The hard X–ray transient 4U 0115+63 in quiescence

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Abstract. We review the properties of the hard transient 4U 0115+63 in outburst as well as during quiescence. 4U 0115+63 is one of the few sources in which a sharp decrease of the X–ray flux at the end of an outburst has been observed, testifying to the action of the centrifugal barrier. Here we discuss explicitely the available upper limit on the X–ray luminosity during the quiescent phase to suggest that 4U 0115+63 is likely in the "propeller" regime.

Key words: stars: individual: 4U 0115+63; X–ray: pulsars; accretion

1. Introduction

4U 0115+63 is a recurrent hard transient observed with a number of X–ray satellites: twelve outbursts have been reported so far. When in outburst, the X–ray flux is modulated by the spin period of 3.6 s (Cominsky et al. 1978), so that 4U 0115+63 hosts one of the fastest spinning neutron star in transient sources. Pulse time of arrival analysis allowed to derive an orbital solution with a period of 24.3 d and an eccentricity of 0.34 (Rappaport et al. 1978). Observations with *Ginga* confirmed earlier results (Wheaton et al. 1979; White, Swank & Holt 1983) of cyclotron line features characteristic of a high magnetic field $B \sim 10^{12}$ G (Nagase et al. 1991).

The optical counterpart has been identified with the variable B0e star V635 Cas (Johns et al. 1978). The 1980, 1987 and 1991 X–ray outbursts were preceded by about 30–80 days by an enhance in the companion's optical luminosity, however no X–ray outburst was observed during or after the 1988 optical outburst (Kriss et al. 1983; Mendelson & Mazeh 1991a, 1991b).

A distance of 2.5 kpc was reported by Rappaport et al. (1978) based on the combination of the observed X–ray luminosity and of the spin-up during outburst. Using the same method, however, *Ariel VI* (Ricketts et al. 1981) and *Ginga* (Tamura et al. 1992) observations gave a value of 4.4 kpc and 4 kpc, respectively. In the following we assume a distance of 5 kpc based on the visual extinction of the optical companion (Johnston et al. 1978). (A large distance allows also to obtain more conservative upper limits on X–ray luminosities.)

The delayed X–ray outbursts (Tsunemi & Kitamoto 1988) and, even more, the sharp end observed for several outbursts (e.g. Tamura et al. 1992) strongly suggest as a regulator of the transient activity, the action of the centrifugal force against gravity, which prevents the accretion of matter down to the neutron star surface (i.e. the centrifugal barrier; see Stella, White & Rosner 1986; Illarionov & Sunyaev 1975).

A marked decrease of the X–ray flux at the end of an outburst has been observed only in two hard transients, namely V0332+53 (Stella et al. 1986) and 4U 0115+63. The detection of an X–ray source when the centrifugal barrier is closed (propeller regime) is rather difficult; only recently the hard transient A0538–66 was observed with *ASCA* at a level of 6×10^{36} erg s^{-1} (1–10 keV; Corbet et al. 1995) and with *ROSAT* at 4×10^{35} erg s^{-1} (0.1–2.4 keV; Campana 1996a). The spin period (69 ms) and the inferred magnetic field ($B \sim 10^{11}$ G; Skinner et al. 1982) are such that this source should be in the propeller regime (e.g. Campana et al. 1995).

Due to the fast spin period and the high magnetic field, the hard transient 4U 0115+63 is a promising target for studing a neutron star in the propeller regime. In section 2 we briefly recall the properties of the propeller regime and in section 3 we report on upper limits during the quiescent phase from different X–ray instruments. In section 4 we discuss our results.

2. Propeller regime

The motion of the matter falling in the potential well of a neutron star becomes dominated by the rapidly increasing magnetic pressure at the magnetospheric radius, $r_{\rm m}$. At smaller radii the flow follows the magnetic field lines and is enforced to corotate rigidly with the neutron star. As a consequence, in order to have accretion onto the neutron star surface, the magnetospheric radius must lie inside the corotation radius ($r_{\rm cor}$), i.e. the radius at which a test particle in Keplerian orbit would corotate with the neutron star.

Due to the scaling of $r_{\rm m}$ with the accretion rate a minimum value, $\dot M_{\rm min}$, exists below which the matter does not provide sufficient pressure to withstand the centrifugal acceleration. In the case of 4U 0115+63 this limiting accretion rate is $\dot M_{\rm min} \sim 2 \times 10^{16}$ g s^{-1} and it corresponds to a minimum accretion luminosity down to the neutron star surface of

$$L_{\rm min} = \frac{G\,M\,\dot M_{\rm min}}{R} = 4 \times 10^{36}\,\bar\mu^2\,M_{1.4}^{-2/3}\,\bar P^{-7/3}\,R_6^{-1}\ {\rm erg\,s^{-1}}\ , \qquad (1)$$

Table 1

Year	Instrument	Durat. (d)	Max. Lum. (erg s^{-1})	Spin Period (s)	Refs.
1969 Aug	*Vela 5B* (3–12 keV)	~ 14	2×10^{37}	....	1
1970 Jan	*Vela 5B* (3–12 keV)	~ 10	1×10^{37}	....	1
1970 Aug	*Vela 5B* (3–12 keV)	~ 28	1×10^{37}	....	1
1971 Jan	*Vela 5B* (3–12 keV)	~ 30	1×10^{37}	....	1
"	*Uhuru* (2–6 keV)	~ 60	4×10^{36}	3.614640(19)	2
1974 Aug	*Vela 5B* (3–12 keV)	~ 30	9×10^{37}	3.6142(1)	1
1978 Jan	*Vela 5B* (3–12 keV)	~ 50	3×10^{37}	....	1
"	*SAS-3* (1–27 keV)	.....[b]	1×10^{37}	3.6145737(9)	3
"	*Ariel V* (3–6 keV)	~ 35	3×10^{37}	....	4
"	*HEAO 1 A-2* (3–13 keV)	.....[b]	3×10^{37}	3.61360(4)	4
"	*HEAO 1 A-4* (13–180 keV)	~ 25	1×10^{35}	....	5
1981 Jan	*Ariel VI* (2–10 keV)	~ 15	1×10^{37}	3.6146643(18)	6
"	*Einstein MPC* (2–10 keV)	.....[b]	1×10^{36}	pulsed	7
1987 Feb	*Ginga ASM* (1–20 keV)	~ 22	1×10^{37}	....	8
1990 Feb	*Ginga ASM* (1–20 keV)	~ 30	3×10^{37}	3.614690(2)	9
1991 Apr	*Batse* (20–50 keV)	~ 17	4×10^{36}	3.61451658464	10
1994 May	*Batse* (20–50 keV)	~ 60	9×10^{36}	3.6145107(10)	11
1995 Nov	*Batse* (20–50 keV)	.....[b]	4×10^{36}	3.6144992(40)	12
1995 Nov	*WATCH* (8–20 keV)	.....[b]	3×10^{37}	....	13

References: 1: Whitlock et al. (1989); 2: Forman et al. (1976); 3: Cominsky et al. (1978); 4: Rose et al. (1979); 5: Levine et al. (1984); 6: Ricketts et al. (1981); 7: Kriss et al. (1983); 8: Tsunemi & Kitamoto (1988); 9: Tamura et al. (1992); 10: Cominsky et al. (1994); 11: Wilson et al. (1994); 12: Finger et al. (1995); 13: Sazonov & Sunyaev (1995).

[a]: all luminosities are calculated for a distance of 5 kpc and assuming a conversion of 1 Crab $= 5 \times 10^{37}$ erg s^{-1} (e.g. Whitlock, Roussel-Doupré & Priedhorsky 1989).
[b]: sporadic observations.

where $\bar{P} = 3.6$ s is the neutron star spin period and $M_{1.4}$ its mass in units of 1.4 $M_\odot$. The neutron star magnetic moment $\mu = B\,R^3/2$ is in units of $\mu = 5 \times 10^{29}\,\bar{\mu}$ G cm^3, being $R = 10^6 R_6$ cm the neutron star radius (e.g. Stella et al. 1994).

Below this minimum luminosity, the accretion flow is halted at the magnetospheric boundary, which behaves like a closed barrier. Entering the propeller regime a drop in the accretion-induced luminosity is

Table 2

Epoch	Instrument	Luminosity (erg s^{-1})^a	Refs.
Aug 1970 – Jan 1971	*Vela 5B* (3–12 keV)	2×10^{36}	1
Mar 1971 – Mar 1972	*Uhuru* (2–6 keV)	5×10^{35}	2
Aug 1972 – May 1973	*OSO 7* (3–10 keV)	8×10^{35}	3
Jul 1977	*Rocket* (2–6 keV)	4×10^{36}	4
May 1969 – Jun 1979	*Vela 5B* (3–12 keV)	$\lesssim 1 \times 10^{36}$	1
Oct 1974 – Dec 1977	*Ariel V* (3–6 keV)	$\lesssim 4 \times 10^{36}$	5
Aug 1978	*HEAO 1 A-4* (13–180 keV)	1×10^{34}	6
Sep 1979	*Einstein SSS* (0.6–4 keV)	$\lesssim 6 \times 10^{33}$	7
Aug 1980	*Einstein IPC* (0.1–3 keV)	$\lesssim 9 \times 10^{33}$	7
Nov 1980	*Hakucho* (2–10 keV)	$\lesssim 1 \times 10^{36}$	8
beg 1983 – end 1983	*Tenma* (2–25 keV)	$\lesssim 7 \times 10^{36}$	9
mid 1984 – end 1985	*Tenma* (2–25 keV)	$\lesssim 7 \times 10^{36}$	9
Dec 1983 – Feb 1984	*EXOSAT ME* (1–10 keV)	$\lesssim 3 \times 10^{34}$	7
Dec 1983 – Feb 1984	*EXOSAT CMA* (0.1–1.5 keV)	$\lesssim 4 \times 10^{34}$	7
Feb 1987 – Nov 1991	*Ginga ASM* (1–20 keV)	$\lesssim 2 \times 10^{36}$	10
Mar 1991 – Feb 1996	*Batse* (20–50 keV)	$\lesssim 4 \times 10^{35}$	11
Feb 1993	*Rosat PSPC* (0.1–2.4 keV)	$\lesssim 4 \times 10^{32}$	7

References: 1: Whitlock et al. (1989); 2: Forman et al. (1976); 3: Markert et al. (1979); 4: Sharma et al. (1983); 5: Rose et al. (1979); 6: Levine et al. (1984); 7: this work; 8: Kriss et al. (1983); 9: Tamura et al. (1992); 10: Tsunemi & Kitamoto (1988); 11: Finger et al. (1995).

^{a}: all luminosities are calculated for a distance of 5 kpc and assuming of 1 Crab $= 5 \times 10^{37}$ erg s^{-1}. For upper limits the luminosity has been calculated assuming a Crab-like spectrum and a column density of $N_H \sim 10^{22}$ cm^{-2} derived by the extinction of the optical companion star (Johnston et al. 1979).

expected to occur down to

$$L_{\rm cor} = \frac{G\, M \dot{M}_{\rm min}}{r_{\rm cor}} \simeq 10^{34}\, \bar{\mu}^2\, M_{1.4}^{-1}\, \bar{P}^{-3}\ {\rm erg\, s^{-1}}\ . \qquad (2)$$

(for more details see Campana et al. 1995).

3. X–ray observations

As shown in Table 1, all X–ray observations of 4U 0115+63 in outburst are characterized by a minimum luminosity higher than the centrifugal barrier limit (cf. eq. 1). Moreover, when the X–ray luminosity approaches this limit, a sharp decrease takes place as testified, in particular, by *Ginga* observations (Tsunemi & Kitamoto 1988; Tamura et al. 1992).

During the quiescent phase several detections of 4U 0115+63 have been reported (first half of Table 2). These observations provide an X–ray luminosity which are only slightly below the centrifugal barrier and considering the uncertainties involved (e.g. the magnetic field responsible for the centrifugal barrier should be smaller that the value measured through cyclotron line features due to multipole field components; for more details concerning the uncertainties see Campana et al. 1996b), we can conclude that these values are consistent with accretion down to the neutron star surface. The upper limits provided by *Ariel V, Tenma* and *Ginga* satellites (second half of Table 2) are not tight enough to confirm or exclude accretion onto the neutron star surface. Here we will focus on the strong upper limits derived from *Einstein, EXOSAT* and *Rosat* data.

3.1. *Einstein*

An IPC observation was carried out on 1980 Aug. 19: 4U 0115+63 was not detected providing a $3\,\sigma$ upper limit of 2×10^{-2} c s^{-1}. For a Crab-like spectrum and a column density of 10^{22} cm^{-2} derived by the high interstellar absorption towards 4U 0115+63 (which allows also more conservative values on luminosity), the upper limit on the 0.1–3 keV luminosity at 5 kpc is $\sim 9\times10^{33}$ erg s^{-1}. (Note that this value is less stringent than the one reported by Rappaport 1980 due to the high column density assumed).

An HRI observation taken contemporary failed to detect the source at a level of 2×10^{34} erg s^{-1} (0.1–3 keV).

An upper limit of $\sim 6\times10^{33}$ erg s^{-1} (0.6–4 keV) comes from an SSS observation of 4U 0115+63 on 1979 Sep 3. Even if the count rate derived from a standard background subtraction might suggest a detection, a careful analysis reveals that no source is present (S. Drake, personal communication). A contemporary observation with the MPC instrument (1.5–10 keV) failed to detect the source at a level of $\sim 10^{36}$ erg s^{-1}.

3.2. *EXOSAT*

Four pointings have been performed with the *EXOSAT* satellite. By summing up the three CMA observations (spread over a month 1984

Jan – 1984 Feb), we obtain a $3\,\sigma$ upper limit on the count rate of 7×10^{-4} c s^{-1} (for a total exposure of $\sim 42,000$ s), providing an upper limit on the 0.1–1.5 keV luminosity of $\sim 3.6\times10^{34}$ erg s^{-1}. Four observations have been carried out with the Medium Energy (ME) instrument: the first three pointings failed to reveal 4U 0115+63 enabling to set an upper limit of $\sim 10^{34}$ erg s^{-1} in the 1–10 keV range. A possible detection of the source is provided by the last observation (1984 Feb 24) with $L\sim 3\times10^{34}$ erg s^{-1}, but a closer inspection of the lightcurve reveals that the source probably remained undetected.

3.3. *Rosat*

Rosat PSPC observations were carried out during 1993 Feb, in order to monitor the predicted outburst based on a 3 yr cycle (Whitlock, Roussel-Dupré & Priedhorsky 1989). The observations were spread over several days, in order to maximize the temporal coverage of the outburst. By summing up the available public data (for a total exposure time of $\sim 19,900$ s), we obtain a $3\,\sigma$ upper limit on the count rate of 7.5×10^{-4} c s^{-1}, yielding an upper limit on the 0.1–2.4 keV luminosity of $\sim 4.2\times10^{32}$ erg s^{-1}.

4. Discussion

Einstein IPC and SSS, EXOSAT CMA as well as *Rosat* PSPC observations provide upper limits which are below the maximum allowed luminosity in the propeller regime (cf. eq. 2) even if they were collected with low energy instruments. The possible emission mechanism responsible for X–ray emission in the propeller regime is not known, however the experience of the hard transient A0538–66 suggests that the bulk of the flux is emitted at low energies as testified by the *ASCA* (Corbet 1996) and *ROSAT* (Campana et al. 1996a) detections during quiescence and the contemporaneous non-detection with high energy instruments such as *BATSE*.

If the centrifugal mechanism does not operate during the quiescent phase of 4U 0115+63 (and if the bulk of the emitted flux is indeed emitted inside the observed energy range, see Table 2 for contemporaneous observations by other satellites) a very low accretion rate can be inferred by the upper limits discussed above ($<3\times10^{13}$ g s^{-1}) which, in turn, implies a low mass-loss rate from the Be companion $<5\times10^{-12}\,v_8^2\ M_\odot$ yr^{-1} (where v_8 is the wind velocity in units of 10^8 cm s^{-1}). On the contrary, accretion down to the magnetospheric radius allows a much higher mass-loss from the Be star ($<10^{-5}\,v_8^2\ M_\odot$ yr^{-1}) in agreement with observations on early type stars, which predict for a B0 star a loss rate of $10^{-8} - 10^{-7}\ M_\odot\,\mathrm{yr}^{-1}$ (de Jager, Nieuwenhuijzen & van der Hucht, 1988).

Observations with the *ASCA* and *SAX* satellites could reveal the emission from matter falling onto the magnetosphere in 4U 0115+63 during quiescence only if the mass-loss rate from the Be companion is $\gtrsim 10^{-6}\, v_8^2\ M_\odot\,\mathrm{yr}^{-1}$ (yielding a luminosity of $\gtrsim 5\times 10^{32}\ \mathrm{erg\,s^{-1}}$): for lower accretion rates in fact, the intrinsic flux of the Be companion (Meurs et al. 1992) might be stronger. The required mass-loss rate is somewhat higher than the typical value for a B0 (de Jager et al. 1988), suggesting that a small shell-ejection episode like the "missing" outburst of 1988 (Mendelson & Mazeh 1991a) should be better suited to detect 4U 0115+63 in the propeller regime.

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