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LOW-FREQUENCY VARIABILITY OF EXTRAGALACTIC RADIO SOURCES

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ABSTRACT Interpretations of low-frequency variability, flickering and intra-day variability of extragalactic radio sources are reviewed with emphasis on refractive interstellar scintillations and models involving relativistic boosting. Coherent emission is severely constrained by induced Compton scattering.

INTRODUCTION

Variability of compact extragalactic radio sources was first reported by Hunstead (1972) and soon recognized to be relatively common (Shapirovskaya 1978). Flat-spectrum sources are now known to exhibit several different forms of variability (e.g., Rickett 1990): low-frequency variability, flickering, intra-day variability (IDV) and extreme scattering events (Fiedler et al. 1987). These are in addition to flaring and other forms of variability that are clearly intrinsic to the source (e.g., Marscher and Gear 1985). The properties of these phenomena may be summarized as follows. (1) Low-frequency ($\lesssim 1\,\mathrm{GHz}$) compact ($\lesssim 10\,\mathrm{mas}$) sources show variations of amplitude 3–30% over months to years. These variations depend on the galactic latitude of the source (e.g., Mantovani et al. 1990), which is strongly indicative of a scintillation in the interstellar medium. (2) Flickering involves a few per cent flux variations on a time scale of a few days at frequencies of a few GHz (Heeschen 1982). (3) IDV involves more rapid variability of a few percent on time scales of a few hours at higher frequencies (Heeschen et al. 1987; Witzel 1990). There is evidence for a correlation between the radio and optical variations (Wagner and Witzel 1992). (4) Extreme scattering events involve changes up to 50 percent over a few days.

A constraint on the interpretation of such variability arises from the maximum brightness temperature, $T_B \approx 10^{12}\,\mathrm{K}$, that is determined by inverse-Compton losses in a self-absorbed synchrotron source. If observed variations on a time scale Δt are assumed to imply a source size $\sim c\Delta t$, then the implied brightness temperature can exceed the inverse-Compton limit. The inferred values for IDV, $T_B \sim 10^{17}$–$10^{19}\,\mathrm{K}$ are well in excess of the limit. Three ways of avoiding this difficulty have been suggested: (1) attribute the variability to scintillations in the interstellar medium (ISM) (Shapirovskaya 1978; Rickett, Coles and Bourgois 1984); (2) invoke relativistic boosting together with some intrinsic time-dependence in the source, such as shocks (e.g., Marscher and Gear 1985; Qian et al. 1991) or a lighthouse effect (Camenzind and Krockenberger 1992); (3) abandon the synchrotron hypothesis and invoke some coherent emission process (e.g., Colgate 1967; Baker et al. 1988).

In this paper, these interpretations of the radio variability of compact sources are reviewed. First, the theory of scintillations is summarized, emphasizing refractive interstellar scintillations (RISS), and then its application to the interpretation of the variability is discussed. Next the relativistic beaming and lighthouse models are described, and finally, coherent emission mechanisms are discussed critically, emphasizing a limitation imposed by induced Compton scattering.

THE THEORY OF SCINTILLATIONS

Scintillations are a result of fluctuations, $\delta\phi$, in the phase of a wave due to variations in the refractive index along the line of sight. In a plasma, variations in the refractive index are due to spatial variations, δn_e, in the electron density, n_e. The observer sees a phase deviation from the straight-line path

$$\delta\phi(\mathbf{r}, L) = r_e \lambda \int_0^L dz\, \delta n_e(\mathbf{r}, z), \tag{1}$$

where the z-axis lies along the line of sight, $\mathbf{r} = (x, y)$ denotes a transverse displacement, $r_e = 2.82 \times 10^{-15}\,\mathrm{m}$ is the classical radius of the electron, and λ is the wavelength of the wave. The properties of the fluctuations may be characterized by the autocorrelation function of the phase variations, usually written as the wave structure function, $D(\mathbf{r}, L)$, with

$$D(\mathbf{r}, z) = \langle[\delta\phi(\mathbf{s}, z) - \delta\phi(\mathbf{s} - \mathbf{r}, z)]^2\rangle, \tag{2}$$

where the angular brackets denote an ensemble average, intended to describe averages over nearby lines of sight. Through (1), the phase fluctuations are related to the density fluctuations, which may be described by

$$R_n(\mathbf{x}) = \langle\delta n_e(\mathbf{x}')\delta n_e(\mathbf{x}' - \mathbf{x})\rangle, \qquad Q_n(\mathbf{K}) = \int d^3\mathbf{x}\, R_n(\mathbf{x}) \exp(i\mathbf{K} \cdot \mathbf{x}), \tag{3}$$

that is, $Q_n(\mathbf{K})$ is the spatial Fourier transform of $R_n(\mathbf{x})$. The density fluctuations in the ISM are assumed to be isotropic with a power-law dependence on wavenumber,

$$Q_n(\mathbf{K}) = C_n^2 K^{-\beta}, \tag{4}$$

with cutoffs at an inner scale, $K > 2\pi/r_{\mathrm{in}}$, and an outer scale, $K < 2\pi/r_{\mathrm{out}}$, and where C_n^2 is the (density) structure constant. A Kolmogorov spectrum corresponds to $\beta = 11/3$. For such a spectrum, the phase structure function is a power law,

$$D(r) = (r/r_{\mathrm{diff}})^{\beta-2}, \tag{5}$$

where r_{diff} includes all normalization constants, and where cutoffs at $r < r_{\mathrm{in}}$ and $r > r_{\mathrm{out}}$ are not included explicitly. In the theory, r_{diff} plays the role of a coherence scale, defining the width of the visibility function (e.g., Rickett et al. 1984), with $\theta_0 = \lambda/2\pi r_{\mathrm{diff}}$ a scattering angle.

There are two important lengths in scintillation theory. One is r_{diff}, which characterizes the size of the density inhomogeneities. The other is the Fresnel

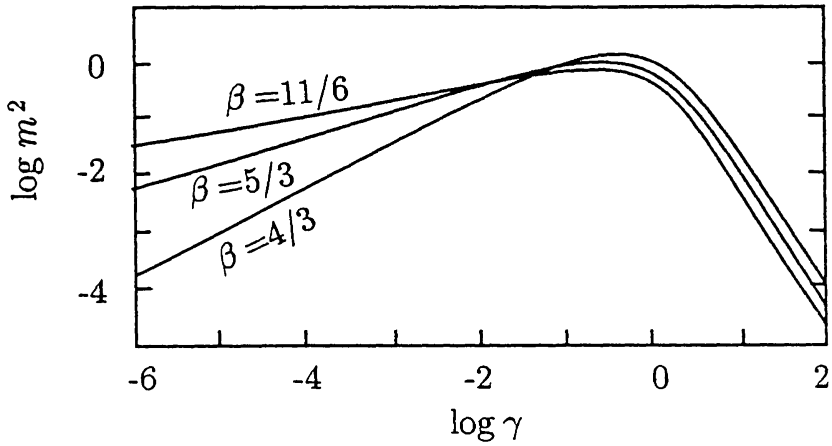

FIGURE I Plots of the square of the scintillation index versus $\gamma = r_{\rm in}/\theta_0 L$ for a source with $\theta_{\rm S} \ll \theta_0 = \lambda/2\pi r_{\rm diff}$, and for various power-law density spectra with inner scales $r_{\rm in}$. [After Coles et al. (1987).]

scale $r_{\rm F} = (L/k)^{1/2}$, $k = 2\pi/\lambda$, which characterizes the contribution, $r^2/2r_{\rm F}^2$, to the phase from diffraction, with L the distance between the scattering inhomogeneity and the observer. The *strength* of the scattering may be described using the parameter $u = r_{\rm F}/r_{\rm diff}$ (e.g., Rickett 1990). For $u \ll 1$ the scattering is said to be *weak*, in which case (5) implies $D(r) \ll 1$, so that the phase fluctuations are small. For $u \gg 1$ the scattering is said to be *strong*.

Strong scattering separates into two distinct scales: diffractive scintillations on a scale $r \lesssim r_{\rm F}$, and refractive scintillations on a scale $r \sim u r_{\rm F}$. Thus refractive scintillations occur on a characteristic scale $r_{\rm ref} = r_{\rm F}^2/r_{\rm diff}$. Estimates for $\lambda = 6\,{\rm cm}$ give $r_{\rm diff} \sim 10^6\,{\rm m}$, $r_{\rm F} \sim 10^9\,{\rm m}$, $r_{\rm ref} \sim 10^{13}\,{\rm m}$ (Mutel and Lestrade 1990). Diffractive scintillations can be observed only for a source with an angular size less than the diffractive limit, $\lambda/r_{\rm diff} \sim 0.1\,{\rm mas}$, which is not satisfied for the extragalactic sources of interest here. Only RISS are relevant for compact extragalactic sources with angular diameter $\theta_S \gtrsim 1\,{\rm mas}$. The properties of RISS may be deduced using geometric optics (e.g., Blandford and Narayan 1985), which is much simpler than the wave theory for strong scattering.

The strength of scintillations is usually described in terms of the scintillation index, m, which is related to the fluctuations in the intensity, I, by $m^2 = \langle (I - \langle I \rangle)^2 \rangle / \langle I \rangle^2$. In Figure I, m^2 is plotted for an extended source with a gaussian angular profile, $\propto \exp(-\theta^2/2\theta_{\rm S}^2)$, with $\theta_{\rm S} \gg \theta_0$. Note that the strongest scintillations occur for a certain combination of parameters that involves the inner cutoff scale and the wavelength of the radiation. It follows from Figure I that large amplitude variations ($m^2 \gtrsim 10^{-1}$) due to RISS are possible only in a relatively narrow parameter range. However, variations of a few percent ($m^2 \gtrsim 10^{-4}$) can occur over six orders of magnitude in the parameter γ.

The characteristic size scale, $r_{\rm scint}$, time scale, $t_{\rm scint}$, modulation index and decorrelation bandwidth for RISS were estimated by Narayan (1992) for a Kolmogorov spectrum ($\beta = 11/3$):

$$r_{\rm scint} \approx r_{\rm ref}\frac{\theta_S}{\theta_{\rm scatt}}, \qquad t_{\rm scint} \approx \frac{r_{\rm ref}}{v}\frac{\theta_S}{\theta_{\rm scatt}},$$
$$m \approx \left(\frac{r_{\rm diff}}{r_{\rm F}}\right)^{1/3}\left(\frac{\theta_S}{\theta_{\rm scatt}}\right)^{-7/6}, \quad \delta\lambda_{\rm dc} \approx \lambda, \tag{6}$$

with $\theta_{\rm scatt} = r_{\rm ref}/L$, and where v is the transverse speed of the inhomogeneities relative to the observer, which is thought to be of order the orbital speed of the Earth, $v \sim 50\,{\rm km\,s^{-1}}$. The decorrelation width $\delta\lambda_{\rm dc}$ is the range of wavelengths over which correlation in the fluctuations in lost.

The scaling of the quantities in (6) with wavelength follows from $r_{\rm ref} \propto \lambda^{\beta/(\beta-2)} \propto \lambda^{2.2}$, where the latter form is for $\beta = 11/3$. However, this dependence is complicated by the dependence of the source size, θ_S, on λ in (6). An intrinsic dependence of the angular size θ_S of the source on λ is implied by standard models to explain the flat spectrum (e.g., Marscher 1977; Blandford and Königl 1979). Rickett (1986) described the dependence of the various models for the flat spectrum in the form $\theta_S \propto \lambda^x$, with x in the range $0 \lesssim x \lesssim 1.25$. This gives $t_{\rm scint} \propto \lambda^x$ and $m \propto \lambda^{2-7x/6}$.

INTERPRETATION OF VARIABILITY IN TERMS OF SCINTILLATIONS

Some, but not all the variability of compact extragalactic radio sources may be explained in terms of RISS.

For the low-frequency variability, the original suggestion (Shapirovskaya 1978; Rickett et al. 1984) that it is due to RISS is generally supported by the observations (e.g., Rickett 1990). The observed dependence of the variability on galactic latitude (e.g., Mantovani et al. 1990) is strongly indicative of RISS. Some of the variability over months to years appears to be intrinsic, associated with flaring and other secular changes in the source. This type of variability does not violate the 10^{12} K limit. Nevertheless there are observed features that are not readily explained. For example, the amplitude of the variability can be higher than the theory for RISS implies. There is also the variability reported by Slee and Siegman (1988) at 80 MHz and 160 MHz which does not show the dependence on galactic latitude expected for RISS. However, scintillation theory does not explain all the phenomena satisfactorily for pulsars, where the theory is very well established. For example, Gupta, Rickett and Coles (1993) argued that RISS theory applied to pulsars at 74 MHz seemingly underestimates the strength of the actual scattering, as described by the scintillation index. These authors noted that this raises questions over the quantitative application of a simple version of RISS theory to extragalactic sources.

As an example, consider the source 1741–038, which has a compact, flat-spectrum core with an extended steeper-spectrum component. VLA observations of the variation of this source were reported by Hjellming and Narayan (1986), who found that the variations at 1.49 GHz and 4.9 GHz are independent of stronger variations at higher frequencies 15 GHz and 22 GHz. Some of the data from recent monitoring of this source at NRL and by the MOST are

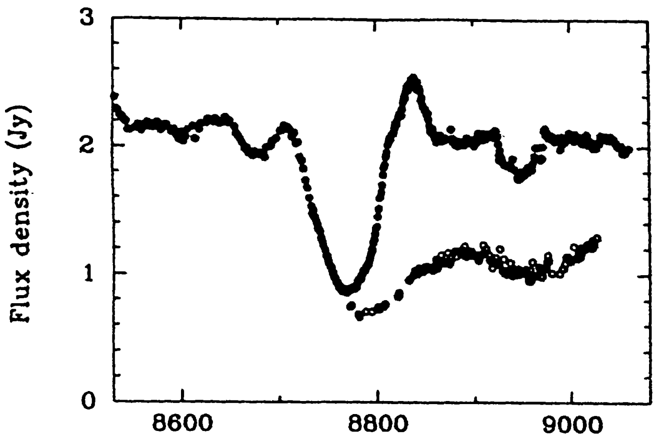

FIGURE II The variation of the flux of the source 1741–038 at 2.3 GHz (upper plot, courtesy NRL) and 843 MHz (lower plot, courtesy MOST) as a function of time (Julian days 244000).

illustrated in Figure II. At 8.3 GHz (not shown) the source shows a secular increase by about 30% over ~ 3 yr, with some fluctuations. The amplitude of the variations is very large at 2.3 GHz, and only slightly smaller at 843 MHz, with indications of a delay of about a week. It appears that at the minimum in the fluctuations at 843 MHz, the signal from the flat-spectrum core falls below that of the steeper-spectrum component (Hunstead, private communication). This would imply a scintillation index $m \approx 1$, which is higher than predicted by the existing theory for RISS.

The interpretation of flickering in terms of RISS was initially thought to be unfavorable (Hjellming and Narayan 1986; Simonetti, Cordes and Heeschen 1985). However, Blandford, Narayan and Romani (1986) showed that the flickering can be explained in terms of RISS in an extended medium provided that the intrinsic source size varies with wavelength. An additional complication in the earlier applications of RISS to flickering is that the distinction between the average image, and the ensemble-average image was not recognized. These depend on whether the observation involves an average over a time, t, in the range $t_{\rm diff} \ll t \ll t_{\rm ref}$ or in the range $t \gg t_{\rm ref}$, respectively, where $t_{\rm diff} = r_{\rm diff}/v$ is the time scale for diffractive scintillations and $t_{\rm ref} = r_{\rm ref}/v$ is the time scale for refractive scintillations. Narayan and Goodman (1989) argued that observations are in the average-image regime, rather than the ensemble-average regime as had been assumed implicitly, and Mutel and Lestrade (1990) reported observations that support this suggestion.

The scintillation index is expected to decrease strongly with increasing frequency, and the smaller amplitude of the flickering at higher radio frequencies, compared with the low-frequency variations is consistent with this. The strength of the scattering also decreases with increasing frequency, and another possibility is that at higher frequencies the scattering is weak rather than strong. Rickett (1990) noted that all possible regimes for the interpretation of the observed variabilities had not yet been explored, in particular the limit of weak scattering

(WISS).

Blandford et al. (1986) developed a model for flickering due to refractive scintillations. The main observation that these authors aimed to explain is the structure functions of the flux density fluctuations, $D^{(1)}(\tau) = \langle\delta F(t)\delta F(t)\rangle - \langle\delta F(t)\delta F(t+\tau)\rangle$, with τ the time lag between two observations. The observations suggest $D^{(1)}(\tau) \propto \tau$ throughout the observation period, which is not consistent with the predictions of simple theory. Blandford et al. (1986) assumed the inhomogeneities to be moving relative to the observer at speed v, and for simplicity assumed a power law $\beta = 4$ in (5). They argued that the intensity correlation is of the form

$$D^{(1)}(\tau) = \frac{Q_0}{2\pi k^4\theta^2} \exp\left(-\frac{v^2\tau^2}{2L^2\theta^2}\right), \tag{7}$$

where Q_0 is defined by writing the Fourier transform of (5) in the form $D(K) = Q_0K^{-\beta}$. In the case $\beta = 4$, the scatter image of a point source would lead to $\theta \propto \lambda^2$. Then, if the scatter broadening is negligible, the coefficient in (7) varies as λ^2. The observations suggest that the intensity fluctuations are roughly independent of λ (Simonetti et al. 1985). Moreover, for $v^2\tau^2 \ll 2L^2\theta^2$, (7) implies $D^{(1)}(\tau) \propto \tau^2$, again contrary to observation.

Blandford et al. (1986) made two assumptions to resolve these inconsistencies. First, they assumed that the scattering occurs over a large range of distances, rather than in a single screen at distance L and, second, they assumed that the intrinsic size of the source varies with wavelength as $\theta_I \propto \lambda$. The first assumption requires that Q_0 in (7) be replaced by a local value per unit length, which they took to be $dQ_0(L)/dL = (2Q_0/\sqrt{\pi}H)\, exp(-L^2/H^2)$, where H is the scale height of the Galactic disk. For $v\tau \ll H\theta$ this leads to

$$D^{(1)}(\tau) \approx \frac{Q_0 v}{\sqrt{2}\pi k^4\theta^3}\left(\tau - \frac{\sqrt{2}v\tau^2}{H\theta}\right), \tag{8}$$

which gives the desired form $D^{(1)}(\tau) \propto \tau$. For a flat spectrum source with a constant brightness temperature core, the angular size varies as $\theta_I \propto \lambda$, and then (8) implies rms fluctuations varying $\propto \lambda^{1/2}$, in reasonable agreement with the observations. The success of this model supports the interpretation of flickering in terms of RISS.

INTERPRETATION OF THE IDV

In discussing the interpretation of IDV one needs to decide whether to take account of the suggested correlation between radio and optical variations, because such a correlation would exclude RISS. Suppose this suggested correlation is ignored. Consider refractive scintillations due to a plasma inhomogeneity of size Δr at a distance l that causes variations on a time scale $\Delta t = \Delta r/v$. For the inhomogeneity to cover a source of angular size θ_S at a distance L, requires $\Delta r \gtrsim l\theta_S$, implying $l/L \lesssim (v/c)(\theta_{\Delta t}/\theta_S)$, where $\theta_{\Delta t} = c\Delta t/L$ is the angular size estimated from the light propagation time. For the inverse-Compton limit to be satisfied, IDV then requires $l/L \lesssim 10^{-3}(v/c)$, which can only plausibly be satisfied for a screen in our Galaxy, e.g., $l/L \sim 10^{-7}$, $v/c \sim 10^{-4}$. For example, RISS with $\Delta r \sim 10^9$ m, $l \sim 3$ kpc, $v \sim 30\,\mathrm{km\,s^{-1}}$ appears capable of accounting for IDV (e.g., Wambsganss et al. 1989).

Some emphasis has been placed on the rapid changes in polarization that sometime accompany IDV (e.g., Krichbaum, Quirrenbach and Witzel 1992). Such variations are expected due to random changes in the rotation measure associated with scintillations (Melrose 1993). The polarization fluctuations should increase rapidly with wavelength (Melrose 1993), providing a test for this suggested interpretation.

Now assuming the correlation between radio and optical variations to be real, there are at least three suggested explanations for the IDV. (1) Doppler boosting enhances the observed value of T_B compared to that in the rest frame of the source. Consider a source moving toward the observer at an angle θ to the line of sight with Lorentz factor $\gamma_S = (1-\beta_S^2)^{-1/2}$. The ratio of the observed to the intrinsic T_B equals $\mathcal{D}^3$, with $\mathcal{D} = [\gamma_S(1-\beta_S\cos\theta)]^{-1}$. For IDV the inferred T_B exceeds the inverse-Compton limit by a factor 10^6, which is equal to $\mathcal{D}^3$ for $\mathcal{D} \sim 10^2$. Thus this model requires $\gamma_S \sim 10^2$, which is larger than seems plausible for radio-emitting jets (e.g., Qian et al. 1991). (2) A model proposed by Qian et al. (1991) is a modification of a model for flaring due to shocks propagating along a jet (e.g., Marscher and Gear 1985). A shock is assumed to brighten on hitting inhomogeneities in the jet, producing variations on a time scale $\Delta t = \Delta L(1+z)/c\beta_S\mathcal{D}\gamma_S$, with z the red shift and ΔL the separation between the inhomogeneities. Suggested parameters $\Delta L = 0.16$ pc, $\gamma_S \approx 14$, $\mathcal{D} \approx 28$ can account for $\Delta t \approx 1$ day. (3) Camenzind and Krockenberger (1992) suggested a lighthouse model in which plasma bubbles are ejected at relativistic speed nearly along the axis of a magnetized jet. These bubble spiral about the axis of the jet, and the variations are attributed to the changing angle between the line of sight and the bubbles.

COHERENT EMISSION

Several different coherent emission mechanisms have been proposed to overcome the difficulty with the 10^{12} K-limit. Here these various mechanisms are reviewed briefly, and some critical comments are made on their application to extragalactic sources.

All the coherent emission mechanisms proposed for extragalactic sources (Colgate 1967; Baker et al. 1988; Sol, Pelletier and Asséo 1989; Krishnan and Wiita 1990; Weatherall and Benford 1991; Benford 1992) involve a two stage process in which some instability generates longitudinal waves which produce the escaping radiation either through nonlinear plasma processes (e.g., Melrose 1991) or through scattering by relativistic particles. For example, Baker et al. (1988) developed a model in which a relativistic electron beam injected from the central engine into the inner portion of a jet produces Langmuir turbulence. The electromagnetic radiation is assumed to be due to a form of free electron maser emission (e.g., Attwood et al. 1985), which is related to linear acceleration emission (e.g., Rowe 1992a, 1992b), with the Langmuir turbulence acting as the wiggler field. The coherence is attributed to bunching, in the sense that the total power radiated is assumed to exceed the power radiated incoherently by a factor $N \sim n_b\lambda^3$, where N is the number of particles per bunch, n_b is the number density of the beam electrons and $\lambda = 2\pi c/\omega$ is the wavelength of the Langmuir waves. (In my opinion this is not correct, and the correct factor is the number of beam electrons per coherence volume of the *emitted* radiation.) Baker et al. (1988) estimated the ratio of the power radiated by this process to the power radiated in synchrotron emission to be $G = (E^2/c^2B^2)(N^2N^*/n_e)$, where N^* is the number of bunches, and n_e is the number of electrons, and where E is the electric field strength in the waves. The other models for coherent emission differ from this model in specific details of the instability and the conversion mechanism to electromagnetic radiation.

The main motivation for invoking coherent emission is to explain radio emission brighter than the 10^{12} K-limit. However, as pointed out by Rees (1992) and Coppi, Blandford and Rees (1993), the effective optical depth for induced Compton scattering is of order T_B/m_ec^2 times the optical depth for Thomson scattering, $\sim \sigma_T n_e L$, where L is the depth of the source. The typical optical depth for a broad-line emission region in an AGN is $\sim 10^{-2}$. Although the optical depth in any postulated source of coherent emission needs to be estimated directly, it is clear that $\sim \sigma_T n_e L$ cannot be very small because a relatively high value of n_e is required for the mechanisms discussed above to operate, and a relatively large value of L is required on energetic grounds. It follows that for $T_B \sim 10^{18}$–10^{20} K, which is required in the most extreme cases, induced scattering would be a very strong effect. The expected signatures of induced Compton scattering in AGN were discussed by (Coppi et al. 1993), who argued that the absence of these signatures implies a limit on the Thomson optical depth, and hence on the electron density. For a source with $T_B = 10^{18}$ K and radius $r = 10^{15}$ cm, they estimated $n_e \leq 10\,\text{cm}^{-3}$, which they noted to be ten orders of magnitude smaller than the value required in the source region to sustain the observed power.

Another physical process that can modify and prevent escape of radiation involves a collimated beam of photons generating Langmuir waves, which then scatter the beam photons. This process appears to be important in eclipsing pulsars (Gedalin and Eichler 1993), where it can prevent the beam of photons propagating through a seemingly transparent plasma. The constraints imposed by induced scattering and this photon-beam instability appear to be severe, and seemingly preclude any coherent emission mechanism producing the very bright emission postulated.

DISCUSSION AND CONCLUSIONS

(1) Low-frequency variability includes both RISS, which depends on the galactic latitude of the source, and intrinsic variations that do not violate the inverse-Compton limit.
(2) Flickering appears to be due to RISS
(3) IDV may be due to RISS if the suggested radio-optical correlation is not real. Otherwise, it must be intrinsic to the source, and can be explained in terms of relativistic boosting, with Lorentz factor $\sim 10^2$, a relativistic shock encountering inhomogeneities on a scale ~ 0.1 pc, or a specific lighthouse model involving relativistic (Lorentz factor ~ 14) motion of plasma bubbles in a twisted magnetic field.

(4) Fluctuations in polarization associated with IDV may be due to random changes in rotation measure (Melrose 1993), which suggestion can be tested through a strong predicted dependence on wavelength.
(5) Coherent emission mechanisms are significantly constrained by induced scattering, and perhaps also by photon-induced plasma turbulence in or near the source.
(6) There remain features that are not obviously consistent with the existing theory of RISS, notably the large amplitudes of some variations. It may be that enhanced refraction from specific structures needs to be invoked, e.g., as suggested by Romani, Blandford and Cordes (1988) for the extreme scattering events.

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