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Interstellar scintillation, ISS, and intrinsic variability of radio AGN

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Abstract

We investigate the relationship between the 5 GHz interstellar scintillation (ISS) and the 15 GHz intrinsic variability of the compact, radio-selected active galactic nuclei (AGN) common to the Microarcsecond Scintillation-Induced Variability (MASIV) Survey and the Owens Valley Radio Observatory blazar flux density monitoring program. As part of this investigation, we also re-examine the reported intrinsic nature of the February 1990 VLA observations of the blazar S5 0716+714. We are also examining the presence of IDV/ISS in the Owens Valley 15 GHz flux density monitoring data. We find a significant relationship between the Owens Valley 15 GHz modulation index and the MASIV modulation index. We also discuss the implications of these findings for RadioAstron.

Keywords: Active galactic nuclei; Radio continuum: Quasars; Variability; Interstellar scintillation

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1. Introduction

Variability on timescales of days or less in the cm-wavelength emission from flat-spectrum extragalactic radio sources was discovered in the mid-1980s (Heeschen, 1984; Witzel et al., 1986; Heeschen et al., 1987). Both intrinsic variability and extrinsic inter-stellar scintillation, ISS, were proposed as possible causes of this intra-day variability, IDV. The first IDV pattern time-delay measurements (Jauncey et al., 2000; Dennett-Thorpe and de Bruyn, 2002; Bignall et al., 2006) provided direct evidence that the very rapid IDV discovered in PKS0405−385, J1819+3845 and PKS1257−326, was clearly caused by inter-stellar scintillation, and was not intrinsic to the source.

Since then the discovery of annual cycles in the sources J1819+3845 (Dennett-Thorpe and de Bruyn, 2003), 0917+624 (Jauncey and Macquart, 2001; Rickett et al., 2001) and PKS1257−326 (Bignall et al., 2003), and the subsequent discovery of annual cycles in the IDV of an increasing number of sources, provided a clear demonstration that ISS was the principal cause of the IDV seen in compact, flat-spectrum AGN.

During the first year of observations of PKS1257−326, Bignall found the annual cycle, demonstrating clearly its ISS origin. What was also interesting was the annual cycle found in the time displacement between the two frequencies, through which it became possible to determine the scale between where the micro-arcsecond scintillating component became optically thick at the two frequencies, with micro-arcsecond precision (Bignall et al., 2003).

The argument for an ISS origin in the many AGN with annual cycles was supported by the Galactic latitude dependence found in early IDV surveys (Heeschen and Rickett, 1987), which has been further investigated with the extensive MASIV IDV survey results at 8.4 and 4.9 GHz plotted verses the Hα intensity (Koay et al., 2011).

2. A possible ISS origin for the 'unusual' event in S5 0716+714, February 1990

While the accumulated evidence for an ISS origin for the observed intraday variability at cm wavelengths in many compact AGN is strong, there remained the specific February 1990 VLA observations of S5 0716+714, and the optical observations from Calar Alto, Spain, and Landessternwarte, Heidelberg, Germany. Based on the observed radio-optical spectral index correlation, Fig. 1 below, seen in the February data, this was claimed to be intrinsic with an implied brightness temperature of $\sim 10^{19}$ K (Wagner and Witzel, 1995). We note that Kravchenko et al. (2019, this ASR issue) have taken a close interest in searching the RadioAstron data for exceptionally high brightness temperatures in S5 0716+714, specifically based on the earlier claimed radio-optical correlation as demonstrating an intrinsic origin for this particular event.

Later, many observational attempts were made to find a repeat of this behavior, but none has been successful, as discussed, for example, by Fuhrmann et al. (2008).

Twenty years later, 5 GHz observations over a 4.5 year period revealed a clear annual cycle in the IDV of 0716+714 (Liu et al., 2012, see Fig. 2), establishing that the mechanism responsible for the observed IDV was interstellar scintillation. They also found that 0716+714 exhibited prominent IDV in all of their 40 observing sessions. Despite this, there remained a view that during February 1990 there could have been intrinsic variability, and that during the February episode 0716+714 may have been an 'extreme blazar.'

We looked again at the original February 1990 VLA data on 0716+714, which was later published in full (Quirrenbach et al., 2000). The major difference with the earlier published data is the addition of the 15 GHz observations for which the authors had earlier expressed concern about possible weather effects (Wagner et al., 1996), but the

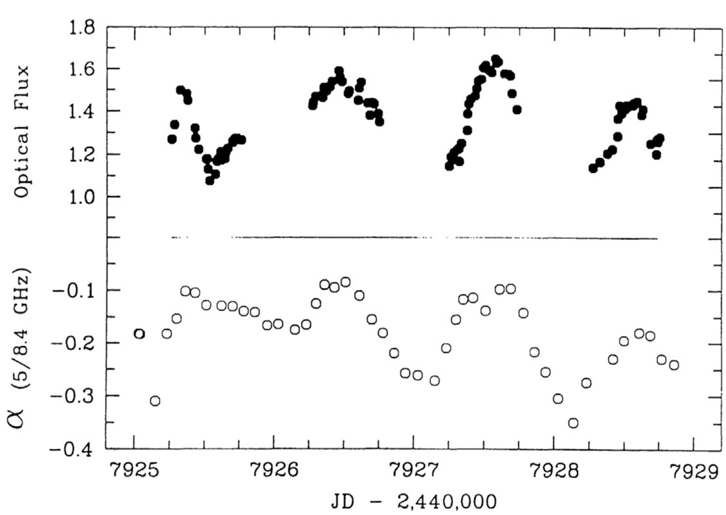

Fig. 1. Correlation of the radio spectral index (open circles) with the optical flux (650 nm, filled circles) in 0716+714, from Wagner and Witzel (1995).

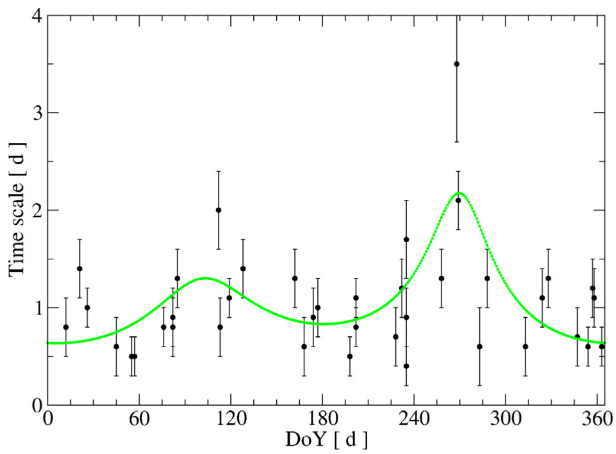

Fig. 2. The annual cycle plot of 0716+714 from Liu et al. (2012).

2000 publication includes the 15 GHz data with quoted uncertainties of 2%.

An examination of these data, shown in Fig. 3, demonstrates that, while there is the clear correlation between the observed optical and 5–8 GHz radio spectral indices over the range day 7925 through 7929, as shown above in Fig. 1 from Wagner and Witzel (1995), the 15 GHz data shows no evidence of any significant variability at all over this same period. Thus for the idea that the radio variability and the optical observations implied the same 'intrinsic' change over this whole radio-to-optical frequency range, the lack of any observed change at 15 GHz reveals that this cannot be the case.

Looking again at the annual cycle results from Liu et al. (2012), it is apparent that the observed time-scale of the February 1990 variability at 5 GHz is in complete agree-

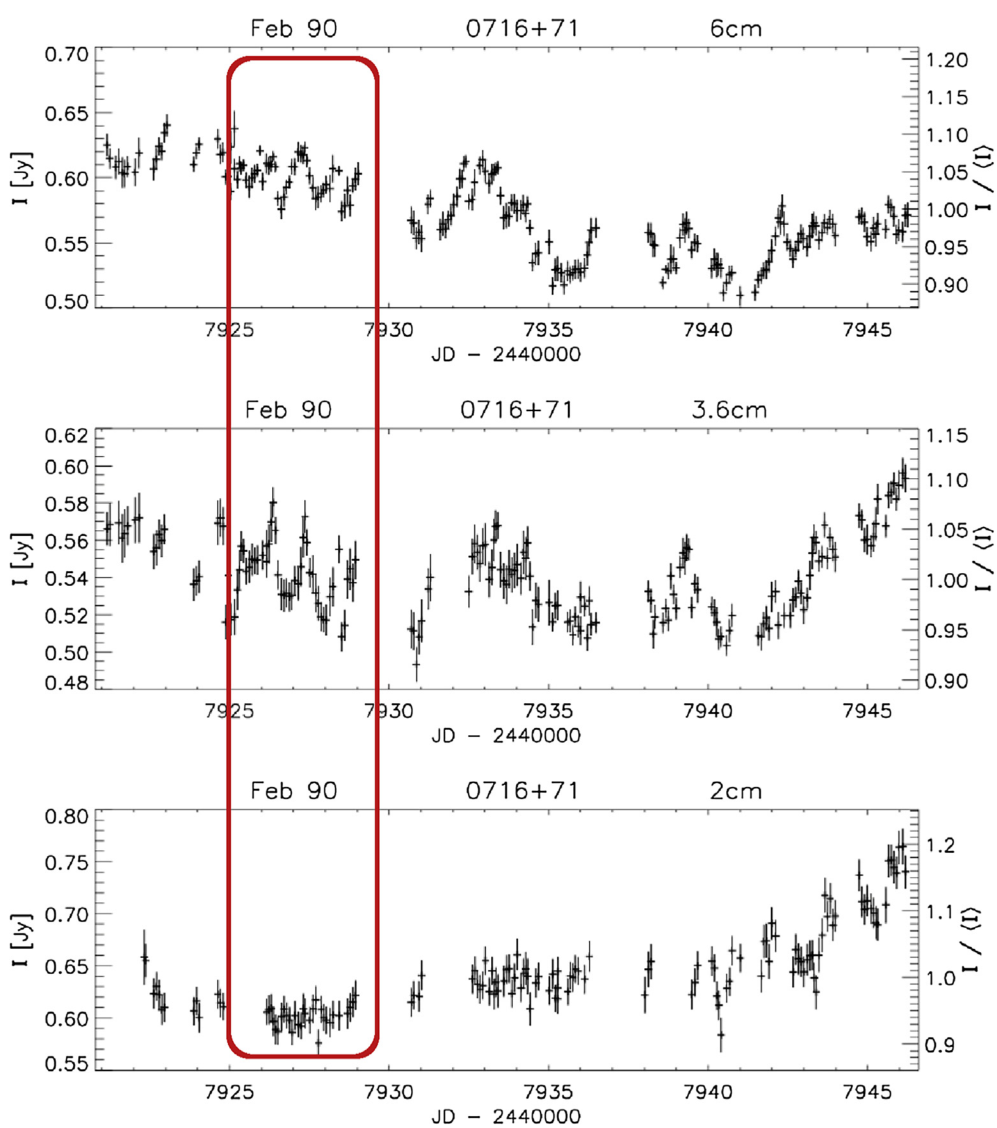

Fig. 3. The February 1990 4.86, 8.44 and 15.0 GHz VLA observations of 0716+714 emphasizing the period DOY 7915–7929, from Quirrenbach et al. (2000).

ment with the observed annual cycle timescales for February found some 20 years later. This clearly demonstrates that the February 1990 observations are entirely consistent with an ISS origin, and rules out the idea that they could be intrinsic.

3. Relationship between AGN Variability at 5 and 15 GHz

We also present the first results of a study of the relationship between ISS and longer time-scale intrinsic variability. We have seen that at 5–8 GHz, AGN variability on time-scales of hours to days is dominated by scintillation due to scattering in the ionized interstellar medium (ISM) of our Galaxy. The Micro-Arcsecond Scintillation Induced Variability (MASIV) Survey (Lovell et al., 2003; Lovell et al., 2008) of 500 compact, flat-spectrum AGN at 5 GHz provided the first large statistical study of intraday and inter-day variability. 58% of the MASIV Survey sources were found to exhibit IDV in at least one of the four epochs of observations (Lovell et al., 2008); the observed strong Galactic dependence of the variability amplitudes confirms that the flux variations are predominantly due to interstellar scintillation. The sensitivity of ISS to source sizes at microarcsecond (μas) scales makes it an excellent probe of compact structures in radio AGN (e.g. Macquart and Jauncey, 2002; Rickett et al., 2002; Macquart et al., 2013), as well as the properties of the ISM (Armstrong et al., 1995; Walker et al., 2017).

Richards et al. (2014) present the 15 GHz variability amplitudes of 1500 blazars based on 4 years of monitoring by the OVRO 40 m telescope. Each source is observed at a cadence of two flux density measurements a week since 2008 January. Here we focus only on the radio-selected sources from the Richards et al. (2011) sample, since we are interested in understanding the variability characteristics of radio-selected AGNs. To characterize the variability amplitudes of the OVRO light curves, the intrinsic modulation index, described in Richards et al. (2011), is used. This estimate uses the maximum likelihood method to determine the standard deviation of the flux densities of each source light curve, normalized by the mean flux density.

A total of 178 of the MASIV sources overlap the original radio-selected OVRO 15 GHz monitoring sample. Of this sample, 173 sources are radio-strong ($S_5 \geqslant 0.3$ Jy), while only five sources are radio-weak with $S_5 < 0.3$ Jy. Our results for this paper therefore pertain mainly to bright, high flux density radio AGN.

Fig. 4 is a plot of the 15 GHz OVRO modulation index verses the MASIV 5 GHz modulation index for 178 sources. It is clear that there is a level of correlation between the OVRO modulation index and the MASIV modulation index. However, this plot reveals an important Bayesian relationship showing that while all of the strong MASIV scintillators, $m_5 > 0.02$, are strongly variable at 15 GHz, not all of the strongly variable sources with $m_{15} > 0.1$, are strong scintillators. This makes clear the dependence of scintillation on the properties of the interstellar medium along the AGN line-of-sight through the Galaxy. This observed relationship makes a strong case that potentially all of the strong 15 GHz slow and intrinsic variables that exhibit little or no ISS, themselves possess μas-scale components similar to those revealed by their scintillation IDV.

4. Is ISS present in the OVRO lightcurves on inter-day timescales?

Given that IDV at 15 GHz was first found serendipitously in B1156+295 (Savolainen and Kovalev, 2008), we began looking for further evidence of IDV in the OVRO flux density monitoring data. It soon became apparent that there was a significant number of OVRO blazars that exhibited IDV at 15 GHz.

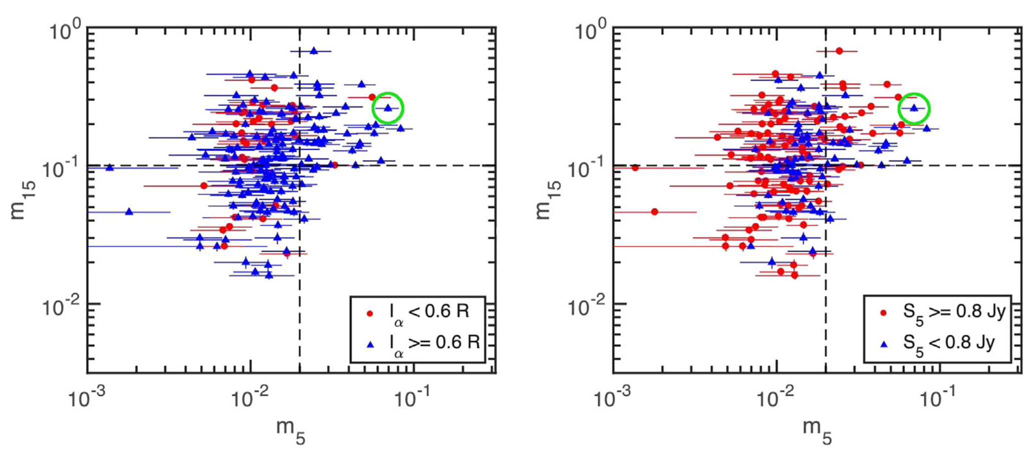

Fig. 4. The 15 GHz OVRO modulation index verses the MASIV 5 GHz modulation index for 178 sources, with separation based on their line-of-sight Hα intensity (left) and flux density (right). Sources along sightlines with high Galactic Hα intensity tend to have larger short-term modulation indices from the MASIV Survey, while lower flux density sources tend to show both larger fractional IDV and larger fractional long-term variability at 15 GHz. The vertical and horizontal line denote $m_5 = 0.02$ and $m_{15} = 0.1$ respectively; from Koay et al. (2018). The point representing source J0502+1338 is enclosed by a green circle.

One of the first examples we found was the BL Lac source J0502+1338 (PKS0459+136). It was identified with a faint red object (Condon et al., 1977), whose featureless optical spectrum led to BL Lac classification (Perlman et al., 1998), although a distance estimate of $z = 0.45^{+.09}_{-.08}$, based on the size of the host galaxy, has been determined (Meisner and Romani, 2010). The MASIV Survey also found J0502+1338 to be a strong scintillator at 5 GHz (Lovell et al., 2008), and it is also a strong variable at 15 GHz, c.f Fig. 4.

The 15 GHz OVRO plot, shown in Fig. 5, reveals the presence of significant variability on the shortest sampling interval of 4 days. Over the entire light curve, the average rms variations (modulation index) on the 4-day timescale are 4.4%. This is well above the measurement noise and systematic uncertainties of 2.9% for this source on that timescale. Fig. 5 shows that the source appeared to be in a low flux density state, ~ 0.27 Jy, roughly from day 500 to day 1500. Day 1600 marks the onset of a dramatic increase in flux density to a maximum of ~ 0.78 Jy. Present during this rise is increased inter-day variability. The structure functions shown in Fig. 5, with ”high” and ”low” states separated for flux density above and below the average (dashed line across the light curve), confirm that the variations, in Jy, visible in the light curve are larger during the observed outburst than prior to the flare. Such behaviour is entirely consistent with the presence of ISS at 15 GHz in the new component, implying a microarcsecond component angular size, with a residual, long-lived, compact scintillating component present throughout the monitoring period.

5. Summary

We have revisited the February 1990 4.86, 8.44 and 15.0 GHz published observations of S5 0716+714 and found that while there is a clear correlation between the observed optical and 5–8 GHz radio spectral index variations over the range days 7925 through 7929, as shown above in Fig. 1 from Wagner and Witzel (1995), the 15 GHz data shows no evidence of any significant variability at all over this same period. Thus for the idea that the radio variability and the optical observations implied the same ‘intrinsic’ change over this whole radio-to-optical fre-

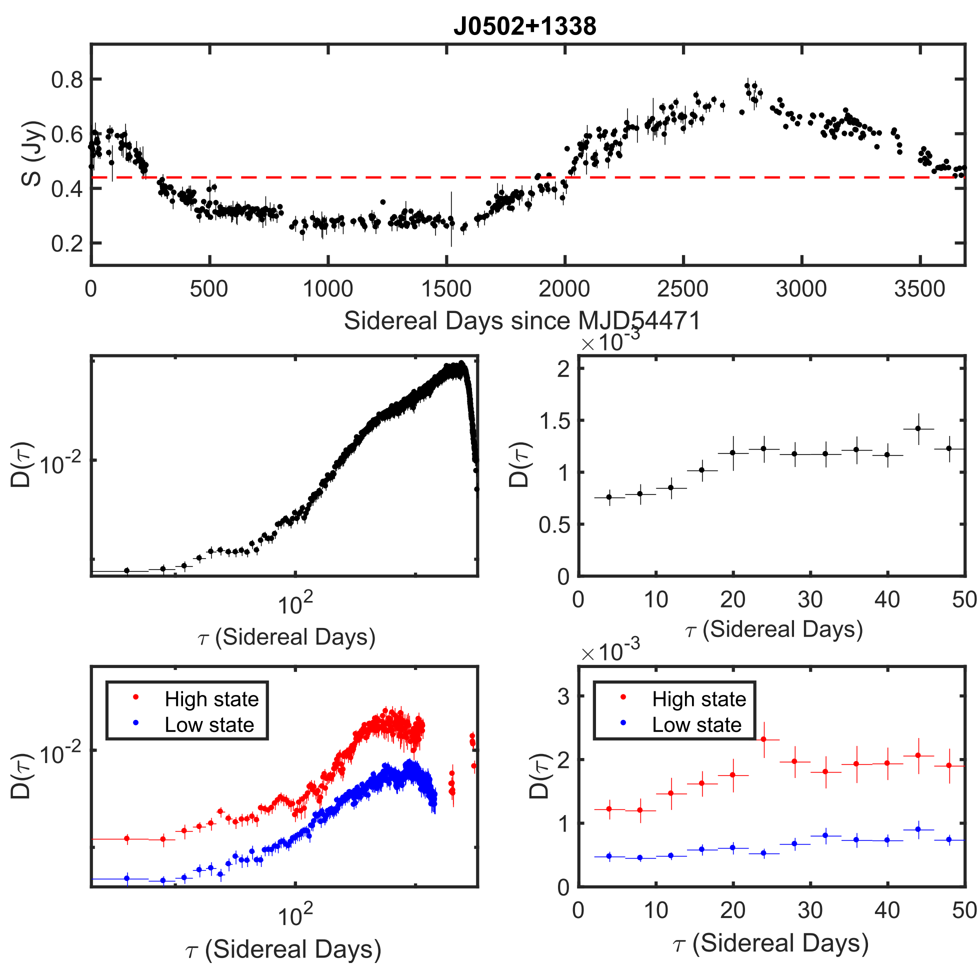

Fig. 5. The Owens Valley 15 GHz light curve for J0502+1338, with structure functions, $D(\tau)$, calculated from the light curve shown in their entirity, and for $\tau \leqslant 50d$. Note that the flux density has not been normalised by the mean for the structure functions shown here; the variations in Jy are larger during the observed flare, and are significantly higher than the measurement uncertainties.

quency range, the lack of any observed change at 15 GHz reveals that this cannot be the case. Moreover, this, combined with the 1990 5 GHz timescale being the same as found in the annual cycle two decades later, make it clear that the February episode was due to ISS and was not intrinsic.

Our plot of the 15 GHz OVRO modulation index verses the MASIV 5 GHz modulation index for the 178 common sources shows clearly that there is a high level of correlation between the OVRO modulation index and the MASIV modulation index. All of the most compact sources that scintillate also exhibit strong variability at 15 GHz. We also found a strong Galactic dependence of the sources showing inter-day variability at 15 GHz, confirming that interstellar scintillation is the mechanism responsible (Koay et al., in preparation). This result along with the above finding for S5 0716+714 leads us to conclude that there is thus far no evidence for significant intrinsic IDV in AGN across the centimetre-wavelength band.

There are significant implications for RadioAstron. The MASIV Survey at 5 GHz implies the presence of μas source component angular sizes, and these in turn imply the presence of component brightness temperatures of $\sim 10^{13}$ K up to in excess of 10^{14} K (Macquart and Jauncey, 2002). We have established the presence of ISS at 15 GHz on the shortest inter-day timescales in a significant number of the Owens Valley monitoring sources. We have shown that the most compact scintillating sources are also intrinsically variable, so it is possible to see both processes underway in the same sources. The presence of IDV in the scintillating sources places considerable emphasis on the careful total flux density and variability monitoring during and around each RadioAstron observation, a point also emphasised by Liu et al. (2018). Given the presence of ISS at 15 GHz in a number of sources, such careful monitoring is essential even at 22 GHz. This raises the question as to how high a frequency is needed to completely avoid the effects of ISS.

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