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ULTRACOMPACT X-RAY BINARIES WITH NEON-RICH DEGENERATE DONORS

Adrienne M. Juett, Dimitrios Psaltis,[1] and Deepto Chakrabarty[2]
Department of Physics and Center for Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139;
ajuett@space.mit.edu, dpsaltis@sns.ias.edu, deepto@space.mit.edu
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ABSTRACT

There are three low-mass X-ray binaries (4U 0614+091, 2S 0918−549, and 4U 1543−624) for which broad-line emission near 0.7 keV was previously reported. A recent high-resolution observation of 4U 0614+091 with the *Chandra* Low-Energy Transmission Grating Spectrometer (LETGS) found evidence of an unusually high Ne/O abundance ratio along the line of sight but failed to detect the previously reported 0.7 keV feature. We have made a search of archival *ASCA* spectra and identified a fourth source with the 0.7 keV feature, the 20 minute ultracompact binary 4U 1850−087. In all four of these sources, the 0.7 keV residual is eliminated from the *ASCA* spectra by allowing excess photoelectric absorption due to a nonsolar relative abundance of neon, just as in the LETGS spectrum of 4U 0614+091. The optical properties of these systems suggest that all four are ultracompact ($P_{\rm orb} < 80$ minutes) binaries. We propose that there is excess neon local to each of these sources, as also found in the ultracompact binary pulsar 4U 1626−67. We suggest that the mass donor in these systems is a low-mass, neon-rich degenerate dwarf and that the binaries are all ultracompact.

Subject headings: binaries: close — stars: individual (2S 0918−549, 4U 0614+091, 4U 1543−624, 4U 1850−087) — X-rays: binaries

1. INTRODUCTION

There have been many searches for linelike features in the low-resolution X-ray spectra of neutron stars (NSs) in low-mass X-ray binaries (LMXBs; see White, Nagase, & Parmar 1995 for a review). The detections fall into several categories. A broad emission feature near 0.7 keV has been repeatedly reported from 4U 0614+091 (Christian, White, & Swank 1994; White, Kallman, & Angelini 1997; Schulz 1999; Piraino et al. 1999). A similar feature has also been reported from 2S 0918−549 and 4U 1543−624 (White et al. 1997). Linelike features near 1 keV have been reported from Cygnus X-2 and Scorpius X-1 (Kuulkers et al. 1997; Vrtilek et al. 1991), and an unusual complex of Ne/O emission lines is detected in the ultracompact LMXB pulsar 4U 1626−67 (Angelini et al. 1995; Owens, Oosterbroek, & Parmar 1997; Schulz et al. 2001). Fluorescent Fe K line emission (6.4–6.7 keV) has been reported from a number of systems (e.g., Asai et al. 2000). More recently, high-resolution observations with the *Chandra X-Ray Observatory* and *XMM-Newton* have led to a number of new line detections (Brandt & Schulz 2000; Cottam et al. 2001a, 2001b; Schulz et al. 2001).

In this Letter, we focus on the origin of the 0.7 keV feature reported from several sources. A recent high-resolution observation of the brightest of these, 4U 0614+091, with the *Chandra* Low-Energy Transmission Grating Spectrometer (LETGS) failed to detect the feature; a failure attributed to source variability (Paerels et al. 2001). Paerels et al. (2001) did, however, find an unusually high Ne/O abundance ratio from absorption edges, which we show could produce a linelike residual near 0.7 keV in low-resolution data when not taken into account. We report here on a comprehensive search of the LMXB spectra in the *ASCA* public data archive for additional examples of sources with the 0.7 keV feature. We identify a fourth source with this feature, the ultracompact LMXB 4U 1850−087. Finally, we show that the *ASCA* spectra of these four systems, as well as the *Chandra* LETGS spectrum of 4U 0614+091, can all be well fitted *without* a 0.7 keV line feature if excess photoelectric absorption due to neon-rich material near the source is present.

2. OBSERVATIONS AND DATA REDUCTION

The *ASCA* satellite (Tanaka, Inoue, & Holt 1994) operated from 1993 February to 2000 July carrying four instruments: two Solid-State Imaging Spectrometers (SIS0 and SIS1; 0.5–10.0 keV) and two Gas Imaging Spectrometers (GIS2 and GIS3; 1.0–10.0 keV). The SIS instruments had superior resolution (0.07 keV at 1 keV), making them better suited for soft X-ray line studies. We used both BRIGHT and FAINT mode SIS data in our analysis. The SIS CCDs gradually degraded after launch because of radiation damage, and we note that the BRIGHT mode data are more susceptible to this damage than the FAINT mode data are. However, since the observations that we used all took place before 1996, we believe that any systematic problems due to radiation damage are smaller than the statistical uncertainties in the data. We used the XSPEC v.11 spectral-fitting package to perform the analysis presented here (Arnaud 1996).

We examined the observations of all 56 NSs in LMXBs in the *ASCA* public data archive as of 2000 April in order to identify sources with a 0.7 keV feature similar to that reported in 4U 0614+091. For our preliminary search, we used the preprocessed standard spectral data products for each source and fitted the SIS data with an absorbed power-law or power-law + blackbody model. Nine sources showed significant residual excess below 1 keV. However, three of these sources (4U 1254−690, 4U 1755−338, and 4U 2127+119) are known X-ray dippers and were excluded from further analysis since their spectrum can be well described by partial covering models (Church et al. 1997; Sidoli, Parmar, & Oosterbroek 2000), unlike the spectrum of 4U 0614+091. Two of the other candidates

[1] Current address: School of Natural Sciences, Institute for Advanced Study, Princeton, NJ 08540.
[2] Alfred P. Sloan Research Fellow.

TABLE 1
ASCA Observations

Source	Date	Exposure (ks) GIS	SIS	GIS2 Count Rate (counts s^{-1})
4U 0614+091	1993 Apr 18	8	6	31.23 ± 0.07
2S 0918−549	1995 Jun 01	14	15	13.86 ± 0.03
4U 1543−624	1995 Aug 17	12	14	17.13 ± 0.04
4U 1850−087	1995 Oct 06	20	17	3.95 ± 0.01

(2S 0921−630 and 4U 1822−371) are known accretion disk corona (ADC) sources. These were also not considered further because of the distinct differences in their residuals from the 0.7 keV feature that we are concentrating on. (The ADC sources have a much broader residual, which is better described as a poorly fit continuum rather than a linelike feature.) After narrowing down the candidates, we were left with four sources with an almost identical feature at 0.7 keV. These four remaining sources include the three previously identified with a 0.7 keV feature as well as a new source: 4U 1850−087.

For these four sources, we made a detailed reanalysis of the relevant data (see Table 1) obtained from the *ASCA* public data archive, using the standard data reduction techniques recommended by the instrument team (see the *ASCA* Data Reduction Guide 2001).[3] We discarded telemetry-saturated SIS frames and applied any necessary dead-time corrections to the GIS data. Source and background spectra were extracted from the screened event files, with 6′ and 4′ radius source regions for GIS and SIS, respectively. We used the 2–10 keV GIS data to constrain the high-energy continuum and the 0.4–7.0 keV SIS data to study the soft X-ray features.

It was necessary to correct for pileup in the SIS data of 4U 0614+091, 2S 0918−549, and 4U 1543−624. Since the CCDs are only read every 4–16 s, it is possible for sources brighter than ∼10 counts s^{-1} per sensor to have 2 or more photons detected at the same pixel. When this happens, the instrument reads just one event at an energy comparable to the sum of the original photon energies, thus changing the shape of the spectrum. The large point-spread function (PSF) of *ASCA* is useful in reducing the effect of pileup as well as correcting for it. To correct for pileup, events in the inner core of the PSF should be rejected, and the wings of the PSF used to predict the original spectrum of the source. The sources 2S 0918−549 and 4U 1543−624 were both taken in 1-CCD mode, and the standard pileup correction tool (CORPILEUP FTOOL) could be applied. The observations of 4U 0614+091 were taken in 4-CCD mode, so the standard correction tool could not be used. Instead, we manually determined the area affected by pileup and rejected any events within this area. Pileup correction was unnecessary for 4U 1850−087.

We attempted to fit a variety of continuum models to these spectra. The simplest model that provided a reasonable fit was an absorbed power-law + blackbody model, although more complex models could also be fitted to the data. In all cases, however, a strong residual emission feature near 0.7 keV was present (see Fig. 1, *top panels*). These residuals can be fitted with a broad (≈300 eV FWHM) Gaussian emission line. Our fit results are summarized in Table 2. The feature is remarkably similar in all four sources, suggesting a common origin. It is not seen in the *ASCA* data from other NSs in LMXBs.

3. AN ALTERNATIVE MODEL: HIGH NEON ABUNDANCE

Prior to the launch of *Chandra*, every previous observation of the four sources identified above with sufficient statistics detected the 0.7 keV feature. The nondetection in 4U 0614+091 with the *Chandra* LETGS, with its superior resolution, is thus quite surprising if the feature is indeed unresolved line emission. Paerels et al. (2001) attribute the nondetection to the time variability of the feature, although we note that this would be the

[3] Maintained at the *ASCA* Guest Observer Facility, NASA/GSFC (http://heasarc.gsfc.nasa.gov/docs/asca/abc/abc.html).

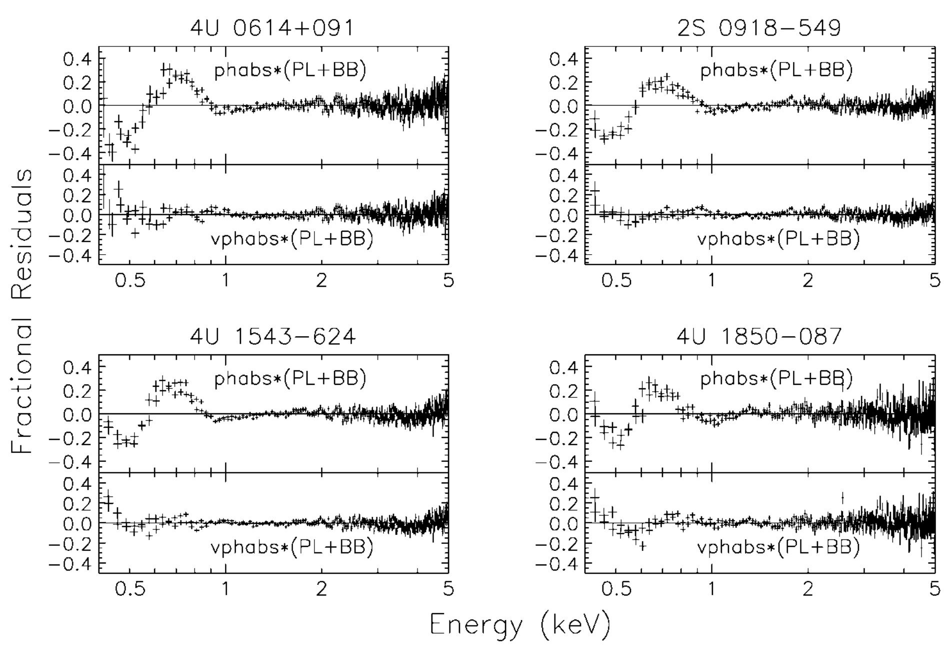

Fig. 1.—*Top panels*: Fractional residuals [(data − model)/model] using a standard absorbed power-law + blackbody model. For clarity, only the SIS data are included. *Bottom panels*: Residuals of the same *ASCA* SIS spectra when a variable abundance absorption model (vphabs, with Ne and O allowed to vary) is used with the power-law + blackbody model.

TABLE 2

Spectral Fits[a]

Model[b]	N_H ($\times 10^{21}$ cm^{-2})	PL: Γ	PL: A_1[c]	BB: kT (keV)	BB: R^2_{km}/d^2_{kpc}	Line Parameters: E_L (keV)	Line Parameters: FWHM (keV)	Relative Abundance[d]: O/H	Relative Abundance[d]: Ne/H	χ^2/Degrees of Freedom
4U 0614+091										
phabs × (PL + BB)	2.77 ± 0.08	2.03 ± 0.02	58 ± 2	0.54 ± 0.02	2.7 ± 0.5	…	…	…	…	2057/735
phabs × (PL + BB + line)	4.2 ± 0.3	2.21 ± 0.02	81 ± 2	0.44 ± 0.02	2.1 ± 0.8	0.619 ± 0.009	0.30 ± 0.03	…	…	1208/732
vphabs × (PL + BB)	3.74 ± 0.11	2.17 ± 0.03	75 ± 4	0.49 ± 0.03	1.7 ± 0.8	…	…	0.50 ± 0.04	2.87 ± 0.16	1249/733
2S 0918−549										
phabs × (PL + BB)	2.75 ± 0.08	1.73 ± 0.02	18.4 ± 0.8	0.52 ± 0.03	0.61 ± 0.16	…	…	…	…	1821/766
phabs × (PL + BB + line)	3.68 ± 0.17	1.80 ± 0.02	21.1 ± 0.2	0.37 ± 0.04	2.0 ± 0.3	0.636 ± 0.012	0.32 ± 0.04	…	…	1106/763
vphabs × (PL + BB)	3.47 ± 0.09	1.80 ± 0.02	20.9 ± 0.7	0.42 ± 0.03	0.8 ± 0.4	…	…	0.49 ± 0.04	2.39 ± 0.15	1139/764
4U 1543−624										
phabs × (PL + BB)	2.71 ± 0.06	1.86 ± 0.02	22.0 ± 0.7	0.426 ± 0.009	2.5 ± 0.3	…	…	…	…	2535/756
phabs × (PL + BB + line)	3.51 ± 0.16	1.93 ± 0.01	24.9 ± 0.2	0.351 ± 0.012	5.5 ± 0.9	0.65 ± 0.02	0.25 ± 0.03	…	…	1531/753
vphabs × (PL + BB)	3.33 ± 0.07	1.92 ± 0.02	24.6 ± 0.8	0.357 ± 0.014	5.2 ± 1.0	…	…	0.52 ± 0.04	2.86 ± 0.16	1541/754
4U 1850−087										
phabs × (PL + BB)	3.78 ± 0.07	2.228 ± 0.009	9.07 ± 0.11	0.12 ± 0.01	1300 ± 500	…	…	…	…	1157/669
phabs × (PL + BB + line)	3.0 ± 0.3	2.18 ± 0.03	8.5 ± 0.3	0.20 ± 0.06	8^{+32}_{-7}	0.68 ± 0.02	0.23 ± 0.04	…	…	790/666
vphabs × (PL + BB)	2.93 ± 0.13	2.14 ± 0.04	7.8 ± 0.6	0.41 ± 0.07	$0.26^{+0.25}_{-0.18}$	…	…	0.37 ± 0.06	1.9 ± 0.3	822/667

[a] All errors are quoted at the 90% confidence level.

[b] PL = power law; BB = blackbody; phabs = photoelectric absorption with standard abundances; vphabs = photoelectric absorption with nonstandard abundances. In our fits, only the abundances of O and Ne were varied.

[c] PL normalization at 1 keV in units of 10^{-2} photons keV^{-1} cm^{-2} s^{-1}.

[d] Abundance ratio relative to solar, $(X/H)/(X/H)_\odot$.

only one of ≈10 spectral observations of the source that did not detect the feature.

We point out here, however, that it is possible to explain *all* the previous data, including the *Chandra* LETGS spectrum, without recourse to time variability. Paerels et al. (2001) found that the relative strengths of the photoelectric absorption edges of O and Ne in their spectrum of 4U 0614+091 could only be explained by an anomalously large abundance ratio by number of Ne/O ≈ 1.25, a factor of 7.5 times larger than the solar value. It is possible that this is due to unusual abundances in the interstellar medium along the line of sight. Alternatively, there may be excess absorption in neon-rich material local to the binary. This would not be unprecedented since the presence of neon-rich local material has been reliably established through both absorption-edge and emission-line measurements in the LMXB pulsar 4U 1626−67 (Angelini et al. 1995; Schulz et al. 2001).

Motivated by these points, we refitted the *ASCA* data for these four sources with a new absorbed power-law + blackbody model, allowing the relative abundances of O and Ne to vary (using the "vphabs" model in XSPEC). The best-fit parameters are given in Table 2, and the residuals from this model are shown in the bottom panels of Figure 1. Note that a strong 0.7 keV feature is no longer present. The remaining weak structure in the low-energy residuals is consistent with previously known, unexplained features in the SIS low-energy response.[4] As a consistency check, we note that our *ASCA* fit results for 4U 0614+091 are in rough agreement with the values derived by Paerels et al. (2001) from their *Chandra* LETGS spectrum.

4. DISCUSSION

We have shown that the ultracompact LMXB 4U 1850−087, like the previously identified sources 4U 0614+091, 2S 0918−549, and 4U 1543−624, has a residual broad emission feature near 0.7 keV in its *ASCA* spectrum when fitted with an absorbed power-law + blackbody model. We have also shown that, in all four of these sources, the 0.7 keV feature is eliminated if the model includes a Ne overabundance in the absorbing material along the line of sight. This is consistent with the results of the recent high-resolution *Chandra* observation of 4U 0614+091, which found a stronger than expected Ne absorption edge but no emission features (Paerels et al. 2001).

In principle, it is possible that the interstellar medium along all four lines of sight is neon-rich, although we know of no plausible mechanism for producing such a widespread enhancement. Instead, we conclude that there is cool material local to these binaries that is neon-rich. There is already strong evidence for neon-rich material around another LMXB, the ultracompact ($P_{\rm orb} = 42$ minutes) binary pulsar 4U 1626−67 (Angelini et al. 1995; Schulz et al. 2001). *Chandra* observations of this source have resolved the individual photoelectric absorption edges due to Ne and O, which are considerably stronger than expected based on the known interstellar value of $N_{\rm H}$ toward the source (Schulz et al. 2001). As noted earlier, this source also shows a strong complex of Ne/O emission lines, demonstrating a local origin for these elements. Ultracompact ($P_{\rm orb} \lesssim 80$ minutes) binaries *must* have H-depleted donors, usually white dwarfs (Nelson, Rappaport, & Joss 1986), and there are several indications that the mass donor in 4U 1626−67 is indeed probably a white dwarf (e.g., Chakrabarty 1998). Schulz et al. (2001) show that either a C-O or an O-Ne white dwarf can have a high Ne/O ratio, especially if crystallization has occurred (see also Segretain et al. 1994 and Gutierrez et al. 1996).

Our four sources may also be ultracompact binaries. Only 4U 1850−087 has a measured orbital period: $P_{\rm orb} = 20.6$ minutes, making it another ultracompact binary with a likely degenerate companion (Homer et al. 1996). The other three sources do not have known binary periods. However, their optical counterparts are faint and blue, suggesting that the optical emission is dominated by the accretion disk and that the donor has very low mass. We can constrain their orbital periods using the strong empirical correlation between absolute magnitude M_V and the quantity $\Sigma = (L_{\rm X}/L_{\rm Edd})^{1/2}(P_{\rm orb}/1\ {\rm hr})^{2/3}$ (van Paradijs & McClintock 1994), where $L_{\rm X}$ is the X-ray luminosity and $L_{\rm Edd}$ is the Eddington luminosity. Based on the available measurements, we estimate that all four sources have M_V in the range of 3.5–4.5. The above correlation then gives $\log \Sigma \simeq -1$, which for $L_{\rm X} \approx 10^{-2} L_{\rm Edd}$ implies that the binaries are indeed ultracompact with $P_{\rm orb} \lesssim 1$ hr. We therefore propose that 4U 0614+091, 2S 0918−549, 4U 1543−624, and 4U 1850−087 are all ultracompact binaries with low-mass, Ne-rich degenerate dwarf donors and surrounded by neutral material, possibly expelled from an accretion disk.

While the degenerate donor in an ultracompact binary must be H-depleted, it need not necessarily be a C-O or O-Ne dwarf as in 4U 1626−67. For example, the donor in the 11 minute ultracompact LMXB 4U 1820−30 is known to be an He dwarf, on the basis of its X-ray burst properties (Bildsten 1995). However, we note that the apparent *underabundance* of O in our four sources is not inconsistent with their having C-O or O-Ne donors. Since the (unresolved) O absorption edge dominates the *ASCA* determination of $N_{\rm H}$, the true $N_{\rm H}$-values would be considerably lower if there is a large amount of O-rich material local to the binaries. A direct Lyα measurement of $N_{\rm H}$ might clarify this point, as has already been done for 4U 1626−67 (Wang & Chakrabarty 2001; Schulz et al. 2001). Another way to determine the donor composition is through emission-line spectroscopy. No reliable X-ray lines have been detected for any of the sources. In the optical spectrum of 4U 0614+091, no H or He lines are seen, although there is a weak detection of the C III/N III Bowen emission blend near 4640 Å (Davidsen et al. 1974; Machin et al. 1990). This is essentially identical to the optical spectrum of 4U 1626−67 (Cowley, Hutchings, & Crampton 1988; Wang & Chakrabarty 2001).

One crucial difference between our four binaries and 4U 1626−67 is that the latter is a pulsar with a strong (3×10^{12} G; Orlandini et al. 1998) magnetic field, while our four sources are presumed to contain weakly magnetized NSs. This may result in a different ionization structure in the disk, thus explaining the absence of a strong Ne line complex in the weak-field systems. These systems should also be subject to thermonuclear X-ray bursts (Joss & Li 1980), although an unusual donor composition might lead to atypical burst properties. In particular, calculations for thermonuclear flashes in pure C layers indicate very long ($\gtrsim$0.5 yr) recurrence times and correspondingly large burst fluences; these general trends will be true even for C mass fractions as low as 10% (Cumming & Bildsten 2001), which is relevant for C-O donors. Few type I X-ray bursts have been reported from our four sources: two bursts from 4U 0614+091 (Swank et al. 1978; Brandt et al. 1992), one from 2S 0918−549 (Jonker et al. 2001), and three

[4] The *ASCA* Calibration Uncertainties as of 2001 January 5, submitted by K. Arnaud et al. (http://heasarc.gsfc.nasa.gov/docs/asca/cal_probs.html).

from 4U 1850−087 (Hoffman, Cominsky, & Lewin 1980). However, none of these bursts have an unusually large fluence, and two of the bursts from 4U 1850−087 were separated by only 17 hr. This may indicate that the donors in these systems are not C-O dwarfs. In that case, some other mechanism for producing an Ne enhancement is required.

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