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LETTER

Letter to the Editor

An evolutionary model for SAX J1808.4–3658

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Abstract. An evolutionary scenario to explain the transient nature and short total duration of the X-ray burst of SAX J1808.4–3658 is proposed. An optical companion of the neutron star(a"turn-off" Main-Sequence star) fills its Roche lobe at the orbital period ($P_{\rm orb}$) $\sim$ 19 hours. During the initial high mass-transfer phase when the neutron star is a persistent X-ray source, the neutron star is spun up to a millisecond period. Due to its chemical composition gradient, the secondary does not become fully convective when its mass decreases below 0.3 $M_{\odot}$, hence a magnetic braking remains an effective mechanism to remove orbital angular momentum and the system evolves with Roche-lobe overflow towards a short orbital period. Near an orbital period of two hours the mass transfer rate becomes so small ($\sim 10^{-11} M_{\odot}$/yr) that the system can not continue to be observed as a persistent X-ray source. During further Roche-lobe filling evolution deep mixing allows the surface of secondary to become more and more helium rich. Since the accreted matter is helium rich, it is easy to explain observed short total duration of the burst. This evolutionary picture suggest that radio emission can be observed only at shorter wavelength's. Our model predicts a faster orbital period decay than expected if the orbital evolution is driven only by gravitational wave radiation.

Key words: stars: binaries: close – stars: evolution – stars: neutron – stars: pulsars: individual: – X-rays: bursts

1. Introduction

The transient X-ray burster SAX J1808.4–3658 was discovered in September 1996 with the BeppoSAX Wide Field Cameras (in't Zand et al., 1998). Two very bright type I X-ray bursts with short decay times $\sim$ 8 s (2–8 keV) separated by 14.61 hours were observed. The double-peaked time history of both bursts at high energies suggests a peak luminosity close to the Eddington limit which implies a distance to this object of 4 kpc (in't Zand et al. 1998). The observed peak flux of the steady emission was about 2×10^{-9}erg s^{-1} cm^{-2} at 2–10 keV. For a power-law spectrum and a distance, d = 4 kpc the luminosity is $\sim 6\times10^{36}$ erg s^{-1} and for a bremsstrahlung spectrum the luminosity is $\sim5\times10^{36}$erg s^{-1}. From these values the mean accretion rate is $\sim 3\times10^{16}$g s^{-1} (assuming that the neutron star radius is equal to 10 km and the mass is 1.4 $M_{\odot}$). Recently a transient source XTE J1808–365, positionally coincident with SAX J1808.4–3658 to within a few arcmin, was detected with the Rossi X-ray Timing Explorer. The 2–10 keV X-ray flux ($F_{\rm X}$) on 1998 April 11 was 1.5×10^{-9}erg s^{-1}cm^{-2}(Marshall, 1998). Wijnands & van der Klis (1998) discovered a coherent 2.49 millisecond signal from this source and they estimated an upper limit on the magnetic field strength B of $\sim (2-6)\times10^{8}$ Gauss. Gilfanov et al. (1998) found that between April 25 and 29 1998 this X-ray pulsar showed an abrupt decline of the X-ray luminosity which they interpreted as a result of centrifugal inhibitation at the luminosity level of a few $\times10^{35}$erg s^{-1}. From this they estimated an upper limit on the magnetic field strength of B$\leq 3.5\times10^{7}$ d(kpc) $(M/1.4M_{\odot})^{1/3}(F_{\rm X}/10^{-9} ergs^{-1}cm^{-2})^{1/2}R_{6}^{-8/3}$ Gauss, which for d = 4 kpc and a canonical neutron star mass (1.4 $M_{\odot}$) and radius (R= 10 km) is 1.4 $\times10^{8}$ Gauss. Gilfanov et al. (1998) have estimated that the total energy of the 1998 outburst was $\approx 7.8\times10^{42}$ erg (3–150 keV), corresponding to an accreted mass of $\sim10^{-11} M_{\odot}$. Since the time between two ourburst was $\sim$ 1.5 years the average accretion rate is $\sim10^{-11} M_{\odot} yr^{-1}$.

Chakrabarty & Morgan (1998) found the source is a binary with orbital period of 2.01 hours, and a very small mass function f($M_{\odot}$)=3.85$\times10^{-5} M_{\odot}$. Assuming a random distribution of binary inclinations, the a priori probability of observing a system with inclination i or smaller is (1–cos i). For an assumed 1.35 $M_{\odot}$ pulsar, the 95%-confidence upper limit on the secondary mass is $M_2 < 0.14 M_{\odot}$ and for a $2M_{\odot}$ pulsar this limit is 0.18$M_{\odot}$. Chakrabarty & Morgan (1998) discussed a possible evolutionary scenario of this system, and proposed that it is closely related to the "black-widow" millisecond radio pulsar (PSR 1957+20, PSR J2051–0827) which are evaporating their companion through irradiation.

Filippenko & Leonard (1998) have found that Keck spectra (range 554-685 nm) of the suspected optical counterpart (Roche et al. 1998, Giles et al. 1998) of SAX J1808.4-3658 reveal a possible very weak, double-peaked H_{α} emission line.

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In this short note we propose a model of the evolutionary history for this system which is able to explain the main observed properties.

2. Evolutionary picture

Orbital period determination for low-mass X-ray binaries (LMXB) have been a rather difficult task. Up to now $\sim$ 20 LMXB with the orbital periods less than one day are known (van Paradijs, 1995). If we compare the distribution of the orbital periods of LMXB and the systems with white dwarfs as accretor (catalysmic variable – CV) then we can see that the orbital period distribution for two classes (LMXB and CV) is different. For both classes the orbital periods show a clustering between 3–10 hours. There are no LMXB in the CV period gap of 2–3 hours but if the orbital period distribution for CV shows second peak between 1–2 hours there was no LMXB between orbital periods from 50 min to 3 hours (White & Mason, 1985). So SAX J 1808.4–3658 is first transient X-ray source discovered in this orbital period range.

Based on data for soft X-ray transients and persistent low-mass X-ray binaries with known distance and orbital period van Paradijs (1996) showed that for these systems the distributions in a ($P_{\rm orb}$, $\dot{M}$) diagram can be understood with the dwarf nova instability criterion adapted to account for X-ray heating of the accretion disk. Soft X-ray outbursts can occur if the mass transfer rate, $\dot{M}$, is below a critical value $\dot{M}^{irr}_{\rm crit}$ (which depends on orbital period). For neutron star low-mass X-ray binaries King et al. (1996) have obtained the following formula for the critical mass accretion rate $\dot{M}^{irr}_{\rm crit}$

$$\dot{M}^{irr}_{\rm crit} \approx 5.0 \times 10^{-11} M_{\rm ns}^{2/3} \left(\frac{P_{\rm orb}}{3hrs}\right)^{4/3} M_{\odot} yr^{-1} \qquad (1)$$

where $M_{\rm ns}$ is the neutron star mass in units of solar mass.

The evolutionary history of an LMXB and CV depends on two main time scales: (i) The hydrogen burning time scale $t_{\rm nuc}$ and (ii) the angular momentum loss time scale $t_{\rm am}$ by magnetic braking, gravitational radiation and by mass loss from the system.

First case

If the Roche lobe filling secondary is an unevolved main-sequence star then $t_{\rm nuc} \gg t_{\rm am}$. Near the orbital period $\sim$ 3 hours the magnetic braking switches off and the secondary loses its Roche lobe contact. Second Roche lobe filling takes place near the orbital period of 2 hours and mass exchange rate is now $\approx 10^{-10}$ $M\odot$/yr. Since this mass accretion rate is larger than $\dot{M}^{irr}_{\rm crit}$ the persistent X-ray sources with short orbital periods must be observed.

In the period gap the evolutionary paths for CV and LMXB may greatly differ. A neutron star with sufficiently weak magnetic fields accreting for a long time from a surrounding Keplerian disk can be spun up to millisecond periods. Van den Heuvel & van Paradijs (1988) proposed that the evaporation of

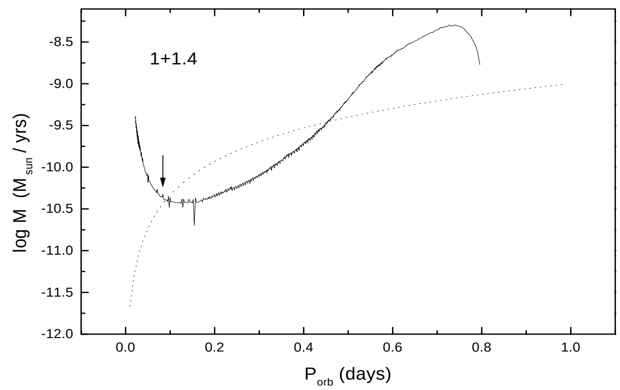

Fig. 1. Evolution of the mass accretion rate versus orbital period. The critical mass accretion rate (Eq. (1)) is also shown (dashed line). The arrow shows the position of SAX J1808.4–3658

companion stars (induced by MSP) could account the lack of persistent low-mass X-ray sources below the period gap.

Second case

If the Roche lobe filling secondary is an "turn–off" Main–Sequence star then$t_{\rm am}{\sim}t_{\rm nuc}$. For this case according to the results of computations (Tutukov et al. 1985, Pylyser & Savonije, 1989, Ergma et al., 1998) at first the mass exchange proceeds on the thermal time scale of the secondary, but later $\dot{M}$ quickly decreases. Due to a chemical composition gradient the secondary did not become fully convective when its mass had decreased below 0.3 $M_{\odot}$. Magnetic braking is still the most effective mechanism to remove orbital angular momentum and the system evolves towards a short orbital period via Roche-lobe overflow. In the period gap the mass accretion rate is very low ($\ll$ $10^{-10}M_{\odot}$/yr) which is less than the critical mass accretion rate for system to be persistent X-ray source.

First case allows easily to understand the evolution of the LMXB with the orbital period between 3 and 10–12 hours.

Since SAX J1808.4 –3658 is transient X-ray source we propose that the progenitor SAX J1808.4–3658 evolves according to second case. Using the evolutionary program of Sarna & De Greve (1994, 1996) we have calculated an evolutionary sequence for a binary with a 1.4$M_{\odot}$ neutron star and a 1$M_{\odot}$ companion. The secondary fills its Roche lobe a $P_{\rm orb}$ = 0.8 days. When the orbital period is two hours the $\dot{M}$, is 4.7$\times10^{-11}$ $M_{\odot}yr^{-1}$ and the surface hydrogen abundance has been decreased to X = 0.3. As we will see later this value is important to explain the short duration of the X-ray bursts.

In Fig. 1 we have drawn the value of the critical mass accretion rate as a function of $P_{\rm orb}$. Near an orbital period of two hours the calculated mass accretion rate is below the critical value and hence the system can not be a persistent X-ray source.

Chakrabarty & Morgan (1998) proposed that if the X-ray bright state lasts long enough (or if the pulsations remain detectable in quiescence), further X-ray longer-term timing observations may yield a detection of orbital period evolution, which would probe effects of gravitational radiation, tital interactions and mass loss. If the orbital evolution is driven by gravitational wave radiation then the orbital period will decay according to (Landau & Lifshitz, 1971)

$$\dot{P}_{\rm orb} = -\frac{192\pi}{5}\left(\frac{2\pi}{P_{\rm orb}}\right)^{5/3}\frac{M_{\rm s}}{M_\odot}\frac{M_{\rm ns}}{M_\odot}\left(\frac{M_{\rm T}}{M_\odot}\right)^{-1/3} \times\left(\frac{GM_\odot}{c^3}\right)^{5/3} \quad (2)$$

where $\frac{GM_\odot}{c^3}$ = 4.925 $\times 10^{-6}$s $M_{\rm s}$ is the mass of secondary and $M_{\rm T}$= $M_{\rm s}$ +$M_{\rm ns}$ is the total mass. If the secondary has a mass of $0.05M_\odot$ and $M_{\rm ns}$=1.4$M_\odot$ (as discussed by Chakrabarty & Morgan, 1998) then $\dot{P}_{\rm orb}\sim-$ 8.1 $\times 10^{-14}$. In our model, since the orbital evolution is driven by magnetic braking the orbital period decay is faster ($\sim -4.5\times 10^{-13}$). So the determination of the value of orbital period decay may give important clue to understanding the prehistory of this system.

2.1. The chemical composition of the secondary and the X-ray bursts

In our scenario the secondary is a helium rich star. There are two systems, namely MXB 1916–05 ($P_{\rm orb} = 50$ min) and MXB 1820–30 ($P_{\rm orb} = 11.4$ min), which according to current understanding of the low-mass binary evolution with compact object as an accretor, must have a Roche-lobe filling helium rich secondary in order to explain its short orbital period (Paczynski & Sienkewicz, 1981).

Computations of X-ray bursts at the surface of accreting neutron stars have shown (Ayasly & Joss, (AJ) 1982, Kudrjashov & Ergma,1983) that a short total duration $\tau_{\rm d}$ of the burst is possible only if the matter is helium rich (X$\leq$0.2-0.3, where X is the hydrogen abundance by mass) before unstable burning starts. It may be possible that during the accretion phase the hot CNO hydrogen burning takes place in the accreted matter on a timescale $\sim 10^2\times(N_{\rm p}/N_{\rm CNO})$ s $\approx 10^5$ s. If the recurence time between two succesive burst is longer that this hot CNO hydrogen burning time the hydrogen may be exhausted at the bottom of the accreted envelope. Crude estimate using the bursts light curve published by in't Zand et al. (1998) gives $\tau_{\rm d}\sim$ 14–15 s. Let us analyze the observed data for the X-ray burst using the AJ numerical models. Since the accretion rate (from observations) is a few times 10^{16}g s^{-1} then we may compare it with the AJ model 1 which has been computed with a similar mass accretion rate (Z = 0.01 where Z is the metallicity of the accreted matter). In this model the hydrogen abundance, $X_{\rm b}$, at the base of the freshly accreted matter prior to the flash is 0.59. The burst total duration, $\tau_{\rm d}$, is 34 s and the burst recurence time, $t_{\rm rec}\sim$ 4.7 hours. The maximum burst luminosity $L_{\rm max}$ is 5$\times 10^{37}$erg s^{-1}. The AJ model 3, in which the mass accretion rate is one order magnitude less, has $X_{\rm b}$ = 0.0004, $t_{\rm rec}\sim$ 16.3 hours, $\tau_{\rm d}\sim$ 7 s and $L_{\rm max}$ = 2.5$\times 10^{37}$erg s^{-1}. The AJ model 16 with the same accretion rate as for model 1, but with Z=0.001, has $X_{\rm b}$ = 0.65, $t_{\rm rec}\sim$ 11.2 hours, $\tau_{\rm d}\sim$ 38 s and $L_{\rm max}$ = 7.5$\times 10^{37}$erg s^{-1}. From these results it can clearly be seen that in order to have a short total duration of the burst, the hydrogen must either be exhausted or the accreted matter must be helium rich in the envelope. In SAX J1808.4–3658 the time between two observed successive bursts is $\sim$ 14 hours, which is much longer than for model 1 with a similar mass accretion rate. One possible explanation is that the amount of CNO elements is reduced due to spallation, as it was discussed by Bildsten et al. (1992), and hence the recurrence time will increase (compare AJ models 1 and 16). It is also possible to speculate that the burst recurence time may increase with increase of the radius of the neutron star (referee comment). For example in AJ model 14 ($R_{\rm ns}$=13 km) the recurrence time is $\sim$ 16 hours. In our analyze we used AJ standart model results ($R_{\rm ns}$ = 6.57 km) since according to in't Zand et al. (1998) a burst emitting sphere radius is of 8 km (at the distance of 4 kpc). Although the neutron star radius was determined by in‘t Zand et al. using a simple black body fit to the burst spectrum and can therefore underestimate the radius of the emitting sphere (Titarchuk, 1994).

So to explain the short total duration of the burst and the Eddington luminosity we propose that the accreted matter must be helium rich. In order to explain long recurrence time one would need either reduced Z value or large $R_{\rm ns}$.

2.2. The possibility of detection of the millisecond radiopulsar

Since the millisecond X-ray pulsar SAX J1808.4-3658 has orbital parameters very close to those of the eclipsing binary pulsar system PSR J2051-0827, it has been proposed (Chakrabarty & Morgan, 1998, Wijnands & van der Klis, 1998) that this system may emerge as a radio pulsar after the X-ray state ends. Lets us estimate the optical depth for the free–free process (Illarionov & Sunyaev, 1975)

$$\tau_{\rm ff} = \frac{100\left(\dot{M}/\dot{M_{\rm Edd}}\right)^2}{M_{\rm s}+M_{\rm ns}}\left(\frac{\lambda}{75cm}\right)^2\left(\frac{T}{10^4}\right)^{-1.5} \times\left(\frac{P_{\rm orb}}{1yr}\right)^{-2} \quad (3)$$

where $\dot{M_{\rm Edd}}$ is the Eddington mass accretion rate. Accepting $\dot{M}\sim 10^{-11}M_\odot yr^{-1}$, T=6000 (less than the hydrogen ionization temperature), $M_{\rm ns} = 1.4M_\odot$, $M_s = 0.1M_\odot$, $\lambda = 3$ cm and $P_{\rm orb} = 2$ hours we can find that $\tau_{\rm ff}$ is $\sim$ 1, which means that at $\lambda < 3$ cm it may be possible to observe radio emission. For longer wavelenghts (20 or 70 cm) $\tau_{\rm ff}$ is greater that unity.

3. Conclusion

We propose that the progenitor of SAX J1808.4–3658 was a low mass binary with a neutron star and a secondary that filled its Roche- lobe at the turn-off Main-Sequence.During the bright X-ray phase the neutron star will spin-up to a millisecond period. Due to a chemical composition gradient, the secondary does not become fully convective when its mass has decreased below 0.3 $M_\odot$ and magnetic braking is therefore still the most effective mechanism to remove orbital angular momentum. Near an orbital period of two hours the mass transfer rate is so small ($\sim 10^{-11} M_{\odot}$yr^{-1}) that the system can not be a persistent X-ray source. In our evolutionary scenario, due to deep mixing, the secondary is a helium rich star. Since the accreted matter is helium rich it is easy to expain the observed short total duration of the burst. It is estimated that in this evolutionary picture it may be possible to observe radio emission from the pulsar only at short wave lenghts, $\lambda <$ 3cm. Our model predicts a faster orbital period decay than in the case where the orbital evolution is driven only by the gravitational radiation.

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