An intergalactic origin for the low-frequency flux variations of extragalactic radio sources

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Measurements of the X-ray background[1], absorption-line spectra of quasars[2] and the depolarization of their radio emission[3] indicate that the intergalactic space is filled with clouds of thermal plasma. These clouds are likely to contain density inhomogeneities on a wide range of physical scales, like the interstellar medium (ISM) of our own galaxy[4]. Here I discuss a new possibility, viz. that the flux-density variations of compact extragalactic radio sources observed at low frequencies ($\nu < 1$ GHz) could substantially arise from refractive focusing and defocusing of their emission by intervening *intergalactic* plasma inhomogeneities (on parsec scale), possibly associated with the cooling flows[5] in the cores of clusters of galaxies. The observed time-scales of a few years for the low-frequency variability (LFV) of bright compact radio sources can be understood by considering[6] that such sources are parts of relativistic jets and usually appear to separate from the parent galactic nucleus at superluminal velocities[7,8]. Consequently, the line of sight to such a source is expected to sweep past any distant intervening plasma cloud typically at apparent speeds $> c$. Observational relevance of the resulting 'superluminal refractive scintillations', as proposed here, is briefly discussed.

BROAD-BAND amplitude fluctuations of compact extragalactic radio sources, commonly observed on time-scales of months to years at metre wavelengths[9-14], are believed to be associated almost exclusively with bright, milliarcsecond radio components[15]. Radiating by the incoherent-synchrotron mechansim, such components are now thought to be mostly Doppler-boosted constituents of the jets, ejected relativistically from an active galactic nucleus, at small inclinations from the line of sight[15,16]. In the beaming model[16], many reported events of LFV require extremely large Lorentz factors for the jet flow ($\Gamma > 50$) (ref. 17). Moreover, there appears to be, usually, little time correlation between the variabilities of the same source at metre and centimetre wavelengths[11]. Thirdly, LFV is found to be more common at lower galactic latitudes[18-21]. Thus, while some candidates for intrinsic LFV might exist[11,22-25], the phenomenon of LFV is now perceived[15] as being largely a propagation effect arising within the ISM of our galaxy, similar to the slow flux variations of pulsars[26,27].

In an appealing interpretation of the LFV of extragalactic sources Shapirovskaya[28] proposed that their metre-wave radiation could be partially focused at distances of ~ 100 pc by the galactic plasma structures on scales of $\sim 10^{13}$ cm. Later work by Rickett *et al.*[27] established that an extended power-law spectrum of density inhomogeneities in the ISM can cause LFV of compact radio sources on time-scales of months to years, by refractive focusing and defocusing of the rays propagating through the medium. The same mechanism may also explain the observed flickering of compact radio sources at decimetre wavelengths[29]. A recent analysis[20] of the 408-MHz flux-density time series of 39 extragalactic sources, spanning a decade, has revealed that: (i) the galactic latitude modulation of the measured LFV parameters is significant, albeit obscured by much larger random variations, (ii) the source-to-source variations are not lessened when only the objects in close proximity on the sky are considered, and (iii) two different time-scales are probably present in the time series of at least half the sources. The last point, in particular, provides an indication that more than one processes might be involved in the LFV phenomenon[20]. While it is tempting to link the longer of the two time-scales with intrinsic variability, there is no indication of correlation between high- and low-frequency variations in many of the sources showing the dual time-scales. Moreover, in several cases, even the longer time-scales are found to be just a few years, and thus not much different from the 'shorter time-scales' deduced for many sources in the sample[20]. These findings provide motivation for exploring additional *extrinsic* processes to evolve a more comprehensive description of the LFV phenomenon. Here I examine the possibility that refractive scintillations caused by plasma inhomogeneities located far outside our galaxy may contribute significantly to the observed LFV on time-scales of a few years.

Although intergalactic scintillations have been touched upon in some early literature[10] the idea has not gained much attention. Possible reasons for this include the lack of information about the electron density perturbations in the intergalactic medium (IGM) and the general impression that any refractive scintillations caused by such plasma would only be observable on time-scales exceeding 10^2–10^3 yr and hence carry little practical significance. Such time-scales follow from the presumption that a compact radio source remains fixed in direction and the intervening IGM irregularities would cross the line of sight to the source, say, at a velocity typical of galaxies inside clusters ($\sim 10^3$ km sec^{-1}). However, such a premise can be grossly misleading in the context of compact radio sources[6]. There is ample evidence that such sources are blobs of synchrotron plasma ejected relativistically from the parent galactic nucleus, roughly along the line of sight, and, consequently, they are expected[7,8,15,16] to appear separating from the nucleus at a speed $v_s \approx \gamma c$, where γ is the Lorentz factor of the bulk motion. Thus, against the celestial frame of reference defined by the nuclei of distant galaxies, the line of sight to a given compact radio source would appear to sweep past any intervening IGM plasma concentration at a speed $v_* = v_s\,(D_*/D_s)$, where D_s and D_* are, respectively, the angular-size distances to the radio source and the IGM concentration. As v_* can often exceed c by a large factor depending on the value of γ (ref. 16), the time-scale of the postulated intergalactic scintillations could, in fact, be much shorter than those inferred conventionally ($\tau > 10^2$–10^3 yr, see above).

For our galaxy, the power spectrum of interstellar electron density is usually parametrized[30] as a power law in spatial wave number $q : P_n(q) = C_n^2 q^{-\beta}$. While the coefficient C_n^2 varies by a large factor for different directions[30–32], β is found to be close to 4 from a variety of pulsar measurements[4,33–36]. Since, at present, for the IGM (or the intracluster medium, ICM) such knowledge is grossly inadequate, I shall only attempt a broad consistency check on the intergalactic 'superluminal refractive scintillation' scenario proposed here. The standard thin-screen approximation can be used to restrict the intergalactic plasma inhomogeneities to a thin layer located at a distance D_* which is roughly half the angular-size distance D_s from the observer to the source lying at an assumed typical red shift $z_s = 1$. In a typical source of, say, 1 Jy, the flat-spectrum core would account for about half the flux at metre wavelength[37]. The implied angular size θ for a brightness temperature[38] of $\sim 10^{12}$ K would be ~ 2 milliarcsec for the compact emission, corresponding to a physical size $d_* = \theta . D_* \simeq (\theta . D_s/2) \simeq 5$ pc at the distance of the plasma layer (assuming $H_0 = 75$ km sec^{-1} Mpc^{-1} and $q_0 = 1/2$). As the bulk of the refractive focusing leading to the flux variability would be caused by density inhomogeneities on a characteristic scale[39] $a \sim d_*$, the corresponding focusing angle ψ should exceed θ in order to obtain substantial flux variability, where[26]

$$\psi(a) \simeq \left(\frac{\pi^3}{2}\right)^{\frac{1}{2}} \left(\frac{L}{a = d_*}\right)^{\frac{1}{2}} \alpha(a)\, \bar{N}_e\, r_0\, \lambda^2. \qquad (1)$$

Here $\alpha(a).\bar{N}_e$ is the rms fluctuation of the average density $\bar{N}_e$ (on the scale a), r_0 the classical radius of an electron, and L the depth of the refractive medium. It is interesting to identify this postulated medium with the gaseous cores of clusters of galaxies for which X-ray observations[40] suggest a typical diameter $L \sim 500$ kpc and an average electron density $\bar{N}_e \gtrsim 10^{-3}$ cm^{-3}. There is considerable evidence that large density perturbations develop in the cluster cores owing to thermal instabilities, and cooling flows are set up[5]. Further, the probability for the cooling flows to intersect the line of sight to a distant source ($z_s \sim 1$) is close to unity[41]. Thus, with the above estimates for L, d_* and $\bar{N}_e$, the condition $\psi > \theta$ is satisfied for $\alpha \gtrsim 5$ [eq. (1)]. This estimate is quite similar to the observationally supported value of $\alpha(\sim 10)$ for the large-scale perturbations within the ISM of our galaxy[42]. Thus, based on this simplified, phenomenological picture, it seems quite plausible that the gaseous medium of cosmologically distant clusters can impress significant LFV on background compact radio sources (see below). As discussed above, the expected time-scale τ for such superluminal refractive-flux variations would be $\sim d_*(D_s/D_*)(1+z_s)\,\gamma c \sim 6$ yr, taking typical values $d_* \sim 5$ pc, $(D_s/D_*) \sim 2$, $z_s = 1$, and $\gamma = 10$. Clearly, the variability characteristics would depend in this picture on the distance of the source, in contrast to the model[27,28] where the low-frequency variability is attributed to refractive scintillations within the ISM of our galaxy.

Here, it is pertinent to ask whether the parsec-scale electron inhomogeneities with rms density fluctuations $(\partial\rho/\rho) \sim 10$, as required in the present scenario, are indeed expected to be a substantial component of the cluster cooling flows. The latter are now believed to be a multiphase medium[43], the clearest evidence for which has come from the detection of emission lines due to highly ionized oxygen, iron and other elements in the soft X-ray spectra of several nearby clusters[44,45]. The consistency of the cooling rates derived from the observed luminosities of such lines with the inwardly decreasing mass-accretion rates inferred from X-ray surface-brightness deprojections[46] indicates that the material in the ICM is cooling out over a wide range in radius. An analysis[44] of the Fe XVII and other X-ray lines observed in the Perseus cluster suggests that the $10^{6\ 6}$-K gas mainly responsible for the iron line, which forms part of a multiphase medium in pressure balance, is ~ 10 times denser than the surrounding medium and occupies $\sim 1\%$ of the volume (thus, the denser component inferred from just one prominent X-ray line accounts for $\simeq 10\%$ of the total gaseous mass within the cluster core). Such relatively dense blobs of plasma cannot arise owing to thermally unstable growth of infinitesimal initial-density fluctuations ($\delta_i = (\partial\rho/\rho) << 1$) (refs. 47,48). Even for finite values of $\delta_i = 0.1$–1, as inferred[43,49] from the deduced profiles for mass-accretion rate in several clusters, the growth process remains efficient only for blobs in a limited range of physical sizes, as determined by the complex dynamical coupling between the blobs and the background flow[49,50]. A recent quantitative analysis[50] has shown that, in the absence of such a coupling, even regions with *finite* overdensity would perform relatively rapid buoyant oscillations in the cluster potential, suppressing the thermal instability. Such thermal-convective oscillations of the blobs could, however, be effectively damped out owing to the ram-pressure drag caused by the surrounding medium, thus allowing the blobs to 'cool out' of the background flow[49,50]. For this to happen, a substantial cooling must occur before the blob reaches its equilibrium position (or falls into the cluster centre), when moving relative to the background flow at the terminal velocity set by the drag forces[49]. As discussed by Loewenstein[50], this condition is likely to be realized for blobs starting with finite overdensity (say δ_i 0.1–1) (refs. 43, 49), provided their sizes do not exceed a few parsecs. Initially larger inhomogeneities, stirred up, for example, by galaxy motions within the cluster cores, would then 'cool out' after entering the parsec-scale regime, via a continuous fragmentation resulting from the internal hydrodynamic stresses induced by the ram pressure[49,50]. Thus, aside from possible but poorly understood complications introduced by additional factors, such as magnetic field, it seems reasonable to expect, on the basis of the recent theoretical modelling, that parsec scale may be a fairly common feature of the relatively dense plasma ($\partial\rho/\rho \gtrsim 10$) that is observationally inferred[44,45] to be cooling out of the hot ICM throughout the cluster core. An irregular ICM of this type would not be dissimilar to the one invoked above for a refractive focusing of the metre-wave radiation from compact radio sources. Further, attributing the 'long' time-scale variations to intervening clusters of galaxies (see above) would be fully consistent with the observed[20] characteristics of such variations, namely the lack of their dependence on galactic latitude and the dissimilarity of the variability characteristics between compact sources projected close on the sky.

To summarize, it seems quite plausible that compact extragalactic radio sources producing relativistic jets could display significant flux variations at metre wavelengths due to *superluminal refractive scintillations* caused by density inhomogeneities in the intervening intergalactic plasma, conceivably associated with cosmologically distant clusters and groups of galaxies. The expected time-scale for such variability, in fact, can be fairly short (down to a couple of years), depending on the cosmological model, the scattering properties of the medium, as well as the emissivity, kinematics, geometry and distance of the source. Such low-frequency variability of intergalactic origin could then often be mistakenly linked to processes intrinsic to the source, or, alternatively, to refractive effects occurring within our own galaxy. The intergalactic contribution to LFV may be partly responsible for the large scatter found[10] in the latitude dependence of the measured variability parameters and for the frequent occurrence of dual time-scales in the flux-density time series of many sources, especially in cases where no correlation is apparent between the variations at centimetre and metre wavelengths.

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High-resolution radio images of the Crab nebula

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High-resolution images of the Crab nebula at a wide range of radio frequencies from 327 MHz to 5 GHz have been made using the Very Large Array. The image at 327 MHz shows the pulsar and the radio jet very prominently. The emission from the jet has a radio spectrum steeper than the nebular emission.

THE Crab nebula is one of the most interesting and fascinating astronomical objects. It is the remnant of the supernova explosion 1054 AD. It is basically a pulsar-driven synchrotron nebula, where the relativistic electrons generated by the pulsar emit radiation by synchrotron process. Bright filaments emitting optical lines are also embedded within this nebula. About 20% of the Crab pulsar's spin-down energy is converted into synchrotron radiation in the radio to X-ray wavelengths. Indeed, it provides an excellent astrophysical battleground for testing high-energy plasma processes. In spite of the fact that it has been one of the most well-studied objects over several decades, modern imaging techniques have continued to reveal more and more intriguing details. For example the jet-like feature protruding outside the nebular boundary, first noted by van den Bergh[1] in 1970, has been recently studied in detail in [OIII] (ref. 2); radio emission from this feature was detected by Velusamy[3] at 20 cm. Although several radio images of the Crab nebula have been made in the last two decades[4,5], there are many unresolved questions: for example the existence of a low-surface-brightness shell characteristic of typical supernova remnants, the magnetic field structure in the filaments, the energy distribution of the relativistic electrons in the filaments vs the nebular regions, interaction of pulsar wind with the surrounding nebula. Detailed study of such problems requires high-resolution images with high dynamic range over a wide range of frequencies. For example, the present upper limits are not low enough to rule out the existence of any shell around the Crab with surface brightness comparable to that in the remnant of supernova AD 1006 (ref. 6). In view of the above, we have been observing the Crab nebula at radio frequencies using the Ooty synthesis radio telescope (OSRT)[7] and the Very Large Array (VLA)[8]. In this paper we present an OSRT map at 327 MHz and high-resolution (4 to 5 arcsec) images of the Crab nebula at 327 MHz, and 1.5 and 5 GHz obtained with the VLA.

The observations at 327 MHz were first made with OSRT[7] during 1986. The OSRT contour map of the Crab obtained with a resolution of 56 × 33 arcsec^2 is shown in Figure 1. The overall structure is consistent with the high-resolution maps at higher frequencies, e.g. at 1.5 GHz (ref. 9). The jet protruding out of the northern boundary is seen very prominently at 327 MHz. A comparison of this map with the 1.5-GHz map[9] suggests a steepening of the spectrum outward along the jet, with spectral index $\alpha \sim -0.25$ (where $S_\nu \sim \nu^\alpha$) near the nebula to -0.7 near the tip of the jet. However, in view of the low dynamic range in this OSRT map, observations at 327 MHz were also made with the VLA to confirm this.

The VLA is best suited for multifrequency high-