Redshift dependence of rapid radio scintillation from the MASIV survey: evolution of compact radio jets or angular broadening in the IGM?

Barney Rickett (UC SanDiego, visiting ATNF)
Jim Lovell & Cliff Senkbeil (U Tasmania)
Dave Jauncey (ATNF Canberra)
J-P Macquart (Curtin, CalTech)
Hayley Bignall (Curtin, JIVE, ASTRON)
Lucyna Kedziora-Chudczer (ATNF Epping)
Roopesh Ojha (ATNF & USNO)
Tapio Pursimo (NOT)
Stas Shabala (MRAO Cambridge)
Source Sample:

- 710 compact sources
- Flat spectral index (NVSS) $\alpha > -0.3 \quad S \propto \nu^\alpha$
- “Weak” sources $0.1 < S < 0.13$ Jy at 5 GHz
- “Strong” sources $0.6$ Jy $< S$
- Sources selected to be $>95\%$ unresolved on VLA at 8.5 GHz

Sources monitored at 5 GHz

- for 3 days every 2 hr using 5 subarrays of the VLA
- 4 epochs at 4 month intervals
- Removed sources that showed effects of resolution on VLA baselines
- 50\% of the remaining 449 sources scintillated on times from 2-72 hrs at 1-20\% in 2 or more epochs
- Conclude that those sources have extremely compact components (cores?) $\sim 10-50$ micro-arcsec - presumably Doppler-boosted by relativistic jets directed toward the Earth.
- At angular diameter distance $\sim 1$ Gpc, 50 micro-arcsec probes a linear size $\sim 0.25$ pc
InterStellar Scintillation (ISS) Geometry

Sight lines from quasars and pulsars (dashed)

40 years of ISS of pulsars give a “calibration” of the phenomenon for point sources

Warm Ionized Medium Turbulent & Inhomogeneous
Scintillation from a Phase screen

Incident plane wave front

Phase Screen

Phase modulated wave

Amplitude modulated wave
Scintillation of Extended Source  Brightness $B_I(\theta)$

$$\Delta I(s) = \int \Delta I_0(s - L \theta) \ B_I(\theta) \ d\theta$$

$\Delta I_0(s)$ is point source scintillation pattern $s = (x,y)$

$\Delta I_0$ has spatial scales:

- $s_d = s_o = \frac{1}{(k \theta_{scat})}$  Diffractive scintillation  DISS $f < f_w$
- $s_r = L \theta_{scatt} = L/(k s_d)$  Refractive scintillation  RISS
- $s_w = \sqrt{L/k}$  Weak Scintillation  WISS $f > f_w$

Suppressed Scintillation if:

$$\theta_{source} > \theta_{Fresnel} \sim (2\pi L/\lambda)^{-0.5} \text{ at } 6 \text{ cm}$$
Screen simulation in weak scintillation
(Left) point source               (right) extended source
3 times $\theta_F = (kL)^{-0.5}$

Note reduced amplitude and increased spatial scale
Sample lightcurves

Left plots:
Flux density (Jy) sampled every 2 hrs for 1 minute from over 500 flat spectrum sources.
Each epoch was 3-4 days
4 epochs separated by ~110 days

Right plots:
Structure functions D(t) of flux density normalized by mean out to time lag of 2.3 days
Model fitted to estimate:
\[ D(t=2 \text{ day}) \] & timescale \[ t_{\text{ISS}} \]
Amplitude of ISS

We characterize the amplitude of the variations on time scale $t$ by their structure function: 

$$D(t) = < [I(t') - I(t'+t)]^2 >$$

Where $I(t')$ is the intensity normalized by its long term mean. $D(t)$ gives the variance in the difference on time lag $t$

We characterize the MASIV variations by $D(t=2 \text{ days})$, after correction for noise, as it can be quantitatively modelled by scintillation theory.

We classify sources as variable if $D(t=2 \text{ d}) > 0.0004 \text{ (epoch averaged)}$ (ie 2-day modulation index $> 1.4\%$)

**Time Scale of ISS** $t_{ISS}$

$D(t)$ can also be used to define a time scale for the variations. Omitting the details, we classified the time scale for variable sources:

- **Fast**: $t_{ISS} < 0.5 \text{ d}$
- **Medium**: $0.5 \text{ d} < t_{ISS} < 3 \text{ d}$
- **Slow**: $t_{ISS} > 3 \text{ d}$
D(2d) vs H-alpha

There is a clear increase in the variation (on 2-days) with increasing $H\alpha$ emission (sampled by WHAM on a 1 degree grid).

Thus more variation in flux occurs for a larger emission measure. This is strong evidence that the cause is ISS in the ionized ISM.

The increasing fraction of slow versus fast variations is because the higher emission measure occurs for longer paths through the ISM, which cause larger scale in the ISS pattern.
Note wide range in D(2d) at within each bin.

=> Wide distribution of flux density of very compact component.

Note drop in scintillation with increasing mean flux density.

\[ S = 2k \frac{T_b \theta^2}{\lambda^2} \]

\[ \theta \propto \sqrt[0.5]{\lambda(S/T_b)} \]

For sources with a fixed maximum brightness temperature, we expect larger angular diameters for larger mean flux density S, which suppresses ISS.
D(2day) vs z for 250 sources

D(2d) shows a large scatter, but high values are found for redshifts below 2.

Mean D(2d) in redshift bins decreases rapidly for $z > 2$

Fraction of fast variables decreases somewhat more quickly than slow ones.

Implies decrease is due to increased diameter of the compact core.
Mean Flux Density vs Redshift

No trend of S with $z$ in the sample
Interpretation of ISS in MASIV sources

- Over half the sources show ISS at a few percent
- Hence they have a “compact fraction” \( f_c \) of flux density in components of apparent Brightness Temperature \( 10^{11} - 10^{14} \) K with \( 0.01 < f_c < 1 \)
- MASIV shows reduced ISS from sources at \( z > 2 \)
- This must be due to either an increase in angular diameter \( \theta_{\text{obs}} \) with \( z > 2 \)
  - OR
- A reduction in flux density of the ultra compact components with \( z > 2 \)

ISS Model for D(t)

depends on:
- The compact fraction \( f_c \) of flux density
- The distance \( d_{\text{ism}} \) to the scattering layer in our ISM

For ISS at 5 GHz for component of diameter \( \theta_{\mu\text{as}} \gg \theta_{\text{Fresnel}} \) and \( d_{\text{ism}} \approx 500 \) pc

\[
D(2d) \sim 90 f_c^2 (\theta_{\mu\text{as}})^{-7/3} (1+L\theta_{\text{obs}}/\sqrt{2d})^{-1}
\]

where \( \theta_{\text{Fresnel}} = (\lambda/2\pi L)^{0.5} \approx 5 \mu\text{as} \)
Redshift Dependence

For a Doppler-boosted synchrotron source limited by inverse Compton or self-absorption there is a maximum brightness temperature e.g.:

\[ T_{\text{bemit}} \sim 3 \times 10^{11} \text{K} \ \delta/(1+z) \quad \text{For Doppler factor } \delta \]

This gives an observed angular diameter \( \theta_{\mu\text{as}} \) at fixed observation wavelength

\[ \theta_{\mu\text{as}} \sim \theta_{\mu\text{as,emit}} (1+z)^{0.5} \quad \text{for constant max emitted brightness temp} \]

Hence Model for \( D(t=2d) \)

\[ D(2d) = 90 \ f_c^2 \ (\theta_{\mu\text{as,emit}})^{-7/3} \ (1+z)^{-7/6} \ (1+L\theta_{\text{obs}}/V \ 2d)^{-1} \]

If we assume no source evolution effects

\[ \Rightarrow \ f_c, \ \theta_{\mu\text{as,emit}} \quad \text{are independent of } z \]

So for constant max emitted brightness temp we expect

\[ D(2d) \ \propto (1+z)^{-7/6} \]

if the weak \( z \)-dependence in this reduction factor is ignored.
D(2day) vs z

\[ D(2d) \propto (1+z)^{-7/6} \]

prediction for constant emitted \( T_b \), constrained at \( z=0.75 \)

Observed deficit at \( z=3.7 \) is 5 times too low
Change in compact diameter or in “compact fraction”? 

Model for $D(t=2d) \propto (1+z)^{-7/6}$ assumes no source evolution of $f_c, \theta_{\mu as,emit}$ with $z$.

But observations show a steeper drop: At $z=2.2$ observe $D(2d) = (1 \pm 0.4) \times 10^{-3}$

$\Rightarrow$ at $z=3.7$ predicts $D(2d) = 4 \times 10^{-4}$
but observe $D(2d) \leq 0.8 \times 10^{-4}$

So either the emitted source diameter $\theta_{\mu as,emit}$ increases with redshift or the compact fraction $f_c$ of flux decreases with redshift.

Evolution of the AGN jets could be responsible for either change. Both correspond to a decrease in brightness temperature of the most compact radio emission from the jets
eg a decrease in Doppler factor at epochs earlier than redshift $\sim 2$?

Or angular broadening of the radio components as they propagate through the IGM.

Blue contours of $\log_{10}[D(2d)]$
Assume $d_{ism} = 500$ pc
Red contours of $\log_{10}[T_b/SJy]$
Questions re evolution of jets in AGNs

- What fraction of flat (or inverted) spectrum sources should be seen as Doppler boosted jets with max $T_b > 10^{12}$ K?
- How long is lifetime of relativistic (radi emitting) jets?
- When is the epoch of maximum AGN jet activity?
- What evolution in Doppler factor expected?

Alternative explanation:

The apparent angular size increases due to propagation through the intergalactic medium:
- Angular broadening due to inhomogeneous density of ionized IGM

[OR Angular broadening due to random gravitational lensing effects]
Source ID plot
Inter-Galactic Scattering

Inter Galactic Lyα Clouds, Lyman Limit & DLA systems

$\theta_{IG}$ is the cumulative angle of scattering

$\theta_{IGobs}$ is the effective angle of scattering

$\theta_{IGobs} = \theta_{IG} \left( \frac{D_{S-IG}}{D_S} \right)$
Angular Broadening due to turbulence in ionized IGM?

Model Assumptions:
Partially neutral Ly$\alpha$ clouds of size $L$ and HI column density $N_{\text{HI}}$:
- Ionization by ambient UV from Quasars $n_e \sim (4 \, N_{\text{HI}}/L)^{0.5} \, \text{cm}^{-3} \Rightarrow$ very high ionization fraction (Haardt & Madau 1996)
- Clouds are internally turbulent (fully developed Kolmogorov with outer scale $\sim L$)
- $n_e$ and $L$ do not scale with expanding Universe

Hence angular broadening due to one cloud

$$\theta_{\text{ig1}} \propto n_e^{1.2} \lambda^{2.2} L^{0.2} \propto (N_{\text{HI}}/L)^{0.6} L^{0.2} \lambda_{\text{obs}}^{2.2} (1+z)^{-2.2}$$
Integrating over redshift

Since the scattering by each cloud is independent we sum the squares of the scattering angles

\[ <\theta_{\text{IGobs}}^2> = \int dz \int dN_{\text{HI}} \theta_{i g_1}(N_{\text{HI}}, z)^2 g(N_{\text{HI}}, z) \left[\frac{D(z_s)-D(z)}{D(z_s)}\right]^2 \]

weighted by the intersection probability \( g(N_{\text{HI}}, z) \) dz dN_{\text{HI}} and distance reduction factor.

i.e. \( g(N_{\text{HI}}, z) \) from Ly\( \alpha \) forest observations is weighted by:

\[ n_e^2.4 \ L^{0.4} \ (1+z)^{-4.4} \left[\frac{D(z_s)-D(z)}{D(z_s)}\right]^2 \]

with \( n_e \sim (4 \ N_{\text{HI}}/L)^{0.5} \Rightarrow \) the weight \( \propto N_{\text{HI}}^{1.2} \ L^{-0.8} \)

The integral emphasizes small \( L \), but I now assume

\( L = 10 \ \text{kpc} \) for all \( N_{\text{HI}} \) and all \( z \) !!

The integral emphasizes: large \( N_{\text{HI}} \) and large \( z \)
Cosmology z - dependence

\[ g(N_{HI}, z) \, dz \, dN_{HI} = f(N_{HI}, X) \, (dX/dz) \, dz \]

where \( (dX/dz) = (1+z)^2/\left[ \Omega_m (1+z)^3 + \Omega_\Lambda \right]^{0.5} \)

\( \Omega_m = 0.27, \quad \Omega_\Lambda = 0.73 \) describe the \( \Lambda \)CDM cosmology

In terms of comoving density of clouds \( n_{cL} \)
\[ f(N_{HI}, X) = n_{cL} L^2 \] which describes any evolution of the clouds

Observers often estimate \( g(N_{HI}, z) \) as \( A(1+z)^\gamma \)

\[ \int_{N_{HImin}}^{N_{HImax}} g(N_{HI}, z) \, dN_{HI} = dn/dz \]

which depends on lower limit \( N_{HImin} \)

and already includes the cosmology \( \Rightarrow \)
Lyman Alpha Number counts vs Redshift
(Janknecht, Reimers, Lopez & Tytler et al. 2006)

\[ N_{\text{HI}} > 4.4 \times 10^{13} \text{ cm}^{-2} \]

Empirical curve: \[ \log_{10}(dn/dz) = 1.3 + \log_{10}(1+z)[1 + \log_{10}(1+z)] \]
I use this curve as the z-scaling factor for all \( N_{\text{HI}} \)
Line density distribution at $z=2.7$

(Proachaska, Herbert-Fort & Wolfe, 2005)

Defining $f \propto N_{\text{HI}}^{-\beta}$

Integral over $N_{\text{HI}}$: $f(N_{\text{HI}}, X)$ multiplied by $N_{\text{HI}}$

is dominated by large $N_{\text{HI}}$ if effective slope $\beta < 2$

Integral determined by line density at $N_{\text{HI}} \sim 10^{21.5}\text{cm}^{-2}$

ie by DLAs!

Fig. 12.—Figure depicting the $f_{\text{HI}}(N, X)$ distribution of the quasar absorption line systems at $z = 2.7$. The distribution for the damped Ly$\alpha$ systems corresponds to the $\Gamma$ function fit to the SDSS DR3–4 sample. The distribution for the line systems is dominated by DLAs.
MASIV At z=3.7: The deficit of ISS gives broadening 
\[ \theta_{\text{IGS,obs}} \sim 5-100 \, \mu\text{as.} \] ie the model is too small by a factor 5-100 !!

Estimate of angular diameter of expanding Gamma Ray Afterglow 970508 gave 
\[ \theta_{\text{IGS}} < 10 \, \mu\text{as} \] (scaled to 5 GHz)
Conclusions

- Half of 449 sources showed 6cm ISS - characterized by variance in amplitude over 2-days which increases with emission measure from the ISM
- Implied minimum size 5->50 µas depending on compact fraction
- ISS amplitude decreases strongly for z > 2
- Decrease is steeper than predicted for emission from a fixed maximum brightness temperature model
- Alternative Explanations:
  1. Decrease in Doppler-boosting factor in AGN jets earlier than z=2
  2. Angular Broadening due to propagation through:
     1. Ionized Inter-Galactic Medium
     2. Random Gravitational lensing effects
- In either case we have a new observational tool for cosmology
- Ideas on the interpretation are welcome!