Scintillation Arcs: Probing Turbulence and Structure in the ISM

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Abstract Multi-path scattering through inhomogeneities in the interstellar medium causes many related effects. In this review, I concentrate on the phenomenon of scintillation arcs, which are parabolic patterns in the secondary spectrum caused by interference between different angular components of the scatter-broadened image of a pulsar. Scintillation arcs are now fairly well understood. The measured curvature of the arc, together with proper motion and distance information about the pulsar, can be used to determine the location of thin scattering screens along the line of sight to the object. Some recent work of this type is presented. The puzzle of substructure in the power distribution of scintillation arcs is poorly understood, however, and is commented on as an open puzzle. In particular, some inferred physical structures in the ISM are small scale (~1 AU) and over-dense with respect to the background medium. Finally, an application of scintillation arc studies to the correction of high-precision pulsar timing is presented.

Key words: ISM — pulsars: individual (B0355+54, B1133+16, B1642-03, B1737+13, B1933+16) — pulsars: general — scattering

1 BACKGROUND

The study of scintillation in the interplanetary medium gave rise to the serendipitous discovery of pulsars (Hewish et al. 1968), and the following 38 years have yielded many new insights into the interstellar medium (ISM) through scintillation and dispersion measure (DM) studies of these same objects. The small angular size of pulsars makes them the only objects that routinely scintillate due to inhomogeneities in the ISM, and the ability to accurately measure the column density of electrons (DM) along the line of sight is invaluable for modeling the electron component of the Galaxy. This is a companion review to that provided by Rickett (2006; hereafter R06). There, he sets out most of the relevant physics and discusses a broad range of scintillation phenomena. He concentrates, in particular, on the temporal broadening of the pulsar signal by scattering and on the effect that anisotropic scattering has on various scintillation observables. In this contribution, I will concentrate on the remarkable information contained in the secondary spectrum, $S_2(f_t, f_\nu)$, which is the 2-d Fourier power spectrum of the main scintillation observable, the dynamic spectrum $\Delta I(t, \nu)$ (see R06, fig. 4).

Scintillation arcs are parabolic loci of power in the $S_2$ plane, $f_\nu = af_t^2$, using the R06 notation. In their sharpest form they represent interference between the brightest central “core” of the scatter-broadened image on the sky and a weaker “halo” of scattered light that can extend out to 10–20 times the angular width of the core. More generally, the power distribution in the $S_2$ plane provides information about the full scatter-broadened image as it illuminates and scans (because of large pulsar transverse velocities) the inhomogeneous ISM. I will argue that it is this scanning power that may, in the end, prove to be the most useful feature of scintillation arc studies.

Scintillation arcs were discovered serendipitously in high dynamic range observations with the newly upgraded Arecibo telescope (Stinebring et al. 2001). Since then, their study has progressed on both the observational front (Hill et al. 2003, H03; Hill et al. 2005, H05) and the theoretical front (Walker et al. 2004,
Observationally, some key features are: 1) arcs appear along almost all lines of sight (more than 25 now) that can be probed with high sensitivity, 2) they often have a sharp outer boundary with minimum tilt or offset of the parabola from the origin, 3) the curvature parameter, $a$, accurately scales with observing frequency as $a \propto \nu^{-2}$ (H03), 4) substructure or patchiness is frequently observed along the arc and translates along the main parabola (over days to weeks) in a systematic fashion at the same angular rate as the pulsar’s proper motion (H05), 5) the substructure often shows pronounced inverted arclets (or subarcs) that have the same (absolute value of) curvature as the main parabola, and 6) multiple main arcs are present along many lines of sight (Putney & Stinebring 2006), and the value of curvature parameter, $a$, remains constant for each arc over decades of time.

2 OBSERVATIONAL SUCCESSES

The main theoretical studies of scintillation arcs (W04; C06) have succeeded in explaining some basic features of scintillation arcs: their cause in a two-component brightness distribution, $B(\theta)$; the edge-brightening toward the boundary of the parabola; the frequency dependence of their curvature; and the constancy of that curvature over time. These overall features are telling us about the distribution of scattering material along the line of sight. In general studies of the ISM, it is of great interest to determine how much of the scattering material is distributed fairly evenly along the line of sight (los) and how much is concentrated in sheets, bubbles, or filaments that are intercepted by the los.

2.1 Determining Screen Locations

Since many scintillation arcs have sharp boundaries (see Fig. 1, panels $b$ and $c$), it is reasonable to use a thin-screen model as a starting point for the distribution of scattering material. The curvature of a scintillation arc for a thin screen is given by

$$a = \frac{s}{(1-s) \frac{\lambda^2}{2c\mu^2D}}, \tag{1}$$

where $\lambda$ is the observing wavelength, $\mu$ is the proper motion, $D$ is the distance from the pulsar to the observer, and $s$ is the location of the scattering screen along the los, with the convention that $s = 0$ for a screen at the pulsar and $s = 1$ for a screen at the observer. This expression assumes that the velocity of the pulsar dominates the relative transverse velocity (see H05 for adjustments if this is not the case). Although no systematic study of the distribution of scattering material — and its effects on the sharpness of scintillation arcs — has been done, a heuristic argument indicates that much of the scattering must be confined to physical thin screens. Since the arc curvature depends on screen placement according to Equation (1), a range of screen locations will lead to a blurring of the arc boundary. In many cases the sharpness of a particular scintillation arc limits the range of $s$ to less than a few percent of the los distance. A more systematic and quantitative study of this effect is needed, but we will adopt the approximation that most of the scattering probed by scintillation arcs is localized in physical screens.

2.2 Multiple Scattering Screens

In fact, Putney & Stinebring (2006, in this volume), show examples along six sight lines in which multiple scattering screens are present (see Fig. 2). This is work in progress, and it will be augmented by the analysis of other pulsars for which we have detected multiple arcs, but it leads to a picture in which the scattering material is sporadic along the line of sight and is, perhaps, linked to large-scale bubbles and sheets in the ISM.

2.3 Constancy of Screen Locations

The physical reality of discrete scattering screens is reinforced by the constancy over time of the arc curvature (hence screen location). Using archival data obtained by J. M. Cordes and observations that we have obtained since 1999 (all at the Arecibo Observatory), we can plot the curvature of multiple scintillation arcs as a function of observing epoch (Fig. 3). These data show the continuity of four scintillation arcs over more than 20 years of observation. For a given arc, if we interpret the scatter about the mean arc curvature as an upper bound on the arc thickness, the four arcs have fractional thicknesses of between 1%–4% of the distance along the los. The combination of arc curvature constancy over decades and screen localization along the los are powerful arguments for the physical reality of these scattering screens.
Fig. 1 PSR B 1133+16 observed at three epochs and two different frequencies. The top row shows the dynamic spectrum using a grayscale linear in flux density. The bottom row is the secondary spectrum displayed using a logarithmic grayscale to show faint power features (the faintest plotted features are, respectively, 52 dB, 64 dB, and 77 dB below the peak power). Notice the marked difference in dynamic and secondary spectra between panel a and b, separated by about 1.9 years, with panel a showing inverted arclets on the left hand side of the main parabola. Panel c shows at least two distinct parabolas, and close inspection shows all four that have been detected for this pulsar (see Fig. 3 and the discussion accompanying it). The obvious outer parabola is arc 2 and the inner parabola is arc 4 in the labeling of Figure 3. The main parabolas in panels a and b are arc 2.

3 AN OBSERVATIONAL PUZZLE

Despite overall success in the interpretation of scintillation arcs, there is detailed phenomenology that is not yet well understood. Foremost is the occasional patchiness of power in the $S_2$ plane, as shown in Figure 4. H05 showed that for one pulsar (PSR B 0834+06) this patchiness could be tracked for about 25 days as it translated along the right hand side of the main parabola. The angular offset of the spot on the screen giving rise to a particular patch on the parabola is given by $\theta_x = -s \lambda f_t/[\mu D]$, where $f_t$ is the fringe frequency coordinate of the patch on the $S_2$ plane and the $x$-axis is directed along the velocity vector of the pulsar (assumed to be dominating the motion). To give an idea of the impressive resolving power and field of view represented by a typical observation, the data reported by H05 had an $f_t$ resolution of better than 1 mHz and a range of $\pm 50$ mHz, which corresponded to an angular resolution of 0.5 mas and a range of angle of $\pm 24$ mas. Thus, the single-dish interferometry made possible by the multiple ray paths through the scattering screen yields extremely high resolution and, simultaneously, a large field of view.

As the pulsar’s proper motion — usually quite considerable — carries the los past the scattering screen, a relatively large angular disk is scanned across the scattering screen. If there are regions of anomalously high scattering strength (or lens-like structures of substantial bending power), they will be detected by this
Fig. 2 A projection onto the Galactic plane of sight lines to six pulsars toward which we have detected multiple scintillation arcs. Screen locations are indicated by a short line perpendicular to the sight line and are determined from Equation (1) and known pulsar parameters. This figure also appears in Putney & Stinebring (2006) as figure 3.

Fig. 3 A display of arc curvature values, adjusted to a reference frequency of 1 GHz, for more than 20 years of data for PSR B 1133+16. The data prior to 1990 were provided by J. M. Cordes. The screen locations, calculated using Equation (1) and the known proper motion and distance to this nearby pulsar (D = 0.36 kpc), are shown in the inset in the upper left corner of the plot.

method and will lead to patchiness in the secondary spectrum that translates along the main parabola in the manner detailed by H05.

What is causing the enhancements of scattering or, alternatively, the lens-like steering of a portion of the beam that gives rise to the secondary spectrum patchiness in the first place? We have not yet done a comprehensive analysis of the observations that show this effect, but H05 inferred a scale size of about 1 AU and an electron density of $\sim 200 \text{ cm}^{-3}$ if the patchiness in those data are caused by lens-like structures. Such structures would be strongly over-pressurized with respect to the ambient warm ionized ISM and,
Fig. 4 Three examples of arclets: inverted parabolic patches of power in the secondary spectrum. As in Figure 1, the dynamic spectra (top rows) are linear in power, and the secondary spectra are plotted with a logarithmic grayscale. Data for PSRs B 0355+54 and B 1642–03 were obtained with the NRAO GBT in collaboration with A. Minter and S. Ransom, and PSR B 0834+06 was observed with the NAIC Arecibo telescope. The B 0834+06 arclets translate along the main parabola at the rate of the pulsar proper motion (H05), and the arclets for the other two pulsars behave in a similar fashion, although we have not fully quantified their motion yet.

hence, would dissipate on a thermal time-scale of something like $1 \, \text{AU} / (10 \, \text{km s}^{-1}) \sim 0.5 \, \text{yr}$ unless otherwise confined.

If the preceding picture has physical validity, it will be a challenge to understand how discrete structures (or small-scale stochastic features) can give rise to the observed substructure in secondary spectra over months to years of observation. This is not observed along all lines of sight, but it may be a limited region of observational parameter space that yields a clear view of these small-scale features. In any case, this is a promising area for further observational and theoretical work.

4 APPLICATIONS

The previous section outlined the application of scintillation arc studies to high-resolution probing of the warm ionized ISM on AU-size scales. There is one other area of immediate application of these studies: high-precision pulsar timing. As discussed in several talks at the meeting, pulsar timing is the most powerful method known for detecting a stochastic background of gravitational radiation from massive black hole binaries. Many other important applications of pulsar timing exist, such as the exploration of the neutron star mass spectrum, various other tests of general relativity, and the search for more neutron star-based planetary systems. The accuracy of pulsar timing is hampered, however, by the same multi-path scattering effects that give rise to pulsar scintillation.

This is well known in the pulsar timing community, which has primarily dealt with this problem by moving timing observations to higher observing frequencies where the effects are lessened.
Fig. 5 LEFT: Secondary spectrum (power spectrum of the dynamic spectrum) for PSR B 1737+13 observed at 1400 MHz with the Arecibo telescope on MJD 52636. The patchy scintillation arc power translates left to right along the parabola and changes substantially from month to month. RIGHT: The delay of the signal as determined from the secondary spectrum by the method described in Hemberger & Stinebring (2006) for two pulsars. The data for PSR 1737+13 includes the data in the LEFT panel. The observations of the distant, heavily scattered pulsar PSR 1933+16 show substantial variation from year to year, but are smoothly connected over the closely spaced observations shown in the inset. This is as expected from variations due to refractive scintillation.

We report at this meeting (Hemberger & Stinebring 2006), however, that the same substructure that gives rise to interesting effects in scintillation arc analysis may be causing unrecognized timing noise in high-precision timing programs. We have begun to explore a post-detection scheme for adjusting timing points based on moments of the autocorrelation of the impulse response function. In addition to this approach, Walker and Stinebring (2005) present a method for using the phase of the scintillation arc signal to fully correct for the presence of scattering along the line of sight. It remains to be seen how effectively this technique can be employed in practice.

5 CONCLUSIONS

Although much is now known about scintillation arcs, both observationally and theoretically, many questions remain unanswered. For example, to what extent is the scattering dominated by thin screens, and what implication does that have for the distribution of the material in the warm ionized medium? What are the physical features — stochastic or organized structures — that give rise to the dramatic arclet behavior? In either case, how are they produced, how long do they last, what are their physical parameters, and what is their relation to other SINS (small ionized and neutral structures) in the ISM? Finally, in addition to their use as probes of the ionized ISM, to what extent can scintillation arc analysis be used to correct high-precision timing data for the effects of multi-path scattering? With the help of colleagues, I look forward to making progress on these questions and others that we do not yet know enough to ask.

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References