Scattering as a nuisance (and as a tool)

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Scattering as a nuisance (and as a tool)

• nuisance
  ⋆ pulsars in centre of Milky Way?
  ⋆ a magnetar near the GC
  ⋆ temporal and angular broadening
  ⋆ a one-baseline VLBI experiment
  ⋆ aim
    ✴ scattering properties
    ✴ distance of screen

• tool
  ⋆ extreme resolution via scintellometry
  ⋆ use scattering disk as interferometer
  ⇝ low-frequency VLBI
Motivation

• How to test General Relativity?
  ★ need extreme gravity $\leadsto$ black hole
  ★ precise measurements $\leadsto$ time $\leadsto$ pulsar

• Where to find them?
  ★ black hole in GC, $M \approx 4 \cdot 10^6 M_\odot$
  ★ high density of stars $\leadsto$ there should be many pulsars in close orbits!

• What can be done? [Liu et al. (2012)]
  ★ precision mass, spin (cosmic censorship), quadrupole moment (no hair theorem), perturbations, . . .
  ★ mass distribution around centre
The problem: scatter broadening of pulses

B1815–14 at 1.4 GHz

- stronger at lower frequencies: $\tau \propto \lambda^4$ or $\lambda^{4.4}$
- strong dependence on line of sight (GC worst)
- can wash out pulses if $\tau \gtrsim P$

[ Löhmer et al. (2001) ]
How many have we spotted so far?

... nearly, ooh, nearly one. Er, call it none.

- rough estimate: \( \tau \sim (\text{few 100 sec}) \left( \frac{f}{\text{GHz}} \right)^{-4} \)

- go to higher frequencies (despite steep spectrum)

- *Macquart et al. (2010)*
  15 GHz with GBT within 1–2 pc should have found \( \sim 90 \), found 0

- *Eatough (2013), MRU2013 and priv. comm.*
  19 GHz with Effelsberg within 1–2 pc total time 1 year, integration time \( \sim 2 \) days should have found very many, found 0
Interstellar scattering: geometry

\[ c\tau = \frac{1}{2} \theta^2 D' \]

\[ D' = \frac{D(D - \Delta)}{\Delta} \]

diverges for \( \Delta \to 0 \)

- screen close to pulsar: large \( \tau/\theta^2 \)
- screen close to observer: small \( \tau/\theta^2 \)

Where is the screen?
GC Scattering screen

- for Sgr A*: $2\theta = 950 \text{mas} \left( \frac{f}{\text{GHz}} \right)^{-2}$

- distance from GC: fit to scattering sizes, DM, free-free, . . .  
  \[ \Delta = \left(133^{+200}_{-80}\right) \text{pc} \implies \tau = 150 \text{sec} \left( \frac{f}{\text{GHz}} \right)^{-4} \]

- “somewhere in the middle”

\[ \Delta = \frac{D}{2} \implies \tau = 2 \text{sec} \left( \frac{f}{\text{GHz}} \right)^{-4} \]

\( \implies \) difficult/impossible to find pulsars at low frequencies
Then suddenly...

- Swift X-ray flare 26th April 2013 in Sgr A* area
- NuSTAR finds 3.76 sec period, probably magnetar
- Chandra: ca. 3'' from Sgr A*
- radio search begins: first detection 2nd May (Effelsberg)

[ Mori et al. (2013) ]
[ Eatough et al. (2013), ATel 5040 ]
Temporal scatter broadening of J1745–29

- fits to averaged profiles and single pulses
- including intrinsic width
- \( \tau = 1.3 \text{ sec} \left( \frac{f}{\text{GHz}} \right)^{-3.8} \)
- compare to 150 or 2 sec
- why so much less?

[ Spitler et al. (2014) ]
Angular scatter broadening of J1745–29

- VLBA + VLA at 8.7 and 15.4 GHz
- $16.1 \times 8.8 \text{ mas}^2$ and $5.4 \times 3.7 \text{ mas}^2$
- consistent with Sgr A* 

$$2\theta \approx 980 \text{ mas} \left(\frac{f}{\text{GHz}}\right)^{-2}$$

[Bower et al. (2014)]

- combine $\tau$ and $\theta$: $\Delta = (5.9 \pm 0.3) \text{ kpc}$

if same thin screen!
Testing the ‘one thin screen’ model

- so far: compared only $<\tau>$ and $<\theta^2>$ averaged over profile
- can do this for slices: measure $\theta(\tau)$ or profile($\theta$)
- only for thin screen: $\tau \propto \theta^2 D'$ (expanding ring)
- allow resolving $\tau$: 1.4–2 GHz
- sizes: 500–250 mas
- baselines: 90–125 km
- sensitivity: LEAP (Large European Array for Pulsars)
  - Effelsberg, Lovell, Nancay, Westerbork, now also Sardinia
  - pulsar backends: 8-bit sampling
  - data distribution logistics
- observed 9th November 2013

Thanks to LEAP group!
Observations

- 9th Nov 2013 13:48–14:55 plus calibrators
- frequency range 1604–1732 MHz in 8 bands (RFI in lower 2)
- Effelsberg, Lovell, Nancay, Westerbork
- Lovell: lost most data, Nancay: different format
- so far only analysed Ef–Wb
  - baseline 267 km, projected 42–79 km
  - resolution $\sim 0.'9–0.'45$
  - Ef close to saturation (affects single-dish profile)
    (Ef noise near Sgr A is 8 times higher than normal)
  - time offset 409 msec
- use Sgr A* as in-beam calibrator only 2''4 away
UV coverage Ef-Wb

![Graph showing UV coverage for different frequencies (1612 MHz, 1628 MHz, 1644 MHz, 1660 MHz, 1676 MHz, 1692 MHz, 1708 MHz, 1724 MHz). The graph plots v [k\(\lambda\)] against u [k\(\lambda\)].]
Correlation, calibration

- DADA format, not readable by DiFX (or SFXC)
- used own correlator, binning/gating possible
- convert Wb to circular polarisation
- 3.764 sec period, used bins of 0.005 sec, here 0.1 sec
- fringe-fitting for disp delay, non-disp delay, rates, DFR, orientation
  finally used: delay, rate, phase (and predicted parallactic angle)
- bandpass in amplitude and phase
- gated for Sgr A* or magnetar (with Sgr A* subtracted)
- consistent offset, finally used Sgr A* for calibration, then phase shift to magnetar
Gated dirty maps

- beam not optimal, but can separate both objects
- Sgr A* extended as expected
- J1745–29 slightly offset from VLBI position
- peak of J1745–29 slightly more compact
Profile as function of $\tau$ and $(u, v)$
Profiles for different \((u, v)\)
Visibility functions for different $\tau$
Fits of (uniform circular) rings
Size vs. time (binned)
Distance of scattering screen

Temporal and angular broadening dominated by the same screen!

- \( c\tau = \frac{1}{2}D'\theta^2 \)
- \( 2\theta = 0''62\sqrt{\frac{t}{\text{sec}}} - 1.5 \)

\[ \leadsto D' = 8.85 \cdot 10^{11} c \text{sec} = 8.6 \text{kpc} \]

- \( D' = \frac{D(D - \Delta)}{\Delta} \)

\[ \leadsto \Delta = \frac{D^2}{D' + D} \]

- \( D = 8.5 \text{kpc} \)

\[ \leadsto \Delta = 0.50D = 4.2 \text{kpc} \]
Summary

• Sgr A* and J1745–29 have same scattering properties

• temporal and angular broadening from one screen

• preliminary result \[ \Delta = 0.50 \quad D = 4.2 \text{ kpc} \]
  - Lazio & Cordes (1998) 0.13 pc
  - Bower et al. (2014), Spitler et al. (2014) 5.9 kpc

• caveats
  - not full time resolution yet (will be done)
  - not anisotropic yet (will be done)
  - not consistent global fit yet (will be done)
  - variability not considered yet (will be done)
  - bad uv coverage, will include other baselines
Questions

• inconsistency with models of GC

• why strong scattering close to Sgr A* in projection but 4 kpc away?

• still open: Where are all the pulsars?
  ✴ line of sight to J1745–29 special (hole in screen)?
  ✴ additional scattering very close to Sgr A*?
  ✴ could be studied with Sgr A* scintillation (prevented by source size)
  ✴ evidence for increased broadening (summer 2014)

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Scattering as a tool

- turbulent plasma causes delays
- phase fluctuations $\rightarrow$ subimages
  $\rightarrow$ scatter-broadening $\theta \propto \lambda^{2.2}$
  * $< \mu\text{arcsec to } > \text{arcsec}$
- subimages interfering
  $\rightarrow$ interstellar scintillation
- observed in
  * compact AGN, masers
  * pulsars

[ Moniez (2003) ]
interstellar scattering interferometry (scintellometry)

• scattering disk $\alpha_1 \propto \lambda^{2.2}$, $\mu$arcsec–arcsec

• linear resolution

\[ d = \frac{\lambda}{\alpha_1} \frac{D - \Delta}{\Delta} \propto \lambda^{-1.2} \frac{D - \Delta}{\Delta} \]

pulsars 150 MHz–20 GHz: 10 – 10$^7$ km

• angular resolution

\[ \Delta \theta = \frac{\lambda}{\alpha_1} \frac{D - \Delta}{D \Delta} \propto \lambda^{-1.2} \frac{D - \Delta}{D \Delta} \]

pulsars 150 MHz–20 GHz: milli-arcsec – pico-arcsec

• potentially extreme resolution!

• lower frequencies $\rightarrow$ higher resolution
Scintellometry for pulsar B0834+06

[ Pen et al. (2014) ]
Result for pulsar B0834+06

Pen et al. (2014)

[ Pen et al. (2014) ]
Ongoing project: LOFAR+KAIRA+GMRT+ARO

• Jul 2013, Jan 2014
• for orbits
• J1012+5307, B1957+20, J1810+1744, ...
• fringes B1919+21
• VLBI around 150 MHz
• > 10,000 km baseline
• U.-L. Pen, M. v. Kerkwijk, OW, ...

GMRT–LOFAR

GMRT–ARO

LOFAR–ARO
Summary: Scattering as a tool

- natural interferometers provide extreme resolution
  \[\Delta \theta \propto \frac{1}{\lambda} \implies \text{low frequencies!}\]

- in almost all cases: too much resolution

- exception: pulsars
  - measure motion of emission regions
  - maybe resolve emission regions?
  - measure proper motion in binary pulsars
  - determine orbits, GR tests, etc.

- unfortunately not: Sgr A*
  - resolution in L band: \(\sim 100\) km!
  - resolved out even at high frequencies
Bonus: Scattering across GC region

scattering size of extragalactic radio sources at $\lambda = 1 \text{ m}$

evidence for region of 150 pc around Sgr A*
Bonus: Radio profile of J1745-29

![Radio profile of PSR J1745-2900 at 8.35 GHz](image)
Bonus: Profile and gating functions

- integrated profile on baseline
- gating weights Sgr A*
- gating weights J1745-29

phase [sec]
Bonus: Visibilities

![Graph 1: visibility Sgr A*](image1)

- **Real (red)**
- **Imag (green)**

![Graph 2: visibility peak J1745-29](image2)

- **Real (red)**
- **Imag (green)**
Bonus: Dirty maps as function of $\tau$