TWO NEUTRON STAR SOFT X-RAY TRANSIENTS IN QUIESCENCE: 4U 2129+47 AND EXO 0748−676

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ABSTRACT

We report on X-ray observations of two soft X-ray transients containing neutron stars, 4U 2129+47 and EXO 0748−676. Our emphasis is on the quiescent properties of these sources. The X-ray spectrum and light curve of the eclipsing low-mass X-ray binary (LMXB) 4U 2129+47 was measured with the ROSAT Position Sensitive Proportional Counter during its current quiescent state. The quiescent X-ray luminosity of $\sim 10^{32.7}$ erg s$^{-1}$ and blackbody temperature $kT \sim 0.21$ keV are similar to other quiescent LMXBs. The quiescent X-ray light curve may show orbital modulation, but the statistics are insufficient to distinguish between a V-shaped partial eclipse (as seen in the high state) or a total square-wave eclipse. The similarity in the luminosity and temperature to other (non-eclipsing) quiescent LMXBs implies that the vertical structure in the disk that blocked our direct view of the neutron star in the high state has collapsed, and the neutron star is seen directly. EXO 0748−676 was serendipitously observed with the Einstein IPC in quiescence before it was discovered as a bright transient with EXOSAT. Our reanalysis of this quiescent observation finds $L_x \sim 10^{34.0}$ erg s$^{-1}$, and blackbody temperature $kT \sim 0.22$ keV, again similar to other LMXBs in quiescence.

Key words: binaries: close — stars: individual (4U 2129+47 = V1727 Cygni, EXO 0748−676) — stars: neutron — X-rays

1. INTRODUCTION

4U 2129+47 and EXO 0748−676 are two low-mass X-ray binaries that undergo high-low transitions in their X-ray flux. Both are viewed nearly edge-on, and their eclipse light curves show evidence of an extended X-ray emission region often called an accretion disk corona (ADC). The source 4U 2129+47 is currently the only ADC source in a low state, and was very well studied in the 1980s, when it was in the high state (McClintock, Remillard, & Margon 1981; McClintock et al. 1982; White & Holt 1982; Thorstensen & Charles 1982; Horne, Verbunt, & Schneider 1986). The source EXO 0748−676 is currently in the high state, but it was serendipitously observed in a low state by the Einstein Observatory before it was discovered as a bright transient source (Parmar et al. 1986).

The optical and X-ray light curves of 4U 2129+47 in the 1970s and 1980s showed a V-shaped partial eclipse, which led to the model of a partial eclipse of an extended X-ray emission region (McClintock et al. 1982). The inclination is believed to be high enough so that the accreting neutron star is not directly visible but is shielded from our view by vertical structure at the outer edge of the accretion disk. The X-rays we observe are only the few percent of those emitted from the vicinity of the neutron star that are scattered into our line of sight by the ADC. EXOSAT observations in 1983 failed to detect the source, and the optical modulation seen previously was also found to be missing (Pietsch et al. 1986). We previously reported on observations of this source in quiescence with the ROSAT HRI, which, although sufficient to detect the source at $L_x \sim 10^{33.0}$ erg s$^{-1}$, could not measure the spectrum or a detailed light curve (Garcia 1994).

EXO 0748−676 was discovered in outburst with EXOSAT (Parmar et al. 1986). While it shows sharp (square wave) eclipses, there is a residual flux of a few percent at the bottom of the eclipse. This residual flux is interpreted as due to an accretion disk corona, which covers a large geometric area and is therefore not fully eclipsed. It was serendipitously observed with the Einstein IPC before it entered the high, discovery state.

Because of their transient nature, 4U 2129+47 and EXO 0748−676 are often referred to as soft X-ray transients (SXTs). Several SXTs have been shown to have mass functions greater than 3 $M_\odot$ and on this basis are considered black holes, or BH SXTs (van Paradijs & McClintock 1995; Tanaka & Shibazaki 1996). Because they show type I X-ray bursts, 4U 2129+47 and EXO 0748−676 clearly contain neutron stars (NSs) and are therefore NS SXTs. Observations of BH SXTs provide good evidence that they accrete via advection-dominated accretion flows (ADAFs; Narayan, McClintock & Yi 1996; Narayan, Barret, & McClintock 1997a), rather than by thin disks, when they are in quiescence. The theoretical basis for ADAFs applies equally well to NS SXTs in quiescence (Yi et al. 1996). Detailed study of the accretion, including the effects of a rotating magnetic field, certainly allow that ADAFs exist in NS SXTs (Menou et al. 1999). Comparison of outburst and quiescent X-ray luminosities in SXTs may have provided evidence for the existence of event horizons in BH SXTs (Narayan, Garcia, & McClintock 1997b; Garcia et al. 1998; Asai et al. 1998). Extending the small sample of objects used in these studies may help to prove (or disprove) this fundamental result; hence, these observations of two NS SXTs in quiescence are of interest.

In addition, these sources are of interest because they offer an opportunity to study the way the structure of the accretion disk and ADC are affected by wide variations in the X-ray flux of the central source. Accretion disk models predict that the both the vertical structure and temperature as a function of radius change dramatically under the influ-
ence of strong X-ray irradiation (Shakura & Sunyaev 1973; Vrtilek et al. 1990), but there are few chances to study its structure (in a single source) over very wide ranges in X-ray luminosity. The ADC is formed as a result of the strong X-ray irradiation (Begelman, McKee, & Shields 1983), and once again there are few opportunities to study its structure (in a wide range) over very wide ranges in X-ray luminosity.

The layout of the rest of this paper is as follows: § 2 introduces the observations and describes the data analysis methods. The results are detailed in the following subsections, beginning with those for the spectrum of EXO 0748 − 676 (§ 2.1), followed by those for the spectrum and light curve of 4U 2129 + 47 (§§ 2.2, 2.3 respectively). Section 3 discusses these results in the context of accepted models for these and other SXTs, concluding with some remarks on how future observatories might be used to answer remaining questions.

2. OBSERVATIONS

EXO 0748 − 676 was serendipitously observed in its low state during a 10 ks observation with the Einstein Observatory in May 1980. The ROSAT Position Sensitive Proportional Counter (PSPC) observed 4U 2129 + 47 in the low state for a total of ∼ 30 ks on 1994 June 3, and these data were processed with the standard SASS pipeline. Both data sets were analyzed using IRAF/PROS version 2.3.1 and XSPEC version 10.0. Poisson weighting of the errors (Gehrels 1986) was used. The results from PROS and XSPEC were found to be consistent. When necessary, we grouped the data in larger energy bins to maintain the number of counts per bin at more than 9. Previous studies have shown that under these conditions, the results from Poisson weighting of \( \chi^2 \) fitting are consistent with those from maximum likelihood methods (Narayan et al. 1997a).

To guide our extraction of the source counts from the images, we first generated the azimuthally averaged radial profile of counts centered on the sources. For 4U 2129 + 47 we found that a 0.5 radius extraction maximized the signal-to-noise ratio (S/N). For EXO 0748 − 676, we found that a 2' radius extraction maximized the S/N. For both sources the background was determined from a larger annulus around the source.

For both sources, we found that a variety of simple models (Raymond-Smith thermal, bremsstrahlung, blackbody, power law) yielded equally acceptable fit results. As our main interest in the spectral fitting is to derive quiescent luminosities, to allow comparisons between NS and BH luminosity swings (see, e.g., Narayan et al. 1997b or Asai et al. 1998), we limit ourselves below to simple blackbody fits and compute unabsorbed luminosities over the 0.5–10 keV range. We note that the computed luminosities are insensitive to the exact form of the spectrum; for example, using a bremsstrahlung spectrum results in only 10% changes in the luminosities.

2.1. EXO 0748 − 676 Quiescent Spectrum

Approximately 70 source counts extracted from the IPC image were fitted to a variety of simple spectral models. The best-fit blackbody parameters are \( kT = 0.14 \text{ keV} \) and \( N_H = 10^{21.5} \text{ cm}^{-2} \). The very low number of counts allow a wide range in acceptable parameters. To limit the parameter space, we restrict ourselves to \( N_H = 10^{21.5} \text{ cm}^{-2} \) (which is within the allowed range). This is the value predicted by the relation of Predehl & Schmitt (1995), given the optical reddening of \( E(B - V) = 0.42 \pm 0.03 \) (Schoembs & Zoeschinger 1990). We then computed the confidence regions for temperature and emitted (unabsorbed) luminosity, as shown in Figure 1. The best-fit blackbody temperature and 0.5–10.0 keV luminosity, assuming a distance of 10 kpc (Parmar et al. 1986), are

\[
kT = 0.22^{+0.14}_{-0.16} \text{ keV}, \quad L_X = 1.0^{+0.5}_{-0.2} \times 10^{34} \text{ ergs s}^{-1}.
\]

These results are fairly insensitive to the value of \( N_H \) assumed, in that a 50% increase results in only a 15% decrease in best-fit temperature and a 20% increase in the emitted 0.5–10.0 keV luminosity. This energy band contains at least 70% of the bolometric luminosity at the best-fit temperature. At the lowest temperatures allowed by the 90% confidence interval (Fig. 1), this band contains only 30% of the bolometric luminosity.

The effective radius of this possible blackbody emitter \( [R = (L_{bol}/4\pi kT^4)^{1/2}] \) is \( R = 8.2^{+12}_{-17} \) km, comparable to the radius of a neutron star.

2.2. 4U 2129 + 47 Quiescent Spectrum

Various simple models (as above) yield acceptably good fits to the ∼ 200 source counts extracted from the image, and the fit statistics show no preference for one model over any other. The best-fitting blackbody model has \( kT = 0.18 \) keV and \( N_H = 10^{21.5} \text{ cm}^{-2} \). As with EXO 0748 − 676, we fix the absorption at the optically determined value (which is within the fit range) to reduce the allowed parameter range.

The optical extinction has been found to be \( A_V = 0.9 \) (Cowley & Schmidtke 1990), which corresponds to \( N_H = 10^{21.2} \text{ cm}^{-2} \) (Predehl & Schmitt 1995). We then computed the confidence regions for temperature and emitted (unabsorbed) luminosity, as shown in Figure 2. The best-fit blackbody temperature and 0.5–10.0 keV luminosity, assuming a distance of 6.3 kpc (Parmar et al. 1986), are

\[
kT = 0.21^{+0.04}_{-0.03} \text{ keV}, \quad L_X = 5.3^{+0.8}_{-1.0} \times 10^{32} \text{ ergs s}^{-1}.
\]

We note that this \( A_V \) is measured to the F7 IV counterpart of 4U 2129 + 47, which is clearly not the secondary transferring mass to the neutron star. In using this \( A_V \) and a spectroscopic distance of 6.3 kpc (Cowley & Schmidtke

![Figure 1.](image-url)

**Figure 1.** The \( \chi^2 \) grid for blackbody spectral fits to the IPC data on EXO 0748 − 676 in quiescence, using Poisson (Gehrels 1986) weighting. The plus sign corresponds to the best-fit value. The 68% and 90% confidence regions are shown. The source distance is assumed to be 10 kpc, and the absorption has been fixed at \( N_H = 10^{21.35} \text{ cm}^{-2} \), corresponding to the optical reddening \( E(B - V) = 0.42 \).
1990), we are implicitly assuming that this star is in the physical proximity of the mass-transferring binary (Thorstensen et al. 1988; Garcia et al. 1989; Cowley & Schmidtke 1990; van Paradis & McClintock 1995).

Once again, these results are fairly insensitive to the value of $N_H$ assumed, in that a 50% increase results in only a 10% drop in best-fit temperature and a 40% increase in the emitted bolometric luminosity. The 0.5–10.0 keV band contains ~80% of the bolometric luminosity at the best-fit temperature, and ~70% at the lowest allowed temperature.

The effective radius of this possible blackbody emitter [\( R = \left( \frac{L_{bol}}{4\pi \sigma T^4} \right)^{\frac{1}{2}} \)] is \( R = 1.7^{+0.5}_{-0.6} \) km, substantially smaller than the radius of a neutron star.

We previously reported the quiescent ROSAT HRI flux (Garcia 1994), assuming the spectral parameters measured in the high state. This overestimates the flux by a factor of 2. When the softer quiescent spectrum determined above is used, we calculate an emitted luminosity (0.5–10.0 keV) of \( 9.7 \times 10^{38} \) erg s\(^{-1}\). The 68% confidence bounds on the PSPC spectrum correspond to a ~20% uncertainty in the calculation of the HRI flux. Thus it appears that the source has faded by a factor of ~2 during the 2.5 yr interval between the HRI and PSPC observations.

2.3. 4U 2129 + 47 Quiescent Light Curve

We generated the quiescent light curve of 4U 2129 + 47 (Fig. 3) by binning the background-subtracted PSPC data into seven bins based on the McClintock et al. (1982) ephemeris. Two other light curves are plotted in Figure 3: the scaled on-state light curve reextracted from the IPC CD-ROM archive, and a square-wave light curve with an eclipse width of 0.1. The eclipse duration of this last light curve is about half the width of the high-state eclipse, which is what one expects if the X-ray source was a point (rather than extended) source.

To determine whether the observed low-state light curve was well described by either the square-wave or the scaled on-state light curve, we calculated \( \chi^2 \) for each of these. The trial light curves were first artificially binned to match the sampling of the observed (seven-bin) light curve. For the scaled on-state light curve, we calculate a reduced \( \chi^2 \) for 6 degrees of freedom of \( \chi^2/\nu = 0.53 \) (80% random probability), and for the square wave we find \( \chi^2/\nu = 1.7 \) (10% random probability). Clearly, either trial light curve is an acceptable representation of the observations, although the scaled on-state light curve may be somewhat favored.

Given the limited statistics, one might reasonably ask if any source variability has been formally detected at all. Testing the seven-bin light curve against a steady source, we find \( \chi^2/\nu = 1.2 \), clearly allowing that the source is steady. However, two other tests provide evidence that some sort of an eclipse still occurs in the quiescent state.

First, we have cross-correlated the observed seven-bin light curve against the scaled on-state curve to determine the phase of minimum light. The best-fit phase and 68% confidence limits are \( 0.0 \pm 0.2 \) on the ephemeris of McClintock et al. (1982). The accumulated error in the ephemeris is \( \pm 0.1 \), so, while the present data agree with this ephemeris, they are not able to refine it. Given the large error in the determination of phase zero, this provides only weak evidence for an eclipse.

Second, we realized that if the quiescent light curve mimics that during the on state, a more nearly optimal binning scheme would use fewer bins. We therefore binned the data into four equal bins, one of which is centered on the eclipse phase. Testing this more coarsely binned light curve against a steady source, we find \( \chi^2/\nu = 3.3 \), which has a random probability of only ~2% for a steady source. In addition, the minimum of this binned light curve occurs at the expected phase of eclipse, which has a random probability of one in four. This provides somewhat stronger evidence that an eclipse may still be occurring at phase zero.

3. DISCUSSION

A glance at Figure 3 shows that the quiescent light curve appears similar to a scaled version of the outburst light curve. However, the statistics are poor, and the light curve binned into seven phase intervals is formally consistent with a steady source, a square wave (eclipse), or a scaled version of the on-state light curve. Similarly, our analysis of ROSAT HRI data obtained ~2.5 yr before these data also
is consistent with a steady source, but the flux is about twice that found with the PSPC.

There is one other possible difference between the HRI and PSPC results. The count rates in the HRI data are highest near eclipse (see Fig. 1 of Garcia 1994), while the rates in the PSPC data are lowest near eclipse. Statistical tests show that the PSPC data are consistent with a scaled version of the on-state light curve, while the HRI data are only marginally consistent with a scaled version of the on-state light curve (Garcia 1994). This hints that the light curve may have changed shape, which might not be surprising given that the flux level changed by a factor of ~2 between the observations. However, we stress that this indication is marginal, and both data sets are consistent with steady sources.

During quiescence, the eclipse (square wave) light curve is what one expects based on the standard models of the system. At this low luminosity, the ADC should have collapsed (White & Holt 1982; Begelman et al. 1983), and the secondary should eclipse the X-ray emission from the neutron star for ~10% of the orbit. A smoothly modulated light curve (similar to a scaled version of the on-state light curve) would be hard to understand, as it would imply that the structure of the accretion disk has not changed and the ADC is still present despite the observed large change in X-ray luminosity and, presumably, mass transfer rate. The observed light curve provides marginal evidence against the standard models, as the scaled on-state light curve is a marginally better fit than the expected eclipse light curve, and binning, which is more nearly optimal for the on-state light curve, provides stronger evidence for variability. However, the fact that the quiescent luminosity is similar to other NS SXTs and is not lower by a factor of ~100, as would be expected if we detected only flux scattered in the ADC, provides a strong indication that the NS is seen directly.

In the high state, the modulation of the X-ray flux was accompanied by a strong modulation of the optical flux. What optical modulation should we expect given the apparent modulation in the low-state X-ray flux? To answer this question, we need an estimate of the quiescent disk V magnitude, which we make by comparing 4U 2129+47 with Cen X-4. This SXT also contains an NS primary, and the quiescent disk has been measured to have an absolute magnitude $M_V \approx 9$ (McClintock & Remillard 1990). The disk in Cen X-4 may be somewhat larger than that in 4U 2129+47, because of its longer period (15.1 hr), and also may appear somewhat brighter because of its more face-on viewing angle ($i \approx 40°$; Shahbaz, Naylor, & Charles 1993). Based on the amplitude of the optical modulation in outburst (McClintock et al. 1981) and the correlation between modulation and inclination (van Paradijs, Van der Klis, & Pedersen 1988), the inclination of 4U 2129+47 is likely to be $i \geq 80°$. The differences in the period and inclination would lower our estimate of the absolute magnitude of the quiescent disk in 4U 2129+47 by several magnitudes, based on the correlations found in cataclysmic variables (i.e., eqs. [2.63] and [3.3] from Warner 1995). Thus $M_V \approx 9$ is a comfortable lower limit to the quiescent disk in 4U 2129+47. At the 6.3 kpc distance of 4U 2129+47, and with $A_V = 1.5$, this disk would have $V \approx 24.5$. The quiescent counterpart has $V = 17.9$, so even if the disk were 100% modulated we would expect a fractional modulation of only ~0.2%, which is well below the observed limit of 1.2% amplitude (99% confidence; Thorstensen et al. 1988).

### 3.1. Comparison with Other Quiescent SXTs

The X-ray temperatures of ~0.2 keV that we find for these two SXTs in quiescence are similar to those found for other NS SXTs (Verbunt et al. 1994; Asai et al. 1996; Asai et al. 1998 and references therein). The luminosity of 4U 2129+47 is also similar to that found in these sources, but EXO 0748−676 is at the extreme high end of the distribution (Narayan et al. 1997b). There is no obvious reason for this; in particular, the orbital period of EXO 0748−676 is typical, so the average mass transfer rate should be typical as well (Menou et al. 1999). Given the observed variability of quiescent NS SXTs (Campana et al. 1997), it is possible that the single quiescent measurement caught this system in a particularly luminous state.

The emitting radius we compute assuming a blackbody spectrum is smaller than an NS in the case of 4U 2129+47. Blackbody fits often indicate emitting areas smaller than an NS surface, indicating either that the accretion is channeled onto a small fraction of the NS surface (Asai et al. 1996; Menou et al. 1999) or that the blackbody spectral fits erroneously indicate a small surface area (Rutledge et al. 1999). EXO 0748−676 is unusual in that the blackbody radius is consistent with the entire NS surface, because of the larger than typical luminosity in quiescence.

In summary, we note that the difference in the luminosity swings of outbursting and quiescent SXTs may indicate the existence of event horizons in BH SXTs (Narayan et al. 1997b; Garcia et al. 1998; Asai et al. 1998; Menou et al. 1999; but see Chen et al. 1998 for an opposing view). Observations with Chandra (formerly AXAF) and XMM will undoubtedly add more SXTs to the studied sample, and push upper limits lower, helping to more definitively test this difference. XMM may allow an accurate measurement of the quiescent light curve of the eclipsing NS SXT 4U 2129+47, therefore providing a spatially resolved picture of an ADC in a quiescent system.

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