On a Theoretical Interpretation of the Period Gap in Binary Millisecond Pulsars

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ABSTRACT

We reexamine evolutionary channels for the formation of binary millisecond pulsars in order to understand their observed orbital period distribution. The available paths provide a natural division into systems characterized by long orbital periods ($\gtrsim$ 60 days) and short orbital periods ($\lesssim$ 30 days). Systems with initial periods $\sim 1-2$ days, mainly driven by the loss of orbital angular momentum, ultimately produce low mass helium white dwarfs ($\lesssim 0.2M_\odot$) with short orbital periods ($\lesssim$ 1 day). For longer initial periods ($\gtrsim$ few days), early massive Case B evolution produces CO white dwarfs ($\gtrsim 0.35M_\odot$) with orbital periods of $\lesssim$ 20 days. Common envelope evolutionary channels result in the formation of short period systems ($\lesssim$ 1 day) from unstable low mass Case B evolution producing helium white dwarfs in the range $\sim 0.2-0.5M_\odot$, and from unstable Case C evolution leading to CO white dwarfs more massive than $\sim 0.6M_\odot$. On the other hand, the long orbital period group of binary millisecond pulsars arise from stable low mass Case B evolution with initial orbital periods $\gtrsim$ few days producing low mass helium white dwarfs and orbital periods $\gtrsim$ 30 days and from stable Case C evolution producing CO white dwarfs with masses $\gtrsim 0.5M_\odot$. The lack of observed systems between 23 and 56 days probably reflects the fact that for comparable initial orbital periods ($\gtrsim$ few days) low mass Case B and early massive Case B evolution lead to very discrepant final periods. We show in particular that the lower limit ($\sim$ 23 d) cannot result from common–envelope evolution.

We discuss the importance of a phase of nonconservative evolution where mass and angular momentum can be lost from the system through the ejection of matter from accretion disks around the neutron stars in these systems. This leads to a dependence of pulsar mass on evolutionary history. In particular, most low–mass X–ray binaries with orbital periods $\gtrsim$ 2 days are probably transient; the super–Eddington accretion rates likely during outbursts mean that the neutron stars in such systems gain relatively little mass.

Subject headings: binaries: close — stars: evolution —- stars: neutron —- pulsars: general

1. INTRODUCTION

Ever since the discovery of the 1.55 ms radio pulsar PSR 1937+21 by Backer et al. (1982), the study of millisecond pulsars has yielded fundamental insights into the properties of neutron stars and to their evolution in binary star systems. In order to determine the statistical properties of the population, numerous radio surveys have been undertaken recently covering both the northern hemisphere (e.g., Camilo 1999) and southern hemisphere (Manchester et al. 1996: Lyne et al. 1998). The discovery that many pulsars of this class are members of binary systems confirmed the hypothesis that the underlying neutron star had accreted mass and been recycled to short spin period (Radhakrishnan and Srinivasan 1982; Alpar et al. 1982). The recent discovery of the 2.49 ms coherent pulse period in the X-ray pulsar SAX J1808.4-3658 by Wijnands and van der Klis (1998) and the discovery of its orbital period of 2.01 hours by Chakrabarty and Morgan (1998) provided the first direct observational link between the two classes of systems confirming that the progenitors of these systems are, indeed, low mass X-ray binaries. For a review of the properties of the millisecond binary pulsars see the paper by Phinney and Kulkarni (1994).

A compilation of binary millisecond radio pulsars by Camilo (1995, 1999) and more recent data reported in Manchester et al. (2000), Edwards (2000), and Tauris, van den Heuvel, & Savonije (2000) reveals a population of 35 galactic binary pulsars with almost circular orbits and orbital periods ranging from about 2 hours to 175 days (see Table 1). It is found that the distribution of systems with respect to orbital period is non uniform, and that there is a significant absence of systems between about 23 and 56 days. This is illustrated in Fig. 1 in the form of a cumulative distribution of the orbital periods. Since it is not likely that the absence of systems in this period interval reflects a selection effect in their discovery (Camilo 1995; Bhattacharya 1996), its origin must provide insights to the evolutionary channels of these pulsar systems. Recently, Tauris (1996) examined the possibility that the observed "period gap" reflected the operation of a bifurcation mechanism in their formation associated with distinct evolutionary histories. In particular, the long period systems were attributed to the evolution of low mass systems along the red giant branch as shown by Joss and Rappaport (1983), Paczynski (1983), and Savonije (1983) following earlier work by Taam (1983) and Webbink, Rappaport, & Savonije (1983). On the other hand, the short period systems were assumed to be produced from short period ($P < 2$ days) low mass X-ray binary systems which evolve to ever shorter orbital periods under the action of angular momentum loss associated with magnetic braking (see Pylyser & Savonije 1988), and from long period ($P > 100$ days) X-ray binaries which underwent a phase of common envelope evolution (van den Heuvel and Taam 1984). In this picture, the pulsar companions are primarily helium white dwarfs in the long period population and a mixture of helium and carbon-oxygen white dwarfs in the short period population. The lower edge of the long period group (at ~ 56 days) is attributable to the evolution of systems above the bifurcation period dividing converging from diverging systems, see §2.1.1 below (~ 2 days, Tauris 1996). The upper period edge of the short period group (at ~ 20 days) is assumed to be the maximum orbital period for systems emerging from the common envelope phase.

In this paper, we reexamine these conjectures in light of the additional formation channel involving early massive Case B evolution recently identified by King & Ritter

(1999), and the current theory of common envelope evolution (Iben & Livio 1993; Taam & Sandquist 2000). The description of the evolutionary paths as applied to the binary millisecond pulsars is presented in §2 and an interpretation of the orbital distribution and period gap in terms of the evolutionary processes is discussed in the final section.

After our paper was submitted (July 1999) two further papers (Tauris & Savonije, 1999; Tauris, van den Heuvel & Savonije, 2000) relevant to this subject appeared. We refer extensively to these papers in what follows.

2. EVOLUTIONARY MODELS

In this section the contributions of the various formation channels to the binary millisecond pulsar stage are elucidated. To place them into context the individual paths are described in some detail. Low mass Case B, early massive Case B, and common envelope evolution are presented in turn.

2.1. Case B Evolution

In this phase of evolution, mass transfer is driven by stellar expansion accompanying core contraction and the establishment of a hydrogen burning shell prior to the ignition of helium in the core. The three distinct formation channels associated with this phase can be termed early low mass, late low mass, and early massive evolutions. Here, low mass refers to stars ($M < 2.25 M_{\odot}$) which develop a helium degenerate core and massive refers to stars developing a nondegenerate core.

2.1.1. Early Low Mass

If mass transfer is initiated close to the main sequence, corresponding to initial orbital periods $\lesssim 1$ day, the binary evolution is affected by angular momentum loss processes associated with a magnetically coupled stellar wind (e.g., Verbunt & Zwaan 1981). The effectiveness of the tidal interaction between the components enforces synchronism, thus draining orbital angular momentum from the system. As a consequence, mass transfer is enhanced (producing a brighter low mass X-ray binary than would have been the case in the absence of such processes) and the system evolves to shorter orbital periods (Pylyser & Savonije 1988). Provided that the mass transfer is initiated for a sufficiently evolved star such that a degenerate core has formed the system can become detached producing a binary pulsar system (otherwise, the system continues its evolution as a low mass X-ray binary). For the masses relevant to the binary pulsar evolutions, the critical period (i.e., $P_{\rm bif}$ in the language of Pylyser & Savonije 1988) is about 0.4 - 0.8 days in the mass conservative case. The actual value for the bifurcation period is dependent on the detailed assumptions concerning mass and angular momentum loss from the system. Specifically, in the case of a strong consequential angular momentum loss the bifurcation period can be significantly longer than in the conservative case (e.g. Ergma et al. 1998).

2.1.2. Late Low Mass

In contrast to the above, binary stars with initial orbital periods greater than $P_{\rm bif}$ evolve into low mass X-ray binary systems with increasing orbital periods (Taam 1983; Webbink et al. 1983). Here, the orbital separation increases as a result of mass transfer from the less massive component to its neutron star companion. As the mass losing star evolves along the red giant branch the hydrogen rich envelope is depleted through a combination of nuclear evolution and mass loss, eventually leading to the formation of a white dwarf remnant in a wide detached binary. Since the radius of a giant is primarily a function of its core mass, the evolution can be described analytically (Ritter 1999). Based on the core mass radius relation for Population I composition of Rappaport et al. (1995), the relationship between the initial (P_i) and final (P_f) orbital periods, expressed in days, for mass transfer driven by nuclear evolution in the conservative mass transfer approximation is

$$\log P_{\rm f}(d) = 1.31 + 0.70 \log P_{\rm i}(d) \tag{1}$$

where it has been assumed that the neutron star has an initial mass, $M_{1,\rm i} = 1.4 M_\odot$ and the low mass companion has an initial mass $M_{2,\rm i} = 1 M_\odot$. On the other hand, if the mass transfer process is non-conservative such that all the transferred mass is ejected with the specific orbital angular momentum of the neutron star, then the relationship with $M_1 = 1.4 M_\odot$, $M_{2,\rm i} = 1 M_\odot$ is

$$\log P_{\rm f}(d) = 1.45 + 0.69 \log P_{\rm i}(d). \tag{2}$$

The correlation between the final orbital period and remnant white dwarf mass, M_{WD}, is given by

$$P_{\rm f}(d) \sim \frac{8.5 \times 10^4 M_{\rm WD}^{5.5}}{(1 + M_{\rm WD}^3 + 1.75 M_{\rm WD}^4)^{1.5}} \tag{3}$$

(see King & Ritter 1999) where the white dwarf mass is expressed in $M_\odot$. For Population II composition (which may be appropriate for millisecond pulsars with spindown ages exceeding several Gyr), the corresponding eqn. 6 of Rappaport et al. (1995) leads to periods which are smaller than the estimate (3) by about a factor 2.

We note that Tauris & Savonije (1999) have recently recalculated low mass Case B evolution using newer input physics. In particular this produces binary millisecond pulsars with $P_{\rm orb} \simeq 1$ d and $M_{\rm WD} \simeq 0.2 M_\odot$, which were missing from the results of Rappaport et al. (1995).

2.1.3. Early Massive

This type of evolution (see Kippenhahn & Weigert 1967) describes a binary in which the mass losing component has a radiative envelope and is sufficiently massive that helium is ignited under nondegenerate conditions (M $\gtrsim 2.25 M_{\odot}$). As applied to binary pulsars (see King & Ritter 1999) any mass transferred to the neutron star at rates above the Eddington limit is assumed to be ejected from the inner regions of an accretion disk in the form of a wind. This implies that the mass of the neutron star is little changed during this thermal timescale phase. The mass transfer is interrupted either by the complete loss of the envelope or by the contraction of the nondegenerate component within its Roche lobe when helium is ignited at its center. In these evolutions, the ultimate fate of the binary is dictated by the initial mass ratio of the donor to the gainer. For initial mass ratios $q = M_{\rm donor}/M_{\rm NS}$ slightly smaller than a critical mass ratio (which depends on the donor star's initial mass and on the initial orbital separation), the evolving star detaches from its Roche lobe with a thick hydrogen rich envelope. Further evolution of the star to its double shell burning phase leads to the resumption of mass transfer and to the expansion of the orbit. The depletion of the envelope on the asymptotic giant branch leads to the contraction of the core and to the formation of a CO white dwarf with a neutron star companion in a long period orbit ($\lesssim 50 - 70$ d, cf figs 2 and 4 of Tauris et al., 2000). For the critical mass ratio the donor detaches from its Roche lobe with a thin hydrogen envelope. Near the end of mass transfer such an evolution leads to a system resembling Cyg X-2, with an orbital period of ~ 10 days and to the eventual formation of a binary pulsar system consisting of a CO white dwarf and a neutron star similar to J0621+1002 (King & Ritter 1999). Finally, for systems characterized by initial mass ratios much greater than the critical value, mass transfer removes the entire hydrogen rich envelope and the remnant helium star directly evolves to form a CO white dwarf. For this type of evolution, larger initial mass ratios result in shorter orbital periods for the binary pulsar system and to more massive CO white dwarf companions (King & Ritter 1999). An approximate relation for the minimum final period expressed in days for such systems is given by

$$\log P_{\rm f} \approx 2.56 - 3.1 \frac{M_{\rm WD}}{M_{\odot}} \tag{4}$$

yielding, for example, a maximum of ~ 30 days for the minimum mass of a CO white dwarf ($0.35 M_{\odot}$) produced in this evolution.

2.2. Common Envelope Evolution

Systems evolving through the common envelope phase can also contribute to the binary millisecond pulsar population (see Taam & Sandquist 2000). In such systems the mass transfer is unstable, leading to the formation of a differentially rotating common envelope. This evolution is particularly relevant to binary systems characterized by a large mass ratio and a giant star component. For sufficiently large mass ratios, the binary is subject to a tidal instability (Darwin 1879; Kopal 1972; Counselman 1973; Hut 1980) occuring when the orbital angular momentum of the binary is less than 3 times the spin angular momentum of the giant star. For orbital separations less than a critical value, where the total angular momentum is a minimum, the two stars must spiral together. Progenitor systems can also evolve into a common envelope provided that the envelope of the nondegenerate component is convective. In this case, the envelope can expand upon mass loss for evolutionary stages where the fractional mass in the convective envelope exceeds 0.5 (Hjellming 1989). For mass ratios $\gtrsim 1.2 - 1.5$ a giant cannot be constrained within its Roche lobe and a runaway mass transfer episode is expected.

Successful ejection of the envelope without requiring the two stars to merge can be achieved given that sufficient energy is released from the orbital motion and that the mass losing star is sufficiently evolved (see Taam & Sandquist 2000). The outcome of such an evolution would resemble a short–period binary pulsar like PSR 0655+64 (van den Heuvel & Taam 1984). For an interaction of a neutron star with a companion on the first ascent red giant branch a helium white dwarf companion of mass $\gtrsim 0.2 - 0.25 M_{\odot}$ is expected (Sandquist, Taam, & Burkert 2000; see also Sarna, Marks, & Smith 1996). On the other hand, an interaction on the asymptotic giant branch leads to a CO white dwarf with mass $\gtrsim 0.55 M_{\odot}$. We note that the evolution into a common envelope phase is less likely for a star characterized by a radiative envelope (since the star contracts upon mass loss) and for mass ratios not significantly larger than unity (where the mass ratio can be reversed, leading to orbital expansion).

The upper limit to the orbital period for the short-period population of binary millisecond pulsars has been identified with the outcome of common envelope evolution (Tauris 1996). Although evolution via a common envelope may be expected to populate the region at short orbital periods ($\lesssim$ a few days), there is insufficient orbital energy to produce a system with a period as long as 20 days for the intermediate mass progenitors characteristic of the white dwarf component in the system. To circumvent this difficulty, Tauris (1996) had to increase the efficiency of mass ejection in the common envelope phase significantly above unity (i.e. to 4). At the time the cutoff was 12 days: the current value of 23 days (J1618-3919) exacerbates the problem if we assume that this system also evolved through a CE phase. Tauris (1996) invoked unspecified sources of energy to accommodate this choice; however, the ionization energy and nuclear energy sources that have been invoked in the past are ineffective (see Sandquist et al. 2000). Specifically, the ionization energy cannot be tapped directly (see Harpaz 1998) and is unimportant for ejecting matter in the deep gravitational potential of the binary where the major phase of mass ejection takes place. Nuclear energy is tapped on a timescale too long compared to the mass ejection timescale to be important.

One might try to get round this argument by assuming that systems such as J1618-3919 have low–mass helium white dwarf companions. However this is ruled out because the fairly large values of $P_{\rm spin}$ (32.82 ms, 71.09 ms) for J1810-2005 and J1904+04 ($P_{\rm orb} = 15.0$ d and 15.75 d respectively), as well as the large value of $\dot{P}_{\rm spin}$ for J1810-2005, strongly indicate that these systems passed through a phase of very high mass transfer and that the neutron star cannot have accreted much matter. Since CE evolution is probably ruled out by the argument of the last paragraph, we conclude that the short $P_{\rm orb}$ population below the gap, but longer than a few days must be the result of early massive Case B evolution.

3. DISCUSSION

Given the possible evolutionary channels for the formation of binary millisecond pulsars presented in the previous section, we consider their implications for the period distribution of these systems. As described in §2, it is unlikely that the common envelope path is responsible for the period cutoff of the short period systems and therefore that the efficiency for mass ejection greater than unity is required. We suggest that the cutoff near 23 days is a natural consequence of the early massive Case B evolution near the critical mass ratio (see King & Ritter 1999). The lower period cutoff for the long period systems is likely to result from low mass Case B evolution, but it is not related to the bifurcation mechanism favored by Tauris (1996) since a bifurcation period at 2 days requires angular momentum loss rates significantly greater than commonly believed. On the contrary, we suggest that this period distribution is a natural consequence of the small phase space available to those systems which evolve into the 20 - 60 day period interval. That is, although the formation of binary millisecond pulsars with orbital periods as short as 20 days is possible in this evolutionary channel, it is not likely, since the initial core mass of the progenitor must be very low, i.e. $\sim 0.17 M_{\odot}$. The initial orbital period corresponding to this evolution is ~ 1 day. As pointed out by Tauris (1996) such systems evolve to shorter orbital periods because of angular momentum losses associated with a magnetized stellar wind (Pylyser and Savonije 1988). For those systems which do not evolve to shorter periods, the final period is extremely sensitive to the initial period at which mass transfer is initiated. For example, small initial core masses ($\sim 0.2 M_{\odot}$) yield orbital periods $\gtrsim 60$ days for initial orbital periods of about 3 days. We suggest that the small range of core masses means that only a few systems can finish their evolution with a period in the range of 20 – 60 days.

Implicit in the evolutionary scenarios we discuss, and especially important for understanding the short period population ($\sim 1 - 20$ days), is the assumption that the neutron star accretes only a small fraction of the transferred mass because accretion on to the neutron star is likely to occur at super–Eddington rates. This occurs either because the mass transfer timescale is $\lesssim 10^8$ years or because matter is accreted at high rates in a transient manner. This latter circumstance probably results from a thermal instability in the accretion disk (King, Kolb, & Burderi 1996; King, Kolb, & Szuszkiewicz 1997; Li, van den Heuvel, & Wang 1998). The orbital separations of long–period low–mass X–ray binaries (LMXBs) imply very large accretion disks, whose outer regions cannot be maintained in the hot (ionized) state, even by self–irradiation via X–rays. Thus all LMXBs with $P_{\rm orb} \gtrsim 2$ d are probably transient (King, Kolb & Burderi, 1996). In this case, accretion on to the neutron star occurs only during outbursts. A short outburst duty cycle, as inferred from observation, implies super–Eddington central accretion rates. Only a small fraction is accreted, while the remainder is ejected as a wind. Calculations neglecting this mass loss predict final neutron star masses systematically larger than the upper limits on the observed masses, often by several times $0.1 M_{\odot}$, cf Fig. 4b of Tauris & Savonije (1999).

Ejection is unlikely at short periods because most neutron star systems are persistent, although transients do exist, e.g., SAX J1808.4-3658 (Chakrabarty & Morgan 1998) at 2 hours and EXO 0748-676 (Parmar et al. 1986) at 3.8 hours (cf King et al. 1996; King & Kolb 1997). In this case, the neutron star gains mass and is likely to be spun up to millisecond periods.

Given the circumstances under which mass can be transferred at high rates, one can expect that the mass of the pulsar is dependent on the particular evolutionary path leading to its formation. As the mass transfer rates driven by nuclear evolution of highly luminous giant stars exceed the Eddington rate, the neutron stars in the long period population are not likely to have accreted much matter. That is, the neutron star components in those systems which have been formed via the low mass Case B and intermediate early massive Case B evolutionary channels are likely to have accreted little mass, and should differ little from their formation masses. Likewise, the neutron stars that evolve through a common envelope phase are also not likely to have accreted much matter. Although it has been hypothesized that they can accrete sufficient matter in the neutrino dominated regime (Zeldovich, Ivanova & Nadyozhin 1972) to form black holes (Chevalier 1993; Brown 1995), recent studies (Chevalier 1996) indicate that neutron stars are expected to survive when account is taken of rotational effects in highly evolved giants. In this context, the more evolved state of the giant companion makes it less likely that the neutrino accretion dominated regime is reached. The lower rates of accretion characteristic of the lower density envelopes of more evolved stars, in combination with the short evolutionary phase of the common envelope ($\lesssim 10 - 100$ years) suggest that accretion is not important. On the other hand, pulsars in systems with short orbital periods ($\lesssim 1$ day) should be more massive than the other pulsars in their class since the mass transfer rates are less than the Eddington value. The observational measurement and improved estimates of pulsar masses in such systems following up on the work by Thorsett & Chakrabarty (1999) is highly desirable for testing such an evolutionary dependence.

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Table 1. Galactic ms-pulsars and pulsars in (circular) binaries

PSR	$P_{\rm spin}(ms)$	$\dot{P}$		$P_{\rm orb}(d)$	e	$(\frac{M_2}{M_\odot})$ [a]
J2051-0827	4.50864	1.27	10^{-20}	0.09911	<0.00008	0.0316
J0751+1807	3.47877	8.0	10^{-21}	0.26314	<0.0001	0.153
B1957+20	1.60740	1.69	10^{-20}	0.38197	<0.00004	0.0254
J1756–5322	8.87			0.453		0.682
J1012+5307	5.25575	1.46	10^{-20}	0.60467	<0.00002	0.128
B0655+64	195.67094	6.86	10^{-19}	1.02867	0.00000075	0.813
J0613–0200	3.06184	9.57	10^{-21}	1.19851	0.000007	0.153
J1435–60	9.35			1.355	0.00	1.11
J0034–0534	1.87782	0.7	10^{-20}	1.58928	<0.00002	0.169
B1831–00	520.95431	1.43	10^{-18}	1.81110	0.0001	0.075
J1232–6501	88.28	1.0	10^{-18}	1.863	0.00	0.175
J0218+4232	2.32309	8.00	10^{-20}	2.02885	<0.00002	0.200
J2317+1439	3.44525	4.42	10^{-21}	2.45933	0.0000005	0.206
J1911–1114	3.62575	1.34	10^{-20}	2.71656	<0.000013	0.143
J1157–5112	43.6	<0.9	10^{-18}	3.507		1.48
J1045–4509	7.47422	1.74	10^{-20}	4.08353	0.000024	0.190
J0437–4715	5.75745	5.73	10^{-20}	5.74104	0.000019	0.168
J1603–7202	14.84195	1.4	10^{-20}	6.30863	<0.00002	0.346
J2129–5721	3.72635	2.0	10^{-20}	6.62549	<0.000017	0.158
J2145–0750	16.05242	2.9	10^{-20}	6.83890	0.000018	0.514
J1022+1001	16.45293	4.2	10^{-20}	7.80513	0.000098	0.870
J0621+1002	28.85386	<0.8	10^{-19}	8.31868	0.002458	0.539
J1804–2717	9.34303	4.2	10^{-20}	11.12871	0.000035	0.240

Table 1—Continued

PSR	$P_{\rm spin}(ms)$	$\dot{P}$		$P_{\rm orb}(d)$	e	$(\frac{M_2}{M_\odot})$ [a]
B1855+09	5.36210	1.78	10^{-20}	12.32717	0.000027	0.290
J1453–58	45.25			12.422	0.00	1.07
J1810–2005	32.82	1.3	10^{-19}	15.012	0.00	0.341
J1904+04	71.09			15.750	0.04	0.270
J1709+23	4.631			22.7		
J1618-3919				23.3		
J2033+17	5.94896			56.2	<0.05	0.223
J1713+0747	4.57014	8.52	10^{-21}	67.82513	0.000075	0.332
J1455–3330	7.98720	<0.6	10^{-21}	76.17458	0.000167	0.304
J2019+2425	3.93452	7.02	10^{-21}	76.51163	0.000111	0.373
J2229+2643	2.97782	1.46	10^{-21}	93.01590	0.000256	0.146
B1953+29	6.13317	2.97	10^{-20}	117.34910	0.000330	0.231
J1643–1224	4.62164	1.84	10^{-20}	147.01740	0.000506	0.142
J1640+2224	3.16332	2.83	10^{-21}	175.46066	0.000797	0.295
J1803–2712	334.41542	1.73	10^{-17}	406.781	0.000507	0.172
B0820+02	864.87275	1.04	10^{-16}	1232.47	0.011868	0.231

[a] $\frac{M_2}{M_\odot}$ is calculated assuming a pulsar mass of $1.4 M_\odot$ and a system inclination angle of 60 degrees.

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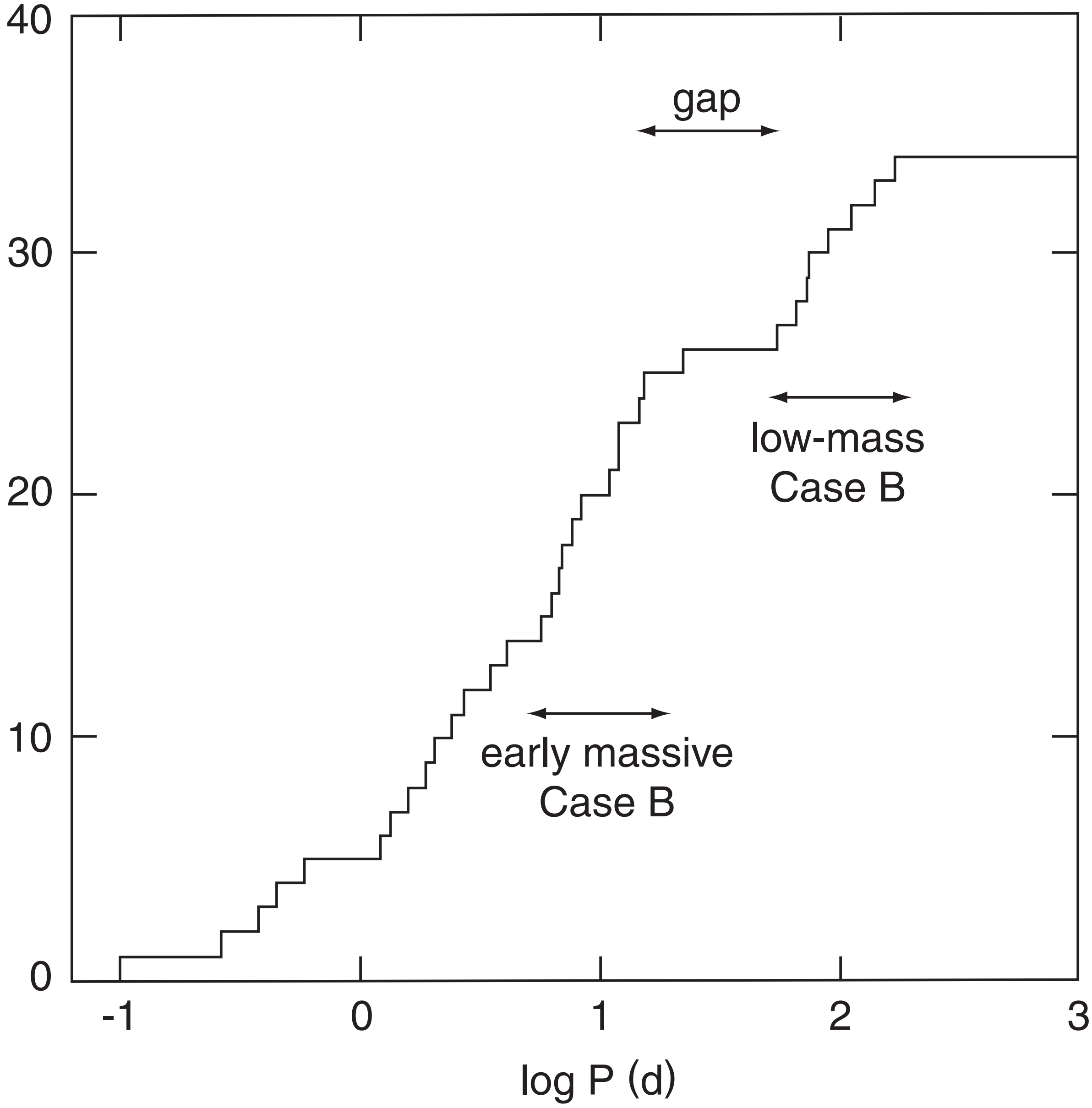

Fig. 1.— The cumulative distribution of orbital periods of known binary galactic millisecond pulsars with circular orbits. The gap region in which there exists one object between 12 and 56 days is indicated. Also shown are the major evolutionary channels contributing to systems just below and above the gap (see text).