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*Letter to the Editor***Evidence for neutron star formation from accretion induced collapse of a white dwarf****J. van Paradijs<sup>1,2</sup>, E.P.J. van den Heuvel<sup>1</sup>, C. Kouveliotou<sup>3,4</sup>, G.J. Fishman<sup>4</sup>, M.H. Finger<sup>3,4</sup>, and W.H.G. Lewin<sup>5</sup>**<sup>1</sup> Astronomical Institute "Anton Pannekoek," University of Amsterdam & Center for High Energy Astrophysics, Kruislaan 403, 1098 SJ Amsterdam, The Netherlands<sup>2</sup> Physics Department, University of Alabama in Huntsville, Huntsville, AL 35899, U.S.A.<sup>3</sup> Universities Space Research Association<sup>4</sup> NASA Marshall Space Flight Center, ES-84, Huntsville AL 35812, U.S.A.<sup>5</sup> Center for Space Research, MIT 37-627, Cambridge, MA 02139, U.S.A.

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**Abstract.** The orbital parameters of the recently discovered transient burster/pulsar GRO J1744–28 indicate that this system is a low-mass X-ray binary in an advanced stage of its mass transfer, with several tenths of a solar mass already transferred from the donor to the compact star. All neutron stars known to have accreted such an amount have very weak magnetic fields, and this has led to the idea that the magnetic fields of neutron stars decay as a result of accretion. The observation of a strongly magnetized neutron star in GRO J1744–28 then suggests that this neutron star was formed recently as a result of the collapse of a white dwarf during an earlier stage of the current phase of mass transfer. It is shown that this model can consistently explain the observed characteristics of GRO J1744–28. Attractive progenitors for such an evolution are the luminous supersoft X-ray sources detected with ROSAT.

**Key words:** neutron star - X-ray binaries - Stars: GRO J1744–28**1. Introduction**

Bursts of hard X-rays were discovered with the Burst and Transient Source Experiment (BATSE; Fishman et al. 1989) from a region near the Galactic center early December 1995 (Fishman et al. 1995; Kouveliotou et al. 1996a). Initially the bursts came at intervals as short as three minutes, but after a few days the burst rate settled at an average of 20 per day, at which rate the source so far kept emitting bursts. Ten days later a persistent hard X-ray source, GRO J1744–28, was discovered near the position of the burst source (Paciesas et al. 1996). This source is an X-ray pulsar (Finger et al. 1996a), with a pulse period of 467

ms in an 11.8 day binary orbit, and a remarkably small mass function  $f(M) = (M_2 \sin i)^3 (M_X + M_2)^{-2} = 1.3 \cdot 10^{-4} M_\odot$  (Finger et al. 1996b). Here  $M_X$  and  $M_2$  are the mass of the pulsar and the companion star (the 'secondary'), respectively, and  $i$  is the orbital inclination angle. The average (20–60 keV) flux of this source increased from  $\lesssim 10^{-9}$  to  $\sim 4 \cdot 10^{-8}$  erg cm<sup>-2</sup>s<sup>-1</sup> between mid December 1995 to mid February 1996 (Harmon, private communication). The presence of pulsations during the bursts with strongly enhanced amplitude showed that the burst source and the pulsar are one and the same source (Kouveliotou et al. 1996b). Subsequent XTE observations (Swank et al. 1996) showed that the 2–100 keV spectrum of GRO J1744–28 is typical for that of X-ray pulsars.

With ROSAT a 10 arcsec error box was derived (Kouveliotou et al. 1996c). K band observations led to the identification of the counterpart to the X-ray source (Augusteijn et al. 1996a,b).

**2. System properties**

There are several arguments that GRO J1744–28 is a low-mass X-ray binary (LMXB). In the first place, a high-mass companion is unlikely because of the observed low value of the mass function. For example, the probability of a companion mass of  $10 M_\odot$  or higher, typical for the companions in high-mass X-ray binaries (HMXB) is only  $3 \cdot 10^{-4}$ , as such mass would imply an orbital inclination  $i < 1.47^\circ$ .

All known transient pulsating hard X-ray sources are Be/X-ray systems, in which the outbursts are caused either by periodic accretion episodes when the neutron star in its elliptic orbit passes through the dense equatorial wind of the Be star, near periastron, or by the shedding of an equatorial envelope from the rapidly rotating Be type companion, part of which is captured by the neutron star. However, Be/X-ray binaries have

very eccentric orbits and generally substantially longer orbital periods than GRO J1744–28 (Van den Heuvel and Rappaport 1987); none is known at an orbital period below 15 days.

It is also highly unlikely that GRO J1744–28 is an HMXB with a massive evolved companion, with mass transferred through a stellar wind, since the regular spin-up of the X-ray pulsar (Finger et al. 1996b) indicates that the mass transfer proceeds through an accretion disk. Several HMXB are known to transfer mass by (incipient) Roche lobe overflow, e.g. SMC X-1 and Cen X-3; however, these are not transients, but always very luminous X-ray sources. It is conceivable that X rays were not detected from GRO J1744–28 before because the mass transfer rate was so high that any X rays were ‘smothered’; the appearance of the source would then indicate a sudden substantial decrease of the mass transfer rate. Although it may be hard to disprove this possibility, we consider this unlikely, since the pulsar spin up rate (Finger et al. 1996) indicates that the neutron star spin rate is lower than corresponding to the accretion rate inferred from its luminosity early 1996. Moreover, the vanishingly small probability for having an orbital inclination below  $\sim 1.5^\circ$ , as required for an HMXB, virtually rules out the HMXB option.

Based on these considerations we conclude that GRO J1744–28 is an LMXB. The infrared properties of its counterpart support this conclusion (Augusteijn et al. 1996b).

An estimate of the magnetic field of the neutron star in GRO J1744–28 may be obtained from its observed rate of spin up during the outburst. We note that since the average mass transfer rate is much smaller than the value observed during the outburst, the observed spin period of the neutron star is likely to be substantially larger than the equilibrium value corresponding to the X-ray luminosity observed during the outburst. From the standard model for the spin up of an accreting magnetized neutron star (Henrichs 1983) we then infer from the observed pulse period and spin-up rate ( $\dot{P}/P \sim 4 \cdot 10^{-12} \text{ s}^{-1}$ ; Finger et al. 1996b) that the magnetic field strength of the neutron star is of order  $10^{11} \text{ G}$ .

### 3. Evolutionary considerations

We can think of two possible evolutionary histories that can lead to a low-mass star orbiting a neutron star in an 11.8-day circular orbit : (i) inspiralling of a neutron star in the expanding envelope of a low-mass ( $< 2.3 M_\odot$ ) star that evolved off the main-sequence and has a degenerate helium core; (ii) GRO J1744–28 is a late stage in the evolution of a binary in which mass transfer is driven by the nuclear evolution of the mass donor, in combination with magnetic braking.

The first possibility encounters two unsurmountable problems. First of all, in order to obtain the present large orbital radius ( $26 R_\odot$ ) from spiral-in, the progenitor system must have been so wide that prior to spiral in the progenitor of the donor was on the Asymptotic Giant Branch (AGB). This holds even for a pre-spiral-in mass as low as  $0.8 M_\odot$  (we calculated the orbital shrinking with the ‘Webbink formalism’, using the highest possible efficiency for ejecting the envelope, as discussed for ex-

ample by Van den Heuvel 1994). With an AGB progenitor, the mass of the degenerate (CO) core would be  $> 0.5 M_\odot$ . Regardless of the hydrogen envelope mass the radius of such star would always be  $> 60 R_\odot$ , i.e., much larger than the present system; therefore, such a post-spiral-in star would never fit into this system. The second problem is that in order to evolve to a supernova, the progenitor of the neutron star must have been more massive than  $8 M_\odot$ . A wide binary system with a  $1 M_\odot$  companion, as is required for model (i), would then always have been disrupted by the supernova, as more than half of the system mass would have been explosively ejected (Blaauw 1961). An origin from model (i) can therefore be ruled out, and only the second possibility remains.

For a low-mass binary in which the mass transfer is driven by the nuclear evolution of the low-mass donor star, the core mass – orbital period relation (Pylyser and Savonije 1988; Van den Heuvel 1995) indicates that the mass of the degenerate helium core of the donor is about  $0.25 M_\odot$ . The radius of such a star depends only on its core mass, and is independent of the mass of its hydrogen-rich envelope. However, the mass transfer driven from this envelope *does* depend strongly on this envelope mass. In particular, if at its present orbital period of about 12 days the companion is just *at the beginning* of its mass transfer then from the calculations of Joss and Rappaport (1983) it follows that during the first  $10^7$  years of the mass transfer the mass transfer rate is super-Eddington, decreasing from  $> 3 \cdot 10^{-8} M_\odot/\text{yr}$  to  $\sim 10^{-8} M_\odot/\text{yr}$ . In the subsequent  $3 \cdot 10^7$  years it levels off to about  $7 \cdot 10^{-9} M_\odot/\text{yr}$ , which is maintained until some  $4 \cdot 10^7$  years later the envelope is exhausted.

On the other hand, if the system is currently *near the end* of its mass transfer, it should have had an orbital period of  $\sim 1.2$  days at the onset of the mass transfer (cf. Van den Heuvel and Bitzaraki 1995), and the present mass transfer rate is expected to be  $\sim 4 \cdot 10^{-10} M_\odot/\text{yr}$  or somewhat less.

Thus, if one were able to estimate the present (time averaged) mass transfer rate in the system, one could distinguish between these two possible alternatives for the evolutionary state of the system. As the following argument shows, it is indeed possible to set an upper limit to the mass transfer rate in GRO J1744–28.

Since GRO J1744–28 is an LMXB, the transient nature of its X-ray emission makes it similar to the soft X-ray transients (White et al. 1984; Tanaka and Lewin 1995; Van Paradijs and McClintock 1995); the only difference with these transient LMXB is the presence of pulsations in its X-ray emission. Observational evidence (Van Paradijs and McClintock 1995) shows that for all SXTs with information on their component masses the mass ratio  $q = M_X/M_2$  is very high ( $q > 4$ ). This is the case not only for systems with black holes (i.e., most of them), but also for those with neutron stars (e.g., Cen X-4 has a secondary with mass less than  $0.2 M_\odot$ , see Chevalier et al. 1989; McClintock and Remillard 1990). (In addition, the orbital periods of such systems are usually rather long, typically  $> 7$  hours, which is fairly long for an LMXB.) Furthermore, all transients have very low mass transfer rates (see, e.g., White et al. 1984). A comparison of the stability conditions for accre-

tion disks in cataclysmic variables and in LMXB explains this observed correlation between mass-transfer rate and disk (in-) stability as the result of the stabilizing effect of X-ray heating of the disk at higher accretion rates (Van Paradijs 1996). According to this analysis, at its orbital period of 12 days the transient nature of GRO J1744–28 implies an average mass transfer rate of  $< 5 \cdot 10^{-10} M_{\odot} \text{ yr}^{-1}$ .

This is just the rate that one expects if the donor star is in an advanced stage of transferring its envelope. In that case, of course, the high  $q$  of the system, required by its transient nature, follows naturally. We thus conclude that the transient nature of GRO J1744–28, which implies a low mass transfer rate and a high  $q$ , finds a natural explanation if the system is an LMXB which is approaching the end of its mass transfer phase, the donor having transferred already most of its envelope mass.

The condition  $q > 4$  then constrains the donor mass between 0.25 and  $0.35 M_{\odot}$ .

#### 4. Accretion induced collapse of a white dwarf

In order to start evolving from the main sequence the initial mass of the donor star should have been at least  $0.9 M_{\odot}$ . Thus, the secondary in GRO J1744–28 must have transferred a substantial amount of mass. Evolutionary calculations which include magnetic braking (Pylyser and Savonije 1988; Van den Heuvel 1995) show that a 12-day orbital period near the end of the mass transfer stage requires an initial orbital period of about 1.2 days if the donor star started out with a mass of  $\sim 0.9$  to  $1.0 M_{\odot}$ . During the evolution the mass transfer rate in such a system is never larger than a few times  $10^{-9} M_{\odot}/\text{yr}$ , i.e., below the Eddington limit for a neutron star. All the accreted matter will therefore be retained by the neutron star.

There is strong evidence that the magnetic fields of neutron stars in binaries decay, and that this decay is not spontaneous, but is induced by accretion (Taam and Van den Heuvel 1986; Van den Heuvel and Bitzaraki 1995). Both observational and theoretical studies indicate that at the estimated magnetic field strength of about  $10^{11}$  G the neutron star cannot have accreted more than a few percent of a solar mass (Taam and Van den Heuvel 1986; Shibazaki et al. 1989; Van den Heuvel and Bitzaraki 1995; Urpin and Konenkov 1996; Young and Chamugan 1995; Romani 1995). Since at the sub-Eddington accretion rates (expected in this system) the neutron star would have accreted all the transferred mass (at least  $0.4 M_{\odot}/\text{yr}$ ), we conclude that the neutron star was formed after most of the mass had already been transferred. This can only have happened if during most of the mass transfer stage the compact star was a white dwarf, which as a result of the mass transfer reached the Chandrasekhar limit, and collapsed to a neutron star near the end of the mass transfer phase.

During the initial phase after this accretion induced collapse (AIC) the young neutron star likely rotated rapidly, and could not accrete because the orbit had widened due to mass loss in the neutron star formation (at least the  $0.2 M_{\odot}$  mass equivalent of the binding energy of the neutron star is lost, in the form of neutrinos). To fill the Roche lobe again the secondary star had

to expand for a time interval of at least several million years (Pylyser and Savonije 1988; Van den Heuvel 1995). During this time (re-)circularization of the orbit could take place, as tidal dissipation in convective envelopes is very efficient (Phinney and Kulkarni 1994).

A possible objection that might be raised against the AIC model is that, in order to have a white dwarf collapse to a neutron star, it should be composed of O, Ne and Mg (cf. Nomoto and Yamaoka 1992), and such white dwarfs are always born with masses  $\gtrsim 1.2 M_{\odot}$ . Hence, not more than  $0.24 M_{\odot}$  of mass transfer can have taken place before reaching collapse, and, since at least  $0.40 M_{\odot}$  was transferred, still the neutron star should have accreted  $> 0.16 M_{\odot}$ , and thus its magnetic field should have decayed to a very low value.

However, such a reasoning need not be correct, as the donor star may have lost part of its envelope mass during and immediately after the formation of the neutron star, as a result of (i) the impact of the supernova shell, and (ii) the strong evaporative mass loss from its envelope, caused by the relativistic wind of the extremely young and energetic pulsar next to it.

We expect the latter effects to be the most important ones. The evaporative mass loss from the companion in this phase may be estimated by using the formulation of the problem by Van den Heuvel and Van Paradijs (1988), according to which substantial evaporation of the companion will occur if the ratio of the time scale  $\tau_{\text{evap}}$  for evaporation and the pulsar spin-down time scale  $\tau_{\text{sd}}$  is smaller than unity. This ratio can be written as (Van den Heuvel and Van Paradijs 1988):

$$\tau_{\text{evap}}/\tau_{\text{sd}} = 0.1 f^{-1} (a/2R)^2 (P/15 \text{ ms})^2 (M/M_{\odot})^2 (R_{\odot}/R)$$

where  $P$  is the neutron star spin period,  $a$  the orbital separation,  $M$  and  $R$  are the mass and radius of the secondary, and  $f$  is the efficiency factor for evaporation, i.e., the fraction of the impinging pulsar wind energy used for driving the evaporative wind off the companion.

With the secondary near its Roche lobe and the mass ratio  $q = 4$ , we have  $a/2R \sim 2$ . In GRO J1744–28  $R \sim 7.5 R_{\odot}$ , and  $M < M_{\odot}$ . With these values and  $P = 15$  ms one obtains  $\tau_{\text{evap}}/\tau_{\text{sd}} < 0.05/f$ . Hence, a newborn pulsar like the Crab pulsar at its birth ( $P = 15$  ms) will be able to evaporate a substantial part of its companion if  $f > 0.05$ . As this seems a very modest requirement, it seems very likely that the young pulsar will in the first few thousand years after its birth have evaporated a considerable part of the envelope of its companion. Assuming that some  $0.10 M_{\odot}$  of the H-rich envelope of the companion was left (still sufficient to achieve tidal circularization), the donor needs, as yet, to hardly have transferred any mass following its resumed overflowing of the Roche lobe. Therefore, there is no contradiction between AIC and the present small envelope mass of the secondary in GRO J1744–28.

A second objection that might be raised against this scenario is that at mass transfer rates of  $\sim 10^{-9} M_{\odot}/\text{yr}$ , as expected from an initial donor star of  $1 M_{\odot}$ , the white dwarf will not retain the matter transferred to it, but burn it in strong nova flashes causing

the accreted matter to be ejected (cf. Nomoto 1982; Fujimoto 1982; Iben 1982).

Fujimoto's (1982) analysis shows that for a white-dwarf mass  $> 1.2 M_{\odot}$ , a mass accretion rate  $> 0.5 \cdot 10^{-8} M_{\odot}/\text{yr}$  is required to prevent nova explosions. Such a mass transfer rate is larger than what a donor of initial mass 0.9 to  $1.0 M_{\odot}$  would be able to provide. However, the above described model with AIC works equally well for somewhat higher initial donor masses, in the range 1.2 to  $2.3 M_{\odot}$ . When overflowing the Roche lobe in a binary with orbital period in excess of 0.5 days, such stars will always have a degenerate helium core and a hydrogen burning shell. These companions do, however, drive a higher mass transfer rate, on a thermal timescale of the donor, of  $\sim 10^{-7} M_{\odot} \text{yr}^{-1}$ , as mass transfer from the more massive to the less massive star causes the donor to be thermally unstable. This results in a mass-transfer rate in excess of  $0.5 \cdot 10^{-8} M_{\odot}/\text{yr}$ , such that the hydrogen accumulated on the white dwarf surface will be able to burn steadily, causing the white dwarf mass to increase steadily.

Systems of the above type, consisting of a star of 1.2 to  $2.3 M_{\odot}$  plus a white dwarf in this steady burning phase, have been identified with the luminous supersoft X-ray sources discovered with ROSAT (cf. Van den Heuvel et al. 1992). Presently some 34 of these are known in Local Group galaxies. Their total number in the Galaxy has been estimated to be of order  $10^3$  (Van den Heuvel et al. 1992; Rappaport et al. 1994), with a birth rate of order  $10^{-3}$  per year in the Galaxy. A fraction of them will harbor O-Ne-Mg white dwarfs, and these systems are excellent candidates for neutron star formation by AIC. Also in the case of a more massive donor the young pulsar formed by AIC can evaporate the bulk of the donor's envelope during the first few thousand years of spindown.

In view of the above we therefore conclude that the observed characteristics of GRO J1744–28 can be consistently explained if this is an LMXB near the end of its mass transfer phase, in which the neutron star was formed by AIC. Attractive candidate progenitor systems for such evolution are the luminous supersoft binary X-ray sources in which the white-dwarf companion had a mass in the range 1.2 -  $2.3 M_{\odot}$ .

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