Decay of the Magnetic Field in “Black Widow” Pulsars

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Abstract

A small fraction of the binary relativistic systems display the “black widow” effect: the companion is being ablated by the (recycled) pulsar wind.
In these binary systems, the evolution of the companion star (of the solar-type) reaches the point of filling its Roche lobe, thus initiating the process of mass accretion onto the pulsar.
Accretion is generally believed to result in magnetic field decay [1], while isolated neutron star fields decay very slowly , if at all [2].
We shall show that the very long evolution of the “black widow” system, starting from a solar-type star and lasting > 5 Gyr to reach the observed position in the $P_{orb} \times M$ plane, allows us to conclude that the magnetic field does not decay below the “bottom” value , extending the previous conclusions drawn from younger systems.
In addition, the masses of the “black widow” pulsars are naturally predicted to be $> 2M_0$ due to the accretion history, in full agreement with recent measurements [3, 4].

1. Binary Systems with a “Black Widow” Pulsar

A binary relativistic system contains a neutron star and a companion star, which is initially an isolated object until it reaches the point of filling its Roche lobe (RLOF). After the companion star to reach the RLOF, the mass transfer begins.
We do not kwon exactly how much of the mass transferred by the companion star is accreted by the neutron star. We defined that $\dot{M}_1 = -\beta \dot{M}_2$, where $\dot{M}_1$ is the mass accreted by the neutron star, $\dot{M}_2$ is the mass transferred by the companion star and $\beta \approx \frac{1}{2}$ [5]. The accretions spins up the pulsar, rejuvenating it.
Some very old millisecond systems (rotational periods in the range of about $1 - 10$ milliseconds) show an interesting peculiarity: their companions are being ablated by the winds produced by the pulsar radiation. Because of this effect, they have been called “black widow” pulsar (Fig. 1).

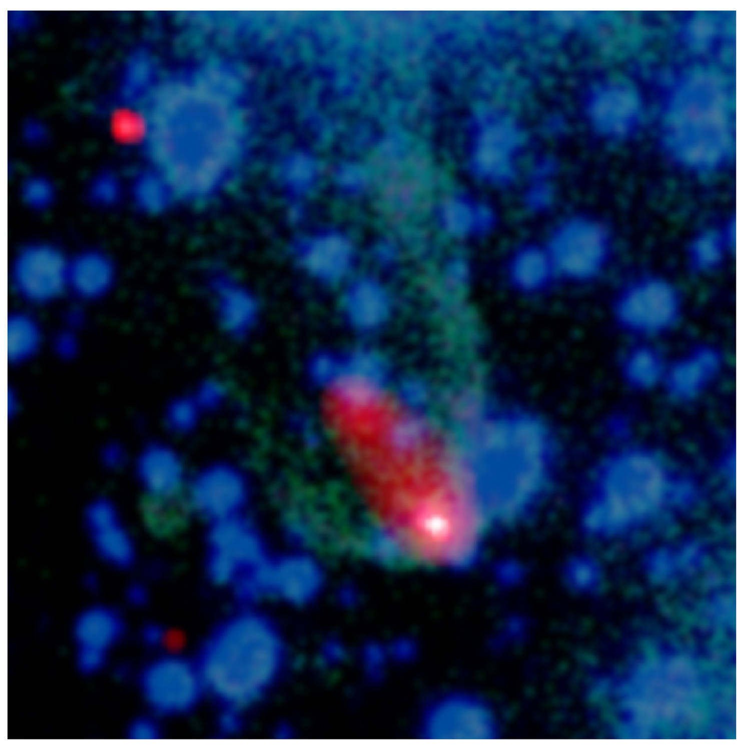

Figure 1: *Image of the pulsar B1957+20 composite by the Chandra X-ray(red and white) and optical (green and blue) image [6].*

2. Evolution of the Magnetic Field

Was believed that neutron star magnetic field decays due to Ohmic dissipation in the crust, but some calculations suggested that this decay is not significant. If only the Ohmic dissipation was responsible by the decays of magnetic field, the time for this decays would be larger for the Hubble time.
In 1995 a correlation between the magnetic field and the orbital period was discovered, and this correlation suggests that the mass accretion leads to the decay of the magnetic field in the pulsar until a bottom field $B_f \approx 2 \times 10^8$ G. In figure 2 we see this correlation.

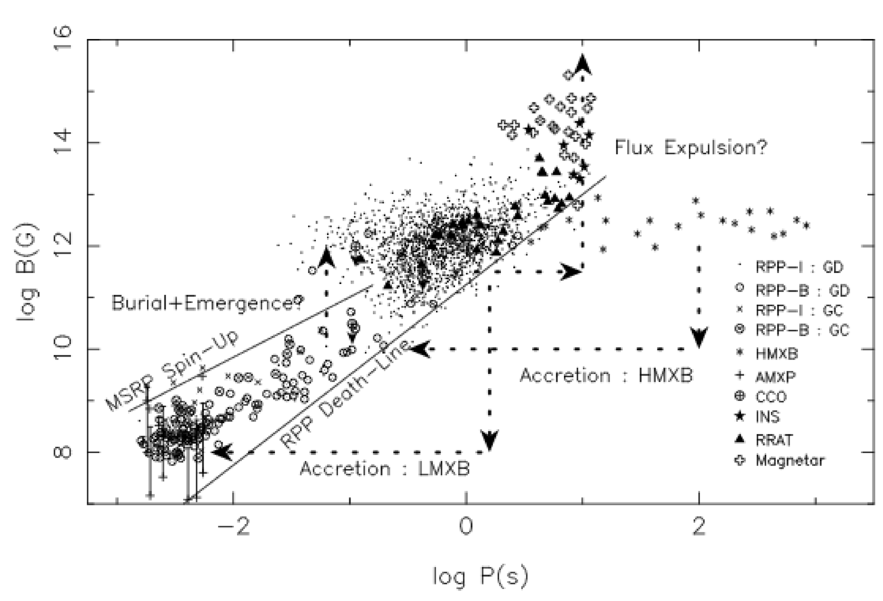

Figure 2: *Correlation between the magnetic field and the orbital period for neutron stars [7].*

When we search correlations between the spin period evolution and the mass accretion, we find that the spin period decreases with increasing mass accretion. In figure 3, we show a plot of the orbital period-mass relation for the companion star. We can see from this figure that the accretion process occurs during ~ 5 Gyr, so in this period the magnetic fiels of the pulsar decays mostly due the accretion process.

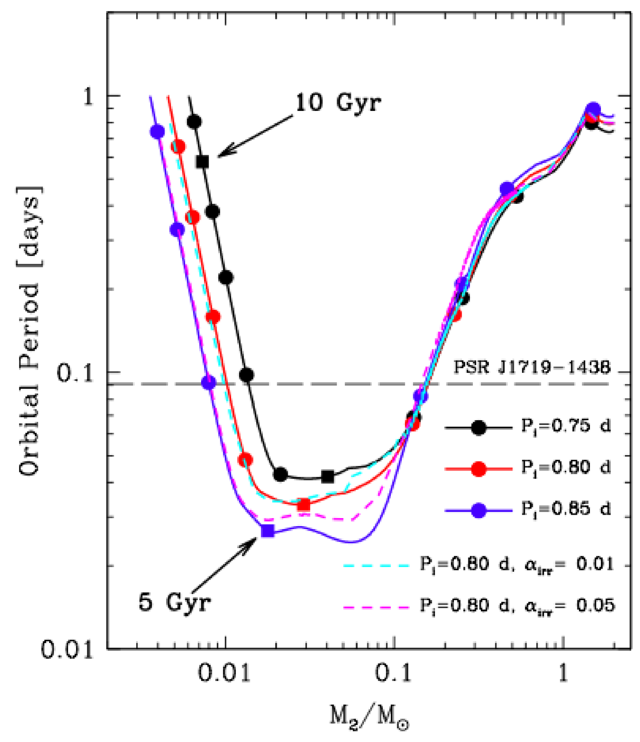

Figure 3: *The orbital period-mass relation for the companion star corresponding to systems with a solar composition, $2M_\odot$ normal star and a $1.4M_\odot$ neutron star in orbits with initial periods P_i of 0.75 d (black), 0.8 d (red) and 0.85 d (blue) respectively [5].*

Considering a neutron star in a LMXB with radius R and the thickness of the crust H, [8] proposed an empirical relation between the magnetic field and the accretion rate. This equation is

$$B \approx 0.8 B_f \left(\frac{\dot{M}t}{M_{cr}}\right)^{-1.75}, \qquad (1)$$

where B_f is the “bottom field”, $\dot{M}$ is the accretion rate, $\dot{M}_{ED}$ is the Eddington accretion rate, t is the time of the accretion and $M_{cr} = 4\pi R^2 \rho H$ is the (outer) crust mass.
A more detailed study on the evolution of the magnetic field in neutron star during the accretion phase has been performed in [7]. If we know the accretion rate and the initial magnetic field of the pulsar, we can find the magnetic field after the accretion through the graph of the figure 4. This figure shows the correlation between the accretion rate and the ratio $\frac{B_{final}}{B_i}$ field calculated for different values of density.

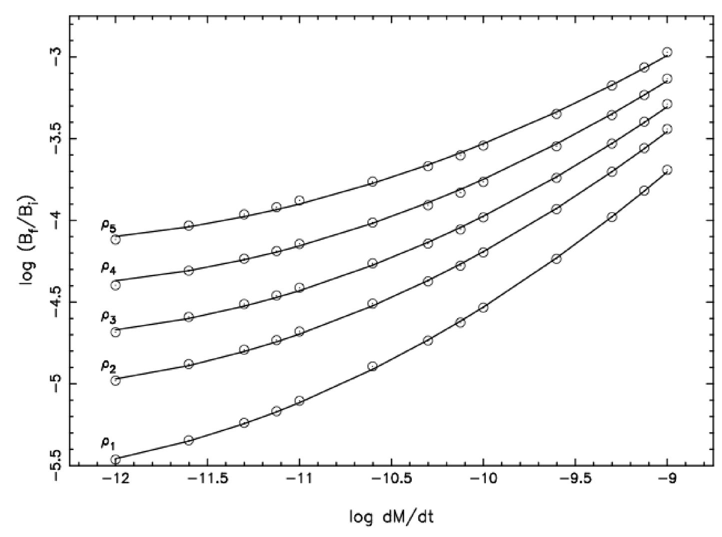

Figure 4: *Final magnetic field (B_f) as a function of accretion rate $\dot{M}$ and ρ_c (increasing from ρ_1 to ρ_5) [7].*

Thus, to find the magnetic field at a given time, we need to know the accretion rate. We estimate $\dot{M}$ of the “black widow” systems through the graph of the figure 5. For t= 5 Gyr, we have $\dot{M} \approx 10^{-10}$M$_\odot$/yr.

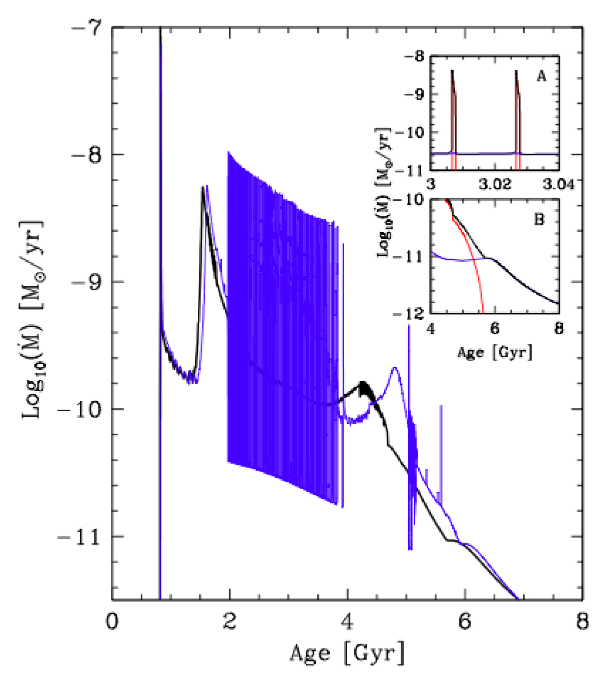

Figure 5: *The evolution of the mass transfer rate from the companion star for the case $P_i = 0.8$ d. After 5 Gyr, approximately, mass transfer is dominated by the evaporation wind driven by the pulsar irradiation [5].*

Using the results in figure 4 as indicated, we find $B_{final} \approx 10^{8.5}$ G (assuming the initial magnetic field $B_i \approx 10^{13}$ G).
After ~ 5 Gyr, the mass transfer rate is dominated by evaporation wind driven by the recycled pulsar radiation. From this moment, the pulsar magnetic field increases again for a time < 1 Gyr which is a short period compared with the total lifetime of the pulsar [9]. We do not need to know exactly how this increase happens, because in a comparable timescale the decay due to Ohmic dissipation of the current loops follows. The magnetic field decay according to the induction equation, given by

$$\frac{\delta \vec{B}}{\delta t} = \nabla \times (\vec{v} \times \vec{B}) - \frac{c^2}{4\pi} \nabla \times \left(\frac{1}{\sigma} \nabla \times \vec{B}\right), \qquad (2)$$

where σ is the electrical conductivity, $\vec{v}$ ($\propto \dot{M}/r^2$) is the radially inward material velocity [7].
The timescale to the Ohmic dissipation is [10]

$$\tau_{Ohm} = 4.4 \left(\frac{\nabla}{10^{24} s^{-1}}\right) \left(\frac{\lambda}{km}\right) 10^6 yr, \qquad (3)$$

where λ is the typical magnetic field length-scale.
Analyzing the “black widow” pulsars with ages of approximately 10 Gyr, we found that their magnetic field is $B \approx 2 \times 10^8$. Therefore, we believe that after the process of accretion and recycling, the pulsar reaches the bottom field and after this the magnetic field of the pulsar remains constant.

3. Conclusions

In this work study the evolution of the magnetic field in “black widow” pulsars. We conclude that for a pulsar with the initial magnetic field of approximately 10^{13} G, after 5 Gyr (time for the accretion phase) the magnetic field reaches a value of approximately $10^{8.5}$. After 5 Gyr, the mass transfer rate is dominated by evaporation wind driven by the pulsar radiation, the pulsar remains effectively isolated and consequently the magnetic fields increase during a time < 1 Gyr (a short period compared with the lifetime of the pulsar). Finally, the magnetic field decays again, due the Ohmic dissipation, up to the bottom field ($\approx 10^8$ G).
Since we know that the “black widow” pulsar’s magnetic field are approximately 2×10^8 G, and that this value should have been reached $4-5$ Gyr ago, we have evidence that the magnetic field does *not* decay further after reaching the bottom field. This is possible because the evolutionary ages of “black widow” pulsars are very large (approximately 10 Gyr) and allowed an observational check of field decay theory.

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