

Scintillation Surveys, Serendipitous, Systematic and MASIV: What do they tell us

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A variety of surveys, both serendipitous and systematic, have revealed the dramatic phenomenon of cm-wavelength refractive inter-stellar scintillation. Throughout these discoveries, the presence of accurate and reliable flux density measurements has been an essential component of progress, as have the various surveys both serendipitous and systematic.

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1. The Discovery of Low Frequency Variability

The discovery and gradual acceptance of inter-stellar scintillation as the principal mechanism for the intra-day variability seen at centimetre wavelengths in many compact, flat-spectrum radio sources has had an interesting history, and has been strongly influenced by a variety of surveys, both serendipitous and systematic. Early flux density calibration measurements, made at 408 MHz using the Molonglo Cross revealed the then new phenomenon of “low frequency variability” (Hunstead 1972). There was at first considerable reluctance to accept Hunstead’s result (e.g. Jones & Burbidge, 1973), as Hunstead stated, “if the variations observed at 408 MHz were intrinsic to the radiating regions, they raise some important astrophysical questions concerning the physical processes operating in non-thermal radio sources” (Hunstead 1972).

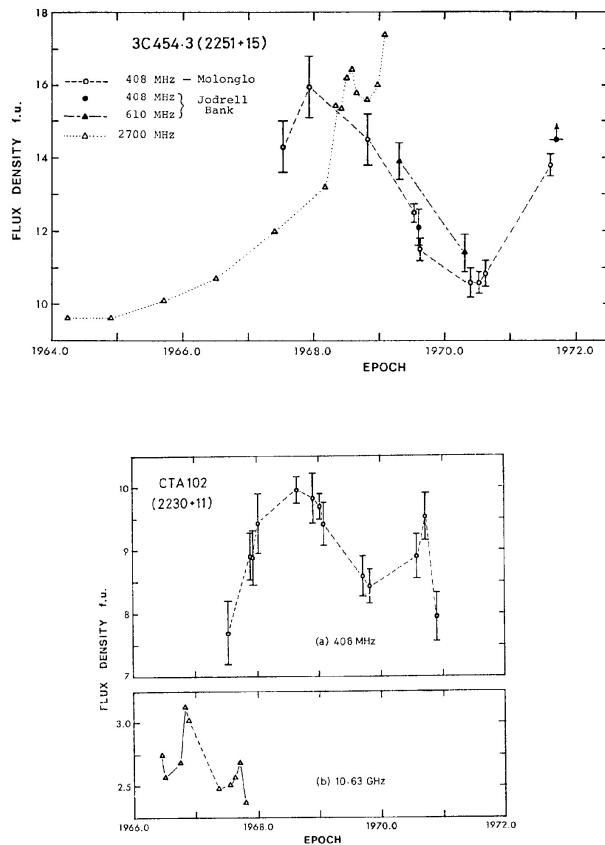


Figure 1: The variations seen at 408 MHz from Molonglo in 3C454.3 and CTA 102 from Hunstead 1972.

Incontrovertible evidence was presented for large fractional variations in the 408-MHz emission from the two quasi-stellar objects, CTA 102 and 3C 454.3, and two radio galaxies, PKS 1504-16.7 and 1524-13. In each source significant changes in flux density occurred on a time scale of months to years. If intrinsic, causality arguments

implied a light-year linear size and hence a brightness temperature far in excess of the generally accepted inverse Compton limits (Kellermann & Pauliny-Toth 1969). Figure 1 shows the results for the two quasars 3C454.3 and CTA102.

After some time Rickett et al., (1984) proposed that what was being seen were examples of refractive inter-stellar scintillation which was taking place in the turbulent, ionized, inter-stellar medium of our Galaxy; the extra-galactic sources were scintillating like pulsars. Curiously, although systematic efforts were made to detect inter-stellar scintillation at 430 MHz at Arecibo (Condon & Dennison, 1978), its discovery came through serendipitous measurements made during a program designed for calibrating the Molonglo telescope. High precision, reliable flux density measurements with a well-calibrated instrument proved critical in the discovery.

2. “Flickering” and the First Successful Systematic Scintillation Survey

Starting in late 1979 and observing at 3.3 GHz through early 1983 using the NRAO 300-foot transit telescope at Green Bank, Heeschen (1984) found variability on time-scales of 2 to 20 days, which he called “flickering”. His observing list consisted of 226 both steep-spectrum and flat-spectrum sources and these were studied in three observing sessions each of about 25 days.

Careful measurements revealed that the steep-spectrum sources did not flicker, while the flat-spectrum sources did with an average amplitude of about 1.5%. Follow-up observations at 5 GHz suggested that the amplitude of flickering was much the same at both frequencies. He discussed both intrinsic variability and inter-stellar scintillation as possible mechanisms, but suggested that, although ISS could not be ruled out, the flickering was not correlated with Galactic latitude. However, he concluded that his results did not provide conclusive evidence for either hypothesis.

Heeschen and Rickett undertook a careful re-analysis of the 300 foot 3.3 GHz data and concluded that the flickering of extragalactic sources does exhibit a significant dependence of amplitude with Galactic latitude, consistent with its being caused by refractive inter-stellar scintillation (Heeschen & Rickett, 1987).

3. Intra-Day Variability at cm-wavelengths

As it was a transit instrument, the 300 foot telescope had a fundamental limitation in that observations were possible only once per day. Moreover, its poor high-frequency capability limited observations to longer wavelengths. The way around this was clearly to undertake further investigations with a large, fully-steerable radio telescope, and Heeschen set up a fruitful collaboration with colleagues in Bonn using the Effelsberg 100-m radio telescope.

Exciting results were soon forthcoming. Heeschen et al (1987) observed thirty-one extragalactic radio sources at 2.7 GHz at 2-4 hr intervals for 3-4 days at each of three epochs. The 15 compact sources in the sample appear to display two types of variability. One is probably weak flickering caused by refractive interstellar

scintillation. The other is a larger amplitude variability, which is characterized by a narrow range of timescales of about 1-2 days. This latter behaviour was dubbed intra-day variability, IDV, where large amplitude variations of 5% to 10 % peak-to-peak were seen in several sources on intra-day time-scales.

Three possible causes of the second type were discussed: (1) intrinsic variability, (2) scintillation from a very narrow disk component of the ISM, and (3) scintillation from clouds associated with a particular region of the ISM. It is suggested the latter as the more likely explanation.

The Bonn group enthusiastically continued the intra-day variability program and followed-up with a series of 100 m observations at 11 and 6 cm. Quirrenbach et al, found variations in the quasar B0917+62, of up to 23% in ~24 hours which were correlated at the two frequencies. Additionally, they found variations of up to 11% in the BL Lac object B0716+71 (Quirrenbach et al, 1989a).

They also found that not only were there large-amplitude IDV in the total flux density, but they also observed even more rapid variations in the linear polarization of the unusual BL Lac object B0917+624 (Quirrenbach et al, 1989b). They concluded that “variations of the linear polarization make extrinsic explanations very unlikely”, and discussed an explanation in terms of shocks propagating in a magnetized jet.

As rapid IDV is a common phenomenon at much higher energies, from Gamma Rays through X-Rays to u-v and optical wavelengths, the Bonn group started a systematic, simultaneous multi-wavelength search at radio and optical wavelengths, to search for correlated variations. Such behaviour would distinguish between ISS, which restricts IDV to cm-wavelengths and does not affect optical wavelengths, and broad-band variations which, if established, would imply an intrinsic origin.

4. Search for Correlated Radio and Optical IDV

During four weeks in February 1990 Quirrenbach et al monitored a number of sources at both optical and radio wavelengths, and reported correlated variations at 6 cm and 6500 Å in the flux density of the unusual BL Lac object B0716+714 (Quirrenbach et al, 1991). They observed at the VLA during a reconfiguration period, while the optical observations were made at Calar Alto, Spain and in Heidelberg. They observed a change from the “fast” to a “slow” time-scale simultaneously at both wavelengths, and argued that this gives strong support for a real physical correlation between the two wavelengths.

These results were discussed in more detail by Wagner et al, (1996), who demonstrated a strong correlation between the optical flux and the radio spectral index, in the sense that the variations were in phase without any measurable lag. This close correlation, they argued, favoured a single radiation mechanism, and they discussed various models and mechanisms. They concluded that the variability is intrinsic to the source. The situation is well summarized in the review article by Wagner and Witzel (1995).

At much the same time Rickett et al, were able to successfully model as inter-stellar scintillation, multi-wavelength IDV observations of B0917+624. To achieve this they analysed simultaneous observations at 2 cm, 3.6 cm, 6 cm, 11 cm and 20 cm. The variations were characterised by a time-scale that increases from 2.5 hours at 2 cm to 18 hours at 20 cm. The variations at the 3.6 cm, 6 cm and 11 cm wavelengths were found to be highly correlated with no significant time offset. Such behaviour is not predicted by intrinsic mechanisms, but is in close agreement with predictions of ISS. Furthermore, a detailed ISS model was constructed giving a specific source structure, brightness temperature of 6×10^{12} K, and a screen distance of 200 pc (Rickett et al, 1995). The authors concluded that while they could not rule out low-level intrinsic IDV, they found that the very compact source does exhibit ISS, which must be included for a full interpretation of the observed IDV.

5. The Discovery of PKS0405-385 and the other “Fast” Variables

As part of a systematic ATCA IDV Survey (Kedziora-Chudczer et al., 2001) discovered the remarkably rapid variability in the southern quasar PKS0405-385 on time-scales of less than an hour (Kedziora-Chudczer et al, 1997). If intrinsic, these variations implied a brightness temperature of $\sim 10^{21}$ K, some 9 orders of magnitude above the inverse-Compton limit.

Alternatively, it was felt that the data could be explained most sensibly by refractive inter-stellar scintillation of a microarcsecond-scale synchrotron source component. ISS fitted well with the high degree of correlation between the variations at 5 and 8 GHz, the change in time-scales at 2.3 and 1.4 GHz, and the variation of modulation index with frequency. At 5 GHz and above, the source is exhibiting weak scattering, while at frequencies below 5 GHz it exhibits strong scattering (Walker 1998). Subsequently, it was shown that such rapid variability results when a compact source is seen behind a nearby cloud in the turbulent ISM (Dennett-Thorpe & de Bruyn 2000).

Such large-amplitude, rapid variability opened the possibility of searching for the time delay that might be expected in the pattern arrival times at widely spaced radio telescopes. If the variability were intrinsic, the time delay would be negligibly small, whereas if the variability was a pattern phenomenon caused by ISS, then a significant time delay might be observed. For telescopes separated by 10,000 km, and an ISM speed close to the ~ 30 km/s of the local standard of rest, then a delay of minutes might be observed.

Observations at 5 and 8 GHz between the ATCA in Australia and the VLA in New Mexico revealed a significant time difference of 140 ± 25 seconds, demonstrating unequivocally that, for this quasar, ISS was the principal mechanism responsible for the intra-day variability (Jauncey et al., 2000).

Soon afterwards the second of these “fast” variables, J1819+3845, was discovered, but this time the discovery was serendipitous, as it was one of a sample of 50 sources being investigated as a possible gravitational lens candidate (Dennett-Thorpe & de Bruyn, 2000). J1819+3845 was found to have shown flux density variations of a factor of two

over 4 days. Subsequent observations with ever decreasing time-scales revealed a source that exhibited over 300% amplitude changes on a time-scale of hours. They successfully modeled the source as having a radius of no more than $16 \mu\text{s}$ radius at 5 GHz that was located behind a scattering cloud only a few tens of pc from Earth. This exciting discovery further strengthened the case for ISS.

Within a year another of these fast variables was discovered, again serendipitously. As part of a radio and X-Ray monitoring program, Bignall et al, discovered rapid variability at the ATCA at 5 and 8 GHz, in the southern quasar PKS1257-326, making it the third fast variable. Subsequent measurements over the course of a year revealed the presence of an annual cycle (Bignall et al., 2003) in the variability pattern, just as had been observed in J1819+3845 (Dennett-Thorpe & de Bruyn 2002).

In subsequent years time-delay measurements have revealed significant pattern time delays for both J1819+3845 and PKS1257-326, making the case unequivocally in favour of inter-stellar scintillation. Moreover, annual cycles have been established not only for the fast variables, but also for many more of the “slower” IDV sources for which a time delay measurement is not feasible. While low-level intrinsic variations cannot be entirely ruled out, refractive ISS is clearly the principal mechanism responsible for the IDV seen in many flat-spectrum, compact radio sources.

6. The Micro-Arcsecond Scintillation-Induced Variability (MASIV) Survey.

In 2002-2003 Lovell et al undertook a large-scale, systematic VLA 5 GHz variability survey, the Micro-Arcsecond Scintillation-Induced Variability survey (MASIV), of in excess of 500 flat-spectrum sources. The objective was to establish a sample of 100 or more IDV scintillators with which to undertake a reliable statistical analysis to ascertain the dependence of ISS on parameters like Galactic latitude, spectral index, source intensity, optical identification and redshift. Moreover, it was expected that many new rapid intra-hourly variables would also be uncovered. Such a large-scale survey was essential, as previous surveys were of typically of order 100 sources where only ~20 IDV sources were found.

Observations at 5 GHz were undertaken with the VLA operating in a 5 sub-array mode during four equally spaced epochs over the course of a year. Each epoch's observations lasted 3 x 24 hours, except the third which lasted 4 x 24 hours, and each source was observed every 2 hours while above the horizon. The observations were undertaken during periods of reconfiguration of the VLA. A strong, $S > 600 \text{ mJy}$, and a weak, $S > 100 \text{ mJy}$, source samples were chosen in order to determine if the fraction of scintillators was intensity dependent, as might be expected if the emission were brightness temperature limited (Lovell et al, 2003).

MASIV showed that a in excess of 50% of all flat-spectrum sources exhibited ISS on one or more occasions over the course of the year's observations, and also revealed the presence of a hitherto unexpected population of episodic variables, that is sources that varied on only one or two occasions over the four epochs of observations. MASIV demonstrated that fractionally more of the weaker sources, those with flux densities of ~

100 mJy, exhibited ISS than the stronger sources, and that, on average, they varied with larger fractional amplitudes (Lovell et al, 2007, Jauncey et al, 2007).

However, MASIV did not reveal the expected population of intra-hourly variables. Such sources, it is now understood, result from the unusual occurrence of the presence of a compact source lying behind a nearby turbulent, ionized cloud, and such clouds are clearly quite rare. A significant Galactic latitude effect was present, as was a clear dependence of variability fraction and amplitude with spectral index, in the sense that the more inverted the spectral index, the larger the variations.

Most importantly, MASIV revealed the presence of a highly statistically significant, (99%), redshift dependence on the fraction of sources which exhibited ISS, with the fraction decreasing dramatically for redshifts in excess of 2 (Lovell et al, 2007, Jauncey et al, 2007). This was interpreted as scattering in the turbulent, ionized inter-galactic medium at redshifts in excess of 2.

Summary

A variety of surveys, both serendipitous and systematic, have revealed the dramatic phenomenon of cm-wavelength refractive inter-stellar scintillation. Throughout these discoveries, the presence of accurate and reliable flux density measurements has been an essential component of progress, as have the various surveys both serendipitous and systematic.

Hunstead's careful observations of "low-frequency variability" at 408 MHz (Hunstead 1972) showed that, if intrinsic to the source, implied brightness temperatures that were extreme and significantly in excess of the inverse-Compton limit. For some time, rather than accept the observations, there was an inclination to reject them as they posed a problem that was "too hard" for theory. It was the growing understanding that these variations were real and were caused by refractive inter-stellar scintillation (ISS) that established the phenomenon as ISS and settled the long-wavelength brightness temperature question.

The discovery of rapid "flickering" at 3.3 GHz, of flat-spectrum radio sources on time-scales of days (Heeschen 1984), revealed the phenomenon of intra-day variability at cm-wavelengths, which again opened the possibility of brightness temperatures well in excess of the inverse-Compton limit. For almost two decades active discussion took place regarding the origin of such IDV, with evidence presented to suggest support for either an intrinsic or extrinsic origin.

Throughout the late 1980s and 1990s, several systematic surveys of typically ~ 100 flat-spectrum sources, were undertaken, initially by the Bonn group using the Effelsberg 100m telescope as well as the VLA. These surveys uncovered many rapidly variable IDV sources which exhibited variations with amplitudes up to many tens of percent over time-scales of days.

The discovery of a small set of extremely rapid, intra-hourly variables, PKS0405-385, J1819+3845 and PKS1257-326, was instrumental in settling the issue. With such short time-scales, measurements were made of a significant time delay in the arrival times of the variability pattern at widely spaced radio telescopes. In addition, observation of an “annual cycle” in the variability characteristics of not only these extremely rapid variables, but in a number of other IDV sources, made it clear that ISS was the principal mechanism responsible. That two of these, J1819+3845 and PKS1257-326, were discovered serendipitously, suggested that there may indeed be many more such rapidly variables.

In 2002-2003 Lovell et al undertook a large-scale, systematic VLA 5 GHz variability survey, the Micro-Arcsecond Scintillation-Induced Variability survey (MASIV), of in excess of 500 flat-spectrum sources. By then the presence of an annual cycle in the variability pattern over the course of the year, had been seen in a number of sources, and it was recognized that the survey needed to be spread throughout the year in order not to miss sources in their “slow-down” period.

MASIV succeeded in covering such a large sample, by dividing the VLA into five sub-arrays. MASIV was highly successful in determining the fraction of sources that scintillate, and in their statistical properties. Moreover, the majority of sources exhibited variability time-scales of order days rather than hours, and it was found that the “fast” variables are indeed rare, implying that nearby scattering clouds are themselves rare.

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