*Approaching Micro-Arcsecond Resolution with VSOP-2: Astrophysics and Technology*
*ASP Conference Series, Vol. 402, © 2009*
*Y. Hagiwara, E. Fomalont, M. Tsuboi, and Y. Murata, eds.*

# Intraday Radio Variability and Micro-Arcsecond Resolution

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**Abstract.** Intraday variability (IDV) of AGN at centimeter wavelengths has been shown to be predominantly due to interstellar scintillation (ISS). Recent VLBI observations have shown that IDV sources are more compact than non-IDVs on milliarcsecond scales, and a significant fraction are completely unresolved with ground-based VLBI. Additionally, very rapid IDV due to ISS has been observed in some extragalactic water masers at 22 GHz, implying masers $\sim 10$ micro-arcseconds in angular size. Such bright, compact sources will be excellent targets for observation with VSOP-2 in order to study the sub-pc scale regions of AGN.

## 1. Introduction

Variability on timescales of days or less in the centimeter-wavelength emission from extragalactic sources was discovered in the 1980s (Heeschen 1984, Witzel et al. 1986, Heeschen et al. 1987). Both source-intrinsic variability and interstellar scattering were proposed as possible causes of the observed intraday variability (IDV). Variations on short timescales are observed in blazars across the whole electromagnetic spectrum (e.g. Wagner & Witzel 1995). However, radio IDV interpreted as intrinsic to the source often implied extremely high source brightness temperatures, difficult to reconcile with standard emission models. The observed IDV is also not generally consistent with gravitational microlensing scenarios (Wagner & Witzel 1995, and references therein). On the other hand, if a typical quasar or BL Lac object is compact enough to vary on timescales of months or less, it will scintillate due to scattering in the Galactic interstellar

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medium (ISM). §2 describes observed signatures of interstellar scintillation (ISS) which demonstrate that IDV at centimeter wavelengths is predominantly due to ISS. §3 discusses properties of scintillating sources and implications for VSOP-2.

## 2. Signatures of Interstellar Scintillation

The theory of interstellar scattering has been reviewed by, e.g., Rickett (1977, 1990) and Narayan (1992). Electron density irregularities in the turbulent, inhomogeneous ionized ISM introduce phase fluctuations in a wavefront passing through the medium. Mutual interference converts the phase fluctuations to transverse spatial fluctuations of intensity in the observer's plane. The relative transverse motion of the Earth with respect to the scattering plasma causes a telescope's line of sight to move through the spatial intensity modulation pattern.

*Frequency Dependence of ISS* A critical scale in scintillation is the angular size of the first Fresnel zone, $\theta_{\rm F} = \sqrt{c/2\pi\nu L}$, at the distance $L$ of the equivalent scattering "screen" from the observer. Weak scattering occurs when the phase changes introduced by the scattering medium are smaller than $\sim 0.5$ radian across the first Fresnel zone. Thus weak scintillation occurs at high frequencies and for nearby scattering screens, on a characteristic spatial scale corresponding to the Fresnel scale. For typical ISM screen distances of tens to hundreds of parsec the angular Fresnel scale at centimeter wavelengths is of order $10\,\mu$as. Strong scattering occurs when the wavefront is highly corrugated on scales smaller than the first Fresnel zone. There are two regimes of scintillation in strong scattering - slow, broad-band changes known as refractive scintillation, and fast, narrow-band diffractive scintillation. Each regime of scintillation has a frequency-dependent characteristic angular scale which sets an upper limit on the angular size for a source to scintillate. For source components larger than the corresponding scintillation scale, the resultant scintillation pattern will have reduced amplitude and increased spatial scale, and in large enough sources the scintillation is suppressed completely.

The largest amplitude broad-band variations due to ISS occur near the transition frequency, $\nu_0$, between weak and strong scattering. For lines of sight out of the Galactic plane $\nu_0$ is typically a few GHz, increasing up to several tens of GHz towards the Galactic plane. Kedziora-Chudczer et al. (1997) showed that the frequency dependence of the extremely rapid flux density variations observed in the $z = 1.285$ quasar PKS B0405$-$385 match with expectations of ISS. Strongly correlated variations were observed at 4.8 and 8.6 GHz, with the largest amplitude variations observed at 4.8 GHz, consistent with weak scattering at 4.8 GHz and above, while at lower frequencies, 2.3 and 1.4 GHz, the timescale of the variations becomes much longer and the modulation index decreases with decreasing frequency, consistent with refractive ISS. Similar behaviour is seen in other well-studied IDVs (e.g. Macquart et al. 2000, Dennett-Thorpe & de Bruyn 2000, Gabányi et al. 2007b). In contrast, source-intrinsic variability is usually more pronounced towards shorter, millimeter, radio wavelengths (e.g. Valtaoja 1994).

*Pattern arrival time delays* For sources which vary sufficiently rapidly, it is possible to search for delays of order minutes between the variability pattern arrival times at widely separated telescopes. The delay arises as the scintillation pattern drifts across the baseline with a relative velocity of typically tens of km $s^{-1}$. Sources must have variations detectable on timescales of order a minute for the ISS pattern arrival time delay to be measurable. Time delay measurements have been possible for the three intra-hour variable sources PKS 0405−385 (Jauncey et al. 2000, Kedziora-Chudczer 2006b), J1819+3845 (Dennett-Thorpe & de Bruyn 2002) and PKS 1257−326 (Bignall et al. 2006), in each case showing that the rapid, large-amplitude variations observed are entirely due to ISS. The fact that the apparent source intensity is different for different antennas simultaneously presents a potential problem for VLBI imaging. However, the MASIV Survey (Lovell et al. 2003, 2008) showed that the vast majority of quasars scintillate only slowly, implying characteristic scintillation scales much larger than $10^5$ km. Therefore in general, time delays should not present any problem for VSOP-2 observations. For long observations, however, time variability may need to be accounted for.

*Annual cycles* The characteristic timescale of ISS is expected to vary on an annual cycle. The bulk velocity of a scattering screen in the ISM is often similar to the Earth's orbital velocity of $\sim 30\,\mathrm{km\,s^{-1}}$ relative to the Sun, so that at some time of the year, the transverse velocity of the scintillation pattern with respect to the observer may be quite small, and an increase in the characteristic timescale of variability will be observed, whereas at a different time of the year the relative transverse velocity is large and the variations observed will be relatively rapid. Annual cycles are clearly observed in the characteristic variability timescales of J1819+3845 (Dennett-Thorpe & de Bruyn 2003) and PKS 1257−327 (Bignall et al. 2003). In both of these cases the scintillation pattern is also determined to be highly elongated in one direction, with an axial ratio $\sim 10:1$ or larger. This anisotropy will also influence the annual cycle, since the characteristic timescale is increased when the scintillation velocity is aligned with the long axis of the pattern. There is evidence that anisotropic scattering is a common phenomenon (e.g. Rickett et al. 2002, Walker et al. 2004, Rickett & Coles 2004), presumably indicating alignment of plasma density structures by the local magnetic field. Repeated annual cycles have been observed in a handful of well-studied sources (e.g. Jauncey et al. 2003), however other sources show an annual cycle only episodically (e.g. Fuhrmann et al. 2002, Kedziora-Chudczer 2006a, Gabányi et al. 2007a) or show no clear annual cycle in their characteristic timescale. A change in scintillation behavior could occur due to intrinsic evolution of the source structure on scales of order $10\mu$as, or to changes in the overall scattering properties along the line-of-sight.

*Galactic dependence* Studies of the statistics of IDV for large source samples show a significant signature of the Galaxy, clear evidence of the IDV being predominantly due to ISS. Rickett et al. (2006) analyzed Green Bank Interferometer (GBI) monitoring observations of 146 extragalactic radio sources, and found a significant Galactic dependence consistent with the ISS model for the short timescale variability observed. The 5 GHz MASIV VLA Survey of the northern sky observed $\sim 500$ flat-spectrum radio sources over 3 or 4 days in four observing epochs spread over the course of a year between January 2002 and January 2003 (Lovell et al. 2003). Over half of the sources were found to exhibit rms variations of $\sim 1\%$ or more on timescales of up to 3 days at 5 GHz. Lovell et al. (2008) find a strong correlation between the level of IDV and the intensity of H$\alpha$ emission from the WHAM Survey (Haffner et al. 2003). This establishes ISS as the dominant cause of the variability. Furthermore, the fraction of sources varying on timescales longer than 2 days, which make up the majority of the variable sources found in the MASIV Survey, clearly increases with increasing emission measure while the fraction of rapidly variable sources, with characteristic timescales less than half a day, decreases with increasing emission measure. This is consistent with stronger scattering, and hence longer refractive scintillation timescales, from strongly ionized regions of the ISM, which are typically at low Galactic latitudes and at greater distances. Rapid IDV in the weak scattering regime is produced in nearby, localized scattering screens. The Galactic latitude dependence of IDV in the MASIV Survey is also consistent with ISS expectations (Lovell et al. 2008).

## 3. Properties of Scintillating Sources

*ISS as a Probe of Micro-Arcsecond Source Structure* ISS probes source structure on angular scales of order 10$\mu$as, corresponding to the Fresnel scale of the scattering screen. Using an ISS model for the GBI monitoring data, Rickett et al. (2006) determined that the scintillating sources typically have about 50% of their compact flux density in a component with maximum brightness temperature $10^{11} - 10^{12}$ K. Similarly an analysis of the MASIV Survey data (Lovell et al. 2003) found the observed ISS to be consistent with maximum source brightness temperatures of $\sim 10^{12}$ K. Thus the results from ISS are consistent with findings from VLBI studies, even though ISS is not subject to the same resolution limits as VLBI.

As the velocity of the observer with respect to the scintillation pattern changes direction over the course of a year, in principle the two-dimensional structure of the scintillation pattern can be mapped out. This is related to the micro-arcsecond scale source brightness distribution (Macquart & Jauncey 2002). Time delay and timescale measurements can be combined to determine the velocity and characteristic spatial scale of the scintillation pattern, as well as the distance to the scattering screen (Bignall et al. 2006). Unfortunately, highly anisotropic scattering results in degenerate solutions for the scintillation pattern scale and velocity component along the long axis of the pattern; in this case the scintillation parameters may be determined only in the direction perpendicular to the elongation. Nevertheless, ISS offers a unique probe of micro-arcsecond-scale source structure and evolution (e.g. Macquart & de Bruyn 2007). Observing at multiple frequencies and with full polarization measurements provides additional information on both source and scattering screen properties. IDV sources often show substructure in linear polarization that is not seen in the total intensity scintillating component. Rickett et al. (2002) used cross-correlation analysis to model the ISS of Stokes I, Q, U for PKS 0405−385. The data were fitted by a source model having strongly polarized core components with a rapid rotation of $\sim 180°$ in the angle of polarization across the long axis of the source, corresponding to polarized structure on a linear scale of $\sim 0.2$ pc. Measurement of the micro-arcsecond scale polarized structure of AGN cores is not generally possible with VLBI observations due to beam depolarization.

*VLBI Observations of Scintillating Sources* VLBI and ISS studies are complementary, with VLBI allowing direct imaging of the source structure typically on milliarcsecond scales, while ISS observations provide information on the flux density distribution of the most compact components unresolved with VLBI. Ojha et al. (2004), Ojha et al. (2006) present VLBA observations of sub-samples of MASIV Survey sources, finding that both low and high flux density scintillating sources have significantly different mas-scale morphologies than their non-scintillating counterparts. The scintillators have a higher proportion of the flux in a compact core, and have a smaller overall angular size, often being completely unresolved with the VLBA. VSOP-2 observations will therefore be important to study the physics of these very compact AGN jets. This will be particularly of interest for studies of gamma-ray blazars, with GLAST anticipated to discover many gamma-ray emitting AGN. A high fraction of gamma-ray blazars detected with EGRET are radio IDVs, as discussed by Wajima et al. (2006) and Bignall et al. (2008).

*Scintillation of 22 GHz $H_2O$ megamasers* Rapid IDV on timescales of minutes to hours has been observed in the 22 GHz $H_2O$ megamaser features of both the Circinus galaxy (Greenhill et al. 1997, McCallum et al. 2005, 2007) and NGC 3079 (Vlemmings et al. 2007). The line-of-sight to Circinus passes through the Galactic plane, so that strong scattering would be expected at 22 GHz. McCallum et al. (2007) conclude that the rapid variations of the $H_2O$ megamaser emission lines in the Circinus galaxy are best modeled as diffractive scintillation of masers a few micro-arcseconds in angular size. NGC 3079 has a Galactic latitude of 48°, and at 22 GHz only weak ISS of the maser features is expected on this line-of-sight. The observed rapid variability is well modeled as weak ISS due to a scattering screen at $\sim 25$ pc, and the inferred size of the maser features is $\sim 12\mu$as (Vlemmings et al. 2007), consistent with models assuming a thick, clumpy accretion disk (Kondratko et al. 2005). Variability due to gain variation along the maser amplification path would occur on much longer timescales, typically days.

## 4. Conclusions

ISS is the dominant cause of centimeter wavelength IDV in extragalactic radio sources. A large fraction of all compact, flat-spectrum radio sources show ISS, which implies the presence of a component tens of micro-arcseconds in angular size. This is comparable with scales observable directly with VSOP-2. Although interstellar scattering provides a useful probe of micro-arcsecond source structure, its effects may ultimately limit astrometric precision. ISS and high-resolution VLBI observations are complementary in detailed studies of the central compact regions in AGN.

**Acknowledgments.** HEB is grateful to the SOC for the invitation to present a talk at the VSOP-2 Symposium, and to the Leids Kerkhoven-Bosscha Fonds for travel support.

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