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THE EVOLUTIONARY STATUS OF PSR 1259–63

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ABSTRACT

The PSR 1259–63 system is unique in that it is the first radio pulsar found to be in a binary system with a massive main sequence companion. As such, it may be the evolutionary missing link connecting the radio pulsars to the X-ray emitting Be binaries. In this paper, we consider the conditions under which PSR 1259–63 may be the progenitor of the less eccentric, more slowly rotating X-ray Be binaries such as 4U0115+63, A0535+26, and A0538–66. Scenarios invoking the interaction of the pulsar with the stellar wind of the companion are proposed to account for the rapid spin-down phase that must occur in this system if it is evolutionarily linked to accreting X-ray binaries. The unexpected X-ray emission observed from PSR 1259–63 may indicate that the interaction between the pulsar and the Be star occurs at greater distances and produces a greater spin-down efficiency than has been previously calculated.

1. INTRODUCTION

PSR 1259–63 is a 47.7 msec radio pulsar which is apparently in a 3.4 year, highly eccentric ($\epsilon = 0.87$) binary orbit with the ~ 10 solar mass Be star, SS 2883 (Johnston et al., 1992). The pulsar has a relatively young characteristic age of 3×10^5 y, and a moderate magnetic field strength of 3×10^{11} G (Johnston et al., 1993).

Nonpulsed but variable X-ray emission has been detected from the binary system containing the radio pulsar PSR 1259–63 during two pointed ROSAT observations, taken five months apart (Cominsky, Roberts, and Johnston, 1993). Detectable X-ray flux has only been observed post-apastron, and has increased with orbital phase. It is significantly greater than what would be expected from the Be star's corona, and is too variable, yet not sufficiently pulsed, to be due to rotational spin-down losses. Low-level accretion is possible only if the radio pulsar inhibition mechanism can be overcome. However, emission from a shocked pulsar wind remains a viable mechanism. The X-ray observations and the standard scenarios for X-ray emission are briefly reviewed in the sections that follow.

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2. OBSERVATIONS

Cominsky, Roberts, and Johnston (1993) have obtained $\sim 46 \times 10^3$ s of ROSAT Position Sensitive Proportional Counter (PSPC) data in two multiday periods, separated by ~ 5 months. The ROSAT PSPC images clearly indicate a significant source at a position consistent with PSR 1259–63. The intensity of the source is $2.38 \pm 0.18 \times 10^{-2}$ counts s^{-1} and $3.15 \pm 0.11 \times 10^{-2}$ counts s^{-1} during the 1992 August 30–September 4 and the 1993 February 7–16 intervals, respectively.

Assuming a distance to the system of 1.5 kpc (Johnston et al., 1993), the X-ray luminosity in the PSPC 0.1–2.4 keV band that is required to explain the observed count rates is at least 6×10^{32} ergs s^{-1} and may be as high as 1×10^{34} ergs s^{-1}, depending on the assumed spectral model. Pre-apastron ROSAT PSPC observations of PSR 1259–63 by Bailes and Watson detected less than ten photons (private communication), yielding a 99% confidence upper limit of $< 0.26 \times 10^{-2}$ counts s^{-1} during a multiday observation that occurred in 1992 February. The system was also observed prior to apastron in 1991 September using the Ginga LAC. Makino and Aoki (private communication) have found an upper limit for these observations of 0.1 mCrab (2–10 keV), equivalent to an X-ray luminosity of $\sim 6 \times 10^{32}$ ergs s^{-1} (assuming a Crab-like spectrum).

The overall flux from PSR 1259–63 has increased by at least a factor of 10 between the pre- and post-apastron observations, and by an additional $\sim 50\%$ between the first and second post-apastron observation periods, which are separated by about five months. Significant variability on a time scale of hours was also observed during the second observation period. However, no significant pulsed emission has been detected in either observation period, nor in the entire data set. Three sigma upper limits to the pulsed fraction are 21%, 9%, and 9% for the first interval, the second (longer) interval, and the entire dataset, respectively.

Figure 1 from Cominsky, Roberts, and Johnston (1993) depicts the orbital locations of the Ginga observation and the three sets of ROSAT observations.

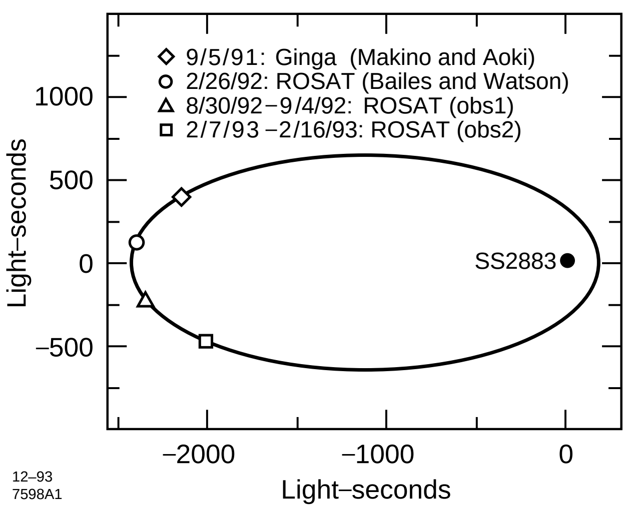

Fig. 1. Schematic of the orbit of PSR 1259–63 indicating observation times. The companion, SS2883, is placed at the center-of-mass of the system.

3. THEORY

In order to account for the X-ray emission observed from the PSR 1259–63 system post-apastron, Cominsky, Roberts, and Johnston (1993) considered four different types of scenarios: coronal emission from the Be star companion, low-level accretion onto the neutron star, rotational spin-down energy from the neutron star, and emission from interacting winds. They found that the luminosity observed from PSR 1259–63 was too high by factors ranging from 15–700, depending on the spectral model chosen. The X-ray luminosity in the ROSAT band, if consistent with previously observed B and Be stars would only be $\sim 3 \times 10^{31}$ ergs s^{-1} (Pallavicini et al., 1981; Meurs et al., 1992). Rotational spin-down was also ruled out as a likely X-ray emission mechanism, due to the small percentage of the spin-down luminosity that could be present as pulsed flux (less than 0.1%) and the extreme variability on short time scales (more than a factor of 10 in five months.)

Direct accretion onto the neutron star does not seem likely to occur, due to the radio pulsar inhibition mechanism (Illarionov and Sunyaev, 1975; Stella, White, and Rosner, 1986). This mechanism should operate until the rapidly rotating radio pulsar spins down to a period where the pressure of the infalling material is greater than the pressure of the relativistic pulsar wind. At this time, the system may begin to accrete for low values of the stellar wind velocity and high rates of mass capture onto the neutron star. Otherwise, X-ray emission will be centrifugally inhibited. High mass capture rates and low stellar wind velocities are most likely to occur at periastron. However, the lack of any historically observed bright ($\sim 10^{36}$ to 10^{37} ergs s^{-1}) X-ray transient outbursts at previous periastron passages (which could have been observed by X-ray satellites between 1970 and 1991) indicates that these conditions have not yet existed (Cominsky, Roberts, and Johnston, 1993.)

As discussed in detail by Kochanek (1993), if the stellar and pulsar winds interact, shocks should occur between the two stars. The shocked stellar wind should radiate X-rays due to thermal bremsstrahlung. The X-ray luminosity expected in this case is a sensitive function of the ratio of the strength of the stellar wind to that of the pulsar (λ). In his model, λ is assumed to be much greater than one, and the calculated emission from the stellar wind shock would be a factor of 5–10 less than the expected coronal emission (see above). However, the pulsar wind should also be shocked, and it is not clear how the available energy in this shock (which comes from the pulsar's spin-down energy and is potentially much greater) will emerge. For values of $\lambda \geq 20$, it seems possible to release as much energy as was observed (see Figure 6 in Kochanek 1993).

Davies and Pringle (1981) considered four phases in the evolutionary history of a binary neutron star system: radio pulsar spin-down phase, very rapid rotator, supersonic (propellar) rotator, and subsonic rotator. Only after the last phase does the neutron star begin to accrete. We wish to determine whether or not the PSR 1259–63 system will evolve into a more circular, more slowly rotating system like the standard X-ray Be binaries, such as 4U0115+63. In order to do this, the neutron star's rotation rate must slow down considerably within the relatively short lifetime of the Be companion star, SS2883 ($\sim 10^7$ years.) Considering first the radio pulsar spin-down phase, and assuming the pulsar's magnetic moment $\mu = 3 \times 10^{29}$ G cm^3, the stellar wind speed, $v_o \sim 300\,\mathrm{km\,s^{-1}}$, and a mass capture rate by the neutron star, $\dot{M}_c \sim 10^{15}$ g s^{-1}, the critical spin period for transition from this radio pulsar spin-down phase to the next phase is given by:

$$P = 0.8\left(\frac{\mu}{10^{30}\ \mathrm{G\ \ cm^3}}\right)^{1/3}\left(\frac{\dot{M}_c}{10^{15}\ \mathrm{g\ \ s^{-1}}}\right)^{-1/6}\left(\frac{M}{\mathrm{M_\odot}}\right)^{1/3}\left(\frac{v_o}{10^3\ \mathrm{km\ \ s^{-1}}}\right)^{-5/6} \approx 1\ \mathrm{second}\ .$$

This will happen on a time scale of:

$$\tau = 3.3 \times 10^7 \left(\frac{P}{1\ \mathrm{s}}\right)^2 \left(\frac{\mu}{10^{30}\ \mathrm{G\ cm^3}}\right)^{-2} \left(\frac{I}{10^{45}\ \mathrm{g\ cm^2}}\right)^{-2} \approx\ 1.5 \times 10^9\ \mathrm{years}\ ,$$

much longer than the life of the Be companion (and there are still three more phases to consider.) It would therefore appear as though this system will not be able to evolve into a traditional X-ray Be binary. However, if conditions at periastron act to spin down the system (e.g., by the propellar mechanism), or if the X-ray emission observed post-apastron from the system is indicative of a propellar-type spin-down, the time required for accretion to begin could be greatly shortened.

4. CONCLUSIONS

The X-ray emission seen from the PSR 1259–63 system is not likely to be explained by coronal emission from the Be companion, rotational spin-down energy, or accretion onto the neutron star's surface. A likely source of energy for the emission is a shocked pulsar wind. This system will not evolve into an accreting X-ray Be binary within the lifetime of the Be companion, unless the neutron star can spin-down more rapidly than expected. This could occur by a propellar mechanism which operates at periastron, and/or post-apastron, giving rise to the X-ray emission which was observed.

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