Parameter Search Ranges for Radio Pulsars

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Abstract

Parameters for searches of binary pulsars include dispersion measure (DM); spin period ($P_{\rm spin}$); number of harmonics (N_h), equivalent to pulse duty cycle; an orbital amplitude parameter ($A \propto a \sin i$); orbital period ($P_{\rm orb}$); and orbital phase (Φ_0). Appropriate search ranges are given for these parameters. To keep search processing at a practical minimum, parsimonious ranges for the orbitally dependent parameters are given.

1 Parameters

Finding pulsar signals involves, at minimum, a search over the parameters:

1. DM = dispersion measure
2. $f = 1/P_{\rm spin}$ pulse or (apparent) spin frequency (Hz)
3. N_h = number of harmonics that optimizes harmonic sum;

$$N_h \sim W/P_{\rm spin} = \text{duty cycle for pulses of width W}$$

For pulsars in circular orbits, three additional parameters are needed; in Kepler-speak these would be:

4. $a_1 \sin i$ = projected orbital radius of the pulsar
5. $\Omega = 2\pi/P_{\rm orb}$
6. Φ_0 = orbital phase

For circular orbits there are six parameters to search for. The first three are dealt with through dedispersion over a grid[1] to identify the best value of DM and by spectral analysis and harmonic summing to get f and N_h. The harmonic sum is the test statistic used to identify candidates through a threshold test.

The last three parameters can be recast in terms of the resulting phase perturbation on the time series. This phase perturbation is

$$\phi(t) = c^{-1} f a_1 \sin i \, \sin(\Omega t + \Phi_0) \equiv f A \sin(\Omega t + \Phi_0),$$

which defines A in time units, which is

$$A = 1.17 \sec \frac{[M P_{\rm orb}^2({\rm hr})]^{1/3}}{(1 + M_1/M_2)}, \tag{1}$$

where $M \equiv M_1 + M_2$ is the total mass (in units of $M_\odot$) and M_1 is the pulsar mass. For convenience, we define $\alpha = fA$.

For the circular binary search the analysis flow would be:

1. dedisperse the data from a given data set over a set of $N_{\rm DM}$ trial values of DM, yielding a time series for each trial value.

[1] This is typically a nonuniform grid because at higher values of DM, pulse broadening from multipath propagation in the interstellar medium dominates the time resolution, so larger spacing between trial DM values can be used.

2. rebin the time series using trial values for the three parameters $\alpha, P_{\rm orb}, \Phi_0$.

3. Take the Fourier transform of the time series, construct and test harmonic sums to identify candidates. (Ignore candidates that are in a list of known contaminating signals.) These candidates will be reported back to the server as the six parameter values, S/N, and a few other diagnostic numbers.

4. For viable candidates, rebin the time series and calculate the synchronous average pulse profiles. These could be displayed on a client's screen, for example. Tests on the profiles such as the duty cycle could also be reported back to the server.

2 Parameter Search Ranges

Specifying the search ranges for the six parameters, we have:

1. $\mathbf{DM} \in [\mathbf{0}, \mathbf{1000}]$ **pc cm**$^{-3}$
   Currently we use 1270 trial values.

2. $\mathbf{P}_{\rm spin} \in [\mathbf{0.5 \times 10^{-3}}, \mathbf{10}]\mathbf{s} \Longrightarrow \mathbf{f} \in$ **0.1 Hz to 2 kHz**
   Magnetars and high-field pulsars have periods in the 8 to 10 s range. The fastest millisecond pulsar is 1.4 ms. Equations of state allow spins as fast as 0.5 ms.

3. $\mathbf{N}_h$ **trial sums up to 16 harmonics**

4. $\mathbf{A} \in [\mathbf{0}, \mathbf{3}]$ **s** $\times\, \mathbf{P}_{\rm orb}^{\mathbf{2/3}}(\mathbf{hr})$
   For a NS-WD binary with $0.5M_\odot$ WD, the coefficient is 0.38 s; for a NS-NS binary with two 1.4 $M_\odot$ NSs, the coefficient is 0.82 s; for a NS-BH binary with 10 $M_\odot$ BH, the coefficient is 2.3 s. The lowest value (zero) follows from $\sin i = 0$ and is degenerate with an isolated pulsar.

5. $\mathbf{P}_{\rm orb} \in [\mathbf{0.1}, \mathbf{8}]$ **hr**.
   For $P_{\rm orb} \gtrsim 8$ hr, orbital effects are negligible for a circular orbit unless the companion is very massive.

6. $\mathbf{\Phi_0} \in [\mathbf{0}, \mathbf{2\pi}]$

3 Astrophysical Constraints

If the parameter space as given above is too large after AND-ing the ranges, astrophysical priors can be used to limit the search volume.

Current lore implies that the fastest pulsars (millisecond pulsars with $P_{\rm spin} \lesssim 20$ ms) will have white dwarf companions or sub-stellar companions (as in the Black Widow pulsar where the companion is being evaporated). NS-NS binaries will have pulsars with $P_{\rm spin} > 20$ ms because (a) if it is a recycled, spun-up pulsar, there was insufficient time to spin it up to a faster period or (b) if the second born pulsar, it would not be recycled and would have a birth period of 20 ms or longer. NS-BH binaries born in the Galactic disk will necessarily consist of a canonical (not recycled) pulsar and will thus have a long spin period, most likely since the birth rate of such systems is low. NS-BH binaries born in globular clusters through exchange reactions could have a much richer range of possible pulsars, including millisecond pulsar companions. Such binaries might also have been evaporated out of globular clusters.

4 Parsimonious Ranges for Subclasses of Binary Pulsars:

Millisecond Pulsar - White Dwarf Binaries:

$f_{\rm spin} \in [50, 2000]$ Hz

$A = 0.38\ s\ P_{\rm orb}^{2/3}(\rm hr)$

$P_{\rm orb} \in [0, 8\ \rm hr]$

NS-NS Binaries:

$f_{\mathrm{spin}} \lesssim 50$ Hz

$A = 0.82\ s\ P_{\mathrm{orb}}^{2/3}(\mathrm{hr})$

$P_{\mathrm{orb}} \in [0, 8\ \mathrm{hr}]$

NS-BH Binaries:

$f_{\mathrm{spin}} \lesssim 50$ Hz

$A = 2.3\ s\ P_{\mathrm{orb}}^{2/3}(\mathrm{hr})$

$P_{\mathrm{orb}} \in [0, 8\ \mathrm{hr}]$

From the table in C. Messenger's document "Estimating the Number of Templates for a Search for Short Period Binary Systems," it appears that the number of templates needed for the NS-NS and NS-BH search will be quite manageable (a few $\times 10^4$ in each case). The MSP-WD binary search is the most challenging. Low-mass WDs reduce the number of templates needed, but searching to 2 kHz requires many templates. To keep the number manageable, perhaps we should compromise by making the maximum spin frequency equal to 200 Hz ($P_{\mathrm{spin}} = 5$ ms).