ANNUAL MODULATION IN THE INTRADAY VARIABILITY OF QUASAR 0917+624 DUE TO INTERSTELLAR SCINTILLATION

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ABSTRACT

The quasar 0917+624 has been one of the best-studied intraday variable radio sources. However, debate continues as to whether the underlying cause is intrinsic or extrinsic. Much previous work has assumed the intraday variability (IDV) to be intrinsic, which implies an extraordinarily compact source for the radio emission; in contrast, an extrinsic variability due to interstellar scintillation (ISS) implies a relatively larger source diameter, although at the smaller end of the range expected for relativistic jet models. Kraus et al. reported a marked slowing of the IDV at a wavelength of 6 cm in 1998 September and suggested that a change in the source was responsible. However, here we show that the slowing is consistent with the annual modulation in the scintillation timescale expected for ISS, under the assumption that the scattering medium moves with the local standard of rest (LSR). The ISS timescale is governed by the ISS spatial scale divided by the Earth’s velocity relative to the scattering plasma. It happens that in the direction of 0917+624, the transverse velocity of the Earth with respect to the LSR varies widely, with a deep minimum in the months of September–November. Hence, the slowing of the IDV in 1998 September strongly suggests that ISS rather than intrinsic variation of the source is the dominant cause of the IDV.

Subject headings: ISM: kinematics and dynamics — quasars: individual (B0917+624) — radio continuum: general — scattering

1. INTRODUCTION

Rapid (faster than a day) variations in the radio flux density of some extragalactic sources have attracted considerable attention in the years since they were first reported by Heeschen et al. (1987). Via the classic light-travel time argument for intrinsic variations, the short variability timescales have been used to infer an extremely small physical size for the radio-emitting regions; the associated apparent brightness temperatures are very much higher than expected from relativistic jets from active galactic nuclei (AGNs) emitting Doppler-boosted radio beams (Qian et al. 1991). The canonical jet model successfully explains “superluminal” motion in VLBI observations, invoking Lorentz factors (bulk jet speeds) in the range of 1–20. In order to explain the high brightness temperatures inferred from the intraday variability (IDV), one needs very small viewing angles, and hence such jets can explain brightness temperatures of up to 10^{21} K. An intrinsically small view of the most extreme IDV at centimeter wavelengths would imply brightness temperatures up to 10^{21} K (e.g., Kedziora-Chudczer et al. 1997; Dennett-Thorpe & de Bruyn 2000). This stretches the jet model too far, and in both cases the authors proposed interstellar scintillation (ISS) rather than intrinsic interpretations.

Quirrenbach et al. (1992) presented the results of the daily monitoring of a complete sample of flat-spectrum sources at 6 and 11 cm. They found a low level of IDV in most of the sources observed, which also had compact VLBI structure. They concluded that this low level of variability seen in almost all such sources was ISS. However, in addition, they argued that about 25% of flat-spectrum sources also showed intrinsic variations that can reach amplitudes as high as 20%. The quasar 0917+624 was one of these strongly variable sources, for which intrinsic models have been invoked (Wagner & Witzel 1995 and references therein).

On the other hand, Rickett et al. (1995, hereafter R95) demonstrated that ISS could successfully account for the IDV in 0917+624 with a source brightness of about 6 \times 10^{12} K by assuming that the path length for the scattering medium was reduced to 200 pc. The 930 pc predicted from the Taylor & Cordes (1993, hereafter TC93) model for the distribution of electrons in the Galaxy. In R95, no consideration was given to the influence of the change in the Earth’s velocity relative to the scattering medium. In this Letter, we reconsider the accumulated observations of the source at 6 cm by the Bonn group, and we study how the timescale and modulation index (rms normalized by mean flux density) vary over the year and compare with predictions.

The 0917+624 observations of 1998 September show a remarkably different character, with the flux varying slowly and nearly linearly over the course of the 5 day observing span. This was reported by Kraus et al. (1999), who suggested that there had been a pronounced change in the scattering structure of the source so that it ceased its intrinsic IDV; but they also suggested that by 1999 February, the source had reverted to its original structure, in order to explain the return of its normal IDV behavior observed at that time. We conclude that this anomalous behavior supports the ISS interpretation since it is simply explained by the changing of the Earth’s velocity.

2. OBSERVATIONS AND DATA ANALYSIS

We have collected together all of the observations of 0917+624 at 6 cm since 1989 that were made at Effelsberg and at the VLA in flux density monitoring campaigns lasting more than 24 hr. We choose 6 cm as the wavelength most commonly observed (since it has good signal-to-noise ratio).

We have used a structure function analysis on each time series to estimate the characteristic timescale and the rms amplitude, as used by R95. The sampling interval for the flux measurements was typically somewhat variable, so the structure
function was binned into uniform intervals ($\delta \tau$) in a time lag about equal to the average time between samples (typical values were 0.05–0.1 days). The maximum time lag computed is about half the duration of each data set. The structure function $D(\tau)$ is first corrected for the noise level, which is estimated as $D$ at the smallest time lag and subtracted from $D(\tau)$ at each lag. A region in the time lag is then identified where $D(\tau)$ saturates. However, it should be noted that, since $D$ is estimated from a finite sample of a stochastic variation, it will fluctuate about a saturation value rather than converge toward an asymptote. The flux variance is estimated as half of the average of $D$ over the saturation region; the timescale is estimated as the lag in which $D$ crosses half the saturation level. Table 1 shows the results for each observation with estimated rms errors, which are dominated by the estimation error from the modest number of independent samples in each series.

The procedure works well provided that the structure function does indeed start to saturate before the maximum lag, as is seen for nearly all of the observations. However, in 1998 September, the flux did not show several maxima and minima per day as it normally does, rather there was an approximately linear increase over 4.5 days. The associated structure function does not show signs of saturation (Kraus et al. 1999), so here we set a lower bound on the timescale and on the flux variance by treating $D$ at the maximum lag as if it were saturated. We consider this data set as if it were a sample of a stochastic variation with a timescale longer than its duration and obtain a substantially longer timescale than from the rest of the observations.

3. ANNUAL MODULATION IN ISS PARAMETERS

The timescale for ISS is determined by the ratio of two quantities: the spatial scale of the scintillation pattern and the relative speed of the Earth through the pattern. The pattern scale depends on the line-of-sight distribution and the wave-number spectrum of the scattering material and also on the angular structure of the compact component in the radio source. The ISS theory and model used by R95 assumed the source to be circularly symmetric and sufficiently extended to partially quench the scintillations, in which case the same theory can be applied for both weak and strong refractive scintillation; furthermore, it assumes the scattering plasma to be isotropic and to be in a thick layer with a Gaussian profile. The natural scale height to choose is that of the ionized disk component in the TC93 model, which gives a characteristic path length of 930 pc for the density variance at the latitude of 0917+624. However, as noted above, a smaller path length (200 pc) was found to be necessary by R95 in order to fit the observations with a speed that was (arbitrarily) assumed to be 50 km s$^{-1}$. In this section, we use the same R95 model for the spatial scale and calculate the Earth’s transverse velocity explicitly versus day of year, under the assumption that the entire scattering medium moves with the LSR; we then compare the observed and predicted timescales. This assumption is consistent with ISS observations of the pulsar B0809+74 by Rickett, Coles, & Markkanen (2000), who concluded that the velocity of the scattering medium is within 10 km s$^{-1}$ of the LSR.

Figure 1 shows the Earth’s velocity relative to the LSR projected perpendicular to the line of sight to 0917+624 versus day of year. The velocity due to the Earth’s orbital motion around the Sun happens to nearly cancel the projected velocity of the Sun relative to the LSR near day number 285. Thus, the predicted ISS speed shows a large annual modulation from a maximum of 40 km s$^{-1}$ to a minimum of 4 km s$^{-1}$. In the top panel of Figure 2, we overplot the observed and predicted timescales against the day of year, including as thin lines the bounds derived from predictions for a range of offsets in plasma velocity relative to the LSR covering $\pm 5$ km s$^{-1}$ in the right ascension direction and $\pm 5$ km s$^{-1}$ in the declination direction.

The striking feature of the predicted timescale is that it should remain fairly constant over much of the year and should exhibit a substantial increase over days 250–330 (September–November). Even though there have been 13 independent observations of the 6 cm IDV, it happens that only one of them lies in this period of predicted slow ISS. Thus, the apparent constancy of the IDV behavior is readily understood, as is the one anomalous observation. Overall, we find a general agreement between the observations and the predictions for the timescale.

Turning to the scintillation (or modulation) index, there is a question of what should be the normalizing flux, since the source may have some of its flux in components that are too large in diameter to scintillate (>1 mas). The VLBI maps of Standke et al. (1996) and new unpublished maps (T. P. Krichbaum 2000, private communication) show that the source exhibits a core jet structure composed of a number of unresolved (<1 mas) and partially resolved (>1 mas) components. However, in considering any annual change in scintillation index, this normalizing uncertainty is unimportant. What matters is whether there should be any annual change in the ISS variance. Since the ISS variance is given by the integral of the intensity
Fig. 1.—Earth velocity (in kilometers per second) relative to the LSR projected transverse to the direction of 0917+624. Top: Speed vs. day of year. Bottom: Velocity plotted as $V_x$ and $V_y$ at 5 day intervals. Note the time near day 285 in which the velocity is close to zero.

Fig. 2.—Top: Timescale vs. day of year for the 6 cm observations of 0917+624. The thick curve represents the ISS prediction for scattering plasma moving with the LSR; the thin curves represent the upper and lower bounds obtained for velocities ranging over ±5 km s$^{-1}$ in right ascension and in declination relative to the LSR. Bottom: Apparent scintillation index vs. day of year. Observations shorter than 3 days are plotted as horizontal bars; longer observations are plotted as filled squares.

It has been argued that the interstellar plasma irregularities are commonly anisotropic (e.g., Desai, Gwinn, & Diamond 1994). The orientation of the velocity relative to the major axis of such anisotropy will vary during a year, as the direction of the Earth’s motion changes. In such a case, the spatial scale of the ISS pattern will show a variation over 6 months, which can combine with the changing of the Earth’s velocity to create a variety in the predicted annual timescale curves. In addition, if the source structure is not circular, its angular orientation would also affect the spatial scale and therefore will contribute to the annual modulation (Dennett-Thorpe & de Bruyn 2000, 2001).

4. DISCUSSION AND CONCLUSIONS

It is clear from Figure 2 that ISS governs the timescale of the IDV, unless there was a transient slowing of intrinsic variability that coincidentally echoed the behavior expected for ISS. Hence, we conclude that the IDV of 0917+624 at 6 cm is predominantly caused by scintillation in the interstellar medium (ISM). If simultaneous intrinsic variations faster than 6 hr are also present, their rms amplitude must be less than 1% (obtained from the structure function analysis of the data from 1998 September).

This confirms the work of R95 and also opens up the possibility of using these seasonal ISS effects to explore anisotropy in both the source and the scattering plasma. Our conclusion does not at all reduce the importance of intrinsic variations in explaining source variations on times of months to years, as is particularly evident in VLBI maps and longer term flux changes. Indeed, both phenomena are needed for a full understanding of AGN behavior.

As discussed by R95, the timescale observations jointly constrain the scattering distance and source diameter in a fashion that depends on the distribution of the scattering plasma. The sense of this constraint is that a large distance implies a smaller source size and vice versa. In the R95 model, the scattering distance was about 200 pc, in preference over the 930 pc expected under the TC93 model. The accompanying source diameter at 6 cm was about 0.07 mas. Models with a larger scale height required a smaller source size and vice versa. R95 assumed that...
the velocity was fixed at 50 km s\(^{-1}\). Now, with a better model for the velocity over the course of a year, we can reexamine the distance/diameter constraint. The best estimate of the ISS timescale comes from the 25 day observations from 1990 February (Quirrenbach et al. 2000). Since the LSR velocity was 42 km s\(^{-1}\) at that time (see Fig. 1), the nominal 200 pc medium thickness is only reduced by the ratio of 42/50 to 170 pc. In a related paper (B. J. Rickett & A. G. Lyne 2001, in preparation), we consider this constraint in the light of diffractive ISS observations of pulsar B0917+63, which, at a nominal distance of 760 pc, probes the same path through the Galaxy.

The agreement in timescale with the prediction based on assuming that the medium is stationary in the LSR allows us to put an upper bound on the range of velocities that contribute to the scattering. If the distribution of speeds in the scattering medium is a Gaussian function, its standard deviation must be no more than the slowest effective ISS speed (defined by the spatial scale in the model divided by the observed timescale). This bounds the standard deviation in speed at about 8 km s\(^{-1}\). In comparison, transverse differential Galactic rotation amounts to about 1 km s\(^{-1}\) at 200 pc along this line of sight. Although there is no distinction possible between a spread of velocities due to shear or due to turbulence in the medium, this result puts an upper limit of 8 km s\(^{-1}\) for any turbulent velocities in the scattering plasma. This is one of the few formal constraints on turbulent plasma velocities that have been extracted from three decades of ISS work. Future observations sampling the full annual cycle of ISS will help us to determine the velocity distribution in the ISM, although the influence of anisotropic scattering will also have to be modeled.

Evidently, there is a strong incentive to verify the annual variation and to study whether similar phenomena exist for other IDV sources, several of which are in directions for which a substantial annual modulation should be expected. Preliminary examinations for IDV sources 0716+714 and 0954+658 do not show the predicted annual modulation in IDV timescale. Thus, the present result for 0917+624 does not rule out the existence of an intrinsic IDV in these sources. A program of IDV observations of 0917+624 was started in 2000 September and is continuing; this program will help us to verify the slow ISS phenomenon for 0917+624. During the final preparation of this Letter, we received a draft of a paper by D. L. Jauncey and J. P. Macquart in which they independently report the same annual modulation and its ISS interpretation, derived from 0917+624 data in the literature.

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