Imaging a Pulsar's Scattering Disk

Happy 70$^{\mathrm{th}}$ Miller!

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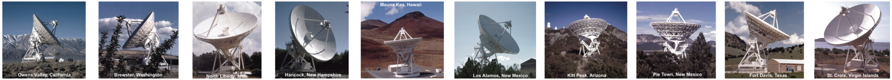
National Radio Astronomy Observatory

2011 May 19



Scintillation Arcs

Dynamic Spectrum

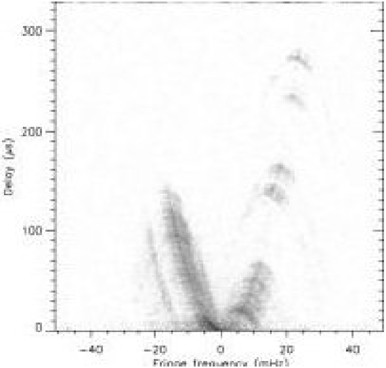
$I(\nu, t)$

Discovery of Scintillation Arcs

Dynamic Spectrum

$I(\nu, t)$

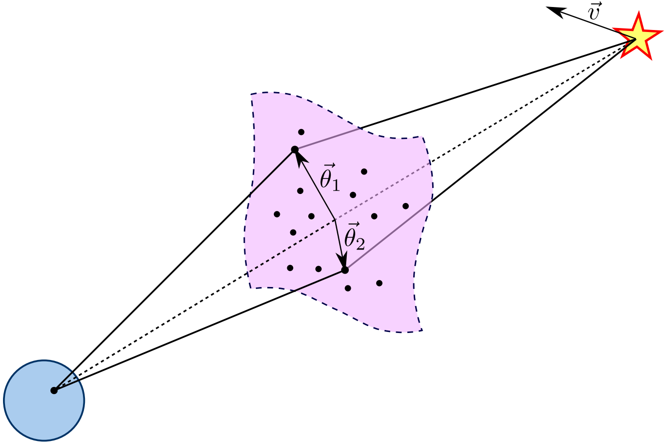
Secondary Spectrum



$$S(T, R) \equiv |\mathcal{F}[I(\nu, t)]|^2$$

see Stinebring et al., 2001 and Walker et al., 2005

Diffractive Scintillation Thin Screen Geometry



- $*$ Distance to pulsar $\equiv D_{\mathrm{psr}}$
- $*$ Distance to screen $\equiv D_{\mathrm{scr}} = (1-s)D_{\mathrm{psr}}$
- $*$ Effective distance $\equiv D_{\mathrm{eff}} = \frac{1-s}{s} D_{\mathrm{psr}}$
- $*$ Effective velocity $\equiv \vec{V}_{\mathrm{eff}} = \frac{1-s}{s} \vec{v}$

see Cordes et. al, 2006

Model of Parabolic Arcs

Delay coordinate

- From geometry

$$T \equiv \tau_1 - \tau_2 = \frac{D_{\rm eff}}{2c}(\theta_1^2 - \theta_2^2)$$

Doppler rate coordinate

- From time derivative of τ:

$$R = \vec{V}_{\rm eff} \cdot (\vec{\theta_1} - \vec{\theta_2})$$

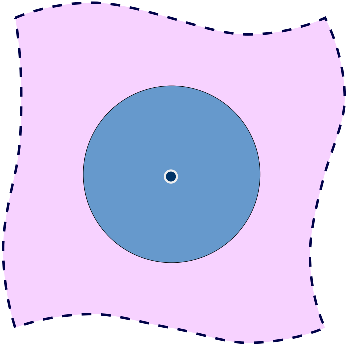
The parabola

- Assume dominating central concentration near $\vec{\theta_2} = 0$
- Then:

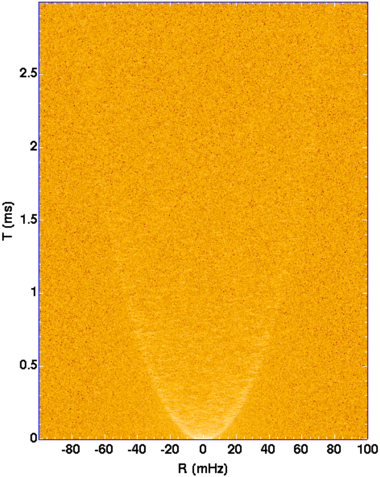
$$T \geq \frac{\lambda^2 D_{\rm eff}}{2cV_{\rm eff}^2} R^2$$

- Equality occurs for $\vec{\theta_1} \parallel \vec{V}_{\rm eff}$

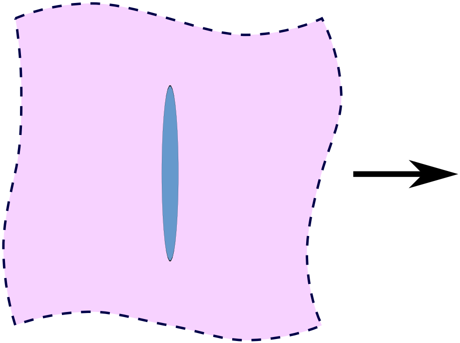
Example 1



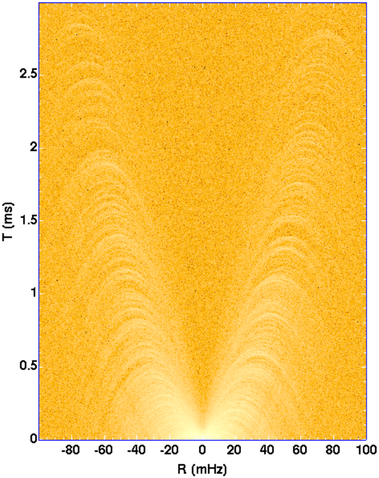
Core Disk Distribution



Example 2



$10{:}1$ Axial ratio $\parallel$ to velocity



VLBI Study of Scattering Screen

Goal 1

* Investigate arcs at very high frequency resolution

Goal 2

* Validate parabolic arc model
* Make model-independent image of scattering screen

Goal 3

* Break degeneracies
  - Measure anisotropy of scattering
  - Determine orientation for improved interpretation of single-dish data

The Ad-hoc VLBI Array

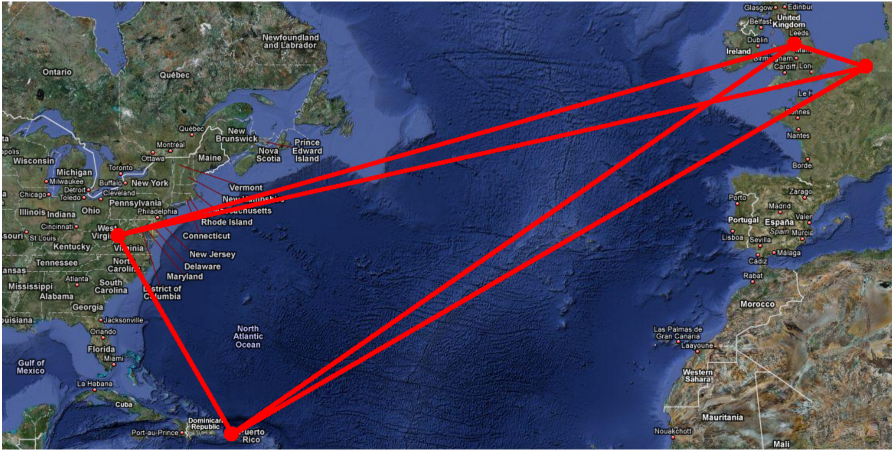


Image courtesy of Google

* Need: Low freq, long baselines, high sensitivity & mutual visibility
* Array: GB (100 m), AO (305 m), JB (76 m) and WB (93 m equiv.)

Experimental Setup

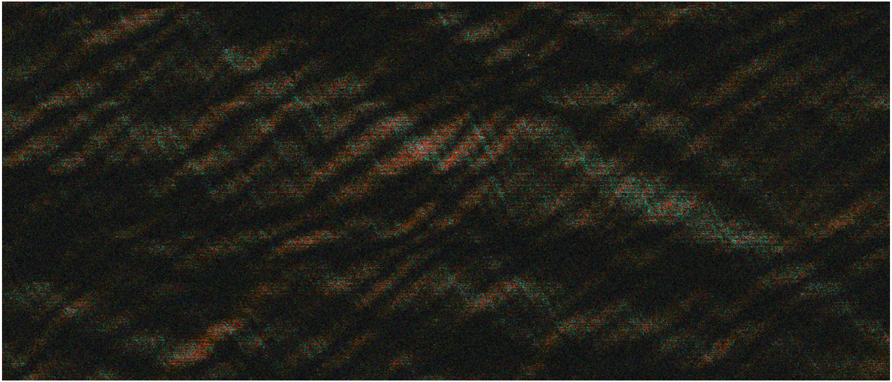
The observation

* Target: pulsar B0834+06
* 2 hours on source
* Frequency: 310 to 342 MHz with dual circular polarization

Correlation

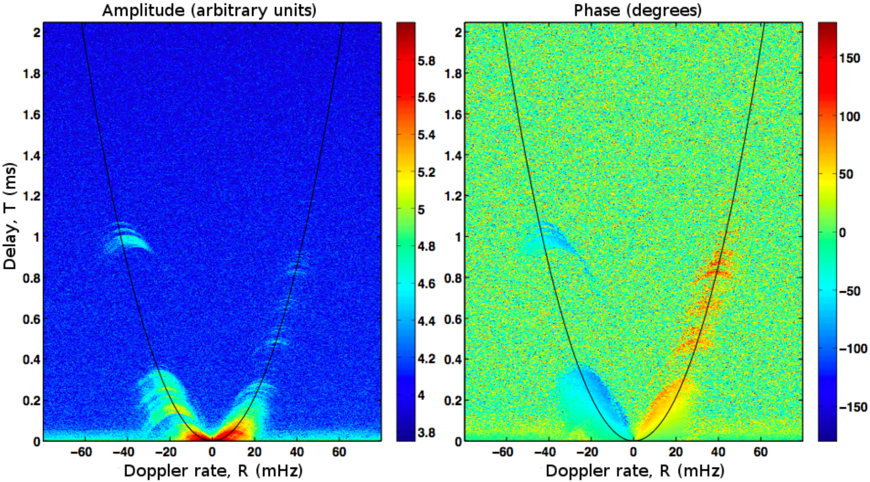
* Used Adam Deller's nascent DiFX software correlator at Swinburne Univ.
* 131072 spectral channels (244 Hz resolution)
* 1.25 second integrations
* Pulsar gate used to boost signal-to-noise ratio

Visibility Dynamic Spectrum (AR-GB)



- ~ 600 seconds $\uparrow$ of data over ~ 200 kHz $\rightarrow$
- Amplitude mapped to intensity
- Phase mapped to color (red to blue)
- Note, only a very small piece of the dynamic spectrum is shown

Visibility Secondary Spectrum (AR-GB)



see Brisken et al. 2010

Mining a rich data set

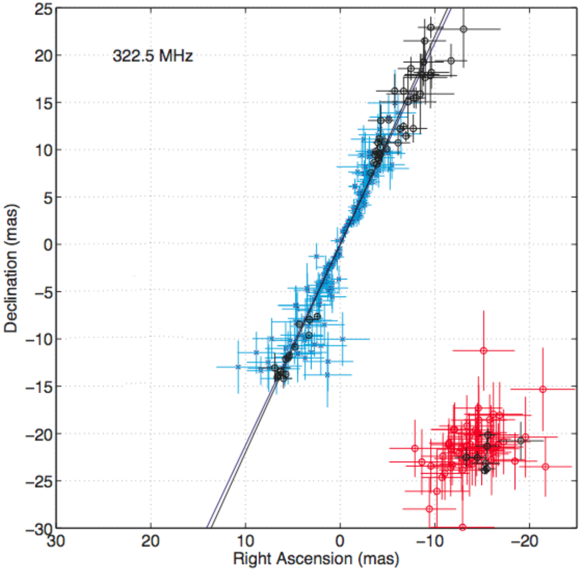
For each point in the secondary spectrum

- ∗ Delay, T
- ∗ Doppler rate, R
- ∗ Amplitude (on each baseline)
- ∗ Phase (on each baseline)

Phases yield sky coordinates

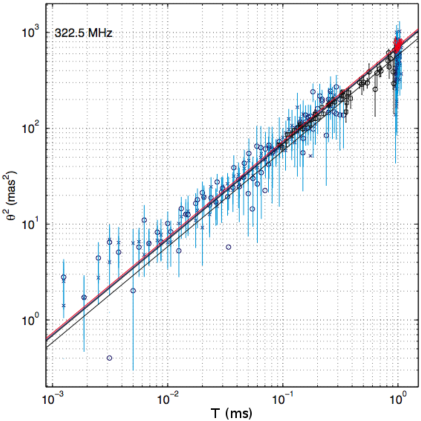
- ∗ $\phi = \frac{2\pi\nu}{c}(ul + vm)$ (as for interferometry)
- ∗ Can directly test $T = \frac{D_{\rm eff}}{2c}\theta^2$ and $R = \vec{V}_{\rm eff} \cdot \vec{\theta} \ldots$
- ∗ … and determine $D_{\rm eff}$ and $\vec{V}_{\rm eff}$

Astrometrically Recovered Image

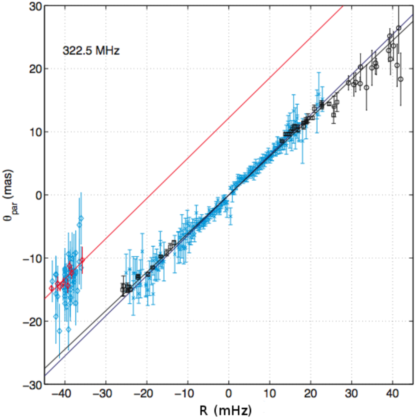


Physical Parameter Estimation

Distance fit

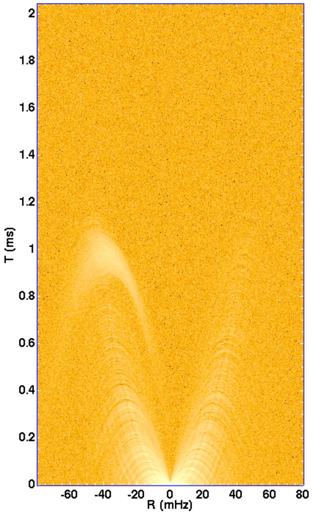


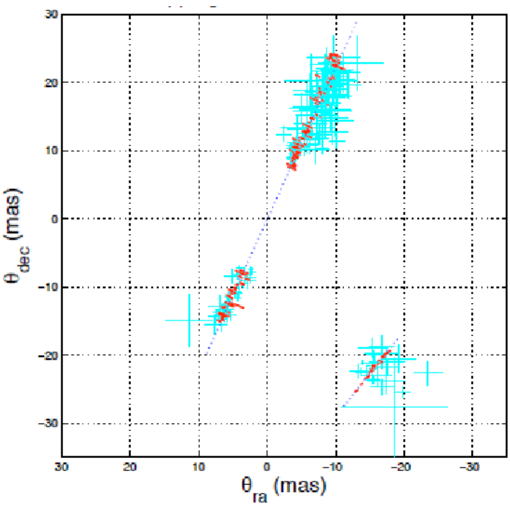
Velocity fit



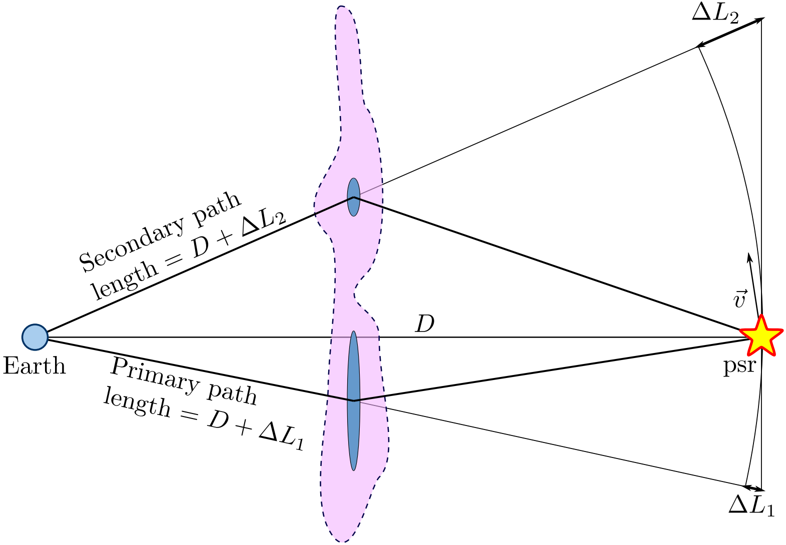
- $D_{\rm eff} = 1171 \pm 10$ pc $\rightarrow D_{\rm scr} = 415 \pm 5$ pc
- $V_{\rm eff,||} = 305 \pm 3$ km s^{-1}
- $V_{\rm eff,\perp} = -150 \pm 5$ km s^{-1}

Model Recovered Image





Pulsar timing effects



Conclusion

Stationary Phase Points I

Delay model

$$\tau(\vec{\theta}) = \frac{D_{\mathrm{eff}}}{2c}\theta^2 \text{ with } \textit{direct path}\text{: } \tau(\vec{\theta} = 0) \equiv 0$$

Propagation via Fresnel-Kirchhoff integral

$$\vec{E}(\nu) \propto \nu \int e^{-2\pi i \nu \tau(\vec{\theta})} d\vec{\theta}\ \vec{E}_{\mathrm{psr}}(\nu)$$

In diffractive scintillation, this integral is dominated by points where constructive interference gives rise to high magnification,

$$\vec{\nabla}\tau(\vec{\theta}) = 0,$$

which are called *stationary phase points*. Their brightness contribution is related to their magnification

$$\mu = \left[\nu \nabla^2 \tau(\vec{\theta})\right]^{-1}$$

Stationary Phase Points II

Propagation (cont.)

The Fresnel-Kirchhoff integral

$$\vec{E}(\nu) \propto \nu \int e^{-2\pi i \nu \tau(\vec{\theta})} d\vec{\theta}\ \vec{E}_{\rm psr}(\nu)$$

can then be turned into a sum over stationary phase points, $\vec{\theta}_j$:

$$\vec{E}(\nu) \propto \nu \sum_j \mu_j e^{-2\pi i \nu \tau(\vec{\theta}_j)}\ \vec{E}_{\rm psr}(\nu)$$

Simplifying assumption

Geometry of screen remains fixed

$$\frac{d\vec{\theta}_j}{dt} = 0$$