PSR J1740–5340: ACCRETION INHIBITED BY RADIO EJECTION IN A BINARY MILLISECOND PULSAR IN THE GLOBULAR CLUSTER NGC 6397

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ABSTRACT

We present an evolutionary scenario for the spin-up and evolution of binary millisecond pulsars, according to which the companion of the pulsar PSR J1740–5340, recently discovered as a binary with orbital period of 32.5 hr in the globular cluster NGC 6397, is currently in a phase of “radio-ejection” mass loss from the system. The optical counterpart is a star as luminous as the cluster turnoff stars, but with a lower $T_{\text{eff}}$ (a larger radius), which we model with a star of initial mass compatible with the masses evolving in the cluster ($\approx 0.85 M_{\odot}$). This star has suffered Roche lobe overflow while evolving off the main sequence, spinning up the neutron star to the present period of 3.65 ms. At present, Roche lobe overflow due to the nuclear evolution of the pulsar companion and to systemic angular momentum losses by magnetic braking is still going on, but accretion is inhibited by the momentum exerted by the radiation from the pulsar on the matter at the inner Lagrangian point. The presence of this matter around the system is consistent with the long-lasting irregular radio eclipses seen in the system. Roche lobe deformation of the mass losing component is also necessary to be compatible with the optical light curve. The “radio-ejection” phase, which had been recently postulated by us to deal with the problem of the lack of submillisecond pulsars, can be initiated only if the system is subject to intermittency in the mass transfer during the spin-up phase. In fact, only when the system is detached is the pulsar radio emission not quenched and possibly able to prevent further mass accretion because of the action of the pulsar pressure at the inner Lagrangian point. We propose and discuss the idea that a plausible reason for the system to be expected to detach is the irradiation of the mass-losing component by the X-ray emission powered during the accretion phase. We finally discuss the consequences of the binary evolution leading to PSR J1740–5340, and its relation to other possible optical counterparts.

Subject headings: accretion, accretion disks — binaries: general — pulsars: individual (PSR J1740–5340) — stars: neutron — X-rays: binaries

On-line material: color figure

1. INTRODUCTION

The widely accepted scenario for the formation of a millisecond pulsar is the recycling of an old neutron star (hereafter NS) by a spin-up process driven by accretion of matter and angular momentum from a Keplerian disk, fueled via Roche lobe overflow of a binary late-type companion (see Bhattacharya & van den Heuvel 1991 for a review). If the NS has a magnetic dipole moment (typical values are $\mu \sim 10^{26}$–$10^{27}$ G cm$^3$), the disk is truncated at the magnetosphere, where the disk pressure is balanced by the magnetic pressure exerted by the NS magnetic field ($P_{\text{mag}} \propto \mu^2 r^{-6}$), where $r$ is the generic radial distance from the NS center. Once the accretion and spin-up process ends, the NS is visible as a millisecond radio pulsar (MSP). 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 the light-cylinder radius $R_{\text{lc}}$ (at which the speed of a body rigidly rotating with the NS equals the speed of light).

An interesting evolutionary phase can occur during the accretion onto the NS if the mass transfer rate drops below the level required to allow the expansion of the magnetosphere beyond $R_{\text{lc}}$, switching on the emission from the rotating magnetic dipole (e.g., Illarionov & Sunyaev 1975; Ruderman, Shaham, & Tavani 1989; Stella et al. 1994). In a standard Shakura-Sunyaev accretion disk, it is common to identify four zones based on the different roles of opacities (free-free or electron scattering) and pressures (radiation or gas pressure). The radius of separation between zone B, in which the electron scattering opacity and gas pressure dominate, and the most external zone C, where the free-free opacity and gas pressure dominate, is $R_{\text{BC}} = 4.18 \times 10^7 L_{37} R_{5}^{-1/3} m^{-1/3}$ cm (see, e.g., Burderi, King, & Szuszkiewicz 1998a), where $L_{37}$ is the luminosity in units of $10^{37}$ ergs s$^{-1}$, $R_{5}$ is the NS radius in units of 10$^5$ cm, and $m$ is the NS mass in solar masses. The typical distance of the inner Lagrangian point from the NS is larger than $\sim 10^{11}$ cm for orbital periods longer than $\sim 30$ hr. Close to the Roche lobe the disk is then in zone C, where opacity is dominated by free-free processes and pressure is dominated by the gas contribution. In this case, $P_{\text{disk}} \propto M_{17/20} r^{-3/2}$, where $\dot{M}$ is the accretion rate. The radial dependence of the pulsar radiation pressure is $P_{\text{rad}} \propto \mu^2 P_{\text{spin}}^{-2} r^{-2}$ (where $P_{\text{spin}}$ is the NS spin period), and it is flatter than the radial dependence of the disk pressure close to the inner Lagrangian point. Therefore, $P_{\text{rad}}$ dominates over $P_{\text{disk}}$ for any $r > R_{\text{lc}}$, and the whole accretion disk is swept away up to the inner Lagrangian point L1 by the radiation pressure of the pulsar. During this “radio-ejection” phase, the mechanism that drives mass overflow from L1 can well be active, but the pulsar radiation pressure at L1 prevents mass accretion onto the NS.

The occurrence of a radio-ejection phase in the pre-MSP evolution has been recently proposed by Burderi et al.
During the active phase of Roche lobe overflow by the place into a low-mass white dwarf, while radio ejection takes place once the companion is detached (and is evolved and relativistic particles) of a MSP (Tavani 1991). The key is the specific angular momentum of the mass-overflowing the Roche lobe. This mass transfer is dictated by the nuclear evolution of the secondary, and the losses of systemic angular momentum also contribute to determine the mass transfer rate.

It is quite possible that mass transfer during the spin-up phase suffers instabilities (see below) and the system temporarily detaches, allowing the pulsar to switch on. However, the companion evolution, which leads to radius expansion, will lead again to overflow.

Mass exchange to the NS and spin-up will go on until the pulsar has been so much spun-up that its radiation pressure at the inner Lagrangian point is high enough to prevent mass accretion. Modeling the binary evolution at the time of the action of this radio-ejection mechanism is nontrivial, and an adequate study of the physics involved and numerical simulations are needed to adequately investigate this problem, as has been done for the case of “evaporation” of low-mass companions of MSPs (Tavani & Brookshaw 1991; Banit & Shaham 1992). The destiny of the system is crucially dependent on the global mass radius exponent of the mass-losing component, on the mass ratio, and on the specific angular momentum of the ejected matter (see Ritter 1988 for general discussion of the stability of mass transfer). We can foresee cases in which the NS will have a very large angular momentum and a dynamical mass transfer will occur (L. Burderi et al. 2002, in preparation). Here we follow only the case in which the NS is the specific angular momentum at the inner Lagrangian point, and the evolution is stationary; the orbit widens and the companion plastically expands on its nuclear timescale, keeping its contact with the Roche lobe.

The main consequence of the occurrence of the radio-ejection phase will be that the matter lost from the secondary will not be transferred to the NS. This phenomenon may look like the so-called “ablation” of the companion irradiated by the wind (composed of electromagnetic radiation and relativistic particles) of a MSP (Tavani 1991). The key difference is that in the ablation mechanism the process takes place once the companion is detached (and is evolved into a low-mass white dwarf), while radio ejection takes place during the active phase of Roche lobe overflow by the secondary, and it is much easier for the energy requirements to be met. Moreover, the energy available to ablate the companion is different, being the orbital binding energy in the case of radio ejection and the pulsar rotational energy in the case of ablation. Observationally, in both cases we expect to be in the presence of a radio MSP which from time to time is obscured by the matter floating around the system.

In this paper we propose that this postulated radio-ejection phase has now been detected in the system containing the eclipsing millisecond pulsar PSR J1740−5340, discovered by D’Amico et al. (2001a) in the globular cluster NGC 6397, and identified (Ferraro et al. 2001) with a slightly evolved turnoff star in the sample studied by Taylor et al. (2001).

We provide convincing evidence that PSR J1740−5340 is an example of a system in the radio-ejection phase, by modeling the evolution of the possible binary system progenitor. We also discuss why we should expect that this type of system may indeed suffer the detachments required in order to initiate the radio-ejection phase; in fact, the X-ray illumination of the secondary star during the accretion phases, which leads to the NS spin-up, is such that the mass transfer rate is probably very unsteady. When (1) as a result of the accretion of matter and angular momentum, the NS spin period is so short that the radiation pressure of a pulsar phase would potentially be high enough to overcome the pressure of the matter overflowing the Roche lobe, and (2) the oscillations in the star are large enough to allow the millisecond pulsar to switch on, the radio-ejection phase begins, leading to the appearance of the system as it looks now.

We also show that the most luminous “hot” objects in NGC 6397 identified by Taylor et al. (2001) as low-mass helium WDs indeed follow the evolution of binaries, which may account for the evolutionary status of PSR J1740−5340, while the less luminous stars in this sample might have radii too large to be helium WDs.

2. PSR J1740−5340

The millisecond radio pulsar PSR J1740−5340 was discovered in the globular cluster NGC 6397 (D’Amico et al. 2001a). It has the longest orbital period (Porb ∼ 32.5 hr) and the most massive minimum companion mass (0.18 M⊙) among the 10 eclipsing pulsars detected up to now. The spin period (Pspin ∼ 3.65 × 10−3 s) and its derivative (P′ spin = 1.59 × 10−19 s), recently derived by D’Amico et al. (2001b), allow the determination of the NS magnetic moment, Μ26 ≃ 7.7. Because of its position with respect to the cluster center, the contamination of Pspin from the NS acceleration in the gravitational field of the cluster is negligible (D’Amico et al. 2001b), implying that the estimate of the NS magnetic moment is reliable.

Ferraro et al. (2001) have extracted, from archive Hubble Space Telescope (HST) data, a star whose position is consistent with the position of PSR J1740−5340 (derived from 1 yr of pulse timing by D’Amico et al. 2001b). This optical counterpart shows light modulation at the same orbital period as the radio data. D’Amico et al. (2001b) have studied the radio eclipses of PSR J1740−5340, which last for about 40% of the orbital phase at 1.4 GHz. Out of eclipse, the pulsar signal at 1.4 GHz shows significant excess propagation delays (up to ~8 ms) and strong intensity variations. Similar variations have been observed at 400 MHz, in the eclipsing pulsar PSR B1957+20 close to the eclipse ingress and egress (Fruchter et al. 1990) and in PSR J2051−0827, at 1.4 GHz, when the pulsed signal is occasionally detected during the eclipse (Stappers et al. 1996). These similarities suggest that in PSR J1740−5340 the signal is propagating through a dense material surrounding the system. In order to investigate this possibility, D’Amico et al. (2001b) have fitted the excess delays measured in two adja-
cent bands of 128 MHz each at 1.4 GHz. They found that the excess delays $\Delta t$ can be well fitted with the equation $\Delta t \propto \nu^{-2.02\pm0.30}$, which strongly supports the hypothesis that the responsible mechanism is dispersion in a ionized medium. In this case the corresponding electron column density variations are $\Delta n_e \sim 8 \times 10^{17} \Delta t_{-3}$ cm$^{-2}$, where $\Delta t_{-3}$ is the delay at 1.4 GHz in ms. For $\Delta t_{-3} \sim 8$ the estimated electron column density is $\sim 6.4 \times 10^{18}$ cm$^{-2}$.

The eclipsing radius is $R_E \sim a \sin (0.4 \pi)$, as the eclipse lasts for $\sim 40\%$ of the orbit (D'Amico et al. 2001b). It is $4.4 \times 10^{11}$ cm, if we take $m_1 = 1.8 M_\odot$ for the NS mass and $m_2 = 0.45 M_\odot$ for the secondary mass (see below) and $P_{\text{orb}} \sim 32.5$ hr (where $a$ is the orbital separation). This radius is larger than the Roche lobe radius of the secondary ($\sim 1.3 \times 10^{11}$ cm). This means that the eclipsing matter is more consistent with Roche lobe overflow driven by nuclear evolution of the secondary and orbital angular momentum mass loss than with a possible wind from the secondary, suggested by D'Amico et al. (2001b) and Ferraro et al. (2001). As our model requires that the mass lost is swept out by the pulsar radiation, the value of $v_8$ given above is consistent with our hypothesis.

3. BINARY EVOLUTION IN THE GLOBULAR CLUSTER NGC 6397

3.1. The H-R Diagram

In order to choose coherently the input parameters for the possible evolution leading to PSR J1740–5340, it is important to take into account what we know of the general properties of the host cluster, which has been carefully studied down to the low end of the main sequence. Figure 1 shows the composite HR diagram of NGC 6397 in the plane $M_*$ versus $V-I$. We have plotted the sample by King et al. (1998) including the low-mass main-sequence (MS) and the white dwarfs (WDs), together with the sample by Cool (1997) for the turnoff and giant stars. The open circles identify the objects examined by Taylor et al. (2001) in the core of this cluster, to select objects that have probably been sub-

![Fig. 1.](image-url)
ject to binary evolution. In fact, they recognize a helium WD sequence on the left of the MS, and many BY Dra stars on its right. The offset from the MS suggests that indeed these latter stars have suffered binary evolution. One of the Taylor et al. (2001) BY Dra candidates, plotted as a filled circle in our Figure 1, is indeed the optical counterpart of PSR J1740–5340, as discovered by Ferraro et al. (2001). On the observational HR diagram we show an isochrone of 12 Gyr for metallicity in mass fraction $Z = 0.006$ and helium mass fraction $Y = 0.23$ from Silvestri et al. (1998), complemented by the models by Baraffe et al. (1997) for masses $\leq 0.5 M_\odot$, while the track on the cluster white dwarfs is the 0.5 $M_\odot$ carbon oxygen WD evolution by Wood (1995), as used in Richer et al. (1997). The isochrone of 12 Gyr that fits the cluster H-R diagram implies that a mass of $\sim 0.81 M_\odot$ is evolving at the cluster turnover (TO), and that its TO luminosity is $\simeq 2.24 L_\odot$. Different interpretations of the H-R diagram morphology, assuming that the distance of the cluster is smaller, may lead to values of the TO luminosity down to $\sim 1.8 L_\odot$.

3.2. Choice of the Initial Parameters

In order to choose the initial system parameters that lead to the present stage of PSR J1740–5340, we make the following considerations.

1. The location of the optical counterpart is at a luminosity similar to the TO luminosity (1.8–2.3 $L_\odot$, based on the previous discussion), but cooler than the TO, that is, at a radius larger than the TO radii. The pulsar luminosity is in fact estimated to be $L_{\text{PSR}} = 1.29 \times 10^{35}$ erg s$^{-1}$ (see below), of which, in the hypothesis of isotropic emission, a fraction $R_\text{L}^2/(2a)^2$ impacts at the mass-losing star surface ($R_\text{L}$ and $a$ being the radius of the secondary and the orbital separation, respectively). Even in the most favorable case of a secondary filling its Roche lobe, the fraction of the pulsar luminosity impacting the secondary is $f = R_\text{L1,2}/(2a)^2 = 5.34 \times 10^{-2} (m_2/(m_1 + m_2))^{2/3}$, where $R_\text{L1,2}$ is the Roche lobe radius of the secondary. We considered secondary masses ranging from 0.25 up to 0.81 $M_\odot$ and corresponding NS masses from 2.0 down to 1.4 $M_\odot$ (conservative mass transfer). We obtained values of $f \times L_{\text{PSR}}$ ranging from 0.4 to 0.9 $L_\odot$, respectively. Therefore, the fraction of the pulsar luminosity reprocessed by the secondary is not very important for determining the H-R diagram location of the star. The orbital period is moderately large, so any stage of mass transfer must have begun while the mass-losing component was still not much evolved.

2. We exclude the possibility that the star is a normal MS star losing a stellar wind at rates $\sim 10^{-10} M_\odot$ yr$^{-1}$, for the reasons given at the end of § 2.

3. The pulsar spin-up to 3.65 ms must be due to mass exchange in a previous evolutionary phase. Indeed, the possibility that the NS was born with such a period seems unlikely, as the spin-down age of PSR J1740–5340 is $\tau = P_{\text{spin}}/2 P_{\text{spin}} \sim 350$ Myr (D’Amico et al. 2001b), which is much shorter than the age of the globular cluster NGC 6397 in which PSR J1740–5340 is located.

The easiest way is to attribute it to the previous evolution of the system. Therefore, we model the initial parameter of the system as starting with a 0.85 $M_\odot$ component and a NS component of 1.4 $M_\odot$. NGC 6397 is a post–core-collapse globular cluster (Djorgovski & King 1986), in which a significant number of interacting neutron star plus main-sequence binaries may have formed by tidal capture or exchange collisions (e.g., Davies, Benz, & Hills 1992; Di Stefano & Rappaport 1992). Implicitly, we are making the assumption that the 0.85 $M_\odot$ component has been captured by the NS at such a separation to be able to begin mass transfer when it is not yet evolved as a giant. This is in line with recent work by Podsiadlowski, Rappaport, & Pfahl (2002), who suggest, supported by the numerous ultracompact binaries found in globular clusters, that tidal capture seems to be a more likely way to produce this kind of system.

3.3. The Binary Evolution

We follow the binary evolution with the ATON1.2 code (D’Antona, Mazzitelli, & Ritter 1989). The mass-loss rate is computed following the formulation by Ritter (1988), as an exponential function of the distance of the stellar radius to the Roche lobe, in units of the pressure scale height. This method also allows us to compute the first phases of mass transfer, during which the rate reaches values that can be much larger than the stationary values, as a result of the thermal response of the star to mass loss. The evolution of the system also includes orbital angular momentum losses through magnetic braking, in the Verbunt & Zwaan (1981) formulation, in which the braking parameter is set to $f = 1$. We also tested a case in which $f = 2$.

We study four cases of evolution (see Table 1). In all cases, we assume that the secondary initial mass is $M_2 = 0.85 M_\odot$, the primary neutron star has $M_1 = 1.4 M_\odot$, and the orbital initial period is 14.27 hr. The nuclear age of the 0.85 $M_\odot$ is $\sim 10$ Gyr when it begins the Roche lobe overflow, so that it is only slightly evolved, and hydrogen is almost exhausted in its (radiative) core. In case 1, we assume a “standard” conservative evolution. This produces mass-transfer rates of $\sim 2-4 \times 10^{-10}$ $M_\odot$ yr$^{-1}$. The system would thus appear as a low-mass X-ray binary (LMXB). The X-ray emission expected from the NS is $\sim 2 \times 10^{36}$ erg s$^{-1}$. The evolution is typical for such systems (e.g., Bhattacharya & van den Heuvel 1991). The end product will be a very low mass helium white dwarf ($M_2 = 0.246 M_\odot$) in a much wider orbit ($P_{\text{orb}} = 119$ hr) with a 2 $M_\odot$ neutron star.

| Case | $M_{\text{NS init}}$ ($M_\odot$) | $M_{\text{WD}}$ ($M_\odot$) | $P_{\text{orb}}$ (hr) | Angular Momentum | Mass Transfer Modalities | $L_{\text{h}}$ (ergs s$^{-1}$) | $\log M_{\text{sm}}$ ($M_\odot$ yr$^{-1}$) |
|------|-----------------------------|-----------------------------|----------------------|------------------|------------------------|-----------------------------|----------------------|
| 1    | 2.004                       | 0.246                       | 119                  | $f = 1$          | $M_1 + M_2 = c$        | 0                           | $-9.5$               |
| 2    | 1.72                        | 0.247                       | 120                  | $f = 1$          | $M_1 = c$ from $P = 25.98$ hr | 0                           | $-9.5$               |
| 3    | 2.03                        | 0.217                       | 278                  | $f = 1$          | $M_1 + M_2 = c$        | $5 \times 10^{34}$          | $-9.9$               |
| 4    | 1.52                        | 0.261                       | 193                  | $f = 2$          | $M_1 = c$ from $P = 17.36$ hr | 0                           | $-9.3$               |
Because the hydrogen is not yet completely exhausted in the stellar core when mass transfer begins, the initial binary period we have chosen is indeed very close to the “bifurcation” period below which the orbital evolution proceeds toward shorter binary periods. Note that in our case the bifurcation period is shorter than that quoted by Podsiadlowski et al. (2002) for a binary composed of a 1.4 $M_{\odot}$ NS plus a 1.0 $M_{\odot}$ secondary, namely, $P_{\text{orb,init}} \sim 18$ hr. This is due to the fact that the main-sequence radius of our 0.85 $M_{\odot}$ Population II secondary is around 20% smaller than the radius of a Population I, 1.0 $M_{\odot}$ companion for comparable consumption of the hydrogen in the core. Since for a Roche lobe filling secondary we have $\Delta P_{\text{orb}} / P_{\text{orb}} = 2.2 \Delta R_2 / R_2$, the bifurcation period for the Population I, 1.0 $M_{\odot}$ companion will be around 44% longer than in our case and therefore consistent with the result of Podsiadlowski et al. (2002).

Having in mind the observed system PSR J1740−5340, we followed another case of evolution (case 2), in which we assumed conservative evolution up to an orbital period of $\sim 26$ hr, and then we assumed that the matter lost from the secondary is all lost from the system at the inner Lagrangian point L1 with its specific angular momentum. This slightly alters the conservative evolution, leading to marginally different mass-loss rates and final parameters for the system when all the secondary hydrogen envelope is lost and the star becomes a white dwarf (see Table 1).

When mass accretion on the NS is assumed, and the binary evolution suffers a LMXB phase, it is also important to consider how the X-ray phase would affect the binary evolution we are considering, since a fraction $R_{2}^{3} / (2a)^{2} \lesssim 2.7 \times 10^{-2}$ of the X-ray luminosity (see point 1 above) impacts at the secondary surface. There have been many attempts to model the effect of this irradiation on the binary evolution, when it has been realized that spherically symmetric illumination in LMXBs can have a dramatic effect on the structure of low-mass secondaries having convective envelopes. In fact, X-rays block the intrinsic stellar flux produced by the nuclear reactions, leading to a stellar expansion, which affects the mass transfer rates (Podsiadlowski 1991; Harpaz & Rappaport 1991). In reality, illumination will be nonspherical, because only one hemisphere is affected—in fact, the donor star is tidally locked as it is filling its Roche lobe during this evolutionary phase—and its effect will depend on the depth at which the energy is deposited below the photosphere and how fast it can be transported to the cool side of the star. If the circulation time is shorter than the cooling time of the heated matter, we go back to the spherical illumination case. Otherwise, the global secular evolution is not much affected, but the mass transfer occurs in “outbursts” whose duration and peak mass transfer rates depend on the efficiency of circulation (e.g., Hameury et al. 1993; Harpaz & Rappaport 1994; Vilhu, Ergma, & Federova 1994; D’Antona 1994). All the existing computations refer to the evolution of LMXBs with main-sequence companions. We are now dealing with a case of evolution in which the mass-losing component is more evolved, and in addition has no important convective envelope at the time the mass transfer begins, so it is important to have an idea of the possible effects of X-ray illumination in our specific case.

On the other hand, self-consistent modeling is really very difficult, since the feedbacks are not easy to describe either physically or numerically. However, we follow the evolution of an ideal limiting case, considering a system in which the secondary is affected by a fixed value of heating luminosity, $L_h = 5 \times 10^{34} \text{ergs s}^{-1}$ (case 3). We include the effect of illumination as described in D’Antona & Ergma (1993), following Tout et al. (1989). In this simplified schematization, the star is immersed in the X-radiation bath, and the total luminosity $L_{\text{tot}}$ that it must radiate is the sum of the stellar luminosity $L_s$ plus the heating luminosity $L_h$, from which an “irradiation temperature” $T_{\text{irr}} = (L_h / 4\pi \sigma R_2^4)^{1/2}$ is defined. The stellar luminosity and $T_{\text{eff}}$ then are related by

$$L = L_{\text{tot}} - L_h = 4\pi \sigma R_2^4 (T_{\text{eff}}^4 - T_{\text{irr}}^4).$$

Consequently, the stellar $T_{\text{eff}}$ becomes hotter because of the irradiation, and the star rapidly evolves in the H-R diagram at a location determined by the amount of irradiation allowed. The phases of mass transfer are slightly altered by the new system conditions, but are globally very similar to case 1. However, as the star loses mass, its radius becomes larger than the radius of the standard sequence. This difference amounts to around 20% at the orbital period of PSR J1740−5340.

Of course the X-irradiation is not self-consistently described by this model. In fact, any fluctuation in the mass transfer rate will be amplified. If the mass transfer decreases further, irradiation decreases as well, and the radius will also decrease, trying to reach its non-irradiated equilibrium value; then the mass transfer rate decreases more. We can foresee that the LMXB phase in fact can alternate phases of mass transfer and detached phases, as was predicted for LMXBs having MS secondaries (Hameury et al. 1993; D’Antona 1994; Harpaz & Rappaport 1995).

To test the sensitivity of the mass-loss rate to the assumptions made concerning magnetic braking, we follow another evolution (case 4) in which $f = 2$ and the mass transfer is nonconservative for $P_{\text{orb}} > 17.36$ hr.

3.4. The Final Phases of Evolution

Figure 1 shows the evolutionary paths of cases 2 and 3 in the H-R diagram. The theoretical values of luminosity and $T_{\text{eff}}$ are converted into the observed magnitudes $V$ and $I$ by means described in Bessell, Castelli, & Plez (1998). The irradiated track (case 3) represents the evolution of the accreting progenitor of PSR J1740−5340 and therefore does not reproduce the location of PSR J1740−5340 for which the accretion is inhibited by the pulsar radiation. The track passing through the optical counterpart of PSR J1740−5340 is the case 2 evolution. The track corresponding to case 1 (purely conservative evolution) is very similar, and is not shown.

All the sequences are evolved until the mass-loss phase finally ends with the stellar remnant evolving into the white dwarf region as low-mass helium white dwarfs. We see that the three most luminous objects among those identified by Taylor et al. (2001) as helium WDs actually may be the end products of such an evolution. Note, however, that further study is necessary to assess whether the lower luminosity objects are helium white dwarfs. In fact, unless their colors are peculiar, they seem too cool to have the radius expected, even for the lowest possible helium WD masses remnant of mass-exchange evolution, which are actually around 0.2 $M_{\odot}$ (F. D’Antona et al. 2002, in preparation). The open triangles in Figure 1 show the location at which sequence 3 achieves a total age of 17, 20, and 26 Gyr ($\sim 10.5$ Gyr of which have been spent in the phases previous to mass exchange). The
point at 20 Gyr, which corresponds more closely to the luminosity of the lowest Taylor et al. objects, is at $T_{\text{eff}} = 8900$ K. The filled squares along sequence 2 correspond to ages from 13 to 20 Gyr in steps of 1 Gyr, and a last square indicates the location at 25 Gyr. We also note that the cooling of such objects (also in the present models) is dominated by proton-proton burning of the remnant hydrogen layer (Driebe et al. 1998; Sarna, Antipova, & Muslimov 1998; Schönberner, Drieve, & Blocker 2000), and that the low initial metallicity of the system prevents hydrogen-shell flashes.

4. THE EVOLUTION OF THE PROGENITOR SYSTEM OF PSR J1740–5340

The computation of case 3 has shown that the binary evolution that we are describing is not dramatically altered by the irradiation due to the LMXB phase in particular, the final evolution is very similar, although the white dwarf remnant mass is slightly smaller. However, it helps to predict that the LMXB phases can be alternated with phases in which the system remains detached, as had already been suggested for systems having MS companions. Let us now consider the evolution of the system, also taking into account the pulsar’s behavior. Any time the system detaches, the radio pulsar will switch on, but it will be quenched again when the mass transfer resumes. In the H-R diagram the position of the secondary component will shift from its “irradiated” position during the LMXB mass transfer phase (track 3 on the left of the MS) to its “standard” position along track 1. However, as discussed in Burderi et al. (2001a, 2001b), when the pulsar is spinning sufficiently fast and the orbital period is sufficiently long (i.e., the orbital separation is large), the radiation pressure exerted by the pulsar at the inner Lagrangian point is larger than the pressure exerted by the matter overflowing the Roche lobe even if the mass transfer rate recovers its secular value dictated by the nuclear evolution of the companion.

This condition is verified for orbital periods longer than

$$P_{\text{orb,crit}} = 0.75 \alpha^{-54/25} \times \frac{n_0}{n_0,615} \times \frac{10^{17.90}}{m_1} \times \frac{1}{m_2} \times \mu_{26}^{-3/2} \times \rho_{\text{avg}}^{24/5} \times \mu_{26}^{48/5} \times \rho_{\text{avg}}^{n/5} \times M_{\text{M-10}}^{51/25} \times t, \quad (5)$$

where $\alpha$ is the Shakura-Sunyaev viscosity parameter, $n_0,615 = n/0.615 \sim 1$ for a gas with solar abundances ($n$ is the mean particle mass in units of the proton mass $m_p$), $g(m_1, m_2) = 1 - 0.462 \times 10^{-12} m_2 / (m_1 m_2)^{1/3}$, $\mu_{26}$ is the magnetic moment of the NS in units of $10^{-26}$ G cm$^3$ ($\mu = B R^2$ where $R$ and $B$ are the NS radius and surface magnetic field along the magnetic axis, respectively), and $P_{\text{spin}}^{(3)}$ is the NS spin period in milliseconds. If $P_{\text{orb}} > P_{\text{orb,crit}}$, the system will remain in the radio-ejection phase during all the subsequent binary evolution. In this case, the matter overflowing the Roche lobe will be accelerated by its interaction with the pulsar radiation and ejected by the system. If we can assume (but at least ballistic simulations should be done) that this matter leaves the system with the specific angular momentum at the inner Lagrangian point, $l = (a - R_{L1} - r_1)^2 (2 \pi / P_{\text{orb}})$ (where $r_1$ is the distance between the NS and the center of mass of the system), which in our case is quite close to the specific angular momentum of the system, the orbital evolution is indeed very similar to the more conventional evolution with conservative mass transfer to the primary (as confirmed by our numerical computations of the conservative case 1 and the nonconservative case 2).

The optical component of PSR J1740–5340 indeed seems compatible with the evolution we have suggested. It lies along case 2 evolution, that not including irradiation, since in fact the pulsar luminosity is not important as an irradiation source for the binary.

5. SUMMARY AND CONCLUSIONS

We have considered the evolution of possible progenitors of the binary MSP PSR J1740–5340 in the globular cluster NGC 6397. We can reproduce the H-R diagram location of the optical companion, starting mass transfer to the NS from a hypothetical secondary of mass 0.85 $M_\odot$ slightly evolved off the MS when mass transfer begins. From equation (5), adopting $\alpha = 1$, $n_0,615 = 1$, $m_1 = 1.8$, $m_2 = 0.45$, $\mu_{26} = 7.7$, $P_{\text{spin}}^{(3)} = 3.65$, and $M_{\text{M-10}} = 1$, the critical period $P_{\text{orb,crit}}$ to reach the “radio-ejection” phase is $\sim 39$ hr, not very different from $P_{\text{orb}}$, given the large uncertainties in the $M_{\text{M-10}}$ estimate. Thus, PSR J1740–5340 is possibly in the radio-ejection phase. Given that $P_{\text{orb,crit}} \sim P_{\text{orb}}$, the fact that $P_{\text{orb,crit}} \sim P_{\text{orb}}$ is compelling.

In conclusion, we suggest that:

1. Orbital evolution calculations shows that a slightly evolved 0.85 $M_\odot$ secondary orbiting a NS can transfer mass to the NS, and reaches a stage in which its mass is reduced to $\sim 0.45 M_\odot$; its optical location in the H-R diagram is then compatible with the recently detected optical counterpart of PSR J1740–5340.

2. PSR J1740–5340 might represent a system whose evolution has been envisioned by Burderi et al. (2001a, 2001b); the spin and the magnetic moment of the pulsar may keep the system in a radio-ejection phase in which accretion is inhibited by the radiation pressure exerted by the pulsar on the overflowing matter, while the mechanism that drives the Roche lobe overflow from the companion is still active, thus causing an intense wind that would be very difficult to explain otherwise. This evolution seems to be the only viable possibility to explain the long-lasting eclipses and the strong intensity variation randomly occurring in the radio emission.
As a final remark, we note that $P_{\text{orb}} \sim P_{\text{orb, crit}}$ suggest the interesting possibility that this system could swiftly switch from the present radio pulsar phase to an accretion phase in which it should be visible as a $L_X \sim 10^{36}$ ergs s$^{-1}$ LMXB.

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