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Microarcsecond Resolution with Interstellar Scintillation

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The rapid, intra- and inter-day variability now seen at cm wavelengths in many compact, flat-spectrum radio sources, was discovered almost thirty years ago based on accurate flux density measurements made with the Effelsberg 100 m radio telescope. It was initially thought to be intrinsic to the sources themselves. However, accumulated evidence now strongly favours interstellar scintillation, ISS, in the turbulent, interstellar medium of our Galaxy, as the principal mechanism responsible for such rapid variability. For a source to exhibit ISS it must contain a compact component whose angular size is comparable to the angular size of the first Fresnel zone; for reasonable screen distances this implies microarcsecond component sizes. ISS now makes it possible to probe source structure with microarcsecond resolution, finer than that achieved with ground-based VLBI and the equal of that achievable now on the longest space baselines with RadioAstron. The presence of ISS therefore has significant implications for VLBI astronomy, astrometry and geodesy.

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1. Introduction

In his short timescale variability survey with the Green Bank 300 ft telescope at 9 cm wavelength, Heeschen[1] found low-level intra-day variability, or flickering as he called it, only amongst the flat-spectrum sources in his sample. He suggested that such variability could be caused either by scintillation in the interstellar medium (ISM), or it may be intrinsic to the sources. Heeschen followed up these flickering sources from the Green Bank survey, with measurements at the Effelsberg 100 m telescope, where a precision of better than 1% was achieved. In the following decade the Bonn group found intra-day variability, IDV, in 15–20% of all flat-spectrum sources[2]. But the most important question remained; is this variability intrinsic to the sources, or is it extrinsic, for example ISS? However, if intrinsic, then brightness temperatures of up to 10^{15} K were implied, and thus the sources are so small that they must scintillate as well. Understanding scintillation was an important aspect of both.

2. The Fast Variable Sources and Strong Evidence for Interstellar Scintillation

The discovery in June 1996 of the remarkable, large-amplitude, inter-hour variability in the southern z=0.875 quasar PKS0405-385[3] revolutionised our understanding of IDV and played a critical role in establishing ISS as its principal cause. The four-frequency data obtained at the ATCA over three days starting June 7 showed dramatic flux density variations of up to 50% peak-to-peak at 4.8 and 8.6 GHz over periods as short as one hour. Our initial reaction during the observations was that there may have been ATCA instrumental problems, but a telephone call to George Nicolson in South Africa soon confirmed the reality of this remarkable variability with his independent measurements at HartRAO. If intrinsic, such variability would imply a sub-microarcsecond source size and brightness temperature of $\sim 10^{21}$ K. Given such a figure, 10^9 times greater than the inverse-Compton limit, we suggested that these variations could perhaps be better understood as a result of interstellar scintillation. The observed frequency dependence of the amplitude and time scale of the variations proved to be in excellent agreement with the expectations of ISS.

To date, only three such remarkable, large-amplitude, fast variable sources have been found, each serendipitously; they are PKS 0405−385, J1819+3845[4] and PKS 1257−326[5].

Such rapid variability allowed a definitive test between an intrinsic or extrinsic cause. This was one of the more interesting "VLBI" observations that I have been involved with, akin to a Brown-Twiss intensity interferometer, which measured the total flux density intensity pattern at each of a pair of widely spaced radio telescopes, in this instance the ATCA and the VLA. If intrinsic, the two patterns will be displaced by no more than milliseconds of time, the difference in the wavefront arrival times. Alternatively, if due to ISS, then the displacement will be given by the time taken for the irregularities in the ISM to pass between the telescopes. For the 10,000 km baseline and an ISM speed of ~ 50 km/sec, this is several minutes. Given the very high SNR determined at each telescope, several hundred to one, the likely uncertainty will be at most a few tens of seconds, sufficient for a deciding measurement.

Measurements of this pattern time delay between telescopes have now been made successfully on each of the three fast variables. The first was with PKS 0405−385 in late 1998. Observations at 5 and 8 GHz between the ATCA and the VLA revealed a significant time difference of

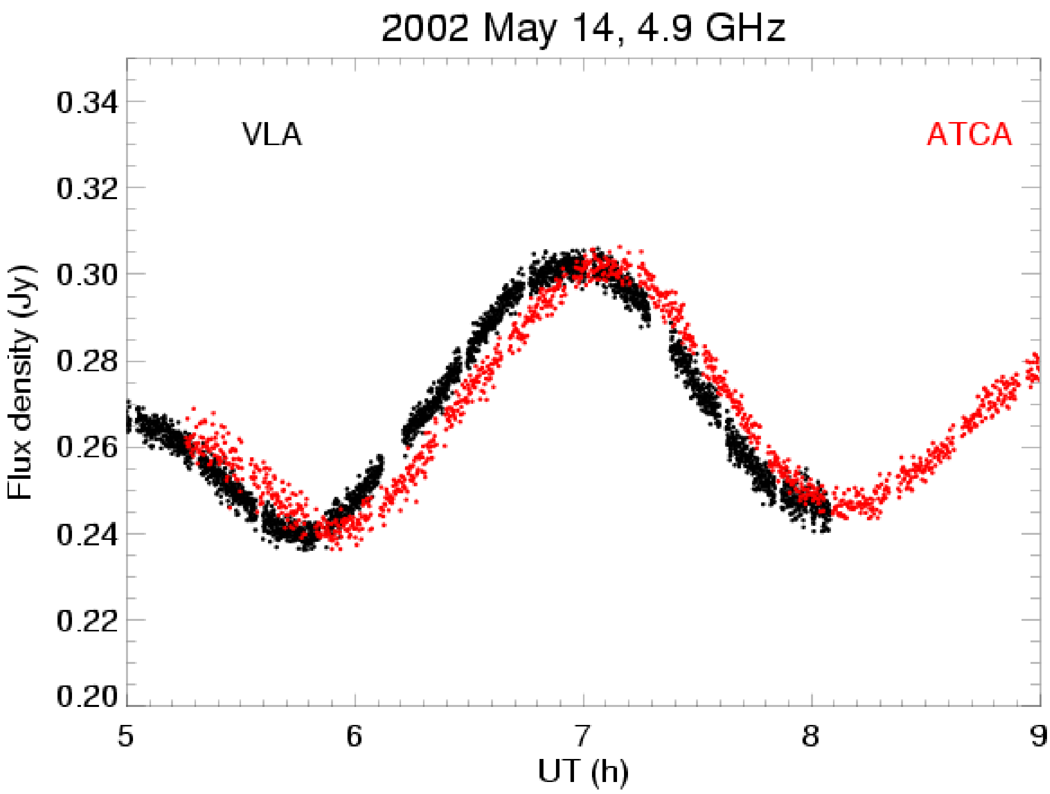

Figure 1: The 5 GHz variability patterns for PKS 1257−326 as seen at the VLA, in black, and the ATCA, in red. The time displacement between the two is a clear demonstration that interstellar scintillation is the principal cause of the rapid variability.

140 ± 25 seconds in the pattern arrival times, demonstrating clearly that ISS was the principal mechanism causing the observed IDV at both frequencies[6]. The second followed in 2001, using J1819+3845[7] and the third, in May 2002 and January 2003 using PKS 1257−326[8]. As an example, figure 1 shows the resultant PKS 1257−326 scans made at 4.86 GHz between the ATCA and VLA on May 14 2002, where the observed delay of several minutes is readily apparent. These observations demonstrate clearly that ISS is the principal cause of the observed IDV.

Moreover, after shifting and subtracting the two patterns, the resulting differences showed no residual variability at a level of a few mJy, placing any intrinsic IDV, if present, at less than $\sim$ 1% of the total flux density. To date the maximum pattern shift we have measured is $\sim$ 8 minutes over this 10,000 km baseline, giving an ISM speed of order 25 km/s. The pattern repeatability at each of the two telescopes implies that the turbulent structures in the ISM are highly elongated[8]. Moreover, such large delays over the 10,000 km baseline carry significant implications for space VLBI with RadioAstron, as noted below.

3. The Annual Cycle of the ISM Speed and the Earth's Rotation

The observed ISM speed of $\sim$ 25 km/s is close to the Earth's 30 km/s rotation speed. Thus when the two are moving parallel, the relative speed will be reduced and the variability pattern significantly slowed, while six months later they will be in opposition, the relative speed will increase and the variability pattern will speed up. The exact changes depend on the detailed geometry. This *annual cycle* was first observed[9] in J1819+3845, and is again a clear demonstration of the role of ISS as the prime mechanism responsible for the observed cm wavelength IDV. Since then, annual cycles have been observed in many sources including B0917+624[10, 11], PKS 1257−326[5, 8], and 1128+592[12]. Such apparent widespread behaviour firmly demonstrates the significant role played by ISS in cm wavelength IDV. Interestingly, for B1128+592 it was demonstrated that the presence of long-term intrinsic changes in the source structure itself, affect the detailed shape of the annual cycle[12].

Combining the observed time delay information with the observed annual cycles for PKS 1257−326 and J1819+3845 has shown that these sources possess scintillating components with angular sizes of 20 to 35 μas, with brightness temperatures as high as 2×10^{13} K. Interestingly, the fast variables have been found to scintillate through very nearby ISM scattering screens at distances of 10 to 30 pc.

It is remarkable that accurate flux density measurements of these IDV sources can yield detailed information on their structure on μas scales, far higher than is achievable with VLBI on Earth baselines, and at the limit of the longest space VLBI baselines. It could be argued that measurements of ISS utilise the turbulent structure in the ISM as a real space VLBI interferometer; all that's required is a single radio telescope able to measure precise flux densities.

4. The Next Step: MASIV, the MicroArcsecond Scintillation-Induced Variability Survey

Having established ISS as the principal mechanism responsible for cm-wavelength IDV, the next step was to seek larger statistics. Until 2000, several IDV surveys of typically $\sim$ 100 flat-spectrum radio sources had shown that 15–20% exhibited IDV. For any serious statistical investigation it was therefore necessary to have a large sample of scintillators in order to investigate their properties. To this end we started a large-scale MicroArcsecond Scintillation-Induced Variability, MASIV, 5 GHz VLA survey to construct a sample of 100 to 150 scintillating sources. The objective was to study both the microarcsecond structure and parent populations of these sources, and to probe the ISM causing the scintillations.

The VLA is the only instrument capable of undertaking such a task; 5 GHz is close to its optimum frequency for flux density measurements, and it was capable of being "broken" into up to five sub-arrays simultaneously, which we did. The survey started in 2002 using reconfiguration time, with four 72 hour epochs, January, May, September and 2003 January. We used five sub-arrays of 5 or 6 antennas each, 60 seconds on-source per scan, 6 scans per source per day, and 10,000 scans per epoch. We used a core sample of equal numbers of strong, $\sim$ 1 Jy, and weak, $\sim$ 0.1 Jy, compact, flat-spectrum sources at 5 GHz. The MASIV program developed a certain reputation in Socorro, where it was at times dubbed the "VLA in Disarray", as we learned that the 5 sub-array mode had not previously been used for observing.

The results were surprising[13]. We found that just over half of all of the sources exhibited 2–10% rms variations on timescales over 2 days during at least one epoch of the four. We also found a strong correlation between this rms variability and the emission measure in the ISM along

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the respective lines of sight, and also with Galactic latitude. Thus we argue that that ISS must be the principal mechanism causing such variability for the IDV population as a whole. Moreover, we found that the weak sample showed fractionally more scintillators than the strong sample, as well as showing fractionally larger amplitude variations. This is as might be expected if the scintillating sources were brightness temperature limited[14]. The long timescale over which ISS has been observed in some sources suggests that such ultra-compact microarcsecond components can be relatively long-lived despite their small sizes.

Most surprisingly, we also found a strong dependence on redshift, in the sense that both the frequency of occurrence and the amplitude of ISS decrease with increasing redshift. A more detailed discussion of these effects, and of the present state of MASIV, is given in the associated paper by Bignall et al, in these proceedings.

As the three fast scintillators had each been found serendipitously, we expected to find more such sources in the MASIV survey. However, we found none. Such rapid scintillation is the result of scattering in a nearby, 10–20 pc, turbulent ISM screen, so it seems that there are few lines of sight through such nearby screens. In a more detailed search for low-level rapid scintillation a further six of the MASIV sources were found to show such rapid variability, but at a much smaller amplitude[15]. Characteristically these sources were all found at mid-latitudes.

5. Implications of Interstellar Scintillation for Space VLBI

With the successful launch of the Russian 10 m radio telescope RadioAstron in July 2011, in its 350,000 km apogee, nine and a half day orbit, careful attention will need to be paid to the potential effects of interstellar scintillation on the observations. As an orbital period extends over many days, it follows that many of the most compact sources will exhibit significant flux density variations due to ISS at all frequencies except probably 22 GHz.

Depending on the details of the observing schedule, the effects of the pattern time delay will likely be significant. For a 10,000 km baseline, delays of up to 8 minutes were found for PKS1257-326, implying pattern time delays of up to 5 hours over a 350,000 km baseline close to apogee. This shows that detailed geometrical effects will of necessity need to be included in the data analysis for most scintillators, as the pattern seen by the space antenna will be displaced from that seen on the ground, and hence the correlated amplitude will differ from that of conventional VLBI. For observations spread over several days, this effect becomes more complicated, and clearly accurate total flux density measurements on the ground will be essential.

Moreover, our knowledge of the scale size of the turbulent ISM suggests sizes of $\sim 100,000$ km to $\sim 500,000$ km, so that not only will the patterns differ due to the time delay, but also due to the finite scale size of the turbulence. Unfortunately, such changes will not be readily observable with the 10 m space antenna with its small aperture and low sensitivity. However, in exceptional circumstances such as very strong maser sources and strong pulsars like the giant pulses in the Crab, the response of the 10 m space telescope can be measured directly.

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