Interstellar Scintillation, AGN Physics and the SKA

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Abstract
A large fraction of compact, extragalactic radio sources exhibit rapid variability at centimetre wavelengths as their radio emission is scattered by electron density fluctuations in the interstellar medium of the Galaxy. Next-generation wide-field radio telescopes will have to account for this in forming deep images of the radio sky. Interstellar scintillation offers a unique probe of very small-scale structure in both the ionized interstellar medium and the compact jets of the radio sources themselves. The effective resolution is two orders of magnitude higher than achievable with very long baseline interferometry. The recent Micro-Arcsecond Scintillation-Induced Variability Survey revealed a reduction in ISS at 4.9 GHz with increasing source redshift, implying either an increase in the apparent angular size of high-redshift radio cores beyond that expected due to a cosmological decrease in brightness, or a decrease in the microarcsecond-scale core dominance towards high redshift. The result could be due either to source-intrinsic evolution in the selected sample, or to scatter-broadening in the intergalactic medium.

Keywords: interstellar medium; quasars; radio continuum; scattering; techniques: high angular resolution

Introduction
Active Galactic Nuclei (AGN) show variability across the whole electromagnetic spectrum. Observations of multi-wavelength variability help to constrain the emission mechanisms and physical properties of the region around the supermassive black hole central engine. In addition to source-intrinsic variability, compact AGN (quasars and BL Lacertae objects) often show intensity variations at radio wavelengths due to interstellar scintillation (ISS). The theory of interstellar scattering has been reviewed by e.g. Rickett (1990) and Narayan (1992).

For very compact AGN, the largest amplitude variations due to ISS are typically observed close to the transition between weak and strong scattering, which occurs at observing frequencies of a few gigahertz (GHz) for most of the extragalactic sky. At frequencies below the transition, in the strong scattering regime, refractive scintillations are commonly observed on timescales of typically weeks to months. Near the transition and in weak scattering, shorter timescale variability, so-called intra-day variability (IDV), may be observed. ISS is now recognised as the dominant cause of IDV at GHz frequencies, while intrinsic variations dominate on longer timescales and at higher frequencies.

ISS probes source structure with effective resolution $\sim 10-50$ microarcseconds (μas) at GHz frequencies, more than an order of magnitude smaller than the resolution achievable with very long baseline interferometry (VLBI). Thus ISS can provide unique information on the structure of the inner radio jet close to the AGN central engine. ISS also probes small-scale structure in the local ionized interstellar medium (ISM).

The Micro-Arcsecond Scintillation-Induced Variability (MASIV) Survey aimed to provide a large, detailed statistical study of the IDV AGN population drawn from a well-defined sample. The present paper highlights some results of the MASIV survey, most of which are described in detail in Lovell *et al.* (2003) and Lovell *et al.* (2008).

Materials and Methods
The MASIV Survey used the NRAO Very Large Array (VLA) observing at 4.9 GHz, which for many sources is close to the transition frequency between weak and strong scattering where the largest amplitude ISS is observed. The first four epochs of observations were carried out in sessions of 72 or 96 hours at 4 month intervals between January 2002 and January 2003. The VLA was split into 5 independent subarrays of typically 5 antennas each, observing subsets of the source sample. 710 compact sources were selected for the first epoch of MASIV Survey observations. The details of source selection are described in Lovell *et al.* (2003). In order to test the dependence of ISS on source flux density

S, "strong" ($S_{8.6\mathrm{GHz}} > 0.6$ Jy; 1 Jy= 10^{-26} W m^{-2} Hz^{-1}) and "weak" ($0.1 < S_{8.6\mathrm{GHz}} < 0.13$ Jy) sub-samples were selected. Additionally, a radio spectral index cutoff $\alpha > -0.3$ ($S \propto \nu^{\alpha}$) was applied. Earlier surveys have shown that steep-spectrum radio AGN don't exhibit short timescale radio variability (Heeschen 1984).

For the MASIV Survey each source was observed for 1 minute every $\sim$ 2 hours while the elevation was above 15°. After the first observing session the number of sources was reduced to a core sample of 578 sources, and the 5th subarray used to better sample those sources which showed evidence of variability on timescales shorter than the 2 hour sampling interval. The results presented here are from analysis of the data from the first four epochs and the first four VLA subarrays.

Source flux densities were extracted in the visibility domain, rather than forming images for all scans. The flux density scale is tied to the VLA primary calibrator 3C 286. Non-variable sources were used to correct gain and pointing errors for the nearby targets. The sources used as calibrators were then excluded from the analysis since they are forced to have zero variation and would therefore bias the statistics if included. Sources that showed effects of resolution or confusion have been excluded from the analysis. The data have a sufficiently high signal-to-noise ratio that the source flux density as a function of time can then be readily measured from the (1-minute) scan-averaged total intensity amplitude averaged over all baselines. The uncertainty in flux density measurements is estimated using $\sigma^2_{\mathrm{err,s,p}} = (s/\bar{S})^2 + p^2$, where $\bar{S}$ is mean flux density, $s = 0.0013$ Jy due to noise and confusion and $p = 0.005$ due to pointing and gain errors. The presence of nearby confusing sources, although generally not a large effect for the VLA at 4.9 GHz, in practice varies from source to source and is often the dominant source of error in the light curves for weak sources. Sources were observed at approximately the same sidereal times on each day of an observing run, and the presence of confusing sources is indicated by a daily repeating pattern in the data. Sources significantly affected by confusion were excluded from the analysis, and we have used a conservative threshold for classifying sources as variable. A total of 443 sources are included in the analysis presented here.

Data analysis
As an initial step the modulation index μ (rms fractional variability) was calculated for each epoch separately, and sources whose modulation index exceeded $2\sigma_{\mathrm{err,s,p}}$ were identified as variable. The initial analysis used conservative error estimates $s = 0.0015$ Jy and $p = 0.01$. Additionally, all light curves were visually inspected and classified independently by 2 members of the team, as many sources not satisfying the $\mu > 2\sigma_{\mathrm{err,s,p}}$ criterion were clearly variable on visual inspection. In particular, many sources showing slow variations did not make the initial cut, as μ is not an ordered statistic and is not sensitive to low-level, slow monotonic changes in flux density. Light-curve inflection points were counted as part of the visual inspection in order to estimate characteristic timescales of variability.

In an independent analysis, the structure function (SF) was used to quantify the amplitude and timescale of variability. A simple model fit was used to estimate the amplitude of the SF at 2 days lag, D(2d), and the lag τ at which the SF reaches half its saturation value. The details of the fit are described in Lovell *et al.* (2008). In order to obtain reliable estimates of these quantities, the four epochs were combined to calculate the SF. In general time scales have large uncertainties due to the limited sampling of the variability pattern, so sources were divided into just three timescale categories: "fast": $2h < \tau < 0.5$ days, "medium": $0.5d < \tau < 3$ days, and "slow" ($\tau > 3$ days). Most variable sources fall into the "slow" category. This implies that the amplitude and timescales of variability are commonly underestimated.

Results and Discussion
Both analysis methods found that approximately half of the MASIV sample showed rms variations between $\sim 1{-}10\%$ on timescales ranging between 2 hours and 3 days in one or more of the four epochs. At any given epoch, $\sim$ 30% of the sources were observed to vary.

No new extreme, intra-hour variable (IHV) sources were discovered in the MASIV Survey. This was initially something of a surprise to the team, as at the time the survey was initiated, two extreme IHV sources had been recently serendipitously discovered (Dennett-Thorpe and de Bruyn 2000; Bignall *et al.* 2003), both from relatively small source samples compared with the MASIV Survey sample, and from observations that were not intended to look for IDV. Another extreme IHV source, PKS 0405$-$385, had earlier been discovered in the Australia Telescope Compact Array IDV Survey which included 118 relatively bright compact sources (Kedziora-Chudczer *et al.* 1997; 2001). It was initially hoped that the MASIV survey would uncover several more such extreme IHVs, since these sources have provided rich datasets for detailed study of the ISS phenomenon and μas-scale source structure, due to the fact that their variability patterns can be well sampled with an interferometer in a relatively short observing session (typically

$\sim$ 12 hours). The IHV sources have been shown to lie behind discrete nearby regions of enhanced scattering (Dennett-Thorpe and de Bruyn 2000; Rickett *et al* 2002; Bignall *et al.* 2006), and the absence of IHV sources in the MASIV Survey implies such nearby scattering "screens" cover only a tiny fraction ($<< 1\%$) of the sky.

In order to investigate the Galactic dependence of IDV, D(2d) was compared with the emission measure (column density of the square of the electron density) as estimated from observations of Hα emission. The intensity of Hα emission from the WHAM Northern sky survey was found on a 1 degree grid (Haffner *et al.* 2003) nearest to each source. The Hα intensity summed over all velocities is interpreted as proportional to the ISM emission measure on that line of sight, assuming the temperature of the emitting gas does not vary by a large percentage (Haffner *et al.* 2003). Figure 1 plots D(2d) against the WHAM Hα emission (in Rayleighs). There is a clear upward trend of D(2d) with emission measure, which establishes ISS as the dominant cause of the variability in the MASIV Survey. The lower panel of Figure 1 shows that the fraction of slowly scintillating sources clearly increases with emission measure and vice-versa for the fast scintillators. This finding that the longer scintillation timescales occur when seen through greater column density of electrons is consistent with enhanced ISS from strongly ionized regions of the ISM, which are typically found towards lower Galactic latitudes and at greater distances L.

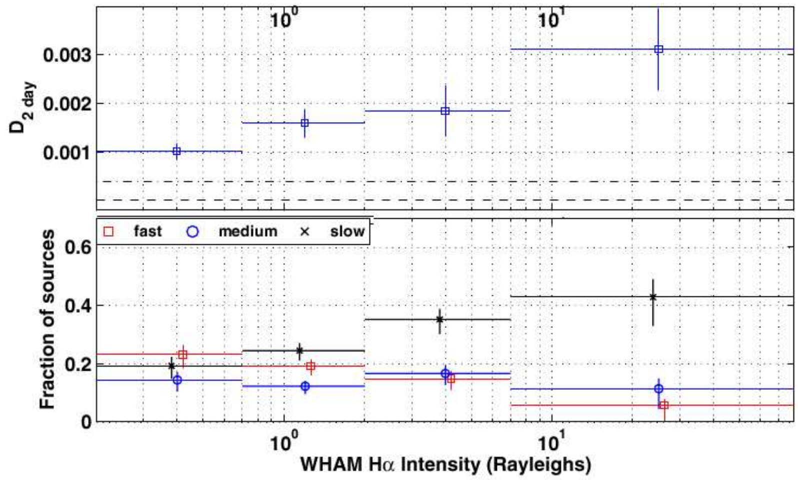

Figure 1: *Upper panel:* Mean value of D(2d) in the indicated bins of Hα emission. The vertical bars give the standard error in the mean. *Lower panel:* Fraction of variable sources in each timescale class in each bin. Error bars assume binomial distributions.

The MASIV Survey found that weaker sources on average show larger fractional varaiations, and the fraction of variable sources increases towards lower flux densities. This is as expected for brightness-temperature limited sources ($\theta_{\rm src} \propto (\bar{S}/T_b)^{0.5}$). At still lower flux densities, ISS may be even more dominant. A simple model of ISS fit to the MASIV observations (Lovell *et al.* 2008) implies maximum brightness temperatures in the range $10^{12} - 10^{14}$ K. This in turn requires substantial Doppler factors in the AGN jets, comparable with those estimated from VLBI and millimetre-wavelength variability studies. Looking at the longer-term inter-epoch variability, which is likely to have a substantial contribution from source-intrinsic variability, no significant correlation with source flux density is seen.

There seems to be a trend for sources detected at GeV energies with EGRET to scintillate more often than non-EGRET-detected sources. Taking only the 17 MASIV sources which are within the 95% confidence radius of an EGRET source position and firmly associated (Hartman *et al.* 1999), 11 sources showed IDV in 2 or more epochs of the MASIV Survey, a larger fraction than expected from sources with the same flux density distribution drawn randomly from the MASIV sample. A simple contingency test shows this difference to be significant at the 95% confidence level, however the source numbers involved are small. The recently launched Fermi Large Area Telescope is expected to detect many more of the MASIV sources and hence allow detailed comparison between ISS and gamma-ray emission.

Figure 2 shows the mean value of D(2d) as a function of redshift for those sources which have measured redshifts, either in the literature or from observations with the Nordic Optical Telescope. This reveals a significant decrease in ISS for sources above a redshift of $z \approx 2.5$. The suppression of ISS of high redshift sources could be caused by either an increase in the apparent diameter of the source, or a decrease in the flux density of the compact fraction. Some decrease in ISS with increasing source redshift is expected for sources limited to a constant rest-frame brightness temperature in the concordance cosmology, however our results indicate an excess suppression of ISS. It remains to be determined whether the observed effect is due to source-intrinsic cosmological evolution and/or selection effects, or may be apparent angular broadening due to scattering in the ionized intergalactic medium. Scatter-broadening would be expected to have a strong frequency dependence. VLBI observations may indicate whether the effect is likely to be due to a fainter μas-scale core fraction if the high-redshift sources show significant milliarcsecond-scale structure.

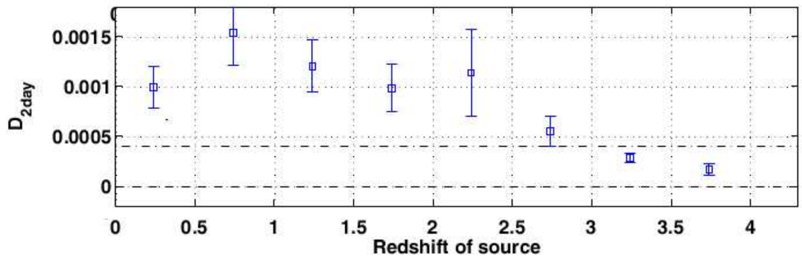

Figure 2: Mean value of D(2d) in redshift bins for 271 sources with measured redshift.

Conclusions

The MASIV Survey showed that a large fraction of compact extragalactic radio sources show variations on timescales of days due to interstellar scintillation at frequencies of a few GHz, implying angular sizes for the radio "cores" of $\sim 10 - 50\mu$as. An excess suppression of ISS is seen for sources beyond redshift $z \sim 2$. Towards lower flux densities, the fraction of scintillating sources increases. Next generation wide-field radio telescopes such as the Square Kilometre Array will have to account for many variable sources in the field of view. Extracting measurements of the variable sources will provide a rich database for large statistical ISS studies.

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