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Pulsars and binary stars

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1. Introduction

About half of all stars occur in binaries. Therefore, for the stars which represent late stages of stellar evolution, *e.g.* pulsars, one can expect a binary parentage although they may be single now. This genesis of pulsars is what we examine in the following. The connection between pulsars and binary stars came about through the studies of stellar evolution in close binary systems. These in turn were inspired by observations of algol type binaries in the early 1950s and later by the discovery of binary x-ray sources. As we shall see, the connection with pulsars emerged slowly and with many surprises on the way. It is only recently that the full significance of this close connection has been appreciated.

As it is beyond the scope of a short review, such as this, to deal extensively with binary systems, pulsars, and the related subject of binary x-ray sources, the next three sections give brief introductions to evolution of close binary systems, pulsars, and the x-ray binaries. Later sections review the developments in these themes, often taking place in interaction with each other. The references wherever possible are to recent reviews which may be explored for further details. The two invited discourses in the IAU General Assemblies of 1979 and 1985 (Paczynski 1980; Radhakrishnan 1986) are especially relevant. For x-ray sources Sreekantan (1990) or van den Heuvel (1983) should be consulted.

2. Close binary systems : evolution to the x-ray stage

Binary systems in which the component stars can interact are called close binary systems (CBS). The most significant mode of interaction between components is the transfer of mass from one to the other. Depending on the closeness of separation the CBS can be further classified as detached, semi-detached, contact, or common-envelope binaries. For a CBS not to be a detached system the orbital period must not be too long. (It should be $\lesssim$ 10 yr). As for single stars, the mass could be lost through stellar wind, supernova explosion etc. The mass loss specific to a binary system and which is most significant from the stellar evolution view point occurs when a star loses mass through a stellar wind or a Roche lobe overflow to its companion. Corresponding to the evolutionary stages of such a mass losing star, different cases of mass transfer can be considered. If the overflow occurs before the end of core hydrogen burning it is case A. If it is after the end of core hydrogen burning but before core helium ignition it is case B and if the star fills its Roche lobe after helium ignition but before carbon ignition it is called case C. A binary system is specified by the orbital period, P_{orb}, of the binary apart from the usual stellar parameters of masses and chemical compositions. We shall always denote stellar masses in units of $M_\odot$. The masses in a CBS change during the evolution. We shall consistently call the initially more massive star as the primary (mass M_1) and the other as the secondary (mass $M_2 < M_1$).

The classification into cases A, B, C etc. is essentially a classification with increasing orbital periods (*i.e.* with increasing separation between the two components). It depends on the primary mass M_1 but not much on the mass ratio $q = M_2/M_1$ or the chemical composition. Figure 1 shows the combinations of M_1 and P_{orb} which lead to different cases. The fraction of binaries which evolve according to case A is much smaller than in cases B or C. We shall mostly deal with the case B.

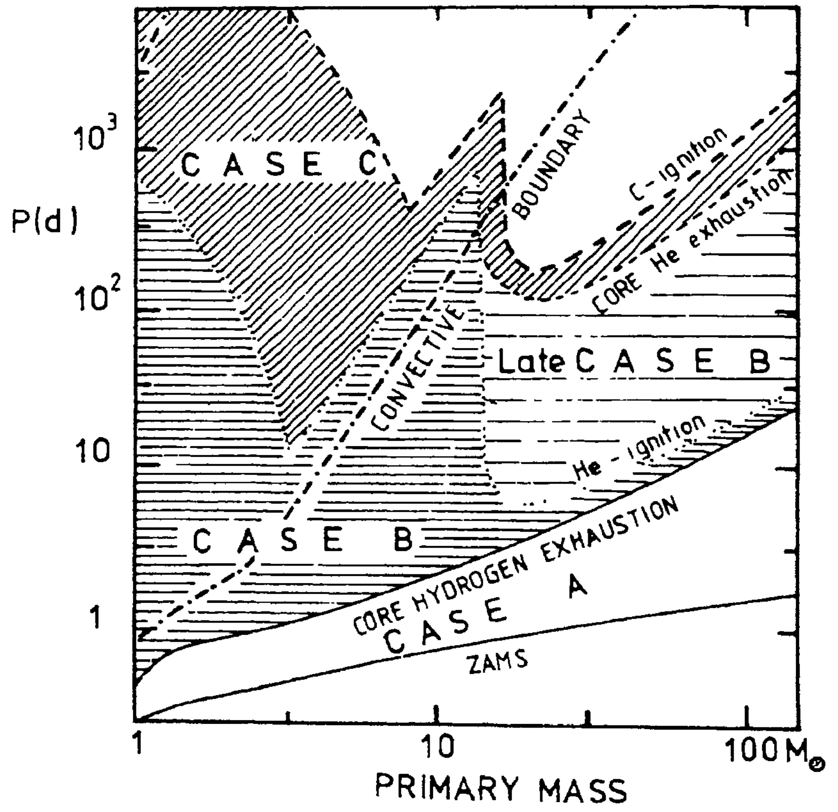

Figure 1. A plot of P_{orb} in days versus the primary mass M_1 showing the regions corresponding to cases A, B, C of mass transfer. (From van den Heuvel 1983)

It is often assumed that the evolution is 'conservative', *i.e.* the total mass M and the total angular momentum J are constant. That is,

$$M = M_1 + M_2 = \text{constant}, \qquad \ldots(1)$$

and (for a circular orbit with radius a)

$$J^2 = \frac{G M_1^2 M_2^2}{M}\, a = \text{constant}. \qquad \ldots(2)$$

The typical evolution of a CBS proceeds as follows. The primary evolves faster and in case B, after core hydrogen exhaustion starts to overflow its Roche lobe. The mass is transferred, through the inner Lagrangian point L_1, to the companion which is still in the hydrogen burning stage. The timescale for this mass transfer is at most the thermal or the Kelvin-Helmholtz timescale, τ_{KH}, of the primary,

$$\tau_{KH} = 3 \times 10^7 \frac{M_1^2}{R_1\, \alpha_1} \text{ yr} \qquad \ldots(3)$$

where R_1 and α_1 are the radius and luminosity of M_1 in solar units. At the end of this first mass transfer about 80% of the primary's mass is transferred to the companion. Of the primary only a He (or a more evolved in case C) core is left behind. It is no more a paradox that at this stage the less massive star in the binary is the more evolved one. (This was the Algol paradox, though Algol type systems fall under the case A.) During mass-transfer from the more massive to the less massive component the orbit shrinks. However, during the above mass transfer the mass ratio reverses and at the end the orbit is wider (longer P_{orb}). At this stage the system resembles a Wolf-Rayet binary (WRB). Further evolution of the primary which is now a He star proceeds rapidly, on a time scale of $\sim 5 \times 10^5$ yr. Depending on the mass, it will evolve into a white dwarf (WD), a neutron star (NS) or a black hole (BH). If a NS is formed the system experiences a supernova explosion (SNE). With a sudden loss of mass the binary will disrupt, if the lost amount is more than a half of the total initial mass of the binary. As the less massive component is exploding, the system is not broken up.

Later evolution of the now more massive secondary leads to mass transfer in the reverse direction. This could be due to a stellar wind or a Roche lobe overflow. Accretion of this matter by the NS remnant of the primary turns the system into an x-ray source.

For further details one may consult Paczynski (1980) and van den Heuvel (1983).

3. Pulsars

Pulsars were discovered in 1967. Soon their identity was established as rotating magnetic NS, the pulse period being the rotation period of the star. This rotation period was observed to be lengthening which implied that pulsars were losing energy with time. Thus, the younger the pulsar shorter would be its period. The pulses are seen because the magnetic (dipole) axis of the star is inclined to the rotation axis. The observed pulse period P and its time rate of increase P allow us to derive both its total luminosity and the surface magnetic field as

$$L_{TOT} = \frac{4\pi^2 I \dot{P}}{P^3} = 4 \times 10^{31} \frac{\dot{P}_{-15}}{P^3} \text{ erg s}^{-1}, \qquad \ldots(4)$$

$$B = \left(\frac{3c^3}{8\pi^2} \frac{I P \dot{P}}{R^6}\right)^{1/2} \cong 10^{12} \sqrt{P \dot{P}_{-15}} \text{ G} \qquad \ldots(5)$$

Here I and R denote the stellar moment of intertia and radius; P is in s; and $\dot{P}_{-15}$ is $\dot{P}$ measured in units of 10^{-15}. The last parts of equations (4) and (5) assume typical values of I and R to be respectively 10^{45} gm cm^2 and 10^6 cm. The energy which is lost by the pulsar from its rotational energy reserve is through the agency of its magnetic field. The field in equation (5) is derived with the assumption that the energy loss is due to magnetic dipole radiation. As one can see the surface magnetic field of pulsars are high and are $\sim 10^{12}$ G.

Another quantity inferred from the energy loss is the spin-down age τ_s,

$$\tau_s = \frac{P}{2\dot{P}} = 1.6 \times 10^7 \frac{P}{\dot{P}_{-15}} \text{ yr.} \qquad \ldots(6)$$

If the magnetic field is constant in time and the initial pulsar period is negligibly small, then τ_s would correspond to the true age of the pulsar. For the pulsar in the Crab nebula, PSR 0531 + 21 $\tau_s = 1200$ yr as compared to its known age of 925 yr.

If the energy radiated by the pulsar can be traced to its rotational energy and its cause to the magnetic field, on general grounds, one can expect that a pulsar will stop functioning when its period is too long or the magnetic field too weak. The far-from-complete theory of the pulsed radio radiation also indicates such a death of pulsars. The condition that a pulsar should be active is

$$B > 0.2 \times 10^{12} P^2 \text{ G.} \qquad \ldots(7)$$

Since NS are born in SNE, at least around young pulsars one expects to see supernova remnants (SNR). At present four pulsars are associated with SNRs. The others are so old that the SNR have dispersed away.

The galactic distribution of pulsars is that of population I objects except for very high values of z, the distance from the galactic plane. (Mean z for pulsars is 350 pc.) This was immediately interpreted as due to pulsars having high velocities about 100-500 km s^{-1} Though born in the galactic plane pulsars migrate during their lifetimes to high z. Later observations of pulsar proper-motions provided direct support for this idea.

Pulsar distances can be derived from observed dispersion delays in arrival times of pulses at different frequencies. Then the proper motions can be used to derive approximate values of V_z, the velocity components perpendicular to the galactic plane. With V_z we can define a kinematic age of the pulsar as τ_k,

$$\tau_k = \frac{z}{V_z}. \qquad \ldots(8)$$

If pulsars are born in the galactic plane and have not undergone oscillations through it, then this too would give the true age of the pulsar. Usually only the transverse velocity is known and τ_k is uncertain to that extent.

Viable among the mechanisms proposed for accelerating pulsars to high velocities are an asymmetry in the supernova explosion and release from a binary orbit. The early data though meagre pointed towards the binary 'sling-slot'. This was one indication of the connection between pulsars and binary stars apart from the general expectation based on 50% incidence in binary systems of all types of stars.

The references for this section are Radhakrishnan (1982) and Taylor & Stinebring (1986).

4. Binary x-ray sources

In the early 70s the binary nature of the galactic x-ray sources was established. The mass determination of these sources identified most of them as neutron stars. The mass accretion in CBS as the mechanism for producing x-rays found a revival. New thrust was given to studies of stellar evolution in CBS, to which x-ray binaries (XB) provided a testing ground.

These binary systems had clearly survived a SNE. A SNE has the following effects on a binary orbit (van den Heuvel 1978).

(a) The ejected mass tends to disrupt the system. It in any case increases the eccentricity of the system.

(b) The impact of the SN shell on the companion and possible subsequent ablation of material from the companion surface can work towards disruption also. However if any of the envelope material is blown off by the SN shell then the impact and ablation effects are diluted.

(c) An asymmetry in the SNE can impart an extra kick velocity.

Clearly in XB none of these could cause disruption. But the centre of mass of the binary would receive a runaway velocity. The XB can then migrate to higher z even if born in the galactic plane. The observed z can be thus used to constrain the evolutionary time scales.

Most of the companions of NS in earlier XB sample were massive, $M_2 > 15$. In case of Roche lobe overflow they would transfer $\sim 10^{-4}$ $M_\odot$ yr^{-1} and smoother all the x-ray activity on the NS. But in the post main-sequence expansion phase before the overflow they can have considerable mass loss $\sim 10^{-6}$ $M_\odot$ yr^{-1} in form of a stellar wind. Only a fraction ($\sim 10^{-5}$-10^{-3}) of this is captured by the NS and leads to observed x-ray luminosities of 10^{35}-10^{37} erg s^{-1}. The lifetime of this x-ray phase is $\sim$ few $\times 10^4$ yr. The total time interval from the formation of the NS till the companion has gone past the Roche lobe overflow phase is $\sim 4 \times 10^6$ yr. In further $\sim 5 \times 10^5$ yr the companion will also end up as a compact star.

5. The first binary pulsar and pulsar 'Recycling'

In 1974 the discovery of the first binary pulsar was reported. This was the Hulse-Taylor pulsar, PSR 1913 + 16. At the time it was the second fastest pulsar known. Soon its spin-down rate (P) was also measured and the following characteristics emerged. (i) $P = 59$ ms was very short. (ii) $B = 2 \times 10^{10}$ G was very low. (iii) There was no supernova remnant around it.

Property (i) implies that the pulsar must be young while (iii) implies that it must be old. If the pulsar is young then the low field has to be one of the rare occurrences. But if pulsar magnetic fields decayed with time then it could also be that this pulsar is old and was born with a usual strong field $\sim 10^{12}$ G, which has now decayed to the present value. In this time interval the SNR could have dispersed away.

As the way out of this dilemma emerged the idea of 'pulsar recylcing'. The accretion models of XB had considered the torques on neutron stars due to accretion. Since the accreted matter originates from the companion in a binary orbit, it carries a part of the orbital angular momentum. The specific orbital angular momentum is usually orders of magnitude larger than the specific spin angular momentum. (This being a simple consequence of the fact that the separation between components is very large compared to their radii). The accretion thus makes the NS to have the same specific spin angular momentum as the orbital one.

The accretion takes place due to the gravitational pull of the NS. However, it is impeded by the pressure of the NS magnetic field and also the centrifugal forces which come about due to the corotation induced in the infalling matter by the NS magnetic field. These opposing factors try to achieve an equilibrium, and for it the period is the equilibrium period, P_{eq} (van den Heuvel 1984),

$$P_{eq} = 2.4 \ B_9^{6/7} \, M^{-5/7} \, R_6^{15/7} \, \dot{M}_E^{-3/7} \ \text{ms}, \qquad \ldots(9)$$

where B_9, M, R_6 are NS surface magnetic field, mass, and radius in units of 10^9 G, $M_\odot$ and 10^6 cm respectively. $\dot{M}_6$ is the mass accretion rate in units of the Eddington or the critical accretion rate of $\sim 10^{-8}$ $M_\odot$ yr^{-1}. The 59 ms period of the PSR 1913 + 16 would correspond to P_{eq} for its magnetic field and $\dot{M}_E = 0.5$.

Consequently, by the time the accretion (and the x-ray) phase is over, the NS has been spun up to a very short period. Only when all the x-ray activity has stopped will this short period old NS be visible as a pulsar. We may at this time observe it as a binary pulsar with a normal stellar companion. Later evolution of the companion, if it is massive enough to evolve into a NS and in the event that the SNE does not break up the binary, will lead to a binary pulsar like PSR 1913 + 16.

It should be noted at this point that the short period can be explained as being due to the accretion spin-up using only the low magnetic field of the PSR 1913 + 16. Was it that this pulsar was born with a very low magnetic field? If yes then pulsars recycled to very short periods may be a minority because generally the initial magnetic fields are believed to be in the range 10^{12} - 10^{13} G. But as we shall see there is evidence that pulsar magnetic fields decay with time. Consequently the low field of PSR 1931 + 16 was not anomalous but had decayed down to this value. Indeed, one should expect many pulsars to have such a low field.

There is no doubt that the history outlined above for PSR 1913 + 16 is correct. Thus the Hulse-Taylor puslar not only gave the first direct link between pulsars and binary systems but also provided a diagnostic for about half of the pulsars with a binary history: the diagnostic being a combination of short period and low magnetic field. This class of pulsars has been named the 'recycled pulsars'. The extrapolation to a class of recycled pulsars was even at this time based on only one binary pulsar out of a total of about 300.

The idea of recycling required that the pulsar magnetic field decay. Theoretically it was considered most improbable because of the predicted superconducting and superfluid interiors of NS. However, proper motions of a few pulsars were measured in the mean time with some precision. The limits on kinematic ages τ_k could then be derived with more confidence. It turned out that these limits were smaller than the spin-down ages τ_s and more markedly so for those pulsars which had large τ_s. The expression for τ_s in terms of the magnetic field is

$$\tau_s = \frac{P}{2\dot{P}} = \frac{P_0^2 + 2k\int_0^t B^2\,dt}{2kB^2} \qquad \ldots(10)$$

$$= \tau_s\,(t = 0)\, e^{2t/\tau_m} + \frac{\tau_m}{2}\,(e^{2t/\tau_m} - 1),$$

where P_0 is the initial period, k a constant, and t the age of the pulsar. The last equality holds if the magnetic field is decaying exponentially on a timescale τ_m. When P_0 is negligible,

$$t = \frac{\tau_m}{2} \ln \left(1 + \frac{2\tau_s}{\tau_m} \right) \quad . \qquad (11)$$

As remarked earlier, it is only in the limit of $\tau_m \to \infty$ that $t = \tau_s$, otherwise τ_s is larger than the age t. This led to the idea that pulsar magnetic fields were decaying The estimates of τ_m from observations were around a few million years. (The assumption that all pulsars are born with short periods can also be questioned but we shall not dwell on it.) Figure 2 depicts some evolutionary tracks of pulsars on a magnetic field-period plot.

For a given value of τ_m, the time interval between the occurence of the first SNE and the onset of the mass transfer from the secondary indicated that pulsar fields would have decayed to $\sim 10^9$ G, and the P_{eq} therefore would be in the millisecond range. These

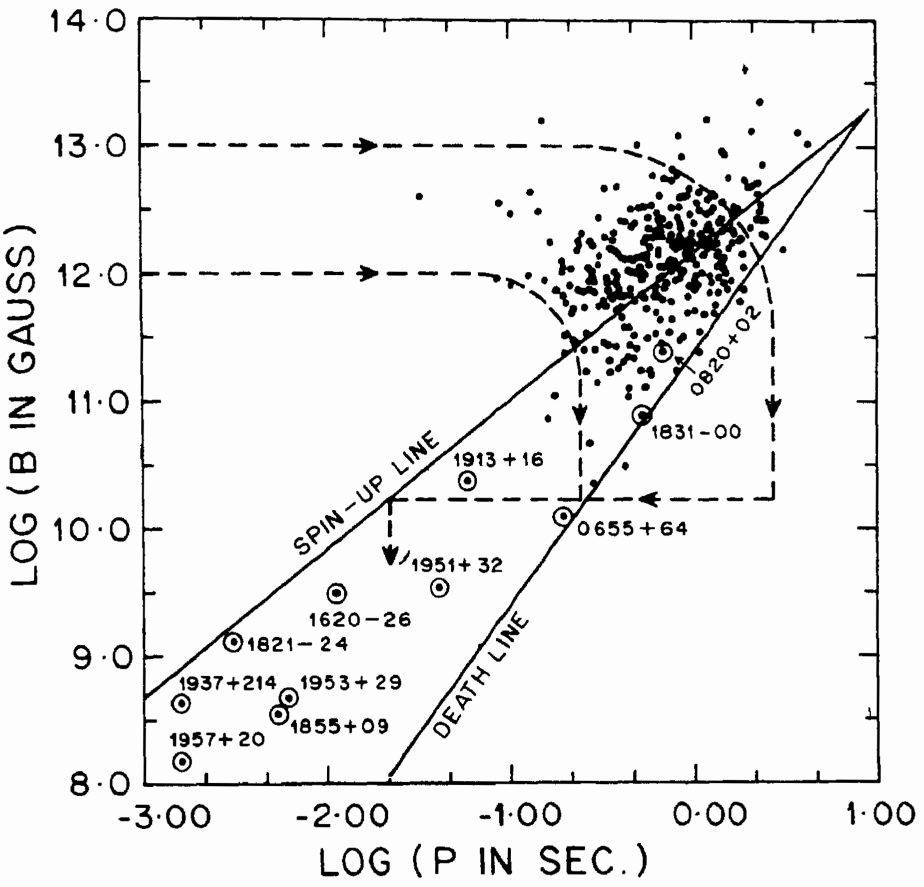

Figure 2. The magnetic field vs period plot for pulsars. Some binary and millisecond pulsars are identified by circles around points representing them. The spin-up and death lines correspond to equations (9) and (7) respectively. Evolutions for initial magnetic fields of 10^{12} and 10^{13} G up to the spin-up are shown schematically. (Adapted from Radhakrishnan 1982).

pulsars would be found in the region between the spin-up line and the death line in figure 2.

Above ideas are dealt with in more detail in Radhakrishnan (1982) and van den Heuvel (1984).

6. Types of binary x-ray sources and close binaries

In MXB the companions of NS have masses $M_2 \gtrsim 10$. From the mid 1970s, on the basis of the nature of the companions two classes among MXB could be distinguished. In summary these classes are:

(i) Standard massive x-ray binary (SMXB)

- (a) $2\ \mathrm{d} < P_{\mathrm{orb}} < 10\ \mathrm{d}$.
- (b) Evolved companion fills Roche lobe.
- (c) Circular orbit.
- (d) Mass transfer rate $(\dot{M}) \sim 10^{-10}\text{-}10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$ by Roche lobe overflow and/or stellar wind.

(ii) Be star x-ray binary (BeXB)

- (a) $15\ \mathrm{d} < P_{\mathrm{orb}}$.
- (b) Unevolved companion underfills Roche lobe.
- (c) Eccentric orbit.
- (d) $\dot{M} \sim 10^{-13}\text{-}10^{-10}\ M_\odot\ \mathrm{yr}^{-1}$ by episodic mass ejection in the orbital plane and/or steady stellar wind.

About the same time some sources were observed which produced bursts of x-rays. They were distributed mostly in the galactic bulge and globular clusters. In some of these the binary nature of the sources is established. They have NS companions with $M_2 \leqslant 2$. These are the low mass x-ray binaries (LMXB). Further classification in this group is possible.

(i) Young population LMXB

- (a) $0.2\ \mathrm{d} < P_{\mathrm{orb}} < 10\ \mathrm{d}$,
- (b) Runaway velocities $\sim 50\text{-}200\ \mathrm{km\ s}^{-1}$,
- (c) Age $<$ few 10^9 yr.

(ii) Old population LMXB

- (a) $P_{\mathrm{orb}} \sim$ hr.
- (b) No runaway velocity,
- (c) Age $\geqslant 5 \times 10^9$ yr.

We shall return to LMXB systems later. Let us now see how far the CBS evolution can account for an MXB (see van den Heuvel 1983 for details). Figures 3 and 4 show the conservative evolution of two binaries with $P_{\mathrm{orb}} = 5$ d, chemical composition $X = 0.60$, $Z = 0.044$ and (i) $M_1 = 25$, $M_2 = 10$ and (ii) $M_1 = 16$, $M_2 = 9.6$. This conservative evolutionary scenario can explain the existence of the SMXB with relatively long periods ($P_{\mathrm{orb}} \gtrsim 9$ d). In the stage (c) of figure 4, the secondary (*i.e.* the Be star) is spinning very rapidly and ejects clouds of gas from its equator. This leads to intermittent x-ray activity seen in BeXB. Thus existence of these sources can also be understood.

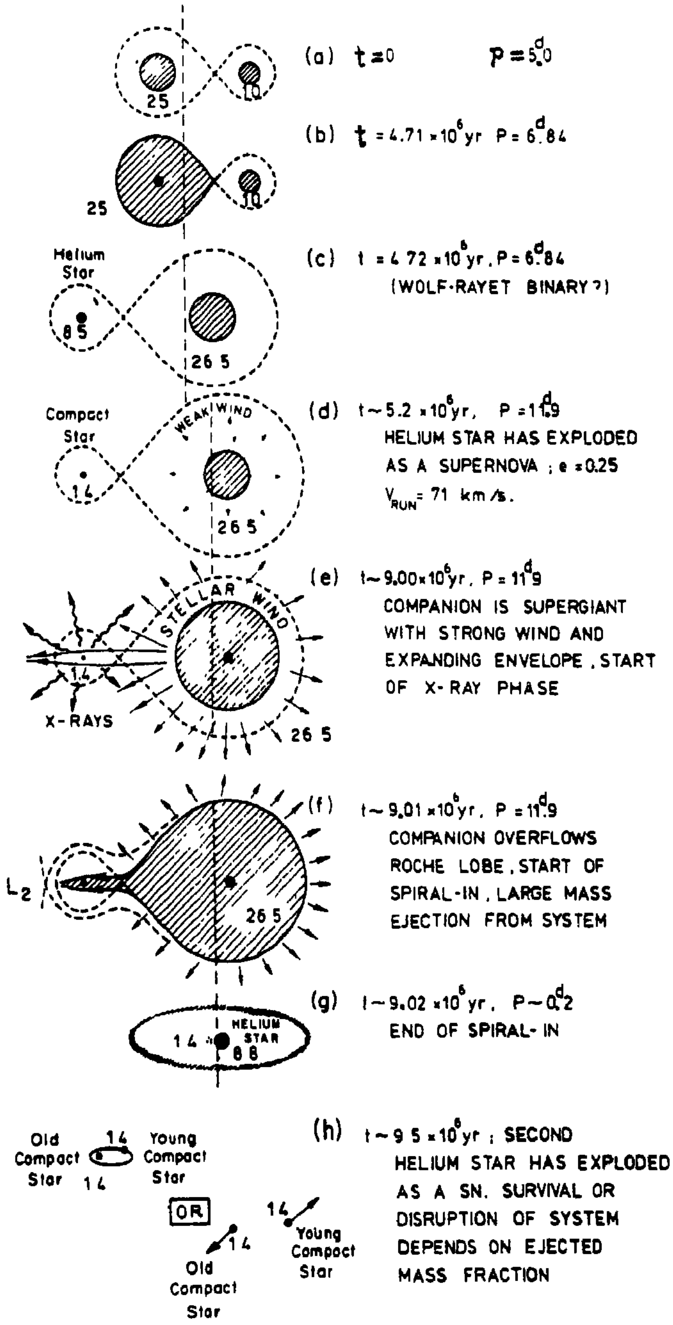

Figure 3. Conservative evolution of a close binary system with initial $M_1 = 25$, $M_2 = 10$ and $P_{\text{orb}} = 5$ d. Approximate ages and orbital periods of the system are on the right. The numbers on left are stellar masses in $M_\odot$. (From van den Heuvel 1983).

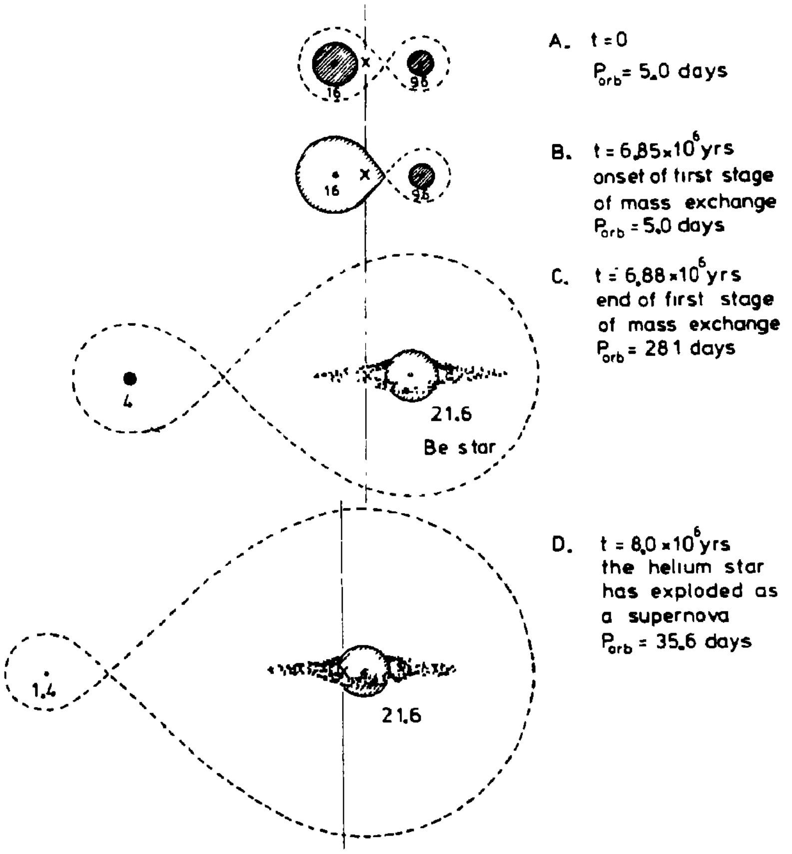

Figure 4. Conservative evolution of a close binary system consisting of B stars of 16 and 9.6 $M_\odot$, leading to a Be x-ray binary. This figure is similar to figure 3 but corresponding stages beyond (d) are not shown (From van den Heuvel 1983).

For BeXB with $P_{orb} \leqslant 15$ d the tidal deceleration makes the rotation slower, and ejection of mass by the secondary is not possible. Therefore B star binaries with $P_{orb} \leqslant 15$ d will be seen as x-ray sources only when the secondaries have become supergiants. The main difference between SMXB and BeXB is the initial primary mass M_1.

If one extrapolates from figure 3, the observed Wolf-Rayet binaries which must be the precursors of SMXB with $P_{orb} \leqslant 3$ d require an initial mass ratio of $\lesssim 0.3$. When the thermal time scales of mass transfering and mass accepting stars are widely different (as is the case if q is small) then the mass is transferred at a rate which is larger than the rate at which it can be accepted. Consequently a common envelope forms around the binary and mass is lost from the binary systems with the matter flowing out through the outer Lagrangian points, L_2 or L_3. The mass lost in this way carries much more than average specific angular momentum. The ensuing angular momentum loss will always cause the system to shrink rapidly. This is the explanation for the existence of SMXB with $P_{orb} \leqslant 3$ d. These short-period systems thus require nonconservative evolution for their explanation. Among unevolved O or B type spectroscopic binaries, about 14% have

$q < 0.4$. These will evolve nonconservatively and produce the short period WRB and SMXB. The majority evolves conservatively and produces the larger $P_{\rm orb}$ systems.

It can be shown that x-ray lifetimes in short period SMXB will be 10-100 times those of the long period ones. The observed sample may thus be dominated by the short $P_{\rm orb}$ systems.

The short period SMXB are liable to be tidally unstable and their periods may be short due to tidal interactions also. The observed close to zero eccentricities of the SMXB can be understood as the effect of the post-SN tidal interaction. For short $P_{\rm orb}$ this can be achieved in a few million years.

7. Massive x-ray binaries : beyond the x-ray stage

Final evolution of MXB also involves a nonconservative common-envelope phase (van den Heuvel 1989). In systems with $P_{\rm orb} \geqslant 4\text{-}5$ d (including BeXB), the envelope of the companion is in the rapid post-main-sequence expansion at the onset of Roche lobe overflow. In a few thousand years the mass transfer rate grows to $\sim 10^{-3}\ M_\odot\ {\rm yr}^{-1}$ but the NS can accept only $10^{-7}\ M_\odot\ {\rm yr}^{-1}$. Most of the mass thus leaves the system. One may alternatively think of the situation as the NS being engulfed by the envelope of its companion. The frictional heating due to the motion of the NS through the envelope will lead to expulsion of matter from the binary. As remarked above the consequent loss of angular momentum leads to a spiralling-in, which will terminate when only the evolved core of the secondary is left. The result is a very close binary with a compact object (WD/NS/BH) and a He star companion. The orbital period is a few hours at this time. The compact star even if it is a NS cannot manifest itself as a pulsar until this time. Now on, it could be observed as a binary pulsar. If the companion has a mass $M_2 < 8\text{-}10$ then after the spiral-in it would end up as a WD. The NS + WD system would have an almost circular orbit as in case of the PSR 0655 + 64. For a more massive companion, *i.e.* $M_2 \simeq 10\text{-}15$, the post spiral-in core has mass M_c in the range 2.5-4.2. It goes through a SNE and produces a NS in the end. The resulting system has two neutron stars in an eccentric orbit, as in case of PSR 1913 + 16. A still massive companion, *i.e.* $M_2 > 15$ leaves behind a core with $M_c > 4.2$ and after the second SNE the binary is disrupted. Two runaway pulsars are produced, with velocities of few hundred km s^{-1}. These alternatives are shown in figure 5.

All the short period SMXB with $P_{\rm orb} \leqslant 4$ d also go through the common-envelope stage, but at the onset of the Roche lobe overflow the companion is still in hydrogen burning phase and does not have a dense core. The NS can completely spiral into the companion core. The outcome will be either a NS with a completely dissipated companion or a Thorne-Zytkow star (*i.e.*, a massive star with a NS at the centre). The Thorne-Zytkow star is expected to lose its envelope in $\sim 10^7$ yr, leaving behind a single NS. During this period, the accretion from the envelope may have spun-up this NS. This sequence is depicted in figure 6.

8. Binary and millisecond pulsars

Up to 1982 two more binary pulsars had been found. Their magnetic field-period combinations put them in the region between the spin-up and the death lines in figure 2. Thus they fitted the recycled description. Not all their parameters were, however, similar

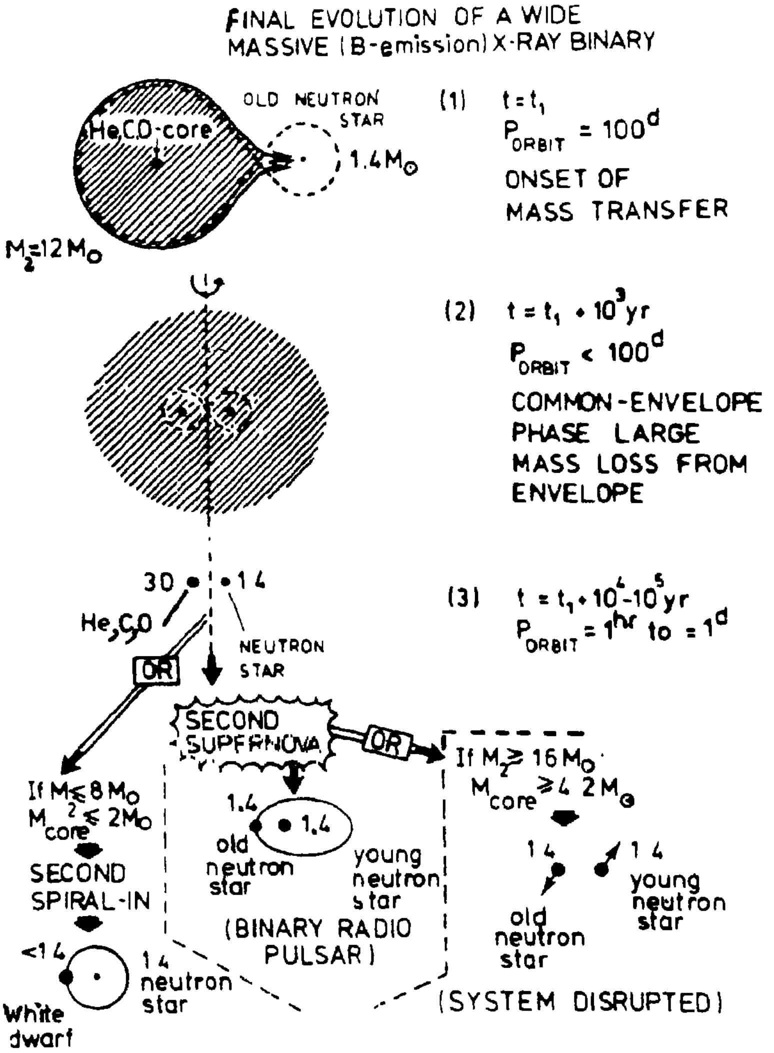

Figure 5. Last evolutionary stages of long-P_{orb} massive x-ray binaries. (From van den Heuvel 1989).

to those of PSR 1913 + 16. Especially the PSR 0820 + 02 system had a mass-function of ~ 10^{-3} $M_\odot$ indicating that the companion mass was low ($\ll 1 M_\odot$).

In late 1982 came the discovery almost as stunning as the original 1967 discovery of pulsars. This was the observation of the millisecond pulsar 1937 + 214. This pulsar has the incredibly short period of 1.6 ms. It will occupy much of our attention in later sections. At this point let it be noted that it too lies almost on the spin-up line. Thus recycling to millisecond periods was no more only a theoretical expectation. Soon afterwards the fourth binary pulsar with a 6.1 ms period was seen. This was PSR 1953 + 29 and this system also had a low mass-function of ~ 2×10^{-3} $M_\odot$.

The parameter which came to differentiate two categories of binary pulsars is the companion mass. One category has companions more massive than a NS and the other

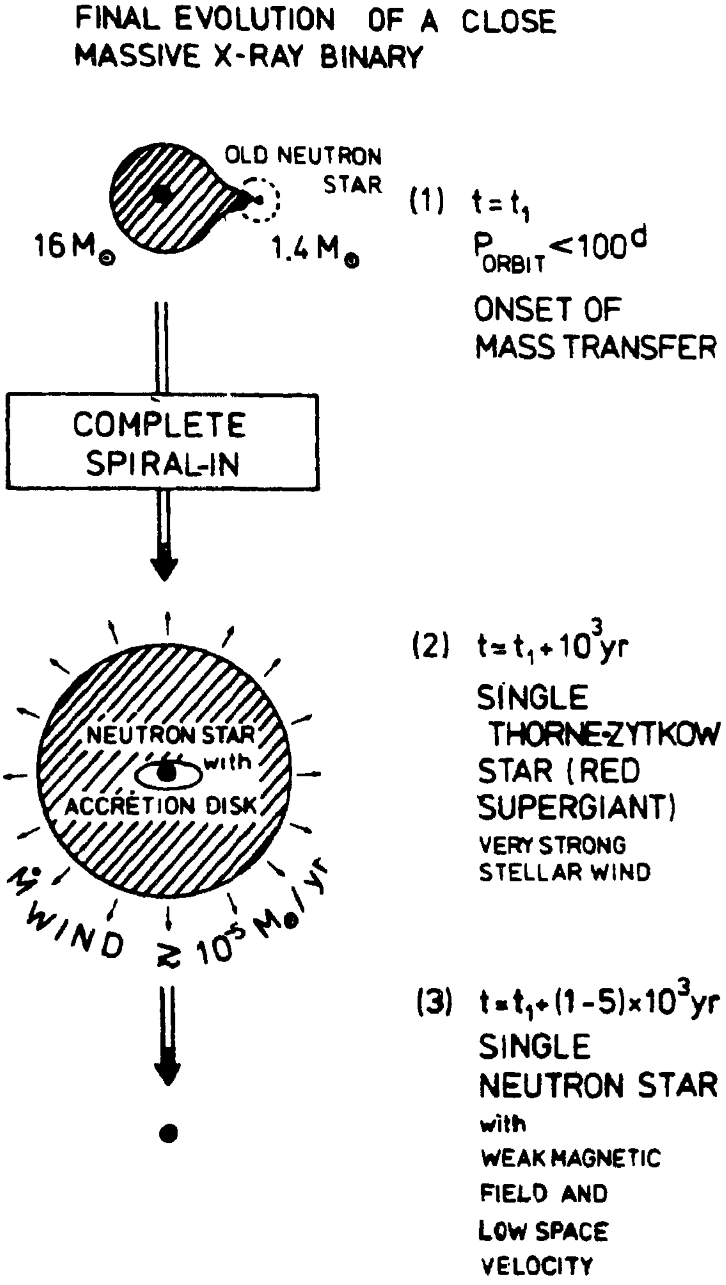

Figure 6. Last evolutionary stages of short-$P_{\rm orb}$ massive x-ray binaries: (From van den Heuvel 1989).

less massive than a NS. Let these be referred to as the high mass binary pulsars (HMBP) and the low mass binary pulsars (LMBP). (See table 1). The HMBP fit in as descendants of the long-period MXB after their final evolution as outlined at the end of section 7.

Pulsars in LMBP have companions of masses ~ 0.2-0.7, very nearly circular orbits, and lower magnetic fields. It was noticed soon after the discovery of PSR 1953 + 29 that

Table 1. A chronological list of binary, globular cluster, and millisecond pulsars

Discovery year	Pulsars	Period (ms)	Magnetic field (gauss)	Orbital period (days)	Orbit eccentricity	Mass function ($M_\odot$)	Remarks
1974	1913 + 16	59.0	2.28×10^{10}	0.32	0.62	1.3×10^{-1}	First binary pulsar
1980	0820 + 02	864.9	3.03×10^{11}	1232.47	0.01	3.0×10^{-3}	
1980	0655 + 64	195.7	1.17×10^{10}	1.03	$<5 \times 10^{-5}$	7.1×10^{-2}	
1982	1937 + 21	1.6	4.09×10^{8}	*	*	*	The millisecond pulsar
1983	1953 + 29	6.1	4.32×10^{8}	117.35	3.3×10^{-4}	2.4×10^{-3}	
1985	2303 + 46	1066.4	7.87×10^{11}	12.34	0.66	2.5×10^{-1}	
1986	1831 − 00	520.9	8.72×10^{10}	1.81	1×10^{-4}	1.2×10^{-4}	
1986	1855 + 09	5.4	3.06×10^{8}	12.33	2×10^{-5}	5.6×10^{-3}	
1987	1821 − 24	3.1	2.25×10^{9}	*	*	*	In globular cluster M28
1988	1620 − 26	11.1	3.04×10^{9}	191.44	0.02	8.0×10^{-3}	In globular cluster M4
1988	1957 + 20	1.6	1.81×10^{8}	0.38	$<10^{-3}$	5.2×10^{-6}	Eclipsing binary
1988	0021 − 72A	4.5	†	0.02	0.33	1.6×10^{-8}	In globular cluster 47 Tuc
1989	2127 + 11A	110.7	$\dot{P} < 0$	*	*	*	In globular cluster M15
1989	2127 + 11B	56.1	†	*	*	*	
1989	2127 + 11C	30.5	†	0.34	0.68	1.5×10^{-1}	
1989	1820 − 11	279.8	6.27×10^{11}	357.76	0.79	6.8×10^{-2}	

* Indicates that the pulsar is single and the parameter is not meaningful.
† Indicates that the measurement has not been made.

these type of systems resemble very closely the descendants of LMXB. Consider a NS and a less massive main sequence star in a relatively wide orbit ($P_{\rm orb} \geqslant 1$ d). After the companion has evolved mass-transfer is stable, because the less massive star is losing mass and the orbit widens. Starting with companions with masses $\leqslant 1.2$, a high mass-transfer rate ($\dot{M} \geqslant 10^{-8}\ M_\odot\ {\rm yr}^{-1}$) can be maintained for 10^6-10^8 yr. Existence of wide LMXB like Cyg X-2 and GX 1 + 4 agrees with this picture. While ascending the giant branch the degenerate He core, ($M_c \sim 0.2$-0.4) gradually grows in mass, causing mass transfer and expansion of the orbit. The duration of mass transfer is determined by initial values of the companion mass and $P_{\rm orb}$. The final outcome is a wide binary containing a NS and a He WD. Since mass transfer occurs for a long duration, the tidal effects will cause the final orbit to be almost circular.

Thus with a 1.3 $M_\odot$ NS, a 1 $M_\odot$ companion and initial $P_{\rm orb} = 12.5$ d one can end up with the PSR 1953 + 29. For the PSR 0820 + 02 the initial $P_{\rm orb}$ should be 1 yr. The LMBP can thus be explained as the progeny of the wide LMXB (van den Heuvel 1989).

The magnetic fields of these pulsars, however, pose a problem. The above evolutionary model suggests that the LMBP systems are at least several billion years old, which is the evolutionary time scale for stars with masses < 1.2. The decay of the pulsar magnetic fields on a time scale of $\lesssim 10^7$ yr would imply that LMBP should have near zero fields. It is also difficult to understand how these systems survived the SNE which produced the NS.

A way out is possible by invoking the accretion induced collapse (AIC) of a WD. The fields are not low enough in LMBP because the NS are not 10^9 yr old. The system started out with a WD instead of a NS and because of accretion of matter the mass of the WD at some point exceeded the Chandrasekhar mass limit. This induced a collapse of the WD to a NS (Cameron & Iben 1986). The NS at this time, presumably, had the standard field strength $\sim 10^{12}$ G. The duration of mass transfer for PSR 1953 + 29 and 0820 + 02 in the above models come to $(3.5\text{-}7.7) \times 10^7$ yr and 4×10^6 yr. In the former case this duration is long enough to permit the magnetic field of the NS, produced by AIC, to decay to the present value of 4×10^8 G, while in the latter case the decay would be less and the present field stronger (3×10^{11} G).

One also expects that the mass ejected in an AIC is very small (just the WD envelope of $\sim 10^{-2}$ $M_\odot$) and therefore the eccentricity of the orbit would be very small ($\sim$ 0.05). The runaway velocity imparted would also be small ($\sim$ 10 km s^{-1}) and thus these systems will maintain their low z values.

9. Pulsar velocities

About the same time when millisecond pulsars made their appearance, precise proper-motion measurements of about 26 pulsars became available. These showed a correlation between velocities (as far as they can be derived from proper motions) and the magnetic fields of pulsars. The high-velocity pulsars had high magnetic fields and the low-velocity ones low fields. The low-field pulsars fitted the recycled description and thus had a binary history. If one proceeded on the assumption that all pulsars were born from binary systems and SNE imparted no kicks then it was possible to relate the masses and separations in the progenitor binaries to the currently observed high pulsar velocities (Radhakrishnan & Shukre 1987). In fact, the binaries from which pulsars are released would contain one NS and one pre-SN star. The system is disrupted up by the SNE which produces the second NS. The mass of the NS as far as one can infer from observations is 1.4 $M_\odot$. This allows one to place limit on the pre-SN stellar mass and also the orbital period. For the observed range of pulsar velocities, *i.e.*, 100-500 km s^{-1}, it was found that $0.01\ \mathrm{d} < P_{\mathrm{orb}} < 1\ \mathrm{d}$ and $4.2 < M_2 < 7$ (separations $0.3\ R_\odot < a < 7\ R_\odot$). Though the highest values of pulsar velocities need orbits to be extremely close, generally these parameters resemble surprisingly well those of the post spiral-in long period MXB. This constitutes an independent connection between pulsars and the common-envelope evolution of MXB. A more recent study by Bailes (1989) invokes kick velocities due to asymmetries in the SNE. The needed kicks are $\sim$ 100-200 km s^{-1}. But since the contribution of orbital velocities to the net pulsar velocity (especially for higher velocities $\sim$ 500 km s^{-1}) would still be the basic one, the relation to binary parameters can still be derived. The limits on M_2 and P_{orb} however get modified. The inter-connection between conclusions derived from pulsar velocities (with related assumptions about magnetic field decay etc.) and the outcomes of the evolution of CBS is not yet fully explored.

The low-velocity low-field pulsars which must be the recycled ones, however, present a problem because some of them have velocities as low as 20 km s^{-1}. If these pulsars have been released from a binary then what would be the nature of these systems? The low field pulsars are old NS, so the companion must be a new born NS whose formation caused the binary to break up. The low velocity implies that the binary must be wide. But then the young pulsar too would have a low velocity. No such pulsars are seen.

One way to form such low-velocity low-field pulsars is to make the companion disappear after it has caused the recycling of the NS. Such an outcome has been contemplated for the short-period LMXB (Ruderman & Shaham 1983).

10. Formation of the millisecond pulsar

Even more problematic is the formation of the millisecond pulsar. It gives clear indications of having a binary history, but its present solitary status is not easy to understand (van den Heuvel 1984).

Among the binary scenarios for the formation of the millisecond pulsar 1937 + 214 one can readily rule out the MXB history. The reasons for it are as follows. In an MXB

(i) the disruption of the binary would have imparted a velocity of at least several hundred kilometers per second. This is so because the pre-SN (*i.e.* the second SN) system would have been a very close binary with a period of few hours (see section 8). The z distance of this pulsar of 30 pc is then hard to explain unless it is exceptional.

(ii) In a system in which two SN can occur the time interval between them can be at most a few times 10^5 yr. It is not possible for the NS to accrete $\sim 0.12\ M_\odot$ required to spin it up to 1.5 ms period in this much time.

(iii) The magnetic field cannot decay to 4×10^8 G in the same time interval.

With MXB the only alternative left then is to consider the coalescence of the NS with its companion due to the evolution after the spiral-in. In short-period MXB this is expected to occur but the outcome cannot be predicted with certainity to be an NS with a period as short as 1.5 ms (see the last part of section 7). However, the end product will have a low velocity and consequently a low z as does the PSR 1937 + 214.

Due to gravitational radiation losses in the NS + WD and NS + NS type systems (*e.g.* PSR 0655 + 64 and PSR 1913 + 16 respectively) the orbit will shrink in course of time. Eventually the stars will be so close that they will coalesce. These alternatives are viable ones. The former is more favoured because the final velocity will be low.

Now let us consider the fate of short-period LMXB which were referred to at end of the previous section. In very close LMXB, the mass transfer is driven by only gravitational radiation losses and the magnetic braking. Though initially the gravitational radiation causes the orbit to shrink and the mass to transfer from the lighter companion to the NS, the inverse dependence of the companion radius on its mass makes the system widen eventually. The stars spiral out at an increasingly slower rate. The companion at the same time keeps becoming lighter. The question whether the companion can disappear altogether is clearly relevant for the solitary millisecond pulsar formation. Various stellar evolution studies concluded that it is highly unlikely that the companion will ever be disrupted (Jeffrey 1986).

11. Recent developments

The impact of the discoveries of millisecond pulsars, both single and binary, on all related fields has been tremendous. The new studies in evolution of CBS are now motivated directly by millisecond and/or binary pulsar discoveries while earlier this role was played by the x-ray observations. The pulsar observations are leading us to more and more millisecond and binary pulsars, at present almost at a rate of one per month. In the following we shall try to highlight a few of the recent developments.

In 1986, optical searches for companions of binary pulsars 0655 + 64, 0820 + 02 and 1855 + 09 succeeded in detecting them. As had been expected theoretically for LMBP 0820 + 02 and 1855 + 09 the companions are consistent with the expected low mass WD and for HMBP 0655 + 64 it is a massive WD. However, the companions of PSR 0655 + 64 and 1855 + 09 from WD cooling times were found to be $\gtrsim 10^9$ yr old, implying that the pulsars were even older. Then magnetic field decay would imply that their fields be much lower than the presently observed values, *i.e.* 1.7×10^{10} G and 3×10^8 G. The magnetic fields of pulsars apparently do not decay below a minimum value of $\leqslant 10^{10}$ G. This was also indpendently conjectured on other grounds. We do not yet have a full understanding of this (Kulkarni 1988).

Existence of x-ray sources in globular clusters has been known for many years. It is not surprising that when the accretion stops in these systems the NS would be observable as a pulsar. The evolutionary connection seen between LMXB and LMBP would make one expect a recycled pulsar. In 1987 the observations motivated by these considerations found the first pulsar in a globular cluster (Lyne *et al.* 1987). It was a solitary pulsar, PSR 1821-24 in the cluster M 28. As expected, its period of 3 ms and magnetic field of 2×10^9 G confirm it as a recycled pulsar. The population of known pulsars in globular clusters has increased since then and is still increasing rapidly. Binary pulsars have also been found. In fact one of them (PSR 0021-72A) in the globular cluster 47 Tuc has a period of 4.5 ms and an orbital period of 32 min. The periastron advance rate for it is 0.5 degrees per day, the highest known (Ables *et al.* 1989). Another one reported a few months ago, PSR 2127 + 11A, in M15 is a single pulsar. Its period of 110 ms does not make it a true millisecond pulsar, but it has a *negative* $\dot{P}$. This shortening in rotation period is attributed to its being bodily accelerated in our direction by the gravitational pull of the collapsed cluster core (Wolszczan *et al.* 1989).

Discussion on the formation of solitary millisecond pulsars in globular clusters is fraught with the same difficulties as those with their disc counterparts. One factor exclusive to globular clusters is the large frequency of collisions between stars inlcuding those between old NS and other normal stars. A three-body collision can release a millisecond pulsar from a binary. Similarly, due to capture collisions, formation of LMXB is also possible. In the galactic bulge, on the other hand, it is not clear how LMXB form. One of the sticky issues is also the LMXB-LMBP relationship. In a steady state, birth rates of both types should match. The statistical analysis of the existing data indicates that in the galactic disc the birthrate of LMBP is about 100 times that of their progenitors, LMXB. A similar mismatch occurs in the two birthrates also for globular clusters (Kulkarni *et al.* 1990). Perhaps our knowledge about final stages of CBS evolution requires a revision.

In fact this is what happened when PSR 1957 + 20 was discovered (Fruchter *et al.* 1988). By any standards it is a most remarkable object. It has the second shortest (1.6 ms) period. It is in an eclipsing binary which has $P_{\rm orb} \sim 9$ hr. The duration of the eclipse is about 0.1 $P_{\rm orb}$. Given the fact that eclipses occur, it implies a size for the 'opaque' portion of the companion to be at least 1.5 $R_\odot$. The companion of mass 0.02 $M_\odot$, which has been detected optically, has a Roche lobe radius of 0.3 $R_\odot$. The surprisingly large size of the eclipsing region is perhaps due to the stellar wind from the companion, and in fact what we are witnessing is the evaporation of the companion due to the high-energy emission from the pulsar, as was theoretically speculated earlier. All the pieces in the jigsaw do not yet fit snugly but disappearance of the companion due to ablation caused by the pulsar is now a serious contender among mechanisms to produce a solitary millisecond pulsar. (See end of section 10, Ruderman *et al.* (1989); van den Heuvel (1989) and references therein.)

The connection between pulsars and binary stars whose unfolding we have followed so far though definite is only partial. There has been great progress in both fields, as well as in the intimately related field of galactic x-ray astronomy. But we still do not know, for example, the fraction of the pulsar population contributed by binary systems. A large number of questions remain. On way to answering these one can be sure that, as it happened in the past, many surprises are yet to be met.

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Discussion

Rathnasree : During the accretion phase would it be possible for x-rays to reach the companion stars and thereby lead to ablation?

Shukre : Ruderman *et al.* find that M eV γ-rays are the most plausible source to drive the ablation.

Rathnasree : Since a LMXRB reaching the period gap would result in the ablation of the companion, would one see any binary pulsars below the period gap?

Shukre : Some are seen below the period gap and the reason could be that the companion had developed a He core which survived the evaporation process. (See *Nature* (1988) **334**, 227).

Bhat : What is the γ-ray luminosity value needed to cause ablation of the companion star? Are you aware of any measurements which have been carried out or are planned to check this postulation? What process is likely to produce these γ-rays?

Shukre : In calculations γ-ray luminosity is taken to be what one would expect on the basis of γ-rays observed from the Vela pulsar. Though theoretical models exist we do not fully understand how these γ-rays are produced.

Chaubey : You referred that orbital angular momentum consume in pumping the tidal distortion. Is any evidence?

Shukre : Cyg X-3 is considered to be an example. You may refer to van den Heuvel (1983) for discussion of tidal effects on orbits.

Narlikar : What is the gravity wave radiation for the binary pulsar (?) with the large periastron motion?

Shukre : It comes to about 3×10^{34} erg s^{-1}, a hundred times more than the value for the Hulse-Taylor pulsar.

Note added in proof: After this talk was given some new and interesting developements, especially concerning the evolution of pulsar magnetic fields have taken place. The review 'Formation and evolution of binary and millisecond pulsars' by D. Bhattacharya and E. P.J. van den Heuvel (to appear in *Physics Reports* 30 July 1990) should be consulted for these.