Variability and Spectra of Two Neutron Stars in 47 Tucanae

C. O. Heinke, J. E. Grindlay, D. A. Lloyd, P. D. Edmonds
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

Abstract. We report spectral and variability analysis of two quiescent low mass x-ray binaries (previously identified with ROSAT HRI as X5 and X7) in the globular cluster 47 Tuc, from a Chandra ACIS-I observation. X5 demonstrates sharp eclipses with an 8.666 ± 0.008 hr period, as well as dips showing an increased \( N_H \) column. Their thermal spectra are well-modeled by unmagnetized hydrogen atmospheres of hot neutron stars, most likely heated by transient accretion, with little to no hard power law component.

1. Introduction

Many neutron stars (NSs) that have been observed in outburst as soft x-ray transients have also been detected in quiescence (\( L_X \sim 10^{32−34} \) ergs s\(^{-1}\)), for example Cen X-4 and Aquila X-1 (see Campana et al. (1998a) for a review of soft x-ray transients, also known as quiescent low-mass x-ray binaries (qLMXBs). Spectral fits with a soft (kT=0.2-0.3 keV) blackbody (BB) spectrum, often requiring a hard power-law tail of photon index \( \sim 2 \), have been acceptable but imply an emission area of \( \sim 1 \) km radius, smaller than a NS surface.

However, Rajagopal & Romani (1996) and Zavlin et al. (1996) showed that the atmosphere of a NS, due to the strong frequency dependence of free-free absorption, shifts the peak of the emitted radiation to higher frequencies; thus a blackbody fit will derive a temperature that is too high and a radius that is too small. Brown, Bildsten, and Rutledge (1998; BBR) showed that the interior of a transiently accreting neutron star is heated during accretion by pycnonuclear reactions, bringing the interior to a steady state temperature \( \sim 10^8 (\dot{m} / 10^{-10} M_\odot \) yr\(^{-1}\))^0.4 K. This heating leads to an isotropic thermal luminosity between accretion episodes of roughly \( L_q = 6 \times 10^{33} \) ergs s\(^{-1}\)((\dot{m}) / 10^{-10} M_\odot \) yr\(^{-1}\) (BBR). Fits of simulated low magnetic-field (\( B < 10^{10} \) G) hydrogen atmospheres to qLMXBs have given implied \( R_\infty \) of roughly 13 km (\( R_\infty \) is the effective radius seen by a distant observer, \( R_\infty = R/\sqrt{1-2GM/Rc^2} \)), with a power law component in Cen X-4 and Aql X-1 suggested to be linked to continued accretion (Rutledge et al. 2001a, 2001b, Campana et al. 1998b).

The deep ROSAT HRI observation of 47 Tucanae of Verbunt & Hasinger (1998) resolved 5 sources, including X5 and X7, in the central core, but without spectral resolution. With Chandra’s ACIS-I instrument, we have identified 108 sources in the central 2’×2.5’ region, and are able to conduct spectral analysis
on a few dozen of these sources (Grindlay et al. 2001a). X5 has been identified with a $V = 21.6$ counterpart, which shows variability and a blue color indicative of a faint accretion disk, while a tentative upper limit for the counterpart of X7 is $V \sim 23$ (Edmonds et al. 2001). Using $F_V = 10^{\left(-0.4V-5.43\right)}$ (using the 5000-6000 Å range) gives $F_X/F_V$ ratios of 43 and $>166$ respectively, which are typical of LMXB systems rather than CVs (typically $\sim 1$). The likely qLMXBs X5 and X7 have blackbody-like x-ray spectra (see below) which show they are indeed hot NSs.

2. Variability

The *Chandra* X-ray Observatory observed 47 Tucanae on March 16-17, 2000, for 72 ksec (in five contiguous exposures) with the ACIS-I instrument at the focus. We derive luminosities for X5 (including eclipses and dips) and X7 of $L_X(0.5-2.5\text{ keV})=7.4 \times 10^{32}$ ergs s$^{-1}$, $9.0 \times 10^{32}$ ergs s$^{-1}$ respectively, consistent with the ROSAT observations.

The lightcurve of X5 shows significant variability (Figure 1), in particular three clear eclipses and significant dips (99% significance for variability outside eclipses, according to a K-S test). X7 shows no significant variability. The three egresses of X5’s eclipses are quite sharp (less than 20 seconds, see Fig. 1a), whereas the two ingresses show a dip of roughly half the normal flux for $\sim 2000$ seconds before the eclipse. Using the 3.2 s ACIS time resolution for the sharp egresses, a value of 8.666±0.008 hours may be estimated for the period. The eclipse lengths for the second two eclipses are 2482±30 seconds. The dips directly before the eclipses suggest an accretion stream obscuring the NS, while the other dips and concomitant increases in the $N_H$ column are typical of occulting blobs in the edge of an accretion disk, as seen in dip sources. Assuming a 1.4 $M_\odot$ NS and a 0.3 $M_\odot$ secondary (to which the calculation is relatively insensitive), the separation is $1.76 \times 10^{11}$ cm, and the secondary must have a diameter of at least $8.8 \times 10^{10}$ cm to perform the eclipse. The restriction on not filling its Roche
lobe, plus the eclipse duration, give a minimum secondary mass of 0.27 $M_\odot$, for a 90 degree inclination and 1.4 $M_\odot$ primary, regardless of the interior structure of the secondary. The size of X5’s secondary rules out a helium white dwarf, and thus indicates that the secondary is likely to be a main-sequence star.

3. Spectra

We fit the spectra of X5 and X7 in XSPEC, using the unmagnetized hydrogen-atmosphere models of Lloyd, Hernquist, & Heyl (2001, and in these proceedings). The atmospheric plasma was assumed to be completely ionized, and the spectrum due to coherent electron scattering and free-free absorption. Initial fits were made using the surface gravity of a canonical NS, $\log g_s = 14.38$ (appropriate for a 1.4 $M_\odot$, 10 km NS). Magnetic fields up to $10^{13}$ G will not affect these fits in either flux or $T_{eff}$ (Lloyd et al., 2001). We use the pileup formalism of J. Davis (2001) incorporated into XSPEC, since X5 and X7 suffer 9 and 10% pileup, respectively. Photoelectric absorption was a free parameter, using the 47 Tuc metallicity, and a residual feature was modeled with an edge around 0.63 keV (perhaps due to hot gas), reducing $\chi^2$ by 0.3.

The spectra of X5 and X7 along with the H-atmosphere model predictions and the fit residuals are plotted in Figure 2. Both qLMXBs give good fits, $\chi^2 = 0.98$ for 30 degrees of freedom. Unfortunately we cannot meaningfully constrain the radius alone, but do constrain a region in M-R space; details of the spectral fitting and implications for the masses of X5 and X7 are given in Heinke et al. (2002, in preparation). For the range of radii generally assumed for neutron stars (9-14 km), we derive temperatures between 92 and 108 eV, and $N_H = 2.5^{+0.9}_{-0.5} \times 10^{21}$ cm$^{-2}$.

The qLMXBs Cen X-4 and Aql X-1 have generally shown a hard power-law tail, of photon index 1-1.5, dominant above 2 keV. Such a tail is nearly absent from X5 and X7, where a PL of index 1.5 is constrained to supply less than 5% of the flux between 0.5 and 10 keV, in either fit. A similar lack of observable PL

![Figure 2. Data and model hydrogen-atmosphere spectra (with Davis pileup model) of X5 (left) and X7 (right), between 0.5 and 10 keV.](image)
tail has been seen in the qLMXB CXOU 132619.7-472910.8 in ω Cen (Rutledge et al. 2001c), and in NGC 6397 (Grindlay et al. 2001b).

We interpret the lack of a power law and variability as signs that accretion onto the NS surface is held at a very low level or completely stopped. Yet accretion to the disk is clearly continuing in X5, as shown by the dips and blue color of the companion. This paradox may be solved by the thermal/viscous instability if little to no ADAF flow is currently taking place (Dubus et al. 2001 and refs therein). Wijnands et al. (2001) suggest that to explain the low luminosity of KS 1731-260 in quiescence after a decade of active accretion, it must spend hundreds of years in quiescence between outbursts, and postulate a population of qLMXBs with long recurrence times and long outbursts. Perhaps these systems and KS 1731-269 have extremely low disk viscosity, and thus long recurrence times and long outbursts due to greater disk accumulation. Upcoming longer observations with Chandra will further constrain the spectra of these objects.

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