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EXOSAT OBSERVATIONS OF THE BLAZAR PKS 1510−089

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ABSTRACT

A detailed study of X-ray emission from the high-polarization quasar PKS 1510−089, also known as a blazar, is presented, based on the *EXOSAT* observations in 1984 and 1985. The data were obtained from the *EXOSAT* archives. There is no evidence for any variations in the X-ray intensity on hourly time scales during either of the two observations. The 2-10 keV X-ray flux shows no significant change over a year. The observed X-ray spectral data is best fitted by a power law with a photon index, Γ, of $1.40^{+0.35}_{-0.30}$ (error bars are with 90% confidence). The slope of the power law is somewhat flatter for PKS 1510−089 as compared with the canonical spectra of the active galactic nuclei; however, the present observations do not rule out a normal Seyfert-type spectrum. There is no detection of any significant low-energy absorption within the blazar, nor is there any evidence for a soft X-ray excess. A line feature modeled as a Gaussian is detected with a high significance near 5 keV. The emission line could be the redshifted 6.4 keV line due to the fluorescence of cold iron present around the nucleus of PKS 1510−089 or the redshifted 6.7 keV line due to ionized iron in a hot plasma. The observed intensity of the line, if produced by fluorescence, would require the cold matter to subtend a very large solid angle to the X-ray continuum source.

Subject headings: polarization — quasars — radiation mechanisms — X-rays: sources

I. INTRODUCTION

Blazars are among the few most energetic of the active galactic nuclei (AGNs). Strong radio emission, variability and high polarization at optical and infrared wavelengths, and strong optical to infrared continuum emission are some of the characteristics of these objects. One such object from the Parkes Catalog of radio sources is PKS 1510−089. It was optically identified as a quasar (Bolton and Ekers 1966) with a redshift of 0.361 measured from its emission-line spectrum (Burbidge and Kinman 1966), marked ultraviolet excess, and a visual magnitude of 16.5 (Bolton and Kinman 1966). Optical polarimetric observations by Appenzeller and Hiltner (1967) detected a fairly strong (10.9% ± 3.8%) polarization from this quasar at a position angle of 177° ± 9°. The variability of its optical brightness was first reported by Lu (1972), who monitored this object for nearly 5 years. Subsequently it was found that its *B*-magnitude had varied from 11.8 to 17.8 since 1899.6, having reached its peak sometime in 1948 (Liller and Liller 1975). The range of brightness spanned is larger than that known for any other quasar, and at its peak it was one of the most luminous quasars. It is also classified as an optically violent variable (OVV).

The measurements of the infrared flux from PKS 1510−089 have been reported by Oke, Neugebauer, and Becklin (1970), Neugebauer *et al.* (1979), Landau *et al.* (1986), and Impey and Neugebauer (1988). It has also been observed in the millimeter band (Landau, Epstein, and Rather 1980; Ennis, Neugebauer, and Warner 1982; Steppe *et al.* 1988).

The quasar is an extremely strong source at the centimeter wavelengths, with nearly 1.3% of its total flux being polarized (Perley 1982). An 8″ long one-sided jet is observed at 20 cm from this core-dominated source. The one-sided radio jet can also be seen at 6 cm in the recent high-resolution radio observations by O'Dea, Barvainis, and Challis (1988). The radio emission shows very rapid and large amplitude variations in the total flux, the polarized flux, and the polarization position angle (Aller, Aller, and Hodge 1981).

The first X-ray observations of PKS 1510−089 were carried out with the *Einstein Observatory* imaging proportional counter (IPC). Soft X-ray emission in the 0.5–4.5 keV energy band was detected (log L_x = 45.3 ergs s^{-1}; Ku, Helfand, and Lucy 1980). Its X-ray spectral measurements have been reported by Canizares and White (1989) from the same observations. According to them, the energy index of the X-ray continuum emitted by the class of objects to which this radio-loud quasar belongs is in the range 0.2–0.5 (90% confidence), assuming a zero value for the line-of-sight column density. The Galactic column density, N_H, toward this source is 7.6×10^{20} cm^{-2} (Stark *et al.* 1990). If this value is adopted, the estimated X-ray energy index would lie in the range 0.4–0.9 (Canizares and White 1989). Clearly, a proper spectral estimation of the X-ray continuum is required.

We have obtained archival data from two extended X-ray observations of PKS 1510−089 carried out in 1984 and 1985 using the *EXOSAT* observatory. The results from the analysis of these data are presented here. These observations were in the broad-band energy range 0.05–10 keV, thus affording an accurate measure of the X-ray spectrum. The long-duration observations were also analyzed for variability. In this paper, we first present the details of observations (§ II), followed by the details of analysis and results in § III. We end with a discussion of the results in § IV.

II. OBSERVATIONS

The X-ray observations of PKS 1510−089 were performed twice—on 1984 August 3–4 and on 1985 July 31, August 1—using both the medium-energy (ME) detectors and the low-energy (LE) telescope having a channel multiplier array (CMA) as the detector. The details of the instruments used are given by Turner, Smith, and Zimmermann (1981) for the ME detectors and by de Korte *et al.* (1981) for the LE+CMA combination. The particulars of the observations are given in Table 1. In the first set of observations done over two days in 1984 the LE data were obtained using two filters, viz., Lexan 3000 (LX3)

TABLE 1

LOG OF *EXOSAT* OBSERVATIONS AND COUNT RATES

Detector Combination	Start Time (UT)	End Time (UT)	Effective Exposure Time (s)	Count Rate[a] (10^{-4} cm^{-2} s^{-1})
		1984		
CMA + LX3	Aug 3 13:10:22	Aug 3 18:11:10	13470	0.37 ± 0.11
CMA + Al/P	Aug 3 18:15:02	Aug 3 22:16:38	8691	0.34 ± 0.11
ME (half 2)	Aug 3 13:21:42	Aug 3 16:00:22	8371	5.16 ± 0.44
ME (half 1)	Aug 3 16:14:30	Aug 3 19:05:50	8735	4.54 ± 0.49
ME (half 2)	Aug 3 19:26:14	Aug 3 22:21:18	4589	4.73 ± 0.55
ME (half 2)	Aug 4 10:33:34	Aug 4 13:05:26	8040	5.45 ± 0.44
ME (half 1)	Aug 4 13:17:10	Aug 4 16:11:18	8491	6.80 ± 0.62
ME (half 2)	Aug 4 16:24:38	Aug 4 19:41:18	5863	5.76 ± 0.50
		1985		
CMA + LX3	Aug 1 04:18:44	Aug 1 11:47:00	21550	0.47 ± 0.09
ME (half 2)	Jul 31 23:41:40	Aug 1 03:24:20	11715	4.3 ± 0.5
ME (half 1)	Aug 1 03:33:56	Aug 1 06:28:52	9422	4.8 ± 0.6
ME (half 2)	Aug 1 06:40:04	Aug 1 09:43:00	8847	3.6 ± 0.5
ME (half 1)	Aug 1 09:55:56	Aug 1 10:58:36	2704	3.7 ± 0.9

[a] The count rates for the ME detectors are for PHA channels 7–24 corresponding to the energy range 1.5–6 keV with the best signal-to-noise ratio.

and aluminum/parylene (Al/P) (see White and Peacock 1988 for filter efficiencies). In the 1985 observations, however, only the LX3 filter was used. The ME data were acquired from the eight argon-filled proportional counters. The eight ME detectors are divided into two half-arrays, viz., the detectors numbered 1, 2, 3, and 4 are collectively known as the half 1 array, and the detectors numbered 5, 6, 7, and 8 are together known as the half 2 array. The ME observations were carried out by alternately pointing one of the arrays at the source while the other array monitored the background. The details of the array pointings on the source are given in Table 1.

III. ANALYSIS AND RESULTS

The data reduction and analysis were performed using the XANADU (X-Ray Analysis and Data Utilization) software package. The two sets of data obtained in 1984 and 1985 were analyzed separately to avoid systematic effects due to background variations and possible source variability.

a) LE and ME Source Counts

Soft X-ray emission from a point source coinciding with the position of the blazar was detected in the LE observations with both the LX3 and Al/P filters. The effective exposure times and the background-subtracted count rates corrected for vignetting, dead time, and the sum-signal distribution are shown in Table 1. The background was obtained from the regions surrounding and adjacent to the position of the source in the detector. The data contaminated with the very high background variations in the detector were not used. No significant variation was detected in the source intensity during the observations.

The ME data analyzed were also selected after weeding out the data with varying background. The background obtained from the same detectors while offset from the source was used for subtraction. The effective exposure times of the selected data and the source counts observed in each half-array are given in Table 1. A weak X-ray emission was clearly detected in each half-array and also in the individual detectors at the same strength. The data are consistent with a constant source intensity in 1984 as well as 1985 observations. A small variation ($\sim 20\%$) is seen in the average count rate for the 1.5–6.0 keV energy range, between 1984 and 1985 observations. Considering the systematics involved in the background subtractions of data obtained a year apart, the observed variation is not very significant.

b) X-Ray Spectrum

The pulse-height (PH) information obtained from the LE and the ME detectors was combined and analyzed together for an estimation of the spectral parameters of the X-ray emission from PKS 1510−089. The spectral data analyzed were obtained from only those detectors that were in the "corner" configuration (viz., detectors 1, 4, 5, and 8), since these are the most reliable and are less prone to variations in the internal background due to changes in the geometrical configurations resulting from the "swap" technique (Smith 1984; Yaqoob, Warwick, and Pounds 1989). We used simple power-law models along with absorption in the line of sight to the source to fit the data in the first instance. The absorption cross sections given by Morrison and McCammon (1983) were used. Using the χ^2 statistic, we find that the simple model gives acceptable fits to both the 1984 and the 1985 data. The best-fit spectral parameters obtained from this analysis, along with their 90% confidence error bars estimated by keeping all the other interested parameters free, are listed in Table 2. (Hereafter, all the quoted errors are with 90% confidence estimated thus.) The photon index (Γ) of 1.15 ± 0.25 indicated by the 1984 data with the longest exposure and the best signal-to-noise ratio is considerably harder than the canonical Seyfert spectra (Turner and Pounds 1989). The data from the 1985 observations ($\Gamma = 1.44 \pm 0.40$) are not inconsistent with such a hard spectrum. The column density of the equivalent hydrogen along the line of sight is not very well determined but is consistent with that estimated from the 21 cm observations (§ I); therefore, there is no evidence for absorption intrinsic to the source from these observations. The PH data from the 1984 observations (combined data from the two days of observations) are shown in Figure 1*a*. In the same figure the

TABLE 2

RESULTS OF THE SPECTRAL ANALYSIS OF *EXOSAT* LE + ME DATA

PARAMETER	DATE OF OBSERVATION	
	1984 August 3, 4	1985 July 31, August 1
Model A: Power Law + Absorption		
Photon index (Γ)	$1.15^{+0.25}_{-0.23}$	$1.44^{+0.41}_{-0.37}$
A (10^{-3} cm^{-2} s^{-1} keV^{-1})	$1.0^{+0.4}_{-0.3}$	$1.46^{+1.0}_{-0.6}$
N_H (10^{20} cm^{-2})	$6.1^{+12.1}_{-4.4}$	$10.9^{+17.9}_{-8.3}$
χ^2/dof	58.4/52	40.4/52
Model B: Power Law + Gaussian Line + Absorption		
Photon index (Γ)	$1.40^{+0.35}_{-0.30}$	...
A (10^{-3} cm^{-2} s^{-1} keV^{-1})	$1.2^{+0.7}_{-0.4}$	...
$E_{\rm line}$ (keV)	$4.95^{+0.25}_{-0.25}$	...
$A_{\rm line}$ (10^{-4} cm^{-2} s^{-1})	$1.07^{+0.57}_{-0.56}$	...
N_H (10^{20} cm^{-2})	$9.8^{+15.5}_{-7.0}$	...
χ^2/dof	48.6/50	...

NOTE.—Quoted errors are at the 90% confidence level computed while keeping the rest of variables as free parameters.

best-fit power-law model convolved with the detector response is shown as a histogram. The residuals between the data and the model are shown in the lower panel of the figure. The residuals show a positive excess near 5 keV. No excess is seen at low energies.

Line features in the spectra of many AGNs have recently been reported from observations with the *EXOSAT* and *Ginga* satellite-borne experiments (Nandra *et al.* 1989; Pounds *et al.* 1989). We examined the data for evidence of line emission. A Gaussian line feature with a fixed width of 0.1 keV and a variable line energy was added to the simple model mentioned above, and fitted. A very significant reduction in the χ^2 was obtained by the addition of a Gaussian feature near 5 keV. $\Delta\chi^2 = 10$ gives a very high significance (>99.9%) for justifying the presence of the line using the F-statistic. The best-fit values of the parameters from this fit are listed in Table 2, and the best-fit model is shown as a histogram in Figure 1*b* along with the PH data. The best-fit value for Γ is now $1.40^{+0.35}_{-0.30}$, which is marginally consistent with the canonical value of 1.7 for the AGNs and in better agreement with the 1985 data. This shows that not accounting for the presence of such features in the observations with poor energy resolution can lead to flatter power-law indices. The value for the line energy is best estimated to be 4.95 ± 0.25 keV. This line energy is consistent with a 6.4 keV and a 6.7 keV redshifted line from iron. The equivalent width of the line is estimated to be 800 ± 400 eV. The estimated equivalent width is quite high. The range of values given here takes into account only the statistical errors. We would like to caution that for weak sources such as PKS 1510−089, systematic errors can be large and can be judged from the data in Figure 1*b*. Therefore, although the existence of the line is fairly certain, the estimated line flux should be treated as tentative pending better observations. No improvement in the fit to the 1985 spectral data was obtained by the addition of a narrow-line feature. We examined the 1984 data

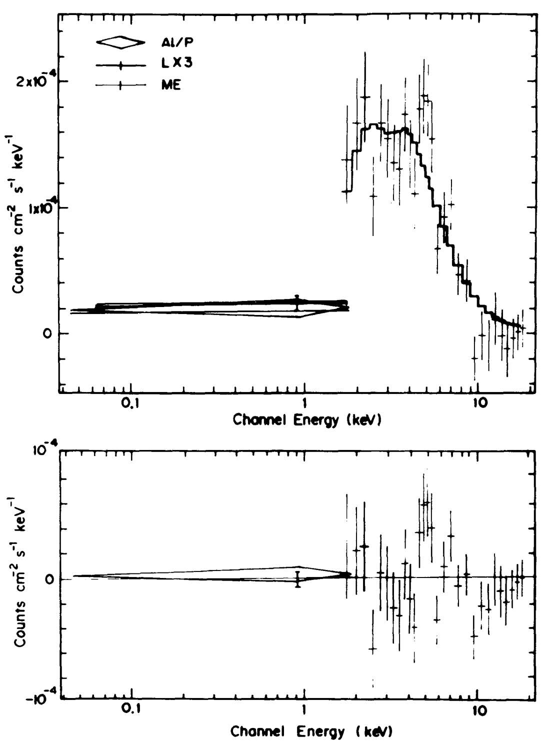

FIG. 1*a*

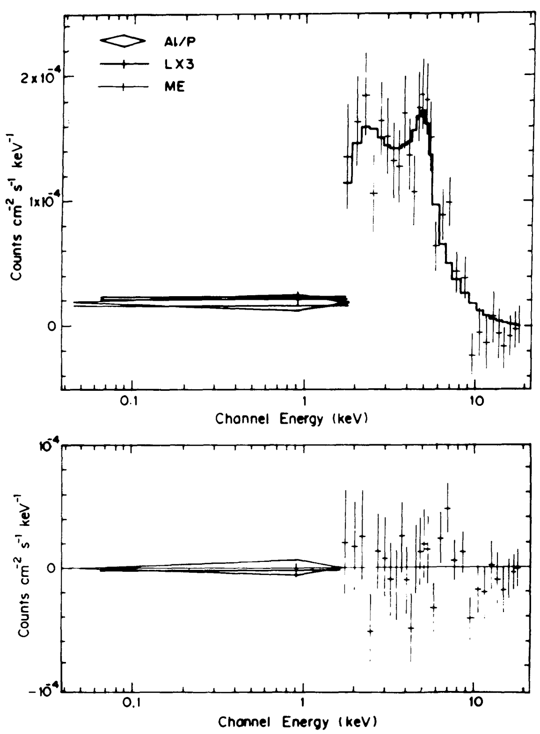

FIG. 1*b*

FIG. 1.—(*a*) Pulse-height (PH) data observed with the LE and ME detectors of *EXOSAT* on days 216 and 217 of 1984 are shown. The two filters used for the LE observations are indicated. The histogram shows the predicted count distribution from the best-fit single power-law model with low energy absorption. The lower panel shows the residuals between the data and the best-fit spectral model. (*b*) Same data as in (*a*) are displayed. The histogram drawn here, however, is for the best-fit model that includes a Gaussian line at 4.95 keV along with a power-law and an absorbing column density. The residuals from the best-fit model are shown in the lower panel.

in more detail, by analyzing the PH data obtained from each half separately. We also included the inner detectors (viz., detectors 2, 3, 6, and 7), and after appropriate corrections for the differences in the background spectra arising as a result of "swap" of the half-arrays, particularly in the inner detectors, we fitted them with the models described above. The line feature at 5 keV was observed with good significance in each half-array but with the equivalent width in the range 150–900 eV (90% confidence).

IV. DISCUSSION

The X-ray flux from PKS 1510−089 as observed with *EXOSAT* detectors in 1984–1985, in the 2–10 keV energy band is 8.9×10^{-12} ergs cm^{-2} s^{-1}. This corresponds to an X-ray luminosity of 7×10^{45} ergs s^{-1} emitted by the source in its rest-frame energy range of 2.7–13.6 keV, assuming a redshift of 0.361, $H_0 = 50$ km s^{-1} Mpc^{-1}, and $q_0 = 0$ in the Friedmann cosmology. To compare our results with those obtained from observations carried out with the IPC aboard the *Einstein Observatory*, we have calculated the flux in the 0.5–4.5 $(1 + z)^{-1}$ keV range used by Ku, Helfand, and Lucy (1980). The source luminosity in the rest frame of the source in 0.5–4.5 keV range is then found to be 3.15×10^{45} ergs s^{-1}. The X-ray luminosity, therefore, appears to have increased between 1980 and 1985 by more than 50%. Considering the uncertainty of 30% in the IPC fluxes (Ku, Helfand, and Lucy 1980), and the uncertainty involved in comparing the fluxes obtained with different instruments at different times, the observed increase may not be very significant. Short-term (i.e., hourly) variations have not been detected.

The present observations provide the best determination so far of the X-ray spectrum of PKS 1510−089. The slope of the power-law spectrum is found to be somewhat flatter than that of the well-studied brighter AGNs (Mushotzky 1984; Turner and Pounds 1989), although the canonical slope is not ruled out by our analysis. Wilkes and Elvis (1987) first showed that there is a correlation between the slope and the radio-loudness of AGNs, with the radio-loud objects having a flatter slope. This correlation was later confirmed by Canizares and White (1989) for quasars with high redshifts. The above correlation is based on the observations with IPC. Our results provide only marginal support for the reported flat spectrum when the presence of line emission is taken into account. Sensitive X-ray observations of high-redshift radio-loud quasars with detectors of wide bandwidth are needed to understand the effect of the line emission on the spectral slope determination.

The X-ray spectra of the BL Lacertae–type objects are usually steeper than those of the Seyferts and radio-quiet quasars. Even though PKS 1510−089 shows a strong BL Lac–type activity in the optical, similar behavior is not reflected in its X-ray spectrum.

A strong radio jet is seen in the VLA (O'Dea, Barvainis, and Challis 1988) and VLBI (Romney *et al.* 1984) radio images. A flatter X-ray component, if confirmed, could imply the existence of a beamed X-ray component also; otherwise we are probably seeing the normal Seyfert-type spectrum. The presence of a strong emission line in the spectrum would, however, argue for the major component of X-ray emission as being unbeamed.

Significant line emission has been detected from PKS 1510−089. Similar narrow features have been reported from only two quasars, viz., 3C 273 (Turner *et al.* 1990) and 1E 1821+643 (Warwick, Barstow, and Yaqoob 1989). The observed narrow-line feature near 5 keV in the X-ray spectrum of PKS 1510−089 could be due to the fluorescence of cold iron around the AGN. The measured equivalent width would, however, require an extremely high column density if the cold matter is distributed isotropically and contains iron with normal abundance (see Inoue 1985; Makishima 1986). But there is no evidence for the presence of high internal absorption in the line of sight to PKS 1510−089. The central X-ray source, however, could encounter a large amount of matter if the matter were distributed in an accretion disk–like structure. An equivalent width of only about 100 eV is expected from such a system when viewed almost face-on and assuming solar abundances (see George, Nandra, and Fabian 1990). To observe higher line emission, either the solid angle subtended by the disk must be greater than 2π or at least a fraction of the directly observed continuum must be intercepted by very dense material ($N_H > 10^{24}$ atoms cm^{-2}). We do not see any soft X-ray excess expected from a face-on disk. We would, however, like to point out that the Galactic column toward the quasar is itself quite high, and unless the soft X-ray excess is very strong, it would not be seen easily.

It has recently been shown that the X-ray continuum in AGNs could flatten between about 10 and 200 keV as a result of reprocessing by reflection from a disk (George, Nandra, and Fabian 1990) or through uniformly distributed cold matter (Guilbert and Rees 1988; Lightman and White 1988). Such an effect has been reported from 3C 273 (Worrall *et al.* 1979) and Mrk 509 (Singh *et al.* 1990). It is, therefore, important to extend the observations beyond 10 keV and to improve the signal-to-noise ratio to see this effect. A flatter index and the presence of strong line emission would be consistent with the above scenario.

In Figure 2 we have plotted the radio, millimeter, infrared, optical, ultraviolet, and X-ray measurements of energy flux from PKS 1510−089. The data were obtained as contemporaneously as possible and redshifted to the rest frame of the source. The radio data for the "core" have been taken from the 1985 March 8 measurements by O'Dea, Barvainis, and Challis (1985). The millimeter data have been obtained from the observations on 1985 February 6 by Steppe *et al.* (1988). The near-infrared flux is from 1983 April 22–24 measurements reported by Landau *et al.* (1986). The object is not listed in the *IRAS* catalog of far-infrared sources. The optical and ultraviolet data are from the 1984 April 21 observations by Malkan and Moore (1986). The far-ultraviolet data from the *IUE* archives, also reported by Malkan and Moore (1986), are from observations in 1981–1982. All data, with the exception of the *IUE* data, were obtained within about a year. The X-ray data are the unfolded best-fit spectrum from the 1984 August observations reported here.

The overall shape of the broad-band continuum resembles that of the radio-loud quasars more than it does that of the blazars (see Fig. 2 of Sanders *et al.* 1989). There is, however, a big gap in the far-infrared region which needs to be bridged before a more detailed comparison can be made. The observed shape from infrared to ultraviolet (and perhaps X-rays) can be synthesized from accretion disk models and nonthermal emission as shown by Band and Malkan (1989) or by thermal processes alone as suggested by Sanders *et al.* (1989). A primarily nonthermal emission for the radio and hard X-ray emission is required in both the models, however. The strong "ultraviolet excess" or the "blue bump" noticed by Malkan and Moore (1986) does not appear to extend into the soft

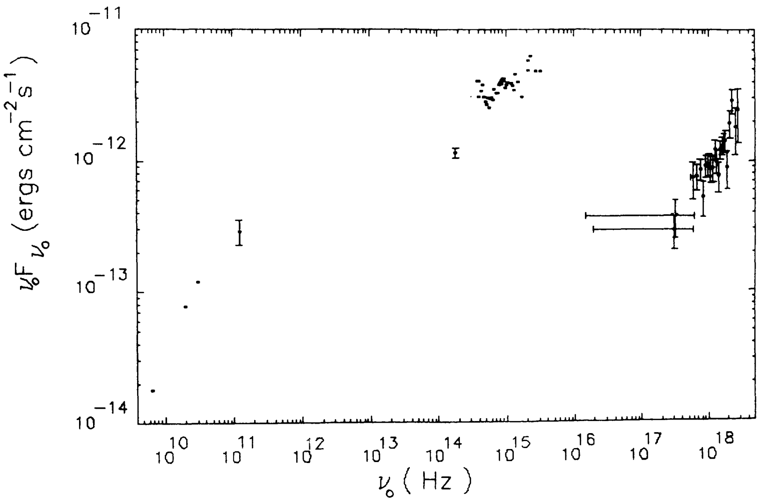

FIG. 2.—Broad-band radio, infrared, optical, ultraviolet, and X-ray continuum spectrum of PKS 1510−089, redshifted to the rest frame of the source (see text for references).

X-ray region. Therefore, the temperature of the blackbody fitted by them to the bump is consistent with the X-ray data. Extreme ultraviolet measurements would be highly desirable to get a more accurate measure of the extent of the big bump.

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