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Interstellar scintillation as a probe of microarcsecond scale structure in quasars

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Abstract. Observations over the last two decades have shown that a significant fraction of all flat-spectrum, extragalactic radio sources exhibit flux density variations on timescales of a day or less at frequencies of several GHz. It has been demonstrated that interstellar scintillation (ISS) is the principal cause of such rapid variability. Observations of ISS can be used to probe very compact, microarcsecond-scale structure in quasar inner jets, as well as properties of turbulence in the local Galactic ISM. A few sources show unusually rapid, intra-hour variations, evidently due to scattering in very nearby, localized turbulence. We present recent findings for the rapidly scintillating quasar PKS 1257−326. The large-scale MASIV VLA Survey showed that such sources are extremely rare, implying that for most scintillating sources, longer-term, dedicated monitoring programs are required to extract detailed information on source structures.

1. Introduction

Since the discovery of inter-day and intraday flux density variations (IDV) in extragalactic radio sources (Heeschen 1984; Witzel et al. 1986; Heeschen et al. 1987), observations have shown that a significant fraction of all flat-spectrum radio sources exhibit such variations at frequencies of several GHz (Quirrenbach et al. 1992; Kedziora-Chudczer et al. 2001; Lovell et al. 2003). For a number of sources, it has been possible to show unambiguously that the rapid variations are due to interstellar scintillation (ISS) and to constrain scintillation parameters, mainly through two types of observation: (i) annual modulations in the characteristic timescale of variability, and (ii) for the three fastest scintillators, discussed in Section 2, through observations of delays between the variability pattern arrival times at widely separated telescopes. Moreover, sources which show intrinsic changes on short timescales are likely to contain compact components with angular sizes of order 10 microarcseconds (μas) or less, which will be affected by ISS at cm wavelengths. On one hand, ISS may complicate interpretation of radio variability, but on the other, the statistics of ISS fluctuations can be used as an ultra-high resolution probe of source structure (Macquart & Jauncey 2002).

2. The intra-hour variables

Sources which show very rapid IDV allow a useful sample of the variability pattern to be obtained in a relatively short observing time. The discoveries of large-amplitude, intra-hour variations in three sources have thus made important contributions to our understanding of ISS of extragalactic sources.

PKS 0405−385, a quasar at redshift z=1.285, was the most extremely variable source discovered in the ATCA IDV Survey of Kedziora-Chudczer et al. (2001). Kedziora-Chudczer et al. (1997) found that the frequency dependence of the observed IDV was consistent with what is expected from ISS, with the break between strong and weak scattering occurring near 5 GHz. Unequivocal evidence that the rapid variations in PKS 0405−385 are a result of ISS came from the detection of a time delay between the variability pattern arrival times at the VLA and the ATCA (Jauncey et al. 2000). Such time delay measurements are only possible when changes in flux density can be detected on timescales of order tens of seconds. Subsequently, a detailed analysis of the scintillation of Stokes I, Q, and U parameters was used to construct a model of the μas-scale polarized structure of this source (Rickett et al. 2002). This analysis also found that scattering in an unusually nearby screen, only 3–30 pc from the observer, is required to explain the observations. A source brightness temperature, T_b, of $\sim 2\times10^{13}$ K is then implied. The rapid ISS of PKS 0405−385 is episodic, lasting for several weeks to months at a time. Between these episodes, the source shows large variations on timescales of months to years, but appears to be stable on short timescales, with observed rms variations not exceeding 1% in 48 hours at 4.8 and 8.6 GHz. After a quiescent period of 4 years, PKS 0405−385 has recently started scintillating again (IAUC 8403).

Even more rapid variations were discovered in the z=0.54 quasar J1819+3845 by Dennett-Thorpe & de Bruyn (2000). Frequent monitoring with the WSRT has shown a persistent annual cycle in the characteristic timescale of IDV, and time delays between the IDV pattern ar-

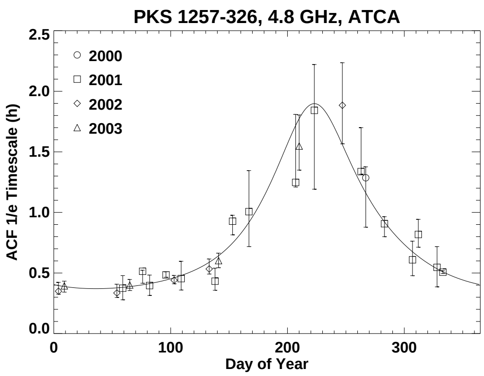

Fig. 1. The annual cycle in characteristic timescale for PKS 1257−326 at 4.8 GHz. The line shows a best fit for the scintillation velocity and an elliptical scintillation pattern, using these data combined with two-station time delay data.

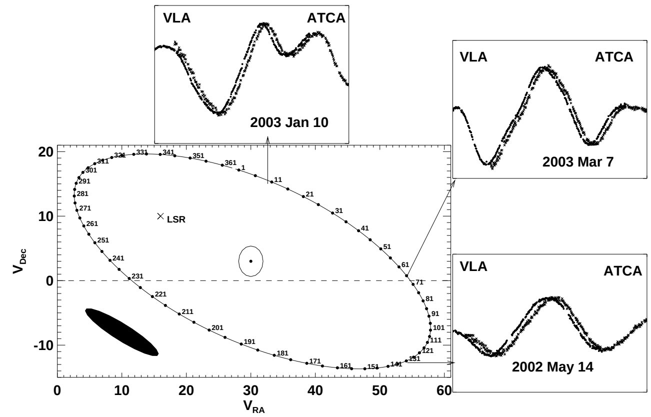

Fig. 2. The 2-D scintillation velocity, in km s^{-1}, over the course of the year for PKS 1257−326, and two-station time delay data at 4.9 GHz observed at three epochs. The velocity ellipse is centered on the best fit screen velocity, with error ellipse indicated. The local standard of rest (LSR) velocity is also indicated. The small filled ellipse shows the orientation of the best fit anisotropic scintillation pattern.

rival times at the VLA and WSRT were observed in January 2001 (Dennett-Thorpe & de Bruyn 2002). Dennett-Thorpe & de Bruyn (2003) used the annual modulation in characteristic timescale to constrain the peculiar velocity and distance of the scattering screen, and to estimate the screen distance (1–12 pc), source size and brightness temperature. The scintillation pattern is highly anisotropic, and the favoured source model implies $T_b \sim 10^{12} K$.

PKS 1257−326, at z=1.256, was the third quasar discovered to show intra-hour variations. Similarly to J1819+3845, this source has shown persistent rapid variations since its discovery in 2000. Bignall et al. (2003) presented results of ATCA monitoring of PKS 1257−326 over more than a year, showing an annual cycle in the characteristic timescale of variability. The combined results of these and more recent observations of this source are presented below, and ongoing analysis is discussed.

2.1. PKS 1257–326: ISS geometry, long-term changes and μas-scale polarized structure

Frequent monitoring of PKS 1257−326 with the ATCA was undertaken from early 2001 until September 2003, revealing a persistent annual cycle in the characteristic timescale of IDV. Fig. 1 shows the characteristic timescale, defined here as the half-width at $1/e$ of the intensity autocorrelation function (ACF), from each ATCA dataset at 4.8 GHz, plotted against day of year. The methods of Rickett et al. (2002) was used to compute estimation errors in the ACFs. Errors are dominated by the limited sampling of the scintillation pattern.

Pattern arrival time delays between the VLA and ATCA have been observed for PKS 1257−326 at three different times of the year, on two consecutive days in each epoch and simultaneously at frequencies of 4.9 and 8.5 GHz. We used observations of the nearby calibration source PKS 1255−316 for relative amplitude calibration of the two arrays. PKS 1257−326 has faint, arcsecond-scale extended structure, although VLBI observations show that the source is dominated by an unresolved component, with no other significant structure visible on mas scales. In order to compare accurately the flux densities of the unresolved, scintillating component measured at each array, a model of the arcsecond-scale extended structure, imaged using VLA data, was first subtracted from the visibilities of both telescopes. The light curves observed at both telescopes are essentially identical apart from a displacement in time. Fig. 2 shows three of the simultaneous observations at 4.9 GHz. The measured time delays were found to be very similar for both frequencies and on consecutive days. We detect no significant change in delay over the course of each observation, although a small change might be expected due to the rotation through $\sim 20°$ of the projected ATCA-VLA baseline. For the May 2002 epoch, the best fit delay is 470 ± 60 s, while for January and March 2003, the time delay is shorter, 330 ± 50 s during January and 320 ± 40 s in March.

The time delay and annual cycle measurements are combined to fit simultaneously for the peculiar velocity of the scattering screen, assumed to be the same for both frequencies, and the length scale s_0, axial ratio R, and position angle of an elliptical scintillation pattern, which was allowed to be different at the two observed frequencies. Fig. 2 shows how the scintillation velocity changes over the course of the year. The large ellipse is centred on the best fit screen velocity. The scintillation pattern is found to be highly anisotropic. The orientation and anisotropy of the fitted scintillation pattern is indicated by the small filled ellipse in Fig. 2. The line plotted in Fig. 1 shows the annual cycle in characteristic timescale expected from the best fit model. We find $s_0 \approx 10^5$ km at 4.8 GHz, and $R \geq 5$. In weak scattering, s_0 corresponds approximately to the size of the first Fresnel zone, $r_F = \sqrt{\lambda L/(2\pi)}$, at the scattering screen distance L. Our model then implies $L \sim 30$ pc and an angular size of the first Fresnel zone, $\theta_F \sim 20\mu$as. Assuming the intrinsic source angular size cannot be much larger than this, a brightness temperature of $\sim 10^{13}$ K is implied. Further investigation, for example analysis of power spectra of the fluctuations, and analysis of multi-frequency and multi-Stokes data, is needed to determine whether the high degree of anisotropy in the scintillation pattern is due to an anisotropic source, or to anisotropic scattering. Highly anisotropic scintillation patterns have been found for all three fast scintillators. Rickett et al. (2002) argued that the anisotropy is a property of the scattering screen for the case of PKS 0405−385, based on the observed power spectrum of the fluctuations. It is interesting to note that an interpretation of parabolic arcs observed in the dynamic secondary spectra of some pulsars (Stinebring et al. 2001) requires highly anisotropic scattering from compact, isolated clumps of scattering material in the ISM (Walker et al. 2004).

Although there has been no detectable change in the annual cycle over the three years of monitoring (see Fig. 1), there has been a significant change in the mean flux density of PKS 1257−326. Fig. 3 shows the mean flux density (Stokes I) and rms variations in Stokes I observed in each epoch, as well as the mean flux density in Stokes Q and U for each epoch, at 4.8 and 8.6 GHz. The data show that the source has undergone a slow outburst, of the kind typical of flat-spectrum quasars, peaking first at the higher frequency and later at the lower frequency, with a corresponding change in polarization. The scintillating component has become brighter as indicated by the increase in rms variations, but evidently the component has not expanded enough to affect the measured scintillation timescale.

Fig. 3 also shows all data at 4.8 GHz from 21–23 May 2003. Rapid variations are observed in Stokes Q and U, with a similar timescale to those observed in Stokes I, suggesting that the polarized sub-structure of PKS 1257−326 is relatively simple. Preliminary analysis of cross-correlations between the polarized and total intensity scintillation patterns indicates that the peak in polarized flux density is displaced from the peak in total intensity, at both 4.8 and 8.6 GHz, by a distance of order 10 μas. We have observations over a range of different directions of the scintillation velocity (see Fig. 2), analagous to cuts at different angles through the (u, v) plane in synthesis imaging. Cross-correlation and cross-power spectrum analysis of all available Stokes I, Q, and U data, and a modelling procedure similar to that used by Rickett et al. (2002), would constrain the μas-scale polarized structure of PKS 1257−326 and its evolution during the observed outburst.

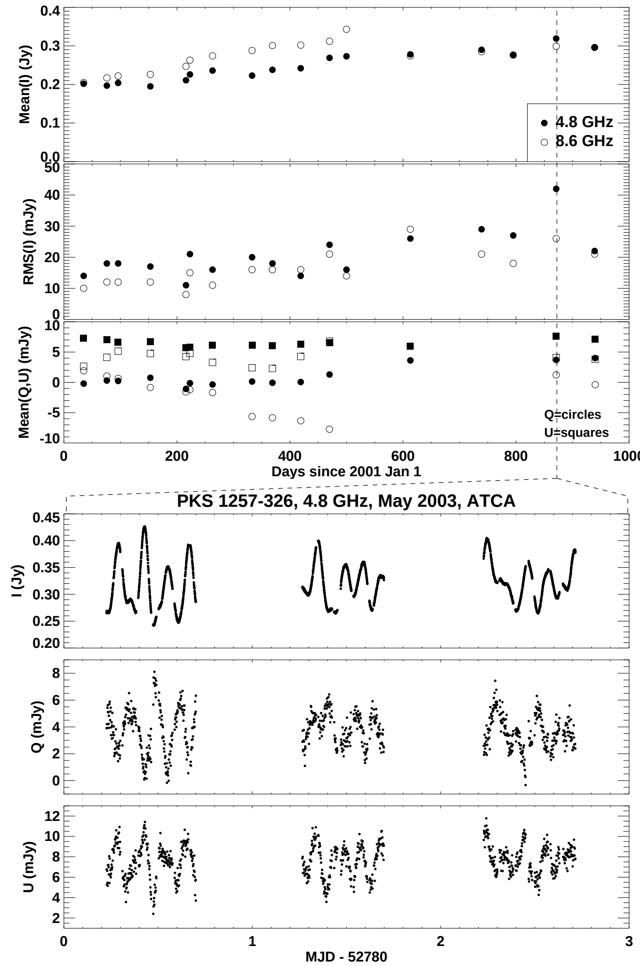

Fig. 3. ATCA data for PKS 1257−326, showing the average value of Stokes I, Q, and U in each observing session at 4.8 and 8.6 GHz as well as the rms variations in Stokes I (top, centre panel). The duration of a typical observing session is 12–48 h. The lower 3 panels show all data for the observation of 21–23 May 2003, with Stokes I data plotted with 30 s averaging, and Stokes Q and U plotted with 2 minute averaging.

3. Findings of the MASIV Survey

The Micro-Arcsecond Scintillation-Induced Variability (MASIV) Survey was in part motivated by the recent serendipitous discoveries of the two fast scintillators, J1819+3845 and PKS 1257−326, which were both too weak to have been included in previous IDV Surveys. MASIV observations were carried out during 2002 and early 2003 with the VLA at 4.9 GHz. Lovell et al. (2003) describe the source selection and observing strategy, and present first results of the Survey.

Sources which showed rms variations larger than 2σ were selected, where σ is the estimated uncertainty due to errors proportional to flux density (antenna pointing offsets, etc.) as well as noise and confusion. In total, 525 unresolved sources were observed in all four sessions. Of these, 146 (28%) showed significant variability in at least one epoch, while in any given epoch, 11–15% of sources were found to be variable. For a significant fraction of sources, rapid variability appears to be episodic. A large range of variability timescales was observed. For those sources which show persistent rapid variations, approximately half show evidence of an annual cycle in characteristic timescale, although there are large uncertainties in timescale estimates due to the limited sampling of the observations. The sky distribution of the variable source fraction is significantly anisotropic. A preliminary analysis of modulation indices based on weak scintillation theory using the Taylor & Cordes (1993) model for the interstellar electron density indicates that the peak brightness temperature of scintillating sources is in the neighbourhood of 10^{12} K. This brightness temperature limit is similar to those obtained from VLBI observations even though ISS is not subject to the same angular resolution limits. A comparison of the strong and weak source sub-samples showed that the fraction of variable sources was significantly larger in the weak source population. A compar-

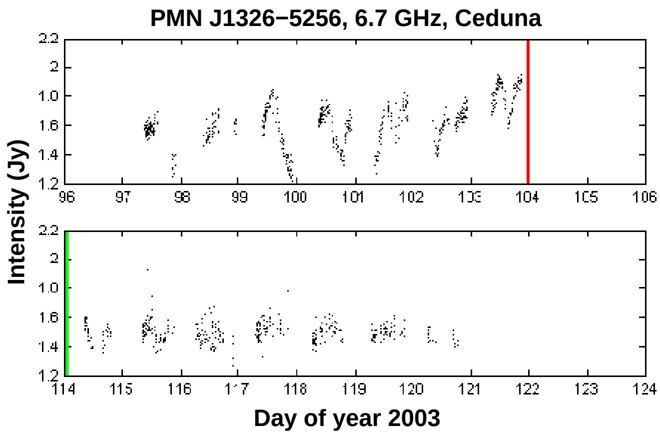

Fig. 4. Ceduna data at 6.7 GHz for PMN J1326−5256 data at 6.7 GHz, showing a change in IDV behaviour over several weeks in 2003 July.

ison of mas-scale VLBI morphologies (Ojha et al. 2004, in press) indicates that scintillating sources have a higher proportion of their flux density in an unresolved core component, and have smaller overall angular extent than non-scintillating sources. No other source in the MASIV Survey showed variations as rapid or modulation indices as large as observed in J1819+3845. It seems that for most sources, scintillation occurs in more distant scattering screens; most lines-of-sight do not intersect the nearby screens responsible for intra-hour variations.

4. Dedicated monitoring: the COSMIC program

The MASIV Survey showed that most ISS occurs on timescales of order days or more. To get the same information as obtained from monitoring of intra-hour variables requires observations over hundreds of days, which is not feasible with current National Facility instruments. However, bright sources which show relatively large-amplitude variations can be monitored with dedicated single-dish telescopes. An example of such a program is the "COntinuous Single-dish Monitoring of Intraday variables at Ceduna" (COSMIC) program, using the University of Tasmania's 30 m antenna at Ceduna. When not participating in VLBI observations, the telescope is operated remotely to observe a small sample of strong southern IDV sources at 6.7 GHz. Based on observations of calibration sources, rms intensity variations larger than ∼ 2% are detectable in sources ∼ 1 Jy or brighter.

Analysis and interpretation of the first year of Ceduna data is ongoing. Various behaviours are observed in the target sources. For example, PKS 1519−273 shows a persistent pattern of variations with a repeated annual cycle. PMN J1326−5253, on the other hand, has shown dramatic changes in its IDV properties. After showing large amplitude IDV for some months, in April 2003 the amplitude of IDV suddenly decreased, as shown in Fig 4. Further investigation is needed to determine whether observed changes in scintillation behaviour are due to source-intrinsic or scattering screen changes.

5. Summary and outlook

ISS of extragalactic sources at cm wavelengths can be used to constrain source structure on microarcsecond scales, and potentially allows measurements of brightness temperatures higher than the ∼ 10^{12} K limit of ground-based VLBI. Dedicated monitoring of small source samples, required in order to extract detailed information on source structure, are complementary to large statistical studies such as the MASIV Survey. A significant fraction of scintillating sources have relatively stable, or slowly evolving, long-lived scintillating components, allowing continued monitoring and modelling of their μas-scale structure. Other sources show dramatic changes with time in their scintillation behaviour, which may be a result of either intrinsic expansion of a source component to quench the scintillation, or a change in the effective scattering along the line-of-sight to the source. For a proper interpretation of ISS it is important to consider the effects of anisotropic scattering, extended source structure, and scintillation behaviour near the transition between weak and strong scattering. ISS studies, combined with other available data, offer a unique probe of the physics of inner jets of radio-loud AGN.

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