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F. A. Rasio and I. H. Stairs

Notes on Informal Theoretical Discussion of PSR J0737−3039

Lars Bildsten

Kavli Institute for Theoretical Physics, Kohn Hall, University of California, Santa Barbara, CA 93106

Abstract. In the hope of eliciting exciting discussions of the new double pulsar binary PSR J0737–3039, we encouraged the speakers in the four-hour (ski-sacrificing) special Wednesday afternoon session to make predictions that can be tested in the near future by the observational community. This document is my attempt to capture the essence of all of the informal presentations. I am sure there are errors in here, but so it goes. Not all participants made a testable prediction. Clear predictions are noted here in **boldface**.

1. Introduction

It is important to keep in mind what was known at the time of the conference, which is the contents of the discovery papers of Burgay et al. (2003) and Lyne et al. (2004), as well as talks given at the conference by Burgay, Kramer, Manchester, and Ransom. Roughly, these were:

- Both pulsars were detected (Pulsar A at 22.7 ms, and the larger $\dot{E}$, and Pulsar B at 2.773 s and much smaller $\dot{E}$) and enough GR parameters determined to measure the two NS masses.
- Both Parkes and GBT had detected a brief, 30-second, eclipse of Pulsar A. GBT data had a mild indication that the depth of the eclipse was frequency dependent (see Kaspi et al. 2004 for an update). Both agree that the ingress eclipse is slower than the egress. GBT finds that the eclipse is total.
- At Parkes Pulsar B is seen most strongly when on our side, whereas GBT shows that we see it all the time except that it experiences a long eclipse by Pulsar A. The pulse profile of B also changes throughout the orbital phase.
- The space motion has been measured, with a large velocity both perpendicular and parallel to the orbit, and all high compared to the local standard of rest.

The session had three components, from binary evolution to magnetospheric physics and then aspects of general relativity.

2. Binary Evolution

Bart Willems spoke on the constraints on the pre-SN binary parameters, finding that the semimajor axis and e requires a most probable isotropic kick velocity of $\sim 150\,\mathrm{km\,s^{-1}}$, but with a distinctive shape that is calculated (Willems & Kalogera 2004). They will be able to predict relative angles between the orbit and the pulsar spins. **Steinn Sigurdsson predicts that the observed space velocity from scintillation rules out that the kick was large enough to allow the young NS to go retrograde. Therefore all of the angular momentum vectors must be in the same hemisphere.**

Duncan Lorimer spoke about how to use the observed spin-down of both pulsars to predict how long ago accretion/recycling was truncated by the supernovae explosion that made Pulsar B. Under the assumptions of: (1) constant braking index between 1.4 and 3, (2) the initial spin of Pulsar B was much shorter than the present spin, and (3) assuming both pulsars have the same timing age, he calculated the probability density functions for Pulsar A's initial spin and the age. The peak was around 18 ms, whereas the current spin is 22.7 ms, and the age distribution was from 50 to 200 Myr. No clear testable prediction.

Ed van den Heuvel started by noting that there was a prior prediction (a few decades ago) that IF a double NS would be found, that one of them must be a non-recycled pulsar, as found. He notes that if $B = 10^{10}$ Gauss, then to get down to 20 ms, the NS must accrete at least $10^{-3} M_\odot$. Assuming an Eddington-limited accretion rate for pure helium (from the He star) and acting at the spin equilibrium set by the magnetic field, then allows for the calculation of this accreted mass (see Dewi & van den Heuvel 2004). Consensus is that the pre-SN companion was a Helium star, like Cygnus X-3, and to accrete this much mass takes 30,000 years of disk accretion, most likely via Roche-lobe overflow. This accretion was truncated by the SN event of the He star that formed Pulsar B. He then noted that fields appear to only die due to accretion and quoted the empirical formula of Shibazaki et al. 1989 of $B(t) = B_o/(1 + \Delta M/10^{-5} M_\odot)$, so that using the implied accreted mass then brings it down to around the observed value from an initial 10^{12} Gauss.

Roger Romani predicts that the finite lifetime of the He star during RL overflow combined with the constraint that the accretion is below the Eddington rate limits the accreted mass to $10^{-2} M_\odot$, so that a Galactic disk recycled pulsar in a DNS will never be found with a spin period shorter than 10 ms.

Matthew Bailes addressed a question asked earlier: "Why do so many observed DNS have small e?" For 0737, he notes that if it was born with $e = 0.617$, then its coalescence time would have been shorter by a factor of ten and the probability of discovery much lower. **Bailes's prediction is that there is a strong selection effect for low e's, so in this case the observer is predicting that when the theorists plot up the eccentricity distribution for observed DNS's it will be peaked towards low values.** Steinn Sigurdsson appeared to have found a paper showing just this via a a real time archival search.

Fernando Camilo notes that 50 Myr at 100 km/s is a movement of 5 kpc, so that the orbit in the Galaxy needs to be calculated so as to better understand its location of origin as well as overall kick velocity.

3. Pulsar Magnetospheres

Alice Harding overviewed the multiple emission models, polar cap, outer gap and slot gap caustic models. All of these models can construct radio and/or high energy light curves in agreement with observations of generic pulsars. She highlighted a new model (Dyks & Rudak 2003) of two pole caustics that has particles radiating along the last open field lines. Its apparent difference with the outer gap model is that it does not require emission from near the light cylinder? Noting that the location of emission (relative to the light cylinder) depends on each model, the eclipsing of the magnetosphere should differentiate these models. She also outlined the nature of the high energy emission from Pulsar A: curvature radiation from primary electrons peaking at a few Gev and synchrotron radiation from pairs peaking around 1–10 MeV. **Pulsar A should be seen in X-rays, but not Pulsar B. Roger Romani predicted that Pulsar A will produce a few $\mathbf{10^{-13}}$ $\mathbf{erg\,cm^{-2}\,s^{-1}}$ in the XMM band.** (The binary was subsequently detected by *Chandra* at $F(0.2-10\,\mathrm{keV}) \approx 7\times10^{-14}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ (McLaughlin et al. 2004), but the origin of the X-rays within the binary remain unclear.)

Don Backer presented a toolkit helpful to understanding the geometry as well as interactions with the assumed equatorially dominated wind, these tend to give many perturbations **twice** per orbit.

Andrea Possenti predicts that as the pericenter rotates in the sky due to the $\dot{\omega}$ the bright pulsing phase of Pulsar B will remain at the same phase relative to us.

Curt Michel reminded us of his previous criticisms of the hollow cone model, and admitted that despite these criticisms, the community appears even more confident today about this model. It is indeed possible that Pulsar A is emitting in a fan beam. He directed the audience to his article (Michel & Li 1999) on the electrodynamics of rotating NSs. **His first prediction is that if anyone finds a credible deviation from GR then it would be blamed on the magnetospheric physics, not on GR.** His claim is that both pulsars are equally pumping their accelerated particles, and that half way through there is some interference. **It is very likely that there is an intense radiation region where the particles are accelerated and that the acceleration is parallel to the orbital plane and that the amount of energy dissipated there is $1/4\pi$ of Pulsar A's wind.**

Fredrick Jenet discussed a "Hare-brained Scheme ..." for the pulse intensity variations of Pulsar B. Under the assumption that Pulsar A is a hollow cone with $\beta < 5$ degrees from the polarization observations (Demorest et al. 2004), he conjectures that the intensity of the B pulsar increases when the hollow cone beam of the A pulsar is illuminating it, which will happen twice per orbit. **Assuming a 90 degree orbital inclination, then "by eye" he found that he could get the right pulse profile when the angle between the spin of**

A and orbital angular momentum vector is 28 degrees and 18 degrees is the angle between the observer's line of sight and Pulsar A's spin. So this gives the orientation of the spin axis for Pulsar A relative to the orbit. But, the A pulsar's spin axis is undergoing geodetic precession, so the orbital locations of the high emission phases from B will change with time. The beam from the other pole of A might also begin to have an influence at some later date. Observers noted that this effect had not been seen yet, but it was clear at the time of presentation that the idea was not yet ruled out.

Don Backer noted that a similar effect (rotating orbital phase for B flux modulation as a result of precession) is inherent in the Berkeley model (see Arons discussion below). That is, IF the B flux modulation is the result of both (a) the variable A wind pressure on the B magnetosphere and therefore its polar cap around the orbit, and (b) the variable response of B's magnetosphere to a constant pressure as a function of spin which aliases to orbital phase, then with precession we would expect the B flux modulation to (first order) rotate around in orbital phase. We are also proposing to confirm the hollow cone model for A (small alpha, large beta in our jargon) by looking for predictable effects of precession.

Brad Hansen noted that there were three previous papers on magnetospheric interactions between merging NSs (Lipunov & Panchenko 1996; Vietri 1996; Hansen & Lyutikov 2001), a scant literature, but maybe worth noting. Applying these ideas to this binary, one finds that the magnetic field of B overwhelms that of A at the surface of A and only when their separation is 60 km, so not relevant today! What about fallback disks? If present, it would be squeezed by the binary. No predictions.

Jon Arons talked about A's wind colliding with B's Magnetosphere (work done with A. Spitkovksy and D. Backer). In the zeroth-order sense Pulsar A's wind is modified by B and that is much of the story. **Given that the opacity behind of all the eclipses is frequency dependent, the A eclipse should clear at high frequency—in the toy model shown here, perhaps above 10 Ghz.** Arons started by presenting the wind properties of A in the simplest MHD version. He noted that the B pulsar's presence at about 100 light cylinder radii will provide a new probe of the pulsar wind. Pulsar B crosses A's neutral current sheet twice each orbit, giving special phases in response of B to A (ala Jenet)? Wind pressure from A acting on B will confine the B's magnetosphere within the light cylinder. Arons showed PIC simulations of the interaction, which look much like the interaction of the Earth's magnetosphere with the solar wind. He noted that the standard torque does not apply for B given the lack of the light cylinder. Looking instead to the drag on B by the passing wind of A gives the same magnetic field for B as the simple dipole spindown, rather by chance, so we are not too far off using standard spin-down formula.

The shock between A's pulsar wind and B's magnetosphere is relativistic and the piling up of material at the shock is likely responsible for the eclipses of A and B at their respective inferior conjunctions. The shock heated pairs provide the optical depth to the radio via synchrotron absorption.

The short eclipse of A implies the LOS traverses the magnetosheath near the upper edge. B's magnetosphere itself (contained within the magnetosheath) may contribute extra optical depth from cyclotron scattering; that depends precisely on how far the bow shock stands off from the magnetopause. **The eclipse will only clear near 10 GHz**; it is sharp because the opacity profile has a sharp edge at the shock (modulo some turbulent broadening). B is seen mostly when looking up the tail; all other LOS must go through the magnetosheath.

4. Gravitational Physics

Sam Finn highlighted the remarkable value of this binary for LISA. It will be at a strain of $h \approx 5 \times 10^{-21}$ at $f = 2.3 \times 10^{-4}$ Hz, with an ephemeris completely determined by radio observations. LISA's strain sensitivity in a one-year integration is 4×10^{-22}, so 0737 is an amplitude SNR=10 LISA calibration source. The LISA observation will measure the distance to the source at ten percent within one year. The high inclination and short period will give light bending in the Shapiro time delay of order $0.1\,\mu$s. What about second-order effects in the Shapiro peak at inferior conjunction? Michael Kramer commented that the light bending effect is a tough measurement but will give the geometry of the system in another way. A discussion ensued regarding the ability to eventually measure the spin-orbit coupling that would allow for a measurement of the NS moment of inertia, thus eventually constraining the NS equation of state.

Cole Miller also commented on 0737 as a LISA calibration source. There will be about 10,000 double WDs in the same frequency bin, so the noise will be well known at that frequency (so we are lucky). Steinn Sigurdsson noted that the higher incidence of DNS triggered by the discovery of 0737 (see Kalogera et al. 2004) implies that population synthesis predicts about 1000–10,000 galactic DNS in the LISA band. 99.5 percent of these are in the double white dwarf (DWD) confusion region and will change the noise characteristics from the large N DWD distribution. There are between 3 and 30 at frequencies higher than the DWD confusion band and they will be bright LISA sources with signal to noise of 100–500 in one year integration.

5. Conclusion

In an attempt to ensure the accuracy of the **predictions**, this document was circulated amongst the participants prior to release. I thank all of the participants for their cooperation and willingness to have their initial thoughts recorded.

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