

## Scintillation Arcs and Binary Pulsars with an Application to PSR J0737–3039

Daniel R. Stinebring, Alex S. Hill

*Oberlin College, Dept. of Physics and Astronomy Oberlin, OH 44074*

Scott M. Ransom

*McGill University, Physics Department Montreal, QC H3A 2T8, Canada*

**Abstract.** Scintillation observations can provide useful information about binary pulsar orbits. In some cases the information is not available otherwise; in other cases it allows standard orbital analyses to be carried further in testing General Relativity and other aspects of the binary system. We report on the first use of scintillation arcs to determine information about a binary system. We analyzed phase-resolved data for the double pulsar system PSR J0737–3039 using the data obtained and analyzed by Ransom et al. (2004; R04). Scintillation arcs were seen in each of the 20 min time slices analyzed. Arc curvature values were determined and used to estimate the scintillation speed as a function of orbital phase. The results were consistent with—but less precise than—the traditional scintillation analysis applied by R04. For this system and observing frequency, a scintillation arc analysis is inferior to the traditional approach, primarily because the scintillation arcs are not sharply defined.

### 1. Introduction

Multi-path scattering in the interstellar medium produces a variety of observable scintillation phenomena when the source is spatially compact, as is the case for pulsars. The average time delay  $\tau$  of a deflected ray causes a coherence (or diffractive) bandwidth  $\Delta\nu_d \approx 1/2\pi\tau$ . Relative source, medium, and observer motion translates an intensity interference pattern past the observer with a coherence timescale  $\Delta t_d \approx s_d/V_{\text{eff}}$ , where  $s_d$  is the characteristic width of interference maxima at the observer plane and  $V_{\text{eff}}$  is the appropriately weighted velocity (Cordes and Rickett 1998).

The diffractive bandwidth  $\Delta\nu_d$  is determined by the screen and the observing frequency, but  $\Delta t_d$  also depends on velocity. Since it is affected by the relative (transverse) motions of the pulsar, the scattering material, and the Earth, binary pulsars will produce modulation of  $\Delta t_d$  that can be used to gain additional information about the binary system. This was recognized and exploited by Lyne et al. (1984) in a pioneering study and, more recently with high precision, in the relativistic binary J1141–6545 (Ord, Bailes, and van Straten 2002).

In recent years a new scintillation phenomenon (*scintillation arcs*) has been identified in the secondary spectrum of pulsars (Stinebring et al. 2001; Hill et al. 2003). The secondary spectrum, which is the power spectrum of the time-vs-frequency radio spectrum of the source, has information about interference between the bright central core of the image and fainter halo emission. Stinebring et al. (2001) showed that this gives rise to a parabolic arc in conjugate time ( $f_t$ ) and conjugate frequency ( $f_\nu$ ):  $f_\nu = \eta f_t^2$ , where

$$\eta = \frac{D}{2c} \frac{\lambda^2}{V_{\text{eff}}^2} s(1-s), \quad (1)$$

and  $s$  is the fractional distance from the pulsar ( $s = 0$ ) to the scattering screen ( $s = 1$ ), with the pulsar at a distance  $D$  from the observer. The effective velocity (Cordes and Rickett 1998) is a weighted sum of the pulsar, observer, and screen velocities (2d on the sky):

$$\mathbf{V}_{\text{eff}} = (1-s)\mathbf{V}_p + s\mathbf{V}_{\text{obs}} - \mathbf{V}_{\text{scr}}. \quad (2)$$

For pulsars for which a distance and a proper motion are known, equation (2) can be used to find  $s$ , as is shown for a nearby pulsar with a sharply defined scintillation arc in Figure 1. Under optimal circumstances, then, the scintillation arc method provides high precision and additional information about the scattering screen geometry. Similar information is available with the standard ( $\Delta t_d$ ,  $\Delta \nu_d$ ) technique, but there is less information about the distribution of scattering material in those two numbers than in the power distribution of the scintillation arc.

The exciting double pulsar PSR J0737–3039 (Burgay et al. 2003 and numerous contributions to these Proceedings) provides a unique testing ground for gravitation theory and other aspects of binary pulsar science. R04 have already performed a standard orbital scintillation analysis of this pulsar. They found a substantial velocity component perpendicular to the line of nodes of the pulsar’s nearly edge-on orbit and concluded that the system was given a substantial birth kick of  $\gtrsim 100 \text{ km s}^{-1}$  by the second supernova.

We applied a scintillation arc analysis to the 820 MHz dataset analyzed in R04. The 5 hour dataset was split into time slices of 20 min. A secondary spectrum was produced for each time slice, and a scintillation arc was fit by eye to the resultant spectrum (see Fig. 2). We then used equations (1) and (2) to solve for the pulsar transverse speed,  $V_p$ , as shown in Figure 3. We did not determine errors for the  $V_p$  values because the results do not appear to warrant a more detailed analysis. The unknown scaling factor related to the distribution of scattering material along the line of sight ( $s$  here) needs to be determined empirically. We simply scaled our resulting  $V_p$  curve so that the minimum four points in Figure 3 had a mean of 100 km/s, which provides an adequate comparison with the shape and maxima of the corresponding plot in Figure 2 of R04.

A visual comparison between our results and those of R04 show that they are consistent with each other. Both curves are double-peaked with maxima around 200 km/s and 400 km/s and a separation in orbital phase of around 0.6.

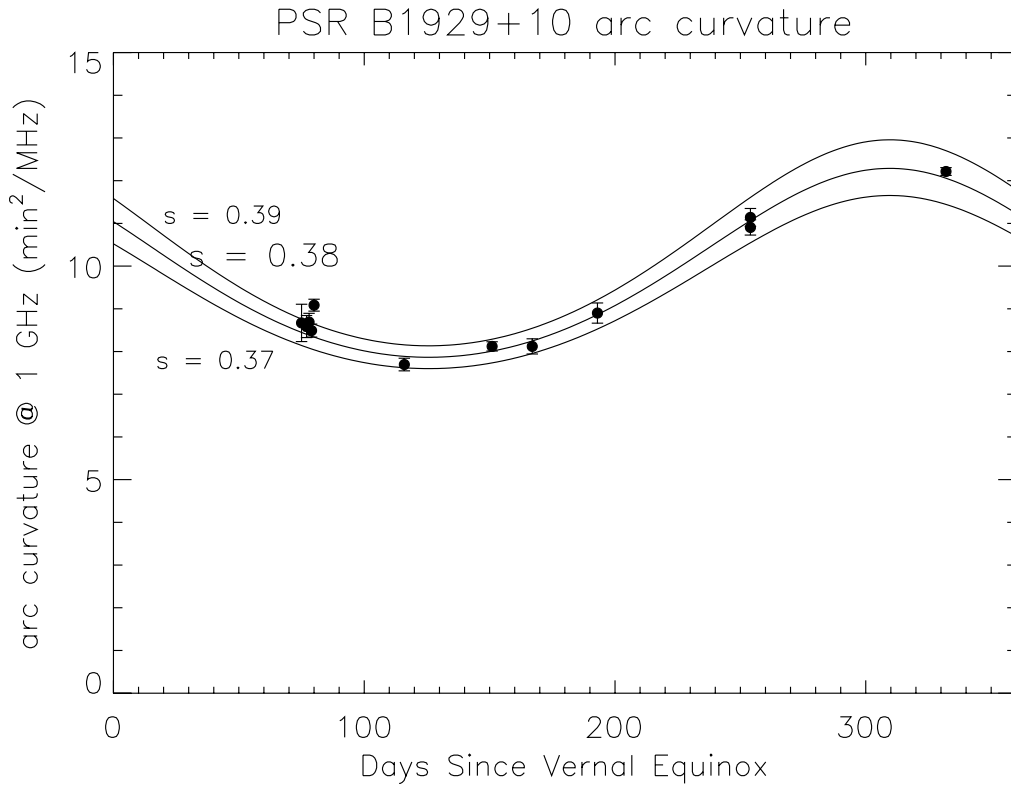


Figure 1. Scintillation arc curvature ( $\eta$  in the text) for the solitary pulsar PSR B1929+10 as a function of time of year. The variation is caused by the Earth's motion around the Sun. The best fit fractional screen location ( $s = 0.38$ ) is shown as well as the sensitive dependence on screen location.

All the parameters relating to orbital motion are much better determined in R04 than here. The relative insensitivity of a scintillation arc analysis to this problem arises from several factors. First, the scintillation arcs for this pulsar (at least at 820 MHz) are blurred out, presumably by considerable depth to the distribution of scattering material along the line of sight. Second, the rapid time development of the scintillation pattern necessitated a short averaging interval. Third, the pulsar speed depends on the arc curvature parameter as  $V_p \propto 1/\sqrt{\eta}$ , which limits the accuracy of the analysis.

In conclusion, this was an interesting exercise, but one that did not yield promising results for future work along these lines. A traditional scintillation analysis is better suited to this particular system and, probably, the determination of scintillation speeds in other binary pulsar systems. A scintillation arc analysis could be competitive only if the arcs were sharply defined for some pulsar–frequency combination and if the orbital period was long enough to allow longer time slices in the calculation of the secondary spectra. Sharper scintillation arcs might be obtained by observing at a higher frequency where the overall scattering is smaller, but this gain would be partially offset by the reduced signal-to-noise ratio of the average profile.

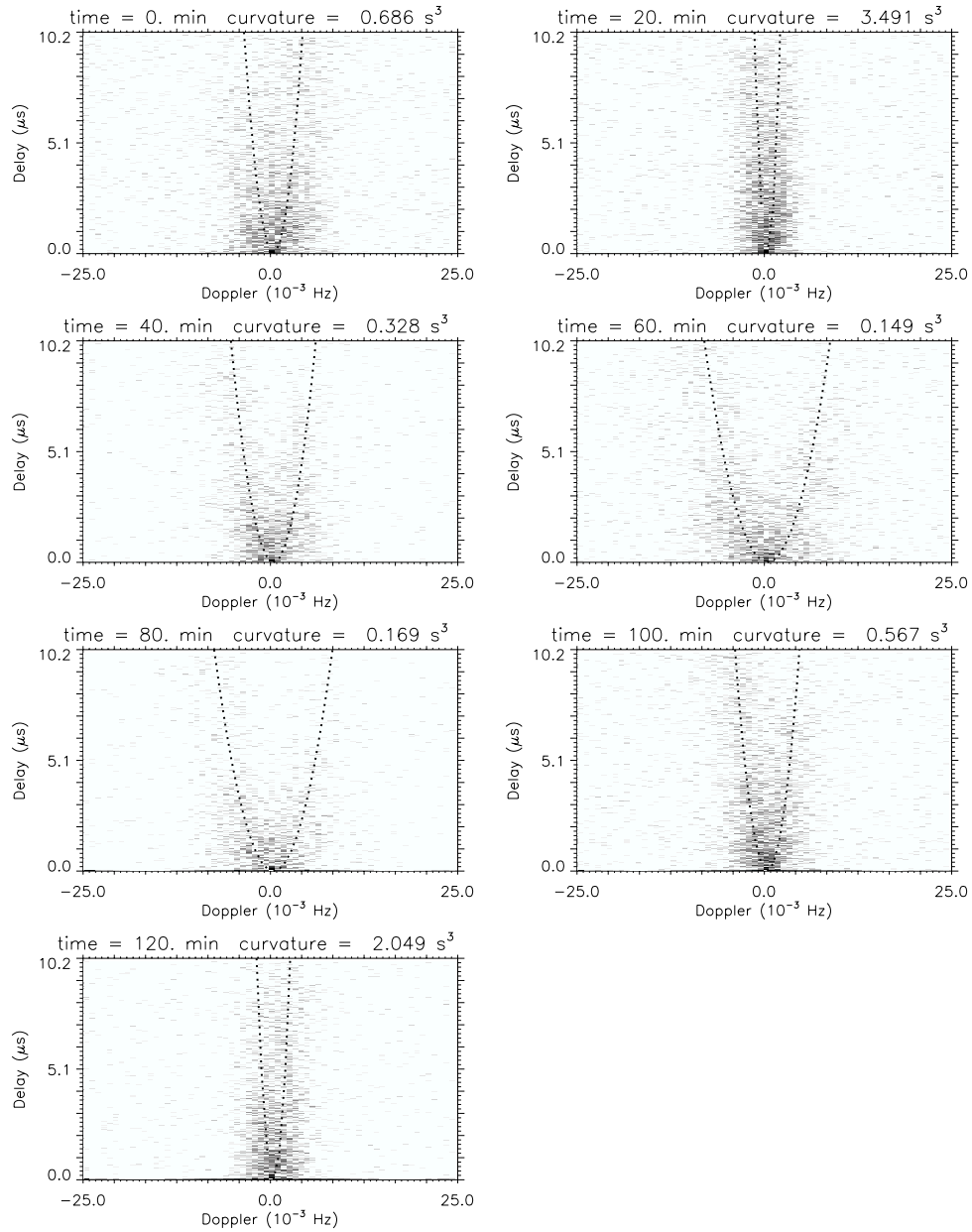


Figure 2. Secondary spectra of PSR J0737–3039 at several orbital phases. These data were taken at 820 MHz by R04 and have been analyzed here in 20 min time slices. A best fit scintillation arc has been superposed in each case.

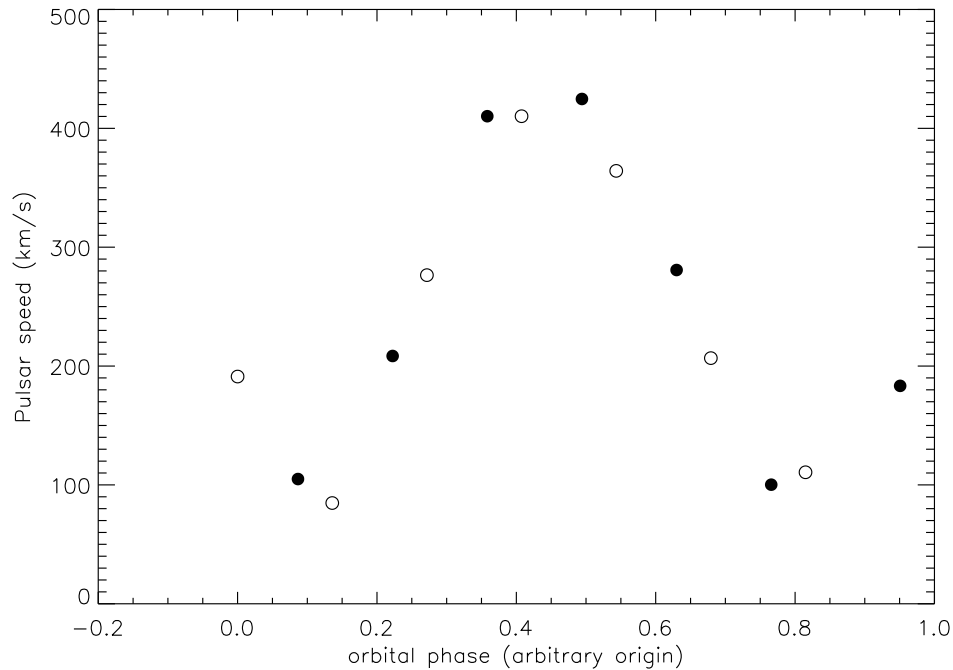


Figure 3. Pulsar transverse speed as a function of binary orbital phase. Data for two consecutive orbits are plotted, the first with open circles and the second with filled circles. The speed values have been multiplied by an empirical factor of 1.9 as discussed in the text. This implies an effective screen location of  $s \approx 0.8$ .

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