BINARY AND OTHER RECYCLED PULSARS

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ABSTRACT. Binary pulsars and others with weak fields and rapid rotation now number several dozen and appear to have been spun up by close binary mass transfer. Some are lineal descendents of X-ray binaries; others may result from accretion-induced collapse of binary white dwarfs or from captures, exchanges, and collisions in clusters. Seven accurate neutron star masses, 1.27-1.44 M_o, have been measured so far. Outstanding issues include the dominant formation process in various sites and the time history of the neutron stars' magnetic fields in and out of binaries.

1. INTRODUCTION AND INVENTORY

The halls of the 1974 Texas Symposium on Relativistic Astrophysics buzzed with the phrase "the binary pulsar." Nearly seven years had passed since Bell and Hewish's "little green men" had burst upon the astronomical scene, and not a single pulsar had yet shown the periodic variations in pulse arrival time that would indicate orbital motion. In a way, this was not surprising. Though we are not often aware of the solar wind, a neutron star at our distance from the sun would find itself (owing to what is generally called Bondi-Hoyle accretion) in a plasma of density about 10^{12} cm^{-3}, where only frequencies in excess of 10 GHz can propagate. And pulsars are low frequency sources. Thus only windless companions could be expected - white dwarfs, other neutron stars, or perhaps helium stars or very low mass objects. Indeed only these sorts have been found.

"The" binary pulsar (1913+16, Hulse and Taylor 1975) and "the" millisecond pulsar (1937+11, Backer et al. 1982), both with small rates of period change, implying magnetic fields of 10^{9-10} G, but rapid rotation, remained unique for several years after their discoveries. Ordinary single pulsars radiate away their rotational kinetic energies in 10^{6-7} year without losing much of their magnetic fields. Thus these two unique objects were quickly attributed to spinning up by accretion during a preceeding X-ray binary phase. The single millisecond pulsar was presumed to have been spun up and then liberated (Alpar et al. 1982), thereby linking the two classes. This scenario is responsible for the named "recycled" and "born-again" pulsars.

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TABLE 1. Properties of Recycled Pulsars and Ancestral X-Ray Binaries

TYPE	NUMBER KNOWN	BINARY ?	ROTN. PER.	ORBIT PER. days	EXAMPLE
pulsars			msec		
binary	22	Yes	1.55-1060	0.075-358	1913+16
glob clust	28	Half	3-290	0.075-191	2127+11 ABCDE
msec singl	12	No	1.55-150	-	1937+21
hi M binar	5	Yes	30-1060	0.208-12	1534+12
X-ray			sec		
MXRB	30	Yes	0.7-850	16-188	Vela X-1
BeXRB	70	Yes	0.06-835	1.4-41	GX 304-1
gl cl XRB	12	Yes?	msec?	0.008-0.35	4U2127+12
bulge XRB	50	Yes?	msec?	0.029-12.5	

Development of techniques for de-dispersing short pulse periods in distant, accelerated objects has led to rapidly growing inventories, as shown in Table 1 (Numbers are epoch about 1991.5). The main classes of X-ray binaries are included for comparison. The one point where I see a difficulty in connecting up the properties is in rotation periods for the massive systems. Most neutron stars in MXRBs are very slow rotators, with periods of up to 800 sec, yet spin-up must occur at some point if recycled pulsars are to result.

Most of the known members of the binary and millisecond classes are faint, even as pulsars go, and about 10% of a volume-limited field sample would be short period, weak field objects (Taylor 1987). Four systems have companions massive enough to be neutron stars and are presumably descended from massive XRBs. The others orbit white dwarfs or other low mass stars and could descend from LMXRBs. About three of the binaries need not have been recycled, since the neutron stars have periods close to a second and fields of nearly 10^{12} G, typical of first-time around pulsars at ages of 10^{6-7} yr.

The binary and millisecond pulsars are, like the LMXRBs, over-represented in globular clusters, even when you allow for searches that have focussed there. The total number of recycled pulsars in the clusters is rather uncertain, since only the very brightest have been seen. Analysis of the completeness of recent surveys suggests as many as 10^4 (Kulkarni et al. 1990), while the total radio flux coming from the clusters seems to impose a limit nearer 10^3 (Wijers and van Paradijs 1991: Fruchter and Goss 1990).

Bhattacharya and van den Heuvel (1991) have published a superb account of the formation and evolution of recycled pulsars and their relationship to the X-ray binaries, to which you are referred for more detail, more references, and more expertise than represented here. Some of the author's additional thoughts on these subjects can be found in Trimble (1991).

2. FORMATION

An X-ray binary will lead inevitably to a binary pulsar if the second star dies without unbinding the system. The alternative is the liberation of a single (probably high velocity) millisecond pulsar. Thus both sorts of recycled pulsar graft naturally onto the evolutionary scenarios of XRBs (Trimble 1992 and references therein). One expects LMXRBs in general to remain bound when the companion becomes a white dwarf and high mass systems to separate, because the second supernova will eject more than half the total system mass. The existence of three field binary pulsars with companions close to 1.4 M_o (1534+12, 1913+16, and 2303+46) shows that the obvious does not always happen. Some of the observed combinations of orbit period, eccentricity, and apparent star and system ages are also somewhat difficult to account for (Bhattacharya and van den Heuvel 1991). So far, we have seen no binary pulsars with black hole companions. Given the rarity of these among XRBs, one is not yet even statistically surprised.

The chief difficulty in supposing all recycled pulsars to be the descendents of XRBs is, however, a statistical one, which shows up most accutely in the globular clusters. These harbor about 10 LMXRBs and anything from 50 to 500 times as many pulsars. The pulsars cannot be more than 10^{10} yr old; thus, either the LMXRBs live at most $2X10^7$ to $2X10^8$ yr, or we are doing the wrong calculation. It is possible to shorten the expected lifetimes of the XRBs if their secondaries are evaporated in the fashion of 1957+20. But one then has considerable difficulty in persuading the clusters to produce enough X-ray binaries!

This statistical difficulty was the focus of a January 1991 workshop (van den Heuvel and Rappaport 1992) and has renewed interest in other formation mechanisms for binary and millisecond pulsars. One possibility is accretion-induced collapse, in which a white dwarf acquires enough additional mass from a companion to be driven over the Chandrasekhar limit and into collapse (van den Heuvel 1981; Bailyn and Grindlay 1990). The advantage of this mechanism is that enough mass is lost from the system to take it out of Roche lobe contact, so that instead of appearing as an LMXRB, it starts life as a pulsar hard at work evaporating its residual low-mass companion. The main problem is that there is competition -- mass transfer on to white dwarfs is also invoked to explain nova explosions (with justifiable confidence) and Type Ia supernovae (with considerably less confidence). And you can't use the same system for more than one of these. Nova explosions probably take more off the white dwarf than preceeding accretion put there, and SN Ia's disrupt it completely. Which happens depends on white dwarf mass, composition, and accretion rate; and the phase space volume available for core collapse is quite small (Canal et al. 1990).

Within globular clusters, various stellar encounters can occur, especially in those clusters that have gone through core collapse. Relevant processes include tidal capture (Grindlay 1988; Johnston and Kulkarni 1991) collisions (Rasio and Shapiro 1991), and star exchange between a primordial binary and a neutron star belonging to the cluster (Phinney and Kulkarni 1991). Capture alone leads to the wrong proportions of close, wide, and single pulsars and probably the wrong dependence of numbers on cluster density. Collisions can leave a disk around the neutron star, so that it spins up without passing through an XRB phase; and a combination of the three processes may well produce a population of cluster pulsars much like the one seen (E.S. Phinney in van den Heuvel and Rappaport 1991). Perhaps the cleanest case for star exchange is 2127+11C, the double NS in M15. Additional evidence for its having undergone an encounter comes from its position well outside the cluster core.

It is probably safe to say of these three sorts of scenarios (descent from initial XRB, accretion-induced collapse, and star encounters) that each works somewhere, none works everywhere, and each operates best in a fairly narrow range of parameter space. Better evaluation of the relative contributions to the field and globular cluster populations requires knowing more than we currently do about the initial stellar populations of the clusters: numbers of stars above the minimum needed to make a neutron star, the fraction of initial binaries, and the distribution of separations and mass ratios among them. More thorough hunts for eclipsing, cataclysmic, and spectroscopic binaries are all obviously relevant. Whether the clusters have contributed significantly to the field population depends on equally-poorly known probabilities for ejection and escape of single neutron stars and binaries and for disruption of clusters.

3. INSIGHTS GAINED

Binary and millisecond pulsars are remarkably stable clocks. Analysis of pulse arrival times, including newtonian, special, and general relativistic effects, therefore permits determination of very accurate orbit parameters. Seven neutron star masses (Table 2) have, so far, been measured to better than a few percent (those in 1913+16 to more significant figures than are shown). All are between 1.27 and 1.44 M_o, rather smaller than most of us would have guessed a few years ago.

In addition, evolution of the orbit of 1913+16 indicates that the standard formula for quadrupole gravitational radiation from two point masses is right to 1% or better (Damour and Taylor 1990) and that the constant of gravity, G, is changing by less than one part in 10^{11} per year. The very small amount of residual timing noise in several millisecond pulsars sets upper limits to the energy density in gravitational radiation with frequencies between kHz and a few cycles per year. Such radiation falls very short of closing the universe (Ho et al. 1991).

Careful monitoring of another pulsar, 1829-10, has, just possibly, resulted in the discovery of the first extra-solar-system planet (Bailes et al. 1991). The ink on the discovery paper was not yet dry when an alternative explanation of the data and an objection to it were put forward (Helfand and Hamilton 1991; Lyne 1991); and preprints of three or more possible formation scenarios were circulating in Buenos Aires and Cordoba (e.g. Podsiadlowski et al. 1991).

Globular cluster pulsars can occasionally probe the gravitational potential of the cluster. The measured dP/dt of 2127+11A, near the core of M15, is negative and could be due either to a recent close encounter or to the effect of the net field. For the binary system 2127+11C, position, velocity, and acceleration together indicate that the cluster core has a mass to light ratio, M/L = 4 in solar units, larger than that of the cluster as a whole. A central massive black hole is ruled out by the

TABLE 2. Component Masses of Binary Pulsars

SYSTEM	PULSAR MASS M_o	COMPANION MASS M_o	RFERENCE
1913+16	1.4409	1.3875	1, 2
1855+09	$1.27^{+.27}_{-.15}$	$0.233^{+.26}_{-.17}$	3 (M_2 = white dwarf)
2127+11C	1.33	1.38	1, 4
1534+12	1.36 ±.03	1.32 ±.03	5
2303+46	2.8 ±.1 (total)		1

1. van den Heuvel and Rappaport 1991
2. Taylor and Weinberg 1989
3. Ryba and Taylor 1991
4. Prince et al. 1991
5. Wolszczan 1991

resolved HST image of the cluster, and the most probable explanation is a significant population of neutron stars and massive white dwarfs in the cluster core (Phinney in van den Heuvel and Rappaport 1991).

4. PERSISTENT PUZZLES AND PROBLEMS

4.1. Completeness of the Inventories

The factor-of-ten uncertainty in the globular cluster supply of binary and millisecond pulsars has already been mentioned. That 47 Tuc has 11, about half binaries, and all with periods between 1.7 and 5.8 msec (Manchester et al. 1991) is particularly remarkable. One wonders what the period distribution would look like in the absence of observational selection against short periods!

Possibly of wider ranging importance is the question of whether our inventory of ideas and processes is complete. Consider the following:

a. Mechanisms of mass transfer. Early work identified cases A, B, and C (depending on evolutionary stage of the primary at onset). The addition of the common envelop binary mechanism (Paczyński 1976) made it possible to explain much more persuasively the origins of cataclysmic variables, LMXRBs, and V471 Tauri stars. CEB evolution and also be regarded as an addition to the inventory of system morphologies - detached, semi-detached, and contact.

b. Ways of putting neutron stars into close binaries. Evolution from a primordial massive binary, capture, and accretion-induced collapse have been with us for 15 years or so. The addition of star exchange with primordial binaries in dense cluster cores (Phinney and Kulkarni 1991) leads to better agreement between models and data for numbers of systems vs. core density of the clusters.

c. Driving of transfer and loss of angular momentum and mass in CBS.

The traditional inventory includes nuclear evolution of the donor, gravitational radiation, and magnetic braking. Radiation driving, first considered for X-ray irradiation and more recently for pulsar irradiation of the companion, may be a significant addition (J. Shaham and M. Tavani in van den Heuvel and Rappaport 1991).

d. Fate of the companion. Orbit periods longer than about a day can be stable if the system is left alone. Alternatively, encounters or loss of mass can unbind the system, and loss of angular momentum or complete transfer of M_2 onto M_1 lead to a merger. The discovery of the binary pulsars 1957+20 (Fruchter et al. 1988), 1744+24A (Nice et al. 1990), and 0021-72J (Manchester et al. 1991), in which a wind from the companion eclipses (or otherwise impedes the passage of) the pulsar radiation during part of each orbit indicates that complete evaporation is also possible.

e. Compact stellar configurations. White dwarfs, neutron stars, and black holes have all been with us for more than 50 years. Zwicky always insisted that there was in infinite sequence of compact, bound, non-singular configurations possible on beyond the neutron star. The next one he called "object hades" He might or might not have accepted its identification with stars made of strange quark matter (as invoked to explain the false alarm 0.5 msec pulsar in 1987A, Glendenning 1989), but who is to say that he wasn't right about the basic concept.

The moral of all these is that even old topics can sometimes benefit from the infusion of new ideas; and that some of the more intractable problems in physics and statistics of recycled pulsars as now perceived may just be waiting for another expansion of the inventory of processes applicable to them.

4.2 Formation and Fate

Binary and millisecond pulsars can be formed in 3-5 different ways, no one of which can possibly apply everywhere. We would like to know which dominates in various contexts. An important clue may be that the globular cluster msec sources have fewer interpulses than do the field ones (H. Johnston, J. Navarro in van den Heuvel and Rappaport 1991), suggesting a different past history (and casting some doubt on the hypothesis that all or most of the field objects were born in globular clusters and liberated from them by encounters or cluster dissolution).

Multiplicity of origins is also indicated by the dependence of number of recycled pulsars per cluster on the cluster central density. Tidal capture should lead to linear dependence and accretion-induced collapse to correlation only with cluster mass, not density. The truth seems to fall somewhere in between, with number scaling as the square root of density (Phinney in van den Heuvel and Rappaport 1991).

Some binary pulsars are clearly well on their way to becoming single. The best-known case, 1957+20, has eroded its companion (presumably degenerate) down to about 2% of a solar mass; 1744-24A and 0021-72J have not gone quite as far. The 10 earth mass companion of 1829-10 could (but probably does not) remain from the failure of this process just before the end. One would like to know how common this is and if the pulsar radiation is powerful enough to drive the winds (Emmering and London 1990), or are we still missing something.

Whether we continue to hear from dead pulsars is not quite certain. Most popular models for gamma ray bursters need to use all the old neutron stars in the galaxy, but also require them to have magnetic fields near 10^{12} G, at least in the case of bursts with 10-60 keV cyclotron resonance lines (Ho et al. 1991). If so, then old recycled pulsars should not manifest themselves this way.

Pairs like 1913+16 should merge in less than a Hubble time. One expects considerable fireworks to result (gravitational radiation and neutrino bursts, r-process nucleosynthesis, photons...), but nothing we have observed so far in other galaxies obviously corresponds to such mergers, except, possibly, again, gamma ray bursts (Paczyński 1990).

4.3. The Time History of Neutron Star Magnetic Fields

Those few pulsars that we know to be young from their association with supernova remnants have fields of 10^{12-13} G. Statistical arguments indicate that the neutron stars in globular cluster recycled pulsars had similar fields in the past (Bhattacharya and van den Heuvel 1991); and the distribution of galactic disk pulsars in a plot of P vs. dP/dt was perceived very early (Gunn and Ostriker 1970) as providing evidence for a gradual decline in mean field strength over 10^{6-7} yr.

Apparently, however, that decline bottoms out at very different field strengths in different objects - 10^{12} G for Her X-1 and the gamma burst sources with cyclotron resonance features; 10^{10} G in psr 0655+64; and a few X 10^{8} G for some binary and millisecond pulsars.

At least two alternatives to intrinsic field decay have been suggested. First, field decay may occur only as a result of accretion onto a neutron star (Taam and van den Heuvel 1986); second, the time evolution of field strength may be a direct result of spin down and subsequent spin up (Srinivasan et al. 1990). In either case, one would expect binary and millisecond pulsars to have the weakest fields,as seen. I find the physics invoked in all these scenarios fairly mysterious and will not attempt to describe it (see van den Heuvel and Rappaport 1991 and Bhattacharya and van den Heuvel 1991 for discussions and references). The association of strong fields with very slow rotation in many massive XRBs would seem to be an objection to these schemes, but can apparently be evaded. In addition, one cannot entirely rule out the possibility of magnetic fields evolving to high multipole configurations, which would turn off pulsar radiation but not cyclotron resonances. And some neutron stars could have fields less than 10^{12} G from the beginning.

Observational clarification could come from (a) direct measurements of rotation periods and fields in typical LMXRBs, (b) firm association of gamma ray bursters with the galactic population of old neutron stars, and (c) measurement of P and dP/dt for pulsars in the young globular clusters of the Large and Small Magellanic Clouds -- this is currently impossible, but not by a large factor.

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