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An update on MASIV: How intrinsic properties influence interstellar scintillation of AGN

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Many flat-spectrum AGN exhibit short timescale variations when observed at radio wavelengths, due to interstellar scintillation (ISS). The observed variations depend on source angular size and "core dominance", as well as on the scattering properties of the intervening interstellar medium, both of which are highly non-uniform when considering large samples. ISS offers a powerful probe of source structure on micro-arcsecond angular scales. However, in order to use the statistics of ISS as a probe, it is necessary to understand the selection effects in the AGN samples under study. One initially surprising result of the MASIV 5 GHz VLA Survey was a drop-off in the ISS amplitudes of sources above z=2. In order to determine the cause of this effect, follow-up VLA observations were conducted at two frequencies. Our sample shows on average a steepening of source spectral index with redshift. Careful analysis shows that, after accounting for the redshift-spectral index correlation, the redshift dependence of ISS can be successfully modelled by the expected $(1+z)^{0.5}$ scaling of intrinsic angular sizes of a flux- and intrinsic brightness temperature-limited sample. The MASIV follow-up observations allow limits to be placed on angular broadening due to interstellar and intergalactic scattering, beyond the resolution achievable with ground-based VLBI.

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1. Introduction

All sufficiently compact sources viewed through the inhomogeneous, turbulent, ionised Galactic interstellar medium (ISM) are subject to interstellar scintillation (ISS) at centimetre wavelengths. A critical scale in weak scattering, which is relevant for most extragalactic lines of sight at observing frequencies ν of a few gigahertz and above, is the angular Fresnel scale, $\theta_{\rm F} = \sqrt{c/(2\pi\nu L)}$; which is of order tens of microarcseconds for scattering screen distances L in the range $\sim 10-100$ pc. The characteristic scale of the scintillation pattern fluctuations in weak scattering is approximately equal to the Fresnel scale, and thus ISS can be used as a probe of source structure on these microarcsecond (μas) angular scales. For example, Rickett et al. [1] modelled the μas-scale polarized structure of the fast intra-day variable quasar PKS 0405$-$385, and Macquart and de Bruyn [2] modelled changes in the μas-scale structure of J1819+3845.

More recently, we have been investigating a new method of studying "core shifts" in AGN by cross-correlating light curves in the weak ISS regime at different frequencies. This technique takes advantage of the fact that scintillation patterns are highly correlated across a broad range of frequencies in the weak scattering regime, and of the availability of new broadband backends at the ATCA and the EVLA, which enable detailed study of the frequency dependence of the core shifts. Cross-correlation of sufficiently well-sampled light curves at different frequencies reveals systematic time delays. When the centroids of the scintillating components at different frequencies are displaced by an angular distance $\Delta\theta$, the resultant scintillation patterns will be displaced by a distance $L\Delta\theta$, where L is the effective scattering screen distance (e.g. Little & Hewish 1966 [3]). The observed time delay depends on the magnitude and direction—relative to the core-shift displacement vector—of the scintillation velocity, which varies over the course of a year due to the Earth's orbital motion; and also on the axial ratio and direction of any anisotropy in the scintillation pattern (see Bignall & Hodgson 2012 [4]; Coles & Kauffman 1978 [5]). In general, scintillating components correspond to the "core" in VLBI images (e.g. Ojha et al. 2004 [6]). In principle, ISS can be used to determine the frequency dependence of core shifts with at least an order of magnitude higher precision than VLBI (Macquart, Godfrey, Bignall & Hodgson 2012, ApJ submitted).

Timescales of ISS in weak scattering range from minutes, in the case where the scattering plasma in the ISM is within a few parsecs of the observer (e.g. [2]), to days for kiloparsec screen distances (e.g. Turner et al. [7]). The "intra-hour variable" quasars PKS 0405$-$385, J1819+3845 and PKS 1257$-$326 have been well-studied due to their ISS being rapid enough to allow a comprehensive sample of the fluctuations to be obtained in a typical, 12-hour observing session with an interferometer such as the ATCA, WSRT or VLA. However, most AGN ISS timescales are much longer, and the AGN components are generally larger than the Fresnel scale, and/or have significant extended emission around the core, so that the scintillation is "quenched"; resultant modulation indices are typically at most a few percent of the total flux density.

In order to study the statistics of both the compact components in AGN and the properties of the Galactic ISM responsible for the scintillation, a large survey is necessary, and this was the motivation for the Micro-Arcsecond Scintillation-Induced Variability (MASIV) VLA Survey by Lovell et al. [8, 9] and dual frequency follow-up observations [10, 11]. In the following section, we briefly review the findings of the MASIV Survey and discuss recent results from the dual frequency follow-up observations, as well as their implications.

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2. The MASIV Survey

The MASIV Survey observations and results are described in the companion paper by Jauncey et al. (these proceedings) and by Lovell et al. [8, 9]. Briefly, we measured flux density variations on timescales between 2 hours and 3 days for a core sample of 443 compact, flat-spectrum radio sources, using the VLA at 5 GHz in four observing sessions between January 2002 and January 2003. Half of the sample was made up of strong sources (catalogued flux density $S \gtrsim 0.5$ Jy), with the other half selected to be ~ 100 mJy, as intra-day variability of such faint sources had not been studied previously. One of the most immediate findings of the MASIV Survey was a significant increase in the incidence and amplitude of variability amongst the weaker radio sources. Figure 1 shows the average amplitude of variability on a timescale of two days, measured from the (error-corrected) structure function for the combined data from the first four MASIV Survey epochs. Such a trend is expected for brightness temperature-limited sources, where angular size is expected to scale as $\sqrt{S}$ assuming no change in the Doppler boosting factor. The large scatter in the data clearly indicates that flux density is of course not the only factor influencing the observed variability.

A comparison of the variability against intensity of $H\alpha$ emission from the Wisconsin $H\alpha$ Mapper (WHAM) Survey (Haffner et al. [12]) nearest to each source also shows a clear trend of increasing variability with increasing $H\alpha$ intensity, which is interpreted as being proportional to the Galactic ISM emission measure on that line of sight. This correlation between the two completely independent datasets provides strong evidence that the variability observed in the MASIV Survey is linked to the ionised ISM, i.e. it is predominantly interstellar scintillation. Figure 2 shows the structure function at two days lag, D_{2d}, plotted against Hα intensity, with the sources separated into two groups by flux density. As discussed by Lovell et al. [9], the timescale of variability is also observed to increase when seen through a greater column density of electrons, which is an indication of stronger scattering through strongly ionised regions of the ISM; these are typically seen at lower Galactic latitudes.

2.1 Optical identification of the MASIV sample

In order to determine the physical properties of sources in the MASIV sample, reliable redshift measurements are essential. We have obtained optical and spectroscopic identifications for the majority of MASIV sources both from the literature and from our own observations with the 2.56 m Nordic Optical Telescope (NOT) on La Palma and the 5 m Hale Telescope at Mount Palomar. In total we have 347 reliable spectral classifications (Pursimo et al. 2012, ApJ submitted).

The sources are primarily flat spectrum quasars (FSRQ; almost 80%) and BL Lac objects ($\sim$ 13%), with $\sim$ 7% being narrow line objects or galaxies. On average, the BL Lacs are most likely to scintillate, and make up 40% of the sources which showed significant variability in all four epochs of the MASIV Survey. This finding suggests that the BL Lac objects in our sample are more strongly core dominated than the FSRQ. This may indicate that the BL Lac jets are typically viewed at a smaller angle to the line-of-sight than FSRQ, thus having higher core dominance or smaller angular size for a given flux density due to increased Doppler boosting factors, or there may be no difference in viewing angle but BL Lacs may simply have less emission on milli-arcsecond (mas) scales than FSRQ, again resulting in increased core dominance. Indeed, for a sub-sample of 30 BL Lacs and 112 FSRQ with available 8 GHz VLBI data [6], the mean core fraction (ratio

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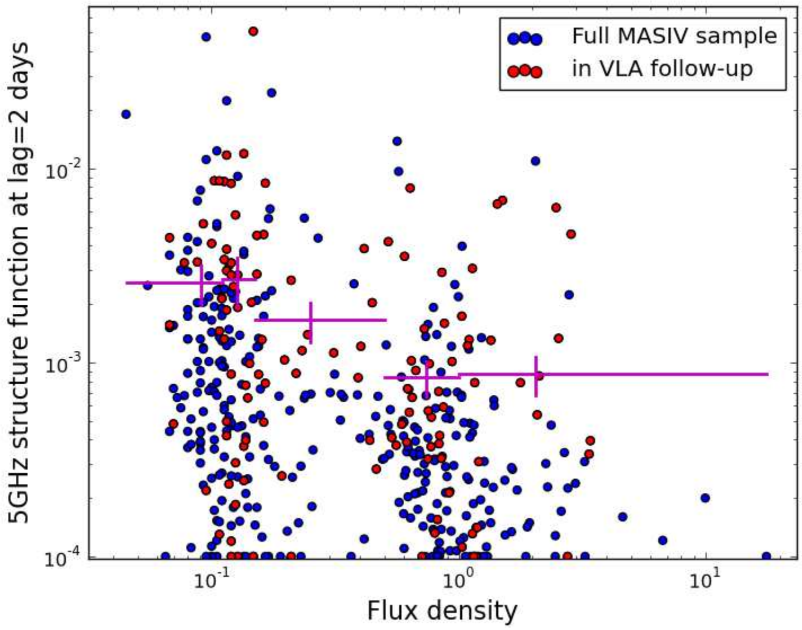

Figure 1: Mean amplitude of variability at 5 GHz from the structure function at 2 days lag from the original MASIV Survey, as a function of mean total source flux density. Binned data are overplotted, with vertical lines indicating the sample error-of-the-mean, and horizontal lines indicating the bin range. The 128 sources which were included in the dual frequency VLA follow-up described in section 2.2 are shown in red. The structure function amplitude is plotted here at 10^{-4} if the actual value is lower than 10^{-4} (well below the threshold for detectable variability).

of unresolved core to total VLBI flux density) of the BL Lac objects (0.83) is significantly larger than that of the FSRQ (0.77) at the 95% confidence level. However the mean values of D_{2d} of these FSRQ and BL Lac VLBI samples are identical ($\overline{D_{2d}} = 0.0019$ for both samples), as this VLBI sample is biased toward scintillating sources. The VLBI results then appear to favour the hypothesis that the less powerful BL Lac jets lead to weaker emission on mas scales outside the "core".

Perhaps the most intriguing result of the MASIV Survey was the discovery of a decrease in ISS towards higher redshifts above $z \approx 2$. This finding implies that sources at higher redshift have larger apparent angular sizes than their low redshift counterparts. As other evidence such as the flux density dependence suggests that we are observing brightness temperature-limited sources, it is important to ask what is the expected dependence of angular size on redshift for such a sample, as previously discussed by Rickett et al. [13] and Koay et al. [11]. If seen at redshift z, the observed brightness temperature will be $T_{\rm b,obs} = T_{\rm b,em}/(1+z)$, where $T_{\rm b,em}$ is the emitted brightness temperature. For a beamed source with Doppler factor δ, $T_{\rm b,em} = \delta T_{\rm b,int}$, where $T_{\rm b,int}$ is the intrinsic brightness temperature in the rest frame of the source. The observed angular size of radio sources of a given flux density, assuming no evolution of Doppler beaming factors, should therefore scale with redshift as $\theta \propto (1+z)^{0.5}$. Initial results of the MASIV Survey suggested suppression of ISS in excess of this effect towards high redshift, above $z \approx 2$.

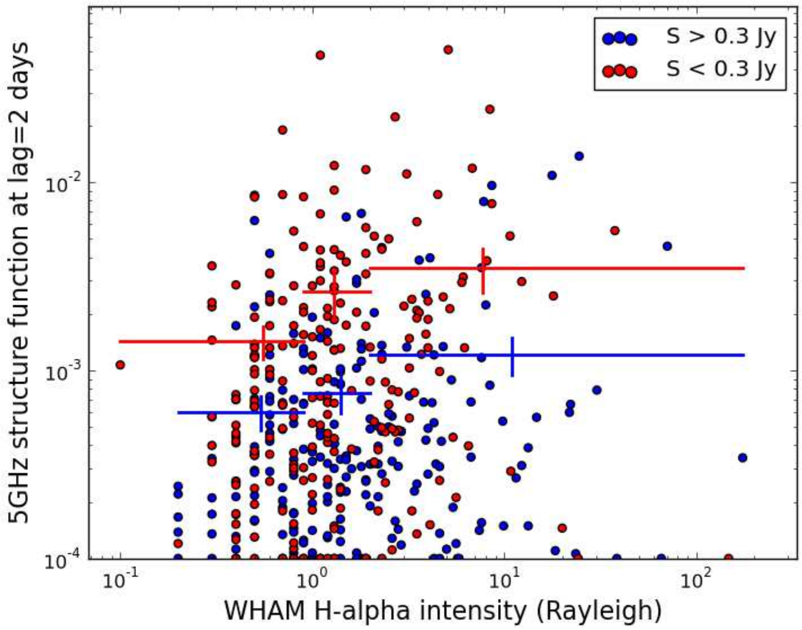

Figure 2: Mean amplitude of variability at 5 GHz from the structure function at 2 days lag from the original MASIV Survey, as a function of Galactic Hα intensity from the WHAM Survey (interpolated onto a 1° grid). Sources are divided into two flux density bins. The structure function amplitude is plotted here at 10^{-4} if the actual value is lower than 10^{-4} (well below the threshold for detectable variability). Binned averages are overplotted, with vertical lines indicating the sample error-of-the-mean, and horizontal lines indicating the bin range.

The observed suppression of ISS of high redshift sources implies either that these sources have significantly larger angular sizes than the predicted $\theta \propto (1+z)^{0.5}$ scaling of their low redshift counterparts, or that they are less core-dominated than the low redshift sources in MASIV. As discussed by Koay et al. [11], several possible effects were considered to explain the observed redshift dependence, including angular broadening due to scattering in the turbulent intergalactic medium (IGM), intrinsic source evolution, sample selection effects and gravitational lensing.

2.2 MASIV VLA follow-up observations

Scatter-broadening and source intrinsic size effects are expected to scale differently with frequency. Therefore, investigating the frequency dependence of ISS provides a means of determining the origin of the observed redshift dependence. With this aim, VLA follow-up observations at 4.9 and 8.4 GHz were conducted for all of the MASIV sources with $z > 2$ (approximately 70 sources at the time of the observations) and a comparison sample of low redshift sources. The low redshift sample was selected to have the same flux density distribution as the high redshift sample, and there was also no significant difference in the Galactic line-of-sight distributions. The sources were observed over 11 days with the VLA in January 2009, during reconfiguration time. The observations and data analysis are described in detail by Koay et al. [10].

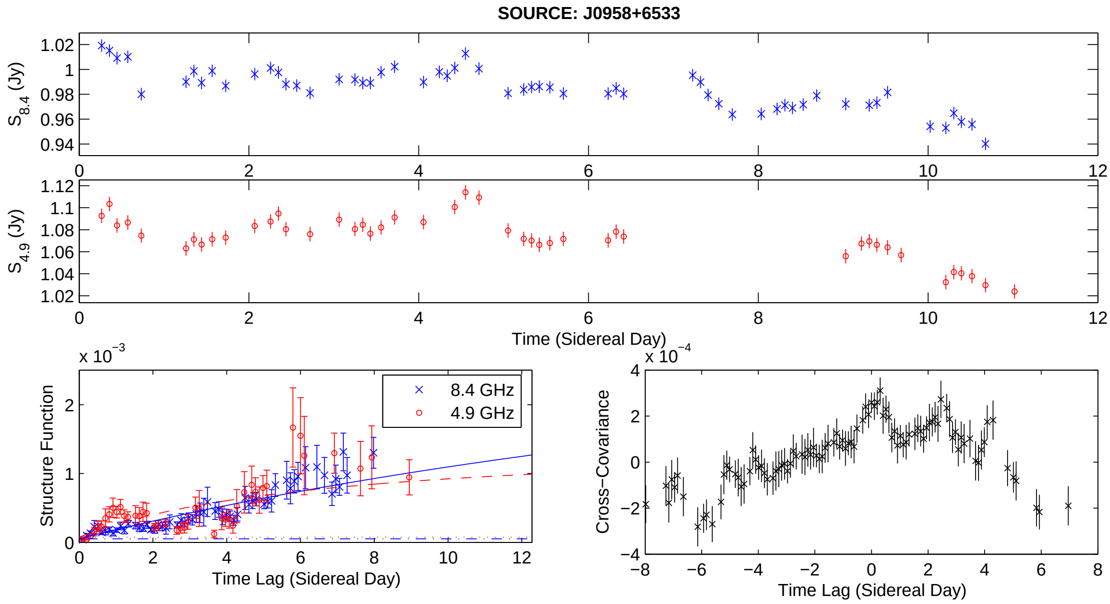

Figure 3: Typical dataset for a source in the 2-frequency VLA follow-up observations. The source shown here is the previously known intraday variable S4 0954+65. The structure function at each frequency and cross-covariance between the two frequencies are also shown.

Figure 3 shows the dataset obtained for the well known intra-day variable S4 0954+65 (e.g. Quirrenbach et al. 1992 [14]; Marchili et al. 2012 [15]). The structure function and cross-covariance of the light curves at each frequency are shown. The location of the peak in the cross-covariance function indicates a possible core shift, although in this case the light curves are not sufficiently well sampled to reliably quantify any offset.

The dual frequency VLA data provide a reliable instantaneous spectral index for all 128 sources included in the follow-up sample. The original MASIV Survey source selection relied on catalogued flux densities from measurements at different epochs; thus the initially calculated spectral indices are somewhat unreliable as most of the sources are variable. Two important findings of the MASIV VLA follow-up observations are (i) a correlation of instantaneous spectral index with variability, in the sense that the steeper spectrum sources showed lower amplitude scintillation, and (ii) on average, the higher redshift sources tended to have somewhat steeper instantaneous spectral indices than the low redshift sources in the follow-up sample.

Figure 4 shows binned values of D_{4d}, the structure function at 4 days lag, for the MASIV follow-up data at 4.9 GHz as a function of redshift. The effect of excluding sources with spectral indices $\alpha_{4.9}^{8.4} < -0.3$ (where $S_\nu \propto \nu^\alpha$) is shown. For comparison, the original MASIV spectral index selection criterion was $\alpha_{1.4}^{8.4} > -0.3$ from catalogued flux densities. Excluding the steeper-spectrum sources results in increased values of D_{4d} in all bins, with the largest increase observed for the high redshift bin, although this effect is only ~ 1 sigma, perhaps due to the small number of sources. After excluding the sources with $\alpha_{4.9}^{8.4} < -0.3$, the resultant decrease in amplitude of ISS with redshift is no longer in excess of the $\theta \propto (1+z)^{0.5}$ dependence expected of a flux-limited sample of sources with a fixed rest-frame brightness temperature, assuming no evolution of Doppler factor

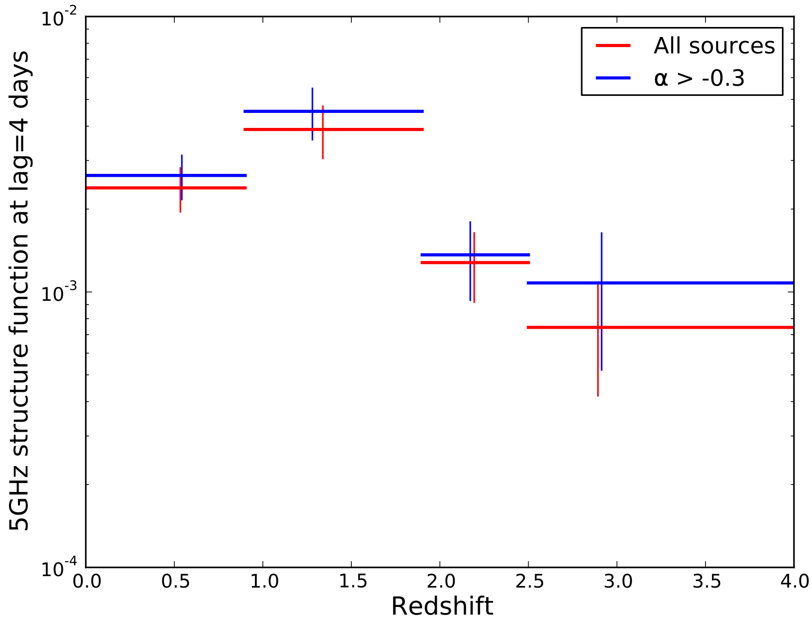

Figure 4: Mean amplitude of variability at 4.9 GHz from the structure function at 4 days lag, binned as a function of redshift, for the 128 sources in the MASIV follow-up observations [10, 11]. Red lines are for all observed sources with reliable redshift information (approximately 30 sources per bin); blue lines show values excluding sources with spectral indices steeper than -0.3 ($S_\nu \propto \nu^\alpha$). Vertical error bars indicate the standard error of the mean. This plot shows that excluding the less variable, steep-spectrum sources results in the largest fractional change in mean variability amplitude for the highest redshift bin.

with redshift.

Limits on scatter broadening for all sources were obtained from an analysis of the ratio of structure functions at each frequency, which removes some source-dependent effects (as individual sources are likely to have very similar parameters such as Doppler factor and compact fraction at 4.9 and 8.4 GHz). As presented by Koay et al. [11], angular broadening in the IGM at 4.9 GHz is inferred to be $\lesssim 110\mu$as for all lines of sight to the MASIV sources, and down to $\lesssim 8\mu$as for sight-lines to the $\sim 10\mu$as sources. No significant scatter broadening was detected at the observed frequencies, due either to the ISM or the IGM.

3. Conclusions

Although there are various effects, both source-intrinsic and extrinsic, to be separated out in a full analysis of interstellar scintillation of compact extragalactic radio sources, it is possible to use the statistics of ISS as a probe of source structure on scales beyond the resolution of ground-based VLBI. Only space VLBI can achieve a similar resolution, but this is currently limited to relatively strong sources observable between ground-based telescopes and the RadioAstron 10 m diameter Space Radio Telescope.

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