*Extragalactic Jets: Theory and Observation from Radio to Gamma Ray*
*ASP Conference Series, Vol. 386, ©2008*
*T. A. Rector and D. S. De Young, eds.*

# The MicroArcsecond Scintillation-Induced Variability (MASIV) Survey: Detection of Angular Broadening at High Redshift?

T. Pursimo,[1] R. Ojha,[2] D. Jauncey,[3] J. Lovell,[4] M. Dutka,[5] H. Bignall,[6] J.-P. Macquart,[7] B. Rickett,[8] and L. Kedziora-Chudczer[3]

**Abstract.** Interstellar scintillation has been shown to be primarily responsible for intra-day variability exhibited by extragalactic sources at centimeter wavelengths. The recent MASIV survey has shown that a very high proportion of flat spectrum extragalactic radio sources scintillate; such behaviour is both too common and too important to ignore. A study of the physical properties of the MASIV objects is severely handicapped by the absence of reliable redshift measurements for most of the objects. We present the first results of the studies of the physical properties of the MASIV sources, based on archival and our own redshift measurements.

## 1. Introduction

The discovery of centimeter wavelength, short term variability in some compact, flat-spectrum extragalactic radio sources (Heeschen 1984; Heeschen et al. 1987) was of immediate and profound astrophysical consequence. This phenomenon, which was soon dubbed Intraday Variability (IDV) (Wagner & Witzel 1995, and references therein), implied brightness temperatures up to $10^{21}$ K in extreme cases (Kedziora-Chudczer et al. 1997) if the variations were assumed to be intrinsic. Such enormous brightness temperatures present a serious challenge to the current paradigm for the physics of extragalactic radio sources.

However, there is now overwhelming evidence that IDV results primarily from scintillation in the turbulent, ionized, interstellar medium of our Galaxy. This conclusion emerges from two lines of observational evidence. Time delays have been detected between the arrival times of the intensity fluctuations from IDV sources at two widely-spaced telescopes (Bignall et al. 2006; Dennett-

[1]Nordic Optical Telescope, Apartado 474, S/C de La Palma, E-38700 Tenerife, Spain

[2]NVI/ U S Naval Observatory, 3450 Massachusetts Avenue, Washington DC 20392-5420, USA

[3]Australia Telescope National Facility, PO Box76, Epping NSW, Australia

[4]School of Mathematics and Physics, University of Tasmania, Hobart Tas 7001, Australia

[5]University of Maryland, Department of Astronomy, College Park, MD 20742, USA

[6]Joint Institute for VLBI in Europe, postbus 2, 7990 AA Dwingeloo, The Netherlands

[7]NRAO Jansky Fellow, Department of Astronomy, Caltech, Pasadena CA 91125, USA

[8]Dept of Electrical & Comp Engg, UCSD, San Diego, La Jolla, CA 92093, USA

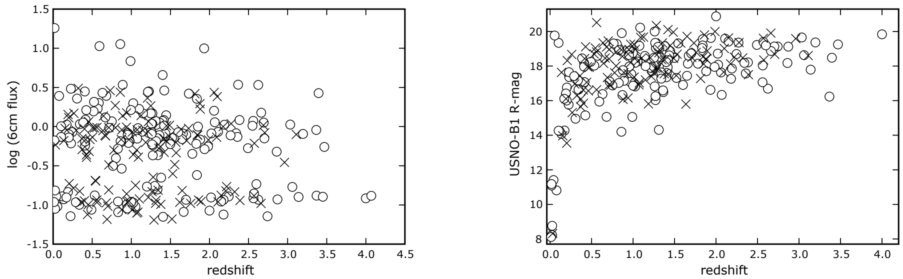


Figure 1. VLA flux and USNO-B1 R-magnitude vs. redshift. The IDV and non-IDV sources are indicated as crosses and circles, respectively.

Thorpe & de Bruyn 2002). Further, annual cycles have been detected in the timescale of IDV sources a periodic modulation that most plausibly results from the change in relative velocity of the Earth and the scattering medium through the course of a year. Interstellar scintillation (ISS) is the only reasonable explanation of these observations.

Though an extrinsic (as opposed to intrinsic) origin for IDV points to less extreme physical conditions for the sources that exhibit this phenomenon, scintillators are still among the most extreme and active radio AGN known. For a source to scintillate its angular size must be comparable to that of the first Fresnel zone (Narayan 1992) which implies microarcsecond angular sizes for screen distances of tens to hundreds of parsecs. Such high resolution cannot be achieved by any other existing technique, including space VLBI. Further, brightness temperatures of some scintillators are well in excess of $10^{14}$ K (Macquart et al. 2000) which implies Doppler factors of several hundred or more (Readhead 1994) which is significantly higher than seen in VLBI surveys (e.g. Zensus et al. 2002). Thus, an investigation of the properties of AGN that exhibit IDV is of considerable astrophysical interest.

## 2. MASIV Survey

The MASIV survey is a large-scale 5 GHz VLA survey of flat-spectrum AGN over the northern sky ($\delta > 0$ degrees) to search for IDV (Lovell et al. 2003, 2007). Our objective is to assemble a statistically significant sample of sources exhibiting IDV.

The sources were chosen from JVAS Patnaik et al. (1992); Browne et al. (1998); Wilkinson et al. (1998) and CLASS Myers et al. (1995) catalogues and the NVSS Condon et al. (1998) was used for the radio spectral index information. The core sample was divided into strong ($S_{8.5GHz}$ >0.6 Jy) and weak (0.105Jy< $S_{8.5GHz}$ <0.13Jy) subsamples, with both containing about 250 sources. The sources were selected to have a uniform distribution on sky to give regular sampling with the VLA observations, aiming at one minute on-source scan per object every two hours. The VLA was sub-divided onto 5 sub-arrays of 5 or 6 antennas and observations were made in 2002 January, May and Septem-

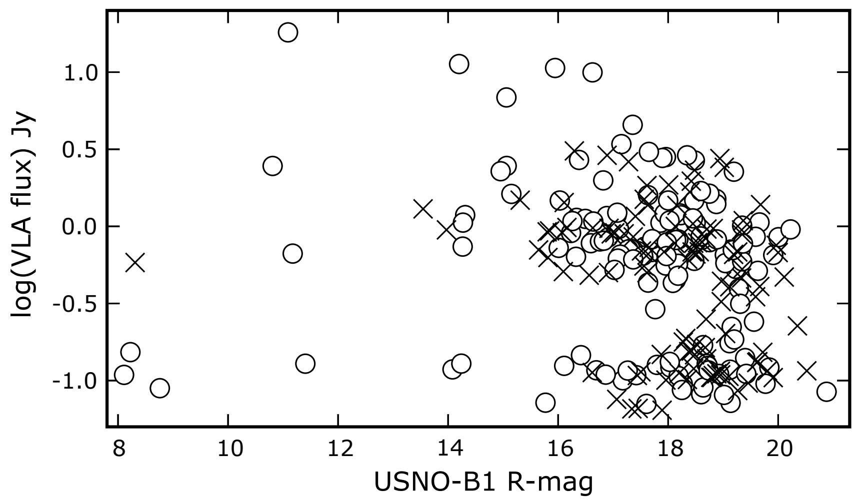


Figure 2. VLA 6cm flux density versus USNO R-magnitude. The symbols are the same as in Fig. 1.

ber and January 2003. Each session lasted 3 days with approximately 10,000 scans per session.

After removing 43 sources that showed structure or confusion we are left with a final sample of 482 sources. The RMS modulation is typically range from 1-5% of the mean source flux density, but values up to 30% were observed. Sources which showed variability in two or more epochs are classified as IDV sources. Over four observing epochs we found that 56% of the sources showed variability on timescales of hours to several days. The variability is found to have dependence on Galactic latitude, with fewer variables at high latitudes. This again demonstrates ISS as the mechanism responsible for the observed variability.

### 2.1. Follow-up Observations

Our investigation of MASIVs is currently greatly handicapped by the lack of source redshift, and especially as the literature redshifts are biased towards the strong radio sources (see below). Emission line redshifts are essential to determine physical properties including linear sizes, accurate brightness temperatures and to determine luminosity distributions.

From the literature we found redshifts for 235 MASIVs. However, especially for blazars and BL Lac objects some of the redshifts have poor quality, e.g. redshift is based on single emission line, or the estimated lower limit is recorded as the redshift. We have an on-going programme at the Nordic Optical Telescope (NOT) to measure redshifts of optically brighter than $R \sim$19.5 MASIVs. So far we have secured redshifts for 55 targets and and found two objects with featureless continuum. The redshifts are measured from at least two emission lines, typically MgII, CIII], [CIV] or Ly-alpha.

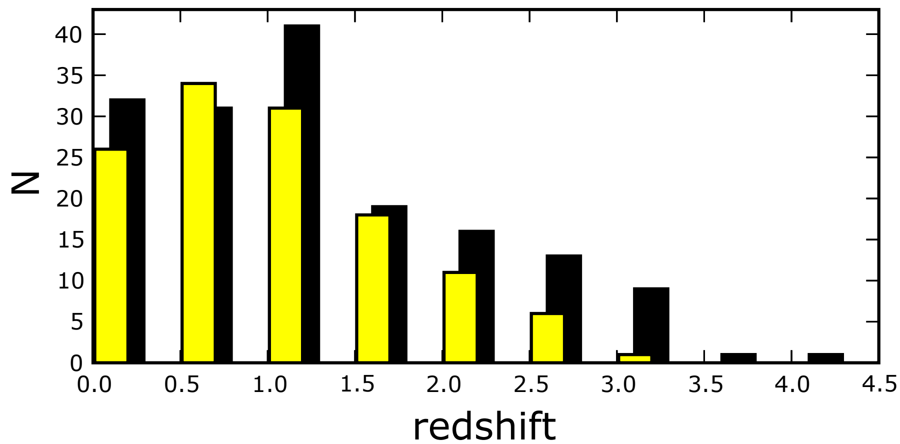


Figure 3. Redshift distribution of IDV (gray) and non-IDV (black) sources.

## 2.2. Possible Selection Effects

As mentioned above the redshifts are biased towards strong radio sources. The averages of the 6cm flux density of the whole sample, the archival and the new redshift objects are 0.70, 1.17 and 0.22 Jy, respectively.

Figure 1 suggests that there is no apparent selection effect between redshift and the flux density. The IDV and non-IDV sources have similar distributions, however, less than half of the faint MASIVs have measured redshift. Using the USNO-B1 catalogue we could identify 393 targets, with limiting magnitude about R = 20. Figure 1 shows the apparent magnitude redshift diagram, without any apparent bias with optical brightness. Note that galactic extinction is not corrected (correction shifts a point downward). On average the IDV sources will have slightly greater correction than non-IDV sources due to IDV and galactic latitude dependence, however apart from close to galactic plane the extinction correction is expected to be small, less than some tenth of magnitude.

The USNO-B1 R-band versus first epoch VLA flux diagram is shown in Figure 2. The distributions overlap each other suggesting that the IDV and non-IDV sources have similar SEDs. Due to the lack of galactic extinction values the radio loudness is presented as radio vs optical brightness plot.

The radio and optical brightness and the radio-optical plot suggests that the IDV and non-IDV sources have similar SEDs. Also the radio and optical brightness distributions suggest that there isn't any strong bias towards faint/strong sources or luminosities. However, only 60% of the sources have redshift, hence we cannot entirely rule out luminosity-related selection effects.

It is interesting to note that 70% of the MASIVs with featureless spectrum are variable. Including all objects classified as BL Lacs or blazars, 51 objects, the fraction drops to 62% However, the spectroscopic classification of BL Lac objects and blazars is in some cases in doubt.

## 3. Results

The preliminary results of the MASIV survey suggest that there appears to be a deficit of variable sources at high redshifts (Fig. 3). The observed drop in ISS with redshift is formally significant at the 98% confidence level. Dividing the sources into only two subsets, those with redshifts above and below $z = 2$, yields a difference that is significant with better than 99% confidence. The increase of apparent source size due to decreasing angular diameter distances at $z > 1$ in a concordance cosmology is too weak to explain the effect observed here. Also microlensing is less likely explanation. We suggest that suppression of ISS as a function of redshift results from scattering in the Intergalactic Medium (IGM)

We have found a deficit of scintillating sources above a redshift of ∼2. The most plausible explanation of this observation is that angular broadening due to scattering in the intergalactic medium makes the higher redshift sources too large to exhibit interstellar scintillation due to the interstellar medium of our Galaxy. If confirmed, this constitutes a direct detection of the turbulent ionized component of the IGM. As such, this result is the first step to understanding the possible inhomogeneity of the IGM at high redshifts and provides a new tool to probe the ionized gas in the IGM which is postulated to be far more widespread then neutral gas at these redshifts

**Acknowledgments.** RO acknowledges the Access to Major Research Facilities Program (AMRFP) of the Australian Government for travel support (Grant Number: 05/06-0-04) for observations with the Nordic Optical Telescope (NOT) during July 2005.

### References

Bignall, H.E., et al. 2003, ApJ, 585, 653
Bignall, H.E., et al. 2006, ApJ, 652, 1050
Browne, I.W.A., et al. 1998 MNRAS, 293, 257
Condon, J.J, et al. 1998, AJ, 115, 1693
Dennett-Thorpe, J., de Bruyn, A. G. 2002, Nat, 415, 57
Dennett-Thorpe, J., de Bruyn, A. G. 2003, A&A, 404, 113
Heeschen, D.S. 1984, AJ, 89, 1111
Heeschen, D.S., et al. 1987, AJ,94, 1493
Jauncey, D. L., & Macquart, J-P. 2001, A&A, 370, L9
Kedziora-Chudczer, L., et al. 1997, ApJ, 490, L9
Lovell, J.E.J, et al. 2003, AJ, 126, 1699
Lovell, J.E.J, et al. 2007, astro-ph 0701601
Macquart, J-P. et al., 2000, ApJ, 583, 623
Myers, S.T., et al. 1995, ApJ, 447 ,L5
Narayan, R., 1992, ApJ, 394, 255
Patnaik, A.R. et al. 1992, MNRAS, 254, 655
Readhead, A. C. S. 1994, ApJ, 426, 51
Rickett, B.,J., et al. 2001, ApJ, 550, L11
Wagner, S., Witzel, A. 1995, ARA&A, 33, 163
Wilkinson, P.N., et al. 1998, MNRAS, 300, 790
Zensus, J. A., et al. 2002, AJ, 124, 662