THE ASTROPHYSICAL JOURNAL, 435:407–410, 1994 November 1

X-RAY EMISSION FROM 4U 2129+47 (=V1727 CYGNI) IN QUIESCENCE

MICHAEL R. GARCIA
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02139. Email: garcia@cfa.harvard.edu
Received 1994 March 4; accepted 1994 May 6

ABSTRACT

Observations with the *ROSAT* HRI allow detection of weak X-ray flux from the low-mass X-ray binary (LMXB) 4U 2129+47 during its current quiescent state. The quiescent luminosity is similar to that seen in several other quiescent LMXBs containing neutron stars. The quiescent X-ray light curve may not show the eclipse seen when the source was in its high state, which would indicate that the enhanced vertical structure present in the disk during the high state has collapsed. This in turn provides 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: accretion, accretion disks — binaries: eclipsing — stars: individual (V1727 Cygni) — X-rays: stars

1. INTRODUCTION

The object 4U 2129+47 is an unusual low-mass X-ray binary (LMXB) in several respects. For example, it is one of the three (along with Cyg X-3 and 4U 1822+37) binaries which originally defined the accretion disk corona class (White & 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 4U 2129+47 consisting of a 5.24 hr 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 ($\sim 80°$; McClintock et al. 1982) and has an extended X-ray emission region (an "accretion disk corona" or ADC; White & Holt 1982; McClintock et al. 1982). At this very high inclination, the accreting neutron star is not directly visible, but, rather, 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, observations with the *EXOSAT Observatory* found that the system had entered a quiescent phase. These observations failed to detect the source, and the previously observed optical variability also disappeared (Pietsch et al. 1986). A search of archival plates revealed that the system underwent a similar quiescent phase ~ 50 yr previously (Wenzel 1983a, b). Optical observations in the current quiescent phase have found an F7 subgiant (Garcia et al. 1989; Cowley & Schmidtke 1990) instead of the late K–M dwarf expected. In addition, the expected ellipsoidal (Thorstensen et al. 1988) and radial velocity variations at the 5.24 hr period were not found, but instead long-term (several months) low-amplitude radial velocity variations were discovered (Garcia et al. 1989; Garcia 1992). These unexpected observations led many authors to speculate that 4U 2129+47 is a triple system, with the F7 IV star being the outer member (Thorstensen et al. 1988; Garcia et al. 1989; Cowley & Schmidtke 1990; van Paradijs & McClintock 1994). Optical observations in 1992 August show that the source was still faint (Molnar & Neely 1992), indicating that the *ROSAT* observations reported herein occurred during quiescence.

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 reanalysis 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 4U 2129+47 were obtained during 1991 December and 1992 January (ROR number rh400002). During the approximately 7000 s of 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 count rate to flux, and to facilitate comparison with previous work, we assume a power-law spectrum with an energy index of 1.0 and $N_H = 5 \times 10^{21}$ cm^{-2} (Pietsch et al. 1986; White & Holt 1982). The observed flux in the 0.3–2.4 keV band is then $2.3 \pm 0.4 \times 10^{-13}$ ergs cm^{-2} s^{-1}, corresponding to an emitted (unabsorbed) flux of $7.5 \pm 1.4 \times 10^{-13}$ ergs cm^{-2} s^{-1}. The 2 σ upper limit found with the *EXOSAT* CMA (Pietsch et al. 1986) of 1.1×10^{-3} counts s^{-1} corresponds to an observed 0.3–2.4 keV flux of 16×10^{-13} ergs 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 1980 June of $240 \pm 10 \times 10^{-13}$ ergs cm^{-2} s^{-1} (as observed in the 0.3–2.4 keV band). Pietsch et al. note that the mean flux from 4U 2129+47 was on average higher in the 1970s than 1980s, dropping by nearly a factor of

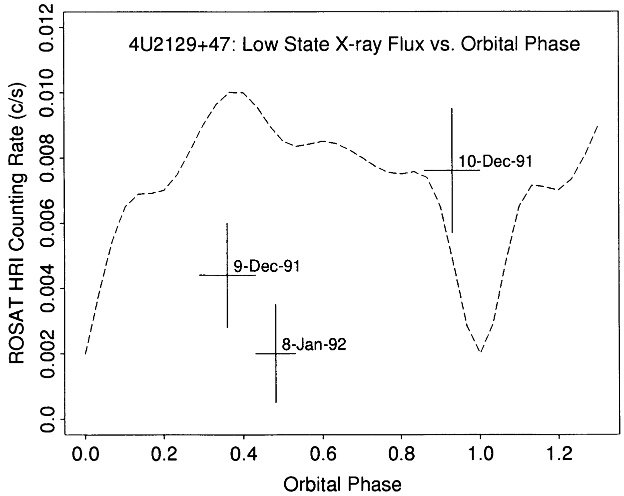

FIG. 1.—The three crosses show the background-subtracted X-ray count rate as measured with the *ROSAT* HRI. The horizontal extent of the crosses indicates the start and stop time for each observation, and the vertical extent is the 1 σ error bar. The dotted line represents the light curve as seen during the high state from McClintock et al. (1982). Based on extrapolation of the McClintock et al. ephemeris, the orbital phases of the *ROSAT* data points are accurate to ± 0.08.

10 between observations with *Uhuru* and *Einstein* (see their Fig. 3). This indicates that the current flux from 4U 2129+47 is a factor of $\sim$1000 below that at which the source was originally detected with *Uhuru*. 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 by nonoverlapping 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 $\sim 2000 \times 10^{-13}$ ergs cm^{-2} s^{-1}.

The *ROSAT* HRI observation of 4U 2129+47 took place in three separate $\sim$2500 s intervals spanning 1 month. In Figure 1 we show the HRI background subtracted counting rate in each of these three intervals versus the orbital phase, computed from the McClintock et al. (1982) orbital ephemeris [T_0 = 2,444,403.7429($\pm$0.0021) + 0.2182579($\pm$0.0000008)]. The vertical bars are the 1 σ 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 light curve, as determined with the *Einstein* IPC in 1980 (McClintock et al. 1982). The highest point in the HRI light curve 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 light curve spans phases 0.78–0.93, which are immediately before the eclipse. However, we note that two other published reports (Horne, Verbunt, & Schneider 1986; Cowley & Schmidtke 1990) have noted 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 light curve does not show the eclipse seen in the high state.

In order to quantify the evidence for a change in the shape of the light curve, we have computed the χ^2 and K-S statistics for the light curve using the nominal ephemeris under two different hypothesis: a steady source and the on-state light curve scaled to produce the observed number of counts. The χ^2 and K-S statistics indicate that the probability the source is steady is 6% and 26%, respectively. Similarly, the probability that the observed counting rate follows the on-state light curve is found to be 0.8% and 0.5%. These tests allow the possibility that the source was steady and provide a fairly strong indication that the shape of the light curve has changed.

TABLE 1

IPC AND SPECTRAL FIT RESULTS AND 90% CONFIDENCE INTERVALS

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

2.2. *Einstein X-Ray Spectra*

During its X-ray–bright phase in early 1980, 4U 2129+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 4U 2129+47 predated the *Einstein* IPC Rev 1B processing and did not include spectral fits to the data. We have extracted the 1980 June 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 the interstellar absorption plus one of thermal bremsstrahlung, power-law, and Raymond-Smith models all produced acceptable ($\lesssim 1$) χ^2/ν. Fits to a blackbody with interstellar absorption resulted in an unacceptable $\chi^2/\nu > 2$. The 90% confidence regions for the acceptable fits are shown 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 4.0×10^{21} cm^{-2} < $N_H < 10.5 \times 10^{21}$ 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 shown 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 perhals not surprising given the lack of intersection in the confidence intervals for temperature and slope. Fits to multiple-component (i.e., blackbody + 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).

3. DISCUSSION

The detection of X-ray flux from 4U 2129+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, McKee, & Shields 1983; White & Holt 1982; Kallman 1989; 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 4U 2129+47 not to have an ADC during quiescence. If an ADC is still present, it may indicate that mechanisms other than X-ray heating (i.e. magnetic fields, Stella & Rosner 1984; convective currents, Cannizzo & Cameron 1988; or acoustic noise, Icke 1976) 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 light curve 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 light curve 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 & 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 (i.e., 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 $\sim 20°$ (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 LMXB with $L_x > 10^{36}$ ergs s^{-1}. This will not be the case in CVs which typically have $L_x < 10^{33}$ ergs s^{-1}. Frank, King, & 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 light curve of 4U 2129+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 very low states. Of these, several that are believed to contain neutron stars (Aql X-1, Cen X-4, EXO 0748−67) have been detected at quiescent luminosities of 10^{33}–10^{34} ergs s^{-1} (Verbunt et al. 1993; Parmar et al. 1983). The low-state luminosity of 4U 2129+47, assuming a distance of 6.3 kpc (Cowley & Schmidtke 1990), is $\sim 3.6 \times 10^{33}$ ergs 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 4U 2129+47 to these sources lends support to the idea that the neutron star in 4U 2129+47 is no longer shielded from view.

While the similarity in luminosity argues for a similar geometry, we caution that the handful of LMXB detected in quiescent states show a remarkably wide variety of transient behavior. For example, A0620−00 apparently has a strong outburst followed by many decades of quiescence (McClintock et al. 1983), Aql X-1 has an outburst nearly every year (Kitamoto et al. 1983), and EXO 0748−67 has long-lived on/off states (Parmar et al. 1983) like 4U 2129+47. This wide variety of behavior may indicate a similarly wide variety of physical characteristics, but more investigation (and a larger sample of sources) is needed to clarify this.

We do not expect detectable levels of X-ray emission from the F7 IV star or the presumed M-dwarf companion to the neutron star. The low-state luminosity of 4U 2129+47 is many orders of magnitude above the $\sim 5 \times 10^{28}$ ergs 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} ergs s^{-1} (Eracleous 1991).

A number of authors have suggested that 4U 2129+47 may be a triple system, with the 5.24 hr 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 Heiles, Stark, & Kulkarni (1981) allows us to compute the optical absorption expected from the X-ray measurements, $A_V^{X\text{-ray}}$. The allowed range in N_H for 4U 2129+47 (§ 2) corresponds to $2.9 < A_V^{X\text{-ray}} < 7.5$, which should be compared to the $A_V^{opt} \sim 0.9$ measured to the F7 IV star (Cowley & 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, LMXBs 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 $A_V^{X\text{-ray}}$ as measured with the *Einstein* OGS with the A_V^{opt} measured for 11 LMXBs and find that $A_V^{X\text{-ray}} > A_V^{opt}$. For the 10 LMXBs in their Table 4 with secure optical identifications (we have excluded GX 17+2), we compute a mean and dispersion on the average "excess" absorption of each object $A_V^{excess} = A_V^{X\text{-ray}} - A_V^{opt}$ of 2.0 ± 1.3. Thus we see that the range of A_V^{excess} allowed for 4U 2129+47 includes the range typically seen in LMXBs, therefore not ruling out the triple hypothesis.

Other LMXBs in low states (i.e. Cen X-4 and Aql X-1) show indications of accretion disk in the optical spectrum (Balmer series and He II emission) during the low state, while V1727 Cyg does not. This is likely because 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 & McClintock (1994). At $M_V = 6.1$, it is ~ 3 mag lower than the F7 IV 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 4U 2129+47. This is not unexpected when compared to other LMXBs (i.e., 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 4U 2129+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 (i.e., with *ROSAT* and/or *ASCA* [*Astro D*]) may help clarify the low-state model for 4U 2129+47. A detailed low-state X-ray light curve 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 $A_V^{\text{X-ray}}$ should be possible with *ASCA* and might allow a more powerful test of the triple hypothesis.

This work was partially supported by NASA contract NAS 8-30751, and *ROSAT* GO grant NAG 5-1724. M. R. G. acknowledges the hospitality of the Institute of Astronomy, Cambridge, England where parts of this analysis were carried out, and helpful discussions with J. McClintock and P. Callanan.

REFERENCES

Begelman, M. C., McKee, C. F., & Shields, G. A. 1983, ApJ, 271, 88
Cannizzo, J. K., & Cameron, A. G. W. 1988, ApJ, 330, 327
Cowley, A. P., & Schmidtke, P. C. 1990, AJ, 99, 678
Eracleous, M., et al. 1991, ApJ, 382, 290
Frank, J., King, A. R., & Lasota, J.-P. 1987, A&A, 178, 137
Garcia, M. R. 1992, BAAS, 24, 1153
Garcia, M. R., Bailyn, C. D., Grindlay, J. E., & Molnar, L. A. 1989, ApJ, 341, L75
Heiles, C., Stark, A. A., & Kulkarni, S. 1981, ApJ, 247, L73
Horne, K., Verbunt, F., & Schneider, D. P. 1986, MNRAS, 218, 63
Icke, V. 1976, in Structure and Evolution of Close Binary Systems, ed. P. P. Eggelton, S. Milton, & A. J. Whelan (Boston: Reidel), 267
Kallman, T. R. 1989, in Accretion-Powered X-ray Binaries, ed. C. W. Mauche (Cambridge: Cambridge Univ. Press), 325
Kitamoto, S., Tsunemi, H., Miyamoto, S., & Roussel-Dupré, D., 1993, ApJ, 403, 315
Mason, K. 1987, in The Physics of Accretion onto Compact Objects, ed. K. Mason, M. G. Watson, & N. E. White (New York: Springer-Verlag), 29
Masnou, J. L., Wilkes, B. J., Elvis, M., McDowell, J. C., & Arnaud, K. A. 1992, A&A, 253, 35
McClintock, J. E., London, R. A., Bond, H. E., & Grauer, A. D. 1982, ApJ, 258, 245
McClintock, J. E., Petro, L. D., Remillard, R. A., & Ricker, G. R. 1983, ApJ, 266, L27
Molnar, L. A., & Neely, M. 1992, IAU Circ., 5595
Parmar, A. N., White, N. E., Giommi, P., & Gottwald, M. 1983, ApJ, 308, 199
Petterson, J. A. 1983, in Accretion-Driven Stellar X-Ray Sources, ed. W. H. G. Lewin & E. P. J. van den Heuvel (New York: Cambridge Univ. Press), 367
Peitsch, W., Steinle, H., Gottwald, M., & Graser, U. 1986, A&A, 157, 23
Prestwich, A., McDowell, J., Plummer, D., Manning, K., & Garcia, M. R. 1992, The *Einstein Observatory* Database of IPC Images in Event List Format, (CD-ROM version), June 1992, Vol. 1, USA-SAO-EINSTEIN-IPCE (Cambridge, Mass: Smithsonian Ap. Obs) (CD-ROM)
Raymond, J. C. 1993, ApJ, 412, 267
Sero, M. 1985, in X-ray Astronomy in 1984, ed. M. Oda & Giaconni (Bologna: CNRS), 1
Shakura, N. I., & Sunyeav, R. A. 1973, A&A, 24, 337
Stella, L., & Rosner, R. 1984, ApJ, 277, 312
Thorstensen, J. R., et al. 1988, ApJ, 334, 430
van Paradijs, J., & McClintock, J. E. 1994, X-Ray Binaries, ed. W. H. G. Lewin, J. van Paradijs, & E. P. J. van den Heuvel (Cambridge: Cambridge Univ. Press), in press
van Paradijs, J., Verbunt, F., Shafer, R. A., & Arnaud, K. A. 1987, A&A, 182, 47
Verbunt, F., Belloni, T., van der Klis, M., & Lewin, W. H. G. 1993, A&A, submitted
Vrtilek, S. D., McClintock, J. E. Seward, F. D., Kahn, S. M., & Wargelin, B. J. 1991, ApJS, 76, 1127
Wenzel, W. 1983a, IAU Circ., 3899
———. 1983b, Inf. Bull. Var. Stars, 2452
White, N. E., & Holt, S. S. 1982, ApJ, 257, 318
Zombeck, M. 1992, *ROSAT* Newsletter 7, 5