

Intra-day variability and the interstellar medium towards 0917+624

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Abstract. The intra-day variable source 0917+624 displays annual changes in its timescale of variability. This is explained in terms of a scintillation model in which changes in the variability timescale are due to changes in the relative velocity of the scintillation pattern as the Earth orbits the sun.

Key words. quasars, 0917+624 – radio sources: ISM: structure – scattering

1. Introduction

The radio source S5 0917+624, identified with a $z = 1.446$ quasar (Stickel & Kuhr 1993), was one of the first discovered to show strong intra-day variability (IDV) at radio wavelengths (Heeschen et al. 1987). Recently, Kraus et al. (1999) reported three-epoch 5 GHz observations, December 1997, September 1998 and February 1999, which show significant changes in the IDV characteristics of this source. They suggest several possible interpretations which have at their basis structural changes, and hence brightness temperature changes, within the source itself.

Alternatively we suggest that the observed changes in IDV result from variations in the interstellar medium (ISM) velocity as the Earth revolves around the sun. We present evidence to support this suggestion based on published data on the IDV of 0917+624.

2. Changes in the intra-day variability in 0917+624

Kraus et al. (1999) undertook to explain the observed changes in the IDV properties as an intrinsic change in the source. This is irrespective of whether the IDV results from intrinsic variability or from interstellar scintillation (ISS). If the variability is intrinsic, changes in the IDV timescale imply source size changes directly, while if the variability is due to ISS, it was argued that the change in timescale could be either the due to disappearance of the compact component or an increase in its angular size sufficient to quench the scintillation. Here we offer an

alternative explanation based on an ISS origin of the variability, showing that changes in the timescale need not reflect changes in source structure.

Over the course of a year the motion of the Earth, projected on the plane of the sky is an ellipse with eccentricity dependent on the ecliptic latitude of the source. Extragalactic sources show negligible proper motion, and hence the relative velocity of the ISM across the line of sight to the source is simply the difference between the ISM and the Earth's motion. If these are comparable in amplitude, then there may be a period when the vectors are parallel, and six months later, anti-parallel. In the first case the apparent ISM velocity as seen from the Earth is low, in the latter, high.

For an ISS origin of IDV, it follows that at times of low relative velocity, the characteristic time-scale of the variability will be lengthened, while six months displaced, it will be correspondingly shortened. This form of behaviour has been seen in the rapidly variable IDV source J1819+3845 (Dennett-Thorpe & de Bruyn 2000), and strongly supports the ISS origin for the IDV in this source.

We have searched the literature on flux density monitoring of 0917+624 to determine its behaviour. The first observations were made in 1985 (Witzel et al. 1986; Heeschen et al. 1987) at 2.7 GHz with the Bonn 100 m telescope. Since then we have located a total of 10 well documented observing sessions undertaken with either the Bonn telescope or the VLA, and these are listed in Table 1.

From this data we have determined the characteristic time scale, T_{char} , (defined for convenience, as the mean time between successive peak-to-trough or trough-to-peak excursions) for each session at 2.7 and/or 5 GHz. This can only be done when the session was of sufficient length that

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Table 1. Values of T_{char} measured from the literature

| Mean Date (year) | ν (GHz) | modulation index (%) | T_{char} (days) | Reference |
|---------------------|-------------|-------------------------|-----------------------------|-----------|
| 1985.63 | 2.7 | 0.9 | > 4 | a |
| 1985.99 | 2.7 | > 2.4 | 1.3 ± 0.1 | a |
| 1988.26 | 2.7 | 5.7 | 0.9 ± 0.1 | b |
| 1988.46 | 2.7 | 4.6 | 1.1 ± 0.1 | b |
| 1989.00 | 2.7 | 7.3 | 1.2 ± 0.1 | c |
| 1989.35 | 2.7 | 8.3 | 0.7 ± 0.1 | d |
| 1988.26 | 5 | 3.7 | 0.3 ± 0.1 | b |
| 1988.46 | 5 | 3.1 | 0.7 ± 0.1 | b |
| 1989.00 | 5 | 6.0 | 0.6 ± 0.1 | c |
| 1989.35 | 5 | 4.4 | 0.4 ± 0.1 | d |
| 1990.12 | 5 | 3.7 | 0.6 ± 0.1 | d |
| 1997.98 | 5 | 5.2 | 0.7 ± 0.1 | e |
| 1998.71 | 5 | 1.8 | > 5 | e |
| 1999.10 | 5 | 5.1 | 0.8 ± 0.3 | e |

a: Heeschen, et al. 1987, AJ, 94, 1493

b: Quirrenbach, et al. 1989a, Nature, 337, 442

c: Quirrenbach, et al. 1989b, A&A, 226, L1

d: Quirrenbach, et al. 2000, A&AS, 141, 221

e: Kraus, et al. 1999, A&A, 352, L107

several peaks/troughs are present in the data. Our choice of T_{char} corresponds to the timescale on which the intensity structure function saturates, and hence closely follows the definition used by Kraus et al. (1999). Table 1 shows that T_{char} is close to one day at 2.7 GHz, and roughly half this at 5 GHz.

Table 1 also shows that the observing sessions for 0917+624 are not uniformly spread throughout the year, most are concentrated around the northern winter and spring. The only other session that we found that shows a slowing down of the IDV similar to that observed in September 1998 was the August 1985 session at 2.7 GHz (Heeschen et al. 1987). These two observations 13 years apart clearly establish an annual cycle in this source.

3. Effect of the Earth's orbital motion

Changes in the variability timescale of a scintillating source occur due to changes in both the direction and speed of the scintillation pattern as it moves across the source-observer line of sight. The scintillation timescale is

$$t_{\text{ISS}} = s_0(\alpha)/v_{\text{app}}, \quad (1)$$

where $s_0(\alpha)$ is the length scale of the scintillation pattern in the direction parallel to the apparent scintillation velocity, α is the direction of motion relative to the pattern, and v_{app} is the apparent speed of the scintillation pattern relative to the Earth. The scintillation timescale is formally defined as the timescale on which the auto-correlation function of intensity fluctuations reaches 1/e of its saturation value; operationally, $t_{\text{ISS}} \approx 0.6 T_{\text{char}}$. We assume that the scattering occurs only at a single screen,

so that the intrinsic velocity of the scattering medium relative to the heliocentre is described by one velocity.

3.1. Changes in the scintillation speed

Annual changes in the scintillation speed result in an annual modulation of the variability timescale. The apparent scintillation speed is the magnitude of the component of the ISM's intrinsic velocity, relative to the Earth's velocity, that is tangential to the line of sight. When the Earth's velocity nearly matches the intrinsic velocity of the scattering material, the scintillation pattern would then appear to be stationary, causing the variability to stop.

For a source at ecliptic latitude θ and longitude ϕ , it is convenient to denote the Earth's velocity as

$$\mathbf{v}_{\oplus} = v_{\oplus}(-\sin \Psi, \cos \Psi, 0), \quad (2)$$

where $v_{\oplus} = 29.8 \text{ km s}^{-1}$ is the Earth's orbital speed about the heliocentre and the orbital phase is $\Psi = 2\pi t - \phi$, and t is the time in years measured from the vernal equinox. The apparent scintillation speed is then

$$v_{\text{app}} = [(v_{\parallel} + v_{\oplus} \cos \Psi)^2 + (v_{\perp} + v_{\oplus} \sin \theta \sin \Psi)^2]^{1/2}, \quad (3)$$

where v_{\parallel} is defined as the speed of the scattering screen parallel to the Earth's ecliptic at closest approach, which occurs at $\Psi = \phi/2\pi$, and v_{\perp} is its speed perpendicular to the ecliptic at this point, with positive values of v_{\perp} indicating motion toward higher ecliptic latitudes.

3.2. Changes in the scintillation direction

Changes in the direction of the scintillation pattern, α , influence the scintillation timescale only if the scintillation pattern is not circularly symmetric, i.e. if s_0 depends on α . Asymmetry in the scintillation pattern may be due to either intrinsic source structure or anisotropy in the scattering medium.

The effect of source structure is important when the angular size of the source exceeds the angle to which a point source would be scatter-broadened by the scintillation pattern, θ_{pt} . The scintillation lengthscale, s_0 , for a source of angular size $\theta_S(\alpha)$ is (e.g. Narayan 1992)

$$s_0(\alpha) \approx \begin{cases} D \theta_{\text{pt}}, & \theta_S(\alpha) < \theta_{\text{pt}} \\ D \theta_S(\alpha), & \theta_S(\alpha) > \theta_{\text{pt}} \end{cases}, \quad (4)$$

where D is the distance to the scattering screen.

The angular scale, θ_{pt} , depends on the strength of the scattering, which is a function of frequency. Above the transition frequency, ν_0 , the scattering is weak, and θ_{pt} corresponds to the angular scale of the first Fresnel zone, $\theta_F = \sqrt{c/(2\pi\nu D)}$.

In the regime of strong scattering at frequencies below ν_0 , one has $\theta_{\text{pt}} = \sqrt{c/(2\pi\nu_0 D)}(\nu/\nu_0)^{-2.2}$. The exponent 2.2 follows from the assumption that the turbulence in the scattering medium follows a Kolmogorov scaling (e.g. Armstrong et al. 1995). The scale of size of the scintillation

pattern of a point-like source increases strongly towards lower frequencies.

IDV in extragalactic radio sources straddles the frequency range where weak and strong scattering occurs. This is particularly important in the case of 0917+624. Weak scattering is likely to be applicable to observations of 0917+624 at frequencies $\nu \gtrsim 5$ GHz (Walker 1998), while the timescale of variability observed at 2.7 GHz is likely to correspond to refractive scintillation in the transition to the strong scattering regime.

Anisotropy in the scattering medium causes elongation of the scintillation pattern in a direction orthogonal to the magnetic field in the scattering medium (e.g. Goldreich & Sridhar 1995). Observations suggest elongations up to $\sim 2:1$ are possible (e.g. Wilkinson et al. 1994; Spangler & Cordes 1998). The effect of anisotropy has been discussed by Backer & Chandran (submitted) on the scintillation parameters of nearby pulsars and IDV radio sources. Effects due to anisotropy become unimportant for source sizes larger than θ_{pt} , since the scale of the scintillation pattern is then dominated by the angular size of the source itself.

3.3. Application to 0917+624

We show that the changes in the scintillation speed due to variations in the Earth's orbital velocity alone are sufficient to reproduce the behaviour of 0917+624. We consider only changes in the scintillation speed, and neglect any possible asymmetry in the source structure. We also neglect the effect of anisotropy in the scattering medium because the characteristic timescale of the intraday variability in 0917+624 is much longer than the Fresnel timescale, suggesting an angular size $\theta_S(\alpha) \gtrsim \theta_F$. (Numerically, one has $\theta_F = 2/4 \cdot 10^8$ m for a screen of $D = 200$ pc at $\nu = 5$ GHz.)

The ecliptic latitude and longitude of this source are $\theta = 0.768$ and $\phi = 2.08$ respectively. We find ISM velocities of $v_{\perp} = -16 \pm 3$ km s $^{-1}$ and $v_{\parallel} = -16 \pm 3$ km s $^{-1}$ reproduce the sharpness of peaks observed T_{char} at 2.7 and 5 GHz. The scale size of the scintillation pattern, s_0 , may be calibrated by a measurement of the variability timescale given an estimate of the scintillation speed at that time. For the v_{\perp} and v_{\parallel} required to reproduce the observed data this implies $s_0 \approx 9.5 \cdot 10^8$ m at 5 GHz and $s_0 \approx 1.9 \cdot 10^9$ m at 2.7 GHz. For a scattering screen at $D = 200$ pc, as used by Rickett et al. (1995), this corresponds to angular sizes $\theta_S = 30$ and $65 \mu\text{as}$ at 5 and 2.7 GHz respectively. This is quite consistent with the derived angular sizes of other IDV sources (e.g. Macquart et al. 2000).

The comparison between the observational data and the model is shown in Fig. 1. The model gives excellent agreement with the data at both 5 and 2.7 GHz. In particular, it clearly reproduces the peak in the August and September values of T_{char} . The location of the peak observed in Fig. 1 is strongly sensitive to the ecliptic

longitude of the source, but only weakly dependent on the intrinsic velocity of the ISM.

The validity of the above model can be readily checked with more data at both frequencies over the July through November period. Our model predicts a steady increase in the characteristic time scale during July, a significant slow-down in the variability through August and into September, with a decreasing time scale probably October through November.

4. Discussion

4.1. The intrinsic brightness temperature of the source

Examination of the light curves during the period when the scintillations slow down can also be used to set limits on any intrinsic variability that may be present at radio wavelengths. During the slow-down the scintillations are virtually suppressed, so that any residual variations observed provide an upper limit to the intrinsic variations. This is an upper limit because there are probably low-level scintillations remaining as the model of a simple screen at a single distance with a single velocity is certainly an oversimplification.

For 0917+624, the August and September data still show the presence of low-level variability. Because of the ~ 5 day extent of both sessions, the derived variability brightness temperature, estimated using a source diameter of 5 light days, is $T_{\text{vb}} < 10^{16}$ K, still well above the inverse Compton limit, but significantly less than the 10^{18} K inferred if the intra-day variability were intrinsic. Future observations of longer duration may better define the slow-down period and further reduce this limit.

4.2. Earth revolution scintillation synthesis

The annual procession of the Earth around the sun and its effects on ISS shows a number of parallels with Earth rotation synthesis: in the latter we have a regularly constructed interferometer that completes its synthesis in half a day (half of the Earth's rotation). In the former case, we have an irregular "interferometer", namely the ISM, and it completes its "synthesis" in half a year, which corresponds to half of the Earth's rotation around the sun.

We suggest that Earth Revolution Scintillation Synthesis can be used to model the microarcsecond structure of compact radio sources. Once the ISM velocity has been determined for a particular source, the the shape of the scintillation light curves may provide information on source structure at microarcsecond resolution.

The technique can be extended to studying the polarization structure. Macquart et al. (2000) make use of this in studying the linearly and circularly polarized light curves for the strong and variable linear and circular polarization in the southern IDV source PKS 1519–273. Here both the linear and circular light curves follow the total intensity light curve quite closely, and it is clear that the microarcsecond source that is responsible for the IDV has

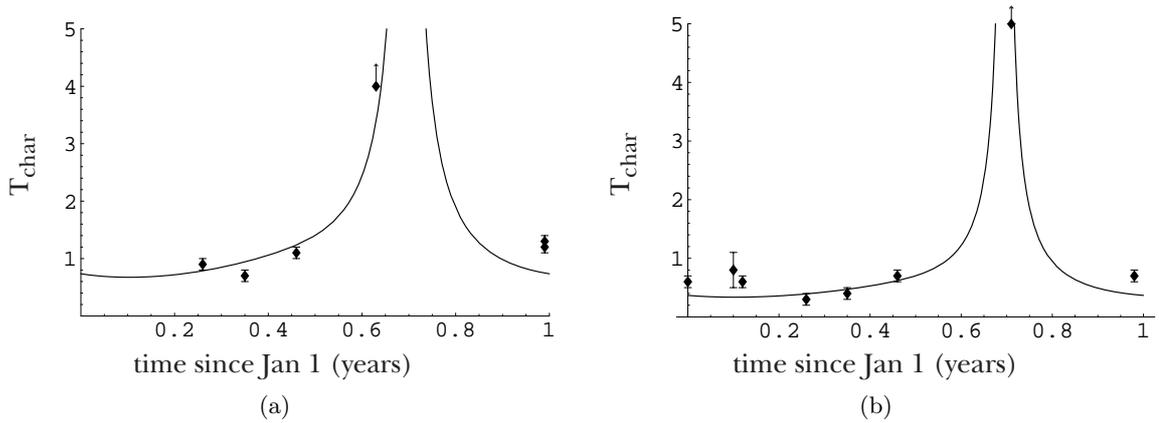


Fig. 1. Comparison of the data at **a)** 2.7 GHz and **b)** 5 GHz with the scintillation model described in Sect. 3.3 with $v_{\parallel} = -18 \text{ km s}^{-1}$, $v_{\perp} = -16 \text{ km s}^{-1}$. Scintillation pattern sizes of $s_0 = 1.9 \cdot 10^9 \text{ m}$ and $s_0 = 9.5 \cdot 10^8 \text{ m}$ have been used at 2.7 and 5 GHz respectively (see text)

the same structure in the total intensity, and linearly and circularly polarized components.

5. Conclusion

We have shown that a simple scintillation model accounts for the annual changes in the intraday variability timescale observed in the source 0917+624. These changes are due to the Earth's orbital motion, which influences the variability timescale because its velocity with respect to the ISM changes with time. This causes a change in the speed at which the Earth moves across the scintillation pattern.

This strongly suggests that ISS is the dominant mechanism of intra-day variability in this source.

We urge further observations of this source in the period July to November to test this model and constrain the velocity of the ISM transverse to the line of sight towards 0917+624.

We also suggest that observations of the source's variability properties at various epochs can be used to gain information on the two-dimensional structure at microarc-second resolution in the source, as the direction of motion across the scintillation pattern varies during the year.

Final Note During final preparation of this paper, we heard that Rickett, Witzel, Kraus, Krichbaum & Qian have independently discovered the annual cycle in 0917+624 and the explanation in terms of ISS and are submitting an independent publication.

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