ROSAT OBSERVATIONS OF SOFT X-RAY TRANSIENTS IN QUIESCENCE

FRANK VERBUNT
Astronomical Institute, Utrecht University,
Postbox 80.000, 3508 TA Utrecht, The Netherlands

Abstract. Four soft X-ray transients, two with a neutron star and two with a black hole, have been detected at quiescence with ROSAT. Blackbody fits to their spectra give temperatures of 160–300 eV, and surface areas of $<1\,km^2$. The small surface area suggests that the actual spectrum may be optically thin. The companion star does not contribute significantly to the X-ray luminosity, except perhaps in the case of A 0620–00. From the observation that accretion continues at luminosity levels of $\sim 10^{33}\,erg\,s^{-1}$ it is concluded that the neutron stars in Aql X-1 and Cen X-4 have a weak magnetic field and rotate rather slowly.

1. Introduction

Occasionally, on average perhaps once a year, the X-ray sky changes due to the sudden appearance of a very bright new source, which after reaching maximum within a week, declines again to its pre-outburst level on a time scale of months. During outburst maximum, these sources are very similar to the permanently bright low-mass X-ray binaries, and they are thought similarly to be neutron stars or black holes that accrete mass from a low-mass companion. Upon cessation of mass transfer, the neutron star in a low-mass X-ray binary may turn into a recycled pulsar. (For reviews see White *et al.* 1984; Van Paradijs & Verbunt 1984; Tanaka & Lewin 1995; for evolution see, e.g., Verbunt 1993.)

A study of the X-ray emission of soft X-ray transients in quiescence is interesting because it may shed light on the mechanism which causes the accretion onto the compact object in these systems to be intermittent, and because the magnetic field and rotation period of the neutron star may

J. van Paradijs et al., (eds.), Compact Stars in Binaries, 333–339.

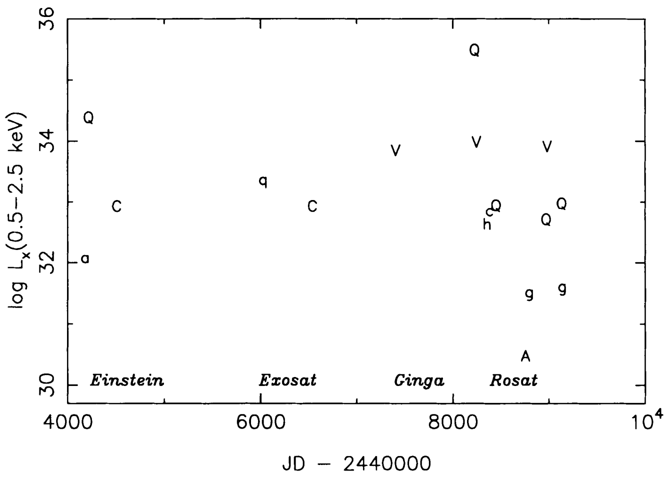

Figure 1. **A history of observations of soft X-ray transients in quiescence. X-ray luminosities are for the range 0.5–2.5 keV. Each letter indicates an observation of Q = Aql X-1, A = A 0620−00, C = Cen X-4, V = V404 Cyg (=GS 2023+338), G = GS 2000+25, and H = H 1705−25. Upper case is a detection, lower case an upper limit. The satellites used are indicated near the bottom. (For details, see text and Verbunt *et al.* 1994.)**

be revealed at low accretion rates. Field strength and period may then be compared with those of the recycled radio pulsars with low-mass white-dwarf companions. In Section 2 of this paper I discuss a history of the X-ray observations of soft X-ray transients in quiescence, and in Section 3 the results obtained on the X-ray spectrum at low accretion rates. A possible contribution of the donor star to this X-ray flux is discussed in Section 4, and the magnetic field and rotation period of the neutron star in Section 5.

2. X-ray Observations in Quiescence

Before the launch of ROSAT, there were only two secure detections of a soft X-ray transient in quiescence, both of Cen X-4, at a level of 10^{32-33} erg s^{-1}, with EINSTEIN and with EXOSAT (Van Paradijs *et al.* 1987). An upper limit at a comparable level was obtained with GINGA (Kulkarni *et al.* 1992). (Here and in the following the X-ray luminosities are quoted for the range of 0.5–2.5 keV.) Detections at $\sim 10^{34}$ erg s^{-1} with uncertain identification due to inaccurate position were reported for Aql X-1 with EINSTEIN (Czerny *et al.* 1987) at a level three times above an upper limit obtained with EXOSAT (Van Paradijs *et al.* 1987), and for V404 Cyg with GINGA (Mineshige *et al.* 1992). A very low upper limit, at $\sim 10^{32}$ erg s^{-1}, was obtained with EINSTEIN for A 0620−00 (Long *et al.* 1981).

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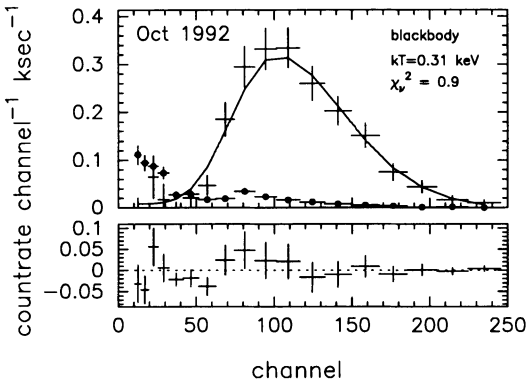

Figure 2. **The ROSAT PSPC countrates of Aql X-1 obtained in October 1992, together with a blackbody fit (upper panel) and the difference between fit and observation (lower panel). Channel n corresponds roughly to $n \times 0.01$ keV. The background level is indicated with •. (From Verbunt et al. 1994.)**

The dramatic improvement in sensitivity with ROSAT has transformed the field (see Fig. 1). Aql X-1 was detected at various flux levels, down to $4\ 10^{32}\,\mathrm{erg\,s^{-1}}$ (Verbunt *et al.* 1994). V404 Cyg was detected twice at similar count rates; the derived luminosity depends critically on the assumed absorption column: for $N_\mathrm{H} = (0.3-1.5)\ 10^{22}\,\mathrm{cm^{-2}}$, the X-ray luminosity is (1-8) $10^{33}\,\mathrm{erg\,s^{-1}}$ (Verbunt *et al.* 1994; Wagner *et al.* 1994). A 0620−00 was detected at $2.5\ 10^{30}\,\mathrm{erg\,s^{-1}}$ (McClintock *et al.* 1995). Upper limits were obtained for H 1705−25 at $4\ 10^{32}\,\mathrm{erg\,s^{-1}}$ for $N_\mathrm{H} = 3\ 10^{21}\,\mathrm{cm^{-2}}$, and for GS 2000+25 at $3\ 10^{31}\,\mathrm{erg\,s^{-1}}$ for $N_\mathrm{H} = 10^{22}\,\mathrm{cm^{-2}}$ (Verbunt *et al.* 1994). Further results are now coming in from ASCA (see Inoue, these proceedings).

Thus, we now have quiescent detections of two transients with a neutron star, Cen X-4 and Aql X-1, and of two with a black hole, A 0620−00 and V404 Cyg. The flux level of all of these is too low to be compatible with models that explain the transient mass transfer as the consequence of irradiation of the donor star (see also Lasota, these proceedings).

3. Spectra

The ROSAT XRT-PSPC combination has a limited spectral resolution, providing about six independent flux points in the 0.1–2.4 keV range. We show the spectrum of Aql X-1 at its lowest observed flux level in Fig. 2 together with the best fitting blackbody spectrum, which has a temperature of 0.31 keV. This temperature, although somewhat lower than the characteristic temperature at higher flux levels, is such that the spectrum peaks in the ROSAT PSPC sensitivity range: the low observed flux therefore corresponds to a low bolometric flux.

Low temperatures have also been found for the detections with the

ROSAT PSPC of V404 Cyg (210 eV, Wagner *et al.* 1994), of A 0620−00 (160 eV, McClintock *et al.* 1995), and with ASCA of Cen X-4 and H 1608−522 (Inoue, these proceedings).

The interpretation of the spectra as blackbody spectra leads to rather small radii of the emitter. The bolometric luminosities at minimum are about 4.25 10^{30} erg s^{-1} for A 0620−00 and 5 10^{32} erg s^{-1} for Aql X-1, corresponding to emitting areas of $< 1\,\mathrm{km}^2$ in both cases, rather too small to be from the accretion disk. In the case of Aql X-1 we may be seeing a ring on the neutron star, the boundary layer, which is heated by continued accretion. Against this interpretation is the observation of a similar emitting area in the black hole system. Perhaps it is more likely then that we do see the spectrum of the accretion disk, which is optically thin. If so, the conversion of observed to bolometric flux is uncertain.

4. Contribution of the Companion

At the very low X-ray luminosities now found of soft X-ray transients in quiescence, one has to investigate the possibility that the donor star contributes to the observed flux. To do this, I use the survey of RS CVn type systems by Dempsey *et al.* (1993), which has the advantage of being made with the same instrument, the ROSAT PSPC, used to detect the quiescent transients. Here the definition of RS CVn systems is taken widely, and includes binaries consisting of main-sequence stars, but with increased magnetic activity due to rapid rotation. In Fig. 3 I show the X-ray luminosity of RS CVn's as a function of the radius of the active star. The luminosity in the 0.5–2.5 keV range is assumed to be half of the L_X tabulated by Dempsey *et al.*, and the stellar radii have been derived from V, $B-V$ and the distance as tabulated by Dempsey *et al.* using the relations of $B-V$, $T_{\rm eff}$ and bolometric correction in Tables 3.3 and 3.5 in Mihalas & Binney (1981). No reddening corrections have been applied.

In the same figure, I plot the detected luminosities of the soft X-ray transients, using radii of 0.6 $R_\odot$ for Cen X-4 (McClintock & Remillard 1990), 0.8 $R_\odot$ for A 0620−00 (Shahbaz *et al.* 1994), and 9 $R_\odot$ for V404 Cyg (Wagner *et al.* 1992). I further assumed a radius for Aql X-1 slightly larger than that for Cen X-4. It should be noted that all these radii are very uncertain. It is seen that the companion may contribute significantly only in A 0620−00. The companion is not expected to contribute significantly to Aql X-1, Cen X-4, or V404 Cyg. As an aside, note that Fig. 3 indicates that the X-ray flux of cataclysmic variables with $L_X < 3\ 10^{30}$ erg s^{-1} may be affected by flux from the donor star.

The comparison of the soft X-ray transients is made with RS CVn binaries rather than with rapidly rotating single stars, because the binaries are

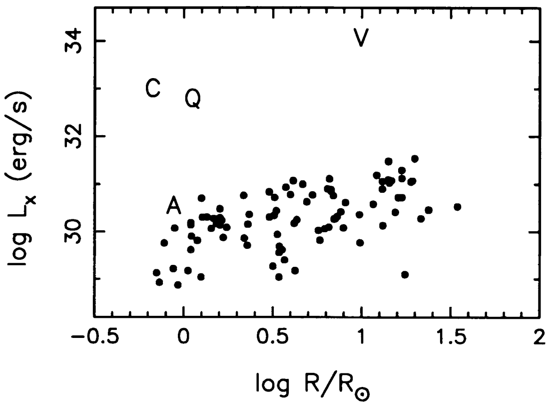

Figure 3. 0.5–2.5 keV X-ray luminosities of RS CVn binaries, adapted from Dempsey et al. (1993), plotted as a function of the radius of the active star (•). The position of some X-ray transients in this diagram is also given, with the same symbols as in Fig. 1.

known to be more active than single stars rotating equally rapidly (Schrijver & Zwaan 1991). HD 22403 is an example of a binary consisting of two low-mass main-sequence stars, a G2 V and a K V star, which is a remarkably bright X-ray source, at $L_X \simeq 0.5\ 10^{31}\,\mathrm{erg\,s^{-1}}$ (Dempsey *et al.* 1993).

5. Magnetic Field and Pulse Period

The observation that soft X-ray transients with a neutron star are still accreting at very low rates provides a strong limit on the magnetic field and rotation period of the neutron star (Stella *et al.* 1994; Verbunt *et al.* 1994). At the surface of the magnetosphere the disk matter is forced into corotation with the neutron star. When the magnetic field B is too strong (i.e. the magnetospheric surface too far from the neutron star), or the rotation period P too short, the centrifugal force caused by the corotation exceeds the gravitational attraction by the neutron star, and the matter is flung out, rather than accreted. Thus, accretion requires

$$P \gtrsim (0.4\ \mathrm{s})\ {B_9}^{6/7} \dot{M}_{13}^{-3/7} \qquad (1)$$

where B_9 is the surface magnetic field of the neutron star in units of 10^9 G, and $\dot{M}_{13}$ the accretion rate in units of $10^{13}\,\mathrm{g\,s^{-1}}$.

The ROSAT observation of Aql X-1 at its lowest quiescent level implies $\dot{M} \sim 3\ 10^{12}\,\mathrm{g\,s^{-1}}$, so that $P \gtrsim (0.6\,\mathrm{s})\ {B_9}^{6/7}$. A somewhat less stringent limit may be derived for Cen X-4. It is clear from these conditions that the neutron stars in Cen X-4 and in Aql X-1 will require a lot of additional spin-up if they ever are to become millisecond pulsars upon cessation of mass transfer.

6. Conclusions

The ROSAT PSPC observations have provided a wealth of unprecedented observations of low-mass X-ray binaries in quiescence.

From these it is clear that accretion continues, albeit at a very low rate, during the quiescent intervals between outbursts. Blackbody spectra fitted to the observed data give surface areas of the order of $1\,\mathrm{km}^2$. This suggests that the spectra are optically thin, and may affect the conversion of observed flux into bolometric flux, and thus luminosity.

The continued accretion onto the neutron stars in Cen X-4 and Aql X-1 at rates $\dot{M} \sim 10^{13}\,\mathrm{g\,s^{-1}}$ indicates that these neutron stars rotate rather slower than expected for the progenitors of millisecond recycled pulsars.

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Discussion

R.W. Romani: Given that the flux in quiescence of these transients is small and that your spectral results suggest that it may be non-thermal, is it possible that this flux is generated via shock acceleration at the hot spot where the accretion stream impacts, at least for the soft X-ray transients?

F. Verbunt: I think that this is unlikely. The gradual change in temperature as the flux decreases suggests that the same process is responsible for the X-ray emission throughout.

R. Sunyaev: In the case of Aql X-1 and Cen X-4 it is possible that the disk exists around the neutron star with a magnetic field but that accretion does not take place (see R.A. Sunyaev & N.I. Shakura 1986, Pis'ma Astron. Zh. 12, 286, translated SvA Lett. 12(2), 117). In that case the disk radiates the energy due to angular momentum transport from the neutron star.

F. Verbunt: Yes, that is a possibility. I remember that W. Priedhorsky put forward a similar mechanism for Sco X-1 (ApJ 306, L97). In my estimates I have used the simplest description.

M. van Kerkwijk: Is it possible that the low X-ray flux that you detected arises at the magnetosphere of the neutron star (i.e. in the inner disk), so that the neutron star could actually spin at a much shorter period than you derive?

F. Verbunt: See my answer to the previous speaker. Perhaps I should add that these mechanisms are not possible in a disk around a black hole, as no magnetosphere is present in that case, whereas the luminosities we derive for the black-hole V404 Cyg are actually rather similar to those for Cen X-4 and Aql X-1, and the spectrum derived is also rather similar. I therefore doubt that a magnetosphere plays an important role.