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The Optical Counterpart of SAX J1808.4−3658 in Quiescence: Evidence of an Active Radio Pulsar?

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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. 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.

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 $10^{31} - 10^{34}$ ergs/s. On occasions they exhibit outbursts, with peak luminosities between 10^{36} and 10^{38} ergs/s, 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 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 $\sim 10^5$.

According to the recycling scenario (see, e.g., Bhattacharya & van den Heuvel 1991 for a review), LMXBs, in which the NS can be spun-up by accretion torques to millisecond periods, are the progenitors of the rotation-powered millisecond radio pulsars (hereafter MSPs). In 1998, the idea that neutron stars (NSs) in LMXBs were spinning at millisecond periods was spectacularly demonstrated by the discovery of coherent X-ray pulsations at $P_{\rm spin} = 2.5\,{\rm ms}$ in SAX J1808.4−3658, a transient source with an orbital period $P_{\rm orb} = 2\,{\rm h}$ (Wijnands & van der Klis 1998). In the last two years four other transient X-ray sources have been discovered in which coherent X-ray pulsations in the millisecond range have been found (see Wijnands 2003 for a review).

In the classical picture the accretion disk is truncated at the magnetospheric radius, $R_{\rm M}$, which is determined by the instantaneous balance of the pressure exerted by the accretion disc and the pressure exerted by the NS magnetic field; therefore $R_{\rm M}$ expands as $\dot{M}$ decreases. In these sources, as mentioned above, the mass transfer rate decreases up to five orders of magnitude in quiescence. If $R_{\rm M}$ expands beyond the light-cylinder radius (where an object corotating with the NS attains the speed of light),

$$R_{\rm LC} = 4.8 \times 10^6\, P_{-3}\ {\rm cm},$$

the NS is expected to become generator of magnetodipole radiation and relativistic particles (i.e., a radio pulsar; 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.

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. The optical emission and modulation during quiescence is therefore the first (indirect) evidence that a magneto-dipole rotator switches-on in these systems during quiescence.

2. The Optical Counterpart to SAX J1808.4−3658

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. In these data a $\sim 6\%$ semi-amplitude modulation at the 2-hr orbital period of the system is 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 is $\sim 10^{31}\,{\rm erg\,s^{-1}}$, inconsistent with the faint intrinsic emission expected from a $\leq 0.14\,M_\odot$ companion (Chakrabarty & Morgan 1998). Also 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. This lead Homer et al. (2001) to interpret the observed optical flux as optical emission from the outer zones of an accretion disk with an accretion rate of $10^{-11}\,M_\odot$/yr.

However the expected X-ray luminosity once this matter approaches the magnetospheric radius in quiescence would be $\sim 10^{34} - 10^{35}$ erg/s. In any case, an X-ray emission of at least $\sim 10^{33}$ erg/s 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 $5 \times 10^{31}\,{\rm erg\,s^{-1}}$

(Campana et al. 2002). We show that these difficulties are solved if we make the case that actually the irradiation of the companion star and/or of the remnant disk is due to illumination by the *radio pulsar*, which is active during quiescence, since the magnetospheric radius is pushed beyond the light cylinder radius.

3. Irradiation by Rotating Magneto-Dipole Emission

Assuming 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 to 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:

$$L_{PSR} = (2/3c^3)\mu^2\omega^4 = 3.85 \times 10^{35} P_{-3}^{-4}\mu_{26}^2 \text{ ergs/s} \sim (1-25)\times 10^{34} \text{ ergs/s},$$

where ω is the rotational frequency of the NS, μ is the NS magnetic moment, and μ_{26} is the NS magnetic moment in units of $10^{26}\,\mathrm{G\,cm}^3$.

If 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 with isotropic emission, we can evaluate the fraction of the irradiation luminosity that will be intercepted and reprocessed by the disk and the companion star, which are $f_D \sim (1.5-2.1)\times 10^{-2}$ and $f_C \sim 1.1\times 10^{-2}$, respectively. 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: $f = f_D + f_C \sim 3.1\times 10^{-2}$, giving an optical reprocessed luminosity of $\sim 3\times 10^{32}\mu_{26}^2$ ergs/s. 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. Note that the fluxes reported in Homer et al. (2001) may be a factor ~ 2 less due to the presence of a contaminating source in the field (D. Chakrabarty, private communication). In this case, the optical modulation can be even higher than 6%, and the irradiating luminosity of $\sim 10^{33}$ ergs/s is still required in their model. Therefore, the uncertainty of a factor of 2 does not change significantly the conclusions of this paper. In principle, a better measurement of the optical luminosity of SAX J1808.4−3658 in quiescence will allow us to constrain the magnetic field.

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