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ON THE ORIGIN OF THE ECLIPSING PULSAR PSR B1718−19 AND ITS WIND

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ABSTRACT

The recent discovery of PSR B1718−19 in NGC 6342, the first globular-cluster pulsar with a high magnetic field and the third eclipsing pulsar (Lyne et al. 1993) may lead to an unambiguous test of pulsar recycling and field decay. The reason for this is that one expects to find rather different companion masses depending on whether the binary was formed via capture of a companion by an old neutron star or whether the neutron star was born in the binary via accretion-induced collapse of a white dwarf. The mass difference leads to almost 2 mag difference in the expected I-magnitude of the companion, which means that one can easily distinguish between the two cases using CCD observations. The mass flow in the system that causes modulation of the radio flux with orbital phase is, in our view, not due to ablation of the companion by radiation from the pulsar. Instead, we propose that the companion is similar to the very active stars found in RS Canum Venaticorum binaries; the cause of mass loss in these binaries is thought to be the combination of convective activity natural to late-type stars and the rapid rotation to which they are forced in close binaries. The analogy with such a well-studied class of binaries offers new perspectives for tackling some of the unsolved problems in the evolution of neutron star binaries.

Subject headings: binaries: close — pulsars: individual (PSR B1718−19) — stars: evolution — stars: mass loss

1. INTRODUCTION

The radio pulsar PSR B1718−19 has a remarkable combination of properties because some of its characteristics are commonly associated with young objects and others with old ones. Among the former are its high magnetic field of 1.5×10^{12} G and its slow spin period of 1 s, resulting in a spin-down age of only 10^7 yr (Lyne et al. 1993). Suggestive of older age are that it is very likely in the globular cluster NGC 6342, and that it orbits a low-mass companion in a short-period orbit, which is characteristic of recycled pulsars and low-mass X-ray binaries. The probability of its association with the cluster being a chance superposition is less than 1%, which is small but not negligible. We shall proceed on the assumption that it is in the cluster. This matter may be resolved in the future, either by detection and study of the companion or by the discovery of more pulsars in the cluster, which should have very nearly the same dispersion measure as 1718−19 if it is in the cluster.

Such an age paradox has been encountered before in X-ray pulsars with high magnetic fields and low-mass companions such as Her X-1 and 4U 1626−67. It arises from the fact that the accepted wisdom in neutron star research has long been that their magnetic fields decay spontaneously on time scales of 10^7 yr or less, much shorter than the ages of the binaries in which they are found. The solution proposed by advocates of field decay is that the neutron stars in such old systems are in fact young, having been formed recently by the accretion-induced collapse of a white dwarf. For X-ray binaries, this solution is now known to be of no avail in some cases, notably Her X-1 (see Verbunt, Wijers, & Burm 1990, and references therein). In the study of ordinary single radio pulsars, field decay has again become an issue of much debate as well (Narayan & Ostriker 1990; Bhattacharya et al. 1992). For 1718−19, the two main possible hypotheses for the origin of the pulsar are (1) capture and recycling of an old neutron star and (2) accretion-induced collapse of a white dwarf. They lead to distinctly different expectations for the mass and optical magnitude of the companion.

2. EVOLUTIONARY SCENARIOS: AN OBSERVABLE PREDICTION

The binary orbit is circular, and has a period of 6.2 hr. The orbital separation is

$$a = 2.1\ R_\odot \left(\frac{M_c + M_p}{1.8\ M_\odot}\right)^{1/3}, \tag{1}$$

in which M_c and M_p denote the companion and pulsar mass, respectively. The fact that we see a substantial modulation of the pulsar flux with orbital phase indicates that there is a significant amount of absorption by a mass flow in the system. But this only leads to flux variations if the inclination is not too small; therefore, we cannot be seeing the orbit close to face-on. From the mass function, we can derive a lower limit to M_c, which is $0.12\ M_\odot$ for $M_p = 1.4\ M_\odot$.

In the capture and recycling scenario, the neutron star acquired its companion via tidal capture, either by a close passage with a single star or during a resonant encounter with a binary (see Hut et al. 1992 for a review on binaries in globular clusters). Such captured neutron stars are then thought to become low-mass X-ray binaries, out of which millisecond recycled pulsars form via spin-up and field decay concomitant of mass accretion. Single millisecond pulsars might then form if the radiation from the fast and luminous pulsar vaporizes the remainder of the companion (Ruderman, Shaham, & Tavani 1989); the existence of eclipsing pulsars appears to support this vaporization scenario nicely. PSR 1718−19 fits into this scenario quite well: its high field and long period imply that it is almost unrecycled. Of course, some recycling must have taken place, because the pulsar must have been spun up from the expected period of very old, dead pulsars (∼10 s) to its present

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spin period. At the present pulsar field strength, accretion of 10^{-5} $M_\odot$ suffices to achieve that spin-up. Since some spillover of material to the pulsar near the time of capture is quite plausible (see below), this occurs fairly naturally in a capture scenario. True recycling, however, which is usually understood to comprise both accretion of significant amounts of material and a substantial decrease of the magnetic field, has not yet taken place. This would make 1718−19 the first globular-cluster pulsar observed in the phase between capture of a companion and onset of a low-mass X-ray binary phase. It may not be the first such case in the galaxy: Phinney & Verbunt (1991) have argued that PSR 1820−11 in the disk is also a prerecycled pulsar. The number of such pulsars that one expects to find in globular clusters if all recycled pulsars descend from them is the number of recycled pulsars (~ 30) multiplied by the ratio of lifetimes of high-field slow pulsars ($\sim 5 \times 10^7$ yr) to recycled pulsars ($\sim 10^9$ yr), which is about 1, as observed. Because the neutron star itself is as old as the globular cluster in this scenario, its high field constitutes evidence against spontaneous, rapid field decay, in the same way as Her X-1 and 4U 1626−67.

If the companion was captured, its distance of closest approach to the neutron star at the first passage, d, must have been close to 3 times its radius R_c, to ensure capture but avoid destruction (Hut et al. 1992). The orbit was near-parabolic just after capture, but is now circular. If angular momentum is conserved during the circularization process, it follows that $a_{\rm now} = 2d = 6R_c$. With a main-sequence mass-radius relation $M/M_\odot = R/R_\odot$ and equation (1), we obtain $M_c = 0.35$ $M_\odot$ (weakly dependent on the choice $M_p = 1.4$ $M_\odot$). It has been shown, however, that tidal encounters can be quite violent and nonconservative (Ray, Kembhavi, & Antia 1987; Kochanek 1992). This means that many encounters end in coalescence of the stars rather than capture. However, we know that coalescence could not have occurred here. According to Kochanek (1992), this implies that d must exceed the above value of $3R_c$ for plausible masses of passing stars in order to ensure their survival through the encounter. Also, the final orbits after these violent encounters tend to have values for $a_{\rm now}/R_c$ which are greater than the value of 6 obtained for the nonviolent case. It is apparent from the above line of reasoning that this means that violent captures lead to smaller values for the present mass of the companion. Mass loss during such captures only reinforces this effect, so we can consider 0.35 $M_\odot$ to be a fairly safe upper limit to the companion mass for any kind of capture scenario.

Note that capture could have happened in two ways: a single field star could have come close enough to the neutron star directly, or the neutron star encountered a binary, and had a resonant scattering with it. During this process, it came close enough to one of the binary members to capture it, and the new binary flew off in one direction, leaving the other member of the binary behind. In fact, because the binary is quite far outside the cluster core (2'.3), the triple scenario may be more likely in this case (see, e.g., Phinney & Sigurdsson 1991).

Alternatively, the progenitor of the present pulsar was a white dwarf accreting mass from its companion. When the mass of the white dwarf reached the Chandrasekhar limit, it collapsed to a neutron star. Among conditions that enable such a collapse (see summary in Bhattacharya & van den Heuvel 1991) is a high accretion rate, which implies that the companion must have filled its Roche lobe before collapse. The binary separation and the mass of the compact object change very little during collapse (Verbunt et al. 1990), so the companion must still be close to filling its Roche lobe today. We can therefore estimate its mass directly from the orbital period, independent of the pulsar mass (e.g., Verbunt 1990), from the relation $P_{\rm orb} = 8.9(M_c/M_\odot)$ hr. This yields $M_c = 0.7$ $M_\odot$, and an a priori unlikely almost face-on orbit ($i = 10°$), which may be in conflict with the eclipse behavior (see above). Also, it may be a problem for this scenario that the orbit is not in Roche contact now.[3] The reason for this is that accretion-induced collapse requires a high accretion rate, which can only be achieved if the orbit prior to collapse shrinks on a time scale of 10^8 yr or less. Since most angular-momentum loss mechanisms that have been proposed do not stop operating after the collapse, the orbit should still be shrinking at such a rate. But because the orbit stays so close to Roche contact through the collapse, the binary should resume accretion within a few percent of that shrinking time scale after collapse. This is not consistent with the fact that it is not accreting now, 10^7 yr or more after formation of the neutron star. Ergma (1993) has suggested that the pulsar did form via collapse of a white dwarf, and that the mechanism that kept the accretion rate high was irradiation-driven bloating of the companion. This mechanism does turn off after formation and subsequent spin-down of the pulsar and cannot presently be excluded. In this scenario the companion mass could be lower than the 0.7 $M_\odot$ derived above, but the companion would probably still have a brightness more typical of a higher-mass star due to the fact that its radiating area is large (the time for it to shrink back to its main-sequence radius is much longer than the age of the pulsar).

The above two scenarios have thus led to very different estimates of the companion mass ($M_c \lesssim 0.35$ $M_\odot$ for capture, and $M_c \simeq 0.7$ $M_\odot$ for accretion-induced collapse). This means that they imply rather different predictions for the optical magnitude and color of the companion, and therefore the manner of formation of this pulsar can be revealed by optical photometry as soon as an accurate position for the pulsar becomes available.

The cluster has a distance of 11.6 kpc, and a nominal reddening of $E(B-V) = 0.46$ (Webbink 1983). From normal reddening and extinction relations (Draine 1989) we then find $E(R-I) = 0.1$ and $A_I = 0.7$; the distance modulus is 15.3 mag. We take spectral types K4V and M2.5V, respectively, for 0.7 and 0.35 $M_\odot$ main-sequence stars (Allen 1973), which have absolute I-magnitudes of 6.6 and 8.5 (Kron, Gascoigne, & White 1957). Accounting for nominal extinction and reddening, we find that an 0.7 $M_\odot$ companion would have $m_I = 22.6$ and $R-I = 0.5$, whereas an 0.35 $M_\odot$ companion would have $m_I = 24.5$ and $R-I = 1.1$. Inspection of Palomar plates shows that there will be some uncertainty in these parameters because the reddening is patchy around the cluster, but the corrections are unlikely to be a significant fraction of the difference between the two cases. Detection of these companions should be trivial with modern CCDs for the 0.7 $M_\odot$ case, and still not hard for 0.35 $M_\odot$, given an accurate position of the pulsar, which will eventually be obtained from timing (The reported pulsar position is 2'.3, or 17 core radii, from the cluster center, so crowding should be manageable). Since we prefer the capture scenario, both for various theoretical reasons and because the orbital inclination for the collapse

[3] We thank the referee for pointing this out to us.

case is so small, we predict that the companion will be found to be faint.

3. CIRCULARIZATION OF THE ORBIT

Irrespective of how the pulsar was formed, and independent of its cluster membership or the companion mass, we may use it to learn the efficiency of synchronization and circularization via tidal coupling: just after the pulsar was born or captured, at most 10^7 yr ago, the orbit was quite eccentric, but now its eccentricity is negligible ($e \lesssim 0.005$). This may help to pin down theories for tidal coupling in low-mass, short-period binaries (Zahn 1977; Campbell & Papaloizou 1983; Tassoul & Tassoul 1990), the predictions of which now range widely. Possibly, though, there is an escape from rapid circularization here which we must address: the system could be an X-ray transient with a very long recurrence time scale. Each time when it goes into outburst, it spins up the pulsar a bit (as seen in transient X-ray pulsars, e.g., EXO 2030+375: Parmar et al. 1989). Since it takes $10^{-5}\ M_\odot$ to spin the pulsar up to a 1 s period, and it stays above the death line for 5×10^7 yr after spin-up, it need only accrete an average $2 \times 10^{-13}\ M_\odot\ \mathrm{yr}^{-1}$, so the total mass transfer in a Hubble time is quite small. This scenario is rather vague, and not very predictive because we have no ab initio theory for transient X-ray sources, but it is hard to rule out this possibility completely. If it applies, the argument for rapid circularization vanishes, but the pulsar is then still old, and again constitutes evidence against spontaneous, rapid field decay.

4. MASS LOSS WITHOUT ABLATION

The flux variation with orbital phase implies that the pulsar is embedded in a wind. If the flux varies due to free-free absorption, the mass-loss rate in a spherically symmetric wind originating from the companion is

$$\dot{M}_c = 4 \times 10^{-12}\ M_\odot\ \mathrm{yr}^{-1} \times \left(\frac{\nu_1}{1\ \mathrm{GHz}}\right)^{1/2} \left(\frac{T_{e,w}}{10^7\ \mathrm{K}}\right)^{0.35} \left(\frac{a}{2\ R_\odot}\right)^{3/2} \left(\frac{v_w}{600\ \mathrm{km\ s^{-1}}}\right) \quad (2)$$

where parameters have been scaled to likely values for a hot stellar wind and the observed pulsar orbit. Here ν_1 is the frequency at which the average wind optical depth is 1, and $T_{e,w}$ is its typical electron temperature. We do not think that vaporization by pulsar radiation can cause this mass flow, because the flux impinging on the companion is eight orders of magnitude less than in the first eclipsing pulsar, PSR 1957+20 (for which good evidence does exist that the companion is heated by the pulsar flux). Rather, the binary parameters remind us of a well-studied class of active binaries, namely RS CVn stars (Rodonò 1992 and references therein). In these systems, a main-sequence or subgiant star is locked in near-synchronous rotation in a binary with a period that can be as short as 12 hr, and usually that star is far from filling its Roche lobe. It loses mass at a rate 10^{2-4} times higher than single stars of the same spectral type and class. Zeeman splitting reveals the presence of high magnetic fields, and strong X-ray emission is indicative of coronal activity and hot outflow. The common cause of mass loss and activity is thought to be the combination of deep convection in the star and the rapid rotation to which it is forced via tidal coupling of the orbital motion to the convection layers. Eggleton (1992) has named this effect Companion-Reinforced Accretion Process (CRAP). We suggest that the term Companion-Reinforced Attrition Process is more appropriate, for it is the forced mass loss of a star that is essential here rather than whether the lost matter is accreted by the other star.

All the ingredients for this process are present in 1718−19: the companion mass is at least 0.12 $M_\odot$, which is above the hydrogen-burning limit ($\sim$0.08 $M_\odot$), so it can sustain a deep convection zone (unlike the 0.02 $M_\odot$ companion in PSR B1957+20). Tidal forces on the companion are larger than in most RS CVn stars because of its closer orbit. We therefore deem this a more likely cause of the mass loss than ablation by the low pulsar flux. A mass-loss rate of about $10^{-11.5}\ M_\odot\ \mathrm{yr}^{-1}$ (eq. [2]) is a few hundred times that expected for a single red dwarf, which puts it comfortably in the observed range for RS CVn stars.

Further support for this is derived from the paper by Deich et al. (1993),[4] in which it is shown that the binary pulsar PSR 1908+00, which has a greater irradiation flux at the companion than PSR 1744−24A, is not eclipsing. If the wind in 1744−24A were caused by irradiation it would be hard to understand why there are no eclipses in 1908+00. In our model, the difference is not surprising, because the companion in 1744−24A is just above the hydrogen-burning limit, whereas the minimum companion mass in 1908+00 is below it.

5. CONCLUSION

We have proposed an observational test to decide how the binary pulsar 1718−19 was formed: if it captured its companion, the optical counterpart should have $m_I > 24.5$ and $R-I > 1.1$. If the pulsar formed via collapse of a white dwarf, we expect $m_I \simeq 22.6$ and $R-I \simeq 0.5$.

We have further proposed that the wind in this binary that causes the eclipses is not induced by companion irradiation, but by excitation of the companion due to tidal coupling, as has been proposed long ago to explain the activity of RS CVn stars. The best support for this proposal would of course be the direct detection of the companion activity. RS CVn stars are quite bright in X-ray and radio radiation, but unfortunately even the brightest known ones would escape detection by *ROSAT* or the VLA in any reasonable integration time, because the cluster is so distant.

It is important to note that many RS CVn systems are easier to study in detail than the faint eclipsing pulsars, and a wealth of data on them is available in the literature. They often exhibit the same kind of unexpectedly rapid orbital evolution that is now intensely studied and debated in the context of neutron star binaries. It may also be that the commonly made assumption that accreting low-mass X-ray binaries are in Roche contact needs reexamination, because the luminosity of the fainter sources in this class might be sustained by RS CVn-type enhancement. It seems worthwhile, therefore, to consider more carefully whether the role of CRAP can be as important in neutron star research as it proved to be in the study of RS CVn stars.

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[4] We would like to note that this paper appeared after the original submission of our paper.

REFERENCES

Allen, C. W. 1973, Astrophysical Quantities (London: Athlone), 209
Bhattacharya, D., & van den Heuvel, E. P. J. 1991, Phys. Rep., 203, 1
Bhattacharya, D., Wijers, R. A. M. J., Hartman, J. W., & Verbunt, F. 1992, A&A, 254, 198
Campbell, C. G., & Papaloizou, J. 1983, MNRAS, 204, 433
Deich, W. T. S., Middleditch, J., Anderson, S. B., Kulkarni, S. R., Prince, T. A., & Wolszczan, A. 1993, ApJ, 410, L95
Draine, B. T. 1989, in ESLAB Symp. 22, Infrared Spectroscopy in Astronomy, ed. B. H. Kaldeich (ESA SP-290), 93
Eggleton, P. P. 1992, in IAU Symp. 151, Evolutionary Processes in Interacting Binary Stars, ed. Y. Kondo, R. F. Sisteró, & R. S. Polidan (Dordrecht: Kluwer), 167
Ergma, E. 1993, A&A, 273, L38
Hut, P., McMillan, S., Goodman, J., Mateo, M., Phinney, E. S., Pryor, C., Richer, H. B., Verbunt, F., & Weinberg, M. 1992, PASP, 104, 981
Kochanek, C. S. 1992, ApJ, 385, 604
Kron, G. E., Gascoigne, S. C. B., & White, H. S. 1957, AJ, 62, 205
Lyne, A. G., Biggs, J. D., Harrison, P. A., & Bailes, M. 1993, Nature, 361, 47
Narayan, R., & Ostriker, J. P. 1990, ApJ, 352, 222
Parmar, A. N., White, N. E., Stella, L., Izzo, C., & Ferri, P. 1989, ApJ, 338, 359
Phinney, E. S., & Sigurdsson, S. 1991, Nature, 349, 220.
Phinney, E. S., & Verbunt, F. 1991, MNRAS, 248, 21P
Ray, A., Kembhavi, A. K., & Antia, H. M. 1987, A&A, 184, 164
Rodonò, M. 1992, in IAU Symp. 151, Evolutionary Processes in Interacting Stars, ed. Y. Kondo, R. F. Sisteró, & R. S. Polidan (Dordrecht: Kluwer), 71
Ruderman, M., Shaham, J., & Tavani, M. 1989, ApJ, 336, 507
Tassoul, J.-L., & Tassoul, M. 1990, ApJ, 359, 155
Verbunt, F. 1990, in Neutron Stars and Their Birth Events, ed. W. Kundt (NATO ASI series C vol. 300) (Dordrecht: Kluwer), 179
Verbunt, F., Wijers, R. A. M. J., & Burm, H. M. G. 1990, A&A, 234, 195
Webbink, R. F. 1983, in IAU Symp. 113, Dynamics of Star Clusters, ed. J. Goodman & P. Hut (Dordrecht: Kluwer), 541
Zahn, J.-P. 1977, A&A, 57, 383

Note added in proof.—Z. Arzoumanian and A. Fruchter kindly drew our attention to a paper in preparation by themselves and J. Taylor in which they report that the period derivative of the archetypical eclipsing and evaporating pulsar 1957+20 has reversed sign. This lends further support to the notion that the observed rapid period changes in neutron star binaries are not secular, contrary to some recent claims, and constitutes another similarity between neutron star binaries and RS CVn systems.