X-RAY SPECTROSCOPY OF THE ACCRETING MILLISECOND PULSAR XTE J0929–314 IN OUTBURST

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ABSTRACT

We present the high-resolution spectrum of the accretion-powered millisecond pulsar XTE J0929–314 during its 2002 outburst, measured using the Low Energy Transmission Grating Spectrometer onboard the Chandra X-ray Observatory. The Chandra spectrum is well fit by a power-law + blackbody model with photon index $\Gamma=1.55\pm0.03$, blackbody temperature $kT_{bb}=0.65\pm0.03$ keV, and blackbody normalization $R_{bb, km}/d_{10kpc}=7.6\pm0.8$. No emission or absorption features are found in the high-resolution spectrum, with a $3\sigma$ equivalent width upper limit of 5 eV for most of the 1.5–25.3 Å wavelength range. The neutral absorption edges are consistent with the estimated interstellar absorption along the line of sight to the source. We found no orbital modulation of the 2–10 keV X-ray flux, to a $3\sigma$ upper limit of 1.1%, which implies an upper limit on the binary inclination angle of $i\lesssim85^\circ$ for a Roche-lobe–filling companion. We also present the broadband spectrum measured over the course of the outburst by the Rossi X-ray Timing Explorer (RXTE). The RXTE spectrum of XTE J0929–314 is also well fit with a power-law + blackbody model, with average values of $\Gamma=1.76\pm0.03$, $kT_{bb}=0.66\pm0.06$ keV, and $R_{bb, km}/d_{10kpc}=5.9\pm1.3$. No significant evolution in the spectral shape was found over the course of the outburst. The blackbody temperature and normalization varied, but were anti-correlated such that the blackbody flux remained constant, with the power-law normalization strongly correlated to the (decreasing) flux of the source. We find that the difference in power-law photon indices measured from Chandra and RXTE spectra can be explained by a change in the power-law photon index at low energies, $E\lesssim4$ keV, and that the combined spectrum is better fit by a either a Comptonization + blackbody model or a broken power-law + blackbody model.

Subject headings: binaries: close — stars: neutron — pulsars: individual (XTE J0929–314) — X-rays: binaries

1. INTRODUCTION

Millisecond pulsars (MSPs) have long been considered one of the possible endpoints of low-mass X-ray binary (LMXB) evolution. The neutron star (NS) is thought to be spun-up to a millisecond period by accretion from its low-mass companion. After the accretion phase has ended, the NS may turn on by accretion from its low-mass companion. We also present the broadband spectrum measured over the course of the outburst by the Rossi X-ray Timing Explorer (RXTE). The RXTE spectrum of XTE J0929–314 is also well fit with a power-law + blackbody model, with average values of $\Gamma=1.76\pm0.03$, $kT_{bb}=0.66\pm0.06$ keV, and $R_{bb, km}/d_{10kpc}=5.9\pm1.3$. No significant evolution in the spectral shape was found over the course of the outburst. The blackbody temperature and normalization varied, but were anti-correlated such that the blackbody flux remained constant, with the power-law normalization strongly correlated to the (decreasing) flux of the source. We find that the difference in power-law photon indices measured from Chandra and RXTE spectra can be explained by a change in the power-law photon index at low energies, $E\lesssim4$ keV, and that the combined spectrum is better fit by a either a Comptonization + blackbody model or a broken power-law + blackbody model.

XTE J0929–314 was discovered in April 2002 by the All Sky Monitor onboard the Rossi X-ray Timing Explorer (RXTE; Remillard 2002). After its initial detection, in which 185 Hz pulsations were found, further RXTE observations exhibited Doppler shifts consistent with a 43.6-min binary orbit (Remillard, Swank, & Strohmayer 2002; Galloway et al. 2002). Radio and optical counterparts with positions consistent with the Chandra position were also detected (Rupen, Dhawan, & Mioduszewski 2002; Greenhill, Giles, & Hill 2002; Capella 2002). An optical spectrum of XTE J0929–314 revealed emission lines from C III/N III $\lambda$4640-4650 and H$\alpha$ $\lambda$6563 (Castro-Tirado et al. 2002). Given the optical detection of emission lines, and the ultracompact nature and high-Galactic latitude of the source, XTE J0929–314 is an ideal candidate for a high-resolution X-ray spectroscopic study to search for emission and absorption features similar to those seen in other ultracompact systems. In this letter, we present results from a Director’s Discretionary Time observation of XTE J0929–314 with the Chandra X-ray Observatory, as well as spectral results from the RXTE pointed observations throughout the outburst.

2. OBSERVATION AND DATA REDUCTION

The 2002 outburst of XTE J0929–314 began around MJD 52370 and peaked at $\approx31$ mCrab (2–10 keV) on MJD 52394 (Galloway et al. 2002). The pointed RXTE observations commenced 2 d later, and proceeded once every few days through MJD 52456. The source dropped below the $3\sigma$ detection limit of $7.5\times10^{-15}$ erg cm$^{-2}$ s$^{-1}$ (2–10 keV; equivalent to 0.32 mCrab) after MJD 52443.

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XTE J0929–314 was observed throughout its 2002 outburst by the two pointed instruments onboard RXTE. The Proportional Counter Array (PCA; Jahoda et al. 1996) aboard RXTE consists of five gas-filled proportional counter units (PCUs) with a total effective area of \( \approx 6000 \text{ cm}^2 \), sensitive to X-ray photons in the 2.5–60 keV range. The two instrument clusters comprising the High-Energy X-ray Timing Experiment (HETE; Gruber et al. 1996) present an effective area of \( \approx 1600 \text{ cm}^2 \) to photons in the energy range 15–250 keV. We extracted average spectra from standard instrument mode data (“Standard-2” and “Archive” for PCA and HETE, respectively) from each PCU/cluster for each observation. Since the instrumental gain is known to vary between PCUs, and also with time, we generated a separate response matrix for each PCU and each observation using PCARSP version 8.0, supplied with LHEASOFT version 5.2. We estimated background spectra using the “combined” gain epoch 5 (beginning 2000 May 13) faint-source model as input to PCABKCAST version 3.0. Over the course of the outburst, we collected 38 observations of XTE J0929–314 totaling 123.5 ks.

We also observed XTE J0929–314 with Chandra on 2002 May 15 (MJD 52409) for 18 ks using the Low Energy Transmission Grating Spectrometer (LETGS) and the Advanced CCD Imaging Spectrometer (ACIS; Weisskopf et al. 2002). The LETGS spectra are imaged by ACIS, an array of six CCD detectors. The LETGS/ACIS combination provides both an undispersed (zeroth order) image and dispersed spectra from the grating with a wavelength range of 1.4–63 Å and a spectral resolution of \( \Delta \lambda = 0.05 \text{ Å} \). The various orders overlap and are sorted using the intrinsic energy resolution of the ACIS CCDs. The observation used a Y-offset of +15 in order to place the O K absorption edge on the back-side illuminated S3 CCD, which has suffered less degradation than the front-side illuminated CCDs.

Using tgdetect, we determined the zeroth order source position of XTE J0929–314 to be: R.A.=09°29′20″15 and Dec.=−31°23′04″3 (90% confidence error of 0″3). The Chandra position is consistent with both the optical and radio counterpart positions (Rupen et al. 2002; Greenhill et al. 2002; Casella 2002). The first order dispersed spectrum of XTE J0929–314 had an average count rate of 7.64±0.02 cts s\(^{-1}\). We examined the total count rate, as well as the count rates in two different energy ranges, to check for changes in the spectral state. We found no evidence for any change of state during the Chandra observation.

The “level 1” event file was processed using the CIAO v2.2 data analysis package\(^4\). The standard CIAO spectral reduction procedure was performed. We filtered the event file retaining those events tagged as afterglow events by the acis_detect_afterglow tool. Since order-sorting of grating spectra provides efficient rejection of background events, the afterglow detection tool is not necessary to detect cosmic ray afterglow events. No features were found that might be attributable to afterglow events.

For bright sources, pileup can be a problem for CCD detectors (see, e.g., Davis 2002). The zeroth order Chandra spectra of XTE J0929–314 was heavily affected by pileup and was not used in this analysis. In addition, it was found that the first order spectrum of XTE J0929–314 suffered from pileup in the range 5–12 Å (1–2.5 keV). In order to use the grating pileup kernel in ISIS, we created ARFs for each chip using the CIAO tool mkgarf and then combined them to create +1 and −1 order ARFs using a custom tool developed by J. Davis of the HETGS instrument team. (This tool is similar to the standard CIAO tool but correctly calculates the fractional exposure at each response bin.) The grating pileup kernel models the effect of pileup on grating spectra, similar to the pileup model available for CCD spectra in ISIS and XSPEC (see, Davis 2002, for a discussion of grating pileup modeling). In addition, the data and responses were rebinned to 0.083 Å to reflect the size of an ACIS event detection cell (3 CCD pixels). Background spectra were extracted from the standard LETG background regions. Spectral analysis of the Chandra observation of XTE J0929–314 was performed using ISIS (Davis 2002; Houck & DeNicola 2000).

3. Searching for Orbital Modulation

The presence (or absence) of orbital modulation of the X-ray flux can help constrain the inclination of the binary, and in turn the mass of the companion. Galloway et al. (2002) determined the orbital period of XTE J0929–314 to be 43.6 min from the Doppler modulation of the pulse arrival times. We searched both the RXTE and Chandra data for orbital modulation of the X-ray flux.

For the RXTE analysis, we calculated background-subtracted, solar-system barycenter corrected, 16-s binned lightcurves for each observation from photons in the energy range 3–13 keV. This range was selected to maximize the signal-to-noise ratio, and is identical to that used for the pulse timing analysis of Galloway et al. (2002). For each observation, we created a phase folded lightcurve of 8 bins using the measured orbital parameters, with phase zero set to the epoch of 90° mean longitude, \( T_{\pi/2} \). The length of each observation was short compared to the decay timescale of the X-ray flux of XTE J0929–314, so it was not necessary to correct for the decline in X-ray flux during a single observation. Each lightcurve was then fit with a sine curve with variable amplitude and phase. From these results, we place a 3\( \sigma \) upper limit on the fractional rms modulation of 1.1%.

We also searched the Chandra data for orbital modulation of the X-ray flux. For the Chandra analysis, we first barycentered and randomized the first order grating events. Randomizing of the event arrival times consists of adding a random quantity uniformly distributed between 0–3.2 s, in order to avoid aliasing caused by the readout time. We calculated the phase of each first order event using the orbital parameters from Galloway et al. (2002) and created a 8 bin phase-folded lightcurve. We found an upper limit of 2.3% rms, consistent with the RXTE results.

Since the Chandra data is not subject to time gaps due to spacecraft motion, we calculated a Fourier transform of the first order events which had been made into a 10-s binned lightcurve. We searched for modulations of the X-ray flux with frequencies between \( 6 \times 10^{-3} \) and \( 5 \times 10^{-2} \) Hz. We found no evidence for any periodic modulation, with a 90%-confidence upper limit of 1.4% for the fractional rms amplitude over the frequency range. The 90%-confidence upper limit for the fractional rms amplitude of a signal at the orbital period is 0.4%, well within the upper limits given by the phase folding analyses.

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3 See http://asc.harvard.edu/cal/ASPECT/celmon/index.html

4 http://asc.harvard.edu/ciao/
4. SPECTRAL ANALYSIS

4.1. RXTE Spectral Analysis

We fitted the combined PCA and HEXTE spectra with a range of models which typically give good fits for other X-ray pulsars, including broken and cutoff power laws and analytical Comptonization approximations. There was no evidence for a high-energy spectral cutoff within the energy range in which the source was detected (typically \( \lesssim 50 \) keV). We did however measure significant residuals below 10 keV. These residuals could be minimized by adopting a broken power law model where the spectral index decreased by \( \sim 10\% \) (i.e. the spectrum became harder) above 7 keV, or by adding a blackbody component with \( kT_{bb} \sim 0.5 \) keV to the power law. While both these models gave fits of similar quality, we rejected the former as unphysical and instead adopted the latter for the remainder of the RXTE fits.

We also included a multiplicative component to take into account the attenuation by intervening (neutral) material with cosmic abundances. The equivalent hydrogen column density \( N_H \) exhibited no significant variations between observations, and in the mean was \( \sim 10^{21} \) cm\(^{-2}\), consistent with the line-of-sight values interpolated from dust and H I maps (7.6 \( \times \) 10\(^{20}\) and 10\(^{21}\) cm\(^{-2}\) respectively; Schlegel, Finkbeiner, & Davis 1998; Dickey & Lockman 1990). For consistency with the fits to Chandra data, we froze the \( N_H \) value in subsequent fits at 7.6 \( \times \) 10\(^{20}\) cm\(^{-2}\). The mean value of the reduced-\( \chi^2 \) (= \( \chi^2 \)) for power law and blackbody fits to spectra from all the observations was 1.04. While the worst-fitting observation gave a \( \chi^2 = 2.44 \), the largest residuals arose from variations between PCUs (particularly at the lower energy bound) rather than any broad trend with energy. By excluding these lowest channels from the fit, and assuming a systematic error of 1\%, we were able to reduce the fit statistic for that observation to \( \chi^2 = 1.30 \).

The weighted mean of the blackbody temperature, \( kT_{bb} \), was 0.66 \( \pm \) 0.06 keV, while the normalization \( \sqrt{\frac{K_{bb}}{d} \frac{d}{10^6} \rho} = 5.9 \pm 1.3 \) (all errors are quoted at 90\%-confidence unless otherwise noted). Both parameters showed significant variations during the outburst; however, they were significantly anticorrelated, so that the estimated bolometric blackbody flux \( \sim \frac{K_{bb} T_{bb}^4}{d} \) remained constant to within our measurement uncertainties (\( \chi^2 = 1.06 \), see Figure 1). In the first observation, the blackbody component comprises only 3\% of the flux in the 2–60 keV band, whereas in the last observation where significant blackbody and power-law components were detected, the blackbody accounted for 16\% of the flux.

We calculated a weighted mean photon index of \( \Gamma = 1.76 \pm 0.03 \). The principal source of flux variation was the normalization of the power-law component (see Figure 1). While all parameters exhibited variations throughout the outburst, the power-law normalization was the only parameter to show a significant correlation with the integrated 2–10 keV flux (Spearman’s rank correlation coefficient \( \rho = 0.908 \), equivalent to 5.4\sigma; Press et al. 1992). A power-law component was not significantly detected in the last observation on MJD 52443. A blackbody-only fit for that day exhibits a significantly (6.6\sigma) lower integrated blackbody flux than the weighted mean level for the previous observations. We did not detect XTE J0929–314 in subsequent observations (3\sigma upper limit on the flux of 7.5 \( \times \) 10\(^{-12}\) erg cm\(^{-2}\) s\(^{-1}\), 2–10 keV).

4.2. Chandra Spectral Analysis

We fit the Chandra spectrum with a power-law + blackbody model including absorption. The +1/5 Y-offset in the observational setup allows for the entire 1.5–25.3 Å (0.5–8.3 keV) +1 order spectrum to be imaged on the S3 CCD. This CCD is backside-illuminated and has suffered less degradation than the front-side illuminated CCDs. Because of this and the lack of counts above 25 Å, we performed our spectral fits on only the +1 order spectrum in the range 1.5–25.3 Å.

Of the three known X-ray MSPs, XTE J0929–314 has the highest Galactic latitude and, probably the smallest interstellar column density along the line of sight to the source. Our Chandra observation allows for a direct determination of the strength of the absorption edges, in particular the O K edge and the Fe L triplet. To account for absorption and measure the optical depths of the edges, we used the tbvarabs absorption model (see, Wilms, Allen, & McCray 2000) with O and Fe abundances set to zero and the \( N_H \) value in subsequent fits at 7.6 \( \times \) 10\(^{20}\) cm\(^{-2}\), the hydrogen column from dust maps (Schlegel et al. 1998). The O edge was fit with an edge model while the Fe L edges were fit using a custom model that employs the optical constant measurements of Kortright & Kim (2000). In addition, the C abundance in tbvarabs was allowed to vary in order to account for the known instrumental contamination of the ACIS CCDs\(^5\). We also included gaussian lines to fit the interstellar atomic O absorption line at 23.5 Å and the absorption feature at 23.36 Å, attributed to a 1s-2p transition in Fe\(_2\)O\(_3\) (see, Schulz et al. 2002).

\(^5\) For more information see, http://cxc.harvard.edu/cal/Links/Acis/acis/Cd_prodqs/qeDeg/index.html
We found a best-fit photon index of 1.55±0.03, with a normalization of \((4.04\pm0.15)\times10^{-2}\) photons keV\(^{-1}\) cm\(^{-2}\) s\(^{-1}\) at 1 keV. The Chandra best-fit blackbody temperature was \(kT_{bb} = 0.65 \pm 0.03\) keV, with \(R_{300} / d_{10kpc} = 7.6 \pm 0.8\). Our best-fit model had a \(\chi^2 = 1.001\) and an unabsorbed 2–10 keV flux of \(2.7\times10^{-10}\) erg cm\(^{-2}\) s\(^{-1}\).

The best-fit optical depth for O was 0.34±0.07, which translates to an equivalent hydrogen column density of \((1.2\pm0.3)\times10^{21}\) cm\(^{-2}\), using the cross-section of Verner et al. (1993) and the O ISM abundance of Wilms et al. (2000). Although this is somewhat higher than the measured hydrogen column from dust maps, an instrumental contribution to the O edge has been reported\(^2\), with an optical depth of \(\approx 0.082\). This contribution would add \(N_{H} \approx 0.3 \times 10^{21}\) cm\(^{-2}\) to the expected value, making the Chandra O edge measurement compatible with the dust map measurement. The best-fit line wavelength and flux of the atomic O absorption line were \(23.52\pm0.06\) Å and \((-1.46^{+0.7}_{-0.14})\times10^{-4}\) photons cm\(^{-2}\) s\(^{-1}\); while the Fe\(_{2}\)O\(_{3}\) absorption line is not significantly detected. The Fe-L edges were also not significantly detected, with an upper limit on the Fe column density of \(3 \times 10^{16}\) cm\(^{-2}\), equivalent to an \(N_{H} = 1.1 \times 10^{21}\) cm\(^{-2}\), also consistent with the dust map measurement. The best-fit C abundance was 7.8\(^{+1.2}_{-0.7}\) times the interstellar C/H ratio of Wilms et al. (2000). This is slightly lower than the expected instrumental + interstellar contribution of 9.9±0.5 times the interstellar ratio. The instrumental edge depths for C and O were estimated using the recent calibration results presented at the Chandra X-ray Center website\(^5\).

Besides the interstellar O absorption line, there were no prominent emission or absorption lines in the high-resolution spectrum of XTE J0929–314 (see Figure 2). We performed a careful search of the Chandra spectral residuals to place limits on the presence of any spectral features. Gaussian models with fixed FWHM = 2000 km s\(^{-1}\) were fit at each point in the wavelength range 1.5–25.3 Å. From this, we can place a 3\(\sigma\) limit of \(< 5\) eV in the range 3.0–25.3 Å on the equivalent width (EW) of any line feature, either emission or absorption. The EW limit at \(\lambda < 3\) Å is greater but below 35 eV. The 3\(\sigma\) flux limit on any line in the 1.5–25.3 Å range is \(< 8 \times 10^{-3}\) photons cm\(^{-2}\) s\(^{-1}\).

Our measured C abundance depends on the assumed continuum model, since the edge depth cannot be directly measured (the C edge at 43 Å is outside our bandpass). In order to test if the C abundance was the cause of the difference in the photon index between the Chandra and RXTE fits, we refit the Chandra spectrum with a fixed C abundance of 9.9 times the interstellar C/H ratio. With the C abundance fixed, the best-fit photon index was 1.62±0.03. This is still significantly different from the best-fit photon index found in the RXTE spectra. The best-fit power-law normalization increased to \((4.50\pm0.07)\times10^{-2}\) photons keV\(^{-1}\) cm\(^{-2}\) s\(^{-1}\). The other fit parameters were consistent with the previous fit within errors. We also considered the possibility that the pileup model was giving rise to the lower photon index in the Chandra spectral fits. When the Chandra data is fit without the pileup model, and excluding the piled-up region (1–3 keV) of the spectrum, we find spectral parameters consistent with the results found using the pileup model.

5. COMBINED CHANDRA AND RXTE SPECTRAL FITS

To investigate the difference in the spectral results between Chandra and RXTE, we performed combined spectral fits with the Chandra and RXTE data. A single RXTE observation (70096-03-05-00) taken within a few hours of the Chandra data was used to represent the RXTE spectrum of XTE J0929–314. To simplify fitting, the piled-up region (1–3 keV) of the Chandra spectrum was set to zero, while best-fit spectral parameters were consistent with the previous fit within errors. We also considered the possibility that pileup was causing the difference in the photon index between the Chandra and RXTE fits. Gaussian models with absorption fixed to the results found using the pileup model.

As a check on the instrumental calibrations, we directly compared the Chandra and RXTE data in the same energy range by fitting the high energy (3–8 keV) Chandra data, in conjunction with the RXTE data, to an absorbed power-law + blackbody model with absorption fixed to \(N_{H} = 7.6 \times 10^{20}\) cm\(^{-2}\). The fits are consistent with the results of the RXTE data, \(\Gamma = 1.74\pm0.02\), \(kT_{bb} = 0.66\pm0.03\) keV, and \(R_{bb,km} / d_{10kpc} = 5.9 \pm 0.7\), with

\[\chi^2 = 1.001\]
We then fit the full Chandra and RXTE spectra with a power-law + blackbody model. When the edge parameters were fixed to the Chandra best-fit values, the photon index had a best-fit value of 1.628±0.009 and with a $\chi^2 = 1.20$ (see Table 1). We note that the $\chi^2$ of the power-law + blackbody fit to the RXTE data alone was 1.06. If we fix the C abundance to the expected value of 9.9 times the interstellar C/H ratio, the photon index increases to 1.656. We note that the fit value of 1.628 to the law + parameters are highly dependent on the assumed absorption.

The estimate of the C abundance from instrument calibration times the interstellar C/H ratio. This value is inconsistent with $kT_0 = kT_{bb}$, but the fit was unreasonable with $\chi^2 > 2.0$. Interestingly, Gierliński et al. (2002) used a different Comptonization model and found $kT_0 = kT_{bb}$ in spectral fits of SAX J1808.4–3658. We employed the same model to fit XTE J0929–314 (comp+Poutanen & Svensson 1996), but found similar values for the input photon temperature and optical depth as found using the comp+ model.

We also fit the data with a broken power-law + blackbody model for low-energy turnover without relying on the assumptions inherent in the Comptonization model. We find that the data is also well fit ($\chi^2 = 1.08$) by a broken power-law + blackbody model with $\Gamma_1 = 1.26–1.56$, $\Gamma_2 = 1.75$, and $E_{break} = 1.4–4.4$ keV, and blackbody parameters consistent with previous fits (see Table 1).

### 6. Discussion

The broadband X-ray spectra of the three millisecond X-ray pulsars discovered to date are all similar, comprising a blackbody component with $kT_{bb} = 0.5–1$ keV, and a power law with photon index $\Gamma_1 = 1.4–1.8$, possibly with a spectral cutoff above 40 keV or so (Gierliński et al. 2002; Markwardt et al. 2002; Miller et al. 2002; Galloway et al. 2002). These components are generally attributed to a “hot spot” on the surface of the neutron star and a shock-heated accretion column, respectively. From our fits, we find a blackbody radius of $R_{bb,km}/d_{10kpc} = 5.5$. Given the lower limit on the distance of 5 kpc (Galloway et al. 2002), we find a lower limit on the radius of $R_{bb} > 2.7$ km. We note that this lower limit does not include a correction for the conversion between the color temperature and the effective temperature of the neutron star atmosphere (see, Lewin, van Paradijs, & Taam 1993, for a discussion). This correction could increase the inferred radius by a factor of $\approx 2$. The inferred radius may imply the existence of a “hot spot” emission region for the blackbody component, but further analysis is required before such a claim can be justified.

### Table 1

**Combined Chandra and RXTE Spectral Fits**

| Model | Carbon Abundance | $kT_{bb}/\text{keV}$ | $E_{break}/\text{keV}$ | $\Gamma_2/\tau$ | $\alpha$ | $kT_{bb}/\text{keV}$ | $R_{bb,km}^2/d_{10kpc}^2$ | $\chi^2$/dof |
|-------|------------------|-----------------------|------------------------|----------------|---------|----------------------|--------------------------|-------------|
| PL    | 7.8 (fix)        | 1.628±0.009           | ...                    | ...            | 4.58±0.07 | 0.730±0.015          | 28±3                    | 1006/837    |
| PL    | 9.9 (fix)        | 1.656±0.009           | ...                    | ...            | 4.90±0.08 | 0.717±0.016          | 28±3                    | 950/837     |
| Comp  | 7.8 (fix)        | 0.144±0.009           | ...                    | ...            | 5.7±0.3 | 0.68±0.02             | 31±5                    | 904/833     |
| Comp  | 9.9 (fix)        | 0.125±0.014           | ...                    | ...            | 5.6±0.2 | 0.707±0.017          | 30±4                    | 906/836     |
| BKN PL | 7.8 (fix)      | 1.26±0.09            | 1.4±0.3                | 1.74±0.02 | 5.06±0.19 | 0.66±0.03 | 34±5 | 894/832     |
| BKN PL | 9.9 (fix)      | 1.56±0.03            | 4.4±0.9                | 1.75±0.02 | 4.67±0.17 | 0.61±0.03 | 60±30 | 897/835    |

*aAll errors are quoted at the 90%-confidence level.
*bCarbon abundance ratio relative to ISM, (C/H)/C/H$_{ISM}$
*cPower-law and broken power-law normalization at 1 keV in units of 10$^{-2}$ photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$. Comptonization normalization in units of 10$^{-3}$.
As with the other two accreting millisecond pulsars, little spectral evolution is seen throughout the outburst of XTE J0929−314. The blackbody component parameters vary significantly, but are anticorrelated such that the estimated bolometric flux of this component is constant. This is in contrast with the behavior of SAX J1808.4−3658, in which both the blackbody normalization and temperature were found to decrease throughout the outburst, along with the hard component normalization (Gierliński et al. 2002).

We find that the spectrum is well described by a power-law + blackbody model over limited energy ranges, with interstellar absorption consistent with $N_H = 7.6 \times 10^{20}$ cm$^{-2}$ the expected hydrogen column density along the line of sight to the source. The Chandra spectrum shows no prominent emission or absorption lines in the spectrum (similar to XTE J1751−305; Miller et al. 2002), with an EW limit of $< 5$ eV for much of the spectral range and a line flux limit of $< 8 \times 10^{-5}$ photons cm$^{-2}$ s$^{-1}$. No orbital modulation of the X-ray flux was detected in either the Chandra or RXTE data. From the lack of dips or eclipses, we can set an upper limit on the binary inclination of $i \lesssim 85^\circ$ for a Roche-lobe–filling companion.

We find that the best-fit photon index is significantly different between the Chandra and RXTE fits with $\Gamma = 1.55 \pm 1.62$ for the Chandra fits, dependent on the assumed instrumental C abundance, and $\Gamma = 1.76$ for the RXTE fits. The difference in the photon index between the Chandra and RXTE spectral fits is similar to that noted by Miller et al. (2002) between the RXTE and XMM spectral fits of XTE J1751−305. From their XMM EPIC spectrum, Miller et al. (2002) found a best-fit power-law photon index of 1.44, while Markwardt et al. (2002) found a best-fit photon index of 1.7−1.9 using RXTE.

We suggest that this difference arises from spectral turnover at low energies. While a power-law model is a reasonable approximation to Comptonization at high energies, extrapolating the power law to low energies leads to a predicted flux that diverges at zero energy. Thermodynamics therefore requires that the power-law spectrum turn over at low energies (see, e.g., Psaltis 1998). Previous X-ray instruments have generally not required low energy turnovers for two reasons: low spectral resolution and limited bandpasses. In low-resolution fits of LMXBs, the interstellar absorption component can generally be used to compensate for possible deviations from a power law at low energies. The high-resolution capabilities of Chandra and XMM allow for a direct measurement of the edge depths and thus the column density to the source, effectively constraining one of the free parameters in the continuum fits. Combining the high-resolution capabilities of Chandra and XMM with the broadband coverage of RXTE allows for more accurate descriptions of the continuum emission from LMXBs.

The combined Chandra and RXTE spectrum of XTE J0929−314 is well fit by either a Comptonization + blackbody model (which implicitly includes a low-energy turnover from the Comptonization component), or a broken power-law + blackbody model, with break energy 1.4−4.4 keV. The high-energy ($E > 3$ keV) Chandra spectrum is consistent with the RXTE spectral results, indicating that instrumental differences alone do not give rise to the spectral turnover. We reject the possibility that the pileup model causes the lower photon index in Chandra-only fits, since fits without the pileup model give consistent parameter values. In addition, the spectral fit of XTE J1751−305 using XMM provides independent support for the presence of low-energy turnover in the spectra of millisecond X-ray pulsars and suggests that this turnover is astrophysical in origin.

A Comptonization + blackbody model was also used to fit the RXTE spectrum of the millisecond X-ray pulsar SAX J1808.4−3658 in outburst (Titarchuk et al. 2002). These authors claim that the low ($\tau_0 \approx 4$) optical depth of the Comptonizing region allows for the pulsations of the NS to be detected, while the higher optical depths ($\tau_0 > 5$) reported in more luminous LMXBs suppress the pulsation amplitudes. We find a best-fit $\tau_0 \approx 2.7$ for XTE J0929−314, consistent with this explanation. However, we note that Miller et al. (2002) did not find an acceptable fit of the XMM spectra of the millisecond X-ray pulsar XTE J1751−305 using a Comptonization model.

Both the power-law and Comptonization models required the addition of a blackbody at $kT_{bb} = 0.65 − 0.7$ keV. The similarity of the blackbody parameters in all of the fits, gives us confidence that the component is required and that the parameters can be reliably measured, even with the 2 keV lower energy limit of RXTE. In the Comptonization + blackbody fits, we find $kT_0 < kT_{bb}$. Similar fits to the same RXTE data of SAX J1808.4−3658 reach different conclusions as to the best-fit values of $kT_0$ and $kT_{bb}$. Titarchuk et al. (2002) found that $kT_0 < kT_{bb}$, while Gierliński et al. (2002) found $kT_0 = kT_{bb}$. Given that the $kT_0$ value found by Titarchuk et al. (2002) is well outside the RXTE spectral range, and that different Comptonization models were used in the fits, it is difficult to compare the SAX J1808.4−3658 results. On the other hand, the low energy range of Chandra allows us to make a more robust measurement of $kT_0$ for XTE J0929−314. The difference in the best-fit values of $kT_0$ and $kT_{bb}$ in our fits, along with the constant blackbody flux during the outburst, suggests that the blackbody is not the input to the Comptonization, but is rather a separate component. Further analyses, including pulse-phase spectroscopy, could reveal more about the geometry of the system and the origin of the emission components.

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