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FLICKER OF EXTRAGALACTIC RADIO SOURCES AND REFRACTIVE INTERSTELLAR SCINTILLATION[1]

ROGER BLANDFORD, RAMESH NARAYAN, AND ROGER W. ROMANI
Theoretical Astrophysics, California Institute of Technology
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ABSTRACT

Recent work has identified variability of flat-spectrum extragalactic radio sources at $\lambda \approx 10$ cm with rms amplitude of $\sim 2\%$–3% and time scale of days. We show that this "flicker" is consistent with intensity fluctuations caused by refractive scintillation in an extended interstellar medium in our Galaxy. Further observation of flicker may allow the structure of suitable sources to be partially resolved on angular scales smaller than those probed by VLBI.

Subject headings: galaxies: Milky Way — interstellar: matter — radio sources: general

I. INTRODUCTION

Variability of compact extragalactic radio sources has been found over a range of frequencies. Large-amplitude intensity fluctuations at centimeter wavelengths on time scales of approximately months are common and are consistent with (possibly relativistic) intrinsic variations of synchrotron sources. Variation at meter wavelengths on time scales of approximately years was originally discovered by Hunstead (1972) and has since been demonstrated to be widespread (e.g., Condon *et al.* 1979). If this variation also is intrinsic to the sources, then highly relativistic internal motions and prodigious energy requirements are indicated for a large fraction of the objects.

As an alternative, Rickett, Coles, and Bourgois (1984) proposed that the low frequency variability of compact extragalactic radio sources might be an effect of propagation through large-scale electron density inhomogeneities in the interstellar medium (ISM) of our Galaxy. With a sufficiently steep power spectrum for these ISM density perturbations (cf. Blandford and Narayan 1985; Goodman and Narayan 1985), intensity fluctuations of large amplitude can be produced in pulsars and extragalactic sources by refractive focusing and defocusing of the radio waves.

There is a third type of variability that has been detected in careful observations by Heeschen (1982, 1984). This is a low-amplitude ($\sim 2\%$) short time scale ($\sim$ few days) "flicker" at wavelengths $\lambda \approx 10$ cm. This variability was also associated by Rickett *et al.* with refractive interstellar scintillation, the small amplitude being attributable to the finite size of the source. However, recent observations by Simonetti, Cordes, and Heeschen (1985) of flicker at two radio frequencies seem at first sight to be in conflict with an interpretation in terms of refractive scintillation. In this *Letter*, we show that the apparent discrepancies can be resolved by including the effect of an extended galactic scattering medium and allowing the source size to vary with the observation wavelength in a manner consistent with synchrotron models of the radio emission.

II. REFRACTIVE SCINTILLATION AND FLICKER

Simonetti *et al.* monitored 14 flat- and 20 steep-spectrum extragalactic sources for 20 days at 1410 MHz and 2380 MHz. The flat-spectrum sources showed flicker in their normalized flux fluctuations $\delta F(t)$ at both frequencies with average rms amplitudes μ of $\sim 2.3\%$ and $\sim 2.8\%$, respectively. Steep-spectrum sources, as expected, do not flicker. First-order structure functions of the flux fluctuations, defined to be $D^{(1)}(\tau) = \langle \delta F(t) \delta F(t) \rangle - \langle \delta F(t) \delta F(t+\tau) \rangle$, of the flat-spectrum sources were found to vary with time lag τ approximately as $D^{(1)}(\tau) \propto \tau$ throughout the observation period. Significant power was also found in the cross-frequency structure function, indicating correlation in the fluctuations at the two frequencies.

Blandford and Narayan (1985) have introduced a simple formalism that gives an approximate description of refractive interstellar scintillation (ISS) and used it to compute the autocorrelation function of the normalized flux fluctuations for the case of an equivalent thin scattering screen at a distance L from the observer. In this *Letter*, we assume a power spectrum of interstellar refractive density perturbations which give rise to a spectrum of phase fluctuations of the form $Q(q) = Q_0 q^{-\beta}$, where $Q(q)$ is dimensionless. (It is widely believed that $\beta = 3.7$ [e.g., Lee and Jokipii 1975; Armstrong, Cordes, and Rickett 1981], though there are suggestions that β may be as large as 4.3 [Blandford and Narayan 1985; Goodman and Narayan 1985].) In this *Letter*, for simplicity, we set $\beta = 4$. The autocorrelation is then

$$\langle \delta F(x) \delta F(x + v\tau) \rangle = \frac{Q_0 \lambda\!\!\!^{-4}}{2\pi\theta^2} e^{-v^2\tau^2/(2\theta^2 L^2)}, \qquad (1)$$

where $\lambda = 2\pi \lambda\!\!\!^{-}$ is the observation wavelength, θ is the apparent angular size of the source, and v is the velocity at

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which the scattering screen moves past the line of sight joining the source and the observer. The angle brackets denote a spatial average in the observer's plane or equivalently a time average in the observations as used above. In the case of flicker, the broadening of the source image due to scattering is negligible and θ is almost equal to the intrinsic angular size θ_I of the source. As noted by Simonetti *et al.*, if θ is constant, the rms fluctuation amplitude μ should scale approximately as λ^2, implying $\mu(1410)/\mu(2380) \approx 3$. The mean of the observed ratios of $\mu(1410)$ to $\mu(2380)$ is 1.0 ± 0.6, arguing against an explanation of flicker in terms of ISS in a thin scattering screen. Further, from equation (1), the average first-order structure function, $\langle D^{(1)}(\tau)\rangle$, is proportional to τ^2, instead of the observed linear scaling.

Since the density perturbations on scales $\sim \theta L$ contribute the bulk of the focusing that leads to flux variations, refractive ISS in an equivalent screen is dominated by a single length scale. In an extended scattering medium, however, the diameter subtended by the image will be a function of distance from the observer, and so a range of scales can contribute to the fluctuations. This changes the functional form of $D^{(1)}(\tau)$. For simplicity, we take the galactic scattering medium to be a Gaussian disk of scale height H (an exponential distribution gives similar results). The scattering strength Q_0 in equation (1) is then replaced by a scattering density

$$\frac{dQ_0(L)}{dL} = \frac{2Q_0}{\sqrt{\pi}\,H} e^{-L^2/H^2}. \qquad (2)$$

We also assume that the velocity v is dominated by Earth's orbital motion and so is the same for all screens. Since $\theta \approx \theta_I$ is the same for all the screens, we can integrate over the scattering medium to obtain

$$\langle \delta F(t)\delta F(t+\tau)\rangle = \int_0^\infty \frac{\lambda^4 Q_0}{\pi^{3/2}\theta^2} e^{-y^2} e^{-v^2\tau^2/(2H^2\theta^2y^2)}\,dy \qquad (3)$$

$$= \frac{\lambda^4 Q_0}{2\pi\theta^2} e^{-\sqrt{2}v\tau/\theta H}. \qquad (4)$$

Expanding for small τ we see that

$$D^{(1)}(\tau) = \frac{\lambda^4 Q_0}{2\pi\theta^2}\left(1 - e^{-\sqrt{2}v\tau/\theta H}\right) \approx \frac{\lambda^4 Q_0 v}{\sqrt{2}\,\pi\theta^3 H}\left(\tau - \frac{\sqrt{2}\,v\tau^2}{\theta H}\right). \qquad (5)$$

Thus, for a total observing time $T \lesssim T_{\rm sat} = \theta H/\sqrt{2}\,v$ the structure function is linear in τ, as observed.

The observed wavelength independence of the rms flicker magnitude can also be understood if the intrinsic source angular size increases with wavelength and we observe for times $T \lesssim T_{\rm sat}$. For example $\theta_I \propto \lambda$ for a flat spectrum, constant brightness temperature core (e.g., Kellermann and Pauliny-Toth 1981), and thus for $T \lesssim T_{\rm sat}$

$$\mu(T) = \left[D^{(1)}(T)\right]^{1/2} \propto \lambda^{1/2}, \qquad (6)$$

which gives an estimate for the effective scintillation index as a function of the observation period. This is in reasonable accord with the observations, given the substantial measurement error.

In addition to producing the observed scaling relations we should also check that the amplitude of the fluctuations is in the expected range. Ideally this should be done on a case-by-case basis using VLBI observations to determine the unresolved flux and low-frequency variability to constrain the scattering properties of the interstellar medium. At low frequencies, the scatter-broadened angular size of a point source, θ_s, which varies as λ^2, will be comparable to or even exceed the intrinsic angular size θ_I, and equations (3)–(5) are not valid. Romani, Narayan, and Blandford (1985) have developed an approximate theory to compute the flux variability amplitude and time scale for a scatter-broadened point source. With a simple extension, this theory can be used for an extended source. For a circular Gaussian source of intrinsic angular radius θ_I and a scattering density described by equation (2), we find that the angular size θ in the integral of equation (3) must be replaced by

$$\theta^2(y) = \theta_s^2(y) + \theta_I^2$$

$$\theta_s^2(y) = \theta_s^2(0)\left\{1 - \mathrm{erf}(y)\left[1 - (1/2y^2)\right] - e^{-y^2}/\sqrt{\pi}\,y\right\}. \qquad (7)$$

Numerically, we adopt a typical flux and brightness temperature of $S \approx 1$ Jy and $T_B \approx 5 \times 10^{11}$ K to obtain $\theta_I \approx 3.6\lambda_m$ mas and take the scattering angular size to be $\theta_s(0) \approx 2.2C_{-4}^{1/2}\lambda_m^2 H_{\rm kpc}^{1/2} csc^{1/2} b$ mas (Cordes, Weisberg, and Boriakoff 1984; Romani *et al.*), where the observation wavelength is in meters, C_{-4} is a measure of the strength of the scattering, and b is the galactic latitude of the source. Thus for an average line of sight with $H_{\rm kpc} \approx 1$, $C_{-4} \approx 1$, and $b \approx 30°$, this gives $\theta_s(0) \approx 4\lambda_m(1 + 0.7\lambda_m^2)^{1/2}$ mas. We assume that the velocity v is dominated by Earth's component of motion perpendicular to the line of sight, on average $v \approx (\sqrt{2/3})30$ km s^{-1}. Using these estimates, we compute the first-order structure functions for flicker at 1410 and 2380 MHz and low frequency variability at 327 MHz and display the results as a function of the observation period in Figure 1.

The saturation time scales for the growth of the intensity fluctuations are 38 days and 23 days at 1410 MHz and 2380 MHz with the above parameters, so after 20 days the observations are still within the linear range. The expected rms flicker amplitudes are 4.4% at 1410 MHz and 3.1% at 2380 MHz, somewhat higher than the observed values, but not unreasonably so in light of the difficulty of estimating the contribution of measurement error. (We note that the presence of source components on angular scales larger than θ_I can quench the flicker.) The ratio of the flicker amplitudes, $\mu(1410)$ and $\mu(2380)$, is 1.4, in reasonable agreement with the average flicker ratio computed by Simonetti *et al.*. The variability time scale at 327 MHz is $T_{\rm var} \approx 1$ yr and the amplitude is $\sim 26\%$, again in reasonable accord with the observations. (Note that this refers to the rms fluctuations in a large sample of similar sources and does not describe the peak-to-peak variations in the currently most variable sources.)

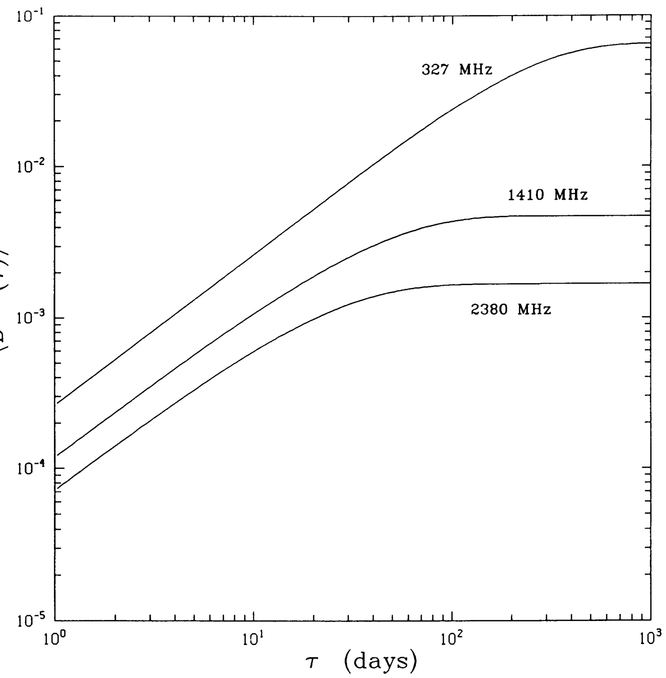

FIG. 1.—Variation of the average first-order structure function $\langle D^{(1)}(\tau)\rangle$ with the observation period τ for flicker at 1410 MHz and 2380 MHz and for low-frequency variability at 327 MHz. For times less than the saturation time scale $T_{sat} = \theta H/\sqrt{2}v$ the growth is approximately linear with τ, and the amplitudes are similar. The saturation time becomes longer at lower radio frequencies, and the saturated amplitude increases. The typical rms fluctuation in the flux is given by the square root of the saturated value of $\langle D^{(1)}(\tau)\rangle$.

We can also demonstrate the broad-band nature of the intensity fluctuations caused by refractive scintillation by considering the cross-correlation between intensity fluctuations measured at two wavelengths λ_1, λ_2. Using the simple model of equations (3)–(5), we obtain

$$\langle \delta F(t, \lambda_1)\delta F(t+\tau, \lambda_2)\rangle = \frac{\lambda_1^2\lambda_2^2 Q_0}{\pi(\theta_1^2+\theta_2^2)} e^{-\sqrt{2}v\tau/H(\theta_1^2+\theta_2^2)^{1/2}}, \tag{9}$$

where $\theta_{1,2}$ are the apparent angular sizes at $\lambda_{1,2}$. Simonetti *et al.* have estimated from their data the first-order cross-frequency structure function, normalized by the autofrequency results and averaged over all flat spectrum sources and find a significant correlation. Computing this object with our theory, we obtain

$$\frac{D_{12}^{(1)}(\tau)}{\left(D_{11}^{(1)}D_{22}^{(1)}\right)^{1/2}} = \frac{2\theta_1\theta_2}{(\theta_1^2+\theta_2^2)} \times \frac{\left\{1-\exp\left[-2v\tau/H(\theta_1^2+\theta_2^2)\right]^{1/2}\right\}}{\left[1-\exp\left(-\sqrt{2}v\tau/H\theta_1\right)\right]^{1/2}\left\{1-\exp\left[-\sqrt{2}v\tau/H\theta_2\right)^{1/2}\right]\right\}}. \tag{10}$$

Inserting our estimates for $\theta(0)$, we find that for τ less than T_{sat} the value is ~ 0.8, becoming ~ 0.9 after saturation. The measured cross-frequency structure function between 1410 and 2380 MHz has large errors but clearly reaches values greater than 0.5.

Note that, except for changes in the intrinsic source structure, the percentage polarization of the source should not fluctuate. This contrasts with the (presumably) intrinsic variation of BL Lac objects where the polarization varies more rapidly than the total flux.

III. DISCUSSION

We have shown how existing observations of flicker in compact radio sources can be interpreted as an interstellar propagation effect if we allow the source size to vary with wavelength and abandon the thin screen approximation. Although some sources probably do vary intrinsically at low frequencies (e.g., AO 0235+164) we endorse the proposal of Rickett *et al.* that low frequency variability and flicker are mainly due to refractive scintillation. Multifrequency observations of selected sources over time scales long enough to measure the saturated structure function should confirm the approximate scaling $\mu_{sat} \propto \lambda^2/\theta_I(\lambda)$ for the flicker amplitude and $T_{var} \propto \lambda^2 H/v$ for the low frequency variability time scale.

Detailed observations of flicker might, in principle, be used via a sort of "Earth orbit aperture synthesis" to obtain a superior angular resolution to that attainable using conventional Earth rotation VLBI. Suppose that the scattering medium moves slowly compared with Earth. We can define a power spectrum of the flux fluctuations $P(k)$ by taking the Fourier transform of the autocorrelation function in equation (1). It is then straightforward to show that for a k^{-4} spectrum

$$P(k) = \lambda^4 \int dL\, L^2 \frac{dQ_0}{dL} |V(kL)|^2, \tag{11}$$

where $V(b)$ is the complex visibility function, the Fourier transform of the normalized intensity of the source. A similar relation between the visibility function, and the intensity autocorrelation has been derived by Salpeter (1967) (and also M. H. Cohen, reference therein). The shape of the effective "beam" and the sampling in the observer plane will, of course, be determined by Earth's motion and the motion of the solar system barycenter. Obviously equation (11) is easiest to invert when the scattering is confined to a thin screen [i.e., when $D^{(1)}(\tau) \propto \tau^2$], and when the wavelength is long enough to give easily measurable fluctuations yet short enough for the interstellar scattering not to obscure the source structure.

In practice, intrinsic source variability and motions of the interstellar plasma will probably prevent this method from ever being implemented. Nevertheless, this analysis does serve to highlight a complementary consequence of refractive fluctuations, namely that daily variation in the angular structure of compact radio sources at the level of $\sim 10^{-2}$ limits the accuracy of VLBI mapping. Dynamic ranges of 1000:1 claimed in some contemporary experiments will not be attainable in strongly flickering sources. It remains to be seen how severe this restriction turns out to be in practice.

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ROGER BLANDFORD, RAMESH NARAYAN, and ROGER W. ROMANI: Theoretical Astrophysics, 130-33, California Institute of Technology, Pasadena, CA 91125