Chin. J. Astron. Astrophys. Vol. 3 (2003), **Suppl.**, 311–315
(*http://www.chjaa.org*)

Chinese Journal of
Astronomy and
Astrophysics

# On the optical counterpart of SAX J1808.4–3658 during quiescence: evidence for an active radio pulsar?

L. Burderi[1 ⋆], T. Di Salvo[2], F. D'Antona[1], V. Testa[1], R. Iaria[2], G. Lavagetto[2] and N. R. Robba[2]

[1] Osservatorio Astronomico di Roma, via Frascati 33, 00040 Monteporzio Catone (Roma), Italy

[2] Dipartimento di Scienze Fisiche ed Astronomiche, Università di Palermo, via Archirafi n.36, 90123 Palermo, Italy

**Abstract** The optical counterpart of the binary millisecond X-ray pulsar SAX J1808.4–3658 during quiescence was detected at $V = 21.5$ mag, inconsistent with intrinsic emission from the faint companion star. We propose that the optical emission from this system during quiescence is due to the reprocessing by the companion star and a remnant accretion disk of the rotational energy released by the fast spinning neutron star, switched on, as magneto-dipole rotator (radio pulsar), during quiescence. In this scenario the companion behaves as a bolometer, reprocessing in optical the intercepted fraction of the power emitted by the pulsar. This reprocessed fraction depends only on known binary parameters. Thus the blackbody temperature of the companion can be predicted and compared with the observations. Our computations indicate that the observed 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 during quiescence.

**Key words:** accretion, accretion disks – stars: individual: SAX J1808.4–3658 — stars: neutron — X-rays: stars — X-rays: binaries — X-rays: general

## 1 INTRODUCTION

Low-mass X-ray binaries (hereafter LMXBs) consist of a neutron star (NS), generally with a weak magnetic field ($B < 10^{10}$ Gauss), accreting from a low-mass ($M \leq 1$ M$_\odot$) companion. NS X-ray transients (hereafter NSXT) are a special subgroup of LMXBs. These transient systems are usually found in a quiescent state, with luminosities in the range $10^{31} - 10^{34}$ erg s$^{-1}$. On occasions they exhibit outbursts, with peak luminosities between $10^{36}$ and $10^{38}$ erg s$^{-1}$, during which their behavior closely resemble that of persistent LMXBs (see Campana et al. 1998 for a review). Recently, due to a significant increase in the sensitivity of the X-ray detectors, X-ray emission from many NSXTs in quiescence has been detected. Adopting the same conversion

⋆ E-mail: `burderi@mporzio.astro.it`

efficiency of the accreting matter energy into X-rays during outbursts and quiescent states, the inferred variations in the accretion rate into the central source are a factor $\sim 10^5$.

Some of these NSXTs also show type-I X-ray bursts. During these bursts nearly-coherent oscillations are sometimes observed, the frequencies of which are in the rather narrow range between 300 and 600 Hz (see van der Klis 2000; Strohmayer 2001 for reviews). This frequency is interpreted as the NS rotation frequency (or twice this value), due to a hot spot (or spots) in an atmospheric layer of the rotating NS. In 1998, the idea that NSs in LMXBs are spinning at millisecond periods (as suggested by the nearly-coherent oscillations detected during type-I X-ray bursts) was spectacularly demonstrated by the discovery of coherent X-ray pulsations at $\sim 2.5$ ms in SAX J1808.4–3658, a NSXT with an orbital period $P_{\rm orb} = 2$ h (Wijnands & van der Klis 1998). For almost four years SAX J1808.4–3658 has been considered as a rare (unique?) object in which some peculiarity of the system (e.g. its inclination) allowed the detection of the NS spin. However, in the last few months, the situation is dramatically changed as three other NSXT has been discovered in which coherent X-ray pulsations in the millisecond range has been found. We are, therefore, facing a new class of astronomical objects, the Millisecond X-ray Pulsars (MSXPs) that could constitute the bridge between the accretion-powered (X-ray pulsators) and the rotation-powered (Millisecond Radio Pulsar, hereafter MSP) NS sources, as foreseen in the so-called reclycling scenario (see *e.g.* Bhattacharya & van den Heuvel 1991 for a review), according to which the former are the progenitors of the latter.

In this scenario (i) The companion star overflows its Roche lobe and transfers mass (at a rate $\dot{M}$) and angular momentum to the NS *via* a Keplerian accretion disc, thereby spinning it up to millisecond periods (recycling). In fact during this phase the spin period quickly reaches the equilibrium period $P_{\rm eq}$, that is close to the Keplerian period at the magnetospheric radius $R_{\rm M} \propto B^{4/7} \dot{M}^{-2/7}$, the radius where the accretion disc is truncated by its interaction with the magnetic field of the NS. $B \sim 10^8$ G implies $R_{\rm M} \sim 10^6$ cm and $P_{\rm eq}$ in the millisecond range. (ii) Mass transfer ceases: the NS is visible as a MSP, orbiting a low mass, $< 0.3$ M$_\odot$, companion that is the remnant of the $\sim 1$ M$_\odot$ mass donor. LMXBs are believed to correspond to stage (i) and binary MSPs to stage (ii).

### 1.1 Traces of a magneto dipole emitter

All these phenomena take a different flavour in transient systems, since in these sources, as mentioned above, the mass transfer rate varies up to five orders of magnitude between quiescence and outbursts. Because the position of magnetospheric radius $R_{\rm M}$ (the radius at which the accretion disk is truncated by the interaction with the NS magnetic field) is determined by the instantaneous balance of the pressure exerted by the accretion disc and the pressure exerted by the NS magnetic field, $R_{\rm M}$ expands as $\dot{M}$ decreases. Accretion onto a spinning magnetized NS is centrifugally inhibited once $R_{\rm M}$ expands beyond the corotation radius $R_{\rm CO}$, the radius at which the Keplerian angular frequency of the orbiting matter is equal to the NS spin: $R_{\rm CO} = 1.5 \times 10^6\, m^{1/3} P_{-3}^{2/3}$ cm, where $m$ is the NS mass in solar masses and $P_{-3}$ is the NS spin period in milliseconds. In this case the accreting matter could in principle be ejected from the system: this is called propeller phase. If $R_{\rm M}$ further expands beyond the light-cylinder radius (where an object corotating with the NS attains the speed of light): $R_{\rm LC} = 4.8 \times 10^6\, P_{-3}$ cm, the NS becomes generator of magnetodipole radiation and relativistic particles. Indeed, a common requirement of all the models of the emission mechanism from a rotating magnetic dipole is that the space surrounding the NS is free of matter up to $R_{\rm LC}$.

Let us consider the behaviour of a NSXT during the decline of an X-ray outburst. Adopting typical accretion rates in outburst, we can calculate the magnetospheric radius in outburst: $R_{\rm OUTB} \sim R_{\rm NS} \sim 10^6$ cm. During the quiescent phase $\dot{M}$ is reduced by a factor $\sim 10^{-5}$ and

$R_{\rm M}$ expands up to $R_{\rm QUIE} = (10^{-5})^{-2/7} \times R_{\rm OUTB} = 2.7 \times 10^{7}$ cm. For spin periods up to few milliseconds the magnetospheric radius might therefore easily expand beyond the light cylinder radius: accretion is certainly inhibited and is likely that, during the quiescent phase of some NSXT, a magneto dipole emitter switches on as predicted by some authors (see *e.g.* Stella et al. 1994; Burderi et al. 2001). In this case it is plausible to expect that the NS turns-on as a MSP until a new outburst episode pushes $R_{\rm M}$ back, close to the NS surface, quenching radio emission and initiating a new accretion phase. Therefore NSXTs can be the missing link between LMXBs and MSPs.

To observe and study such behaviour is certainly one of the main goals in the whole field of NS physics: the compelling possibility that these systems could swiftly switch from accretors to rotation-powered magneto-dipole emitters during quiescence gives us the opportunity to study a phase that could shed new light on the not yet cleared up radio pulsar emission mechanism. Despite the huge observative effort made to catch, in a NSXT, the transition between the accretion powered regime during the outbursts and the (supposed) rotationally powered regime during quiescence, no definitive proofs that this transition ever occurred have been given up to date. The most embarassing problem is certainly the lack of pulsed radio emission from these systems during quiescence: most NSXT has been thoroughly searched in radio during quiescence with disappointing negative results (Burgay et al. 2003). Several mechanisms have been proposed that could hamper the detection in radio. The most promising is the suggestion that free-free absorption from material ejected from the system by the pulsar radiation pressure (Burderi et al. 2002b) could obscure the radio emission *via* free-free absorption as in the case of PSR 1718–19 (Burderi & King 1994).

New circumstantial evidences that a rotating magneto dipole powers the quiescent emission of SAX J1808.4–3658, comes from high resolution CCD photometry of the quiescent emission from its identified optical counterpart (Homer et al. 2001). In this paper we show that the hypothesis that a radio pulsar is active in these systems during quiescence can explain the puzzling optical counterpart of SAX J1808.4–3658 during quiescence.

## 2 THE OPTICAL COUNTERPART OF SAX J1808.4–3658 IN QUIESCENCE

Homer et al. (2001) reported on high time resolution CCD photometry of this optical counterpart observed when the X-ray source was in quiescence with the 1.9-m telescope at the South African Astronomical Observatory. The optical component was detected at $V \sim 21.5$ mag, much fainter than the value observed during the X-ray 1998 outburst ($V \sim 16.7 - 18.5$ mag during the decline of the outburst, Giles et al. 1999). The two observations in quiescence reported by Homer et al. (2001) were performed on 1999 August 10 and on 2000 July 3, respectively. The 1999 August 10 observation, performed in white light, did not allow an accurate calibration and therefore the luminosity of the optical counterpart has been only estimated to be $V \sim 20$ on that date. Colour images in B, V, and R obtained on 2000 July 3, were analyzed and corrected for interstellar extinction towards SAX J1808.4–3658 adopting the equivalent hydrogen column density estimated from RXTE X-ray spectral fits (Heindl & Smith 1998) as an upper limit, and the galactic value in the same direction (Dickey & Lockman 1990) as a lower limit. In particular Homer et al. (2001) obtained $1.8 \times 10^{-17} < f_V < 2.0 \times 10^{-16}$, where $f_V$ is the flux density in units of erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$. In these data a $\sim 6\%$ semi-amplitude modulation at the 2-h 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 measured optical luminosity in quiescence of $\sim 10^{31}$ erg s$^{-1}$ is inconsistent with the faint intrinsic emission expected from a $\leq 0.14\ M_{\odot}$ companion (Chakrabarty & Morgan 1998). The lack of double-humped morphology, due to an ellipsoidal modulation, again excludes the direct optical emission from the companion as the origin of the observed optical flux and modulation. This lead Homer et al. (2001) to interpret the observed optical flux as due to viscous dissipation in an unirradiated accretion disk truncated at the corotation radius, that is $\simeq 30$ km in the case of SAX J1808.4–3658, and fuelled by a mass transfer rate of $\dot{M} \sim 10^{-11}\ M_\odot\ \mathrm{yr}^{-1}$, consistent with gravitational radiation orbital angular momentum losses. However the expected X-ray luminosity once this matter approaches the magnetospheric radius in quiescence would be $\sim 10^{34} - 10^{35}$ erg s$^{-1}$. In any case, an X-ray emission of at least $\sim 10^{33}$ erg s$^{-1}$ would be required to explain the optical modulation in terms of reprocessing. These requirements are incompatible with the measured X-ray quiescent luminosity of this source, that is $5 \times 10^{31}$ erg s$^{-1}$ (Campana et al. 2002).

## 2.1 Irradiation by a rotating magneto-dipole emission

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. The magnetic field of SAX J1808.4–3658 is constrained in the quite narrow range $(1-5) \times 10^8$ Gauss (see Di Salvo & Burderi 2003). Adopting this magnetic field we can calculate the spin-down energy loss of the pulsar: $L_{\mathrm{PSR}} = (2/3c^3)\mu^2\omega^4 = 3.85 \times 10^{35} P_{-3}^{-4}\mu_{26}^2$ erg s$^{-1}$ $\sim (1-25) \times 10^{34}$ erg s$^{-1}$, where $\omega$ is the rotational frequency of the NS, $\mu$ is the NS magnetic moment, and $\mu_{26}$ is the NS magnetic moment in units of $10^{26}$ G cm$^3$.

In the hypothesis that the pulsar beam heats the ring-shaped remnant accretion disk (from the previous outburst phase) and/or the facing 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. For the accretion disk this fraction, $f_D$, 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: $f_D \simeq 1.6 \times 10^{-2}\alpha^{-1/10}\dot{M}_{-10}^{3/20} m_1^{-3/8} R_{10}^{1/8}$, where $\alpha$ is the viscosity parameter, $\dot{M}_{-10}$ is the mass accretion rate in units of $10^{-10}\ M_\odot\ \mathrm{yr}^{-1}$, $m_1$ 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 $\sim 0.8$ of the Roche lobe radius, $R_{L1}$, of the primary. Assuming 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 $f_D$ depends weakly on the mass accretion rate), we find $f_D \sim (1.5 - 2.1) \times 10^{-2}$. The fraction $f_C$ of the pulsar spin-down luminosity that will be reprocessed by the companion star and emitted in the optical band can be written as: $f_C = 2\pi a^2(1-\cos\theta)/(4\pi a^2)$, where $a$ is the the orbital separation and $\theta$ 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 where $R_{L2}/a = 0.49q^{2/3}/[0.6q^{2/3} + \ln(1+q^{1/3})]$ (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: $f_C \sim 1.1 \times 10^{-2}$.

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: $f = f_D + f_C \sim 3.1 \times 10^{-2}$ (where we adopted $f_D \sim 2.0 \times 10^{-2}$), giving an optical reprocessed luminosity of $\sim 3 \times 10^{32}\mu_{26}^2$ erg s$^{-1}$. At a distance of 2.5 kpc, and adopting an average inclination angle $\langle i \rangle = 50°$ of the normal to the plane of the disk with respect to the line of sight (that is the average value of $\cos i$), this corresponds to fluxes of $F_C \sim 1.4 \times 10^{-13}\mu_{26}^2$ erg cm$^{-2}$ s$^{-1}$ and $F_D \sim 3.5 \times 10^{-13}\mu_{26}^2$ erg cm$^{-2}$ s$^{-1}$, from the companion and the disk respectively. The corresponding blackbody temperature are estimated to be $T_C \sim 5430\,\mu_{26}^{1/2}$ K for the companion star and $T_D \sim 5080\,\mu_{26}^{1/2}$ K for the irradiated surface of the disk.

From the sum of two blackbodies of temperatures $T_C$ and $T_D$ and fluxes $F_C$ and $F_D$, we calculated the predicted apparent magnitudes in the three bands used during the July 2000 observation of Homer et al. (2001). The results are shown in Table 1.

**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 |

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. In conclusion, we suggest that the observed optical flux and modulation in quiescence may be the first evidence that a radio pulsar is active in this system during quiescence.

**Acknowledgements** We kindly thank the organizers, the LOC and the SOC, of the workshop in Vulcano for their great job during and after the meeting.

## References

Bhattacharya, D., & van den Heuvel, E.P.J., 1991, Phys. Rep., 203, 1

Burderi, L., & King, A. R., 1994, ApJ, 430, L57

Burderi, L., et al., 2001, ApJ, 560, L71

Burderi, L., D'Antona, F., Burgay, M., 2002b, ApJ, 574, 325

Burgay, M., et al., 2003, ApJ, 589, 902

Campana, S., et al. 2002, ApJ, 575, L15

Campana, S., et al., 1998, A&ARev, 8, 279

Chakrabarty, D., & Morgan, E. H. 1998, Nature, 394, 346

Dickey, J. M., & Lockman, F. J., 1990, ARA&A, 28, 215

Di Salvo, T., & Burderi, L., 2003, A&A, 397, 723

Eggleton, P. P., 1983, ApJ, 268, 368

Giles, A. B., Hill, K. M., Greenhill, J. G., 1999, MNRAS, 304, 47

Heindl, W. A., & Smith, D. M., 1998, ApJ, 506, L35

Homer, L., Charles, P. A., Chakrabarty, D., van Zyl, L., 2001, MNRAS, 325, 1471

Shakura, N. I, & Sunyaev, R. A. 1973, A&A, 24, 337

Stella, L., et al., 1994, ApJ, 423, L47

Strohmayer, T. E., 2001, Advances in Space Research, 28, 511

van der Klis M., 2000, ARA&A, 38, 717

Wijnands, R., & van der Klis, M., 1998, Nature, 394, 344