwarzschild St. 2, Garching bei München 8046, West Germany

© American Astronomical Society • Provided by the NASA Astrophysics Data System