X-ray Emission from 4U2129+47 (=V1727 Cyg) in Quiescence

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ABSTRACT

Observations with the ROSAT HRI allow detection of weak x-ray flux from the low-mass x-ray binary (LMXB) 4U2129+47 during its current quiescent state. The quiescent luminosity is similar to that seen in several other quiescent LMXB containing neutron stars. The quiescent x-ray light curve may not show the eclipse seen when the source was in its high state, which may indicate that the enhanced vertical structure present in the disk during the high state has collapsed. This in turn may provide support for the idea that the vertical structure in LMXB accretion disks is a consequence of high x-ray luminosity. A comparison of the absorption of low energy x-rays due to the interstellar medium (determined from Einstein IPC observations) and the optical extinction does not rule out the triple system hypothesis.

Subject headings: X-ray Binaries

1. Introduction

4U2129+47 is an unusual low-mass x-ray binary (LMXB) is several respects. For example, it is one of the three (along with Cyg X-3 and 4U1822-37) binaries which originally defined the accretion disk corona class (White and Holt 1982), is possibly a triple system, and is a transient x-ray source. X-ray and optical observations obtained in the 1970s and early 1980s led to a model for 4U2129+47 consisting of a 5.24 hour binary containing a neutron star accreting matter from a late-type (K-M) dwarf companion. The partial x-ray eclipse implies the system is viewed at very high inclination ($\sim 80^o$, McClintock *et al.* 1982) and has an extended x-ray emission region (an "accretion disk corona" or ADC, White and Holt 1982, McClintock *et al.* 1982). At this very high inclination 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 do observe are only the few percent of those emitted from the neutron star which are scattered into our line of sight by the ADC.

In the early 1980s the system entered a quiescent phase. X-ray observations failed to detect the source, and the previously observed optical variability also disappeared. A search of archival plates revealed that the system underwent a similar quiescent phase ~ 50 years previously (Wenzel, 1983a,b). Optical observations in the current quiescent phase have found an F7 sub-giant (Garcia *et al.* 1989, Cowley and Schmidtke 1990) instead of the late K-M dwarf expected. In addition, the expected ellipsoidal and radial velocity variations at the 5.24 hour period were not found, but instead long term (several months) low amplitude radial velocity variations were discovered (Thorstensen *et al.* 1988, Garcia *et al.* 1989, Garcia 1992). These unexpected observations led many authors to speculate that 4U2129+47 is a triple system, with the F7 IV star being the outer member (Thorstensen *et al.* 1988, Garcia *et al.* 1989, Cowley and Schmidtke 1990, van Paradijs and McClintock 1993).

The detection of x-ray emission in quiescence, which we report on below, also provides some unexpected results. In particular, the x-ray light curve and luminosity found with the ROSAT HRI provide support for the idea that the accretion disk structure has changed dramatically. The vertical structure at the outer edge of the disk may have collapsed, allowing us to see x-rays directly from the central neutron star instead of just those scattered off the ADC. We also present a re-analysis of previously reported Einstein x-ray observations, which allow a comparison of the optical extinction and low energy x-ray absorption due to the interstellar medium.

2. OBSERVATIONS

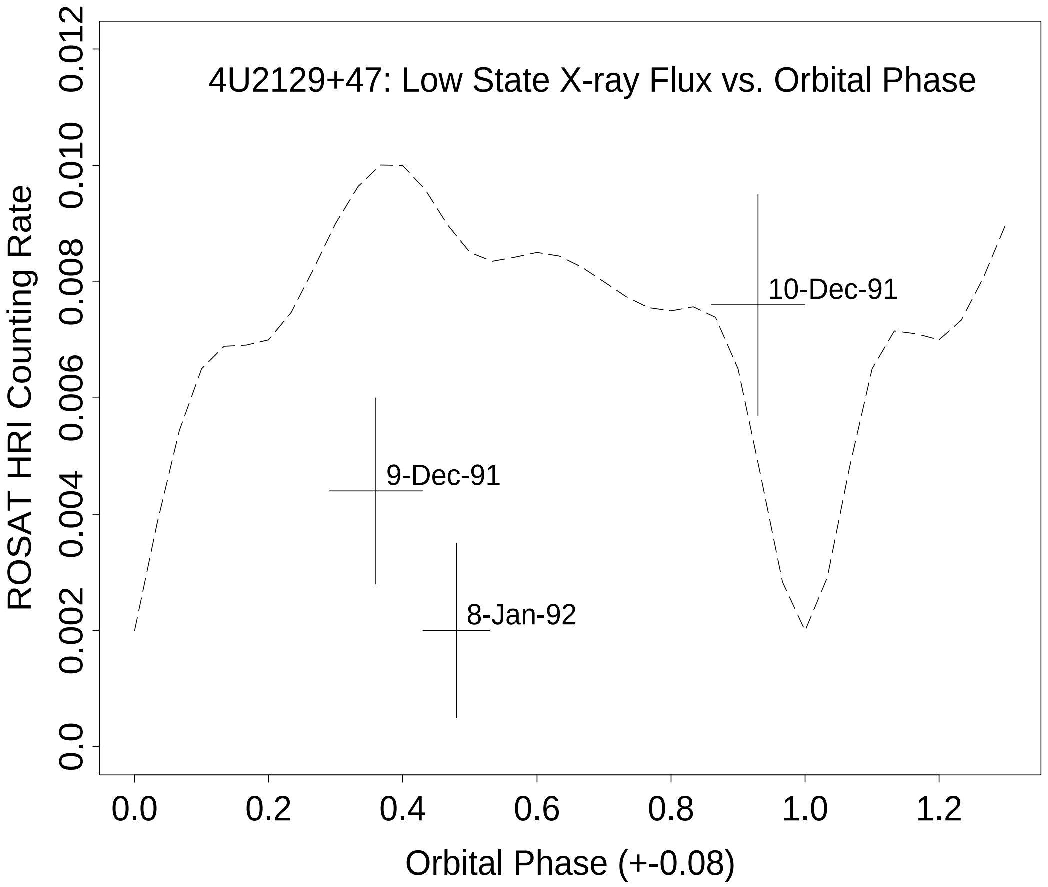
2.1. ROSAT HRI Observations:

ROSAT HRI observations of the field centered on 4U2129+47 were obtained during December 1991 and January 1992. During the approximately 7000 seconds total integration time, 48 photons were detected in a $20''$ radius source circle centered near the position of V1727 Cyg. The centroid of the x-ray events is $7.7'' \pm 2''$ from the optical position of V1727 Cyg (Thorstensen *et al.* 1988), but given the HRI boresighting errors (Zombeck 1992) the positions are consistent. As the expected number of background counts in the source circle is 11.4, the source is detected at high significance ($\sim 10\sigma$). In order to convert the observed counting rate to flux, and to facilitate comparison with previous work, we assume a power law spectrum with an energy index of 1.0 and $N_H = 5 \times 10^{21}\mathrm{cm}^{-2}$ (Pietsch *et al.* 1986, White and Holt 1982). The observed flux in the $0.3 - 2.4$ keV band is then $2.3 \pm 0.4 \times 10^{-13}$ erg cm^{-2} s^{-1}, corresponding to an emitted (unabsorbed) flux of $7.5 \pm 1.4 \times 10^{-13}$ erg cm^{-2} s^{-1}. The 2 sigma upper limit found with the EXOSAT CMA (Pietsch *et al.* 1986) of 1.1×10^{-3} c s^{-1}corresponds to an observed 0.3-2.4 keV flux of 16×10^{-13} erg cm^{-2} s^{-1}. Thus we see that the ROSAT detection is a factor of ~ 7 below the upper limit from EXOSAT, and a factor of ~ 100 times below the average Einstein IPC flux in June 1980 of $240 \pm 10 \times 10^{-13}$ erg cm^{-2} s^{-1}(as observed in the $0.3 - 2.4$ keV band). Pietsch *et al.* note that the mean flux from 4U2129+47 was on average higher in the 1970s than 1980s, dropping by nearly a factor of 10 between observations with UHURU and Einstein (see their Figure 3). This indicates that the current flux from 4U2129+47 is a factor of ~ 1000 below that at which the source was originally detected with URUHU. The conversion from ROSAT HRI and EXOSAT CMA count rate to observed 0.3-2.4 keV flux is relatively insensitive to the assumed spectral shape, while the conversion to the emitted (unabsorbed) flux is more sensitive to the assumed shape. Varying the assumed power law slope by ± 1 and the assumed N_H by $\pm 50\%$ results in changes in the observed flux of $< 25\%$, but changes in the emitted flux of up to 100%. Comparison of the CMA, IPC and HRI fluxes to the flux in the higher energy band of UHURU is further complicated non-overlapping energy ranges and possible changes in the spectral shape with flux, but assuming the spectrum above indicates that the equivalent $0.3 - 2.4$ keV observed flux in the early 1970s was $\sim 2000 \times 10^{-13}$ erg cm^{-2} s^{-1}.

The ROSAT HRI observation of 4U2129+47 took place in three separate ~ 2500 sec intervals spanning 1 month. In Figure 1 we show the HRI background subtracted counting rate in each of these 3 intervals vs. the orbital phase, computed from the ephemeris of McClintock *et al.* 1982 ($T_o = 2,444,403.7429(\pm 0.0021) + 0.2182579(\pm 0.0000008)$). The vertical bars are the 1σ errors, and the horizontal bars span the beginning to end of each observation interval. For reference we also show the approximate shape of the high-state

X-ray lightcurve, as determined with the *Einstein* IPC in 1980 (McClintock *et al.* 1982). The highest point in the HRI lightcurve spans phases $0.86 - 0.01$, which covers the first half of the eclipse seen in the high-state light curve. The uncertainty in the orbital period accumulates to an uncertainty in the orbital phase of ± 0.08 at the time of the ROSAT HRI observations. If this uncertainty is subtracted from the computed phases the highest point in the HRI lightcurve spans phases $0.78 - 0.93$, which are immediately before the eclipse. However, we note that two other authors (Horne *et al.* 1986; Cowley and Schmidtke 1990) have found that **adding** 0.05 to the nominal phases is indicated by data obtained in 1981 and 1988 (respectively). Adjusting our phases in the same manner would place the high point in the HRI light curve squarely in the center of the high-state eclipse, and would therefore provide the strongest evidence that the low-state lightcurve does not show the eclipse seen in the high state.

Fig. 1.— Background subtracted X-ray counting rate as measured with the ROSAT HRI



2.2. Einstein X-ray Spectra

During its x-ray bright phase in early 1980 4U2129+47 was observed with a variety of instruments on the Einstein Observatory, including the IPC, MPC, HRI, and SSS. Previous reports of the IPC observations of 4U2129+47 pre-dated the Einstein IPC Rev 1B processing and did not include spectral fits to the data. We have extracted the June 1980 IPC data from the IPC Event List CD-ROMs (Prestwich *et al.* 1992) and fitted a variety of simple models to the data with the help of the IRAF/PROS analysis package. Fits to interstellar absorption plus one of thermal bremsstrahlung, power law, and Raymond-Smith models all produced acceptable ($\lesssim 1$) χ^2/ν. Fits to a black-body with interstellar absorption resulted in an unacceptable $\chi^2/\nu > 2$. The 90% confidence regions for the acceptable fits are shown below in Table 1. The 90% confidence regions for N_H vary slightly with each acceptable fit, but the union of all allowed IPC regions restricts $4.0 \times 10^{21}\mathrm{cm}^{-2} < N_H < 10.5 \times 10^{21}\mathrm{cm}^{-2}$. Fits to the same models for the simultaneously obtained MPC also yielded $\chi^2/\nu \sim 1$, and the corresponding confidence regions are show in Table 1.

By jointly fitting the IPC and MPC data to a single model one may derive more stringent confidence regions to the fit parameters. Fits of this joint dataset to the simple models above yielded uniformly unacceptable results ($\chi^2/\nu > 3$). This is perhaps not surprising given the lack of intersection in the confidence intervals for temperature and slope. Fits to multiple component (ie, Black-Body + Bremsstrahlung) spectra yielded reduced $\chi^2/\nu \sim 2$, but given the limited energy resolution of the IPC+MPC and the known complex nature of LMXB spectra, such fits are of limited diagnostic value. The fits were not significantly improved by varying the relative IPC and MPC normalization by the 14% offset found by Masnou *et al.* 1992.

Table 1: IPC and Spectral Fit Results and 90% Confidence Intervals

Instrument	Model	$N_H \times 10^{21}(\mathrm{cm}^{-2})$	kT(keV), α
IPC	Power Law	5.5-10.5	1.6-3.0
IPC	Bremss	4.5-7.9	0.8-1.8
IPC	R-S	4.0-6.3	1.4-2.3
MPC	Power Law	< 6.0	0.8-1.2
MPC	Bremss	< 1.6	6.6-9.4
MPC	R-S	< 3.0	4.6-6.2

3. DISCUSSION

The detection of x-ray flux from 4U2129+47 in quiescence is rather confusing when considered in the context of the well supported model developed when the source was brighter. Given that the neutron star is hidden from direct view by vertical structure in the outer edge of the accretion disk and the x-ray flux observed in the high-state is scattered off an ADC, we would expect NO x-ray flux once the luminosity from the central neutron star fell below well below L_{Edd}. This is because models for ADC (Begelman *et al.* 1983, White and Holt 1982, Raymond 1993) typically require an illuminating flux near L_{Edd}, and once this flux drops sufficiently the corona is no longer evaporated from the surface of the accretion disk. We therefore expect 4U2129+47 not to have and ADC during quiescence. If an ADC is still present, it may indicate that mechanisms other than X-ray heating (ie, magnetic fields, Stella and Rosner 1984; or convective currents, Cannizzo and Cameron 1988) are important at low x-ray flux levels.

Alternatively, if the vertical structure in the edge of the accretion disk has collapsed during this low-state, we may now be viewing the central neutron star directly. While the quiescent x-ray lightcurve provides incomplete phase coverage and is of limited statistical accuracy, there is an indication that the eclipse at phase zero seen in the on state is missing. A change in the shape of the lightcurve would indicate that the geometry of the x-ray emitting region has changed substantially in the low state.

The standard α-disk model of Shakura and Sunyeav (1973) is based on an accretion disk that is thin, with thickness less a few percent of the radius, and holds that the disk will be concave, that is that the vertical structure will flare at large radii (Petterson 1983). Studies of LMXB x-ray light curves make it clear that accretion disks are not always thin, but can have half angles of up to ~ 20 degrees (Mason 1987). Evidence for such enhancements in the vertical structure of cataclysmic variables (CVs) is largely lacking, but this might be a selection effect caused by the fact that the bright x-ray source which allows us to see dips in LMXB is lacking (Mason 1987). The cause of the vertical structure is not clear, but Petterson (1983) points out that the standard model does not account for the effects of x-ray illumination on the outer disk, which will dominate the energy balance of the outer disk for a typical LXMB with $L_x > 10^{36}$ erg s^{-1}. This will not be the case in CVs which typically have $L_x < 10^{33}$ erg s^{-1}. Frank, King and Lasota (1987) suggest that the vertical structure in LMXB disks occurs not at the outer edge, but nearer to the central source where the effects of ionization from the large x-ray flux become important. Once again, such an effect would not occur in CVs, suggesting that their disks are indeed thin. The possible change in the lightcurve of 4U2129+47 in quiescence lends support to the idea that LMXB accretion disks are thick as a result of strong x-ray illumination of the disk.

There are a handful of transient LMXB that have been detected in quiescent or low states. Of these, several that are believed to contain neutron stars (on the basis of Type 1 x-ray bursts) have been detected at quiescent luminosities of $10^{33} - 10^{34}$ erg s^{-1}(Verbunt *et al.* 1993). The low-state luminosity of 4U2129+47, assuming a distance of 6.3 kpc (Cowley and Schmidtke 1990), is $\sim 3.6 \times 10^{33}$ erg s^{-1}(0.3-2.4 keV), which is commensurate with these other sources. This low state luminosity is likely due to continued accretion rather than a cooling neutron star (van Paradijs *et al.* 1987). In these sources the central neutron star is not shielded from view, so the similarity in the quiescent flux of 4U2129+47 to these sources lends support to the idea that the neutron star in 4U2129+47 is no longer shielded from view.

We do not expect detectable levels of X-ray emission from the F7IV star or the presumed M-dwarf companion to the neutron star. The low-state luminosity of 4U2129+47 is many orders of magnitude above the $\sim 5 \times 10^{28}$ erg s^{-1}typical of isolated F stars (Serio 1985). The companion to the neutron star is expected to be rapidly rotating and therefore might have enhanced coronal emission, but the maximum luminosity from even rapidly rotating K-dwarfs does not exceed 10^{30} erg s^{-1}(Eracleous 1991).

A number of authors have suggested that 4U2129+47 may be a triple system, with the 5.24 hour binary forming the inner members, and the currently observed F7 IV star as the outer member. A check on the triple hypothesis can be made by comparing the ISM absorption (N_H) measured in the x-ray band with the ISM absorption (A_V^{opt}) measured in the optical band. The empirical relation of Hieles, Stark and Kulkarni (1981) allows us to compute the optical absorption expected from the x-ray measurements, A_V^{x-ray}. The allowed range in N_H for 4U2129+47 (Section 2) corresponds to $2.9 < A_V^{x-ray} < 7.5$, which should be compared to the $A_V^{opt} \sim 0.9$ measured to the F7IV star (Cowley and Schmidtke 1990). Thus it appears there is an excess absorption to the x-ray source of $2.0 < A_V^{excess} < 6.6$, raising the possibility that the F7 IV counterpart is a foreground line-of-sight interloper.

However, LXMB in general show more absorption in the x-ray flux than predicted by the optical extinction, apparently due to excess absorption of x-rays within the binary. For example, Vrtilek *et al.* 1991 have compared the A_V^{x-ray} as measured with the Einstein OGS with the A_V^{opt} measured for 11 LMXB, and find that $A_V^{X-RAY} > A_V^{opt}$. For the 10 LMXB in their Table 4 with secure optical identifications (we have excluded GX17+2) we compute a mean and dispersion on the average "excess" absorption of each object $A_V^{excess} = A_V^{x-ray} - A_V^{opt}$ of 2.0 ± 1.3. Thus we see that the range of A_V^{excess} allowed for 4U2129+47 includes the range typically seen in LMXB, therefore not ruling out the triple hypothesis.

Other LMXB in low states (ie, Cen X-4 and Aql X-1) show indications of an accretion disk in the optical spectrum (H Balmer, HeII emission) during the low state while V1727 Cyg does not. This is likely because of the additional light from the F7 star swamps that from the low state accretion disk. The expected optical magnitude of the accretion disk during the low state can be computed using the relation of van Paradijs and McClintock

(1993). At $M_V = 6.1$, it is ~ 3 magnitudes lower than the F7IV star, indicating that the disk would not be detectable in the optical spectra (as observed).

4. Summary

Quiescent x-ray emission at a level ~ 1000 times below maximum seen in the early 1970s has been detected from 4U2129+47. This is not unexpected when compared to other LMXB (ie, Cen X-4, Aql X-1, EXO 0748-67) which have been seen at similar flux levels during "quiescence". However, detection of this x-ray emission is somewhat confusing when considered in the context of the geometric picture of 4U2129+47 which was constructed when the source was in the high state. The apparent disappearance of the eclipse previously seen in the high state may indicate that the vertical structure in the edge of the disk has collapsed in the x-ray low state.

Future X-ray observations (ie, with ROSAT and/or ASCA) may help clarify the low-state model for 4U2129+47. A detailed low-state X-ray lightcurve and X-ray spectrum would help to determine the structure and physical conditions of the x-ray emitting region. A more accurate measurement of the A_V^{x-ray} should be possible with ASCA, and might allow a more powerful test of the triple hypothesis.

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