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THE DISCOVERY OF 3.9 HOUR PERIODIC DIPS IN THE X-RAY INTENSITY OF XB 1254−690

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ABSTRACT

We report the discovery of periodic intensity dips from the low-mass X-ray binary source XB 1254−690. The dips recur with a period of 3.88 ± 0.15 hr, consistent with the orbital period derived independently from optical data and occur ∼0.2 cycles before optical minimum. The duration of each dip is ∼0.8 hr with considerable variability on time scales of ∼1–300 s. The maximum reduction in 1–10 keV intensity observed during the dips is ∼95%; however, some dips are much shallower than this with a 1–10 keV intensity reduction of less than 20%. The spectral changes observed during the dips are not consistent with simply an increase in low energy absorption and/or a decrease in spectral normalization when compared with the quiescent spectrum but require the presence of a second component with little or no intrinsic low-energy absorption. This is probably X-rays scattered into the line of sight by an accretion disk corona with possibly a small contribution from scattering off interstellar dust grains at low energies. The metallicity of the absorbing material is between 0.25 and 2 times that of cosmic material. Two type I X-ray bursts were observed from XB 1254−690. If their peak luminosity is equal to the Eddington luminosity for a 1.4 $M_\odot$ neutron star, then the distance to XB 1254−690 is ∼10 kpc.

Subject headings: stars: individual — X-rays: binaries

I. INTRODUCTION

There are now seven X-ray binary systems that are known to exhibit periodic irregular dips in X-ray intensity (White and Mason 1985 and references therein; van der Klis *et al.* 1985; Watson, Willingale, and King 1985). X-ray bursts have been observed in five of these sources. The dips recur with intervals between 0.83 hr (XB 1916−053; White and Swank 1982) and 21 hr (X1624−690; Watson, Willingale, and King 1985). The dip recurrence intervals show a similar distribution to that of the orbital periods of other low-mass X-ray binary systems (White 1985). The duty cycle of the dips varies from source to source and is typically 10%–40%. The dip intensity, duration, and shape can vary dramatically from cycle to cycle. Dips are generally associated with an increase in low-energy absorption except in the case of X1755−338 where they appear to be energy independent (White *et al.* 1984; Parmar *et al.* 1985). This energy dependence, along with the irregular variability and periodic nature of the dips, has led to the development of a model for the dips in which the impact of the gas stream from the lobe-filling companion star produces a thickened region at the outer edge of the accretion disk that obscures the central compact X-ray source (White and Swank 1982; Walter *et al.* 1982).

Prior to the *EXOSAT* observations reported here, little was known about the X-ray properties of XB 1254−690. Mason *et al.* (1980), using the *HEAO 1* A2 instrument, discussed that the source showed a power-law spectrum with a photon spectral index α of ∼2.5 between 0.18 and 20 keV. Their fit was significantly improved by the addition of an emission line with a ∼500 eV equivalent width at 6.5 keV. Mason *et al.* also reported the observation of an optical burst of ∼20 s duration from the star identified with XB 1254−690. Griffiths *et al.* (1978), using data accumulated early in the *HEAO* mission, provided evidence for intensity variations of a factor of ∼4 on a time scale of months. The optical counterpart to XB 1254−690 was identified by Griffiths *et al.* to be a 19th mag object, implying a ratio of X-ray to optical luminosity L_x/L_{opt} of ∼200, similar to those of other compact X-ray binary systems with Population II companions (Lewin and Joss 1983). Recently Motch *et al.* (1986) have shown that the optical emission is modulated with a 3.9 hr period.

In this paper we present the results of four *EXOSAT* (Taylor *et al.* 1981) observations of XB 1254−690, all longer than 7 hr and including a 18 hr continuous observation. We report the discovery of irregular intensity dips that recur with an interval of 3.9 hr, and we present a detailed analysis of the 1–10 keV spectra seen during dipping intervals. We find that at least two components are required to represent accurately the observed shape of the spectra. We estimate the metallicity of the absorbing material and use the properties of the X-ray bursts to estimate the distance to XB 1254−690. In addition optical observations made partly simultaneously with the first of the *EXOSAT* observations are used to determine the phase of the dips with respect to the optical modulation. We discuss in § III

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the implications of the fits we obtained in terms of a model in which part of the X-ray flux from the neutron star is scattered in a photoionized accretion disk corona.

II. RESULTS

EXOSAT observed XB 1254−690 on 1984 February 5 starting at 5:30 UT for ~7 hr, 1984 May 15 5:00 UT for ~13 hr, 1984 August 6 21:00 UT for ~18 hr, and 1985 April 14 21:30 UT for ~14 hr. We report here results from three *EXOSAT* instruments: the medium energy detector array (ME; Turner, Smith, and Zimmermann 1981), which is a large area (1500 cm^2) proportional counter array sensitive to X-rays between 1–15 keV (argon chamber) and 6–55 keV (xenon chamber). The detectors are mounted in two independently pointable arrays, one-half of which was pointed directly at XB 1254−690; the other half was pointed toward a nearby source-free region of sky to provide a continuous background monitor. Count rates quoted in the following are always from the array half pointed toward the source. The pointing directions of the array halves were exchanged during the 1984 August 6 and 1985 April 14 observations every ~4 hr to obtain the best estimates of the background counting rates and spectral shape. The gas scintillation proportional counter (GSPC; Peacock *et al.* 1981) provides high spectral resolution between 2 and 17 keV. It was used to confirm the ME results and to set upper limits to any emission features at ~6.5 keV. A channel multiplier array detector (CMA; de Korte *et al.* 1981) behind a low-energy imaging telescope was used with a variety of filters to measure the source intensity between 0.05 and 2.0 keV.

During the first *EXOSAT* observation of XB 1254−690 on 1984 February 5 a single narrow intensity dip (1–10 keV) and an X-ray burst were observed (Courvoisier, Peacock, and Pakull 1984, and Fig. 3). At other times, the 1–10 keV X-ray intensity did not vary significantly. In a subsequent observation on 1984 May 15 we detected three shallow intensity dips (1–10 keV), each separated by ~3.9 hr (Courvoisier, Parmar, and Peacock 1984*a*, *b*). In order to confirm this dip recurrence interval a long (18 hr) observation of XB 1254−690 was made on 1984 August 6. This observation showed five deep irregular intensity dips that recurred with a period of 3.88 ± 0.15 hr (Fig. 1). In addition a second type I X-ray burst was observed. A fourth observation on 1985 April 14 showed a similar light curve to the second observation (Fig. 2). During intervals where the source was neither bursting nor dipping (hereafter referred to as quiescent intervals) the 1–10 keV ME count rate was ~40 counts s^{-1} in the half array pointed toward the source. The quiescent 1–10 keV count rate did not vary significantly from observation to observation.

a) The X-Ray Light Curve

The 1–10 keV light curve obtained with the ME during the 1984 August 6 observation when the dips were deepest is shown in Figure 1. The hardness ratio is the counts in the 1–3.5 keV band divided by those between 3.5 and 10 keV. Five irregular dips in X-ray intensity, each separated by 3.88 ± 0.15 hr, and an X-ray burst that occurred on 1984 August 7 at 07:22 UT are visible. Each dip lasts for ~0.8 hr and is associated with an increase in hardness ratio. The maximum reduction in the 1–10 keV intensity during each dip is ~95% except during the fourth dip where it is ~80%. Figure 2 shows the ME 1–10 keV light curve of the 1985 April 14 observation. It illustrates

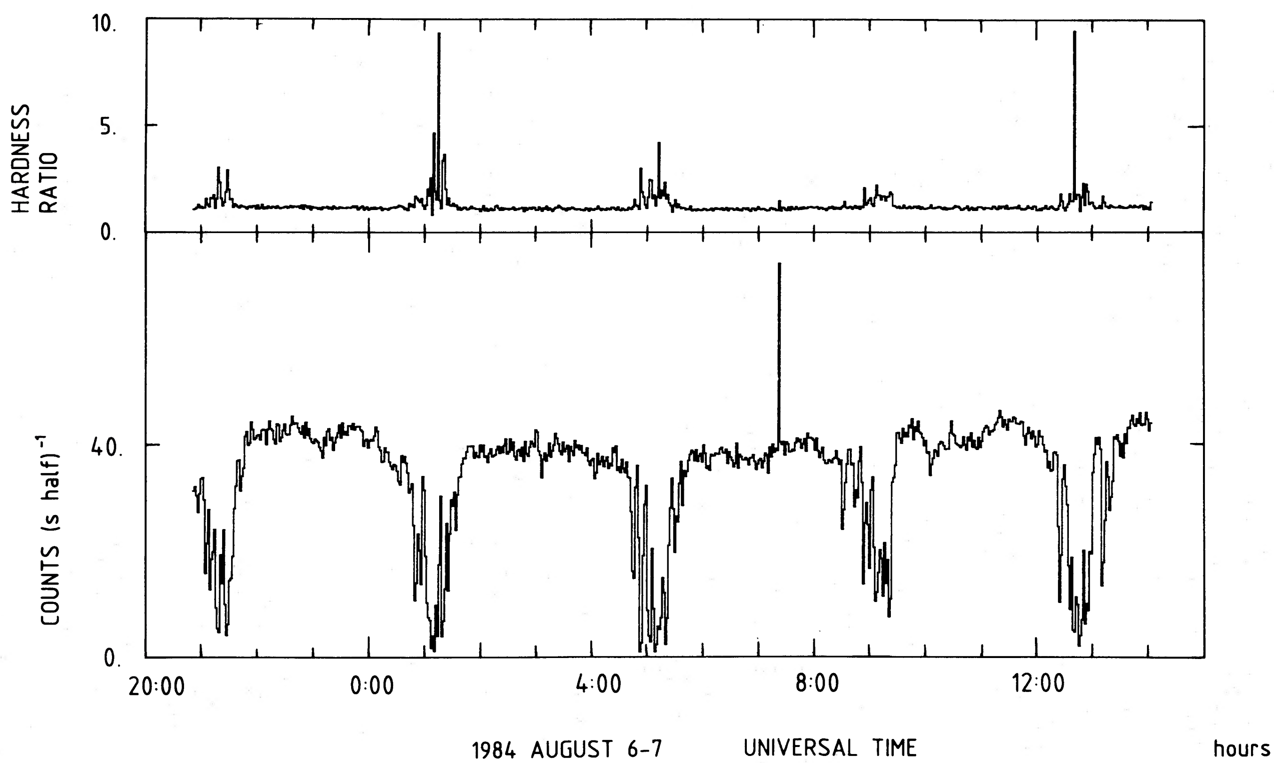

FIG. 1.—The ME light curve (1–10 keV) of XB 1254−690 during the 1984 August 6 *EXOSAT* observation together with the hardness ratio (counts in the 1–3.5 keV band divided by those in the 3.5–10 keV band) plotted with a time resolution of 2 minutes. The dips are separated by 3.88 ± 0.15 hr and are associated with a large increase in the hardness ratio. An X-ray burst can clearly be seen at 7:22 UT.

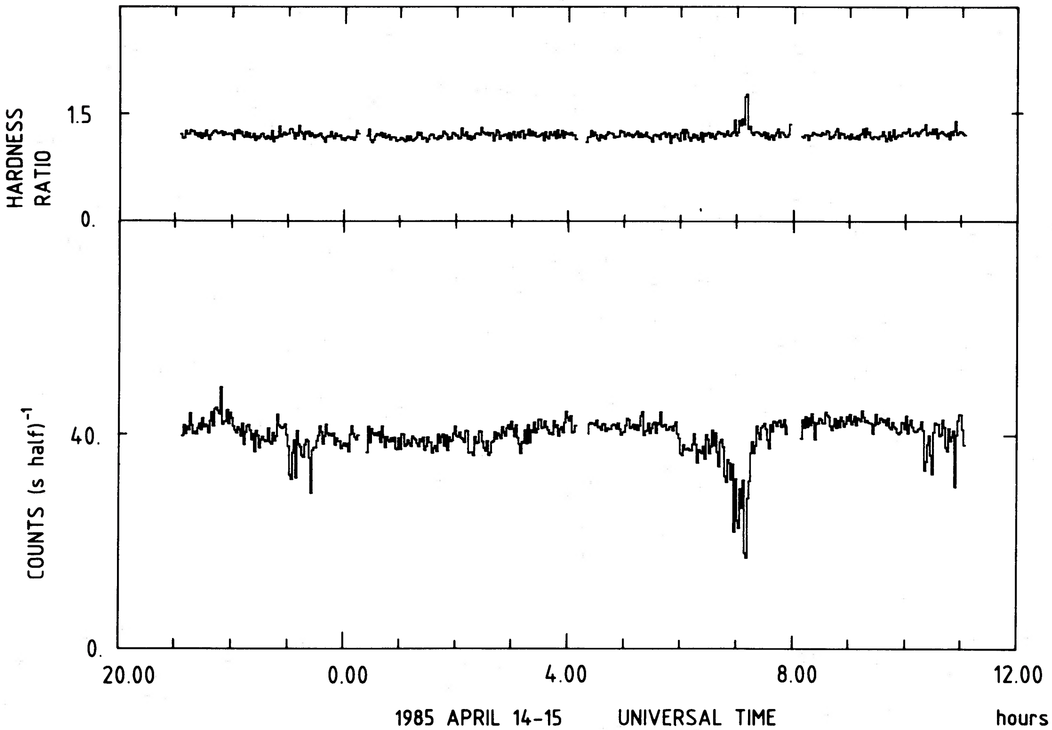

FIG. 2.—The ME light curve (1–10 keV) during the 1985 April 14 observation together with the hardness ratio defined as in Fig. 1. The time resolution and energy bands are as in Fig. 1. The dips are much shallower than during the 1984 August 6 observation and illustrate the large variety of dip depths, shapes, and hardness ratios that were seen during the four *EXOSAT* observations.

the large variations in dip depth and structure that are observed from observation to observation as well as from cycle to cycle. The variations in the hardness ratio are larger by a factor of ~5 during the deep dips of 1984 August 6 than during the shallow dips of 1985 August 14.

According to the 3.9 hr recurrence interval, a further dip should have been observed during the 1984 February 5 observation. The latter was not detected with an upper limit to any 1–10 keV reduction in intensity of 20% (for a 1 hr duration, Fig. 3).

The second dip of Figure 1 is displayed in Figure 4 with a time resolution of 3.125 s to illustrate the irregular intensity variations present during the individual dips. The light curve shown in Figure 4 is typical of all dips seen on 1984 August 6; the shallower dips observed during the other observations show less erratic intensity variations. The 1–10 keV intensity

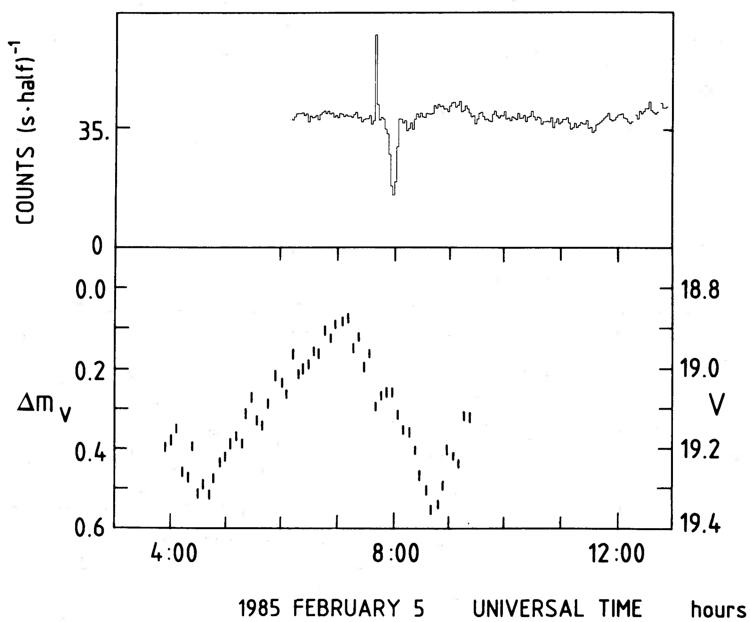

FIG. 3.—Partially simultaneous *EXOSAT* and optical observation of XB 1254−690 on 1984 February 5. The upper panel gives the 1–10 keV ME light curve with a time resolution of 2 min as in Figs. 1 and 2 and the lower panel shows the optical V magnitude with a time resolution of 5 min.

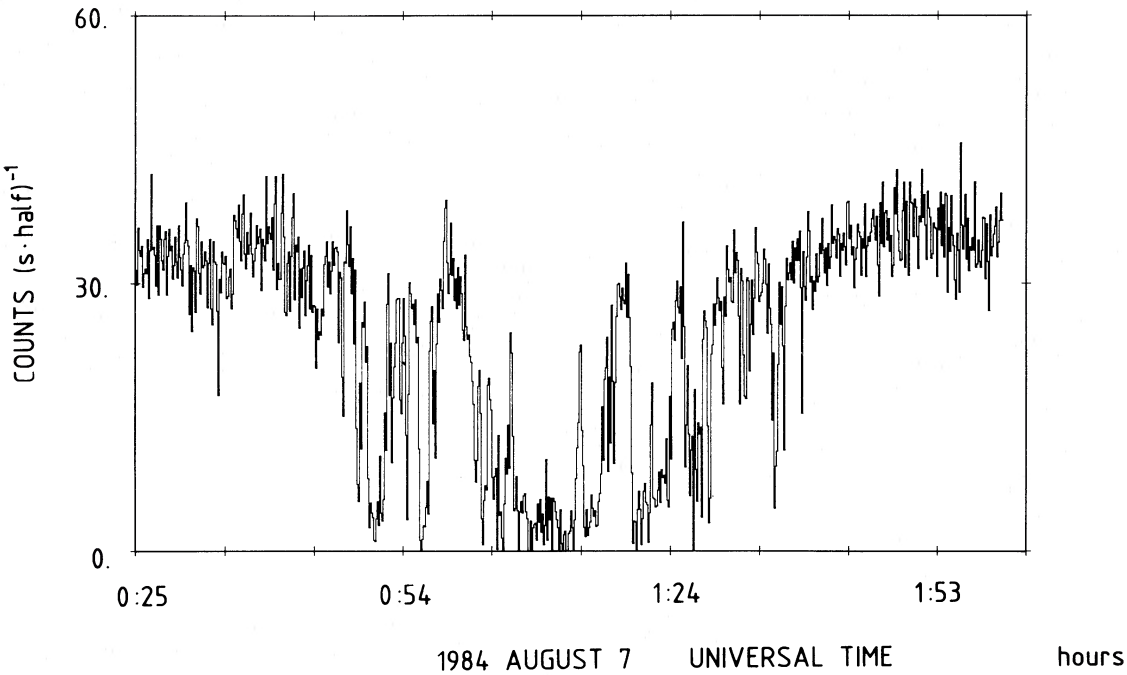

FIG. 4.—High time resolution (3.125 s) 1–10 keV light curve of the second dip of Fig. 1 showing variability on all time scales between ~1 s and ~300 s. The count rate is most of the time either at the quiescent level or at a lower level ~5% of the quiescent emission.

during the deep dips is often either at a lower level of ~2 counts s^{-1} corresponding to ~5% of the quiescent emission or at an upper level similar to the quiescent level. The time during which the counting rate lies in an interval of ~2 counts s^{-1} at intermediate levels is one-third of the time during which the counting rate is at low or high levels in similar bands. The rapid transitions between the two typical dip levels and the large reduction in intensity suggest that the absorbing material is relatively opaque to 1–10 keV X-rays. The maximum observed reduction in intensity during dipping intervals requires an optical depth τ of ~3. There is evidence for variability on all time scales between ~1 s and ~300 s. In contrast, during the quiescent intervals there is no evidence for any significant 1–10 keV excess variability over that expected from counting statistics on time scales less than ~1 hr. There is some evidence for the presence of secondary dips with a reduction in 1–10 keV intensity of ~10%–20% displaced by ~0.5 cycles from the main dips during the 1984 August 6 observation (Fig. 1).

b) The Quiescent Spectrum

Table 1 shows the spectral parameters obtained from fits to the ME argon spectra of XB 1254−690 obtained during quiescent intervals of three observations (all errors are quoted at the 90% confidence level). The statistical uncertainties were increased by 1% of the total count rate to account for systematic uncertainties in the detector calibration. During the 1984 February 5 observation the ME data were affected by solar activity and were not used in the spectral analysis. The data from the long observations on 1984 August 6 and 1985 April 14 were divided into three and four approximately equal duration intervals respectively to search for evidence of spectral variability on time scales of hours. A generalized thermal model of the form $A \exp(-\sigma_E N_H) E^{-\gamma} \exp(-E/kT)$ photons $cm^{-2}\ s^{-1}\ keV^{-1}$, where σ_E are the absorption cross section coefficients of Morrison and McCammon (1983), N_H is the equivalent hydrogen absorption column density, and E is energy in keV, was used to fit to the data. This model gives significantly better fits to the data than a thermal bremsstrahlung model, except for the 1985 April 14 observation where the generalized thermal model converged to a thermal ($\gamma \sim 1.3$) model. The spectral parameters shown in Table 1 indicate that there is no significant variation in spectral shape between any of the quiescent spectra. The 1–10 keV flux of the quiescent emission of XB 1254−690 corresponds to $\sim 6 \times 10^{-10}$ ergs $cm^{-2}\ s^{-1}$.

The GSPC was not affected by the solar activity on 1984 February 5 and its data could thus be used for spectral analysis. The spectral parameters describing fits of GSPC spectra obtained by integrating all of the quiescent data for the three first observations are given in Table 2. The GSPC results confirm the spectral shapes derived from ME data (Table 1). The 90% confidence upper limit equivalent widths to any 500 eV full width at half-maximum emission feature at 6.5 keV are 80 eV, 60 eV, and 45 eV. The GSPC power law indices are similar to those of Mason *et al.* (1980), who did not obtain good fits to a thermal bremsstrahlung model. Mason *et al.* also report the presence of an emission line of 500 eV equivalent width at 6.5 keV for which we find no evidence. There is marginal evidence that the source temperature was slightly higher on 1984 February 5 than during the three following observations. The small effective area (100 cm^2) and high background of the GSPC do not allow the distinction between a generalized thermal model and a thermal model to be made. These results indicate that the quiescent 1–10 keV spectrum of XB 1254−690 is similar to those of other X-ray bursters studied in detail (White and Mason 1985).

c) The Energy Dependence of the Dips

In order to investigate the spectral changes associated with the dips, we accumulated a series of ME argon spectra selected in count rate bands during the dips observed during the 1984

TABLE 1

XB 1254−690 Spectral Parameters Derived from *EXOSAT* Medium Energy Detector Array Measurements

Observation	Model	γ	kT (keV)	N_H (10^{22} cm^{-2})	χ^2/dof
		1984			
May 15	Power law	2.4	...	1.2	90/16
	Thermal	...	5.2 ± 0.2	0.35 ± 0.1	22/16
	Gen. ther.	1.05 ± 0.2	3.9 ± 0.8	<0.4	18/15
Aug 6 I 22:00–02:51	Power law	2.4	...	1.4	167/15
	Thermal	...	5.4 ± 0.2	0.49 ± 0.07	34/15
	Gen. ther.	0.75 ± 0.15	3.4 − 0.2 + 0.6	<0.22	17/14
Aug 7 II 03:07–08:00	Power law	2.4	...	1.4	210/15
	Thermal	...	5.2 ± 0.1	0.47 ± 0.06	35/15
	Gen. ther.	0.85 ± 0.15	3.5 ± 0.3	<0.27	18/14
Aug 7 III 10:25–14:40	Power law	2.4	...	1.5	125/15
	Thermal	...	5.5 ± 0.3	0.53 ± 0.1	20/15
	Gen. ther.	0.94 ± 0.20	3.8 − 0.5 + 0.8	<0.45	13/14
		1985			
Apr 14 I 21:07–22:45	Power law	2.3	...	1.3	90/14
	Thermal	...	5.6 − 0.1 + 0.4	0.35 ± 0.1	24/14
	Gen. ther.	1.2 ± 0.3	4.8 ± 0.5	<0.4	24/13
Apr 15 II 00:25–04:08	Power law	2.4	...	1.2	74/17
	Thermal	...	5.9 ± 0.2	0.25 ± 0.1	30/17
	Gen. ther.	1.5 ± 0.2	7.0 ± 2	0.45 ± 0.2	28/16
Apr 15 III 04:20–05:40	Power law	2.4	...	1.2	57/14
	Thermal	...	5.6 ± 0.3	0.3 ± 0.1	6/14
	Gen. ther.	1.4 ± 0.3	5.5 ± 1.2	<0.6	6/13
Apr 15 IV 08:08–10:20	Power law	2.3	...	1.2	56/14
	Thermal	...	5.9 ± 0.3	0.3 ± 0.1	11/14
	Gen. ther.	1.35 ± 0.25	5.7 ± 1.2	0.35 ± 0.25	11/13

All uncertainties are quoted at the 90% level. The 1984 February 5 data was not analyzed due to solar effects in the ME background. The 1984 August 6 observation was divided into three, that of 1985 April 14 into four, approximately equal duration intervals.

August 6 observation. This observation was chosen because the dips were deep and good estimates of the background counting rate and spectral shape were available. Each spectrum covers a count rate interval of ~ 2 counts s^{-1}, so that about 10 spectra cover the intensity range observed during the dips. Separate series of spectra were accumulated for each detector array half. Figure 5*a* illustrates the fit to a representative dip spectrum with a count rate of ~ 10 counts s^{-1} and a total accumulation time of 247 s using the generalized thermal model discussed earlier. The normalization A and low-energy absorption N_H were allowed to vary, while the slope γ and the temperature were held fixed at the values determined from quiescent intervals. There is a clear excess of counts at low energies over that predicted by the best fitting model, resulting in a poor representation of the data with a χ^2 of 45 for 15 degrees of freedom (dof). Adding a second component with temperature and slope fixed as before, and with low-energy absorption also fixed at the quiescent value, allows a good fit to be obtained, resulting in a χ^2 of 18 for 14 dof (Fig. 5*b*).

Figures 6 and 7 give the results of this spectral analysis as a function of count rate during the dips. Spectra accumulated in each ME array half were analyzed independently and show the same trends. Figure 6*a* shows the χ^2/dof as a function of the count rate for the one-component model described above (Fig.

TABLE 2

XB 1254−690 Spectral Parameters Derived from *EXOSAT* Gas Scintillation Proportional Counter Measurements

Observation	Model	γ	kT (keV)	N_H (10^{22} cm^{-2})	χ^2/dof
1984 Feb 5	Power law	2.1	...	1.7	57/66
	Thermal	...	10 ± 1	<0.7	51/56
	Gen. Therm.	1.4 ± 0.5	<9	<2.0	49/55
1984 May 15	Power law	2.5	...	3.0	64/51
	Thermal	...	6.6 ± 0.5	0.6 ± 0.5	58/51
	Gen. Therm.	1.4 ± 0.4	7.0 − 3 + 13	0.9 ± 0.7	58/50
1984 Aug 6	Power law	2.8	...	4.0	88/55
	Thermal	...	5.1 ± 0.3	1.1 ± 0.4	62/55
	Gen. Therm.	0.9 ± 0.4	37 − 0.4 + 1.5	<1.4	60/54

All uncertainties are quoted at a 90% confidence level.

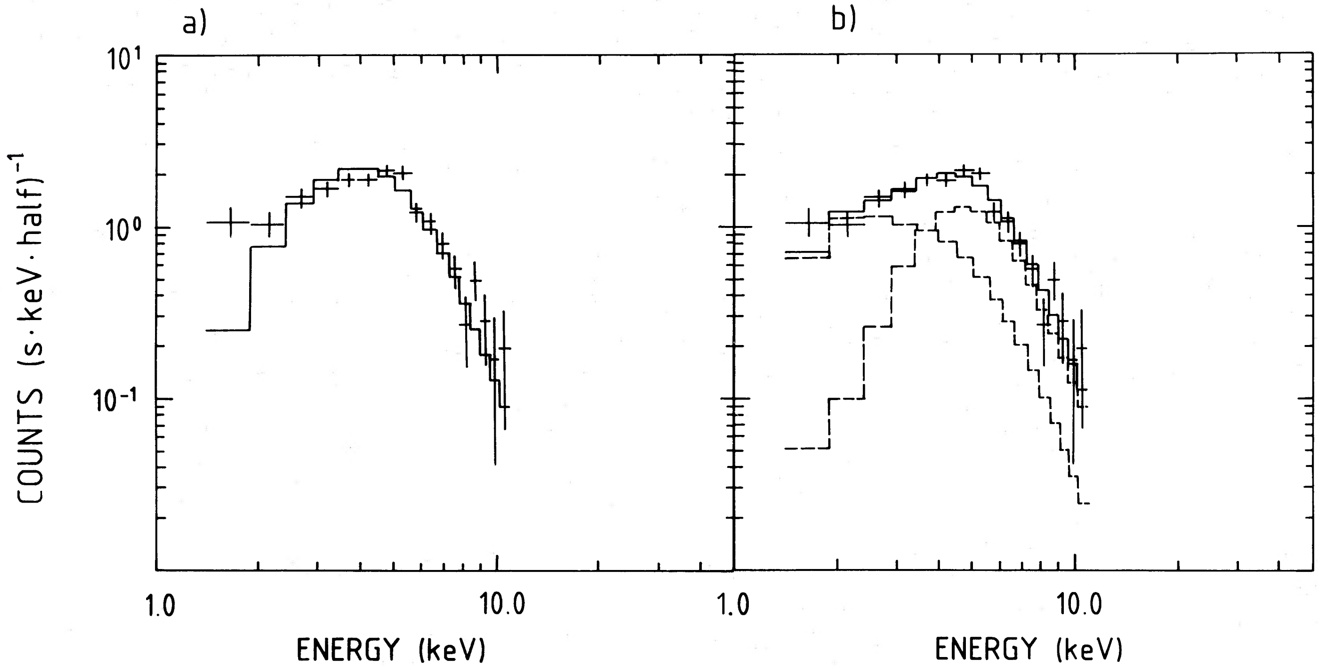

FIG. 5.—ME argon data fits to a representative dip spectrum in a band of ~2 counts s^{-1} centered at ~10 counts s^{-1}. Figure 5*a* gives the fit to a one-component model with power law index and temperature fixed at values measured during nearby quiescent intervals. An excess of counts over the model prediction can clearly be seen. Figure 5*b* shows a two-component model fitted to the same data, each component with power law index and temperature fixed as above but with one component at the same low energy absorption as the quiescent model. The highly absorbed component, the unabsorbed component, and their sum are shown in the figure.

5*a*). It is clear that this model does not represent the changes in spectrum observed during the dips well since the χ^2/dof increases with decreasing count rate and reaches ~7 at the bottom of the dips. This shows that the dips cannot be attributed solely to absorption by cold material of normal cosmic abundance around a compact X-ray source. Figure 6*b* shows the same plot (χ^2/dof as a function of count rate) for the two-component model used in Figure 5*b*. There is no obvious trend of increasing χ^2/dof with decreasing intensity, suggesting that the observed spectral changes are being well modeled.

Figure 7 shows the parameters of the fits to the two-component model as a function of the observed count rate. The temperature and power law index were fixed at the best values obtained from the fits to the quiescent spectra using the generalized thermal model. Panels *a* and *b* of Figure 7 illustrates the increasing contribution of the highly absorbed component and

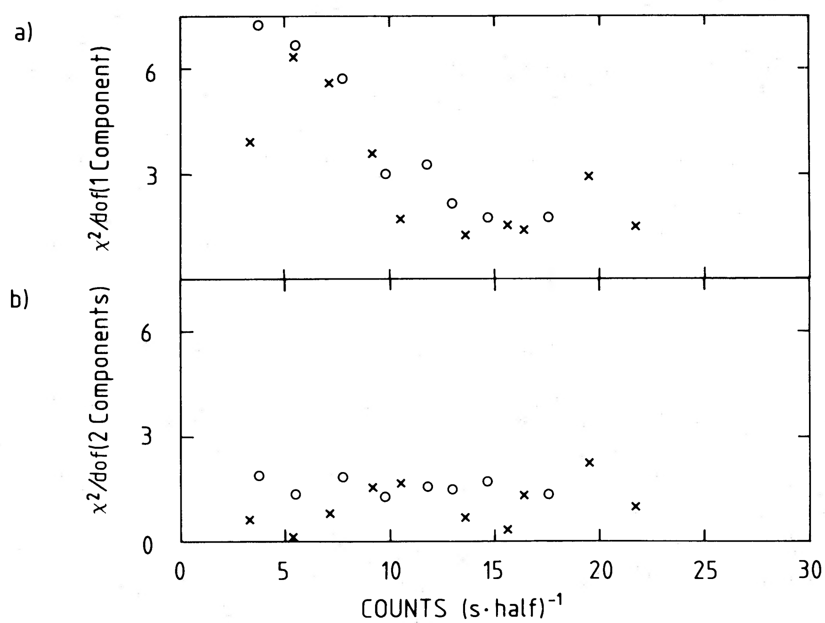

FIG. 6.—χ^2/dof for the single-component model fits (*a*) and the two-component model fits (*b*) as a function of count rate during the dips for the 1984 August 6 observation. Spectra accumulated in different ME array halves are shown separately as crosses and circles. The figure illustrates that the single-component fits get worse as the count rate decreases whereas the two-component fits show no systematic trend as a function of dip depth.

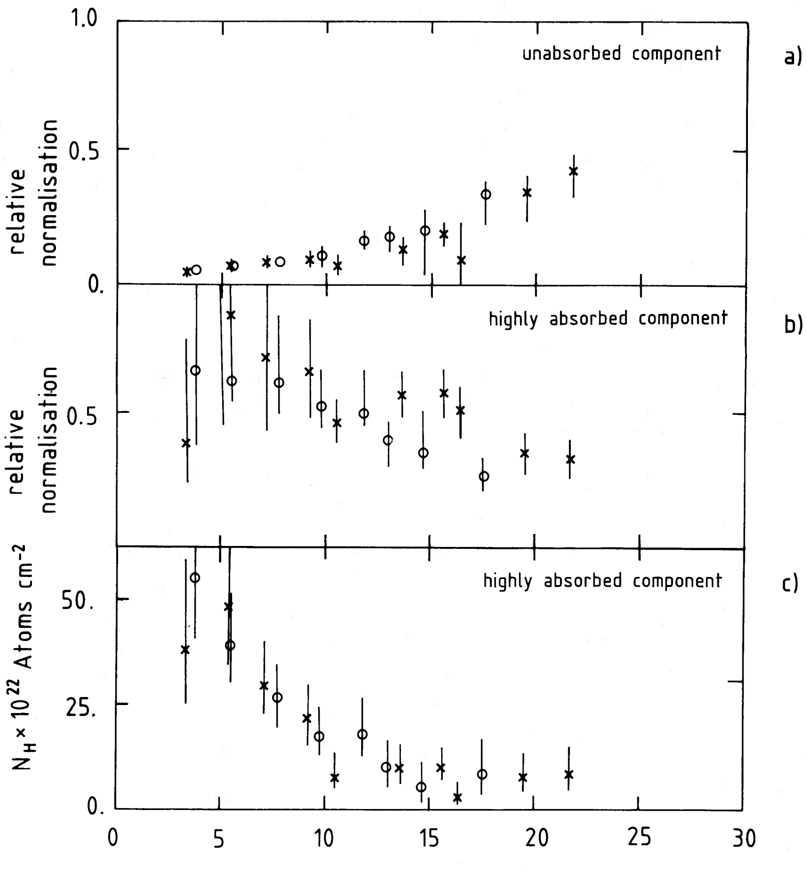

FIG. 7.—Parameters of the two-component model best fitted to the ME argon data as a function of count rate during the dips observed on 1984 August 6. The unabsorbed component normalization (*a*) and the highly absorbed component normalization (*b*) are expressed in units of the quiescent normalization. The absorption column density for the highly absorbed component is given in Fig. 7*c*, the column density of the unabsorbed component was fixed at the quiescent value. Parameters for each array half are shown separately as crosses and circles. Error bars give the 90% confidence level.

the absence of a trend in the sum of the two normalizations as the count rate decreases. Figure 7*c* shows the value of the absorption column density of the highly absorbed component. At the deepest part of the dips the absorption column density is $\sim 5 \times 10^{23}$ H cm^{-2} and the normalization of the unabsorbed component is ~ 0.05 of that of the quiescent level. The increase in normalization of this component observed during less intense dipping intervals is probably the result of vatiations in N_H during the integration intervals of the spectra and the effect of fitting a two-component model during intervals where an acceptable χ^2 is obtained with a single-component model (Parmar *et al.* 1986).

We have used data from the low-energy imaging CMA instrument with a 3000 Å Lexan filter to confirm the presence of the two components seen in the ME fits. We accumulated an ME argon spectrum over all the dipping intervals of the 1984 August 6 observation where the count rate was close to or at its lowest level. The total integration interval is 608 s and the mean 1–10 keV intensity 3.4 ± 0.3 counts s^{-1}. A source was detected in the CMA data at the expected position of XB 1254−690 during the same intervals with a count rate of 0.014 ± 0.006 counts s^{-1}. Fitting both the CMA measurement and the ME spectrum to the single-component model as before gave a poor χ^2 of 33 for 13 dof. The best fitting N_H is 3.8×10^{22} H cm^{-2} and the model predicts only 0.0005 counts s^{-1} in the CMA, a factor of ~ 30 less than that observed. Fitting the two-component model of Figure 5*b* (fixing the low absorption N_H at the quiescent value) gives a much better fit with χ^2 of 3 for 12 dof. The N_H of the highly absorbed component is now $(4.4^{+3.6}_{-1.9} - 1.9 \times 10^{23}$ H cm^{-2}). The low absorption component contributes 0.015 ± 0.003 counts s^{-1} in the CMA and the highly absorbed component less than 0.0001 counts s^{-1}. This confirms the presence of a second component with low N_H and suggests that almost all the flux observed in the CMA is from this low-absorption component.

d) The X-Ray Bursts

During the four *EXOSAT* observations of XB 1254−690 we observed two X-ray bursts. One occurred during the 1984 February 5 observation (Courvoisier, Peacock, and Pakull 1984 and Fig. 3) and the other during the 1984 August 6 observation (Fig. 1). Both bursts had very similar properties: rise times of ~ 1 s followed by a fast decay phase of ~ 5 s followed by a slower phase of ~ 15 s. Two ME argon spectra were obtained for each burst over the fast and slow decay phases separately. The background plus quiescent spectrum were estimated with the data taken during the 30 min preceding each burst and subtracted from the raw burst spectrum. This procedure allows an accurate background subtraction for both burst observations. A blackbody model was used to successfully fit the four spectra. The temperatures characterizing the two phases of the first burst were 1.5 ± 0.15 keV and 1.3 ± 0.2 keV and those characterizing the second burst showed evidence for some cooling from 2.0 ± 0.15 to 1.4 ± 0.2 keV. The ratio of the time-averaged luminosity to burst luminosity is high, ~ 1900, although the uncertainty on this parameter is large since only two bursts were observed.

We have estimated the distance to XB 1254−690 by assuming that the peak burst luminosity is equal to the Eddington luminosity for a 1.4 $M_\odot$ neutron star, $L_{\rm Edd} = 1.7 \times 10^{38}$ ergs s^{-1}. Using the luminosity of the fast decay components corrected for relativistic effects and normalized to the peak count rate gives distances of 12 ± 2 kpc and 11 ± 2 kpc for the two bursts. The uncertainty primarily reflects the error on the blackbody temperature estimates. Since the Eddington luminosity is probably not an accurate measure of the burst absolute luminosity, the distance has another uncertainty of $(L_{\rm burst}/L_{\rm Edd})^{0.5}$. This distance can be used to estimate the radius of the burst-emitting area, which is found to be ~ 10 km for the two phases of each burst. These characteristics are typical of type 1 X-ray bursts.

e) Coordinated Optical Observations

The 1984 February 5 *EXOSAT* observation of XB 1254−690 was partially simultaneous with optical observations made with the ESO 2.2 m telescope at La Silla and a CCD camera with a *V* filter. The optical light curve is shown in Figure 3 together with the 1–10 keV ME light curve. The time resolution of the optical data of 5 minutes was insufficient to resolve the burst that occurred during the simultaneous coverage. The absence of marked feature in the optical light curve during dipping intervals indicates that the material obscuring the X-ray source does not significantly obscure the optical source, which is therefore either much larger than the X-ray absorbing region or situated out of the line of sight to the central X-ray source. A series of optical observations (Motch *et al.* 1986) was made during the spring of 1984 showing that the optical emission is modulated with a period of 3.93336 ± 0.00022 hr, consistent with the recurrence interval of the X-ray dips. The high precision of the optical period determination allows the phase of the X-ray dips with respect to optical minimum to be determined, the dips occurring 0.2 cycles before minimum light.

III. DISCUSSION

We have detected periodic dips in X-ray intensity from the low-mass X-ray binary XB 1254−690. The dip spectra are complex and require the presence of at least two components. During the dips the X-ray intensity varies erratically even returning several times briefly to the quiescent value. The dip depth is very variable: during one observation the reduction in intensity was $\sim 95\%$, while during another observation a dip that would have been detected given the recurrence interval was not with an upper limit to any reduction in 1–10 keV intensity of $\sim 20\%$ to a dip of 1 hr duration.

The orbital parameters of XB 1254−690 can be estimated assuming that the system contains a compact object of mass 1.4 $M_\odot$, that the orbital period is 3.9 hr (dip recurrence interval as well as optical period), and that the companion is a low mass, zero-age main-sequence star filling its Roche lobe. In this case, there is a unique relation between the orbital period and the mass M_c of the companion (Warner 1976). For the XB 1254−690 system, we find $M_c \sim 0.45\ M_\odot$. The separation between the X-ray source and its companion is then $\sim 1.1 \times 10^{11}$ cm and the radius of the accretion disk around the neutron star estimated to fill 70% of the Roche radius $\sim 3.6 \times 10^{10}$ cm. The absence of eclipses of the X-ray source by the companion indicates that the line of sight is inclined by at least $\sim 15°$ from the orbital plane.

The optical light curve shown in Figure 3 indicates a variability of 0.4 mag during a 3.9 hr cycle. This result and the periodicity of the optical light curve are confirmed by the large set of optical observations discussed in Motch *et al.* 1986. In contrast with X1755−338 (Mason, Parmar, and White 1985) the optical light curve shows a steep ingress to minimum and a slower egress. Both sources have optical minima that occur ~ 0.2 cycles after the X-ray dip. As discussed in Motch *et al.* (1986) and Mason, Parmar and White (1985), the optical modulation could be caused by X-ray heating of the companion star, or an azimuthal asymmetry of the accretion disk or by the occultation of the disk by the companion.

We have considered whether the low-energy excess observed in the one-component model during the dipping intervals (Fig. 5*a*) could be caused by photoionization of the absorbing material at the edge of the disk. Using the formulation of McClintock *et al.* (1982), we find the following relation between the compact source luminosity *L*, the distance from the source to the absorbing region *R*, the relative thickness of the absorbing region $\Delta R/R$, the optical depth τ and the ionization parameter $\xi = L/nR^2$ (n = density):

$$\frac{\xi}{10^2} = 0.7 \left(\frac{L}{10^{37}\ \text{ergs s}^{-1}}\right)\left(\frac{R}{10^{11}\ \text{cm}}\right)^{-1}\left(\frac{\Delta R}{R}\right)\tau^{-1}, \quad (1)$$

which is less than 0.2 ergs cm s^{-1} for the observed optical depth of $\tau \sim 3$ and an absorbing region extending all the way to the central source. The luminosity of the compact source as calculated from the quiescent flux and distance of 11 kpc derived from the X-ray burst is $\sim 1 \times 10^{37}$ ergs s^{-1}. This value of the ionization parameter is too low to maintain a photoionized cloud where scattering dominates (McClintock *et al.* 1982).

Another possible way to produce a low-energy excess is to partially cover an extended central source. We believe that this is unlikely since the size of clouds moving at the Kepler speed of ~ 700 km s^{-1} (appropriate for the assumed geometry and neutron star mass) and producing variability on time scales longer than ~ 1 s as observed in XB 1254−690 is more than $\sim 7 \times 10^7$ cm, much larger than the size of a neutron star.

Mauche and Gorenstein (1986) have reported the detection, using the imaging proportional counter on the *Einstein Observatory*, of an X-ray halo around XB 1254−690, which they interpret as caused by scattering off interstellar dust grains. These authors measured the fractional halo intensity to be 0.04 ± 0.02 between 0.2 and 3.5 keV. Since the cross section of scattering of X-rays by dust grains has an E^{-2} dependence (see, e.g., Mauche and Gorenstein 1986 and references therein), this process is unlikely to contribute a significant fraction of the unabsorbed 1–10 keV emission. There may be, however, some contribution from X-rays scattered off interstellar dust grains in the 0.05–2 keV flux observed by the CMA (Xu, McCray and Kelley 1986).

There is evidence for extended accretion disk coronae in some low-mass X-ray binaries. White and Holt (1982) and McClintock *et al.* (1982) showed that the complex X-ray light curves of X1822−371 and XT 2129+470 could be well modeled as being due to scattering of X-rays from a central compact source in an extended accretion disk corona modulated by the obscuration of a thick azimuthally structured accretion disk and by the companion. This accretion disk hides the central X-ray source from direct view, resulting in a low L_x/L_{opt} ratio of ~ 20.

In order to check whether such an accretion disk corona could be present in the XB 1254−690 system, we have calculated the optical depth of electron scattering in the corona τ_T from the ratio f of scattered flux to unscattered flux and the fraction of solid angle β sustained by the scattering region as seen from the central source:

$$\tau_T = f/[\beta \cdot (1 - f)] . \quad (2)$$

If the corona is scattering from one hemisphere one finds that τ_T is ~ 0.2 for 10% scattered flux. The X-ray luminosity necessary to keep such a corona ionized (ionization parameter > 100) is $> 1.2 \times 10^{36}$ ergs s^{-1} for a uniform corona extending to the edge of the disk (eq. [1]). This value is less than the luminosity of the quiescent emission derived from the flux of the quiescent emission and the distance estimate from the bursts, showing that it is possible to photoionize the corona. Equation 1 shows that the luminosity of the compact central source is sufficient to keep the $\tau \sim 0.2$ accretion disk corona photoionized, whereas this luminosity is insufficient to photoionize the optically thicker X-ray absorbing clouds.

Thus we believe it likely that the low-energy excess observed during dipping intervals from XB 1254−690 is from scattering of photons from the central source in such an accretion disk corona. In the energy range 1–10 keV the accretion disk corona contributes $\sim 5\%$ of the total intensity. This suggests that had XB 1254−690 been observed at an angle closer to the orbital plane such that the central compact source is always obscured by the accretion disk, then it would appear to be an extremely low-intensity X-ray source with a L_x/L_{opt} of ~ 10.

It should be remarked that the fits used do not provide an unambiguous determination of the spectral form and that other complex models also give acceptable fits. However, all the acceptable models require at least two components with different low-energy absorption column densities. The model presented here is the simplest in that two variable parameters are needed to explain the change of spectral properties as a function of intensity during dips. The good fits which are obtained with the generalized thermal model for the quiescent emission indicate that no blackbody component is required to describe the XB 1254−690 spectra.

The variations in the dip depth from cycle to cycle are probably caused by variations in the height of the thickened region in the accretion disk. During some dips very little or no material is present in the line of sight, while at other times the large dip depths indicate the presence of substantial amounts of material. The lack of X-ray eclipses suggests that we are observing XB 1254−690 at a lower inclination angle than EXO 0748−676 and XBT 1659−298 which both show eclipses and dips (Parmar *et al.* 1986; Cominsky and Wood 1984), although it is also possible that this difference is due to differing companion mass radius relations. It is interesting to note that of the seven dipping sources observed to date, XB 1254−690 appears to have the largest variations in the maximum dip intensities. This may also be related to observing XB 1254−690 at a lower inclination angle than the other dipping sources. Further X-ray observations of some of the other less well-studied dipping sources are required in order to exclude the possibility that at times these sources exhibit a wider range of intensity variability. It is furthermore interesting to remark that the depth of the dips is not correlated with the observed quiescent X-ray 1–10 keV intensity of the source and hence with the accretion rate. This means that the bulge size or disk thickness at the edge is not related in a simple manner to the mass accretion rate.

The metallicity of the absorbing material surrounding the X-ray source can be estimated by considering the sum of the spectral normalizations of the absorbed and unabsorbed components as a function of the observed flux. A source absorbed by metal-poor matter will show a larger count rate reduction than expected from the derived N_H density, because of the larger relative importance of the scattering processes. In XB 1254−690 the sum of the normalizations of the two components does not strongly depend on the count rate during the dips. At ~ 7 counts s^{-1} (1–10 keV intensity), the sum of the normalizations is 0.8 ± 0.4 of that expected for normal cosmic metallicity. This reduction factor implies that the metallicity of the material causing the intrinsic absorption in XB 1254−690 is between 0.25 and 2 times the cosmic value. Another possible explanation for an intensity reduction different from that expected from absorption in material of normal metallicity would be the presence of completely opaque matter; however, this would be also indicated by the presence of very high N_H values during the dips for which we have no evidence. XB 1254−690 has thus the highest metallicity of any of the dipping sources for which spectral analysis as function of intensity has been carried out. The source with the lowest reported metallicity is X1755−338 (< 600 of cosmic; White *et al.* 1984). Metallicities of 17–40 and 2–7 below solar have been measured for XB 1916−053 and EXO 0748−676 by White and Swank (1982) and Parmar *et al.* (1986), respectively.

IV. CONCLUSION

We have discovered that the low mass X-ray binary XB 1254−690 shows irregular dips in X-ray intensity that recur with a period of 3.9 hr consistent with the optical period derived independently. The spectral changes observed during dipping intervals are complex and can be successfully described using a two-component model. One of these components may be X-rays scattered into the line of sight by an accretion disk corona. In contrast to other X-ray dipping sources for which the metallicity has been measured, the abundance of the material responsible for the dips is close to that of cosmic material.

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