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On the redshift dependence of scintillating AGN: results of the MASIV Survey and follow-up observations

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The Micro-Arcsecond Scintillation-Induced Variability (MASIV) 5 GHz VLA Survey provided a large sample of radio sources showing interstellar scintillation with which to investigate the highest brightness temperature components of AGN. One of the most intriguing findings of MASIV is that compact radio AGN at redshifts above $z \approx 2.5$ show significantly reduced interstellar scintillation (ISS) compared with their lower redshift counterparts. As ISS is strongly dependent on source angular size, this implies that on average, the high redshift MASIV sources appear much less compact to the ionized interstellar medium (ISM) than the lower redshift sources. We discuss the current status of ongoing investigations to determine the cause of the observed effect.

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1. Introduction

With evidence accumulated over the past 15 years to demonstrate that intraday variability of active galactic nuclei (AGN) at centimetre wavelengths is predominantly interstellar scintillation (ISS; e.g. [1]-[9]), it was realised that ISS can be used as a probe of source structure on scales two orders of magnitude smaller than accessible directly even with very long baseline interferometry (e.g. [10]). ISS is also a probe of small scale structure in the ionized interstellar medium (ISM) of our own Galaxy. The Micro-Arcsecond Scintillation-Induced Variability (MASIV) Survey [11] was conceived to provide a large sample of intraday variable (IDV) radio sources with which to investigate the highest brightness temperature components of AGN, their evolution and correlation with multiwavelength source properties, as well as properties of the local Galactic ISM along the line-of-sight to the source.

1.1 Interstellar scintillation of extragalactic radio sources

The ionized interstellar medium of our Galaxy is highly inhomogeneous on scales down to $\sim 10^7$ m and smaller. Radio emission passing through the ISM thus encounters variations in refractive index, resulting in scattering and mutual interference of the scattered wavefronts [12, 13]. Provided a source is sufficiently compact, this results in measurable intensity variations, due to the relative motion of the telescope with respect to the resultant scintillation pattern. Scintillation is strongly dependent on wavelength and geometry, as well as the scattering properties of the medium.

A critical scale in scintillation is the Fresnel radius, $r_{\rm F} = \sqrt{L/k}$, where k is wavenumber ($2\pi/\lambda$ for observing wavelength λ) and L is the distance between the observer and the equivalent scattering screen. If the rms phase changes introduced by the medium are small over the first Fresnel zone (angular size $\theta_{\rm F} = r_{\rm F}/L$), then scintillation occurs in the weak scattering regime. For extragalactic sources at Galactic latitudes $b_{II} \gtrsim 10°$, interstellar scattering is typically weak above frequencies of a few GHz, and $\theta_{\rm F}$, which corresponds to the decorrelation scale of the scintillation pattern in weak scattering, is of order 10 microarcseconds (μas). In the strong scattering regime, at lower frequencies and/or lines of sight passing through strongly ionized regions of the Galaxy at large distances (e.g. typically looking through the Galactic plane), there are two distinct types of scintillation - diffractive (short-timescale, narrow-band interference effects) and refractive (slow, broadband variations). In general, quasars are too large to exhibit diffractive scintillation. However, many flat-spectrum quasars exhibit low frequency variability [14, 15] due to refractive scintillation. For a compact quasar, the largest amplitude variations due to ISS generally occur close to the transition between weak and strong scattering. Thus “weak scattering” does not imply low-amplitude scintillation; often large-amplitude, rapid scintillation is observed in the weak scattering regime.

ISS also affects transient sources which in general (by light travel time/causality arguments) must be extremely compact. For example, Chandra et al. [16] interpret the rapid radio flux density variations observed from the afterglow of the bright gamma-ray burst GRB 070125 as ISS, using this to derive limits on the radius of the fireball.

2. The MASIV Survey and follow up observations

The MASIV 5 GHz VLA Survey comprised observations of ~ 500 compact, flat-spectrum radio sources selected from the CLASS (Cosmic Lens All Sky Survey; e.g. [17]) and JVAS (Jodrell Bank VLA Astrometric Survey; [18]-[20]) catalogues. The initial survey observations were undertaken in four sessions of 72 hours each (96 hours for the September session), spread over the course of a year (January 2002 – January 2003). Details of analysis and major results were published in [21]. Over half (56%) of the sources were found to exhibit significant variability in at least one epoch, with typical rms variations 2–10% on characteristic timescales, $t_{\rm char}$, derived from structure function analysis as described in [21], ranging from < 0.5 days (exhibited by approximately 30% of the variable sources) to longer than 3 days (the maximum timescale probed by the initial Survey observations). Almost half of the variable sources showed evidence for variability on timescales longer than 3 days, i.e. for $\sim 25\%$ of the observed sources, the original MASIV Survey observations do not provide well-sampled light curves for the short-timescale (timescales of days) variability. Additionally, as discussed in some detail in [21], there is evidence of intermittency in short-timescale variability, which may arise due to changes along the line-of-sight in the level of turbulence responsible for ISS, or it may arise if the lifetimes of the bright, microarcsecond source components that undergo ISS are short. MASIV remains the largest survey of intraday radio variability to date, and the size of the source sample has enabled for the first time a number of important statistical tests.

In order to test the dependence of short-timescale variability on mean source flux density, "strong" and "weak" source samples were selected for the Survey observations, where strong sources are defined as having average flux density $S_{\rm 5GHz} > 0.3$ Jy, and weak sources have average flux density $0.3 > S_{\rm 5GHz} > 0.06$ Jy; still bright enough to clearly detect variations on the level of a few percent or less using $\sim 1/5$ of the VLA collecting area and 1-minute scans on source. The MASIV Survey found that ISS of these flat-spectrum radio sources increases with decreasing flux density, in the sense that a larger fraction of the weak source sample showed significant variability compared with the strong source sample, and larger fractional variability was observed in the weak source sample. This is expected for sources which are brightness-temperature limited, as for fixed rest-frame brightness temperature and beaming parameters, increasing flux density implies a larger source angular size, which results in increased suppression of ISS. VLBI results [22, 23] suggest that the increase of ISS with decreasing source flux density is not necessarily due to a brightness temperature limitation, but may be due to the weaker radio sources having less emission in milliarcsecond-scale jets compared with the stronger sources. The stronger sources would then have a much smaller fraction of their flux density in the compact scintillating component, such that the flux density modulations would be largely suppressed.

2.1 Galactic dependence of MASIV

As reported in [21], the average amplitude of short-timescale variability was found to increase with increasing emission measure (column density of the square of the Galactic electron density) along the line of sight. The emission measure was estimated using the intensity of Hα emission extracted from the published WHAM Northern sky survey on a 1 degree grid [24] nearest to each source. Furthermore, a significant correlation was found between characteristic variability timescale from MASIV and Hα intensity, in the sense that the fraction of sources exhibiting "slow" variability ($t_{\rm char} > 3$ days) clearly increases with increasing emission measure, and conversely the fraction of "fast" variables ($t_{\rm char} < 0.5$ days) decreases with increasing emission measure. As the

MASIV and WHAM Survey datasets are completely independent, the strong dependence found between the observed short timescale variability and the Hα intensity from the WHAM Survey confirms that the 5 GHz short-timescale variability is closely linked to the ionized interstellar medium, i.e. the observed variability is predominantly interstellar scintillation.

The observed behaviour is consistent with enhanced ISS from strongly ionized regions of the ISM, which are typically at low Galactic latitudes and relatively large distances. An increase in distance to the scattering screen increases the scale of the scintillation pattern which slows the scintillation time. The lack of very extreme rapid variability, such as exhibited by quasars PKS 0405−385 and J1819+3845, and determined to be due to scattering in extremely nearby "screens" [25, 7], suggests the probability of the line of sight intersecting such nearby regions of enhanced electron density fluctuations is extremely small. This result was initially somewhat surprising to the MASIV team, since three of these extreme, intrahour variable scintillators had been recently discovered in much smaller source samples [1, 26, 8].

2.2 Optical identification of MASIV Survey sources

Redshifts are essential to determine physical properties, such as luminosity, linear sizes and accurate brightness temperatures, of sources observed in the MASIV Survey. We searched the literature for redshifts and spectroscopic identification of objects observed in the MASIV Survey, finding 254 objects with published redshifts (original references are listed in Pursimo et al., in preparation). The objects identified in the literature are predominantly the stronger radio sources. We have subsequently measured redshifts for 71 additional sources using spectroscopic data obtained at the Nordic Optical Telescope in La Palma, Spain and the Palomar Hale telescope in the USA [27]. These observations also identified 5 new BL Lac objects with featureless spectra, and 8 objects with a single emission line.

We now have spectroscopic identifications and redshifts for $\sim 90\%$ of the radio "strong" source sample ($S_{5\mathrm{GHz}} > 0.3$ Jy) and $\sim 50\%$ of the radio "weak" sample ($0.3 < S_{5\mathrm{GHz}} < 0.06$ Jy). About 80% of the "strong" and 60% of the "weak" sources have an optical counterpart with $R < 20$ magnitude. Almost 80% of the identified MASIV sources are classified as flat spectrum radio-loud quasars (FSRQ), $\sim 13\%$ are BL Lac objects, and $\sim 7\%$ narrow-line (Type II) objects or galaxies. Of the ISS sources, 25% are BL Lacs, and the rest are almost exclusively FSRQs. The BL Lac fraction increases with the observed level of ISS, with 40% of the sources which showed IDV in all four epochs of the MASIV Survey being identified as BL Lac objects.

2.3 Redshift dependence of MASIV

ISS depends strongly on the apparent angular diameter of the radio source as seen by the ISM, and should be independent of the quasar redshift. However, the MASIV Survey found a decrease of ISS for sources at higher redshifts. The value of the structure function at 2 days lag, D_{2d}, used to quantify the amplitude of short timescale variability, decreases with source redshift in the range 2–4. D_{2d} depends on both the fraction of flux density in, and the angular diameter of, the compact "core" as seen by the ISM.

[28] showed that if the core emission is limited to a maximum brightness temperature in the co-moving frame, the minimum source diameter should increase as $(1+z)^{0.5}$ due to cosmological

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expansion. However the observed ISS was found to decrease significantly faster than this prediction, indicating an increase in source angular diameter of an additional factor of two from $z = 2.2$ to $z = 3.7$. One tantalising possible explanation of this effect is that the more distant AGN radio cores may be scatter-broadened in the turbulent ionized intergalactic medium (IGM), so that their apparent angular size is then too large for them to scintillate due to scattering in the interstellar medium of our Galaxy. If this can be shown to be the case, then the redshift dependence of ISS offers a unique probe of turbulence in the ionized IGM, where the unseen vast majority of baryons in the Universe reside since the epoch of reionization. This would complement Lyman-α studies (which are sensitive only to the neutral component), as well as UV and X-ray observations of the hot intra-cluster medium. Alternatively, the observed decrease of ISS of high redshift sources may be a result of intrinsic evolution of the AGN radio cores, which would allow studies of the evolution of sub-parsec scale AGN structure with redshift. However, a number of possible selection effects, including luminosity and spectroscopic type, may result in correlations of ISS properties with redshift, and selection effects must be thoroughly investigated before any conclusions can be drawn.

The figures presented in [28] and [21] used all redshifts available at the time, regardless of spectroscopic ID. In Figure 1 we consider only the FSRQ sample, to avoid a possible bias due to lumping together the different types of AGN. An important question to ask is, can we distinguish between a redshift dependence and a luminosity dependence of ISS? Figure 1 shows that the two are strongly correlated. (To calculate the luminosities here we have used $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ and $H_0 = 75$ km s^{-1} Mpc^{-1}.) Selecting only the high-luminosity radio sources with $\log_{10} L_R > 27$, so that the luminosities are relatively uniform across the redshift range, the redshift dependence is weaker but still apparent. Nonetheless, this illustrates that there are many dependencies to consider in interpreting the observed effects. If the increased angular size at high redshifts is dominated by an increasing source size with luminosity, this would seem to contradict previous findings based on VLBI observations of quasar angular size at milliarcsecond scales (e.g. [29]).

2.4 VLA follow-up observations: the frequency dependence of ISS with redshift

If the redshift dependence of sources showing ISS is a result of scatter-broadening in the IGM, this is expected to have a strong frequency dependence, such that the suppression of ISS with redshift should be significantly reduced towards higher observing frequencies where the amount of scatter-broadening is much less. The intrinsic angular size of the radio core is expected to have a much shallower frequency dependence. The expected frequency dependence of ISS can then be modelled for the case of IGM scatter-broadening versus no scatter broadening. To test the predictions of the different models, we proposed VLA observations of the 70 MASIV Survey sources with redshifts $z > 2$ at frequencies of 4.9 and 8.4 GHz simultaneously, along with a comparison sample of 70 sources with $z < 2$, selected to approximately match the flux density and sky distribution of the high redshift sample.

Observations were carried out with the VLA over 11 days from the 15th to the 25th of January 2009. Since a large fraction of MASIV sources showed evidence for variability on significantly longer timescales than probed in the original Survey, the longer duration of the follow-up observations allowed much more accurate characterisation of the variability on longer timescales. Furthermore, the simultaneous observations at different frequencies allow accurate determination of

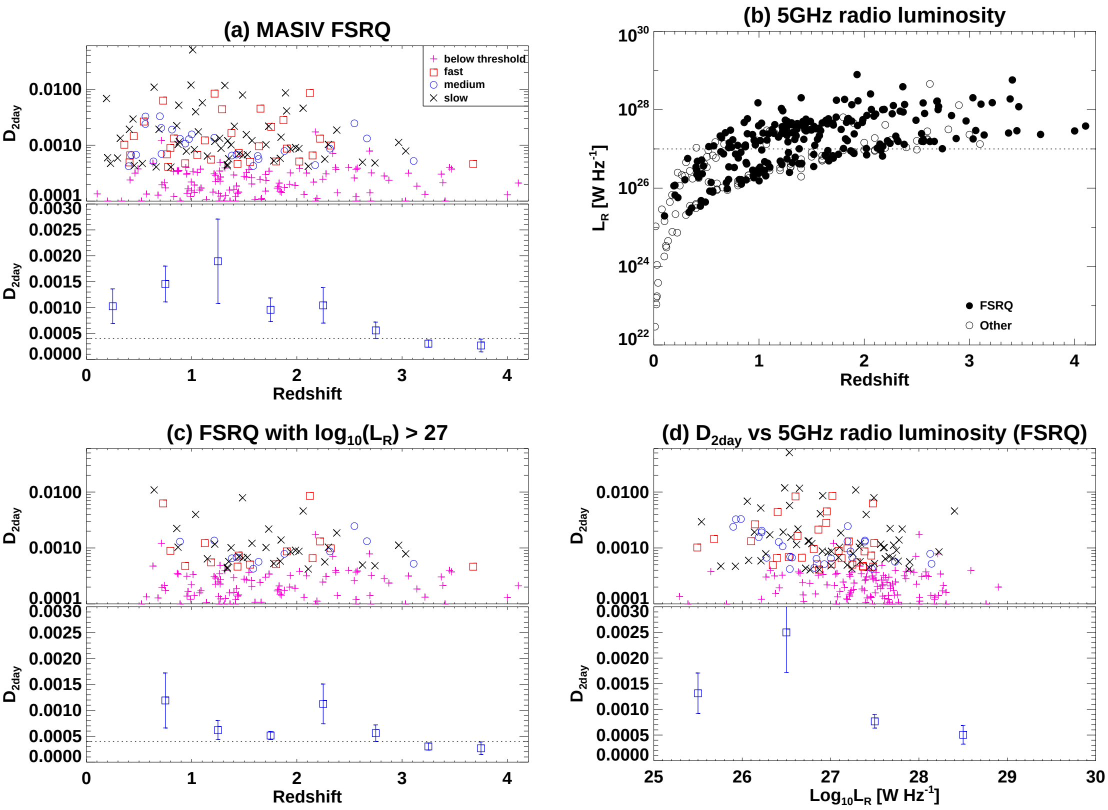

Figure 1: **(a)** *Upper panel:* Scatter plot of $D(2\mathrm{d})$ (note the log scale in upper panels) against source redshift for sources identified as flat-spectrum radio quasars (FSRQ). The different symbols represent the three classifications of ISS timescale. Values below the threshold with $D(2\mathrm{d}) < 10^{-4}$ are plotted here along the lower axis. *Lower panel:* Mean value of $D(2\mathrm{d})$ in redshift bins for the 238 MASIV sources identified as FSRQ (excluding extreme IHV quasar J1819+3845). Note lower levels of ISS at high redshift. Values below the dotted line are upper bounds since they may be raised slightly by low level confusion.
(b) Radio luminosity, L_R, versus redshift for all MASIV Survey sources with measured spectroscopic redshifts. L_R is estimated from the mean 5 GHz flux density from the MASIV Survey observations, assuming spectral index 0 (with no correction for beaming). The dotted line is at $\log_{10} L_R = 27$.
(c) *Upper panel:* Scatter plot of $D(2\mathrm{d})$ against source redshift for FSRQ with $\log_{10} L_R = 27$. Symbols as for upper panel in (a). *Lower panel:* Mean value of $D(2\mathrm{d})$ in redshift bins for the 121 FSRQ with $\log_{10} L_R = 27$.
(d) *Upper panel:* Scatter plot of $D(2\mathrm{d})$ against L_R for the FSRQ. *Lower panel:* Mean value of $D(2\mathrm{d})$ in luminosity bins for the 238 FSRQ.

the spectral index for each source, which previously was not possible for these variable sources as observations at different frequencies had been made at different epochs. Figure 2 shows the light curves and structure function obtained for one of the sources from the January 2009 observations.

The 2009 VLA observations confirmed previous findings of Galactic dependence. Figure 3 shows a very strong correlation between WHAM Hα intensity and the value of the structure function at 4 days lag, at both frequencies. The observed correlation is maintained for structure functions evaluated at all lags from 2 to 9 days, as well as for values determined from simple models fitted to the structure function. This again confirms ISS as the dominant cause of the variability at

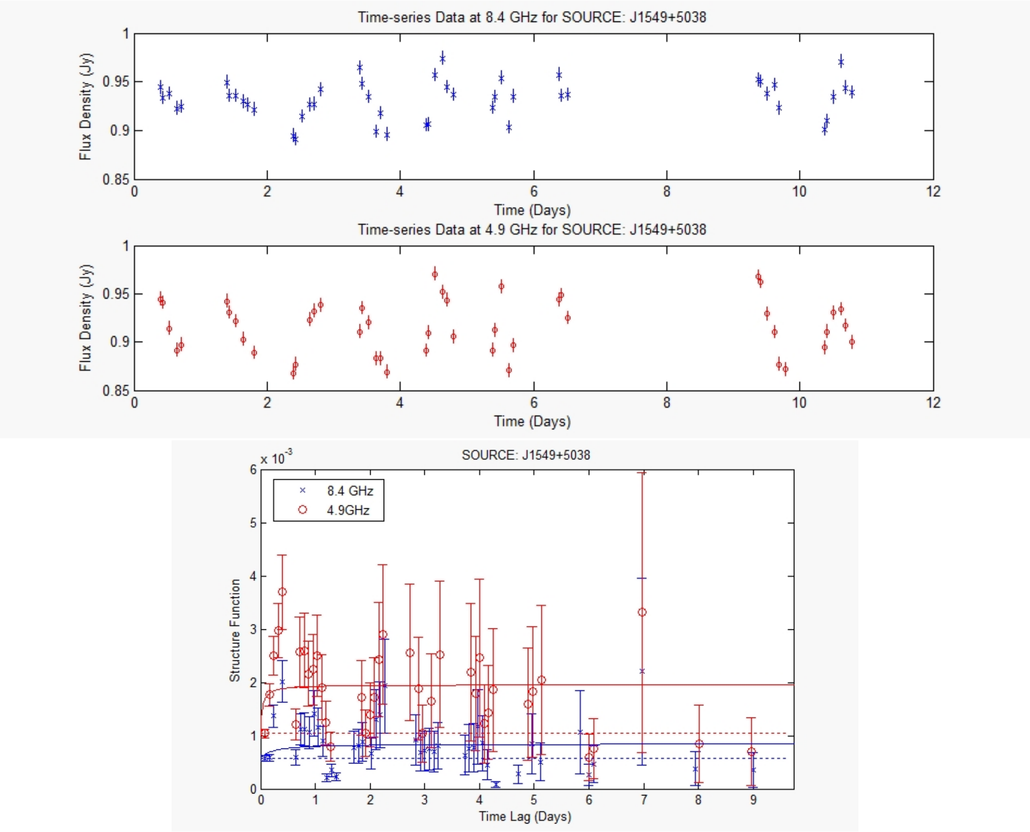

Figure 2: Example light curve and structure function at 8.4 and 4.9 GHz from the VLA follow-up observations for J1549+5038, a FSRQ at redshift $z = 2.175$.

these timescales.

Preliminary results show that the redshift dependence of ISS is less pronounced at 8.4 GHz than at 4.9 GHz. In order to interpret the observed frequency dependence of ISS as function of redshift, a full analysis of all systematic and selection effects is required. This analysis is ongoing and will be presented in a future paper (Koay et al. in preparation).

2.5 VLBI observations of MASIV Survey sources

Previous analysis of VLBI data [22, 23, 30] indicated that scintillating sources are more core-dominated than non-scintillating sources, and are smaller in overall angular extent. Additionally, analysis of VLBI data at multiple wavelengths to investigate scatter-broadening showed no trend of scattering strength with redshift [31]. ISS is sensitive to structure on significantly smaller scales than those which can be resolved with VLBI, but VLBI data can provide useful constraints on the fraction of flux density in the compact core which is otherwise highly uncertain. The earlier comparison of milliarcsecond-scale structure used only early results from the MASIV Survey, separating the sources into “scintillators” and “non-scintillators”. It will be useful to revisit the VLBI comparison in the light of the complete quantitative analysis of VLA data from the MASIV Survey and follow-up observations, and to look for any systematic change in VLBI core dominance and

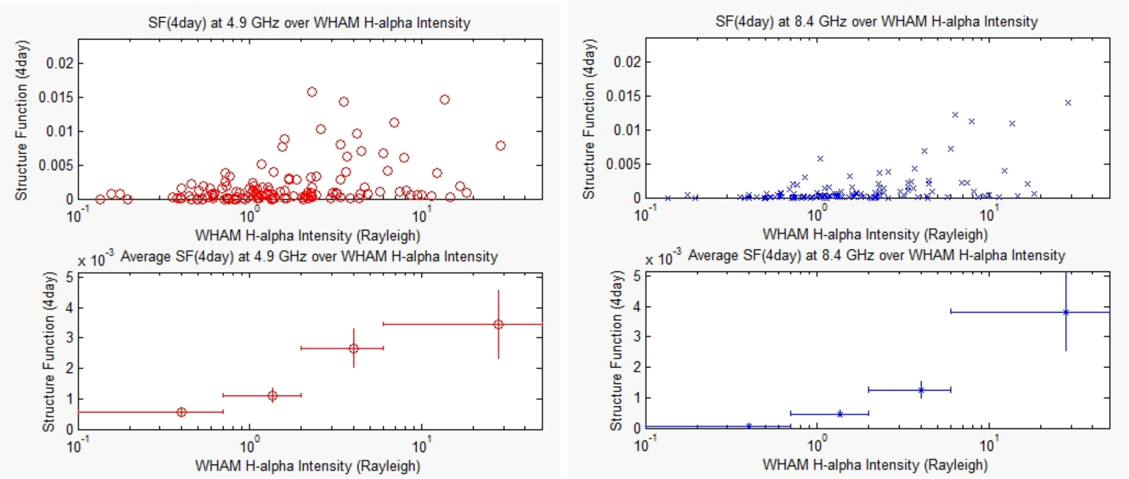

Figure 3: Structure function evaluated at 4 days lag, D_{4d}, for MASIV VLA follow up data at 4.9 GHz (*left*) and 8.4 GHz (*right*) plotted against Hα intensity along the line of sight from the WHAM Survey (with 1° angular resolution); integrated Hα intensity is assumed proportional to emission measure. The lower panels show mean values of D_{4d} in bins of Hα intensity.

angular extent as a function of redshift, which may help confirm or rule out a source-intrinsic redshift dependence. VLBI on the longest earth baselines at $\sim$ 8 GHz would also be useful to show what fraction of the source flux density is unresolved on sub-milliarcsecond angular scales, and if the high redshift quasars show any sign of appearing larger than their lower redshift counterparts.

3. Discussion

Interstellar scintillation of quasars is potentially a unique probe of the ionized intergalactic medium, and/or of cosmological evolution of AGN and their environments. However, a complex superposition of effects go into determining how a source will scintillate, and there are a number of complicating effects to sort out in determining what causes the suppression of ISS in high-redshift sources. Optical identifications, VLBI studies of the milliarcsecond-scale source structure, and multiwavelength monitoring to determine the frequency dependence of ISS behaviour and spectral index all provide important clues to help separate these effects.

Large surveys with next generation wide-field telescopes, such as VAST, an ASKAP Survey for Variables and Slow Transients, will find very large numbers of scintillating sources. Combined with redshifts from large optical surveys, it would be possible to separate various effects, e.g. to investigate large numbers of sources with similar luminosities or similar lines of sight through the Galaxy. It will also be important to consider the effects of interstellar scattering on observations of radio transients, in order to determine the intrinsic properties of the transient radio source populations.

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