A&A 404, L43–L46 (2003)
DOI: 10.1051/0004-6361:20030669

Astronomy & Astrophysics

The optical counterpart to SAX J1808.4–3658 in quiescence: Evidence of an active radio pulsar?

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Received 12 March 2003 / Accepted 26 April 2003

Abstract. The optical counterpart of the binary millisecond X-ray pulsar SAX J1808.4–3658 during quiescence was detected at $V = 21.5$ mag by Homer et al. (2001). This star shows a 6% semi-amplitude sinusoidal modulation of its flux at the orbital period of the system. It was proposed that the modulation arises from X-ray irradiation of the intrinsically faint companion by a remnant accretion disk, and that the bulk of the optical emission arises from viscous dissipation in the disk. The serious difficulty in this scenario lies in the estimate of the irradiating luminosity required to match the observational data, that is a factor 10−50 higher than the quiescent X-ray luminosity of this source. To overcome this problem, we propose an alternative scenario, in which the irradiation is due to the release of rotational energy by the fast spinning neutron star, switched on, as magneto-dipole rotator (radio pulsar), during quiescence. Our computations indicate that the optical magnitudes are fully consistent with this hypothesis. In this case the observed optical luminosity may be the first evidence that a radio pulsar is active in this system in quiescence, a key phase for understanding the evolution of this class of objects.

Key words. accretion discs – stars: individual: SAX J1808.4–3658 – stars: neutron – X-rays: stars – X-rays: binaries – X-rays: general

1. Introduction

SAX J1808.4–3658 is a transient low mass X-ray binary (hereafter LMXB) first detected with the Wide Field Cameras on board BeppoSAX in 1996 (in't Zand et al. 1998). The source showed type I X-ray bursts and was classified as a LMXB in which the compact object is a neutron star (hereafter NS). Analysis of the burst emission, showing Eddington-limited photospheric radius expansion, allowed an estimate of the source distance of 4 kpc (in't Zand et al. 1998). This distance has been recently updated to 2.5 kpc (in't Zand et al. 2001). SAX J1808.4–3658 shows X-ray outbursts, lasting a few tens of days, approximately every two years, with outburst luminosities between 10^{35} and 10^{36} ergs/s and quiescent luminosities between 10^{31} and 10^{32} ergs/s (see e.g. Wijnands et al. 2001; Campana et al. 2002).

In RXTE observations performed during the 1998 outburst Wijnands & van der Klis (1998) detected coherent pulsations, at a frequency of ~401 Hz (corresponding to a NS spin period of ~2.49 ms). Timing analysis on the same data revealed Doppler orbital modulation with a period of ~2.01 hr and negligible eccentricity. The X-ray flux shows a weak modulation of ~2% with a broad minimum when the NS is behind the companion. Adopting a typical NS mass of $M_1 = 1.35\ M_\odot$, the mass function of the system suggests a very low mass companion, $M_2 \lesssim 0.14\ M_\odot$ at 95% confidence level, of inconspicuous intrinsic luminosity (Chakrabarty & Morgan 1998). SAX J1808.4–3658 was the first (low magnetized) LMXB to show coherent pulsations in the millisecond range in its persistent emission, thus providing the first evidence of the current evolutionary scenario, the so called recycling scenario, according to which LMXBs are the progenitors of binary millisecond radio pulsars. These are systems containing a NS, active as a radio pulsar, orbiting a light (~0.1 $M_\odot$) companion and spinning at millisecond periods, with a relatively weak surface magnetic field (~10^8–10^9 Gauss, as derived from the measure of the spin period derivative).

The optical counterpart of SAX J1808.4–3658 was identified by Roche et al. (1998) with the variable star V4584 Sagittarii. Optical spectra of the companion star showed absorption lines which are characteristic of mid to late type stars (Filippenko et al. 1998), thus supporting the conclusion

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that the companion star has a very low mass (probably a low-mass, irradiation-bloated, brown dwarf; Bildsten & Chakrabarty 2001). Giles et al. (1999) reported on optical photometry during the decline of the 1998 outburst (April–June): the source faded from $V = 16.72$ to $V \gtrsim 20.50$. The optical flux also showed a 0.06–0.08 mag semi-amplitude modulation, roughly in antiphase with the weak X-ray orbital modulation, at a period which is consistent with the X-ray binary period of the system. The phasing of the X-ray optical modulation is consistent with X-ray reprocessing on the facing hemisphere of the companion star. Wang et al. (2001) interpreted the observed optical flux in outburst as emission from an X-ray heated accretion disk.

Homer et al. (2001) reported on high time resolution CCD photometry of this optical counterpart observed when the X-ray source was in quiescence. The optical component was detected at $V \sim 21.5$ mag, much fainter than the value observed during the X-ray 1998 outburst. The two observations in quiescence reported by Homer et al. (2001) were performed on 1999 August 10 and on 2000 July 3, respectively. An X-ray outburst of the source occurred between December 1999 and January 2000 and ended around May 2000 (Wijnands et al. 2001). Therefore these observations occurred roughly 4–5 months before the start of this outburst and 1–2 months after the end of the outburst, respectively. Colour images in B, V, and R obtained on 2000 July 3, were analyzed and corrected for interstellar extinction towards SAX J1808.4–3658, and are shown in Table 1. The ratio $F_{\rm X}(2-10\ {\rm keV})/F_V$ is ~1100 in outburst and ~10 in quiescence, respectively. This indicates that while the optical emission in outburst is certainly due to X-ray reprocessing, similar to other outbursting transients, X-ray reprocessing alone cannot be responsible of the bright optical emission observed in quiescence (Homer et al. 2001).

In these data a ~6% semi-amplitude modulation at the 2-hr orbital period of the system is still significantly detected. The photometric minimum is found when the companion star lies between the pulsar and the observer and the shape of the modulation is approximately sinusoidal, similar to what is observed during outbursts. The faintness of the low-mass companion, as well as the lack of double-humped morphology, due to an ellipsoidal modulation, excludes the direct optical emission from the companion as the origin of the observed optical flux and modulation.

Homer et al. (2001) interpret the observed optical flux as due to viscous dissipation in an unirradiated accretion disk truncated at the corotation radius, $r_{\rm co} = (GM_{\rm NS}P_{\rm s}^2/4\pi^2)^{1/3}$ (where G is the gravitational constant, $M_{\rm NS}$ is the NS mass and $P_{\rm s}$ is the NS spin period), that is ≃30 km in the case of SAX J1808.4–3658, and fuelled by a mass transfer rate of $\dot{M} \sim 10^{-11}\ M_\odot$/yr, consistent with gravitational radiation orbital angular momentum losses. Although the adopted accretion rate is consistent with that measured during X-ray outbursts (e.g. Wijnands et al. 2001), this disk model is only consistent with the lower limits on the optical fluxes, indicating that the required mass accretion rate may be even higher than the one adopted. The optical modulation is interpreted as due to X-ray irradiation of the companion star by the remnant accretion disk. From the amplitude modulation the required level of irradiating flux has been estimated to be $L_{\rm irr} \sim 10^{33}$ ergs/s (Homer et al. 2001).

Table 1. Quiescent optical apparent (de-reddened) magnitudes in three different bands of V4580 Sagittarius. The measured values are from Homer et al. (2001).

Band	Measured		Predicted	
	Lower limit	Upper limit	$\mu_{26} = 5$	$\mu_{26} = 1$
B_0	17.7	21.0	17.9	21.8
V_0	18.2	20.8	18.6	21.7
R_0	17.7	21.0	18.7	21.4

As already pointed out by Homer et al. (2001) this scenario meets with some difficulties. First of all, an X-ray luminosity is expected due to accretion onto the NS at a level of $\sim 10^{35}$ erg/s, adopting a standard efficiency of ~10% for accretion onto NSs. In principle a propeller effect could centrifugally inhibit accretion, although a residual 10^{33} erg/s are still needed to heat the companion at the level required from the optical data. This is a factor of 10–50 higher than the measured X-ray luminosity of SAX J1808.4–3658 in quiescence. The quiescent X-ray luminosity of SAX J1808.4–3658 has been measured several times, always resulting lower than $\sim 10^{32}$ ergs/s (Stella et al. 2000; Dotani et al. 2000; Wijnands et al. 2002; Campana et al. 2002). The most recent measure, $L_{\rm q} \sim 5\times10^{31}$ erg/s in the 0.5–10 keV range, was obtained using an XMM observation taken in March 2001 (Campana et al. 2002).

In this letter we show that these difficulties are solved if we make the case that actually the irradiation of the remnant disk and/or the companion star is due to illumination from the *radio pulsar*, which may switch on during quiescence, once the magnetospheric radius is pushed beyond the light cylinder radius (see e.g. Burderi et al. 2001). We suggest that the optical emission and modulation during quiescence is the first evidence that a magneto-dipole rotator (i.e. a radio pulsar) is active in this system during quiescence.

2. Irradiation of the disk and companion star by rotating magneto-dipole emission

It has been demonstrated that a rotating magnetic dipole in vacuum emits electromagnetic dipole radiation. Also, a wind of relativistic particles associated with magnetospheric currents along the field lines is expected to arise in a rotating NS (e.g. Goldreich & Julian 1969). This radiative regime occurs when the space surrounding the NS is free of matter up to the light cylinder radius ($r_{\rm LC} = cP_{\rm s}/2\pi$, where c is the speed of light, i.e. the radius at which an object corotating with the NS attains the speed of light; see Ruderman et al. 1989; Illarionov & Sunyaev 1975). Di Salvo & Burderi (2003) have shown that a magneto-dipole rotator can easily be active in SAX J1808.4–3658 during quiescence. In fact, for a luminosity in quiescence of $\sim 5\times10^{31}$ ergs/s (Campana et al. 2002), the NS surface magnetic field should be $B \lesssim 0.05\times10^8$ Gauss in order to truncate the disk inside the corotation radius and allow accretion onto the NS surface. This upper limit is incompatible with the presence of X-ray pulsations at the highest flux levels during outbursts, which requires the disk to be truncated before the NS surface, and therefore $B \geq 1 \times 10^8$ Gauss (Psaltis & Chakrabarty 1999). On the other hand, the onset of a propeller regime or the intrinsic emission in X-rays by a magneto-dipole rotator switched-on during quiescence, implies upper limits on the magnetic field above 1×10^8 Gauss, compatible with the presence of X-ray pulsations during outbursts.

In the hypothesis that the magneto-dipole rotator is active in SAX J1808.4–3658 during quiescence, we can evaluate the power of the pulsar beam and, consequently the irradiation luminosity. To this aim we need an estimate of the NS magnetic field in this system. As mentioned above, from a measure of the source luminosity in quiescence and using simple considerations on the position of the magnetospheric radius during quiescent periods, it is possible to estimate an upper limit on the NS magnetic field of $B \lesssim 5 \times 10^8$ Gauss (Di Salvo & Burderi 2003). This, together with the lower limit mentioned above, constrains the SAX J1808.4–3658 NS magnetic field in the quite narrow range $(1–5) \times 10^8$ Gauss. Adopting this magnetic field we can calculate the spin-down energy loss of the pulsar, i.e. the energy emitted by the pulsar in the case in which the radio pulsar switches on: $L_{\rm PSR} = (2/3c^3)\mu^2\omega^4 = 3.85 \times 10^{35} P_{-3}^{-4}\mu_{26}^2$ ergs/s $\sim (1–25) \times 10^{34}$ ergs/s, where ω is the rotational frequency of the NS, P_{-3} is the NS spin period in milliseconds, μ is the NS magnetic moment, and μ_{26} is the NS magnetic moment in units of 10^{26} Gauss cm^3.

In the hypothesis that the pulsar beam heats a remnant accretion disk and/or a side of the companion star and assuming isotropic emission, we can evaluate the fraction of the irradiation luminosity that will be intercepted and reprocessed by the disk and the companion star, respectively. For the accretion disk this fraction, $f_{\rm D}$, is given by the projected area of the disk as seen by the central source, $2\pi R \times 2H(R)$ (where R is the disk outer radius and $H(R)$ is the disk semi-thickness at R) divided by the total area, $4\pi R^2$. Adopting a standard Shakura-Sunyaev disk model (Shakura & Sunyaev 1973), we find: $f_{\rm D} \simeq 1.6 \times 10^{-2}\alpha^{-1/10}\dot{M}_{-10}^{3/20} m_1^{-3/8} R_{10}^{1/8}$, where α is the viscosity parameter, $\dot{M}_{-10}$ is the mass accretion rate in units of 10^{-10} $M_\odot$/yr, m_1 is the NS mass in solar masses, and R_{10} is the outer radius of the disk in units of 10^{10} cm assumed to be at ~0.8 of the Roche lobe radius, R_{L1}, of the primary. For a reasonable value of the viscosity parameter, $\alpha = 0.1$, and adopting $R_{10} \simeq 2.9$ and $\dot{M}_{-10} = 0.1–1$ (note that $f_{\rm D}$ depends weakly on the mass accretion rate), we find $f_{\rm D} \sim (1.5–2.1) \times 10^{-2}$.

Indeed the outer accretion disk can still be present in the system during the optical observations performed in quiescence by Homer et al. (2001). In fact, the observations in July 2000 were performed approximately 1−2 months from the end of the nearest outburst (May 2000). This time interval can be compared with the time scale to "evaporate" the disk, once the magneto-dipole rotator is active. This time can be computed from the relation $L_{\rm PSR}\, f_{\rm D}\, t_{\rm evap} = 0.5 < U_{\rm D} > M_{\rm D}$, where $< U_{\rm D} >$ and $M_{\rm D}$ are the average potential and the mass of the disk, respectively. For SAX J1808.4–3658 this rough calculation gives $t_{\rm evap} \sim 30$ days. On the other hand, the time scale to re-form the disk will be of the order of (or larger than) the viscous time scale of the disk: $t_{\rm visc} = 2.6 \times 10^5 \alpha^{-4/5}\dot{M}_{-10}^{-3/10} m_1^{1/4} R_{10}^{5/4}$ s. For SAX J1808.4–3658 $t_{\rm visc} \simeq 130$ days, that is comparable to the time interval between the optical observations performed in August 1999 and the beginning of the following outburst (December 1999). This means that a significant fraction of the disc could still be present during the July 2000 and August 1999 observations.

A fraction $f_{\rm C}$ of the pulsar spin-down luminosity will be reprocessed by the companion star and emitted in the optical band; in this case the intercepted fraction can be written as: $f_{\rm C} = 2\pi a^2(1 - \cos\theta)/(4\pi a^2)$, where a is the the orbital separation and θ is the angle subtended by the companion star as seen from the central source; if the companion star fills its Roche lobe, this can be written as: $\sin\theta = R_{L2}/a$, where R_{L2} is the Roche lobe radius of the secondary and $R_{L2}/a = 0.49q^{2/3}/[0.6q^{2/3} + \ln(1 + q^{1/3})]$ (Eggleton 1983). Assuming a mass ratio of $q = m_2/m_1 = 0.14/1.35$ (Chakrabarty & Morgan 1998), where m_2 and m_1 are the masses of the companion and the NS in solar masses, respectively, we obtain: $f_{\rm C} \sim 1.1 \times 10^{-2}$.

If both the outer accretion disk and the companion star are reprocessing the pulsar spin-down luminosity, the total fraction of this luminosity that will be intercepted and reprocessed is: $f = f_{\rm D} + f_{\rm C} \sim 3.1 \times 10^{-2}$ (where we adopted $f_{\rm D} \sim 2.0 \times 10^{-2}$), giving an optical reprocessed luminosity of $\sim 3 \times 10^{32}\mu_{26}^2$ ergs/s. At a distance of 2.5 kpc, and adopting an average inclination angle $< i > = 50°$ of the normal to the plane of the disk with respect to the line of sight, this corresponds to fluxes of $F_{\rm C} \sim 1.4 \times 10^{-13}\mu_{26}^2$ ergs cm^{-2} s^{-1} and $F_{\rm D} \sim 3.5 \times 10^{-13}\mu_{26}^2$ ergs cm^{-2} s^{-1} from the companion and the disk, respectively. The corresponding blackbody temperatures are estimated to be $T_{\rm C} \sim 5430\ \mu_{26}^{1/2}$ K for the companion star and $T_{\rm D} \sim 5080\ \mu_{26}^{1/2}$ K for the irradiated surface of the disk. From the sum of two blackbodies of temperatures $T_{\rm C}$ and $T_{\rm D}$ and fluxes $F_{\rm C}$ and $F_{\rm D}$, respectively, we have calculated the predicted apparent magnitudes in three optical bands, which are perfectly in agreement with the measures reported by Homer et al. (2001) in the same optical bands. The results are shown in Table 1.

In our model, the optical modulation should again be caused by the heated side of the companion star, in agreement with the lack of ellipsoidal variations that should be expected in the intrinsic optical emission if the companion star fills its Roche lobe, as required in this system.

3. Conclusions

The optical counterpart of the binary millisecond X-ray pulsar SAX J1808.4–3658 during quiescence was detected at $V \sim 21.5$ mag by Homer et al. (2001). This star shows a ~6% semi-amplitude sinusoidal modulation of its flux at ~2.01 hr, i.e. at the orbital period of SAX J1808.4–3658. The absence of a double peaked profile, expected in case of ellipsoidal modulation, implies that the bulk of the optical flux does not arise from the isothermal photosphere of the companion, that is believed to fill its Roche lobe because of the presence of accretion episodes indicated by frequent X-ray outbursts, and suggest irradiation of the companion star. In order to explain these puzzling observations we have proposed here that this irradiation is due to the release of rotational energy by the fast spinning NS, switched on as a magneto-dipole rotator (radio pulsar) once the magnetospheric radius is pushed beyond the light cylinder radius during quiescence. Our computations indicate that the optical magnitudes are fully consistent with this hypothesis. The scenario we propose does not require a high mass accretion rate through the disk nor a quiescent X-ray luminosity of 10^{33} ergs/s, because the luminosity for the reprocessing is supplied by the rotational energy of the pulsar, $L_{\rm PSR} \sim (1{-}25) \times 10^{34}$ ergs/s. Also, we can explain why a similar semi-amplitude of ~6% is observed in the optical modulation both in outburst and in quiescence, since the reprocessor geometry in our scenario does not substantially change between outburst and quiescence.

The presence of an active magneto-dipole emitter during quiescence in SAX J1808.4–3658 as required in this scenario, suggest that SAX J1808.4–3658 should show radio pulsations in quiescence. Indeed, despite thoroughly searched in radio during its X-ray quiescent phase, no pulsed radio emission has been detected from this source up to now. In particular Gaensler et al. (1999) found an upper limit on the radio emission from this source of 0.12 mJy at 1.4 GHz using the Australia Telescope Compact Array. Burgay et al. (2003) found an upper limit of 0.98 mJy at 1.4 GHz searching for pulsed emission at the Parkes radiotelescope. The lack of radio detection can be caused by the presence of a strong wind of matter emanating from the system, i.e. the mass released by the companion star swept away by the radiation pressure of the pulsar, as predicted in the so-called radio-ejection model (Burderi et al. 2001; see also Burderi et al. 2002). This means that SAX J1808.4–3658 may show radio pulsations in quiescence when observed at frequencies higher than the standard 1.4 GHz (the frequency at which radio pulsars are normally searched), where the free-free absorption is less severe, as suggested by Ergma & Antipova (1999). We therefore suggest that the observed optical flux and modulation in quiescence may be the first evidence that a radio pulsar is active in this system when it is in quiescence.

Acknowledgements. We thank the anonymous referee for useful suggestions. This work was partially supported by a grant from the Italian Ministry of University and Research (MURST Cofin 2001) and The Netherlands Organization for Scientific Research (NWO).

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