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Rapid Interstellar Scintillation of Quasar PKS 1257−326

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Abstract. PKS 1257−326 is one of three quasars known to show unusually large and rapid, intra-hour intensity variations, as a result of scintillation in the turbulent Galactic interstellar medium. We have measured time delays in the variability pattern arrival times at the VLA and the ATCA, as well as an annual cycle in the time-scale of variability for this source. Results of the two-station time delay observations are presented here. Implications for the scintillation of this source are discussed in the light of these results, together with results from two years of monitoring with the ATCA.

1. Introduction

The flat-spectrum radio source PKS 1257−326 was first cataloged in the Sixth Part of the Parkes 2700 MHz Survey, with a measured flux density of 0.23 Jy at 2.7 GHz (Shimmins & Bolton 1974). The source is identified with an X-ray emitting, B=18.7 magnitude, quasar at $z = 1.256$ (Perlman et al. 1998). Extremely rapid flux density changes were discovered in ATCA data during 2000 (Bignall et al. 2003), making PKS 1257−326 the third known "intra-hour" radio variable, after PKS 0405−385 (Kedziora-Chudczer et al. 1997) and J1819+3845 (Dennett-Thorpe & de Bruyn 2000).

In recent years, considerable evidence has accumulated to demonstrate that interstellar scintillation (ISS) in the turbulent interstellar medium of our Galaxy is the principal mechanism responsible for the intra-day variability (IDV) seen at cm wavelengths in many flat-spectrum AGN. Two unequivocal demonstrators of ISS are (i) annual cycles in time scales of variability (e.g. Dennett-Thorpe & de Bruyn 2001; Rickett et al. 2001; Jauncey & Macquart 2001; Bignall et al. 2003),

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and (ii) measurement of a delay in the IDV pattern arrival times at two, widely separated telescopes (e.g. Jauncey et al. 2000; Dennett-Thorpe & de Bruyn 2002). Both of these types of observation can be used to extract information on the ISS process and on the source brightness distribution, on scales of order 10–100 microarcseconds (e.g. Macquart & Jauncey 2002). The three "extreme" rapid variables have played a key role in realizing the dominant role of ISS in radio IDV, because their variations can be well-sampled in a typical, 12-hour observing session. Furthermore, pattern arrival time delay measurements are only feasible when the variations are large and rapid enough that the IDV patterns can be located in time to a precision of tens of seconds, i.e. there must be a measurable change in flux density on time scales of order 1 minute.

Here we present results of simultaneous observations of PKS 1257−326 with the VLA and the ATCA, and discuss their implications for the ISS of this source, particularly when combined with the results of two years of ATCA monitoring.

2. Results of simultaneous observations with the VLA and the ATCA

The rapid, large-amplitude fluctuations observed in PKS 1257−326 make this source an excellent candidate for measurement of the variability pattern arrival time delay between two, widely separated telescopes. A significant delay of ~ 2 minutes was found for PKS 0405−385 (Jauncey et al. 2000), between the IDV patterns at the VLA and the ATCA, before its episode of rapid ISS ceased. J1819+3845 was observed simultaneously with the VLA and WSRT on two days in 2001 January, and the IDV pattern arrival time delay was observed to change, and in fact reverse its sign, due to the rotation of the Earth during the simultaneous observation (Dennett-Thorpe & de Bruyn 2002). In the case of J1819+3845, the VLA-WSRT baseline rotates in the plane of the sky through approximately 50° over the course of the observation, and hence a significant change in delay was observed, as the direction in which the baseline cut through the scintillation pattern changed.

PKS 1257−326 has been observed simultaneously with the ATCA and the VLA at three different times of the year. The observations in each period were made on two consecutive days, and used two frequencies simultaneously, 4.9 and 8.5 GHz. On each day, PKS 1257−326 is visible to both telescopes for 2.7 hours. The baseline vector rotates through only 20° during this time. However, the scintillation velocity changes over the course of a year due to the Earth's orbital motion, so the two-station time delay will be different at different times of the year. Repeated measurements of the time delay at different times of the year help to constrain both the velocity and spatial structure of the observed scintillation pattern, which in turn reveals information both on the source, and on turbulence in the local ISM.

The top panels in Figure 1 show VLA and ATCA data for PKS 1257−326 observed on 2002 May 14 and 2003 March 7. The frequency range covered by the data from each telescope is identical, and the 32 second decrement needed to convert the time stamps of the VLA data from IAT to UT has been applied. It is immediately apparent that on each day, the IDV patterns seen by each telescope are almost identical, and that in each case, the pattern arrives at the VLA several minutes before it reaches the ATCA. This is unequivocal evidence that

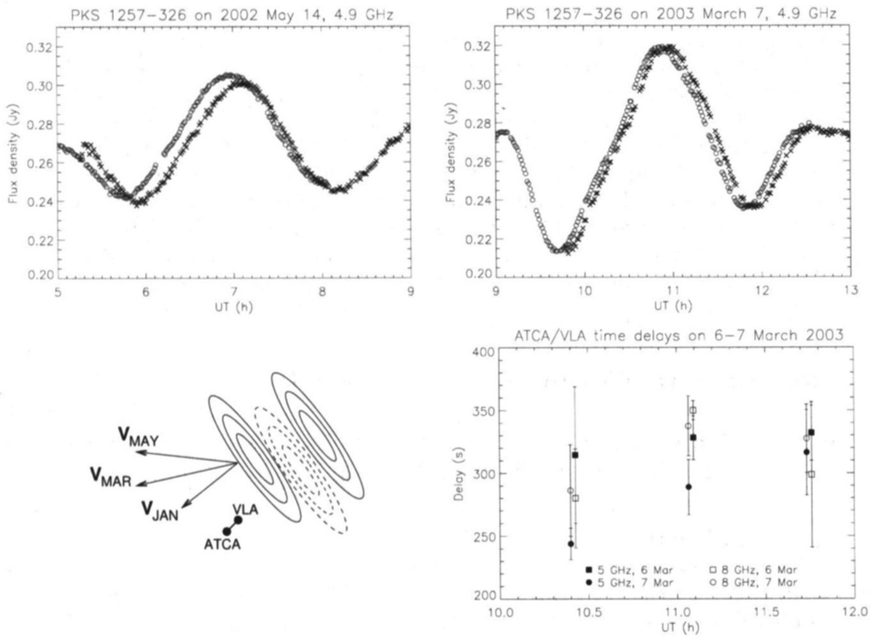

Figure 1. Top panels show simultaneous 4.9 GHz VLA and ATCA flux density measurements of PKS 1257−326, on two different days of the year. VLA data are represented by circles; ATCA data by crosses. The lower left panel shows an illustration (not to scale) of the time delay geometry. Part of the scintillation pattern is represented by elliptical contours. Arrows indicate scintillation velocity at three different times of the year when the source has been observed simultaneously with the VLA and the ATCA. The VLA-ATCA baseline is indicated. The lower right panel shows time delays calculated from the 2003 March data.

the observed rapid variations are predominantly due to interstellar scintillation. We can also immediately infer that the scintillation length scale is much larger than the $\sim 10,000$ km baseline between the two telescopes.

The time delays were clearly evident in the data after applying only a constant correction factor to data from one telescope in order to make the flux density scales comparable. However, in order to best constrain the scintillation parameters it is necessary to compare the flux densities of the scintillating component seen by each telescope with the greatest possible accuracy. As both telescopes are observing at low elevation where pointing errors and atmospheric effects are most severe, it is important to correct for these effects, as well as for any differences due to resolved structure in the source. The flux density measurements shown in Figure 1 have been calibrated using PKS 1255−316, an unresolved, non-IDV source $\sim 1°$ from PKS 1257−326. The calibration source was observed every 15 minutes for ~ 1 minute at both telescopes. PKS 1257−326 itself has a few percent of its flux density in components which are extended on arc-second scales. If not subtracted, this contributes to differences in the total flux density seen by each telescope, as well as adding slight apparent variations, in addition to the IDV, due to the changing (u, v) coverage over the observation. These changes with time are more significant in the ATCA data due to the linear configuration of the array. To remove the effects of resolved source structure, we have modeled the extended components, starting with a short "snapshot" of the VLA data, and subtracted them from the visibilities for both telescopes, leaving only the central part of the source which is unresolved at both telescopes and contains the scintillating component. Flux densities are then obtained by averaging Stokes I data over all baselines. Any residual errors, after applying antenna gain corrections from PKS 1255−316 and subtracting the extended component model, are too small to have a noticeable effect on the measured pattern time delays. Data from both telescopes are directly comparable to an estimated accuracy of $\sim 0.3\%$.

In the data shown from 2002 May 14, there is evidence that the IDV patterns seen by each telescope are not exactly identical; the trough and peak in the ATCA data reach flux densities $\sim 1.5\%$ lower than those in the VLA data, which is significantly different compared with the expected measurement errors. This could be a result of a slightly different part of the scintillation pattern being seen by each telescope. The scintillation pattern can be thought of as a series of bright and dark patches or "scints", assumed to be temporarily "frozen-in", which drifts past each telescope. The time delay depends on both the velocity of the pattern with respect to the projected baseline between the two telescopes, and also on the spatial structure of the pattern. This is illustrated in the lower left panel of Figure 1. The ellipses represent contours of constant intensity in the scintillation pattern. The observed quasi-sinusoidal variations occur as the Earth passes through this pattern. If the scintillation velocity has a large component perpendicular to the baseline, which from the model discussed in Section 3 is expected to be the case in May, then a slightly different part of the pattern would be seen by each telescope. This could easily account for the observed flux density differences.

The lower right-hand panel of Figure 1 shows time delays fitted to the March data for both frequencies and both days. Delays were found by minimizing the sum of squares of the residual flux density difference, assuming that for these data, the scintillation pattern seen by each telescope is identical apart from being shifted in time. For the March data this assumption is reasonable, as no significant difference is evident in the flux density of peaks and troughs measured at each telescope. For each dataset, a running time delay was calculated using a 40-minute window of data, to test whether any change in delay was observable over the observation. The delay estimates were averaged into three UT bins, and the error bars plotted are based on the scatter in the individual delay estimates. From this preliminary analysis, it is evident that the pattern arrival time delay is almost identical at both frequencies and on both days, and does not change significantly over the course of the observations. From this we can infer that successive contours of constant intensity in the scintillation patterns are close to parallel to each other as they cross the baseline. In the data from January, the observed time delays are very similar to those in March, ~ 5 minutes, while the data from 2002 May show larger time delays, on average ~ 8 minutes at both frequencies and on both days.

3. Discussion

Two-station time delay measurements can be combined with observations of annual cycles in the characteristic time scale of variability, $t_{\rm char}$, to constrain the velocity and spatial structure of the scintillation pattern, which in turn can be used to constrain the source angular size and brightness temperature, as well as the distance to the scattering material. More than a year of monitoring PKS 1257−326 with the ATCA, since early 2001, revealed a clear annual cycle in $t_{\rm char}$, and subsequent observations have confirmed its continued presence. The annual cycle, reported in Bignall et al. (2003), was best fit with a screen velocity offset by ~ 5 km s^{-1} in RA from the local standard of rest, and an anisotropic scintillation pattern elongated at $\sim 55°$ to the RA axis, although the axial ratio of the "scints" was not well constrained from the annual cycle.

The model from the annual cycle is consistent with the observed time delays. In fact the time delays are consistent with the successive contours of constant intensity being *always* close to parallel to each other over the ten months between the first and last time delay measurements. One would not expect to see this unless the scints were consistently highly elongated, which could be a result of anisotropic scattering and/or anisotropic source structure. The other two rapid scintillators, PKS 0405−385 and J1819+3845, also show evidence for highly anisotropic scintillation patterns (Rickett et al. 2002, Dennett-Thorpe & de Bruyn 2003). Rickett et al. (2002) argue that the origin of the anisotropy for PKS 0405−385 is in the scattering screen rather than the source. It will be important to confirm this for PKS 1257−326, and also to determine whether highly anisotropic scintillation patterns are a common property of slower scintillators, such as those found in the Micro-Arcsecond Scintillation-Induced Variability (MASIV) Survey recently undertaken with the VLA (Lovell et al. 2003). The MASIV Survey found that sources such as J1819+3845 and PKS 1257−326 are extremely rare. Intra-hour scintillations are thought to be due to unusual, localized scattering "screens" less than ~ 30 pc from the observer, whereas more common, slower scintillations are most likely due to scattering material at distances of order 100 pc or more. Anisotropy in the scintillation pattern would strongly influence observed time scales and annual cycles in scintillating sources, and thus has important implications for extracting information via "Earth Orbital Synthesis" (Macquart & Jauncey 2002).

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