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The Pulsar/B-Star Binary PSR J0045−7319

Abstract

A surprisingly rich variety of astrophysical results has emerged from observations of PSR J0045−7319, a 926-s pulsar in a 51-day eccentric binary orbit with a B star. Here we review these results, which include tight limits on the B-star's mass-loss rate, well-defined constraints on the inclination of the B-star's spin axis with respect to the orbital angular momentum through the detection of classical periastron advance and spin-orbit coupling, strong evidence for a birth kick to the neutron star from an asymmetric supernova, as well as evidence for retrograde differential rotation of the B star.

I Basic properties of the PSR J0045−7319 binary

PSR J0045−7319, the only known pulsar in the Small Magellanic Cloud, was discovered as part of a large survey for radio pulsars in the Magellanic Clouds (McConnell et al. 1991). Timing observations of the pulsar demonstrated that it is in an eccentric 51-day binary orbit with a companion having minimum mass 4 $M_\odot$ (Kaspi et al. 1994). The same timing observations also determined the pulse period derivative for this 926-ms pulsar, which implied a timing age of $\sim 3 \times 10^6$ yr and a surface magnetic field of $\sim 2 \times 10^{12}$ G. Optical observations revealed the presence of a main sequence 16-mag B1V star at the pulsar timing position. Follow-up spectroscopy revealed radial velocity variations of the B star, consistent with Doppler shifts of the expected magnitude and at the predicted orbital phase, confirming the association (Bell et al. 1995b). Those observations also measured the width of He I lines and measured the stellar projected rotation velocity, $v \sin i = (113 \pm 10)$ km s^{-1}, typical of B stars (Allen 1963). The B-star's colors and luminosity at the distance of the SMC implied a temperature of (24000$\pm$1000) K and a radius of (6.4 $\pm$ 0.7) $R_\odot$ (Bell et al. 1995b). The B-star radial velocity curve determined its mass to be (8.8 $\pm$ 1.8) $M_\odot$ and the inclination angle of the orbit $i = 44° \pm 5°$, assuming a 1.4 $M_\odot$ neutron star. This implies that the pulsar approaches its companion very closely at periastron: to within (3.7$\pm$0.5) B-star radii.

II Deviations from a Keplerian orbit and the B-star wind

Continued timing observations of the pulsar revealed that a simple Keplerian orbit provided a poor fit to the pulse arrival times (Kaspi et al. 1996b). Although no eclipses of the radio data were observed at any orbital phase, the proximity of the pulsar to the B star at periastron suggested that the pulsar's radio emission could be dispersed by the ionized component of the B-star's wind, resulting in apparent delays of the single-frequency timing signal. To investigate this possibility, multiple frequency observations were performed near and away from periastron. No significant increase in the pulsar's dispersion measure (DM) was observed near periastron, with a 3σ upper limit of ΔDM< 0.9 pc cm^{-3} (Kaspi, Tauris & Manchester 1996). This permitted a limit to be placed on the mass-loss rate for the B star, $\dot{M} < (3.4 \times 10^{-11})(v_{\infty}/v_{\rm esc})$ $M_{\odot}$ yr^{-1}, where v_{∞} is the terminal wind velocity and v_{esc} is the stellar escape velocity. Though significantly smaller than what is predicted by empirical mass-loss/luminosity relations, derived from Galactic B stars for which $\dot{M}$ has been measured (e.g., de Jager, Nieuwenhuijzen & van der Hucht 1988), so low an $\dot{M}$ is not surprising given the low SMC metallicity and the importance of metals in radiation-driven winds of early-type stars (Lucy & Solomon 1970, Castor, Abbott & Klein 1976, Kudritzki, Pauldrach & Puls 1987).

III Classical periastron advance and spin-orbit coupling

Lai, Bildsten & Kaspi (1995) showed (see also Smarr & Blandford 1976) that a rapidly rotating B star such as the companion to PSR J0045−7319 should have a substantial equatorial bulge, and that the quadrupolar term in the interaction potential should result in classical precession of the line of apsides, i.e., periastron advance ($\dot{\omega}$). In addition, Lai et al. showed that for a B-star spin axis significantly inclined with respect to the orbital angular momentum, the net torque on the B star would force it to precess; since total angular momentum is conserved, the orbital angular momentum would be forced to precess as well, and the inclination of the orbital plane should vary (di/dt), observable as a changing projected semi-major axis, d(a sin$i$)/dt. Kaspi et al. (1996a) showed that the timing model including a Keplerian orbit plus $\dot{\omega}$ and d(a sin$i$)/dt fit the data well. The fitted values $\dot{\omega} = (0\overset{\circ}{.}0259 \pm 0\overset{\circ}{.}0005)$ yr^{-1} and d(a sin$i$)/dt $= (1.17 \pm 0.02) \times 10^{-9}$ lt s s^{-1} require the B-star spin axis to be inclined with respect to the orbital angular momentum by at least 25°.[1] The true value of the inclination angle depends on the unknown precession phase. As the precession period is probably several hundred years, the inclination angle is not likely to be better constrained soon.

[1] Kaspi et al. (1996) constrained the inclination angle to be less than 41°, however it has recently been pointed out (Norbert Wex, personal communication) that a region of phase space exists in which the angle could be as large as $54\overset{\circ}{.}7$.

IV Neutron star birth kicks

Birth kicks to neutron stars resulting from asymmetric supernova explosions have been hypothesized on the basis of large observed pulsar proper motions (e.g., Cordes, Romani & Lundgren 1993, Lyne & Lorimer 1994) but remained unproven because scenarios could be envisioned in which binary disruption in symmetric supernovae resulted in the high pulsar velocities (Iben & Tutukov 1996). Prior to the formation of the pulsar in the PSR J0045−7319 system, the binary must have been very close (see Kaspi et al. 1994), so tidal and/or mass-transfer forces should have aligned the angular momenta. Therefore, the non-zero inclination angle observed today via the detected spin-orbit coupling provides strong, new evidence for a birth kick to the neutron star out of the original plane of the orbit (Kaspi et al. 1996a). The size of the kick required to achieve the minimum possible misalignment is poorly constrained, but was probably $\sim$100 km s^{-1}.

V Orbital period derivative and retrograde differential B-star rotation

From the timing data, Kaspi et al. (1996a) showed that in addition to the classical post-Keplerian parameters $\dot{\omega}$ and di/dt, the best timing model included a significant orbital period derivative $\dot{P}_b = (-3.03 \pm 0.09) \times 10^{-7}$. The implied time scale for orbital evolution is only $\sim$0.5 Myr, comparable to that observed in accreting neutron star/B-star binaries (e.g., Levine et al. 1993); however, in PSR J0045−7319, the evolution is necessarily of a different origin, given the tiny B-star mass-loss rate. Energy dissipation is expected because of oscillation modes excited in the B star by the neutron star's orbit (the so-called "dynamical tide"), however Kumar, Ao & Quataert (1995) showed that the effect should be small, because low-frequency (hence low-energy) modes should be excited most. Lai (1996) proposed retrograde rotation of the B star as a way of exciting high-frequency modes, since in this case, in the B-star's rest frame, the neutron star's relative angular velocity is much larger, thereby exciting high frequency modes. Kumar & Quataert (1997) argued that although higher frequency modes would be excited as Lai suggested, his assumed dissipation rate was too high, and the excited modes would be damped insufficiently quickly to account for the large observed $\dot{P}_b$. However, Kumar & Quataert also show that differential rotation of the B star could result in significantly smaller damping times, and could explain the observed $\dot{P}_b$. Retrograde rotation demands a larger birth kick velocity to the neutron star in order to have made it reverse the direction of the pre-supernova orbital motion; the magnitude, again poorly constrained, was most likely $\sim$200 km s^{-1}.

VI Future observations

We expect future observations of PSR J0045−7319 to yield additional interesting information. Continued timing will determine if the observed orbital period derivative is indeed secular, as opposed to variable as in the eclipsing binary pulsar PSR B1957+20 (Arzoumanian, Fruchter & Taylor 1994). An improved optical light curve for the B star could reduce the uncertainties on the mass ratio significantly, and possibly help determine the apsidal constant for use in comparing with models of the stellar interior. Polarization measurements of the radio pulsar as a function of orbital phase could help map the B-star magnetic field, as has been done for the pulsar/Be-star binary PSR B1259−63 (see Wex & Johnston, this volume). Finally, the wide range of interesting results that has emerged from observations of PSR J0045−7319 (and PSR B1259−63) makes it highly desirable to discover and observe other such systems. Although a number of searches designed specifically with this purpose in mind (Sayer, Nice & Kaspi 1996, Vasisht 1996, Philp et al. 1996, Kaspi, Manchester & D'Amico 1997) have discovered no new binaries, future Galactic-plane pulsar searches hold the most hope for success.

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