IPTA Student Week, Socorro

The Effects of the Interstellar Medium on Pulsar Observations: Worksheet

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1 Introduction

We saw in the lecture how the ionised interstellar medium (ISM) affects observations of pulsars, and hence the observed timing behaviour. Here, we will look at some of the important ISM effects on pulsar observations.

Q 1.1 If the effects of the ISM on pulsar observations are inversely proportional to frequency, why don't we just observe all pulsars at the highest possible frequency?

Q 1.2 The dispersion measure can be used to estimate the distance to pulsars. The Crab Pulsar[a] is well-studied, yet the distance is poorly constrained using this technique. Why might this be the case, for this particular pulsar?

Q 1.3 Why are the ISM effects on pulsar observations more difficult to model than e.g. the pulsar spin evolution or the orbital motion?

[a] B1950 name: PSR B0531+21, J2000 name: PSR J0534+2200

2 Dispersion Measure

The dispersion measure (DM) is a quantity that describes the integrated column density of free electrons $n_{\rm e}$ along the line of sight to a pulsar d. It is given by

$$\mathrm{DM} = \int_0^d n_{\rm e}\ \mathrm{d}l\ \mathrm{pc\,cm^{-3}}. \tag{1}$$

The DM allows us to quantify the frequency-dependent delay Δt between signals at different observing frequencies ν as

$$\Delta t = \frac{\mathrm{DM}}{2.41\times10^{-4}}\left(\frac{1}{\nu_{\rm low}^2}-\frac{1}{\nu_{\rm high}^2}\right), \tag{2}$$

where t and ν have units of seconds and MHz, respectively.

Q 2.1 The dispersion measure of PSR J2145−0750 is $8.98\,\mathrm{cm^{-3}\,pc}$. The distance inferred from measurements of the parallax is $0.64^{+0.05}_{-0.04}$ kpc. What is the mean electron density along the line of sight to this pulsar?

Q 2.2 Figure 1 shows pulse profiles from simultaneous observations of the millisecond pulsar B1937+21[a] at 1520 MHz. One of the observations is coherently dedispersed, the other is incoherently dedispersed. Describe why the two pulse profiles look different.

Q 2.3 You are planning a project to map out the long-term DM variations in your favourite pulsar (which is approximately equally bright across a very broad radio bandwidth), using multi-frequency observations. The telescope operated by your institute typically observes at a centre frequency of 1520 MHz. You can choose to partner with one of two institutes:

Institute A, operating a telescope with a 350 MHz receiver.

Institute B, operating a telescope with a 3200 MHz receiver.

Which institute do you think would be the most sensible choice to partner with for this project?

[a] J2000 name: PSR J1939+2134

3 Scattering

Scattering by free electrons in the ISM arises from inhomogeneities in the electron number density along the line of sight, induced by turbulence. Scattering introduces an exponential scattering tail to the pulse profile, with a time scale given by

$$\tau_{\rm sc} = \frac{\theta_0 D'}{2c}, \tag{3}$$

where θ_0 is the root mean square (RMS) scattering angle, c is the speed of light, and D' is the scattered path length. The scattered path length is related to the distance between the scattering screen and the source by

$$D' = \frac{D(D-a)}{a}, \tag{4}$$

where D is the distance from the Earth to the source and a is the distance from the source to the scattering screen. The RMS electron number density variation is given by

$$\Delta n_{\rm e} = \left(\frac{a \tau_{\rm sc} \nu^4 m_{\rm e}^2 4\pi^2}{e^4 D}\right)^{1/2}, \tag{5}$$

where a is the distance from the source to the scattering screen, $\tau_{\rm sc}$ is the scattering time scale, ν is the observing frequency, $m_{\rm e}$ is the electron rest mass, e is the electron charge, and D is the distance to the pulsar.

There are a variety of different models that explain the influence of scattering on observed pulse shapes, but we commonly use the *thin-screen approximation*. In the thin-screen approximation, all of the scattering occurs when rays pass through a thin screen midway between the Earth and the pulsar.

Q 3.1 The typical scattering time scale in observations of the Crab Pulsar at 610 MHz is 0.15 ms. Assuming the single-screen model, what are the typical RMS electron density variations along the line of sight to the Crab Pulsar?
Hint: you will need to look up certain values.

Q 3.2 What scattering time scale would you expect in observations of the Crab Pulsar with LOFAR (at 110 MHz)? How might this make observations difficult?

Q 3.3 Is the single-screen model valid in the case of the Crab Pulsar?

Q 3.4 How might scattering affect our ability to precisely time pulsars?

4 Scintillation

Like scattering, scintillation arises from electron number density variations due to turbulence in the ISM. The scattered rays interfere with each other and produces an interference pattern, which causes the pulsar to appear to vary in flux density. Scintillation is characterised by the bandwidth Δf_s over which intensity variations occur, and is related to the scattering time scale τ_sc by

$$\Delta f_\mathrm{s} \propto \tau_\mathrm{sc}^{-1}. \tag{6}$$

The scintillation bandwidth is given by

$$\Delta f_\mathrm{s} = \frac{8\pi D' c}{D^2 (\Delta n_\mathrm{e})^2 \lambda^4} \tag{7}$$

where D is the distance to the pulsar, D' is the distance travelled by the scattered ray, c is the speed of light, Δn_e is the RMS of the electron number density variations, and λ is the wavelength.

Q 4.1 Figure 1 shows a simulated dynamic spectrum of PSR B0329+54[a]. Estimate the scintillation bandwidth and time scale. *Hint*: you will need to look up certain values.

Q 4.2 Estimate the scattering time scale.

Q 4.3 If a pulsar has a pulse profile that varies significantly with frequency, how might scintillation lead to difficulties in high-precision timing of the pulsar with a broadband receiver?

[a] J2000 name: PSR J0332+5434

Activity: Measuring DM Variations

PSR J1111+2222 is a fake pulsar that I invented for the exercise. It has large and rapid DM variations. The TOAs in J1111+2222.tim are made up of simultaneous observations at 1440 MHz and 610 MHz.

1. Using TEMPO2, measure the difference in timing residuals for the two different frequencies on each day, and produce a plot of the change in DM over time.
2. Fit for DM and higher order derivatives. Does this seem to properly account for the DM variations? Suggest some parameters in the timing model that might be covariant with the DM terms.
3. Comment on the suitability of this pulsar for inclusion in pulsar timing arrays.

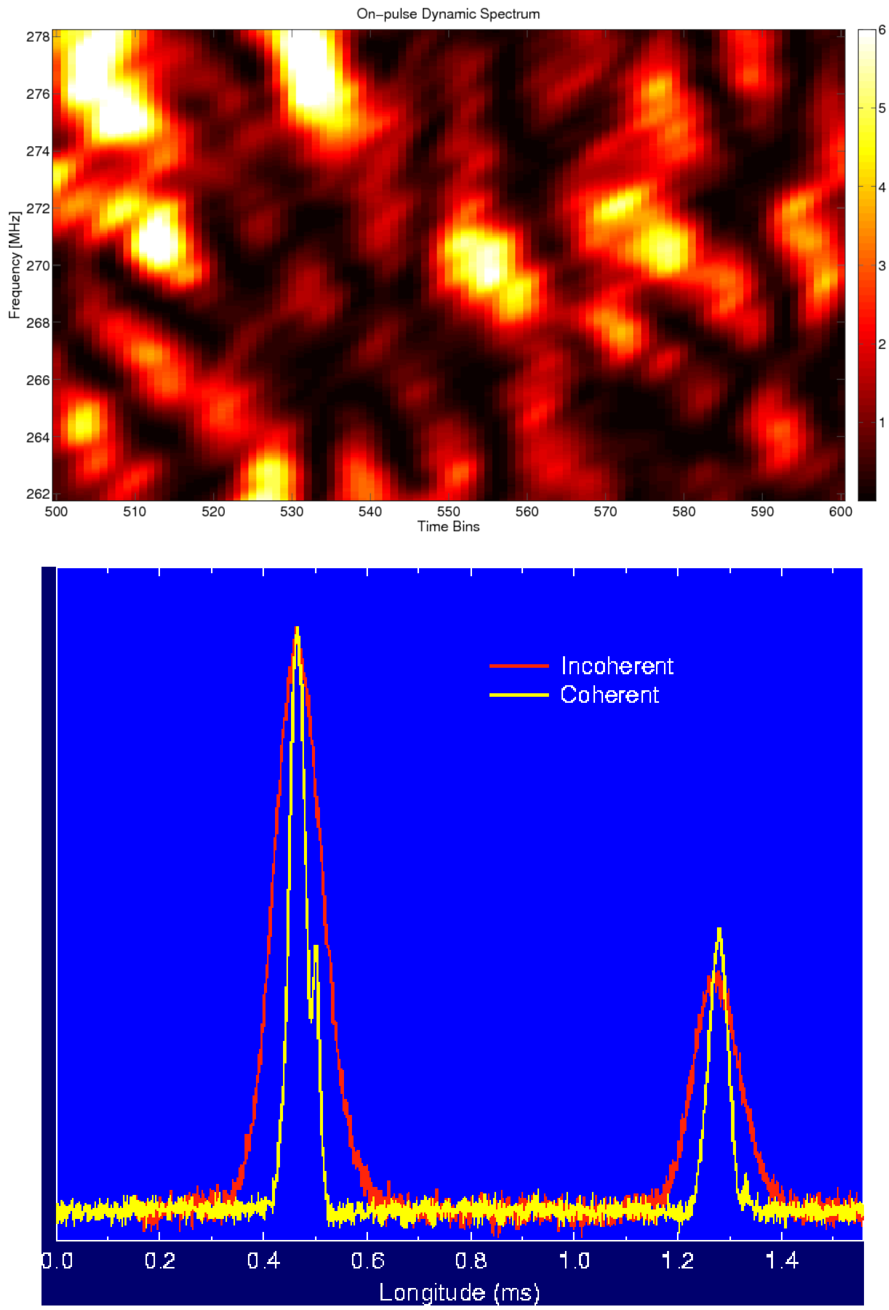

Figure 1: *Above:* Simulated dynamic spectrum for PSR B0329+54, using a centre frequency of 270 MHz and a bandwidth of 7×16.5 MHz. Figure from *Scintillation Based Search for Off-Pulse Radio Emission from Pulsars*, Ravi & Deshpande (2018).
Below: Folded pulse profile of PSR B1937+21 at 1400 MHz using coherent dedispersion (yellow) and incoherent dedispersion (red). Image Credit: Jodrell Bank Observatory.

5 Useful Resources

- TEMPO2 overview paper (Hobbs et al. 2006): arxiv.org/abs/astro-ph/0603381
- TEMPO2 timing model description (Edwards et al. 2006): arxiv.org/abs/astro-ph/0607664
- EPTA data release 1.0 overview (Desvignes et al. 2016): arxiv.org/abs/1602.08511
- TEMPO2 user manual: http://www.jb.man.ac.uk/~pulsar/Resources/tempo2_manual.pdf
- TEMPO2 wiki page (tutorials, documentation, etc.): http://www.atnf.csiro.au/research/pulsar/tempo2/index.php?n=Main.HomePage
- The ATNF Pulsar Database: http://www.atnf.csiro.au/people/pulsar/psrcat/