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A UBIQUITOUS ABSORPTION FEATURE IN THE X-RAY SPECTRA OF BL LACERTAE OBJECTS

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ABSTRACT

We present the broad-band (0.5–20 keV) X-ray spectra of five X-ray bright BL Lac objects observed with the *Einstein Observatory* Solid State Spectrometer (SSS) and Monitor Proportional Counter (MPC) detectors. The combination of moderate energy resolution and broad spectral coverage allows us to confirm the presence of an absorption feature at an energy of $\sim$650 eV in the BL Lac object PKS 2155−304, originally reported by Canizares & Kruper based on higher resolution *Einstein* Objective Grating Spectrometer (OGS) data. Furthermore, the SSS/MPC data indicate that such a feature, presumably due to O VIII Lyα resonant absorption, is present in all BL Lac objects in our sample. This suggests that such features are ubiquitous in at least X-ray–bright BL Lac objects.

Subject headings: BL Lacertae objects — line identifications — X-rays: spectra

1. INTRODUCTION

The rapid variability observed at most wavelengths in BL Lac objects, as well as their apparently large luminosities, present a number of problems in modeling the physical processes responsible for the continuum emission. One plausible model postulates relativistic bulk motions (e.g., a jet) close to the line of sight, so that the emitted radiation is beamed toward the observer (Blandford & Rees 1978). This reduces the true source luminosity as compared to that inferred for the isotropic case and lengthens the true variability time scale. Still, even though such an explanation is attractive, no direct evidence for the presence of relativistic bulk motion has yet been found.

One remarkable observation, the discovery of a broad absorption feature present at $E_{\rm obs} \sim 650$ eV in a high-resolution X-ray spectrum of BL Lac object PKS 2155−304, reported by Canizares & Kruper (1984), could be the best evidence yet for such streaming motion. These authors (see also Krolik et al. 1985) interpret the feature as a Lyα resonant absorption trough of O VIII ($E_{\rm rest} = 654$ eV). Their conclusion is based on the lack of other UV or soft X-ray features in the source spectrum. With the source redshift of 0.117 (Bowyer et al. 1984), the center energy and the width of the feature suggest that the material is streaming away from the source at $\sim$30,000 km s^{-1} with a distribution that cannot be spherically symmetric. A jetlike structure explains this observation well.

Alternatively, the absorption may occur in the hot intergalactic medium (cf. Shapiro & Bahcall 1980; Shapiro 1986), in which case one would expect absorption features in all extragalactic sources. However, the limits on the density and temperature of such a medium are quite restrictive in the light of *COBE* data (Mather et al. 1990). Regardless of its origin, this particular feature is one of very few spectral signatures associated with the active nucleus of a BL Lac object at any wavelength, and thus is one of the few manifestations of the physical conditions in the vicinity of their nuclei. As a result, its discovery raised a question: is it present only in PKS 2155−304, or in all BL Lac objects? The preliminary analysis of the Solid State Spectrometer (SSS) data by Urry, Mushotzky, & Holt (1986) hinted at the presence of such features in PKS 2155−304 and Mrk 501. In this paper, we present evidence that they are common.

In § 2, we report on the reanalysis of the SSS data along with the Monitor Proportional Counter (MPC) data which was acquired simultaneously. This ensures that any possible variability, a common feature of BL Lac objects, would have no effect. The results, discussed in § 3, show that the absorption feature is present in all five BL Lac objects observed by the SSS, namely PKS 0548−322, H1218+304, Mrk 421, Mrk 501, and PKS 2155−304. The absorption features present in these spectra would be unresolved by instruments with more modest spectral resolution, and may appear as spectral flattening below energy $\sim$1–3 keV (e.g., simultaneous, but independently fit *Einstein* IPC vs. MPC data [Madejski 1985; Madejski & Schwartz 1989], and *EXOSAT* data [Barr, Giommi, & Maccagni 1988; George, Warwick, Bromage 1988; Barr et al. 1989]).

2. DATA ANALYSIS

The SSS was a cryogenically cooled, lithium-drifted silicon device mounted in the focal plane of the *Einstein Observatory*. It measured the incident X-ray spectra of celestial sources with a FWHM energy resolution of $\sim$160 eV over the bandpass of $\sim$0.5–4 keV with an effective area of $\sim$100 cm^2 between 0.6 and 3 keV (Joyce et al. 1978; Holt et al. 1979; Giacconi et al. 1979). During the *Einstein Observatory* mission, there was a buildup of ice on the cold ($\sim$120 K) SSS detector surface from residual water contained in the cryostat insulation. This acted as an absorber, preferentially affecting low-energy X-rays. The model used here (N. White, private communication; see also Holt et al. 1989 and Turner et al. 1990), which represents a

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significant improvement over earlier attempts, consists of an ice layer with a time-dependent distribution of thicknesses. It permits the extension of the low-energy limit to ~0.5 keV versus ~0.6 keV used previously. The amount of X-ray absorption by the ice is a function only of time, and can be determined from in-flight calibrations. The SSS background has been subtracted using the procedure discussed in Holt et al. (1979), with changes described in Holt et al. (1989) and Turner et al. (1990). We use only the data collected after 1979 May 1, where the ice layer was significantly less than for earlier observations.

The MPC was an argon-filled proportional counter with an effective area of 667 cm^2, sensitive over the energy range 1.2–20 keV, with a FWHM energy resolution of ~20% at 6 keV (Gaillardetz et al. 1978; Grindlay et al. 1980; Halpern 1982; Garcia 1987). For sources as faint as BL Lac objects, the observed counts are dominated by the background from particles triggering the detector. We have corrected for these using the new background prediction algorithm of Arnaud (1991). This reduces the background by excluding data based on the satellite geomagnetic position and then predicts the magnitude and spectrum of the remainder based on auxiliary data.

The significant improvements over the previous analysis (Urry, Mushotzky, & Holt 1986) are the use of the contemporaneous MPC data (extending the bandpass to 0.5–20 keV), and the more accurate ice model. Here we simultaneously fit data from both instruments using the XSPEC package (Shafer, Haberl, & Arnaud 1989). The model fitting has been accomplished using the standard χ^2 minimization technique, comparing the data against the model folded through the instrumental response; we report the parameters corresponding to the $\chi^2_{\mathrm{minimum}}$ as the best fit. We fit the following spectral forms to our data: (1) A simple power law with a power-law index α (such that flux density S_E and photon energy E are related via $S_E \propto E^{-\alpha}$), absorbed by the Galactic column density, as inferred from the radio 21 cm data (Elvis, Lockman, & Wilkes 1989); (2) the same simple power law, but with the column density allowed to vary; (3) a broken power law with the Galactic absorption. In this model, the data below some break energy E_b are described by one power-law index α_{lo}, while above E_b by another index, α_{hi}. This model (with $\alpha_{\mathrm{lo}} < \alpha_{\mathrm{hi}}$) fits the *EXOSAT* data for PKS 0548−322, with the break at a few keV (cf. Barr et al. 1988), as well as other BL Lac objects (Barr et al. 1989). A similar steepening of the spectrum with energy was reported by Madejski & Schwartz (1989), when the *Einstein* Imaging Proportional Counter (IPC) and MPC data were fitted separately; (4) a simple power law with Galactic absorption as before, plus an absorption trough (of $\tau \gg 1$), as in Canizares & Kruper (1984). Since the lower energy bound of the SSS is ~0.5 keV, we do not expect to observe a significant flux of photons emitted below the trough and thus be able to simultaneously measure its center energy, E_n, and its width, ΔE. We therefore fix ΔE at 100 eV, as suggested by the Objective Grating Spectrometer data, set the covering fraction (trough depth) f to 1, and allow E_n to vary.

In the case of the BL Lac object Mrk 421, the spectrum flattens above ~1.7 keV (cf. Fig. 3, top panel). A similar spectral form has been observed in PKS 2155−304 in the *HEAO* A-2 data by Urry & Mushotzky (1982). We treat Mrk 421 in an analogous manner to the other objects, but take the underlying continuum to be a combination of two power laws with $\alpha_{\mathrm{lo}} > \alpha_{\mathrm{hi}}$. The resulting best-fit parameters and the values of $\chi^2_{\mathrm{minimum}}$ for all five objects are given in Table 1.

3. RESULTS OF THE SPECTRAL FITS

Models (1 and 2): simple power-law fit.—As found by Urry et al. (1986), a simple power law, absorbed by the Galactic column, does not fit the data (χ^2 of ~1.5 per degree of freedom), though when only the data above ~1 keV are considered, it is entirely satisfactory. The residuals from the fit to a simple power law absorbed by the Galactic gas (with the exception of Mrk 421, where a broken power law is used), using the SSS channels above 1 keV and all the MPC channels, are plotted in the top panels of Figures 1*a* through 1*e*. There is a deficiency of counts in the lower energy channels. This spectral behavior is in sharp contrast to Seyfert galaxies, where the combined SSS and MPC data indicate that the soft X-ray spectrum turns up below ~1 keV (Turner et al. 1990).

A power law absorbed by a higher (than Galactic) column density of neutral, cold gas (on the order of a few × 10^{21} cm^{-2}) fits the data better, in agreement with Urry et al. (1986). However, the fit is still not satisfactory (see Table 1). Most importantly, such a highly absorbed power law is inconsistent with the IPC results reported by Madejski (1985) and Madejski & Schwartz (1989). These authors find a good agreement between the N_{H} toward BL Lac objects measured by radio H I means and X-ray absorption, a few × 10^{20} cm^{-2}. These results suggest that the absorption in the range 0.5–1 keV cannot be due to cold (i.e., mostly neutral) gas.

Model (3): Broken power law.—We find that in all cases the quality of the fit for a broken power-law model improves significantly ($\Delta\chi^2 >$ ~10) over a simple power law absorbed by the Galactic column. Our fits find a break energy of ~0.7 keV (cf. Table 1), different from the value of a few keV inferred from the *EXOSAT* data (Barr et al. 1988). Similarly, the results of the IPC analysis (Madejski 1985) do not support a break at 0.7 keV. If we require $E_b \sim 2$ keV, in agreement with *EXOSAT*, then, in general, the fits to our data are even worse than for a simple power law. However, we cannot rule out a gradual steepening of the spectrum to produce $\Delta\alpha \sim 0.3$ over the range covered by our data; this is independent of the inclusion of the feature discussed in model (4) below. Thus the high spectral resolution SSS data allow us to reject with high confidence an intrinsic broken power-law model with a break energy of a few keV as the *sole* description of our data.

Model (4): Power law with a trough.—This model fits our data very well, and is the only acceptable model not in disagreement with previously published results (although in the case of PKS 2155−304, the best-fit parameters for the trough are somewhat different than those derived from the OGS data, which may be due at least in part to imprecise calibration of the SSS at the lowest energies). The residuals for this model are plotted in the bottom panels of Figures 1*a* through 1*e*, which can readily be compared against the top panels in these figures. Since there are source photons detected by the IPC and *EXOSAT* LE below the feature (Madejski 1985; Madejski & Schwartz 1989; Barr et al. 1989), the excess cutoff in the SSS data is due to a distinct, sharp absorption feature. This is evidence for hot, partially ionized matter in the line of sight.

As mentioned before, simultaneous determination of the energy E_n and width of the feature ΔE is difficult since the SSS loses its sensitivity rapidly with energy below ~0.6 keV. It is possible, however, to determine the allowed range in the E_n–ΔE parameter space by plotting contours of constant χ^2. We present such plots for PKS 2155−304 and Mrk 501 in Figure 2, where we allow the trough depth f to vary as well.

TABLE 1

RESULTS OF SPECTRAL FITS FOR FIVE BL LACERTAE OBJECTS

		Simple Power-law Model Fixed N_H (75 d.o.f.)			Simple Power-law Model Free N_H (74 d.o.f.)				Broken Power-law Model Fixed N_H (73 d.o.f.)				Power-law + Trough[a] Fixed N_H (73 d.o.f.)			
Object	Observation Date	N_H[b]	α (range)	χ^2	α (range)	N_H (range)	χ^2	Flux at 2 keV[c]	α_{lo} (range)	E_b (range)	α_{hi} (range)	χ^2	α (range)	E_n (range)	χ^2	Flux at 2 keV[c]
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)
PKS 0548-322	1979 Apr 6	2.49	0.74 (0.69, 0.79)	90.3	0.91 (0.81, 1.01)	9.2 (6.0, 12.7)	77.9	4.62	-0.71 (-5.39, 0.57)	0.71 (0.56, 1.74)	0.82 (0.76, 0.89)	77.4	0.84 (0.80, 0.88)	0.57 (0.55, 0.59)	74.8	4.54
1218+304	1979 Jun 5	1.78	0.95 (0.88, 1.02)	92.8	1.22 (1.05, 1.39)	9.5 (5.4, 13.9)	82.6	2.29	-0.92 (-11.0, 0.59)	0.68 (0.51, 1.13)	1.09 (0.99, 1.19)	78.8	1.12 (1.03, 1.20)	0.56 (0.54, 0.57)	80.9	2.27
Mkn 501	1979 Aug 22	1.73	0.96 (0.93, 0.99)	239.5	1.34 (1.27, 1.41)	13.3 (11.5, 15.0)	104.2	8.81	-0.67 (-1.24, -0.22)	0.79 (0.73, 0.86)	1.16 (1.12, 1.20)	89.5	1.12 (1.09, 1.16)	0.56 (0.55, 0.57)	89.9	8.48
PKS 2155-304	1979 May 26	1.77	1.36 (1.32, 1.40)	140.5	1.73 (1.63, 1.84)	10.3 (8.0, 12.7)	98.6	8.55	-0.50 (-2.61, 0.22)	0.68 (0.59, 0.76)	1.57 (1.51, 1.63)	65.0	1.61 (1.56, 1.65)	0.55 (0.54, 0.56)	72.2	8.35
Mkn 421[d]	1979 May 10	1.45	1.39 (1.20, 1.56)	82.9	1.31 (1.13, 1.53)	0.0 (0.0, 3.4)	81.9	0.75	1.62 (1.41, 1.84)	1.84 (1.37, 2.46)	0.50 (0.12, 0.92)	71.6	α_{lo}=2.51 (2.02, 2.91) α_{hi}=0.41 (0.24, 0.87) E_b=1.41[d] (1.24, 1.87)	0.53 (0.49, 0.55)	62.1	0.74

NOTES.—"Range" represents the 90% confidence region for 1 interesting parameter (χ^2 + 2.7). Column density N_H in cols. (3) and (7) is given in units of 10^{20} cm^2. Power law index is defined using $S_E \propto E^{-\alpha}$. All energies expressed in keV.

[a] Trough has covering fraction fixed to 1 and width fixed to 100 eV.

[b] Galactic column density. Data from Elvis, Lockman, & Wilkes 1988.

[c] Model monochromatic flux given in units of μJansky.

[d] The underlying continuum consists of two power laws, as given in col. (14). See the text for details.

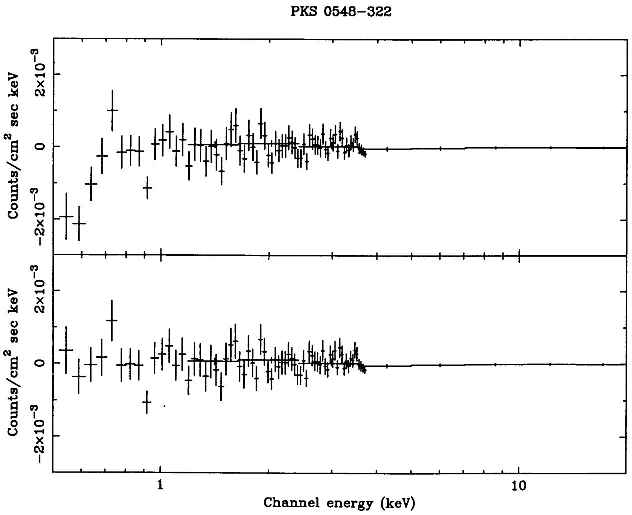

FIG. 1*a*

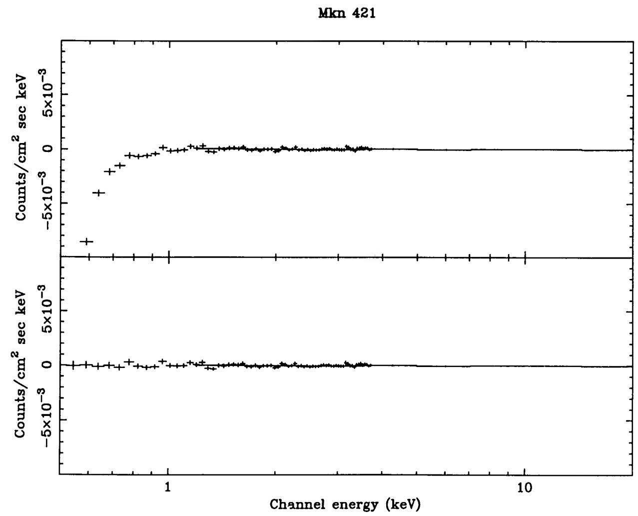

FIG. 1*b*

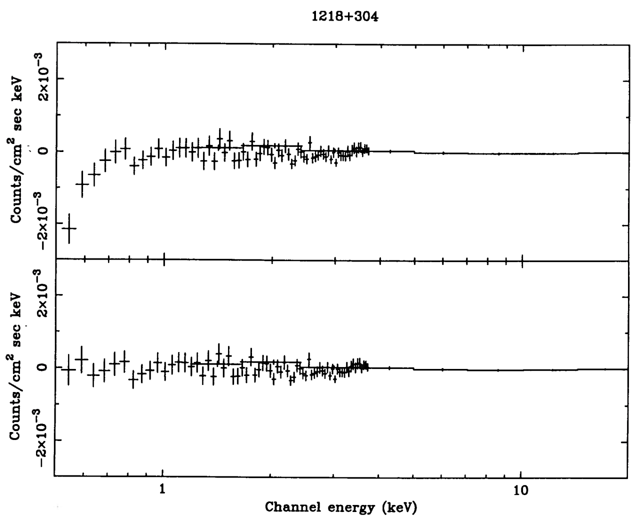

FIG. 1*c*

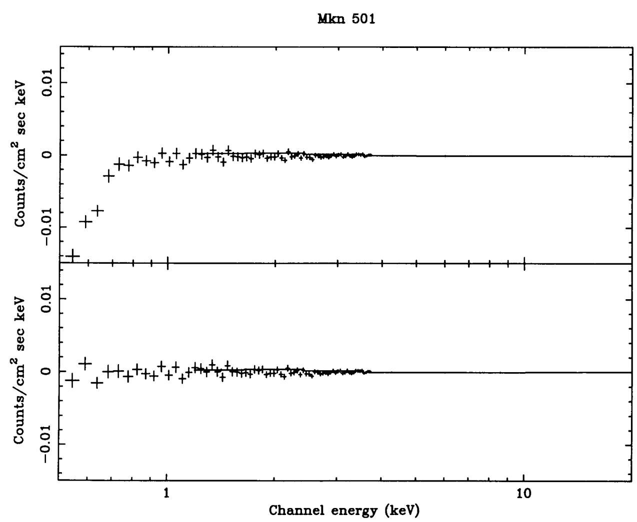

FIG. 1*d*

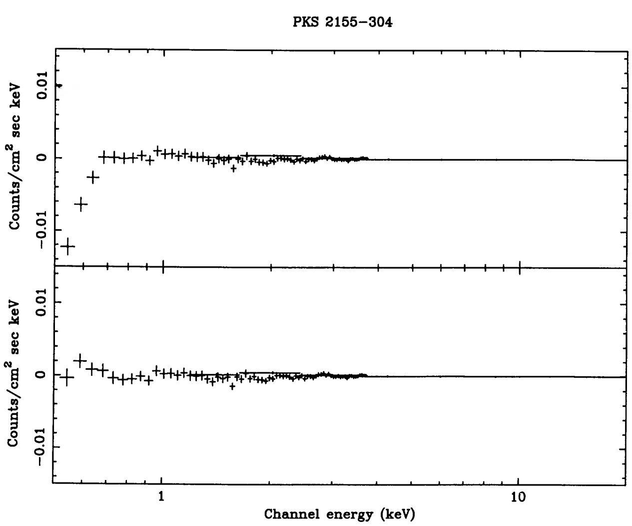

FIG. 1*e*

FIG. 1.—Residuals from a fit to combined SSS and MPC data to five BL Lac objects. In all cases, the galactic gas column density was assumed. *Top panels*: for PKS 0548−322 (*a*), H1218+304 (*c*), Mrk 501 (*d*), and PKS 2155−304 (*e*) a simple power law was adopted, while for Mrk 421 (*b*), a broken power-law model was allowed. Only data nominally above 1 keV were used for the fit. *Bottom pannels*: as for top panels, but with a model incorporating in addition a trough with a covering fraction (depth) f of 1 and a width ΔE of 100 eV, at the fitted energy. All channels are used for the fit.

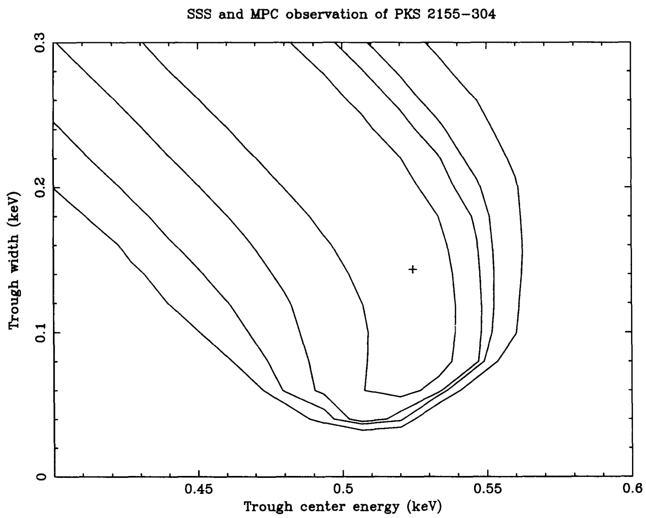

FIG. 2a

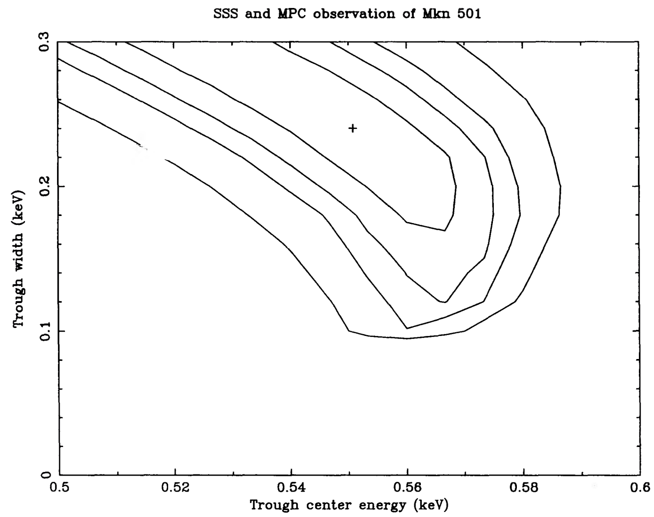

FIG. 2b

FIG. 2.—Contour plots of χ^2 in the E_n vs. ΔE plane for PKS 2155−304 and Mrk 501. The model fitted to the combined SSS and MPC data is a power law absorbed by Galactic gas, where the trough depth f is allowed to vary. The contours represent χ^2 + 1, 2.7, 4.6, and 9.2. See § 3 for details.

Formally, with unrestricted f and ΔE, for PKS 2155−304, we get the best fit $\Delta E = 0.15$ keV, $f = 0.53$, while for Mrk 501, we get $\Delta E = 0.24$ keV, $f = 0.52$. However, these values are primarily determined by the three lowest channels of the SSS, and may be affected by its imprecise calibration at these lowest energies. In general, our data allow f to be in the range 0.5–1.

The IPC alone, with its modest energy resolution and limited bandpass, could not require such a sharp feature (cf. Urry et al. 1986; Madejski 1985). In limited spectral resolution instruments (e.g., IPC or *EXOSAT*), its presence would yield fewer photon counts in the broad range of channels near the middle of the bandpass (where the instruments are most sensitive) without affecting the higher (above ~1 keV) energy channels, and would thus appear as spectral flattening. We compared the results of our fits against these of Barr et al. (1988), who suggested that a broken power law absorbed by our Galaxy yields a better fit to the *EXOSAT* data of PKS 0548−322 than a trough model similar to ours. Using the *EXOSAT* data base, we extracted data for several observations of BL Lac objects, and fit the absorbed power law + trough. With f fixed at 1, we could indeed reproduce poor fits, similar to those obtained by Barr et al. (1988); on the other hand, when we allowed f to vary, the fits become acceptable. Also, a form similar to our model (4) was fitted to the *EXOSAT* data for PKS 2155−304 by Treves et al. (1989), who found it to be a better description of the data than a broken power law. More detailed spectral fitting is beyond the capability of the SSS, and must await higher quality data, such as will be available from the upcoming BBXRT mission.

4. DISCUSSION

The data presented here strongly suggest that absorption features are common in soft X-ray spectra of BL Lac objects; these features are similar to the broad blueshifted optical absorption lines seen in some quasars in terms of their depth and strength. The characteristic width of the X-ray features is ~100 eV, and the energy where they appear E_n is ~600 eV. We illustrate this preferred model in Figure 3 for Mrk 421, Mrk 501, and PKS 2155−304. Such a feature cannot be due to instrumental effects (see Fig. 4). A precise determination of E_n from the SSS is difficult due to the lack of detector sensitivity below ~0.5 keV as well as the uncertainty in its calibration at the low-energy end, and thus must await better data. Nonetheless, we consider the detection of these spectral features to be an evidence for a jetlike outflow in BL Lac objects, or alternatively, for a hot intergalactic medium. In the case of PKS 2155−304, the original discovery was based upon the OGS data taken on 1980 May 21-22. Since we observe it in 1979 May 26 SSS data, we conclude that the feature is stable or at least peristent.

Following Canizares & Kruper (1984), we interpret these absorption features as Lyα resonance absorption in O VIII ($E_{rest} = 654$ eV). For such a high ionization state, the absorbing material must be hot (0.5–2 × 10^6 K). The width of the feature, ~100 eV, implies a velocity spread of ~30,000 km s^{-1}, about 1000 times larger than that expected from the thermal broadening, which, together with the considerations of the fraction of the material that is in the O VIII ionization state, requires the total (velocity-integrated) equivalent hydrogen column density N_H of ~10^{24} cm^{-2} (Krolik et al. 1985). These authors suggest that a spherically symmetric outflow would require an unlikely mass loss of ~10^3 $M_\odot$ yr^{-1}. In fact, a spherically symmetric outflow is excluded and a jetlike structure is preferred, unless the spectrum exhibits a P Cygni profile, which is possibly supported by a steeply rising shape below the feature observed by Canizares & Kruper (1984) in the OGS data, i.e. between 0.3 and 0.5 keV. Unfortunately, the SSS is not sensitive at those low energies.

Alternatively, Canizares & Kruper (1984; see also Shapiro & Bahcall 1980; Shapiro 1986) suggested the absorbing material could well be a hot, oxygen-enriched intergalactic medium at a temperature of ~10^6 K. Such an explanation would require its density to be a substantial fraction of the closure value, and thus would have a severe impact on galaxy formation theories. The best available SSS spectra of Seyfert galaxies (Turner et al. 1990) cannot exclude similar features, so the hot IGM explanation is not ruled out by X-ray data.

If the absorption feature is indeed due to highly ionized oxygen, signatures of other elements might be expected in X-ray spectra of BL Lac objects. Considering the relative

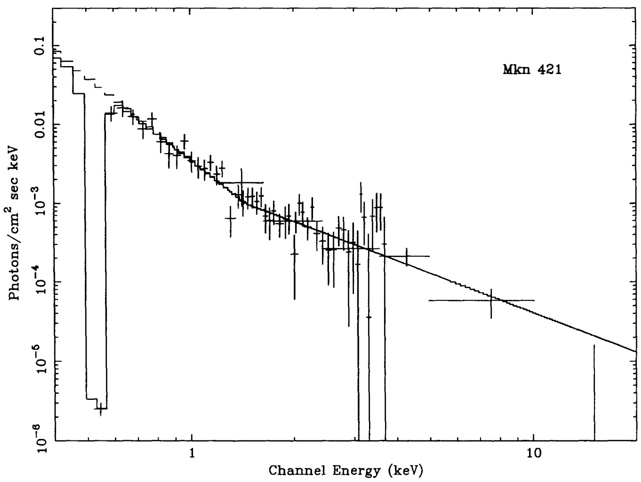

FIG. 3*a*

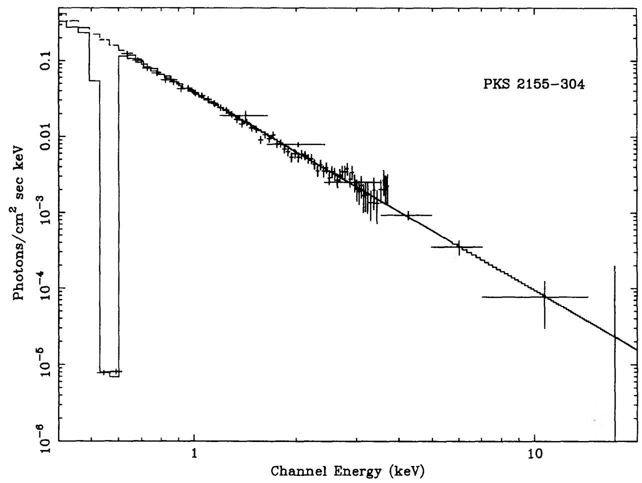

FIG. 3*c*

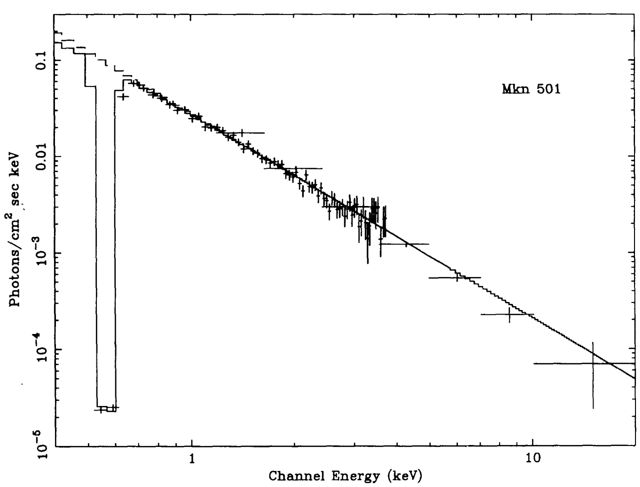

FIG. 3*b*

FIG. 3.—Unfolded spectra of Mrk 421, Mrk 501, and PKS 2155−304 using the power law + trough model as in Table 1. For illustration, the depth of the trough was fixed at ∼0.9999. Note that the "data" points plotted are *not* the measured count rates, but they depend on the particular model used.

cosmic abundances and flourescence yields, the most likely candidate would be Fe XXV or XXVI, at ∼7 keV (Kallman & Mushotzky 1985). Weak evidence for such a feature was seen in the *EXOSAT* ME spectrum of PKS 2155−304 (Treves et al. 1989). A search for this feature is planned for the upcoming *BBXRT* mission. This observation will directly test the O VIII interpretation, and/or will indicate quite unusual elemental abundances in the absorbing matter.

5. SUMMARY

1. Availability of the new ice model for the SSS and simultaneous spectral fitting of contemporaneous SSS and MPC data enables us to get high-quality X-ray spectra for five BL Lac objects over a broad energy range, 0.5–20 keV.

2. The X-ray spectra of BL Lac objects are not consistent with a single absorbed power law over that range. We can also rule out an intrinsic broken power law as the sole explanation for the apparent flattening of spectra at low energies.

3. The model most consistent with our data is a power law, absorbed by the Galactic gas column density, with a ∼100 eV wide trough centered at an energy ∼0.6 keV, presumably due to Lyα-like resonance absorption in O VIII. A similar line due to Fe XXV or XXVI is expected at ∼7 keV.

4. We thus suggest that the absorption feature previously observed at ∼0.6 keV in PKS 2155−304 is common in at least X-ray bright BL Lac objects.

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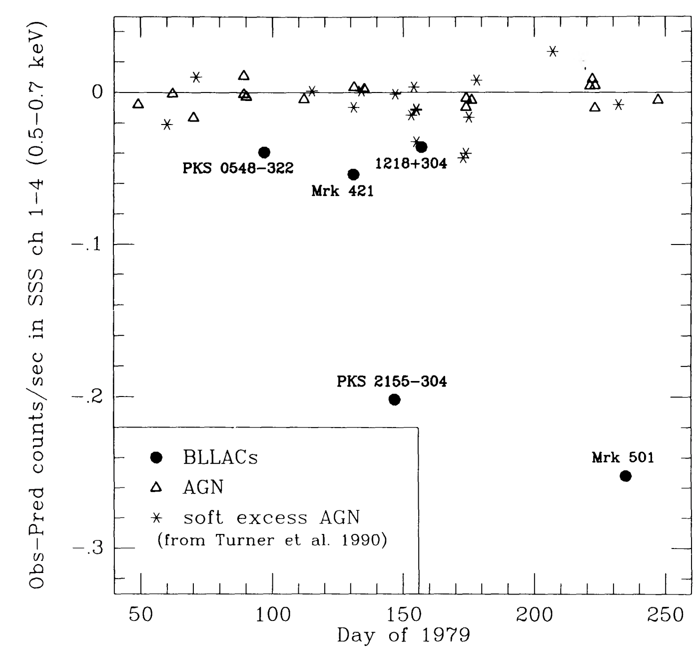

FIG. 4.—Comparison of the residual count rates vs. observation epoch for AGN and BL Lac objects of comparable fluxes, in the SSS channels 1–4 (corresponding to ∼0.5–0.7 keV), after subtracting the best-fit spectrum to the combined SSS and MPC data above 0.7 keV. For BL Lac objects, we use a simple power-law model absorbed by our Galaxy, while for AGNs, we allow a broken power law, steepening below energy fixed at ∼1 keV (to account for commonly observed soft excesses; see Turner & Pounds 1989; Wilkes & Elvis 1987), with variable absorption. Note that only BL Lac objects systematically show a deficiency of counts significantly larger than the scatter. This scatter is likely due to uncertainties in the ice model and statistical errors in the data. We interpret the count rate deficiency in BL Lac objects as the sharp absorption feature discussed in the text. See Turner et al. (1990) for further details.

REFERENCES

Arnaud, K. A. 1991, in preparation
Barr, P., Giommi, P., & Maccagni, D. 1988, ApJ, 324, L11
Barr, P., Giommi, P., Pollock, A., Tagliaferri, G., Maccagni, D., & Garilli, B. 1989, in BL Lac Objects (Lecture Notes in Physics, 334), ed. L. Maraschi, T. Maccacaro, & M.-H. Ulrich (Berlin: Springer), 290
Blandford, R. D., & Rees, M. J. 1978, in Proc. Pittsburgh Conf. on BL Lac Objects, ed. A. M. Wolfe (Pittsburgh: University of Pittsburgh), 328
Bowyer, S., Brodie, J., Clarke, J., & Henry, P. 1984, ApJ, 278, L103
Canizares, C. R., & Kruper, J. 1984, ApJ, 278, L99
Elvis, M., Lockman, F. J., & Wilkes, B. J. 1989, AJ, 97, 777
Gaillardetz, R., Bjorkholm, P., Mastronardi, R., Vanderhill, M., & Howland, D. 1978, IEEET, NS-25, 437
Garcia, Michael 1987, Ph.D. thesis, Harvard University
George, I. M., Warwick, R. S., & Bromage, G. E. 1988, MNRAS, 232, 793
Giacconi, R., et al. 1979, ApJ, 230, 540
Grindlay, J. E., et al. 1980, ApJ, 240, L121
Halpern, Jules 1982, Ph.D. thesis, Harvard University
Holt, S. S., White, N. E., Becker, R. H., Boldt, E. A., Mushotzky, R. F., Serlemitsos, P. J., & Smith, B. W. 1979, ApJ, 234, L65
Holt, S. S., Turner, T. J., Mushotzky, R. F., & Weaver, K. 1989, in AGN and the X-Ray Background, ed. N. E. White, (Paris: ESA/ESTEC) SP 296, 1105
Joyce, R. M., Becker, R. H., Birsa, F. B., Holt, S. S., & Noordzy, M. P. 1978, IEEET, NS-25, 453
Kallman, T. R., & Mushotzky, R. F. 1985, ApJ, 292, 49
Krolik, J. H., & Kallman, T. R. 1984, ApJ, 286, 366
Krolik, J. H., Kallman, T. R., Fabian, A. C., & Rees, M. J. 1985, ApJ, 295, 104
Madejski, Grzegorz, M. 1985, Ph.D. thesis, Harvard University
Madejski, G. M., & Schwartz, D. A. 1989, in BL Lac Objects (Lecture Notes in Physics, 334), ed. L. Maraschi, T. Maccacaro, & M.-H. Ulrich (Berlin: Springer), 267
Mather, J. C., et al. 1990, ApJ, 354, L37
Shafer, R. A., Haberl, F., & Arnaud, K. A. 1989, preprint
Shapiro, P. R. 1986, in Galaxy Distances and Deviations from Universal Expansion, ed. B. F. Madore & R. B. Tully (Dordrecht: Reidel), 203
Shapiro, P. R., & Bahcall, J. N. 1980, ApJ, 241, 1
Treves, A., et al. 1989, ApJ, 341, 733
Turner, T. J., & Pounds, K. A. 1989, MNRAS, 240, 833
Turner, T. J., Mushotzky, R. F., Weaver, K. A., Holt, S. S., & Madejski, G. M. 1990, ApJ, submitted
Urry, C. M., & Mushotzky, R. F. 1982, ApJ, 253, 38
Urry, C. M., Mushotzky, R. F., & Holt, S. S. 1986, ApJ, 305, 369
Wilkes, B. J., & Elvis, M. 1987, ApJ, 323, 243