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THE DISCOVERY OF A 2.78 HOUR PERIODIC MODULATION OF THE X-RAY FLUX FROM GLOBULAR CLUSTER SOURCE Bo 158 IN M31

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ABSTRACT

We report the discovery of periodic intensity dips in the X-ray source XMMU J004314.1+410724, in the globular cluster Bo 158 in M31. The X-ray flux was modulated by ∼83% at a period of 2.78 hr (10,017 s) in an *XMM-Newton* observation taken 2002 January 6–7. The X-ray intensity dips show no energy dependence. We detected weaker dips with the same period in observations taken 2000 June 25 (*XMM-Newton*) and 1991 June 26 (*ROSAT*/PSPC). The amplitude of the modulation has been found to be anticorrelated with source X-ray flux: it becomes lower when the source intensity rises. The energy spectrum of Bo 158 was stable from observation to observation, with a characteristic cutoff at ∼4–6 keV. The photoelectric absorption was consistent with the Galactic foreground value. No significant spectral changes were seen in the course of the dips. If the 2.78 hr cycle is the binary period of Bo 158, the system is highly compact, with a binary separation of $\sim 10^{11}$ cm. The association of the source with a globular cluster, together with spectral parameters consistent with Galactic neutron star sources, suggests that X-rays are emitted by an accreting neutron star. The properties of Bo 158 are somewhat reminiscent of the Galactic X-ray sources exhibiting diplike modulations. We discuss two possible mechanisms explaining the energy-independent modulation observed in Bo 158: (1) the obscuration of the central source by highly ionized material that scatters X-rays out of the line of sight and (2) the partial covering of an extended source by an opaque absorber that occults varying fractions of the source.

Subject headings: galaxies: individual (M31) — galaxies: star clusters — stars: individual (Bo 158) — X-rays: stars

1. INTRODUCTION

The X-ray source XMMU J004314.1+410724 was discovered in M31 by the *Einstein Observatory* (source 85 in Trinchieri & Fabbiano 1991) and was detected in subsequent observations with *ROSAT* (Primini, Forman, & Jones 1993; Supper et al. 2001), *XMM-Newton* (Shirey et al. 2001), and *Chandra* (Di Stefano et al. 2002). Based on the *Chandra* aspect solution, which is currently limited by systematics to ∼0″.6 accuracy, the source location is $\alpha = 00^h43^m14^s.42$, $\delta = 41°07′26″.3$ (2000 equinox; Di Stefano et al. 2002; see Fig. 1). This position of the source is consistent with the optically identified globular cluster candidate Bo 158 (source 158 in Table IV of Battistini et al. 1987; we will use the designation "Bo 158" as a source name throughout this Letter).

The previous observations were too insensitive for detailed study of individual sources in M31. The large collecting area and bandpass of *XMM-Newton* allow us to study the short-term variability and spectral properties of these sources. In this Letter, we report the discovery of a periodic X-ray modulation of the light curve of Bo 158 and its spectra.

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2. OBSERVATIONS AND DATA ANALYSIS

In the following analysis, we use data from three *XMM-Newton* observations of the bulge of M31 (see Table 1 and Fig. 1). The first observation of the central part of M31 was performed on 2000 June 25 as a part of the Performance Verification Program (PI: M. G. Watson; see Shirey et al. 2001 and Osborne et al. 2001). Two other observations were performed on 2001 June 29 (Shirey 2001) and on 2002 January 6 as a part of the Guaranteed Time Program (PI: K. O. Mason and M. G. Watson). We use data from three European Photon Imaging Camera (EPIC) instruments: two EPIC MOS detectors (Turner et al. 2001) and the EPIC PN detector (Strüder et al. 2001). In all observations, the EPIC instruments were operated in the *full window mode* (30′ diameter field of view) with medium (2000 June 25 and 2001 June 29 observations) and thin (2002 January 6 observation) optical blocking filters.

During all three *XMM-Newton* observations, the X-ray source Bo 158 was offset by ∼10′ from the center of the field of view (Fig. 1). In spite of the significant degradation in the sensitivity of the EPIC cameras at high offset angles, the statistics (more than 3000 counts in each observation) were sufficient for a detailed spectral and timing analysis.

We reduced EPIC data with the *XMM-Newton* Science Analysis System (SAS v5.3).[2] We performed standard screening of

[2] See http://xmm.vilspa.esa.es/user.

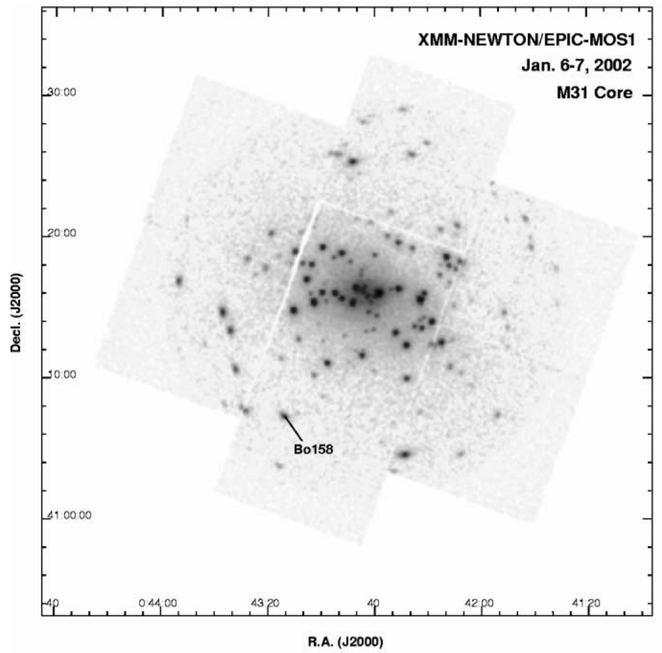

FIG. 1.—X-ray image of the central part of M31, as it appears in the 63 ks exposure with EPIC-MOS1 in the 0.3–10 keV energy range. The position of the X-ray source XMMU J004314.1+410724 associated with globular cluster Bo 158 (Battistini et al. 1987) is marked with an arrow.

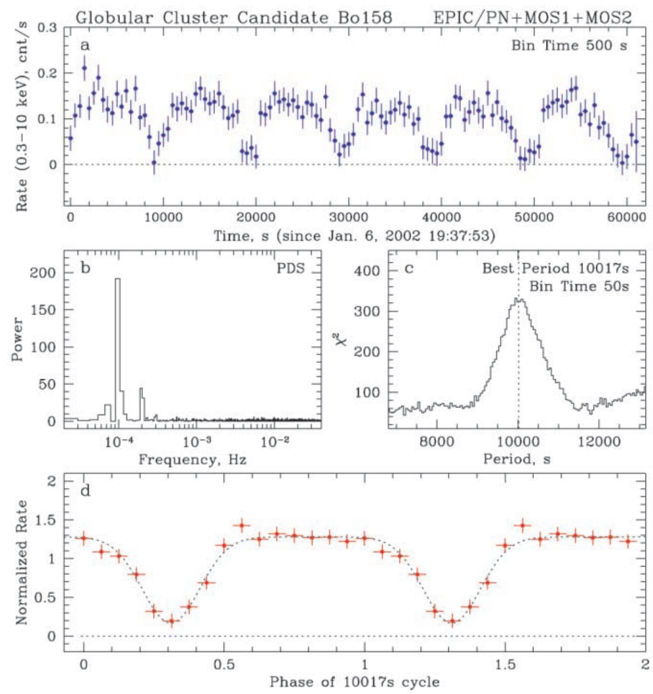

FIG. 2.—(*a*) X-ray light curve of Bo 158 during the 2002 January 6 *XMM-Newton* observation, obtained from combined data of EPIC-PN, MOS1, and MOS2 cameras, the 0.3–10 keV energy range, and a 500 s time resolution. (*b*) Power density spectrum of Bo 158. (*c*) Resulting χ^2 distribution for the epoch-folding analysis of the X-ray light curve. The best-fit value of the period (10,017 s) is shown as a vertical dotted line. (*d*) Normalized light curve of the source, folded at the best-fit period of 10,017 s. The analytic approximation is shown as a dotted line (see text).

the EPIC data to exclude time intervals with high background levels. To generate light curves and spectra of the source, we used an extraction radius of ∼60″ and subtracted as background the spectrum of adjacent source-free regions with subsequent normalization by a ratio of detector areas. We used data in the 0.3–10 keV energy band because of the uncertainties in the calibration of the EPIC instruments outside this range. All fluxes and luminosities presented below apply to this band. In the following analysis, we assume a source distance of 760 kpc (van den Bergh 2000).

We used standard XANADU/XRONOS v5[3] Fourier transform and epoch folding tasks to search for the periodic modulation of the source X-ray flux and determine its period. We used spectral response matrices generated by SAS tasks. The energy spectra of the source were fitted to two analytic models using XSPEC v11 (Arnaud 1996): an absorbed simple power law (POWERLAW) and Comptonization (COMPTT) models.[4] EPIC-PN, MOS1, and MOS2 data were fitted simultaneously, but with independent normalizations.

[3] See http://heasarc.gsfc.nasa.gov/docs/xanadu/xronos/xronos.html.

[4] For model description, see http://heasarc.gsfc.nasa.gov/docs/xanadu/xspec and references therein.

3. RESULTS

We generated X-ray light curves of the source in the 0.3–10 keV energy band using data from the EPIC-PN, MOS1, and MOS2 detectors, combining them in order to improve statistics. The resulting light curve of Bo 158 for the 2002 January 6 observation (Fig. 2*a*) shows a pattern of recurrent dips in the X-ray intensity with a period of ∼10,000 s. The dips are broad, lasting for ∼30% of the 10,000 s cycle. Their FWHM varies between 2200 and 3000 s, and their depths range from ∼80% to ∼100% of the out-of-dip flux. The recurrence period is 10017 ± 50 s. Figures 2*b* and 2*c* show the power density spectrum of the source from 2×10^{-5} to 3×10^{-2} Hz and our determination of the period with an epoch-folding analysis. Figure 2*d* shows the combined EPIC (PN+MOS1+MOS2) light curve for the January 6 observation folded on the 10,017 s best period of the modulation (phase 0.0 is set arbitrarily at TJD = 12279.0). In order to

TABLE 1
XMM-NEWTON OBSERVATIONS OF M31 USED IN THIS ANALYSIS

Date (UT)	T_{start} (UT)	Field	Observation	R.A. (J2000)[a]	Decl. (J2000)[a]	Exp. (MOS)[b] (ks)	Exp. (PN)[b] (ks)
2000 Jun 25	10:44:42	M31 core	0112570401	00 42 43.0	41 15 46.1	34.8	31.0
2001 Jun 29	06:21:38	M31 core	0109270101	00 42 43.0	41 15 46.1	32.6	30.8
2002 Jan 06	18:07:17	M31 core	0112570101	00 42 43.0	41 15 46.1	63.0	61.0

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

[a] Coordinates of the center of the field of view.

[b] Instrument exposure used in the analysis.

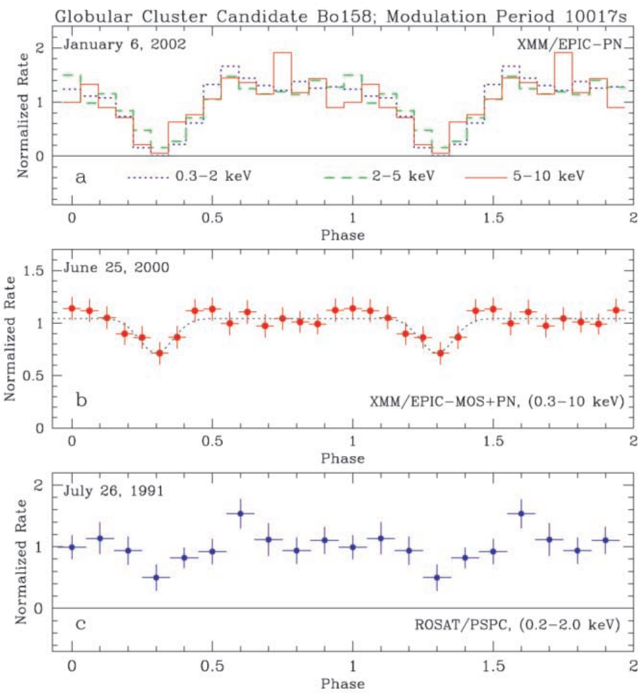

FIG. 3.—X-ray light curves of Bo 158 taken with *XMM-Newton*/EPIC and *ROSAT*/PSPC, folded on a period of 10,017 s. (*a*) Folded X-ray light curves of Bo 158 in the 0.3–2, 2–5, and 5–10 keV ranges during the 2002 January 6 *XMM-Newton* observation shown as dotted, gray long-dashed, and solid lines, respectively (EPIC-PN data). (*b*) Folded X-ray light curve of Bo 158 in the 0.3–10 keV energy range during the 2000 June 25 *XMM* observation (combined EPIC-MOS and PN data). The analytic approximation is shown as a dotted line (see text). (*c*) Folded X-ray light curve of Bo 158 in the 0.2–2.0 keV energy range during the 1991 June 26 *ROSAT*/PSPC observation.

investigate the energy dependence of the X-ray modulation during the 2002 January 6 observation, we constructed light curves in the 0.3–2.0, 2.0–5.0, and 5.0–10.0 keV bands. As it is clearly seen in Figure 3*a*, there is no significant energy dependence of the modulation.

We searched for this modulation in earlier observations of M31, including the 2000 June 25 and 2001 June 29 *XMM-Newton* observations of the center of M31 and the *ROSAT*/Position Sensitive Proportional Counter (PSPC) observation from 1991 July 26. We produced combined EPIC-MOS and PN light curves in the 0.3–10.0 keV energy range and a PSPC light curve in the 0.2–2.0 keV energy band. X-ray flux modulations with periods close to ~10,000 s (~10,500 and ~9700 s, respectively) were marginally detected in the 2000 June 25 and 1991 July 26 observations. Figure 3 shows the *XMM-Newton*/EPIC and *ROSAT*/PSPC light curves folded on the 10,017 s period determined above. The light curves of the 2000 June 25 and 1991 June 26 observations show an ~30% and ~50% intensity drop during the dip (Figs. 3*b* and 3*c*), while for the 2001 June 29 observation, dips were not detected with a 2 σ upper limit of 10%.

In the case of the 2002 January 6 and 2000 June 25 observations, in which regular dips in the X-ray light curve of the source were clearly detected, we fitted the folded 0.3–10 keV light curves with a simple model, consisting of a constant plus a Gaussian with negative normalization centered at the dip minimum:[5] $f(p) = C - A \exp[-(p - p_{\rm dip})^2/2\sigma^2]$ (the best-fit model approximation is shown with dotted lines in Figs. 2*d* and 3*b*). Using this approximation, we obtain a 83% ± 5% amplitude of the dip with respect to the out-of-dip intensity and $\sigma = 0.10 \pm 0.01$ (in phase units of a 10,017 s cycle) for the 2002 January 6 observation and a 30% ± 9% amplitude and $\sigma = 0.07 \pm 0.03$ for the 2000 June 25 observation. The values of σ imply an average FWHM for the dips of order 2500 s.

[5] Here p is a phase of the 10,017 s cycle, C is a source out-of-dip intensity level, and A, $p_{\rm dip}$, and 2.35 σ are the normalization, centroid phase, and FWHM of Gaussian, respectively.

TABLE 2
BEST-FIT MODEL PARAMETERS OF THE ENERGY SPECTRA OF Bo 158[a]

PARAMETER	OBSERVATION DATE: 2000 June 25	2001 June 29	2002 January 6
	Absorbed Power Law (POWERLAW*WABS)		
Photon index	$0.66^{+0.04}_{-0.03}$	$0.58^{+0.04}_{-0.02}$	0.66 ± 0.03
$N_{\rm H}$[b]	0.09 ± 0.02	0.05	$0.07^{+0.02}_{-0.01}$
Flux[c]	1.738 ± 0.035	2.401 ± 0.031	1.082 ± 0.019
χ^2(dof)	302.3(262)	414.6(355)	287.4(267)
	Absorbed Comptonization Model (COMPTT*WABS)		
kT_0[d]	$0.08^{+0.05}_{-0.07}$	$0.08^{+0.05}_{-0.07}$	$0.09^{+0.08}_{-0.07}$
kT_e[e]	$1.78^{+0.10}_{-0.09}$	$1.87^{+0.08}_{-0.06}$	1.73 ± 0.07
τ[f]	$19.7^{+2.3}_{-1.3}$	$20.1^{+2.1}_{-1.0}$	$21.6^{+2.2}_{-1.2}$
$N_{\rm H}$[b]	$0.08^{+0.02}_{-0.03}$	$0.05^{+0.02}_{-0.05}$	$0.05^{+0.02}_{-0.01}$
Flux[c]	1.442 ± 0.029	2.005 ± 0.026	0.914 ± 0.016
χ^2(dof)	263.8(260)	358.1(353)	194.4(265)

[a] During 2000 June 25, 2001 June 29, and 2002 January 6 *XMM-Newton* observations of the central part of M31 (combined EPIC-PN, MOS1, and MOS2 data). Parameter errors correspond to the 1 σ level.
[b] Equivalent absorbing hydrogen column density in units of 10^{22} cm^{-2}.
[c] Model flux in the 0.3–10.0 keV energy range in units of 10^{-12} ergs s^{-1} cm^{-2}.
[d] Temperature of soft photons in units of keV.
[e] Electron temperature in units of keV.
[f] Thomson optical depth for the spherical geometry.

The averaged *XMM*/EPIC spectra of Bo 158 were analyzed by fitting two different spectral models (Table 2). A model with a quasi-exponential cutoff (the Comptonization model in Table 2) at ~4.0–6.0 keV describes the energy spectra significantly better than a simple power law. This spectrum is somewhat reminiscent of Galactic neutron star systems with high luminosity (Iaria et al. 2001; Di Salvo et al. 2001). The spectrum is stable from observation to observation, despite the change in X-ray luminosity from ~6.5×10^{37} (2002 January 6) to ~1.4×10^{38} ergs s^{-1} (2001 June 29), although the cutoff energy may increase at the higher luminosities.

In order to investigate any changes in the energy spectrum during the intensity dips, we divide the spectra from the 2002 January 6 observation into two states corresponding to the out-of-dip and dip intensity (Fig. 4; i.e., the fluxes higher and lower than 0.1 counts s^{-1} in Fig. 2*a*). A saturated Comptonization model with electron temperature $kT_e \sim 1.7$ keV and optical depth $\tau \sim 22$ gives a good approximation to both spectra (Fig. 4). The resulting 2 σ upper limit on an increase in neutral absorbing column density $N_{\rm H}$ during the dips is 2×10^{21} cm^{-2} (assuming a single spectral component). However, if the dips are caused by electron scattering in a cloud along the line of sight, the electron column density must be ~2.7×10^{24} cm^{-2} (83% dipping) and ~5.4×10^{23} cm^{-2} (30% dipping) for the 2002 January 6 and 2000 June 25 observations, respectively.

It should be mentioned that the Comptonization model that fits the spectrum during the intensity dips does not provide a unique determination of the spectral form. Other complex models (e.g., two-component models with different low-energy absorption column densities) also give acceptable fits. The low

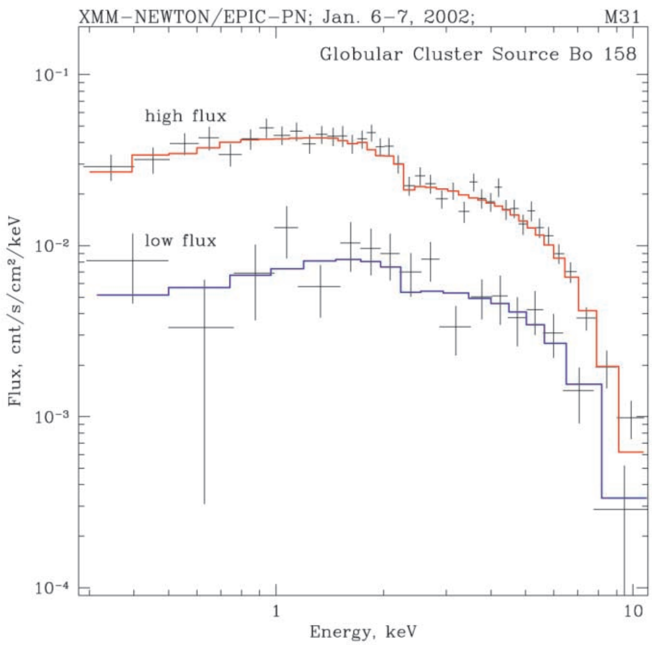

FIG. 4.—Energy spectra of Bo 158 from the nondip (high flux) and dip (low flux) intervals of X-ray flux during the 2002 January 6 observation. EPIC-PN data in the 0.3–10 keV energy range. The best-fit analytic models are shown as red and blue histograms, and they are both saturated Comptonization models with an electron temperature of ∼1.7 keV and an optical depth of ∼22.

statistical significance of the data does not allow us to discriminate between these models.

There is an anticorrelation between the average amplitude of the modulation and the source intensity on a long timescale. The values of the modulation fraction were 83% in the 2002 January 6 observation, 30% in the 2000 June 25 observation, and less than 10% in the 2001 June 29 observation, corresponding to the source luminosities of 6.5×10^{37}, 9.9×10^{37}, and 1.4×10^{38} ergs s^{-1}, respectively. In addition, a dependence of the dip strength on the luminosity on a timescale of hours was marginally detected during the 2000 June 25 observation.

4. DISCUSSION

We have discovered a 2.78 hr periodic diplike modulation with variable amplitude in the X-ray flux of the globular cluster candidate source Bo 158 in M31. The amplitude of the modulation is anticorrelated with source intensity: it becomes lower with increasing X-ray flux. The most interesting feature of this modulation is its lack of energy dependence.

If the 2.78 hr modulation represents the binary period, P_{orb}, the binary separation is $a \sim 7 \times 10^{10} M_X^{1/3}(1+q)^{1/3}$ cm.[6] The association of the source with a globular cluster, and spectral parameters consistent with Galactic neutron star sources, suggest that the compact object in Bo 158 is probably a neutron star in a low-mass binary. This implies a highly compact binary with separation $a \lesssim 10^{11}$ cm. The properties of Bo 158 are somewhat reminiscent of Galactic X-ray sources that exhibit diplike modulations (e.g., Cygnus X-3 and some "dipping" sources).

Although there are similarities between the light curve of Bo 158 and the Galactic binary Cygnus X-3, it is unlikely that these systems have a common nature. The broad minimum in the 4.8 hr cycle of Cygnus X-3 is explained as variable scattering in the dense photoionized wind of a Wolf-Rayet companion (Paerels et al. 2000). Moreover, in contrast to Bo 158, the amplitude of the X-ray modulation in Cygnus X-3 is extremely stable in spite of drastic changes in luminosity.

The duration of the intensity dips in phase is similar to those seen in some Galactic low-mass X-ray binary dipping sources such as X1755−338 (Mason, Parmar, & White 1985), XB 1254−690 (Courvoisier et al. 1986), and XB 1916−053 (Yoshida et al. 1995), although Bo 158 is much more luminous. The lack of energy dependence of the modulation is a common feature of a number of dipping sources. The dips in these systems are believed to be caused by absorption and scattering in an obscuring medium, i.e., a bulge or thickened region of the accretion disk, or inhomogeneities in the mass transfer stream (White & Swank 1982; Lubow & Shu 1976; Frank, King, & Lasota 1987).

If the dips in Bo 158 are caused by an obscuring structure, at least two explanations could be proposed to explain the energy independence of the intensity dips: (1) the obscuring material is highly ionized (Mason et al. 1985), or (2) the dips are caused by the partial covering of an extended source (Church et al. 1997):

1. If the obscuring structure is located close to the X-ray emission region, the obscuring medium could be strongly ionized. The compactness and high X-ray luminosity of Bo 158 could imply a high ionization in the region responsible for the dips. The obscuring matter in the Galactic dipping sources, with their smaller luminosities (10^{36}–10^{37} ergs s^{-1}), is less strongly ionized. For the material causing the dips to be completely ionized, the ionization parameter $\xi = L_X/nR^2$ (where L_X is the central source luminosity, n is the gas density of the cloud, and R is the distance from the central source to the obscuring medium; Hatchett, Buff, & McCray 1976) should be larger than ∼1000 ergs cm s^{-1}. For the 2002 January 6 observation, an average 83% intensity reduction requires a column, N_e, of $\sim 2.7 \times 10^{24}$ cm^{-2}. Assuming an out-of-dip luminosity of Bo 158 to be 6.5×10^{37} ergs s^{-1}, and following Mason et al. (1985), we conclude that all material closer than $\sim 2.4 \times 10^{10}\epsilon$ cm will be highly ionized.[7] Another estimate of the ionization stage of the obscuring medium is based on the duration of the intensity dips (Remillard & Canizares 1984). For $t_{dip} \sim 2500$ s, assuming that the absorbing medium is roughly spherical and fixed in the frame of the binary, $\xi = 2\pi L_X t_{dip}/(NP_{orb}R)$. To obtain $\xi \gtrsim 1000$, the ionized region must be closer than $R \sim 4 \times 10^{10}$ cm (2002 January 6 observation) and $R \sim 2 \times 10^{11}$ cm (2000 June 25 observation). The absorbing medium in a 2.78 hr binary could fall well within these limits and be highly ionized.

2. For an opaque absorber to produce broad dips, the emission region must be extended and the eclipse partial. The source could be a scattering corona-like structure and/or a thick disk/outflow located close to the compact object, and the absorber could be a thickened region of accretion disk or a mass transfer stream from the companion star.

The diminution of the modulation with the increase of the X-ray flux could indicate a decrease of the obscured fraction of the emission region, caused by increasing the size of the emitter or decreasing the size of the absorber.

[6] Here M_X is a mass of the compact object in solar units, and q is a mass ratio of the secondary star and a compact object.

[7] Here the filling factor $\epsilon = (l/R)$, where l is the scattering column length.

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REFERENCES

Arnaud, K. 1996, in ASP Conf. Ser. 101, Astronomical Data Analysis Software and Systems V, ed. G. H. Jacoby & J. Barnes (San Francisco: ASP), 17
Battistini, P., Bonoli, F., Braccesi, A., Federici, L., Fusi Pecci, F., Marano, B., & Borngen, F. 1987, A&AS, 67, 447
Church, M. J., Dotani, T., Balucinska-Church, M., Mitsuda, K., Takahashi, T., Inoue, H., & Yoshida, K. 1997, ApJ, 491, 388
Courvoisier, T. J.-L., Parmar, A. N., Peacock, A., & Pakull, M. 1986, ApJ, 309, 265
Di Salvo, T., Robba, N. R., Iaria, R., Stella, L., Burderi, L., & Israel, G. L. 2001, ApJ, 554, 49
Di Stefano, R., Kong, A. K. H., Garcia, M. R., Barmby, P., Greiner, J., Murray, S. S., & Primini, F. A. 2002, ApJ, 570, 618
Frank, J., King, A. R., & Lasota, J. P. 1987, A&A, 178, 137
Hatchett, S., Buff, J., & McCray, R. 1976, ApJ, 206, 847
Iaria, R., Burderi, L., Di Salvo, T., La Barbera, A., & Robba, N. R. 2001, ApJ, 547, 412
Lubow, S. H., & Shu, F. H. 1976, ApJ, 207, L53
Mason, K. O., Parmar, A. N., & White, N. E. 1985, MNRAS, 216, 1033
Osborne, J. P., et al. 2001, A&A, 378, 800
Paerels, F., Cottam, J., Sako, M., Liedahl, D. A., Brinkman, A. C., van der Meer, R. L. J., Kaastra, J. S., & Predehl, P. 2000, ApJ, 533, L135
Primini, F. A., Forman, W., & Jones, C. 1993, ApJ, 410, 615
Remillard, R. A., & Canizares, C. R. 1984, ApJ, 278, 761
Shirey, R. 2001, IAU Circ. 7659
Shirey, R., et al. 2001, A&A, 365, L195
Strüder, L., et al. 2001, A&A, 365, L18
Supper, R., Hasinger, G., Lewin, W. H. G., Magnier, E. A., van Paradijs, J., Pietsch, W., Read, A. M., & Trümper, J. 2001, A&A, 373, 63
Trinchieri, G., & Fabbiano, G. 1991, ApJ, 382, 82
Turner, M. J. L., et al. 2001, A&A, 365, L27
van den Bergh, S. 2000, The Galaxies of the Local Group (Cambridge: Cambridge Univ. Press)
White, N. E., & Swank, J. H. 1982, ApJ, 253, L61
Yoshida, K., Inoue, H., Mitsuda, K., Dotani, T., & Makino, F. 1995, PASJ, 47, 141