The Formation of Puzzling Binary Pulsars

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Abstract

Many binary pulsar systems have been found that challenge our current understanding of their evolution. How can we explain isolated millisecond pulsars being in the galactic field? How are the systems known as 'Black Widows' or 'Redbacks' formed? The overall evolution of binary pulsars is relatively well understood; studying these puzzling systems will only improve our understanding. This report aims to examine such types of systems and discuss methods for which they may have formed.

1 Introduction

Neutron stars were first conceptualised in 1932 by L.D Landau [20], shortly after the discovery of the neutron [7]. However, it was not until much later in 1968 that the discovery of radio pulsars provided the first observational evidence for the existence of neutron stars [13].

Neutron stars are the stellar remnants of stars with masses between 10 and 25$M_\odot$ (solar masses), although there is some variance dependant on the metallicity of the star [11]. The process by which a neutron star is formed is called supernova. A supernova occurs when a high mass star has fused all its fuel up to the point of iron, where it will fuse no further. Iron is not fused as energy is required to fuse it, rather than released upon fusion. Once this point is reached no more fusion occurs in the core so there is no longer any radiation pressure counteracting the force of gravity. The star proceeds to collapse in on itself, and due to the high density, protons and electrons combine to form neutrons and release neutrinos. A Neutron star is born.

Neutron stars are very small in comparison to their progenitor stars, only having a radius of about 10km [6]. As a consequence, they must spin up to very high periods to conserve angular momentum. A typical neutron star period is that of 1 second, however it is possible for periods of the order of milliseconds[6].

Pulsars are objects which are characterised by their strong radio radiation beam and x-ray emission. The radiation beam is created from charged particles shot out from the magnetic poles of the pulsar. X-ray emission comes from binary pulsars with an accreting companion. The accretion disc surrounding the pulsar formed from the mass of the companion star is the source of any x-ray emission we observe.

Whilst having differing names, neutron stars and pulsars are the same stellar object. What we observe is dependant on the orientation of the object, and can be explained using the lighthouse model of pulsars, figure 1. The axis of the radiation beam is different to that of the rotation of the star, so as the star spins the radiation beam sweeps out a circle like a lighthouse. If an observer happens to be in the circle that the beam sweeps out, they will see regular pulses of the radiation beam and so observe a pulsar. However if an observer is not in the area the beam sweeps out then no pulses will be seen. As a result, an ordinary neutron star is observed.

The radiation beam of a pulsar is possible due to its strong magnetic field. The vast majority of pulsars have magnetic fields stronger than 10^{11}G(Gauss). However all pulsars of a specific type (called millisecond pulsars) have a much lower field strength, less than 10^{10}G [6]. This strong magnetic field beams charged particles out from the neutron star at relativistic speeds creating the jets that we observe.

Pulsars are powered by the loss of rotational kinetic energy, and so we expect their periods to

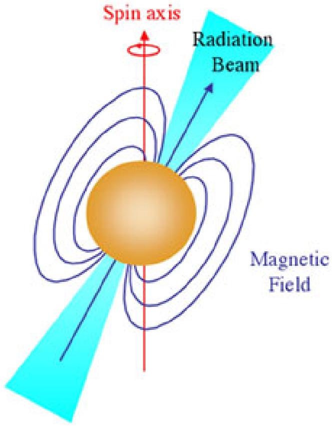

Figure 1: The lighthouse model of pulsars. [1]

increase over time. This so called "spin down rate" can be used to calculate an approximate age of a pulsar, the characteristic age, using equation 1.

$$\tau_c \equiv \frac{P}{2\dot{P}} \tag{1}$$

Where P = Period, $\dot{P}$ = Spin down rate.

This equation requires a number of assumptions to be accurate and is an approximation of a much more complicated equation which can be found in [18]. The assumptions are as follows -

- The initial spin period of the pulsar was much smaller than it is today.
- All spin down energy is lost in the radiation beam.
- The pulsar has a constant magnetic field.
- The object is never spun back up.

Whilst this formula works well for isolated pulsars, in reality most stars exist in binaries which break many of the required assumptions. The overall picture of binary evolution is well understood, however many systems have been observed that don't fit within our models and require special considerations to explain.

2 Binary Pulsar Evolution

When stars are in a binary, interactions between them may occur which affect their evolution in ways not possible for a single star. For instance, a pulsar may evaporate its companion star with its radiation beam. Another important interaction is the possibility of mass transfer between the two stars, which has massive consequences on the future of the system.

2.1 Methods of Mass Transfer

There are 2 main classes of X-ray binaries: low-mass X-ray binaries (LMXBs), in which the companion star is a solar-like star ($\leq 1.5\mathrm{M}_\odot$) and high-mass X-ray binaries (HMXBs), where the companion is a massive O or B type star with mass $\geq 15\mathrm{M}_\odot$. These different classes of X-ray binaries have very different methods of mass transfer as a necessity due to their mass.

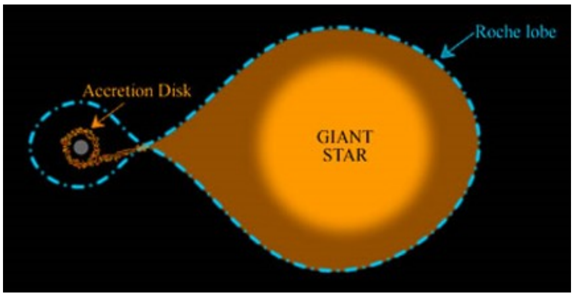

Figure 2: Illustration of the Roche Lobe for a binary star system. [2]

2.1.1 Roche Lobe Overflow and LMXBs

The Roche-lobe of a star is the region around a star in which orbiting material is gravitationally bound to said star. In a binary system, it is a pair of teardrop shapes around each star, with the point of the teardrop pointing towards the other star. The ends of the Roche-lobe for each star meet at an equipotential where mass may be transferred between the two stars, figure 1. In LMXBs, the radius of the donor star may slightly exceed the critical radius of the Roche-lobe (either by being in a close orbit, or from evolving from the main sequence to a red giant) and allow mass to flow freely onto the compact object. For donor stars of solar mass the rate of matter flow stays below the Eddington rate [12] and so creates a stable source of X-ray emission from the resulting accretion disc.

2.1.2 Stellar Winds and HMXBs

In HMXBs, the donor star has a much higher mass compared to an LMXB. Consequently, it deposits mass onto the compact object at a much higher rate. If such a star were to stretch beyond its Roche-lobe, the mass transfer rate would far exceed the Eddington limit by a factor of $\geq 10^4$ [34]. This would completely smother the compact object and cause no X-ray emission to be visible. Therefore, the donor star must not exceed its Roche-lobe. Luckily stars in these systems are evolved O or B type supergiant stars and so have strong stellar winds. The compact object may capture the expelled mass and while the amount is much less than the Eddington limit, there is still enough to power a steady accretion driven X-ray source. A comparison between the two methods may be seen in figure 3.

2.1.3 Intermediate Mass X-ray Binaries

There is a gap in observed systems for what would be Intermediate Mass X-ray Binaries (IMXBs). This gap can be explained as a result of the mass transfer methods mentioned. These methods work for companion masses $\leq 1.5\mathrm{M}_\odot$ or $\geq 15\mathrm{M}_\odot$. Companion stars between these would transfer mass too quickly for Roche-lobe overflow and smother the compact object. In addition, they don't have the strong stellar winds associated with high mass stars, and so that method cannot occur either. Therefore intermediate mass companion stars will never be able to power a strong X-ray source. This explains why we don't observe many would be IMXBs with masses $1.5\mathrm{M}_\odot \leq M \leq 15\mathrm{M}_\odot$ [33]. Some X-ray binaries have been found within this mass range, for example Cygnus X-2 and Hercules X-1.

2.2 Millisecond Pulsars

The consequences of mass transfer in a binary are a new type of pulsar, the Millisecond Pulsars(MSPs). Millisecond pulsars were first discovered in 1982 [5] with no explanation of their existence. Millisecond pulsars are characterised by their low spin periods of the order of milliseconds, and abnormally low magnetic field strengths compared to regular pulsars.

Millisecond pulsars are formed by the accretion of matter from a donor star onto a neutron star.

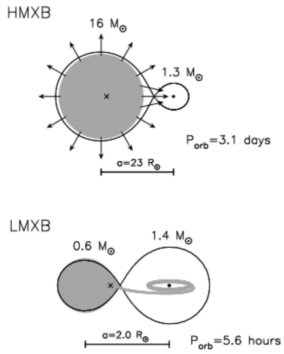

Figure 3: Examples of mass transfer for a typical HMXB (top) and LMXB (bottom). This image depicts neutron stars, however there are known LMXBs and HMXBs in which the compact object is a black hole. [32]

The matter from the accretion disc carries with it angular momentum which must be conserved. Therefore as matter falls from the accretion disc onto the neutron star, it gains angular momentum and spins up to high speeds. This accretion process must occur over periods of 100 of millions of years. Because of this, we expect to see millisecond pulsars in the evolution of LMXBs; the less massive a star, the longer it lives. LMXBs have low mass companion stars which live long enough to spin up the neutron star. The final result of LMXB evolution is therefore a white dwarf - neutron star binary. This is corroborated by observed star systems, indeed most observed white dwarf - neutron star binaries are millisecond radio pulsars. Another consequence of this long period of accretion, the orbit of the binary pair gets almost entirely circularised - we expect millisecond pulsars to have orbits with a very low eccentricities of the order 10^{-3} to 10^{-6} [25].

MSPs are found abundantly in globular clusters compared to the galactic plane. Globular clusters have large stellar densities (up to 1000 stars/cubic parsec in their centres, and 0.4 stars/pc^3 on average [4]) compared to the galactic plane (0.1 stars/pc^3 around the sun, for example [3]). This results in a high encounter rate between stars bringing many single neutron stars into a binary, where an LMXB is formed. Then by the evolution discussed, becomes an MSP. An MSP may form directly in the galactic disc, alternatively it can be ejected from a globular cluster and travel into the galactic disc. This is not surprising, as the escape velocity from a globular cluster is estimated to only be $50kms^{-1}$ [21].

Millisecond pulsars are difficult to age using formula 1 for a number of reasons. They clearly break the required assumptions - the pulsar has been spun up to a very low period over time. In addition, we have observed that the magnetic fields of millisecond pulsars decay over time. We are not sure what causes this decay however.

2.3 The Evolution of HMXBs

The final step in evolution for HMXBs is a double neutron star pair. We follow [29] and [34] for HMXB evolution.

3 An Eccentric Millisecond Pulsar in the Galactic Plane

3.1 PSR J1903+0327

PSR J1903+0327 is an MSP with a highly eccentric orbit (e = 0.44), a mass of 1.67M$_\odot$, a period of 2.5ms, orbiting a solar mass main sequence star, and is located within the galactic disc [15]. Standard models of binary evolution cannot explain the formation of this system. The evolution leading up to a millisecond pulsar should result in a highly circularised orbit over the long period of mass transfer between the two stars. In addition, we expect a white dwarf companion - a main

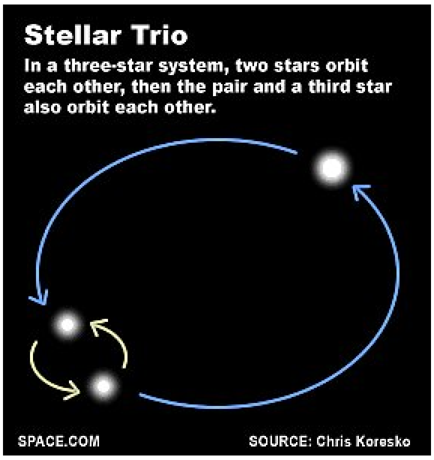

Figure 4: Illustration of a triple star system. [10]

sequence star would not have been able to transfer enough mass to spin up the pulsar to the speed at which we have found it. To explain this pulsar, a non-standard method of formation is required.

3.2 Formation via Accretion Induced Collapse

A possible formation method could be that the pulsar was formed spinning at millisecond periods. This can occur via the accretion induced collapse of a white dwarf. Main sequence stars of masses between $6-16\mathrm{M}_{\odot}$ may form an ONeMg (oxygen-neon-magnesium) white dwarf [22] of mass $1.1-1.3\mathrm{M}_{\odot}$ [31]. A binary partner may then accrete onto the white dwarf. Since the accreting material has angular momentum it cannot fall directly onto the surface of the white dwarf. The material loses angular momentum as heat from friction within the accretion disc and deposits onto the white dwarf. However once the temperature of the material on the surface reaches 10^8k, fusion may temporarily reignite and blow the material away in a process called a novae. Not all of the material accreted is lost in the novae however. As mass builds up on the surface, the white dwarf may reach the Chandrasekhar mass and undergo a carbon detonation supernova leaving no remnant. However, in the case of an ONeMg white dwarf, a neutron star can be left behind. The process by which this occurs for differing types of binary partners is studied in [31]. This method of formation is likely incorrect however, as accretion induced collapse cannot produce eccentric binary millisecond pulsars with periods greater than that of 20 days [9] and the system in question has a period of 95 days.

3.3 Formation in a Triple Star System

A most likely formation scenario is that PSR J1903+0327 originated in a triple star system, figure 4. For PSR J1903+0327, a primary star of mass $9-12\mathrm{M}_{\odot}$ was orbited by a smaller secondary star of mass $0.8-2\mathrm{M}_{\odot}$ in a close orbit of radius $200\mathrm{R}_{\odot}$. A tertiary star that is less massive than the secondary star orbits those, in a wide orbit of $\geq 560\mathrm{R}_{\odot}$ [35]. The tertiary star mass is required to be less than that of the second star as otherwise, it will evolve to fill its roche lobe before the inner binary has undergone evolution from an LMXB. The evolution is then - The inner binary undergoes the standard evolution towards an LMXB. The supernova explosion to form the neutron star and the resultant circularisation due to accretion disrupt the orbits of the system to become unstable. From here, 2 paths may occur. Either the tertiary star may be ejected from the system, forming a standard millisecond pulsar binary. Alternatively, the accreting star (now white dwarf) is ejected from the system leaving an MSP in an eccentric, wide orbit with the main sequence tertiary star as is the case for PSR J1903+0327.

4 Pulsars with Very Low Mass Companions - Black Widows and Redbacks

4.1 Black widows and Redbacks

Black widows and redbacks are a specific class of MSP. They are characterised by the low masses of their companions, black widows have very low companion masses $M \ll 0.1\mathrm{M}_\odot$ while red backs have companion masses of $0.1\mathrm{M}_\odot \lessapprox M \lessapprox 0.4\mathrm{M}_\odot$. In addition, these systems are in tight binaries with orbital periods of $P \leq 24$ hours [8, 26]. A peculiar property of these systems is that these systems suffer from eclipsing of their radio signals, from which it is clear that the companion must be non-degenerate or semi degenerate and experience irradiation driven mass loss [19, 27, 28].

This poses a problem for standard LMXB evolution - we expect the final stage in the evolution to be an MSP with a white dwarf companion. White dwarfs are degenerate stars and generally have masses $0.5\mathrm{M}_\odot \lessapprox M \lessapprox 0.7\mathrm{M}_\odot$ with a peak at $\approx 0.6\mathrm{M}_\odot$ [14] although white dwarfs with masses as low as $0.17\mathrm{M}_\odot$ and as high as $1.33\mathrm{M}_\odot$ have been found [16, 14].

4.2 Production in Globular Clusters

One theory of the formation of these systems (specifically, the black widows) is that they are formed in globular clusters, then ejected into the galactic plane. The first step in evolution is the standard LMXB evolution, resulting in an MSP with a white dwarf companion. Now the system undergoes an exchange encounter. These encounters primarily occur in globular clusters due to their high stellar density. Once the exchange has occurred, the high energy MSP causes the now main sequence companion to suffer ablation and blows the lost mass out of the system. It is important that this occurs, as otherwise the mass would deposit onto the MSP and extinguish it, reverting the system back to an LMXB. This explanation seemed likely, as black widow pulsars were thought to be much more common in globular clusters than in the galactic field. Those that were found in the galactic field were thought to be ejected from globular clusters. This theory is no longer thought to be accurate however as due to advances in technology we have been able to observe more of these systems than before in the galactic field [26]. The theory that they were formed in globular clusters cannot explain the amount of black widow pulsars found in the galactic plane, should they have all been ejected.

4.3 Formation via Ablation

An alternative explanation involves only the original two stars in the system, and the point at which the companion star becomes fully convective. We begin with standard LMXB evolution, to the point where the companion mass reaches $0.3\mathrm{M}_\odot$ at which the companion star becomes convective [23]. At this point, mass transfer is temporarily stopped due to magnetic braking ceasing [24, 17]. If at this point the neutron star has accumulated $0.35\mathrm{M}_\odot$ of mass (which is consistent with a donor mass of $1\mathrm{M}_\odot$ and an accretion efficiency of 0.5) it has accreted enough mass to become an MSP [30]. It can then proceed to evaporate its companion star, reducing its mass and resulting in the low mass companions we observe. Even if the companion star manages to refill its roche lobe via adiabatic expansion due to mass loss, the radiation beam will prevent the mass from accumulating onto the MSP. Whether a black widow or redback system is formed is dependant on the efficiency of the evaporation of the companion star. The reason that this may be different between systems is differences in alignment of the pulsar magnetic axis and the orbital angular momentum axis. However, it is difficult to determine this angle difference from measurements so this theory is untested [8].

5 Conclusions

While the overall picture for evolution of LMXBs, IMXBs, HMXBs and MSPs is well understood for many cases, there are some mysterious systems which challenge our understanding. These problems include different companion stars to what we expect, systems being located in places where we don't expect them to be, having measured quantities (for example eccentricities) that differ from what we expect, and more. This report has examined our current models of binary evolution and then looked at two such systems: An eccentric millisecond pulsar with a main sequence companion located in the galactic field, and the black widow and redback class of millisecond pulsars. Then we have examined how such systems don't fit our current models and give alternative formation methods to explain how said systems come to exist. We must continue to study binary pulsars to bolster our understanding of stellar evolution further, as well as gain understanding of other areas of physics such as general relativity.

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