THE BURST SPECTRA OF EXO 0748–676 DURING A LONG 2003 XMM-NEWTON OBSERVATION

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Received 2007 August 6; accepted 2007 September 21

ABSTRACT

Gravitationally redshifted absorption lines from highly ionized iron have been previously identified in the burst spectra of the neutron star in EXO 0748–676. To repeat this detection we obtained a long, nearly 600 ks observation of the source with XMM-Newton in 2003. The spectral features seen in the burst spectra from the initial data are not reproduced in the burst spectra from this new data. In this paper we present the spectra from the 2003 observations and discuss the sensitivity of the absorption structure to changes in the photospheric conditions.

Subject headings: binaries: general — stars: individual (EXO 0748–676) — stars: neutron — X-rays: binaries — X-rays: bursts

1. INTRODUCTION

In Cottam et al. (2002) we identified discrete absorption features corresponding to electronic transitions in highly ionized iron in the burst spectra of the neutron star in EXO 0748–676. Using data acquired during the commissioning and calibration of the XMM-Newton observatory, we compiled spectra from 28 type I X-ray bursts in EXO 0748–676. After accounting for the effect of circumstellar absorption we identified features originating in the thermal emission spectrum from the neutron star atmosphere. We identified an Fe xxvi n = 2–3 absorption feature (from H-like Fe) in the average spectrum of the early phases of the bursts, and an analogous Fe xxv n = 2–3 absorption feature (from He-like Fe) in the spectrum of the late phases of the bursts. Both features exhibited an identical gravitational redshift of z = 0.35. Additional absorption structure observed between 25 and 27 Å during the late phases of the bursts was tentatively identified as due to O viii n = 1–2 at the same redshift. A gravitational redshift of z = 0.35 at the neutron star surface translates to a mass-to-radius ratio of M/R = 0.152 M⊙ km−1 for the neutron star in EXO 0748–676. This measurement provides an empirical constraint on the equation of state of dense, cold nuclear matter.

In a subsequent analysis Villarreal & Strohmayer (2004) succeeded in measuring the spin frequency for the neutron star in EXO 0748–676 from coherent modulations of the X-ray flux during the decaying portion of an X-ray burst. The spin frequency, 45 Hz, is much lower than measured in any other low-mass X-ray binary (e.g., Chakrabarty 2005). Villarreal & Strohmayer (2004) show that the widths of the narrow line profiles that we observed in the XMM-Newton spectra are consistent with the spin frequency of the star for a neutron star radius between 9.5 and 15 km. The observed strength of the absorption lines implies that the line broadening is dominated by the Stark effect (Paerels 1997; Bildsten et al. 2003), which in principle allows for an independent measurement of the acceleration of gravity at the stellar surface. Chang et al. (2006) performed a more detailed analysis of the observed line profiles including both the intrinsic line broadening and the rotational line broadening. Since the two line-broadening mechanisms are of very similar scale, they show that a direct measurement of the neutron star radius cannot be made from the existing XMM-Newton data. Özel (2006) has used the measured value of the gravitational redshift, combined with an estimate of the stellar radius, to infer a mass for the neutron star of M ≥ 1.8 M⊙ for a stellar radius of R ≥ 12 km in the coordinate frame of the neutron star.

Because of the significance of these first results we requested additional XMM-Newton observations of EXO 0748–676 to repeat this measurement and extend the spectroscopic analysis. Almost 600 ks of XMM-Newton Director’s Discretionary time was awarded. In this paper, we describe these new data and compare them to the 2000 data described in Cottam et al. (2002) (hereafter CPM02). We also requested Chandra observations of EXO 0748–676 to provide independent corroborating evidence for the presence of gravitationally redshifted absorption lines. A total of 300 ks of Chandra HETGS data was acquired during the same time frame as the XMM-Newton data. Those data will be presented in F. Paerels et al. (2007, in preparation).

2. OBSERVATIONS AND DATA REDUCTION

EXO 0748–676 was observed by the XMM-Newton observatory (Jansen et al. 2001) on seven occasions during the fall of 2003 for a total exposure of 570 ks. The first four observations were conducted in sequential satellite orbits beginning on 2003 September 19. Three more observations were conducted beginning on 2003 October 21, October 25, and November 12. The details of these observations are listed in Table 1. For each observation, data were acquired with all of the on-board instruments simultaneously.

We are primarily interested in the high-resolution spectral data from the Reflection Grating Spectrometer (RGS), which cover the wavelength band from λ ~ 5 to 35 Å (E ~ 0.35 to 2.5 keV) with a resolving power of ~300 at 15 Å (den Herder et al. 2001). The RGS data were initially processed with the XMM-Newton Science Analysis Software (SAS) version 5.4.1, and postprocessing was performed using SAS versions 6.0.0 and 6.5.0. For the final spectral analysis we reprocessed all data with SAS version 7.0.0.
In this analysis we used data from the European Photon Imaging Cameras (EPIC) only for the purposes of identifying the bursts. We used the EPIC/pn data (Strüder et al. 2001), which were acquired in “Small Window” mode to minimize CCD pile-up effects during the bright EXO 0748–676 bursts. The EPIC/pn detectors cover the energy range of $0.15 - 15$ keV. A detailed analysis of the EPIC burst data is presented in Boirin et al. (2007).

We identified the type-I X-ray bursts using both the EPIC and RGS light curves. For the EPIC/pn we used only single and double events (patterns 0–4) and restricted the energy range to $5 - 10$ keV (see Boirin et al. 2007). For the RGS we used the standard $m = -1$ events over the full energy range of the instrument.

We defined the start of each burst as the time when the count rate increased above the local preburst persistent level by a factor of 3, and the end as the time when the count rate decreased to the pre-burst persistent level. This is sometimes difficult to determine in the RGS data because of the low contrast of the bursts and the large variations in the persistent count rate caused by the larger effects of circumstellar absorption in the soft X-ray band (see Fig. 1). We therefore used the EPIC/pn data to guide our search for bursts in the RGS light curve.

The detailed burst characteristics from the EPIC/pn data are quoted in Table A.1 in Boirin et al. (2007). In the EPIC/pn light curve, we identify 75 bursts. We classified these as 34 single...
bursts, 13 double bursts, and 5 triple bursts. The burst duration ranges from 15 to 177 s for a cumulative burst exposure time of 6428 s. The peak intensity ranges from 12.2 to 376.4 counts s⁻¹, with an average of 195 counts s⁻¹ over the persistent count rate, which varied from 62 counts s⁻¹ down to 12 counts s⁻¹ during the deepest dips. In the RGS light curve, we identify 68 bursts. One burst is only visible in the RGS light curve because of an offset in the times when the EPIC/pn and RGS instruments were turned on. There are eight bursts identified in the EPIC/pn data that are not distinguishable in the RGS light curve (Homan et al. 2003). The bursts cannot be easily classified as single, double, or triple bursts using the RGS light curve alone. In some cases the second burst and in others the third burst in a series identified by the EPIC/pn as a triple burst cannot be distinguished above the persistent level in the RGS data. The start times of bursts in the RGS data are consistent with the start times in the EPIC/pn data, when bursts are visible in both data sets. The burst durations are naturally longer in the RGS data, which covers a softer energy spectrum, this does not significantly impact our analysis. In the data we present here, the background rate becomes significant a fraction of the source rate longward of 0.64 Å. The peak intensity ranges from 12.2 to 376.4 counts s⁻¹, with an average peak intensity of 9.6 counts s⁻¹ during the 0.2 counts s⁻¹ during dips. We recorded a cumulative exposure time of 8555 s for the 68 bursts defined using the RGS data alone. It should be noted that while this burst exposure time is a little more than twice the burst exposure time of the 2000 observations, since CCD 7 of the RGS1 was lost after the 2000 data were acquired the effective exposure in the critical 13 Å band is comparable between the two data sets.

3. BURST SPECTRA

We started, as we did in CPM02, by extracting the first-order RGS spectra for each of the bursts identified in the RGS light curve using start and stop times defined by the RGS data. For our initial analysis we combined all bursts, treating the two bursts in double burst series and the three bursts in triple burst series as individual bursts. We combined the data within each of the seven observations and generated a single, representative response matrix for each of the seven epochs. Background spectra were generated for each observation using spatially offset regions according to the standard SAS routines. The spectral files and response matrices for each of the seven observations were then combined using the SAS tool rgscombine, and fit using XSPEC version 11 (Arnaud 1996). We verified that the results of fitting the seven individual spectra simultaneously and fitting the single combined spectrum were the same. Using discrete features from known transitions in the persistent spectrum we confirm that the wavelength scale is accurate to ~10 mÅ. According to den Herder et al. (2001) the effective area of the RGS is calibrated to an accuracy of ~5% for wavelengths above ~8 Å. Deviations at the long wavelength end discovered more recently are largely corrected in SAS version 7.0.0. The remaining uncertainty in the effective area is ≤10% at the longest wavelengths (RGS instrument team 2006, private communication). As we are concerned with the discrete spectral structure and not the exact shape of the continuum spectrum, this does not significantly impact our analysis. In the data we present here, the background rate becomes a significant fraction of the source rate longward of ~34 Å. We therefore conservatively consider data only in the wavelength range λ = 8–32 Å.

As in CPM02, we separated the data from each burst into early and late phases in order to account for spectral evolution over the course of the burst. As in our earlier work, we experimented with different ways of defining the “early” and “late” phases (for instance, attempting to have approximately equal numbers of counts in both). In view of the fact that the signal to noise ratio in the spectrum is necessarily limited, the differences between the pairs of spectra extracted using different definitions are not significant. In this analysis we therefore simply divided each burst in half by duration as we did in CPM02. For display purposes we generated spectra for the early and late phases of the average burst by combining all the data from both RGS instruments using the SAS tool rgsf1uxer. The background-subtracted spectra are shown in Figure 2.

The dominant spectral features are generated in highly ionized circumstellar material. We fit the early- and late-phase spectra with the circumstellar absorption model described in CPM02. For every ion, the model self-consistently accounts for absorption in all transitions arising from a given level, out to the photoelectric continuum limit (Sako et al. 2001). We use an empirical continuum model that consists of blackbody and power-law emission with neutral interstellar absorption. We first fit the O vii emission and absorption structure in both spectra. As in the 2000 data analyzed in CPM02, a broad O vii emission feature is evident in the early phases of the bursts. This is dominated by the O vii λ = 1–2 intercombination line (O vii x, y) at a rest wavelength of 21.80 Å. The emission line disappears in the late phases of the bursts as the depth of the O vii absorption edge increases. The intensity of the O vii features in these data is much weaker than in the 2000 data; the equivalent width in the O vii line is EW ≈ 3 eV in the early phases of the bursts compared to EW ≈ 6 eV in the early phases of the 2000 spectra, and the ion column density is N_{O_{vii}} ≈ 4 × 10^{17} cm⁻² in the early phase and N_{O_{vii}} ≈ 1 × 10^{18} cm⁻² in the late phases of the burst, compared to N_{O_{vii}} ≈ 8 × 10^{17} cm⁻² and N_{O_{vii}} ≈ 2.5 × 10^{18} cm⁻² in the early and late phases of the 2000 bursts. The turbulent velocity in the absorbing material, which is constrained by the equivalent width of the O vii resonance absorption line (w) at 21.60 Å, is much lower in these data than in the 2000 data; we measure effectively upper limits to turbulent velocities of v_t ≤ 20 km s⁻¹ in the early phase and v_t ≤ 10 km s⁻¹ in the late phase of the bursts, compared to positive detections of v_t ≈ 100 km s⁻¹ in the 2000 data.

As in CPM02, to fully account for any additional absorption structure due to circumstellar material, we synthesized the absorption spectra for the hydrogen- and helium-like ions of carbon, nitrogen, neon, magnesium, silicon, and the L-shell ions of iron, based on the parameters measured at oxygen. To estimate the fractional abundances for each ion we use an ionization parameter of \( \xi = L/n_e P^2 \approx 10 \), which we estimate is an upper limit based on the lack of observed O viii emission. Using a lower ionization parameter will only decrease the fractional abundance of all these ions except perhaps He-like carbon. We assume solar abundance ratios. We then scaled the turbulent velocity for each ion from the value measured at O vii, assuming a constant temperature for all ions. The full circumstellar model is superimposed on the spectra shown in Figure 2.

After accounting for the circumstellar contribution to the observed spectra we search for the absorption features from the neutron star photosphere that were identified by CPM02 in the 2000 data, or any other significant absorption. The locations of the features we previously identified, 13.0 Å in the early phases of the burst, and 13.8, 25.2, and 26.4 Å in the late burst spectra are indicated in Figure 2. This spectral structure is not repeated here. The simplest nontrivial explanation for this nondetection may be our particular data selection. Since the EPIC data were largely not available during the 2000 observations we do not know what selection biases may have been introduced in that analysis. We therefore explored alternative selection criteria for
the 2003 data, particularly our treatment of double and triple bursts. For example, we extracted spectra selecting only the single bursts and the first of double and triple bursts, which the analysis of Boirin et al. (2007) suggests involve different burning than the second and third bursts in such series. We also explored the effect of using EPIC/pn defined burst start and stop times instead of the RGS defined times. None of these changes in selection criteria had a significant effect on the resulting spectra.

The only evidence of absorption structure that cannot be attributed to the circumstellar material is a marginal absorption feature at \( \lambda = 13.0 \, \text{Å} \) in the late phases of the bursts. We find that this feature has the highest equivalent width when we define the start and stop times using the EPIC/pn light curve, which are shorter than the RGS-defined times and therefore minimize the contribution from the persistent spectrum. Using the EPIC/pn defined times, we estimate a significance by fitting a simple Gaussian to the line. We measure a significance of 3 \( \sigma \) relative to a zero-amplitude fit, and an equivalent width of \( \text{EW} = 0.09 \pm 0.025 \, \text{Å} \). There is no evidence for an absorption feature at \( \lambda = 13.0 \, \text{Å} \) in the persistent spectrum.

4. DISCUSSION

The 2003 burst spectra show different neutron star photospheric absorption structure than the spectra reported in CPM02. In these data we do not see the absorption feature at 13.0 Å that we identified as the gravitationally redshifted \( n = 2-3 \) transition of Fe xxi in the early phases of the bursts, and we do not see the feature at 13.75 Å that we identified as the gravitationally redshifted \( n = 2-3 \) transition in Fe xxi in the late phases of the bursts. Either our initial detections were due to highly improbable statistical fluctuations, or the conditions in the neutron star photosphere have changed.

We see no absorption features in the early phases of the bursts, and a marginal absorption feature at 13.0 Å in the late phases of the bursts. This feature is not particularly statistically significant, and as a single spectroscopic feature it would be difficult to conclusively identify. However, it is at exactly the same wavelength as the feature in the early phases of the 2000 burst data. We have not attempted to subtract the average persistent RGS spectrum from the average burst spectra, because the shape of the spectrum in the RGS band is very sensitive to the precise properties of the 2003 data, particularly our treatment of double and triple bursts. For example, we extracted spectra selecting only the single bursts and the first of double and triple bursts, which the analysis of Boirin et al. (2007) suggests involve different burning than the second and third bursts in such series. We also explored the effect of using EPIC/pn defined burst start and stop times instead of the RGS defined times. None of these changes in selection criteria had a significant effect on the resulting spectra.

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The location of the redshifted Fe absorption feature at 13.0 Å can identify the ionization balance shifted such that Fe ions are sufficiently abundant in the photosphere to generate the observed absorption feature at 13.0 Å. As the photosphere cooled, the ionization balance shifted such that Fe ions became dominant. If we can identify the 13.0 Å feature in the late phases of these new data as the redshifted $n = 2$–$3$ transition in Fe xxvi by its coincidence with the feature in the early phases of the 2000 data, then these spectra could be interpreted similarly. In these new data the lack of absorption features in the early phases of the bursts, and the possible presence of the 13.0 Å feature in the late phases suggests that the ions are fully stripped in the hot early phases of the burst and that the population of Fe xxvi ions only becomes sufficiently abundant in the late phases as the bursts cool. The changes in the observed spectra from 2000 to 2003 could then be understood as an overall shift in the ionization conditions in the neutron star photosphere. We would then expect to observe a gravitationally redshifted line from Fe xxv at still later burst times. Unfortunately, the persistent source emission rapidly dominates the burst emission, and we are unable to distinguish the burst spectrum at later times.

We do indeed expect the absorption structure in the burst spectra to be extremely sensitive to changes in the photospheric conditions. Inspection of just the Saha ionization balance for Fe ions in the relevant regime shows that the fractional abundance of H- and He-like Fe is extremely sensitive to the local electron temperature and density. In addition, the relative population of $n = 2$ is also very sensitive to the details of radiative transfer in the transitions between the lowest several levels (the radiative transition probability $n = 2 \rightarrow 1$ in highly ionized Fe is so high that even at the densities expected in neutron star atmospheres at gas temperatures of order 1 keV, collisions cannot enforce local thermodynamic equilibrium between the lowest levels and the ground state (Bildsten et al. 2003; Chang et al. 2005; F. Paerels et al. 2007, in preparation; T. Lanz et al. 2007, in preparation).

We therefore investigate what independent evidence exists that indicates that average photospheric conditions did, or did not change between the 2000 and 2003 data sets. Obviously, a measurable change in the average burst continuum shape would be a strong indicator of a change in the effective temperature, and hence very likely in the characteristic electron temperature in the photosphere. For this, we need the EPIC spectra, since RGS sensitivity cuts off at photon energies above 2 keV. Unfortunately, the 2000 data were acquired during the commissioning and calibration phases of the mission, so the instrument configurations were not optimized for burst spectroscopy. Only two of the EXO 0748–676 observations in 2000 have simultaneous EPIC coverage, and only part of one observation was acquired with the EPIC/pn in small window mode, such that the spectra are not piled-up during the bursts. We identified three bursts in these data, which we can compare to the 2003 bursts as described in Boirin et al. (2007). The durations of these bursts, 135, 178, and 52 s, are consistent with the range of durations of the bursts in the 2003 data. The peak intensity in the 5–10 keV band, 86, 87, and 51 counts s$^{-1}$ are also consistent with the values for the 2003 bursts. We analyzed the temperature evolution of the two bursts that did not occur during a dip. Following the methods of Boirin et al. (2007) we measure a black body temperature of $kT = 1.8$ keV at the peak of each burst. Both bursts then decay to a temperature of $kT \sim 1.3$ keV. This is consistent with the temperature evolution of the 2003 bursts. However, all three of these bursts occurred during the last 9 ks of the 2000 data. Since the full 2000 data set was acquired over the course of 2 months, these three bursts are not necessarily representative of the conditions throughout the 2000 data set. There are indications from the Rossi X-Ray Timing Explorer (RXTE) data (M. Krauss 2006, private communication) that the peak and average burst temperature in EXO 0748–676 have varied considerably over the lifetime of the RXTE mission, with variations as large as $\pm 0.5$ keV over the course of a few months. Unfortunately we do not have simultaneous RXTE
measurements during the 2000 XMM-Newton observations. On the other hand, comparison of the RGS burst parameters during the 2000 and 2003 observations is straightforward, and the distributions of peak intensity and duration as measured by the RGS, are consistent between the two data sets. But this comparison is less instructive, since the RGS data are affected by (highly variable) obscuration and absorption by the circumstellar material.

Evidence for a change in the effective temperature during bursts is therefore inconclusive. But factors other than the photospheric temperature could affect the appearance of the photospheric absorption spectrum. A change in the average density at which the absorption spectrum is formed would have an equally strong effect on the overall ionization balance, and through the associated shift between the collisional and radiative rates, which affects both the ionization and the excitation balances. And in fact, simply changing the distribution of Fe through the atmosphere could change the absorption spectrum. Unfortunately, we have no independent measurement of the average photospheric density (the discrete absorption spectrum is in fact the best indicator). The broadband shape of the continuum is of course weakly sensitive to the average photospheric density, but, again, we do not have the necessary EPIC spectroscopy to systematically compare continuum shapes in 2000 and 2003.

Bildsten et al. (2003) pointed out that if the measured gravitational redshift of \( z = 0.35 \) is in fact correct, then the neutron star is smaller than the radius of the innermost stable Keplerian orbit, and the accretion disk effectively terminates in vacuo, with the accreting material falling nearly radially into the atmosphere. The result is that heavy nuclei are spalled in the atmosphere, and the distribution of any given element through the atmosphere is inhomogeneous. Should there be any change in the energy with which the nuclei fall into the atmosphere, then this stratification would also change.

The accretion flow does indeed appear to have changed in some respects: the circumstellar conditions in the persistent state of the source have changed considerably from 2000 to 2003 (a detailed comparison of the persistent spectra will be presented in J. van Peet et al. 2007, in preparation). It is immediately evident from the RGS light curve in Figure 1 that the scale height of the circumstellar material, which mostly obscured and reprocessed the soft central emission in 2000, is significantly diminished in 2003. The central emission now dominates the soft X-ray light curve. At the same time, however, the luminosity of the accretion disk appears not to have changed appreciably. Using the hard band EPIC/pn data, which is less sensitive to variability in the obscuring circumstellar material, we find an unabsorbed flux of \( \sim 2.8 \times 10^{-10} \) ergs cm\(^{-2}\) s\(^{-1}\) from 0.6 to 10 keV (Boirin et al. 2007) for the 2003 data with maximum variations of 30% over the course of all observations. Homan et al. (2003) report an unabsorbed flux of \( \sim 9 \times 10^{-11} \) ergs cm\(^{-2}\) s\(^{-1}\) from 5 to 10 keV for the 2000 data, which is equivalent to \( \sim 2.8 \times 10^{-10} \) ergs cm\(^{-2}\) s\(^{-1}\) in the 0.6–10 keV band for their spectral model. Although we note that the source luminosity is not necessarily a direct measure of the local accretion conditions, we conclude that the basic properties of the inner accretion disk have probably not changed much: the mass transfer rate is likely comparable between the 2000 and 2003 epochs, and the inner edge of the disk has likely not moved in radius (which of course it would indeed not be expected to do if it terminates at the innermost stable circular orbit).

5. CONCLUSION

We have analyzed soft X-ray spectroscopic observations with XMM-Newton/RGS of the X-ray bursts from the low-mass X-ray binary EXO 0748–646, obtained during the fall of 2003. The observations were performed to corroborate the detection of narrow soft X-ray atomic absorption lines in the burst spectrum as observed in 2000, in a spectrum of comparable depth. We accumulated a spectrum over 68 bursts, occurring in singles, doubles, and triples, for a total of 8555 s net RGS burst exposure time. The 8–35 Å burst spectrum in 2003 appears to be featureless, even when split into “early” and “late” burst phase spectra, with the possible exception of a marginal feature at \( \lambda = 13.0 \) Å during the late burst phases; this latter feature attracts attention only because it appears at the same wavelength at which the putative Fe xxv \( n = 2–3 \) transition was seen in 2000, during the early burst phases. Whatever measures of the photospheric continuum shape we have available for comparison between the two epochs appear to indicate that the average burst properties have not changed dramatically, but this conclusion is based on only three 2000 bursts observed with EPIC. Given the fact that the photospheric discrete absorption spectrum is very sensitive to the precise conditions in the atmosphere, it remains possible that a change in average burst parameters has reduced the contrast in the absorption lines.

Our research is based on data obtained with XMM-Newton, an ESA science mission with instruments and contributions funded directly by ESA member states and the USA (NASA). We thank Fred Jansen for providing the XMM-Newton Director’s Discretionary time for these observations. F. P. gratefully acknowledges support from NASA under grants NAG5-7737 and NNG05GG09G (NASA ATP Program).

Facilities: XMM

REFERENCES

Arnaud, K. A. 1996, in ASP Conf. Ser. 101, Astronomical Data Analysis Software Systems V, ed. G. H. Jacoby & J. Barnes (San Francisco: ASP), 17
Asai, K., & Dotani, T. 2006, PASJ, 58, 587
Bildsten, L., Chang, P., & Paerels, F. 2003, ApJ, 591, L29
Boirin, L., Keek, L., Méndez, M., Cumming, A., in ’t Zand, J. J. M., Cottam, J., Paerels, F., & Lewin, W. H. G. 2007, A&A, 465, 559
Chakrabarty, D. 2005, in AIP Conf. Proc. 797, Interacting Binaries, ed. L. Burderi (Melville: AIP), 71
Chang, P., Bildsten, L., & Wasserman, I. 2005, ApJ, 629, 998
Chang, P., Morsink, S., Bildsten, L., & Wasserman, I. 2006, ApJ, 636, L117
Cottam, J., Paerels, F., & Méndez, M. 2002, Nature, 420, 51 (CPM02)
den Herder, J. W., et al. 2001, A&A, 365, L7
Homan, J., Wijnands, R., & van den Berg, M. 2003, A&A, 412, 799
Jansen, F., et al. 2001, A&A, 365, L1
Özel, F. 2006, Nature, 441, 1115
Paerels, F. 1997, ApJ, 476, L47
Sako, M., et al. 2001, A&A, 365, L168
Strüder, L., et al. 2001, A&A, 365, L18
Villarreal, A. R., & Strohmayer, T. E. 2004, ApJ, 614, L121

\[ \frac{Y}{C_0} = \frac{Y}{8} ; \quad \frac{Y}{C_0} = \frac{Y}{10 \text{ keV}} \]