IX. PULSARS AND SUPERNOVAE

https://doi.org/10.1017/S0074180900093165 Published online by Cambridge University Press

ASYMMETRIC SUPERNOVA EXPLOSIONS: THE ORIGIN OF RUNAWAY PULSARS AND BINARY PULSARS

Jean-Pierre De Cuyper
Astrofysisch Instituut, Vrije Universiteit Brussel, Belgium

It is known from observations that pulsars are high velocity objects. As a sizable fraction of these collapsars originates from low velocity single stars, they must have received a "kick" velocity at their birth. Which we assume to be due to the asymmetry of the SN-explosion and to be randomly orientated. Hanson (1979) estimated this asymmetric velocity in a statistical study to be about 10^2 km s^{-1}. For SNe occurring in binaries the runaway velocities depend on the initial conditions. According to hydrodynamical calculations by Fryxell and Arnett (1979) the momentum imparted by the SN shell to the companion is some 80% of the momentum incident on the geometric cross-section of the star. This is due to mass stripping, which reduces the radius of stars with extended atmospheres, and to a smooth flow of the SN shell around the spherical companion and the nearly spherically symmetric ablation of some mixed stellar material. The mass loss of the companion is negligible.

WR-binaries, consisting of a WR star and an O- or B-star companion, are supposed to be the progenitors of the first SN in massive close binaries. In this case a spherically symmetric SN-explosion can hardly disrupt the remaining system since the WR star is the less massive component. On the other hand an asymmetric SN explosion may cause the disruption. As the orbital velocities involved ($\leqq 5 \times 10^2$ km s^{-1}) are much smaller than the observed SN-ejection velocities ($5 - 20 \times 10^3$ km s^{-1}), the SN-explosion can be assumed to occur instantaneously.

For the ten best known WR-binaries we evaluated the survival probability P after an SN-event leaving a 1.5 $M_\odot$-remnant with a randomly orientated kick velocity $\bar{v}_k$ of 75 km s^{-1} (case a) or 150 km s^{-1} (case b) respectively. The influence of the impact is found to be marginal. The runaway velocity of the remaining system $\bar{v}_g$ or of the disrupted OB-star $\bar{v}_{OB}^{\infty}$ is comparable and of the same order of magnitude, but smaller than the initial orbital velocity of the OB-companion and decreases for increasing values of the initial orbital period. It is found to be independent of the magnitude of the kick velocities involved, and to obey a different velocity distribution as a function of the direction of the

W. Sieber and R. Wielebinski (eds.), Pulsars, 399–401.

kick. Hence the possible values of $\bar{v}_g$ are slightly higher than those of $\bar{v}^{\infty}_{OB}$. Systems with an initial period up to a few weeks stay together for case a and have a survival probability of $0.85 \geqq \mathcal{P} \geqq .7$ for case b. Indicating that most of the high velocity OB-stars ($v_g \geqq 60$ km s^{-1}) have a collapsar companion. For systems having an initial period of the order of months $\mathcal{P}$ lies in the range $.9 \geqq \mathcal{P} \geqq .7$ (case a) and $.6 \geqq \mathcal{P} \geqq .4$ (case b) respectively. Hence single runaway OB-stars are less numerous and most of them have a low runaway velocity ($v^{\infty}_{OB} \leqq 60$ km s^{-1}). These results are in agreement with the observed bimodal runaway velocity distribution of OB-stars (Stone 1979) and the observed properties of massive X-ray binaries.

In cases where the system is disrupted a single pulsar is formed with a runaway velocity up to 100 km s^{-1} (case a) and 200 km s^{-1} (case b) respectively, independent of the initial orbital period; few of them have a negligible runaway velocity.

The highest velocity pulsars, such as PSR 0450-18 with $v^{\infty}_p \geqq 650$ km s^{-1} (Helfand et al. 1980) are thought to originate from systems consisting of a "single" WR-star and an old collapsar companion which were disrupted by the second SN-explosion. PSR 0450-18 can be associated with a nearby 30000 yr old SN remnant. Its slow period of P = .549 s, together with the high spindown-age of $t \approx 2 \times 10^6$ yr suggest that it is the re-activated remnant of the first SN.

If the system survives the second SN-explosion, a binary pulsar is formed such as PSR 1913+16. We calculated the circular pre-SN systems which, for an appropriate kick, reproduce the observed orbital parameters of PSR 1913+16 (Taylor 1981). The possible pre-SN semi-major axis satisfies: $1.07\ R_{\odot} = (1 - e^f)\ a^f \leqq a^o \leqq (1 + e^f)\ a^f = 4.54\ R_{\odot}$. For a kick in the orbital plane a prograde and a retrograde set of solutions is possible and for a kick out of this plane all the intermediate ones. A unique symmetric solution occurs for the minimum value of a^o and for a mass of the pre-SN system $M^o = (1 + e^f)\ M^f = 4.61\ M_{\odot}$ with $v_g = 170$ km s^{-1}. The prograde solutions need a maximum value of $v_k \geqq 350$ km s^{-1}, increasing with M^o, for an initial separation $a^o = 2\ R_{\odot}$. In the region around the symmetric solution we have $\mathcal{P} = 1$ with $M^o < 5.2\ M_{\odot}$, $v_k \leqq 250$ km s^{-1} and $v_g \leqq 240$ km s^{-1}. For $\mathcal{P} > .5$ we get $M^o < 5.7\ M_{\odot}$, $v_k \leqq 370$ km s^{-1} and $v_g \leqq 300$ km s^{-1} and $\mathcal{P} \leqq .3$ for $M^o > 6.5\ M_{\odot}$ and $v_k \geqq 200$ km s^{-1} with $v_g \geqq 300$ km s^{-1}. The survival probability depends also on the previous mass and angular momentum loss during the spiral-in phase, which precedes the second SN. Possibly the binary pulsar PSR 0655+64 is just such a pre-SN system, with a small inclination and a still unobserved companion with $v_c \sin i \leqq 40$ km s^{-1} and $M_c \geqq 3\ M_{\odot}$.

REFERENCES

Fryxell, B.A. and Arnett, W.D.: 1979, Enrico Fermi Inst. Preprint N° 78-64.
Hanson, R.B.: 1979, Mon. Not. R. Astr. Soc. 186, p. 357.

https://doi.org/10.1017/S0074180900093165 Published online by Cambridge University Press

Helfand, D.J., Taylor, J.H., Backus, P.R., and Cordes, J.M.: 1980, Astrophys. J. 237, p. 206.
Taylor, J.H.: 1981, this volume.
Stone, R.C.: 1979, Astrophys. J. 232, p. 520.

DISCUSSION

KUNDT: I cannot see a mechanism that would make a supernova explosion asymmetric by more than $\Delta v/v \gtrsim E_{turb}/E_{grav} \gtrsim 10^{-8}$. Question: aren't the binary break-up velocities large enough to account for the observations?

DE CUYPER: A sizable fraction of pulsars originates from single stars and as we do not observe low velocity pulsars there must be a mechanism which speeds them up just after they are formed. The timescale on which this acceleration is effective is very short if it is due to the explosion itself; or of the order of months if it is a result of off-centre low frequency dipole or quadrupole radiation. (In the last case time-dependent calculations need to be done.) The break-up velocities cannot account for the fast runaway pulsars with $v > 300$ km s^{-1}.