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REFRACTIVE INTERSTELLAR SCINTILLATION IN 1741−038

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ABSTRACT

A year of VLA observations of the radio source 1741−038 show that it exhibits pronounced variability at 1.49, 15, and 22 GHz, and somewhat reduced activity at 4.9 GHz. We interpret the unusually strong 1.49 GHz variability as due to refractive interstellar scintillation, and the high-frequency variability as being intrinsic to the source. Most of the scintillation is caused by a single thin screen within a few hundred parsecs of the Sun, probably located in the North Polar Spur. 1741−038 offers a unique opportunity to test the refractive scintillation hypothesis through VLBI observations.

Subject headings: interstellar: matter — quasars — radio sources: variable

I. INTRODUCTION

Low-frequency variability in compact radio sources has been known since the work of Hunstead (1972) and is usually found at meter wavelengths. If the variability is intrinsic to the radio source, then it implies brightness temperatures significantly greater than 10^{12} K, leading to severe theoretical difficulties (Jones and Burbidge 1973; Kellerman and Pauliny-Toth 1981; Jones 1983). However, Rickett, Coles, and Bourgois (1984) have recently argued that the variability may be an extrinsic effect due to refractive interstellar scintillation, and that the same phenomenon may also cause the observed flicker of radio sources (Heeschen 1984) at shorter wavelengths.

1741−038 is a strong, compact radio source located at galactic coordinates, $l = 21^\circ.6$, $b = 13^\circ.1$. It is unresolved ($\leq 0''.05\lambda_{\rm cm}$) at 20, 6, 2, and 1.3 cm for the 35 km configuration of the VLA. Peterson and Bolton (1973) identified it with an $18^{\rm m}.5$ QSO. Vijayanarasimha, Ananthakrishnan, and Swarup (1985) reported 327 MHz observations of 1741−038 and from the observed interplanetary scintillation they deduced an angular size of ∼100 mas. In this paper we report frequent observations of 1741−038 over a period of one year at four frequencies. These data show strong variations at 1.49 GHz and somewhat weaker variations at 4.9 GHz, that are both independent of strong variations at 15 and 22 GHz. While high-frequency variability is likely to be intrinsic to the source, we argue that the data provide clear evidence of "low-frequency variability" at 1.49 GHz that is similar to (only significantly stronger than) that normally seen at 408 MHz (Fanti *et al.* 1981) and interpret this variability in terms of refractive interstellar scintillation.

II. OBSERVATIONS

Thirty-five epochs of observation of 1741−038 and 3C 286 were made during the period from 1985 February 24 to 1986 February 20, at the VLA frequencies of 1.49, 4.9, 15, and 22 GHz, as part of an extensive study (Hjellming *et al.* 1986) of the radio source produced by the 1985 outburst of RS Oph. Because of the initial rapid variability of RS Oph, the average interval between observations ranged from a few days to a week during the first 100 days of observation. These indicated that at some VLA frequencies, and at certain epochs, the calibrator, 1741−038, was varying more rapidly than RS Oph itself. Fortunately, the stable radio source 3C 286 was always used to "bootstrap" the flux scale for 1741−038, so we can state with confidence that the variability of 1741−038 is real at all four VLA frequencies. All flux calibrations were based upon the scale of Baars *et al.* (1977) for 3C 286. The spectrum of 1741−038 measured on 1985 October 20 is shown in Figure 1 and is seen to be inverted. Additional observations were made at this time at 327 MHz using the eight antennas of the VLA then instrumented at this frequency. The measured flux of 0.56 Jy at 327 MHz is consistent with the inverted nature of the rest of the spectrum; however, refractive scintillation could cause large fluctuations in the flux at this frequency, so this measurement is not a reliable indicator of the intrinsic source strength. In fact, Vijayanarasimha *et al.* (1985) estimated a flux of 1.5 Jy, so the VLA 327 MHz measurement indicates the presence of strong variability at this frequency.

Figure 2 shows plots of the variation with time (JD −2,446,000) of the flux densities of 1741−038 at 1.49, 4.9, 15, and 22 GHz, normalized by 1.4, 2.4, 3.0, and 3.0 Jy, respectively. The mean flux densities and the rms fluctuations about the mean for the data in Figure 1 are 1.47 Jy ± 11% (1.49 GHz), 2.45 Jy ± 6% (4.9 GHz), 3.19 Jy ± 12% (15 GHz), and 3.26 Jy ± 18% (22 GHz), respectively. Other data on 1741−038 are available in the VLA "calibrator manual," which lists flux densities varying between 1.1 and 2.0 Jy at 1.49 GHz and between 1.9 and 2.7 Jy at 4.9 GHz. Perley (1982) reported 1.49 and 2.7 Jy at 1.49 and 4.9 GHz, well within the range found in Figure 1; however, Wall and Peacock (1985) found 1.0 and 3.63 Jy at 1.4 and 5 GHz. This "random" sampling thus confirms the fluctuation scales seen in Figure 1.

It is convenient to analyze the data in Figure 1 in terms of the structure functions used by Simonetti, Cordes, and Heeschen (1985). Let $F(t)$ be the measured flux at time t for some frequency. If we define a normalized flux variation, $\delta F(t) = [F(t) - \langle F \rangle_t]/\langle F \rangle_t$, then the structure function of variability is given by

$$D(\tau) = \langle [\delta F(t + \tau) - \delta F(t)]^2 \rangle_t \,, \tag{1}$$

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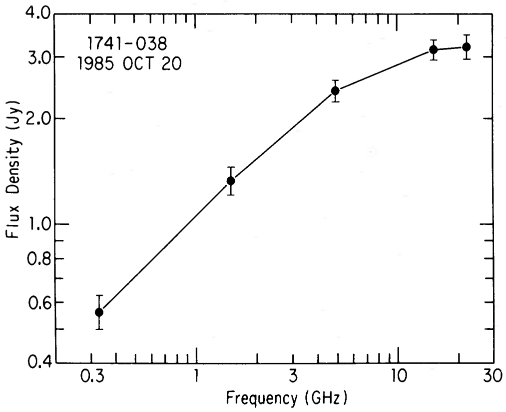

FIG. 1.—The radio spectrum of 1741−038 on 1985 September 28 plotted in the form of log (flux density) vs. log (frequency) for VLA measurements at 0.327, 1.49, 4.9, 15, and 22 GHz.

where $\langle \cdots \rangle_t$ means averaging over all t. Figure 3 shows the structure functions, corrected by subtracting the appropriate noise bias (see Simonetti *et al.* 1985), corresponding to the four data trains of Figure 2. The structure functions were determined by calculating $D(\tau)$ for all lags in the data and then binning them in equal logarithmic intervals of t. Now, if $\delta F_{\rm rms}$ is the rms variation in the normalized flux, then the asymptotic value of $D(\tau)$ for large τ is $D(\infty) = 2(\delta F_{\rm rms})^2$. Taking $\delta F_{\rm rms}$ from the data, we estimate $D(\infty)$ to be 0.024, 0.007, 0.029, and 0.065, respectively, at the four frequencies of interest. The true values of $D(\infty)$ may be somewhat higher than our estimates for frequencies where the structure function has not saturated even after 300 days. We define the variability time scale $t_{\rm var}$ to be the $1/e$ width of the intensity autocorrelation function, given by $D(\tau) = (1 - e^{-1})D(\infty)$. At 1.49 GHz, the value of $t_{\rm var}$ is seen

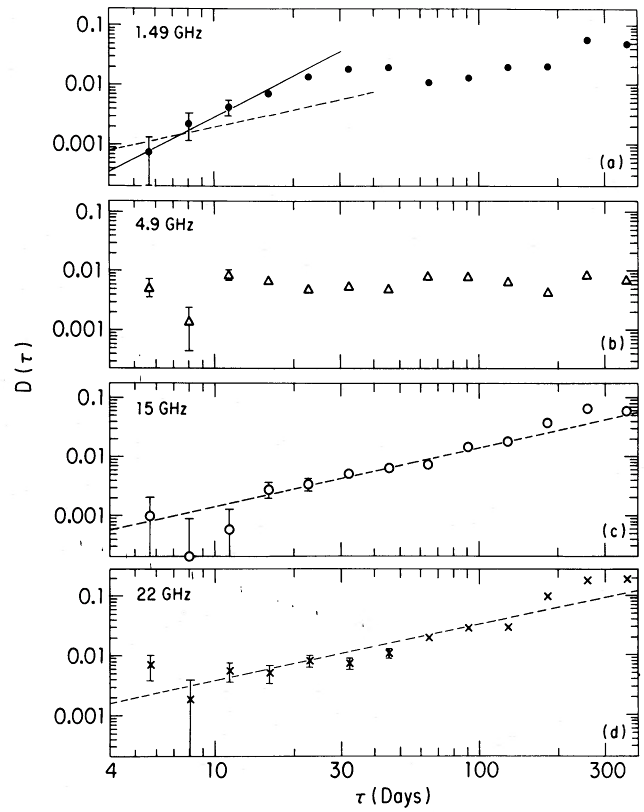

FIG. 3.—The structure functions $D(\tau)$ for the time variations of 1741−038 at (*a*) 1.49, (*b*) 4.9, (*c*) 15, and (*d*) 22 GHz, plotted as functions of the time scale τ, with solid and dashed lines showing functions proportional to τ^2 and τ, respectively.

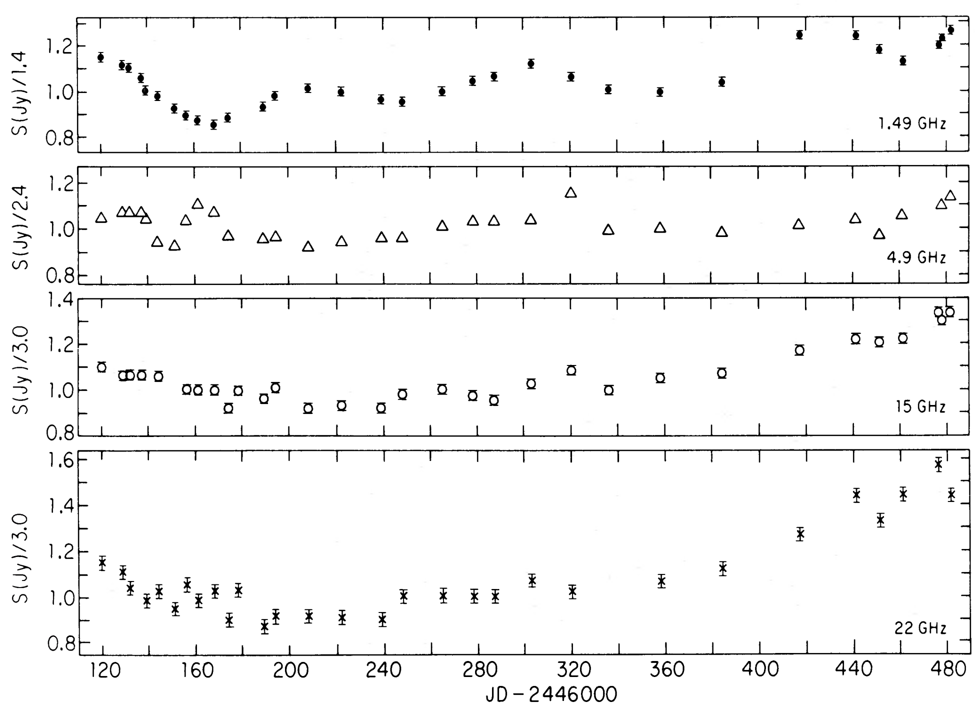

FIG. 2.—Flux density measurements for 1741−038 at 1.49 (*filled circles*), 4.9 (*open triangles*), 15 (*open circles*), and 22 (*crosses*) GHz, divided by the scaling flux densities of 1.4, 2.4, 3.0, and 3.0 Jy, respectively, plotted as a function of (JD −2,446,000) for dates between 1985 February 24 and 1986 February 20. The error bars at 4.9 GHz are essentially the size of the triangles.

from Figure 3*a* to be ~ 20 days. At 4.9 GHz, the data do not have the necessary resolution (Fig. 3*b*) and all that one can say is that $t_{\rm var} < 10$ days. The structure functions at 15 GHz and 22 GHz both indicate that the variations have not saturated even over the 1 yr stretch of data, therefore $t_{\rm var} \geq 200$ days.

III. INTRINSIC VARIABILITY VERSUS INTERSTELLAR SCINTILLATION

Let us first consider the possibility that the variability observed in 1741−038 is intrinsic to the source. The redshift $z \approx 1.135$ estimated by Wall and Peacock (1985) and the time scale $t_{\rm var} \approx 20$ days at 1.49 GHz correspond (by light-travel-time arguments) to an angular size 0.002 mas or smaller (assuming a Hubble constant of 50 km $\rm s^{-1}$ $\rm Mpc^{-1}$). With ~ 160 mJy in the variable component, this implies an apparent brightness temperature greater than 2×10^{16} K. This is significantly larger than the 10^{12} K limit associated with inverse Compton scattering in a synchrotron source (see Kellerman and Pauliny-Toth 1981). If the radiation is emitted by a source moving relativistically with velocity $v/c = \beta$ toward the observer at an angle ϕ to the line of sight, then the observed flux will be boosted by a factor $[\delta/(1+z)]^{\alpha+3}$, where $\delta^{-1} = \gamma(1 - \beta \cos \phi)$ and α is the spectral index. Taking $\phi \approx 0$ and $\alpha \approx -0.5$ (see Fig. 1), we find that 1741−038 should have $\gamma > 100$ for compatibility with the inverse Compton limit at 1.49 GHz. This is far too large to be plausible since the range deduced from superluminal motions is typically only ~ 5–10 (Kellermann and Pauliny-Toth 1981). The variability amplitude of ~ 0.5 Jy at 22 GHz with $t_{\rm var} \approx 100$ days corresponds to a brightness temperature of only 1.5×10^{13} K, which corresponds to a more reasonable $\gamma \approx 6$. Thus, it is the 1.49 and 4.9 GHz variability which is difficult to understand, whereas the 15 and 22 GHz variability could well be intrinsic to the source.

Another interpretation of rapid low-frequency variability has been pioneered by Hesse (1972) and Shapirovskaya (1978), who argue that it is due to the focusing action of density irregularities in the interstellar medium (ISM) of the Galaxy. Rickett *et al.* (1984) showed that this idea is compatible with a hitherto neglected regime of interstellar scintillation (ISS). Standard ISS in pulsars on time scales of 10^2–10^3 s is known to be caused by interference of multiple rays from the source to the observer (Scheuer 1968; Rickett 1977). The effect generally requires the source to have an angular size less than a few microarcseconds. Condon and Dennison (1978) showed that compact extragalactic sources do not display this kind of *diffractive* ISS, implying that their angular sizes are larger than the above limit. The important contribution of Rickett *et al.* (1984) was to point out that an extended power-law spectrum of density inhomogeneities in the ISM produces a slower type of variability, with time scales of days to years, because of the *refractive* focusing and defocusing of rays propagating through the medium. This effect, called refractive interstellar scintillation (RISS), should be seen in sources up to several mas in size, making it of interest for flat spectrum extragalactic sources.

Rickett *et al.* (1984) proposed that variability at meter wavelengths (see Fanti *et al.* 1981) and flicker at shorter wavelengths ~ 10–20 cm (Heeschen 1984) in compact extragalactic radio sources is due to RISS, and also ascribed slow intensity variations in pulsars to the same effect. A point to be stressed is that RISS will always be present (in addition to any intrinsic variability) if there are density fluctuations of appropriate amplitude at length scales $\sim 10^{13}$–10^{15} cm in the ISM. Lee and Jokipii (1976) and Armstrong, Cordes, and Rickett (1981) have plausibly argued on the basis of observational evidence that the ISM does indeed have the extended power-law spectrum of electron-density inhomogeneities required for RISS. They propose that the spectrum has a power-law form $Q(q) \propto Q_0 q^{-\beta}$ with $\beta = 11/3$, as given by Kolmogorov turbulence theory, where q is the wavenumber of the turbulent size scale. The theory of RISS (Rickett *et al.* 1984; Blandford and Narayan 1985) predicts a somewhat lower amplitude of refractive flux variability than observed if one assumes a spectrum of the above form. This difficulty can be overcome by invoking an inner scale in the spectrum (Rickett *et al.* 1984) or a steeper spectrum with $\beta > 4$ (Blandford and Narayan 1985; Goodman and Narayan 1985). Apart from this, there is presently no serious objection to the refractive ISS explanation. On the other hand, only a few predictions of the theory have so far been observationally verified. One success for the theory is that it explains why the time scale of variability of galactic pulsars increases with distance to the source (Sieber 1982). Also, Cawthorn and Rickett (1985) have found some evidence for the "latitude effect," whereby the frequency of occurrence of flux variability in extragalactic radio sources increases with decreasing galactic latitude. The effect is weaker than expected, presumably because the ISM is extremely inhomogeneous in its scattering properties (e.g., Cordes, Weisberg, and Boriakoff 1985). Several other predictions of the theory have been worked out (Blandford and Narayan 1985; Romani, Narayan, and Blandford 1986), but these are yet to be verified. In particular, there are certain crucial tests that can be made using VLBI observations, for which 1741−038 may be very important, as we discuss in § V. In what follows, we interpret the 1.49 GHz variability of 1741−038 as RISS and draw conclusions about the ISM along this particular line of sight.

The theory of RISS for a source with a finite angular size has been developed by Blandford *et al.* (1986) and Rickett (1986). The strength of the phenomenon depends critically on the ratio of the angular scatter-broadening θ_S to the intrinsic size of the source θ_I. For an average line of sight in the Galaxy at latitude b, Blandford *et al.* quote $\theta_S \approx 2.2 C_{-4}^{1/2} \lambda_m^2 H_{\rm kpc}^{1/2} (\csc b)^{1/2}$ mas and $\theta_I \approx 3.6 \lambda_m S_{\rm Jy}^{1/2}$ mas. Here, $H_{\rm kpc} \csc b$ kpc is the path length through the galactic disk of thickness $H_{\rm kpc}$, λ_m is the wavelength in meters, $S_{\rm Jy}$ is the flux in Jy, and $C_{-4} = C_N^2/10^{-4}$, where C_N^2 measures the strength of electron density fluctuations in the medium (e.g., Rickett 1977). For the above estimates, θ_I is much greater than θ_S for $\lambda_m \leq 0.2$, and in this regime RISS should manifest itself as a weak flux variability at the level of a few percent. This naturally accounts for the flicker of flat spectrum sources found by Heeschen (1984) and Simonetti *et al.* (1985). On the other hand, for $\lambda_m \gg 1$ one has $\theta_S \gg \theta_I$, and in this regime RISS should lead to strong variability. The low-frequency variability of flat spectrum sources reported by Fanti *et al.* (1981) at $\lambda_m = 0.74$ corresponds to the transition between the two regimes. These sources would presumably display more intense variations at $\lambda_m > 1$.

Vijayanarasimha *et al.* (1985) quote an angular radius of 50 mas for 1741−038 at $\lambda_m = 0.92$. Scaling by λ^2, this implies a radius of ~ 2 mas at 20 cm. Comparing with the estimate from Blandford *et al.* (1986) given above, we see that there must be significant excess scattering along this line of sight, with C_N^2 being larger than that for an average line of sight by a factor of more than 100. Therefore, for this source the transition between strong variability and flicker should occur, not at $\lambda_m \approx 1$, but at $\lambda_m \approx 0.1$. This is precisely what we see in our data. At $\lambda_m = 0.2$, 1741−038 shows 11% variations in flux. In comparison, note that only one out of a homogeneous sample of 45 flat spectrum sources observed by Fanti *et al.* (1981) shows this level of variability even at 408 MHz. At 4.9 GHz, 1741−038 displays ~6% flux variations, which is more in line with the Fanti *et al.* variability at 408 MHz. Thus, 1741−038 behaves like other flat spectrum sources except that, because of the substantially increased scattering, the wavelength scale is shifted by a factor 10 or greater. The flicker of ~2% seen by Simonetti *et al.* (1985) at $\lambda_m = 0.21$ should occur in 1741−038 at $\lambda_m \leq 0.02$, but it is masked by strong intrinsic variability at these wavelengths.

The time scale of RISS is given by $t_{\rm var} \approx 17\theta L_{\rm kpc}/v_7$ days, where θ is the measured angular size of the source given by $(\theta_S^2 + \theta_I^2)^{1/2}$ mas, $L_{\rm kpc}$ is the distance (in kpc) to the scattering region in the ISM, and $10^7 v_7$ cm s^{-1} is the effective transverse velocity of the scintillation pattern past the observer. If we take $v_7 = 0.3$ (because of the combined effect of the peculiar motion of the Sun and the orbital velocity of Earth round the Sun), then our estimate of $t_{\rm var} \approx 20$ days for 1741−038 at 1.49 GHz implies $L_{\rm kpc} \approx 0.14$. This is very much smaller than the $L_{\rm kpc} \approx 4$ that one expects if the scattering were produced by a uniform slab of thickness 1 kpc. We thus conclude that the bulk of the scattering of 1741−038 occurs in a localized screen within a few hundred parsecs of the Sun. For $L_{\rm kpc} = 0.14$, the predicted variability time scale at 4.9 GHz is ~3 days, which is not inconsistent with the structure function in Figure 3*b*. At 327 MHz, $t_{\rm var}$ is predicted to be ~400 days, which is consistent with the ~3 yr time delay between the 1.5 Jy flux measurement of Vijayanarasimha *et al.* (1985) and the 0.56 Jy measurement reported in this paper.

The previous discussion made use of the angular radius of 50 mas given by Vijayanarasimha *et al.* (1985) from interplanetary scintillation (IPS) data. While IPS is excellent for establishing the presence of compact components, it might be argued that it is not always accurate in estimating source sizes, particularly when the source is weak. Vijayanarasimha *et al.* (1985) recognized this limitation and quoted conservative error limits. In the case of 1741−038, the true angular size could be less than the IPS estimate, but not by a factor greater than ~2. As we now show, a similar conclusion can be reached from another independent argument. From the estimates given earlier on the basis of the physics of self-absorbed synchrotron sources, the intrinsic size of 1741−038 at 1.49 GHz is $\theta_I \approx 0.9$ mas. The strong variability of this source at this frequency (stronger than normal 408 MHz "low-frequency variability") argues that its scattering radius should be at least comparable to θ_I, say $\theta_S \approx 1$ mas. This is down only by a factor of 2 compared to the ~2 mas deduced from IPS data. Let us now consider the worst case, namely that the scattering radius is 1 mas instead of 2 mas at 1.49 GHz. In this case C_N^2 is less by a factor ~4 compared to the estimate given earlier, but is still substantially larger than the mean C_N^2 of the local interstellar medium. Also, the scattering screen is moved out to ~300 pc, which is still far short of the 4 kpc expected for a uniform 1 kpc–thick slab. Thus our conclusions that the scattering is excessive in the line of sight to 1741−038 and that the scattering is concentrated in a relatively nearby portion of the interstellar medium, remain valid even in this worst case.

IV. EXCESS SCATTERING BY THE NORTH POLAR SPUR

In our view it is most likely that the excess scattering in 1741−038 is produced in the region where its line of sight passes through the edge of the North Polar Spur (NPS). Shapirovskaya (1978, 1982) has long argued that the variability of extragalactic sources is caused by the refractive focusing of specific features in the Galaxy such as various spurs, loops, and ridges seen in radio continuum maps. The NPS figures prominently in these arguments, and is believed to be part of an almost complete ring of enhanced emission centered on $l \approx 330°$, $b \approx 17°$ with radius ~60° (Large, Quigley, and Haslam 1966). Berkhuisjen, Haslam, and Salter (1971) have argued that this structure (their Loop I) is the shell of an old supernova remnant. Their 408 MHz radio observations and those of Haslam, Large, and Quigley (1964) show that, apart from the main NPS at $l \approx 30°$, $-2° < b < 18°$, there is an additional "intense inner ridge ... beginning at $l \approx 22°$, $b \approx +14°$." The line-of-sight to 1741−038 ($l = 21.^\circ6$, $b = 13.^\circ1$) lies exactly on the latter feature. The distance to the NPS is estimated to be ~200 pc (Berkhuisjen *et al.* 1971), which is consistent with the $L_{\rm kpc} \approx 0.14$ we derived from the observed variability time scale.

Blandford *et al.* (1986) pointed out that scattering in an extended medium has a different observational signature from that in a single (thin) screen. For small τ, the structure function $D(\tau)$ should vary as τ in the former case, and as τ^2 in the latter case. The NPS interpretation above requires that 1741−038 must have characteristics appropriate to a single screen. Figure 3*a* shows that $D(\tau)$ for 1741−038 at 1.49 GHz is indeed closer to the τ^2 case (*solid line*) than the τ case (*dotted line*). In the study of Simonetti *et al.* (1985), all the flat spectrum sources had $D(\tau) \propto \tau$, except 2144+09 which showed a τ^2 dependence. The line of sight to 2144+09 passes close to the turbulent outer shell of the NPS identified by Rickard and Cronyn (1979), which explains its single-screen characteristics. As further confirmation, 2144+09 has a significantly greater amplitude of flicker than all the other sources in the Simonetti *et al.* (1985) sample. Thus there is strong evidence that the NPS profoundly influences RISS.

V. CRITICAL VLBI OBSERVATIONS OF 1741−038

We showed in the previous section that both our flux variability data and the IPS data indicate an enhanced scattering diameter of ~2–4 mas at 1.49 GHz for 1741−038. It is clearly important to confirm this by VLBI observations. In addition, several features make 1741−038 an ideal source for VLBI tests of the RISS hypothesis. First, because of the strongly enhanced scattering, its scatter-broadened image can be resolved by Earth-diameter VLBI for all wavelengths $\lambda_m \geq 0.1$. Second, the scattering comes predominantly from a single screen, a case for which the theory is straightforward and well understood. Third, the proximity of the screen to the Sun significantly reduces the time scale of variability, and so it is feasible to make multiple observations covering several variability time scales. Multiple-epoch VLBI observations of 1741−038 could look for the following effects predicted by RISS theory:

1. Blandford and Narayan (1985) showed that fluctuations in the angular size of the image should be strongly correlated with fluctuations in the flux (correlation coefficient >60%).

2. Romani *et al.* (1986) showed that if the scattering medium is isotropic and has a Kolmogorov spectrum, then the scatter-broadened image would in general be slightly elliptical, with an elongation ~10%. The direction of the major axis on the sky would vary randomly on a time scale $\sim t_{\rm var}$. If the medium were anisotropic, then the elongation would be predominantly in one direction.

3. The existence or lack of substructure within the scatter-broadened image would give important information on the spectrum of electron density fluctuations in the scattering screen. Goodman and Narayan (1985) argued that if the fluctuation spectrum were a power law with $\beta > 4$, then the image would have a patchy structure (with a fractal morphology), whereas for $\beta < 4$, it would be smooth. A spectrum with $\beta > 4$ is one of the possibilities that will bring the theory of RISS into more quantitative agreement with the observed strength of flux variability in pulsars (Goodman and Narayan 1985). A spectrum with $\beta > 4$ will also produce a much more elongated image (elongation up to 50%).

VI. CONCLUSIONS

The data in this paper show that the radio source 1741 − 038 has flux variability due to at least two causes. At 15 and 22 GHz, we see predominantly long time-scale variations that are probably intrinsic to a compact, self-absorbed synchrotron radio source. At 1.49 and 4.9 GHz, however, there are short time-scale variations consistent with the refractive interstellar scintillation phenomenon (Rickett *et al.* 1984). The behavior of the structure function at 1.49 GHz shows the RISS is of the "thin screen" type, and the anomalously short time scale implies that the screen is very close to the Sun. Since the line of sight to 1741 − 038 passes through the edge of the NPS, the dominant cause of the RISS at 1.49 GHz must be the NPS at a distance of ~200 pc, thus confirming the arguments of Shapirovskaya (1978, 1982). Multifrequency observations of 1741 − 038, or other compact radio sources, made with sampling intervals of a few days or less over periods of the order of a year or more, should allow one to study the RISS phenomenon in detail. At the same time, VLBI observations on 1741 − 038 promise to supply critical tests of the RISS hypothesis. Ultimately, when the phenomenon is sufficiently well understood, one may be able to use it for a type of source structure synthesis for sources smaller than those currently studied with VLBI, in the manner suggested by Blandford *et al.* (1986).

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