Session 5

Binary Pulsars

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Binary pulsar evolution: unveiled links and new species

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Abstract. In the last years a series of blind and/or targeted pulsar searches led to almost triple the number of known binary pulsars in the galactic field with respect to a decade ago. The focus will be on few outliers, which are emerging from the average properties of the enlarged binary pulsar population. Some of them may represent the long sought missing links between two kinds of neutron star binaries, while others could represent the stereotype of new groups of binaries, resulting from an evolutionary path which is more exotic than those considered until recently. In particular, a new class of binaries, which can be dubbed Ultra Low Mass Binary Pulsars (ULMBPs), is emerging from recent data.

Keywords. stars: neutron, pulsars: general, stars: white dwarfs, binaries: general, binaries: close, binaries: eclipsing

1. Introduction

The focus of this contribution is on the so-called *recycled* pulsars (see e.g. Alpar *et al.*1982, Radhakrishnan & Srinivasan 1982), i.e. neutron stars which are supposed to have experienced at least one phase of accretion of mass and angular momentum from a companion star, during which the system appeared as an X–ray binary. This phase should lead to a significant acceleration of the spin rate P of the star, accompanied by a decay (the physical origin of which is still subject of discussion, e.g. Konar 2010) of the surface magnetic field B_s (Bisnovatyi-Kogan & Komberg 1974). At the end of the process, the value of P and B_s are suitable for the neutron star to shine as a radio pulsar, located in the lower left part of the $P - B_s$ diagram, with $P \lesssim 100$ ms and $10^7 \lesssim B_s \lesssim 10^{10}$ Gauss.

During the last years, many new effective pulsar search experiments (see later) have favored a flourishing in the discoveries of this class of pulsars in the Galactic field. That is expected to trigger a new *Golden Era* for the studies of the evolution of the binaries including a neutron star. That already happened in the past decade for the class of the high mass binary pulsars (HMBPs) and for that of the binary pulsars in the globular clusters, with a wealth of studies stimulated by the doubling of the catalogued double neutron star binaries (including the first and still unique *double pulsar*) and by the doubling of the known pulsars in the clusters.

In the framework of the *recycling* scenario, HMBPs are expected to evolve from a neutron star with a massive companion ($\gtrsim 6-8\ M_\odot$), the rapid evolution of which leads to a relatively short X–ray phase and then only to a mild spin-up (P of order tens of milliseconds, hence the name of *mildly recycled* pulsars) and a moderate magnetic field decay, $B_s \gtrsim 10^9$ Gauss. If the binary survives the (second) supernova, we are typically left with a double neutron star binary in an eccentric orbit (see e.g. van den Heuvel & de Loore 1973, Bhattacharya & van den Heuvel 1991). The high stellar density in the globular cluster cores - where most of the pulsars are expected to reside due to mass segregation - strongly enhances the probability that the binary evolution is affected by the internal dynamics of the cluster, as a result of 3 (or 4) body encounters. Many works have been devoted to study these intriguing physical conditions (see Freire's contribution in this volume), but obviously they are not ideal for tracing the evolution of a binary due to purely internal effects, as is the case for the binary pulsars in the Galactic field.

The main focus here will be on objects belonging to the classes of the intermediate mass (IMBPs) and low mass binary pulsars (LMBPs). After an update on the demography of the *recycled* pulsars population follows a summary of some recent observational results about the evolution of those two families of systems, also listing the cases of few binaries which, in my personal opinion, represent the highlights for the current research in this field. In view of the space limitation, in many cases the reader will be forwarded to other contributions in this volume for a detailed presentation of the various models/sources.

2. Demography

Figure 1 shows the occurrence, during the last 2-3 years, of a steep increase in the number of catalogued *recycled* pulsars. In particular the overall count of *recycled* pulsars has almost doubled with respect to the year 2009 (left panel), nowadays accounting for over 10% of the whole known population of $\sim$2100 pulsars (right panel). This was due to the combination of two factors. *(i)* The possibility of performing targeted searches in the radio bands of properly selected unidentified *Fermi* γ–ray sources. These led to a (somewhat unexpected) very high efficiency in discovering *recycled* pulsars (43 at the time of writing) in the proximity of the Sun, i.e. typically within $1-2$ kpc (see e.g. Guillemot *et al.*, this volume). *(ii)* The launch of a series of new pulsar search experiments designed to have better spectral and time resolution than any previous large scale survey (see e.g. Keith *et al.*, Lazarus *et al.* and Lynch *et al.* in this volume). As a whole, these searches have added 60 new objects to the catalog (as of August 2012), a significant fraction of them showing a high dispersion measure and thus located in regions of the Galaxy where the population of *recycled* pulsars had been poorly sampled by previous experiments. In fact, in recent surveys the fraction of new *recycled* pulsars ranges between 15% and 25%, well beyond the typical $5-10$% values of past blind searches.

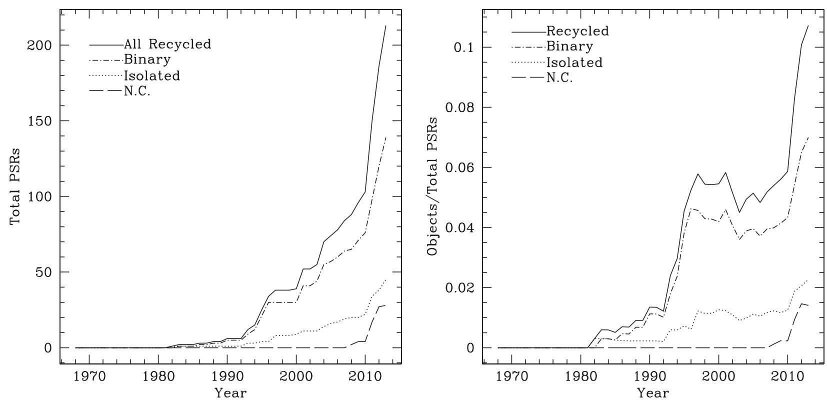

Figure 1. Chronological trends (*left panel*) in the number of catalogued *recycled* pulsars (*solid line*) and (*right panel*) in the ratio between known *recycled* pulsars and the total population of pulsars. The trends for the subgroups of the binaries, the isolated and the not yet classified (N.C.) *recycled* pulsars are also reported. Pulsars belonging to the globular clusters have been excluded. Data are taken from the ATNF pulsar catalog (Manchester *et al.*2005) on August 2012 (`http://www.atnf.csiro.au/research/pulsar/psrcat`) as well as from some private communications (thanks in particular to Lorimer and to Burgay) for the still unpublished objects.

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3. IMBPs and LMBPs

A recent attempt to summarize most of the current knowledge about the evolution leading to the formation of IMBPs and LMBPs has been provided by Tauris (2011) and Tauris, Langer & Kramer (2012) (see also Tauris' contribution, this volume). In these systems the initial companion mass is $\lesssim 1 - 2\ M_\odot$ for the LMBPs and around 3-6 $M_\odot$ for the IMBPs (although an initial companion mass up to $\sim 9\ M_\odot$ can be invoked for IMBP binaries which evolved from a very large orbit), implying longer stages of accretion than for HMBPs. That can lead, mostly for the LMBPs, to re-acceleration of the neutron star to millisecond periods (*fully recycled* pulsars), while the surface magnetic field weakens to $B_s \sim 10^7 - 10^8$ Gauss. For both IMBPs and LMBPs the endpoint is a pulsar in an almost circular orbit, and the most common companion is a white dwarf, the mass and chemical composition of which depends on the original companion mass and orbital period. In particular Tauris (2011) classifies 3 main paths for the formation of IMBPs and 2 roads for the LMBPs (see Table 1 of Tauris 2011). Tauris, Langer & Kramer (2012) also report in Appendix a Table which can be used as a sort of *finding chart* for guessing the most likely nature of the companion to a pulsar, on the basis of the observed constraints on orbital period, eccentricity and mass of the companion.

3.1. *Classical tests for LMBPs with a He-WD companion*

There exist two well known predictions of the standard evolutionary models for the case of the LMPBs with a He-WD companion: *(i)* a correlation between eccentricity and orbital period (see Phinney 1992 for the underlying physical explanation) and *(ii)* a correlation between the orbital period and the companion mass (see e.g. Tauris & Savonije 1999 and references therein for the rationale beyond that). A recent analysis (Burgay *et al.*2012) confirms that the relation *(i)* is in general in agreement with the observations, although the spread in the data is slightly larger than predicted (see Fig. 2, left panel).

As to the correlation *(ii)*, some discrepancy with the observations was noticed for the binaries with longer orbital periods, but in fact the theoretical predictions can be reconciled with the available data if the correlation is drawn for a distribution of pulsar masses (between 1.3 and 2 $M_\odot$) instead than for a single mass (Shao & Li 2012). However, the

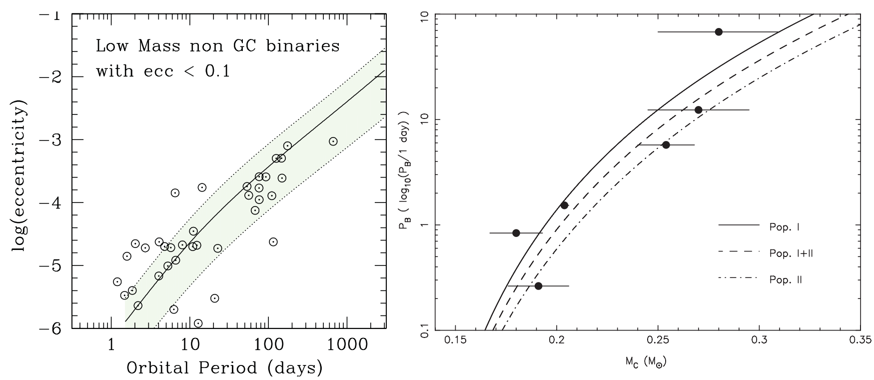

Figure 2. *Left panel*: the correlation between eccentricity and orbital period for LMBPs with He-WD companions not included in globular clusters (GCs). The dashed lines should enclose the 95% of the observed binaries (Phinney & Kulkarni 1994). Current data show that this is the case for the 75% of the objects (adapted from Burgay *et al.*2012). *Right panel*: The correlation between orbital period and companion mass for the 6 LMBPs for which the mass of the He-WD companion has been obtained via the observation of the Shapiro delay in the times of arrival of the pulses from the pulsar. The three lines refer to the Tauris & Savonije (1999) relation for various ensembles of stellar populations (adapted from Corongiu *et al.*2012).

capability of the correlation to really constrain the models is in general hampered by the usually very large uncertainties on the observed mass of the He-WD companion. More useful results can be obtained focusing on subsets of binaries for which accurate determination of the companion mass have been obtained. For example, in Fig. 2 (right panel) shows all binaries for which the He-WD mass has been derived from the measurement of the Shapiro-delay effect in the system.

3.2. *Some noteworthy cases of study: unveiled links, new species, new ideas*

J1023+0038: is a 1.69-ms fully recycled pulsar in a 4.75-hr circular orbit with a $\sim 0.25\,M_\odot$ main sequence companion, displaying extended radio eclipses, X-ray orbital modulation and γ–ray emission (Archibald *et al.* 2009, 2010; Tam *et al.* 2010; Bogdanov *et al.* 2011). The so far unique feature of this binary is that there are evidences for it to have hosted an accretion disk until around 2001 (Wang *et al.*2009). The system may thus currently be in a bi-stable status, switching among a X–ray accreting phase and a non-accreting radio emitting phase. In view of this characteristics, the binary may likely represent *the long sought link between the largest subgroup of the LMBPs (those with a He-WD companion) and their supposed progenitors, i.e. the Low Mass X–ray Binaries (LMXBs).* The recent measurement of the parallax distance of the system (1370±40 pc, Deller *et al.*2012) and the related updated determination of the pulsar mass (1.71±0.16 $M_\odot$) open the possibility of a largely improved modeling of the last stages of the recycling with emphasis on the interaction between the pulsar wind and the matter lost by the companion. In fact, given the features of the radio eclipses and the parameters of the system, PSR J1023+0038 also represents a stereotype for the so-called *Red Back* pulsars (see Roberts' contribution to this volume).

J1719−1438: This is a 5.7-ms fully *recycled* pulsar, orbiting in 2.2 hr a Jovian-mass companion (as indicated by the very small pulsar mass function) having a minimum average density > 23 g cm^{-3}, significantly larger than what observed in planets (Bailes *et al.*2011). That suggests that it represents the first unambiguous case - and thus the prototype - of a *recycled* pulsar descending from a so-called Ultra Compact Accreting X-ray Millisecond Pulsar (UC-AXMSP, for a review see e.g. Patruno & Watts 2012), i.e. X–ray binaries containing a rapidly spinning neutron star and a very low mass companion (typically few hundredths of solar masses) in ultra compact systems with orbital period from ~ 40 min to ~ 80 min. More recent investigations by Haaften *et al.* (2012; also this volume) and by Benvenuto *et al.*(2012) have supported the aforementioned *evolutionary connection between the J1719−1438 binary and the UC-AXMSPs* , although some additional ingredients (e.g. a combination of wind mass loss and expansion of the donor) are necessary for explaining all the features of the system (see also Horvath 2012, and Weber, this volume, for a more exotic explanation of J1719−1438).

ULMBPs: It is very intriguing that J1719−1438 is not a unique case anymore: two additional fully *recycled* pulsars with a Jovian-mass companion have emerged among the very recent discoveries of the ongoing pulsar surveys (see Ng; Lynch; both this volume). Therefore it is tempting to introduce *a new subclass in the family of the LMBPs with short orbital period ($\lesssim$ 1 day), which may be dubbed Ultra Low Mass Binary Pulsars (ULMBPs)* : these could be characterized by ultra small values ($x \lesssim 0.01$ sec) of the quantity $x = a_p/c$, where a_p is the projected semi-major axis of the pulsar orbit and c is the speed of light. Assuming that the orbit is not almost face-on, those values of x translate in a companion mass within the range $\sim 0.001\ M_\odot \rightarrow \sim 0.01\ M_\odot$.

The distinct nature of the progenitors would be a good reason for distinguishing the new class of the ULMBPs from that of the so-called Very Low Mass Binary Pulsars (VLMBPs: short orbital period pulsars with 0.01 sec $\lesssim x \lesssim$ 0.1 sec and corresponding

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companion masses in the range $\sim 0.01\ M_\odot \rightarrow \sim 0.1\ M_\odot$.). In fact, VLMBPs cannot be truly descendent of the UC-AXMSPs, since the companion masses are typically larger in VLMBPs than in UC-AXMSPs and the mass of the companion cannot ever increase during the evolution of these binaries†.

Isolated recycled pulsars: The mechanism leading to the formation of the isolated fully *recycled* pulsars is not yet clarified. Ablation and finally evaporation of a low mass companion by the pulsar's energetic flux was proposed early (see e.g. Ruderman *et al.*1989). The discovery of the eclipsing binary pulsars, and in particular the class of the so-called *Black Widows* (Fruchter *et al.*1988; see Roberts' contribution, this volume, for an updated list) seemed to strongly corroborate this hypothesis. However, various observations indicate that the timescale for the evaporation process may be too long (i.e. larger than a Hubble time) for considering the observed systems as progenitors of the isolated *recycled* pulsars (e.g. Stappers *et al.*1996). Alternatively, the companion star in a ULMBP could eventually disrupt for the insurgence of internal instability when its mass becomes too small (Deloye & Bildsten 2003).

Until recently, the VLMBPs (the family which the *Black Widows* belong to) were mostly found in GCs, where the formation of isolated pulsars can easily occur via ionization of a binary following a dynamical encounter (see Freire; Belfiore; both this volume). Now, the *blossom of discoveries of VLMBPs/ULMBPs, as well as of isolated recycled pulsars in the Galactic field, starts eventually enabling a direct statistical comparison of the two populations*, aiming to search for relationships and putative evolutionary connections (Possenti *et al.* in preparation).

J1614−2230: is a 3.15-ms fully *recycled* pulsar in a 8.7-day almost circular and highly inclined orbit with a $\sim 0.500 \pm 0.006\ M_\odot$ white dwarf companion. The inferred mass of the pulsar, $1.97 \pm 0.04\ M_\odot$, (Demorest *et al.*2010) makes it the most massive neutron star known to date, providing a discriminant test for few proposed equation of state for the nuclear matter. The accurate determination of the geometry of the orbit and of the masses of the binary components was made possible by the accurate measurement of the Shapiro delay. Besides the impact on nuclear physics, the J1614−2230 system is very interesting also as far as binary evolution studies. The companion mass and the orbital period clearly suggest that it belongs to the class of the IMBPs, however the rapid spin period is at odds with the *mild* recycling which is expected for these pulsars. Tauris, Langer & Kramer (2011, 2012) solved the issue showing that J1614−2230 descended from a previously overlooked formation path for the IMBPs: i.e. evolution in a close binary system with a $4-5\ M_\odot$ main sequence donor star via Case A Roche Lobe Overflow (see also Lin *et al.*2011 and Bhalerao & Kulkarni 2011). Given this model, it is possible to constrain *the original mass of the pulsar* (i.e. immediately after the supernova explosion and prior any accretion): the resulting $(1.7 \pm 0.15)\ M_\odot$ *is significantly larger than what was measured in e.g. ,the double neutron star binaries* and is relevant for the investigation of the physics of the core-collapse supernova.

J1903+0327: is a 2.1-ms fully *recycled* pulsar, orbited by a $\sim 1\ M_\odot$ main sequence star in a 95.2-day orbit, with a high eccentricity $e = 0.44$ (Champion *et al.*2008). Based on these observables, this binary could hardly be formed via the standard recycling mechanism, which should have led to an almost circular orbit. Freire *et al.*(2011) showed that the most viable hypothesis is that the neutron star was in a close orbit with a main sequence star and the current companion was a tertiary farther out. After having spun up the pulsar, the inner companion vanished, maybe due to a chaotic three-body

† An exception could result from the evolution of a triple system, but no observational hint of the presence of a third star has been collected so far in the observed UC-AXMSPs.

interaction with the outer star or due to ablation by the newly *recycled* pulsar. Similar conclusions have been derived by various other authors (e.g.: Portegies Zwart *et al.*2011, Bejger *et al.*2011, Pijloo *et al.*2012, Khargharia 2012). After many years for which it was mostly a theoretical exercise, first the *discovery of J1903+0327 and now* (see Lazarus's contribution) *that of a truly triple system in the Galactic field, promise to open the doors of a new gym for evolutionary and dynamical studies.*

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