High-mass X-ray Binaries: Illuminating the Passage from Massive Binaries to Merging Compact Objects
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Evolution of High-mass X-ray binaries in the Small Magellanic Cloud

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Abstract. In order to understand the progenitor of rotation powered pulsars, we compare them with High-mass X-ray binary (HMXB) pulsars, (or X-ray pulsars), in the Small Magellanic Cloud. The plot of period period vs. period derivative shows that isolated neutron stars could be evolved from HMXBs. The pulsars with long spin period might spin up to 0.001-1 s. The mechanism is a third-body interaction that detaches the donor, leaving an isolated, small period neutron star behind.

Keywords. pulsars: general – stars: neutron – stars: evolution – X-rays: binaries – accretion, accretion disks

1. Introduction

When large stars end their lives in a supernova explosion, the remains of the core of these stars could form neutron stars or even black holes (Timmes *et al.* 1995). Stellar remnants with the mass between 1.35 and 2.1 $M_{\odot}$ are too heavy to exist as white dwarfs, and too light (not dense enough) to become black holes, so they will form neutron stars or possibly other strange stars or quark stars (Rosswog 2015). Kundt (2012) states that spin rates of a neutron star at birth tend to be slow, much slower than expected by conservation of angular momentum during core collapse.

A neutron star then is a type of stellar remnant that can result from the gravitational collapse of a massive star after a supernova. Neutron stars are the densest and smallest stars known to exist in the universe; with a radius of only about 12 - 13 km, they can have a mass of up to 3 $M_{\odot}$, with a surface temperature of 6×10^5 Kelvin (Kiziltan 2011; Haensel *et al.* 2007). Neutron stars have overall density of 3.7×10^{17} to 5.9×10^{17} kg/m^3 (2.6×10^{14} to 4.1×10^{14} times the density of Sun) (Shapiro & Teukolsky 2008).

Pulsars send out beams of X-ray, radio and visible light. As they rotate, the beams sweep over the earth, resulting in a periodic modulation of the received flux. Although neutron stars are very hot at birth, they do not have a source of fuel for nuclear fusion. We still detect a tremendous amount of energy from neutron stars, such as the X-ray and radio beams. There are three broad classes of pulsars depending upon their principle energy source. (1) Rotation-powered radio pulsars convert their rotational energy into radiation (Becker & Trümper 1997). These pulsars slow down very slowly at a rate attributable to magnetic dipole braking losses. (2) Accretion-powered X-ray pulsars: Most X-ray pulsars are in binary systems, and they accrete materials from their companion stars and form an accretion disc of material around them (Perna *et al.* 2006; Karino *et al.* 2008). (3) Magnetars are neutron stars with exceptionally strong magnetic fields in the range 10^{13} to 10^{16} G, compared to 10^{11} to 10^{13} G for most radio and X-ray pulsars

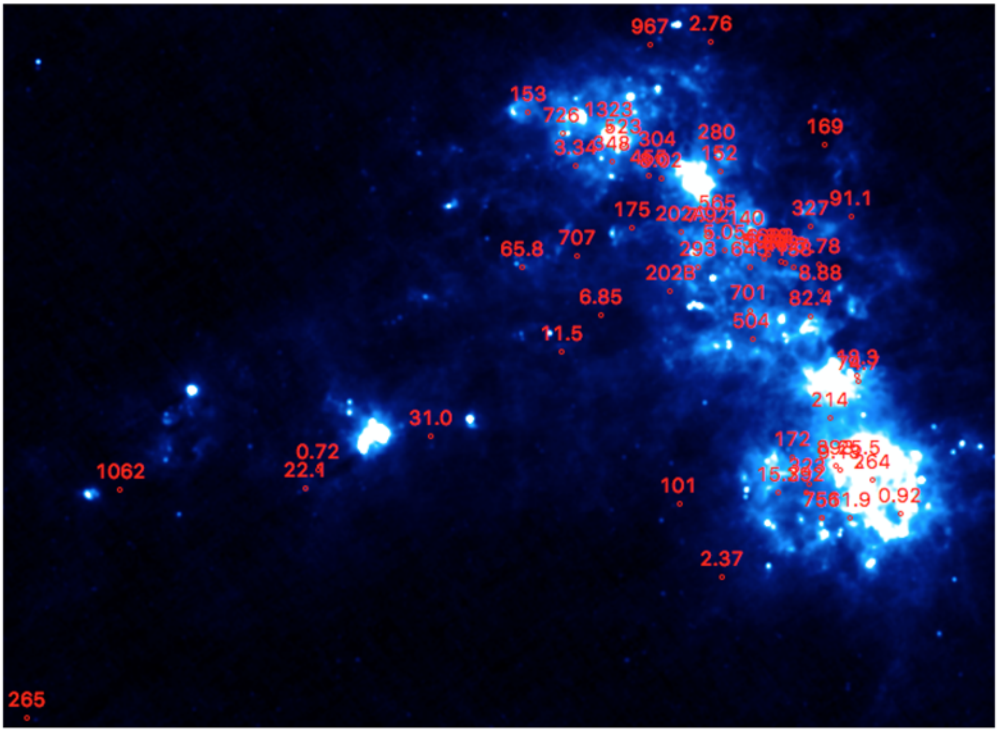

Figure 1. This figure above shows the location of the known Small Magellanic Cloud pulsars. The red numbers present their pulse periods in seconds. The background image is from the NASA/Infrared Processing and Analysis Center infrared science archive.

(Beskin *et al.* 2015). The slow decay of the magnetic field powers the radiation emission (Rees & Mészáros 2000; Heyl & Kulkarni 1998).

X-ray binaries have three distinct classes: High-mass X-ray binaries (HMXB), which have companion stars with masses $> 8\ M_{\odot}$, low mass (companion masses $< 1\ M_{\odot}$), and intermediate-mass X-ray binaries. A new class of HMXBs, Supergiant Fast X-ray Transients (SFXTs), with the unusually short transient X-ray emission and the association with blue supergiant companions, was discovered by the INTEGRAL satellite launched in October 2002 (Masetti *et al.* 2006; Negueruela *et al.* 2006; Nespoli *et al.* 2008).

2. Overview

The Small Magellanic Cloud (SMC) is a dwarf irregular galaxy near the Milky Way at a distance of about 62 kpc (Graczyk *et al.* 2013; Scowcroft *et al.* 2016). It contains a large and active population of X-ray binaries (e.g., Galache *et al.* 2008; Townsend *et al.* 2011; Klus *et al.* 2013; Coe & Kirk 2015; Christodoulou *et al.* 2016; Haberl & Sturm 2016; Yang *et al.* 2017a,b; Yang *et al.* 2018). The most numerous HMXB species in current catalogs (e.g., Yang *et al.* 2017a) are Be-HMXBs, where the companion is a Be star (Reig 2011). A Be star is a B type star (the second hottest temperature class with color temperatures in the range 20,000-40,000 K) which has at some time exhibited emission lines (signified by the letter *e*, suggesting a wind is present). The X-ray pulsars in the SMC are shown in Figure 1. The spin periods of pulsars range from seconds to thousands of seconds. The SMC provides a unique laboratory to study an important branch of stellar evolution.

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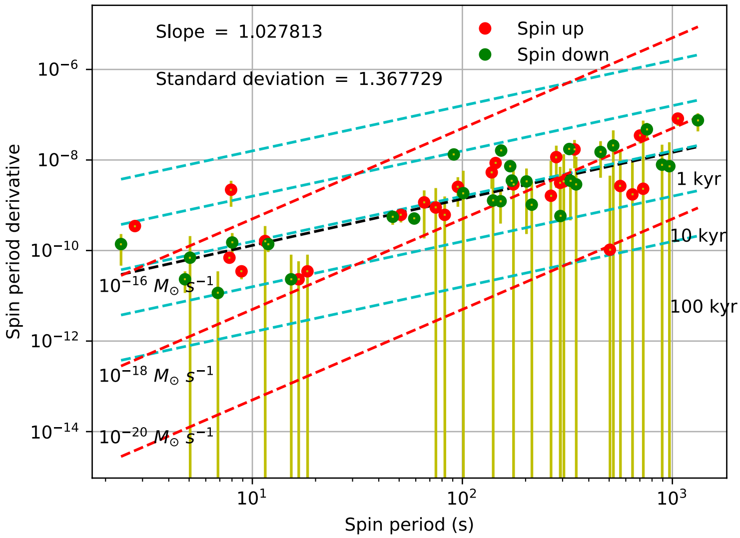

Figure 2. The filled circles show spin period derivatives of SMC pulsars as a function of spin period in seconds. Red mean this pulsar spins up and green indicates spinning down. Black dashed line is the linear fit to all pulsars in log-log space. Cyan dashed lines map the age of the pulsars. Red dashed lines are related to the mass accretion rate.

3. Implications

Bhattacharya & van den Heuvel (1991) suggest many millisecond pulsars are old, rapidly rotating neutron stars which have spun up by accreting matter from a companion star in a binary system. Massive X-ray binaries in the end might leave a single recycled neutron star which has 'evaporated' or merged with its companion star.

After accretion ceases, neutron stars could become isolated if their companions have subsequently disrupted the binary by their tidal break ups (Alpar *et al.* 1982).

Figure 2 shows the relation between spin period derivative and spin period of SMC pulsars. Red dots indicate pulsars that spin up and green symbols indicate they spin down. The error bars of the spin period derivatives are plotted in yellow. The black dashed line is the linear fit to the two variables in log-log space. Cyan dashed lines show the age map of the SMC pulsars. The majority of the sources are shown as 1 or 10 kyrs old. Interestingly, the age map is parallel to the linear fit line of spin period derivative and spin period. Within a standard deviation of 1.37, the fitting slope is consistent with 1, which implies there is no exponential relationship between spin period derivative and spin period.

Comparison of Figure 2 with the P-Pdot Diagram in Figure 3 shows that the two variables have a similar trend. In order to estimate the evolution of SMC pulsars, we consider a random source SXP 101 as and example, which spins up at the rate of 1.6×10^{-4} s/s. This pulsar is located around the 1 kyrs old line of the age map. If we assume the spin up rate is constant, after 626 kyrs later, the spin period of this pulsar will be 1s, which is located above the death line in Figure 3.

The mass accretion rate ($\dot{M}$) is plotted in red lines in Figure 2. $\dot{M}$ is estimated by assuming that the magnetic radius equals corotation radius, and the magnetic moment of the pulsar equals 10^{30} G cm^3. The deep explanation and verification about these mass accretion maps still need further study.

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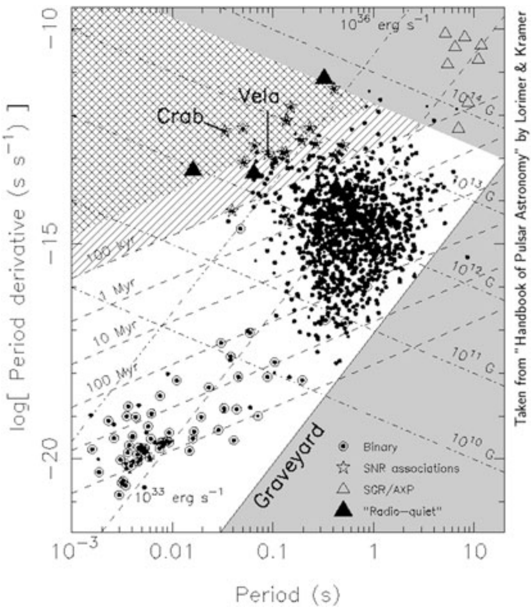

Figure 3. P-Pdot Diagram. This diagram shows the properties of the pulsars with short spin periods. Its role is similar to the Hertzsprung-Russell diagram for ordinary stars. From the spin period and spin period derivative of these pulsars, we can estimate their age, magnetic filed strength, and spin-down power (See the Handbook of Pulsar Astronomy, by Lorimer and Kramer).

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