Eclipse Study of the Double Pulsar

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Abstract

The double pulsar system PSR J0737-3039 offers an unprecedented opportunity for studying general relativity and neutron-star magnetospheres. This system has a favourable orbital inclination such that the millisecond pulsar, A, is eclipsed when its more slowly spinning companion, B, passes in front. High time resolution light curves of the eclipses reveal periodic modulations of A's radio flux corresponding to the fundamental and the first harmonic of pulsar B's spin frequency. Eclipse modelling is highly sensitive to the geometrical configuration of the system and thus provides a unique probe for parameters like the inclination of pulsar B's spin axis as well as their time evolution due to relativistic effects. We report on detailed fitting of pulsar A's eclipse light curves to a model that includes a simple dipolar magnetic field for pulsar B. We find that the eclipses can be reproduced very well, and we obtain precise measurements of pulsar B's orientation in space. We also report on a search for secular changes caused by geodetic precession of pulsar B's spin axis.

Introduction

PSR J0737-3039 is the only pulsar-pulsar system that has been discovered so far. Luckily, this very tight 2.4-hour system is seen almost perfectly edge-on. This results in eclipses of the 23 ms pulsar called "A" when its 2.8 s companion, "B", passes in front.

The physical size of the eclipse region is about 30000 km. This is much smaller than the light cylinder radius of pulsar B which is 130000 km. Such a situation is indicative of a strong interaction between the relativistic wind of A and the magnetosphere of B.

Kaspi et al. (2004, ApJ, 613, L137) observed only a weak radio frequency dependence in the eclipse duration which led Lyutikov & Thompson (2005, ApJ, 634, 1223) to propose that the eclipses are caused by synchrotron absorption of plasma heated by A's wind and trapped in B's magnetosphere.

McLaughlin et al. (2004, ApJ, 616, L131) found, using high resolution 820 MHz data, that A's pulsed flux intensity is modulated according to B's spin phase during the eclipse (Fig. 2).

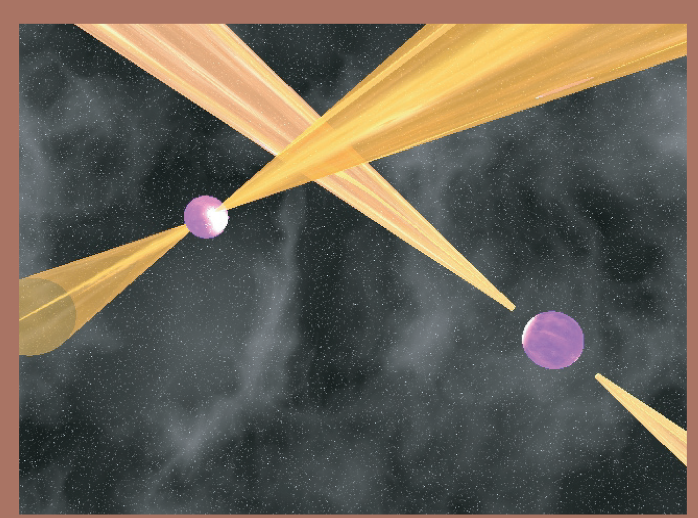

Figure 1. Artist's conception of the double pulsar system PSR J0737-3039 (Credit: Michael Kramer)

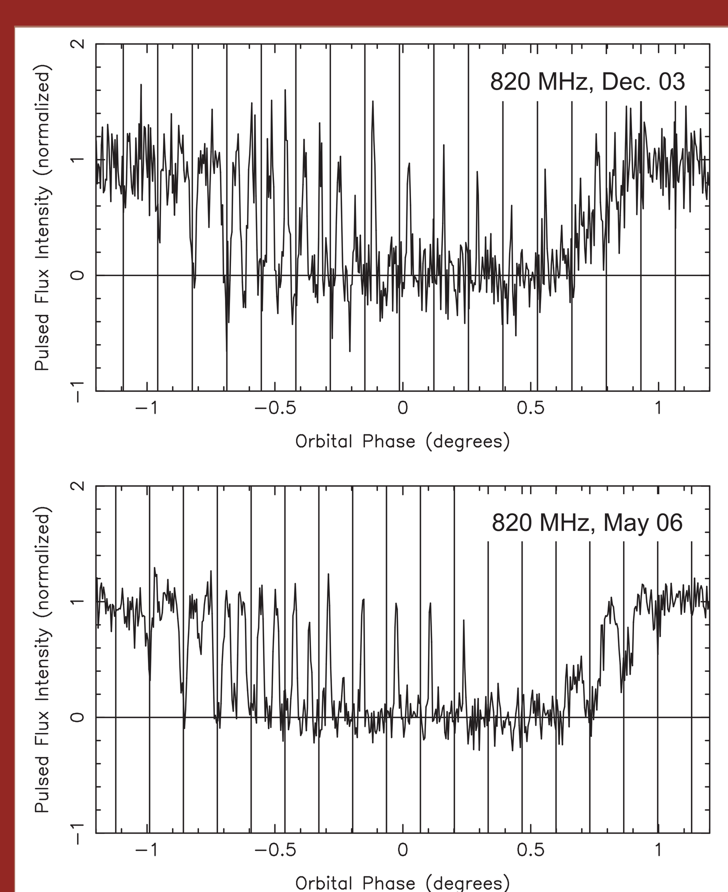

Figure 2. Eclipse light curves of pulsar A at 820 MHz (Dec. 03 and May 06). Three and eleven single eclipses have been averaged, respectively, to produce the profiles. Vertical lines are the times of arrival of B pulses.

Observations

Data were obtained with the SPIGOT instrument on the Robert C. Byrd Telescope at Green Bank with the receiver operating at center frequencies of 325, 427, 820 and 1950 MHz. Typical observations were long enough to cover between one and three consecutive eclipses of A.

We processed the data using the SIGPROC and PRESTO packages and folded according to our timing solution for A. Then, we generated pulsed flux time series by matching a high signal-to-noise ratio template to pulse profiles which are an average of four single pulses of A. For each data point in the time series, we determined the orbital phase and corresponding pulse phase of B.

Results: Mapping the Eclipses

Since the modulations are correlated with B's spin period, we can fold A's eclipse light curves at the period of pulsar B in order to investigate the interconnection between the eclipse evolution and B's spin phase.

Figure 3 shows that modulations also exist at 325, 427 and 1950 MHz and are similar to those at 820 MHz. There are two windows of "transparency" centered at spin phase 0.25 and 0.75 (i.e. when B's magnetic pole is perpendicular to our line of sight). In the first window, there is almost no eclipse at all.

This method of folding maps out the three-dimensional structure of the magnetosphere in the plane intersected by our line of sight.

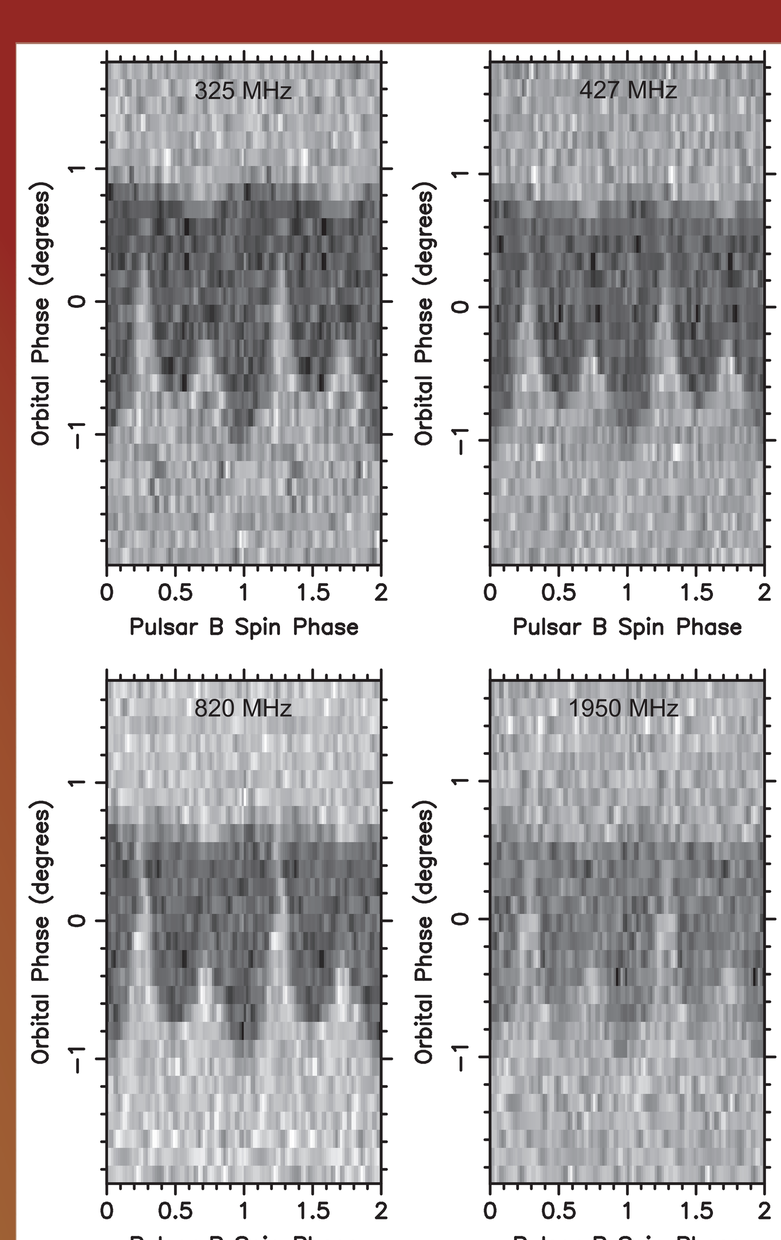

Figure 3. Eclipse light curves of pulsar A folded at the spin period of pulsar B. Each panel is the average of two or three consecutive eclipses at a given frequency (325, 427, 820 and 1950 MHz). Darker grey colour corresponds to lower pulsed flux intensity.

Results: Eclipse Modeling

Eclipse modeling is highly sensitive to the geometrical configuration of the system. We follow the prescription of Lyutikov & Thompson (2005) and assume that, for pulsar B, absorbing plasma fills the closed field lines of a simple dipolar magnetic field.

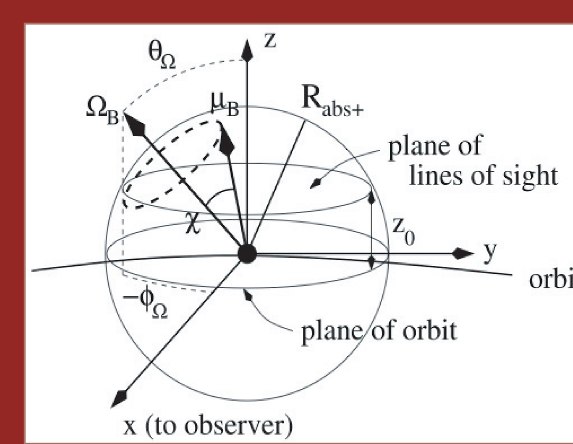

Figure 4. Schematic view of the geometrical parameters used in the eclipse model. Pulsar B is at the center of the coordinate system. (From Lyutikov & Thompson 2005)

Our eclipse model has 6 free parameters, all related to the geometry of the system. R_{min} and R_{max} define the inner and outer radius where the plasma absorbs efficiently. Z_0 is the impact parameter (i.e. projected separation between A and B at conjunction), which is related to the orbital inclination angle, i. θ, ϕ, and χ define the spatial orientation of the spin and magnetic axes.

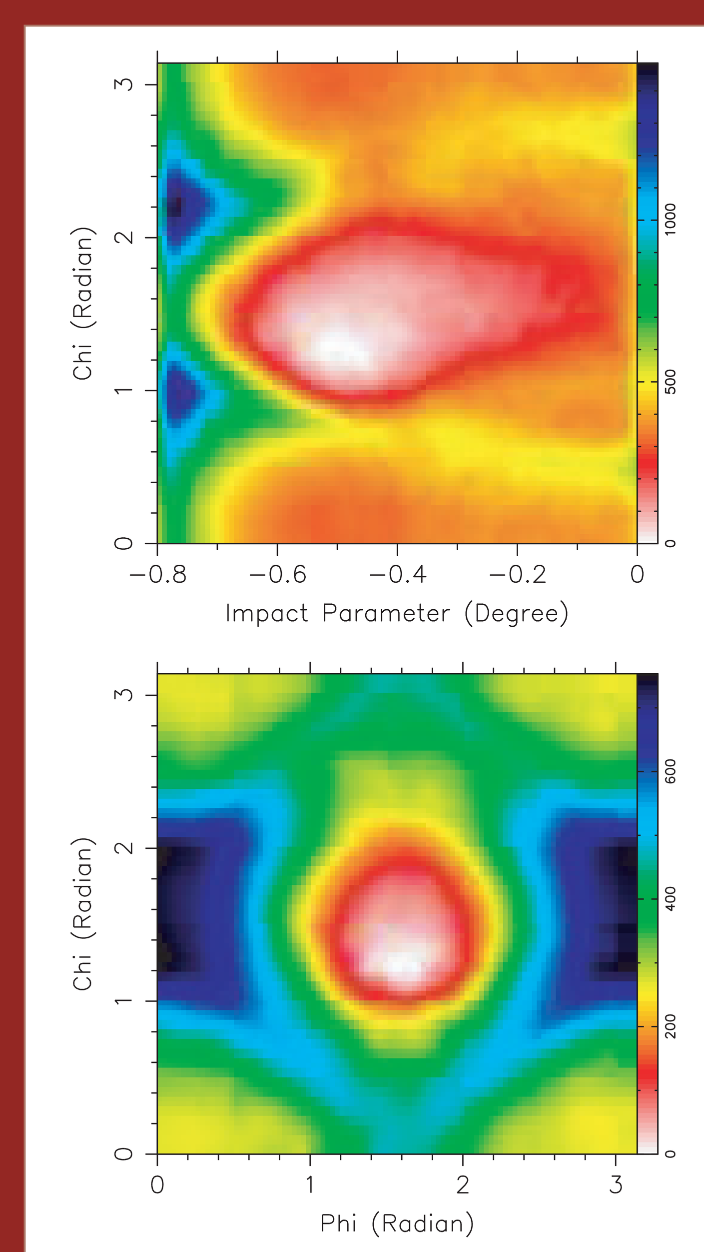

Figure 5. Different views of the likelihood space obtained from our model fitting of December 2003, 820 MHz data. The color scale corresponds to $\Delta\chi^2_{min}$ = -2ln($\mathcal{L}$) and hence, after marginalization, the 1σ error on a given best-fit parameter would correspond to $\Delta\chi^2_{min}$ = 1.

We search the entire parameter space for best-fit solutions using a combination of simulated annealing and Markov Chain Monte Carlo (Fig. 5&6).

The geometrical configuration of the system is uniquely determined but doubly degenerate; switching B's spin vector from prograde to retrograde rotation leads to nearly identical results:

$\langle\theta\rangle = 129^o \pm 2^o$
$\langle\chi\rangle = 63^o \pm 2^o$
$\langle\phi\rangle^* = 95^o \pm 2^o$
$\langle i\rangle^{*\dagger} = 89.50^o \pm 0.05^o$

Preliminary results

(* should not be constant in time and thus the quoted error is underestimated)
(† scintillation measurements give 89.71º ± 0.14º (Coles et al., 2005, ApJ, 623, 392), timing measurements give $88.69^o\,^{+0.50^o}_{-0.76^o}$ (Kramer et al., Science submitted))

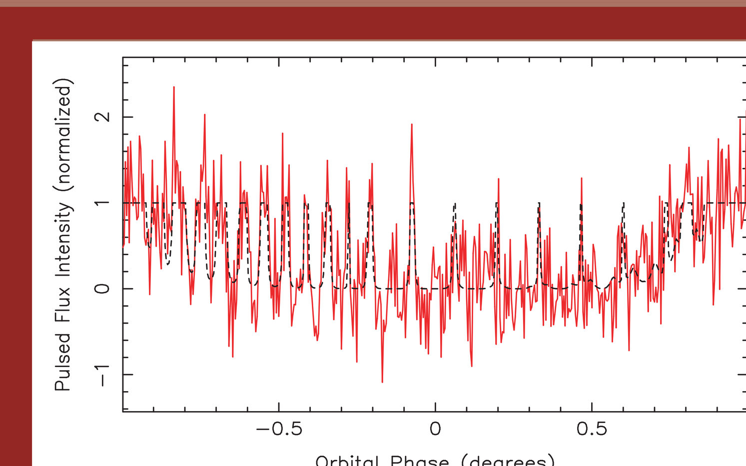

Figure 6. Best-fit eclipse model (dashed black line) for an 820 MHz eclipse observed in December 2003 (plain red line).

Future Perspectives: Testing GR

General relativistic effects change the geometry of the system on relatively short time scales (advance of periastron: ~17º/yr, predicted geodetic precession period of B: 71 years). With data spanning over 30 months, we noticed changes in the eclipse profile (Fig. 2). We are currently searching for evidence of secular evolution of geometrical parameters due to general relativity (Fig. 7). However, our actual results are not consistent with prediction of geodetic precession...

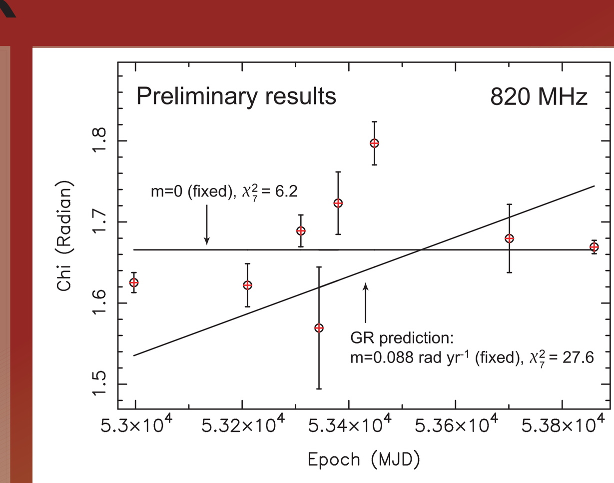

Figure 7. Best-fit ϕ value as a function of time (from 820 MHz data). ϕ defines the longitudinal direction of B's spin axis projected onto the orbital plane and should change at a constant rate due to geodetic precession of B which is predicted to have a period of 71 years.

Conclusions

A's pulsed flux modulation exists at all radio frequencies where eclipses are observable.

On the physical scale of the eclipsing region, a simple dipolar magnetic field successfully accounts for most of the features seen in the eclipse light curves.

Using the Lyutikov & Thompson eclipse model, we found a unique solution set of geometrical parameters, which are doubly degenerate because of the unknown direction of B's spin rotation.

More timing baseline might be required to get a significant measurement of the geodetic period of pulsar B, but stringent constraints already exist on the system geometry.