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On the Interacting Winds of PSR J0737−3039

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Abstract. The theoretical expectations before and after this conference are contrasted. The unique theoretical opportunities for deciphering what sort of wind flows from pulsars in this system are outlined. We suggest that this system may provide evidence for fan beams, which should be clearer after a few years of spin-precession. There is also a reasonable expectation of a partially linearly polarized x-ray nebula due to wind/wind interactions between the two pulsars.

1. Introduction

This conference has emphasized what marvelous opportunities to test general relativity are already provided by the recent discovery of PSR J0737−3039. In particular the rapid precession of the pulsar spin axes (about 5°/yr) in a system that is seen almost edge-on, which will eventually allow the system to be views from all angles in the orbital plane. But the opportunities for understanding the magnetospheric physics of pulsars are also exciting.

2. Prior Knowledge

Little was generally known to me about this system prior to this conference other than the rough spin period (about 2 sec) of the slower pulsar ("B"), the orbital period (about 0.1 day) and the fact that the system was nearly edge-on.

2.1. The Beam Shape

The first thing I wrote down in anticipation of this meeting was that to see both pulsars in an edge-on system strongly implied radio emission in the form of fan beams (with any plausible assumptions about spin axis and magnetic dipole orientation). Accordingly, I was surprised with how ubiquitous the assumption of narrow hollow cone emission patterns had become at this conference. We have recently discussed problems with any theoretical underpinning for such a model (Smith et al. 2001; Michel 2004), so I will not repeat them here. In an earlier book (Michel 1991) I provided simulations that showed no evidence for magnetic field decay (the earliest such simulation I know of, which was also reported at IAU Coll. 128: Michel 1990). The same simulations also showed statistical problems with the hollow cone beaming assumption as well.

2.2. The Winds

One can guess from the periods that the magnetic fields would be about 10^{12} G for B and about 10^{10} G for A. One then had a system with spin periods differing by about 10^2 and magnetic fields also differing by about the same factor. With the usual scalings (dipole $1/r^3$ fall off out to the wave zone [aka "light cylinder"] and wave zone $1/r$ fall off beyond, one finds that the (wind) magnetic field of A at the distance of B is 10^2 that of B at A. Given the actual displacement (about 3 lt-s), the two fields would be 10 G and 0.1 G respectively. As also noted in Lyne et al. (2004), the two fields would have equal values *inside* the "magnetosphere" of B (a somewhat non-standard but understandable use of the term). Although A has the weaker **surface** field, the smaller wave zone gives it a hundred-fold stronger **wind** field than B.

3. New Information

Coming to this meeting and getting the more precise numbers actually didn't change much in the above rough picture. The pulse profile for A turned out to be interesting because it consists of two roughly equally spaced pulses (also shown in Burgay et al. (2003), but as an imprecise looking figure inset). With polarization information as well, the two pulses look vaguely like mirror images, having linear polarization on the leading edge of one and on the trailing edge of the other (Manchester, in this volume), not at all inconsistent with intercepting the same fan beam twice (although that might be pushing a fan beam model a bit too hard).

3.1. Winds Again

The wind energetics becomes an interesting issue here. Actually it is already an interesting issue in the Crab nebula, where the wind interacts with the surrounding filamentary material as well as in PSR 1957+20 where the wind interacts directly with the surface of a companion and also terminates in a cometary nebula at large distances. I would like to call attention to Michel & Li (1999), which was written as a public service in anticipation of eventual future work involving actual calculations (as opposed to cartoons). Here we re-calculate the complete vacuum solutions for an inclined rotator as well as give examples of exact solutions for particle acceleration in the asymptotic wave zone. Numerous authors have neglected the intrinsic charge on a rotating magnetized neutron star. This same intrinsic charge creates severe difficulties for hollow cone models because it leads to trapping of particles over the polar caps, as opposed to the free emission expected when only the induced quadrupolar fields are considered. This paper can be downloaded from www.sciencedirect.com by following the physics & astronomy links to Physics Reports.

While the magnetic fields of the two pulsars balance close to B, there are other issues such as at what distance would a charged particle be equally buffeted by each pulsar. For pickup in a unidirectional wind, the acceleration is completely described by

$$g = \frac{\omega_\perp}{\omega} \tag{1}$$

where ω is the wave frequency and $\omega_\perp = eB/m$ is the ("nonrelativistic") cyclotron frequency in the magnetic field of the wave. We show that charged particles are accelerated to velocities of the order of g times c perpendicular to the wave and g^2 in the direction of the wave. For small g the acceleration is nearly all tangential, leading to Thompson scattering of the wave, while for large g the particle is accelerated to huge Lorentz factors (the velocities becoming proper velocities). The energetics are easier to understand if we note that g is proportional to $E \times P$, the wave electric field times the period, which measures how long the charged particle is subjected to the wave electric field (plasma texts assume uniformly magnetized plasmas and ignore the wave **B** fields as "second order" and small compared to the assumed uniform magnetization, so these solutions are simply ignored!).

The g for the one pulsar seen at the distance of the other is then the same! The stronger **B** field of A is compensated by the smaller period. The value of g for A (at the distance of B) is then the cyclotron frequency at 10 G (2.8×10^7 Hz) divided by the 44 Hz spin frequency giving $g \approx 6.4 \times 10^5$. If these energies were achieved, the electrons would have radiative lifetimes of about 10 sec (in a 3 lt-s wide system) and would radiate at about 10^{17} Hz (X-rays). Such estimates have to be taken with large amounts of salt until direct numerical simulations are made. Our thinking here is that the high frequency waves from A can accelerate particles near the nulls of the long wavelength waves from B, but eventually B accelerates the particles in the opposite direction. Somewhere in the system, perhaps midway where the two values of g balance, electrons would be accelerated back and forth many times before escaping to the sides. One would then expect some linear polarization in the orbital plane. But in this more complicated geometry the electrons probably get smaller Lorentz values than the full g^2.

Before this conference I was surprised by the ratio of spin-down luminosities between the two pulsars, a factor of 10^4 using my original round numbers. If the radio luminosities were also that far apart, it would seem quite a data analysis coup to detect one in the glare of the other. In this regard, I was surprised that there was no quantitative discussion at this conference on what limits one could place on the pulsations from the unseen companion in the several other known double neutron star systems, beyond having "tried very hard" in the cases of PSR 1913+16 (Taylor). I had guessed (to split the difference) that perhaps the radio luminosities differed by only a factor of 10^2. But I didn't then know that B was seen only a small part of the time, and then at almost the same intensity (1-2 mJy) as A. Two possibilities come to mind: (1) B really is dim, but the interaction of the two winds provides conditions for "giant pulses" to be seen at certain points in its orbit, or (2) B really is bright but the interaction of the two winds interfere with with it being seen. The later has been a point of theoretical contention for some time. Isolated pulsars send out both winds (presumably) and radio signals, but if the winds are as relativistic as we tend to think, the radio signals have very little time to interact with the wind plasma while it expands into space. Pulsar A, having the stronger field, could interfere with the wind acceleration by B and enhance the interaction of B's waves with its own wind. At the moment these are empty speculations, but I think suggest possibilities that can be tracked down and might reveal much about pulsar action. However, I must confess that none of the observers I talked to thought this seemingly huge factor of 10^4 to be interesting or worth remarking on (certainly one could make statistical estimates based on known pulsars of similar periods).

4. Concluding Remarks

Someone probably already knows whether or not there is an x-ray nebula in the direction of 0737, but that is a possibility that is open to numerical estimates. The question of fan beams is underscored by the hollow cone interpretation (as kindly explained to me by Don Backer), which at present assumes that the pulsar A is spinning in the orbital plane, so that we are essentially looking down its hollow cone at all times. The pulse pairs are then accounted for by having the cone wobbling slightly so that our line of sight passes inside the cone at the one phase and back outside at the other, with a pulse seen at each crossing. That they appear equally spaced is then an accident. That we see no interpulse emission even though we would be **inside** the emission cone for half the period seems a puzzle, but then the hollow cone model suffers from few if any constraints. Conventionally, interpulses are interpreted as seeing the opposite magnetic pole half a rotation apart, so equal spacing is expected in that model. Since the pulsar spin directions are expected to precess about 5°/yr, it will not take long to see if this model is viable, since it is already so delicately constructed that small angular changes should cause large changes in pulse spacing, etc.. Indeed, Burgay et al. (2003) expressed concern that the pulsar might "disappear" in a few years, a comment I only now could understand. No problem if it's a fan beam (my prediction)! Regretfully I can also predict that nothing will shake the pulsar community loose from its embrace of hollow cones (e.g., if A doesn't disappear, the seeing-the-other-pole model will be dusted off). As an aside here, I invited people at the meeting to think about how an orthogonal pulsar might produce a hollow cone. Not obvious because the electrification would change sign inside such a cone and the accelerating electric field essentially vanishes (Michel 1991, Chap. 5). This is not the specific theoretical problem (Smith et al. 2001; Michel 2004) that makes me suspicious of the model, but it's easily visualized.

I was also surprised by the several talks devoted to flinty-eyed "testing" of general relativity, which lead me to also predict (predictions having been encouraged at this conference) that if any credible deviation from the theory were actually found, the next such meeting would be devoted to *explaining away* such deviations (as magnetospheric effects, etc.), and **not** embracing some ad hoc scalar-tensor variant.

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