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DISPERSION OF RADIO WAVES BY PLASMA AROUND BL LAC OBJECTS

DEBORAH DULTZIN-HACYAN, SHAHEN HACYAN AND MARGARITA ROSADO

Instituto de Astronomía
Universidad Nacional Autónoma de México
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RESUMEN

Se da una explicación para el retardo de un día observado entre los pulsos rápidos de radio en dos frecuencias distintas para los objetos BL Lac y OJ 287. Se argumenta que estos retardos se deben a la dispersión de las ondas de radio producida por plasma eyectado con velocidades ultrarelativistas desde el núcleo central.

ABSTRACT

An explanation is given for the observed time lags of one day between radio "spikes" at two different frequencies in the objects BL Lac and OJ 287. It is argued that these delays are due to the dispersion of radio waves produced by plasma ejected at ultrarelativistic speed from the central core.

Key words: **BL LAC OBJECTS — PLASMAS.**

I. INTRODUCTION

Since the identification of the "variable star" BL Lac with the peculiar radio source VRO 42.22.01 (MacLeod and Andrew 1968) and subsequent study of its unusual properties, more than 30 BL Lac type objects have been found.

The sources BL Lac, OJ 287 and 0048-09 are among the most rapid and most violently variable sources known, and represent an extreme case of the variable radio source phenomenon. For two of these objects (BL Lac and OJ 287) extremely rapid radio flux variations with a time scale of about one day have been observed in the form of radio "spikes". These "spikes" are superimposed on longer term variations which have time scales ranging from a few weeks to a few months (Andrew *et al.* 1971; MacLeod *et al.* 1971). The reality of this very short term variations is established by their simultaneous detection at two different frequencies: 10.7 GHz and 6.6 GHz ($\lambda\lambda$-2.8 cm and 4.5 cm). The time lag between "spikes" at these two frequencies is reported to be of the order of one day for BL Lac (Mac Leod *et al.* 1971). In the case of OJ 287, the delay is not given explicitly by Andrew *et al.* (1971), but from Figure 4 of their paper one can easily see that it is also of the order of one day.

For the longer term radio flux variations, the time lags observed for different frequencies range from a few days to a couple of months in the case of BL Lac (MacLeod *et al.* 1971; Andrew 1973; Ekers *et al.* 1975). These delays are in rough agreement with the predictions of expanding source models (van der Laan 1966; Rees 1966; Pauliny-Toth and Kellermann 1966) although these models meet several difficulties (see e.g., Medd *et al.* 1972; Ekers *et al.*

1974; Giacconi 1978) and certainly cannot account for delays as short as one day.

To our knowledge, there has been no satisfactory explanation of the observed delays between radio "spikes" at different frequencies. In this work, we will give an explanation to these delays in terms of dispersion by a plasma, and we shall argue that the existence of such small delays is a good evidence for the ejection from the central region of large amounts of gas at ultrarelativistic velocities.

II. THE MODEL

It is a well known fact that a plasma has the property of dispersing electromagnetic waves. In this section, we will show that, under suitable physical conditions, the plasma dispersion can account for the observed one day delays between radio "spikes" at 10.7 GHz and 6.6 GHz. Clearly, the effect will be present in the long term variations also, but there it is combined with much longer time delays predicted by well known expanding source models.

Let us consider for concreteness the case of BL Lac. From the radio observations and light travel time arguments it follows that the size of the central region which emits the radiation does not exceed a few light-weeks, whereas the occasional radio "spikes" are emitted by a region of less than a light-day. Suppose now that there is a large amount of plasma flowing from the central region, and that the radio waves received on the Earth have travelled through this plasma. Let us examine under which conditions this plasma can account for the observed time delays.

An electromagnetic wave of frequency ν travelling in a plasma of temperature $T < \sim 10^8$ °K and electron density N has a group velocity

$$v_g = (1 - \nu_p^2/\nu^2)^{1/2}, \qquad (1)$$

where the plasma frequency is $\nu_p = 8.9 \times 10^3 N^{1/2}$ Hz (c.g.s. units will be used unless otherwise specified). Two waves of wavelengths λ_1 and λ_2 emitted simultaneously, and travelling a distance l in the plasma will therefore emerge with a relative time delay

$$\Delta t \simeq 1.6 \times 10^{-24} (\lambda_2^2 - \lambda_1^2) N l \text{ sec.}, \qquad ((2)$$

the wave with shorter wavelength being the first to be received (we assume for simplicity that the plasma is homogeneous). On the other hand, a plasma with a temperature in the range 5×10^5 K – 10^8 K has an optical depth due to electron free-free transitions given by

$$\tau_\nu \simeq 4.6 \times 10^{-12} N^2 (l/\text{pc}) \nu_{10}^{-2} T_6^{-3/2} \qquad (3)$$

where ν_{10} is the frequency of the wave (in units of 10^{10} Hz) and T_6 is the electron temperature (in units of 10^6 K).

Suppose now that the dispersion of the waves is produced by a homogeneous cloud of plasma moving with velocity $-v$ towards an observer on the Earth. In the system in which the plasma is at rest the time delay, $\Delta t'$, due to dispersion is related to the delay, Δt, observed on the Earth by the relation

$$\Delta t = D \Delta t', \qquad (4)$$

where D is the Doppler factor

$$D = (1 + v/c)^{1/2}/(1 - v/c)^{1/2}.$$

Similarly the wavelength transforms as

$$\lambda = D\lambda'. \qquad (5)$$

Therefore, equation (2) must be rewritten as

$$\Delta t \simeq 1.6 \times 10^{-24} D^{-1} (\lambda_2^2 - \lambda_1^2) l' N' \text{ sec.} \qquad (6)$$

where, now, t and λ are measured in the system of reference of the Earth, and l' and N′ in the plasma system. Similarly, equation (3) must have an extra factor D^{-2} in its right-hand side. Clearly, there is no reason to expect thermodynamical equilibrium in the plasma cloud; for this reason the temperature in equation (3) must be interpreted as expressing the average kinetic energy of the electrons in the plasma rest frame. We shall explicitly assume that this energy is small compared with the rest mass energy of an electron, i.e., the internal velocity dispersion of the electrons is non-relativistic. Whatever the actual energy distribution of the electrons is, a Maxwellian distribution approximation is sufficient as long as we are interested only in order of magnitude estimates.

If two radio waves with wavelengths 4.5 cm and 2.8 cm reach the Earth with a time delay of about one day, i.e., $\Delta t \simeq 10^5$ sec., then according to equation (6) we have

$$N'(l'/\text{pc}) \simeq 1.6 \times 10^9 D. \qquad (7)$$

On the other hand, since the wave managed to traverse the plasma, necessarily $\tau < 1$, and therefore:

$$\tau \simeq 10^{-11} D^{-2} N'^2 (l'/\text{pc}) T_6^{-3/2} < \sim 1. \qquad (8)$$

Combining these last two equations, we obtain the inequalities

$$N' < 60\ T_6^{3/2}\ D \quad cm^{-3} \tag{9}$$
$$l' > 2.6 \times 10^7\ T_6^{-3/2} \quad pc \tag{10}$$

These quantities are referred to the plasma reference system. However, their product $N'l'$ (given by equation (6)) is an *invariant* quantity: it gives the number of particles in a column of unit base along the trajectory of the waves; the cross section of this column is not altered by a Lorentz contraction. From equation (6) we can calculate the mass in the column supposing that there is an equal number of protons and electrons. The result is 4×10^7 D $M_\odot/pc^2$.

At this point we can see the importance of the Doppler factor. Without it the mass of the plasma cloud would be exceedingly high if delays of about one day in radio signals are to be interpreted as due to plasma dispersion. For instance, if the plasma is at rest and distributed in a sphere of radius l, it mass would be of the order of 4×10^7 $M_\odot/pc^2$ multiplied by $4\pi l^2/3$. This gives a value higher than 10^{21} T_6^{-3} $M_\odot$!

On the other hand, if the plasma is in the form of an ultrarelativistically expanding shell, the thickness of this shell in the earthbound reference frame is $l = \gamma^{-1} l'$, where γ is the Lorentz factor corresponding to the velocity of expansion v:

$$\gamma = (1 - v^2/c^2)^{-1/2} >> 1.$$

As for the Doppler factor, it is $D \simeq (2\gamma)^{-1}$ in the case in which $\gamma >> 1$. If the radius of the plasma shell is R in the earthbound frame, then its mass is

$$M_{shell} = 4\pi\ R^2 l N m_{proton}$$
$$\simeq 4\pi\ (R/pc)^2 \times 2\,\gamma^{-1} \times 10^7\ M_\odot, \tag{11}$$

and the kinetic energy of this shell is

$$E_{shell} \simeq 4\pi\ (R/pc)^2 \times 4 \times 10^{61}\ ergs. \tag{12}$$

(It has been assumed that there is an equal number of protons and electrons; if the plasma consists of electrons and positrons the above numbers are reduced by a factor of ~ 1800).

The radius of the shell R, and its thickness l, are unknown parameters, and the best we can do is to assume that they are of the order of 10^{-1}–10^{-2} pc in order to obtain reasonable values for the mass and the energy given by equations (11) and (12). The crucial point is that, although the shell thickness l'—along the visual line— as seen in the co-moving frame is of the order of some megaparsecs, this same length as seen on the Earth is reduced by a Lorentz contraction, i.e. $l = \gamma^{-1}\ l'$. Thus, it follows from inequality (10) that, if for instance, $l \sim 10^{-2}$ pc, then necessarily

$$\gamma\ T_6^{\ 3/2} > 10^{10}.$$

Assuming the temperature to be non-relativistic ($T <\sim 10^8$ K), the Lorentz factor of the plasma must be extremely large: of order 10^7 or higher (*). The implication from equations (11) and (12) is that matter with a relatively small *rest* mass, perhaps about 10^{28} gr, is accelerated to ultrarelativistic speeds, the release of energy being about $10^{57} - 10^{58}$ ergs. (The optical appearance of the shell as seen on the Earth is that of an elongated ellipsoid of eccentricity v/c with the source at one focus, and the major axis along the visual line [Rees 1966]).

What is the subsequent evolution of the ultrarelativistic plasma cloud? *First,* if the temperature in the plasma does not exceed a few million degrees, it could be expected that the plasma emits some emission lines; these lines, however, would appear blueshifted to the hard X ray or gamma ray region. *Second,* the electrons can interact with the primeval background radiation through inverse Compton scattering. The power emitted by a single electron is $\sim 2 \times 10^{-14}\ \gamma^2$ U ergs s^{-1}, where U, the energy density of the background radiation, is about 10^{-12} ergs cm^{-3}. It follows that an electron will travel a distance of about 10^6 γ^{-1} Mpc before losing half its initial energy. The photons emitted by this process have frequencies of $\sim 10^{11}\ \gamma^2$ Hz and the flux of these photons which may be expected to be received on the Earth is $\sim 50\ \gamma\theta^2$ erg s^{-1} cm^{-2}, where θ is the angular diameter of the emitting region; this flux is too low to be detected. *Third,* if there is matter surrounding the core, such as a nebulosity or a galaxy, the ultrarelativistic electrons may lose their energy by bremsstrahlung, producing gamma rays of energy $\sim \gamma\ mc^2$ (i.e., the electron loses an important fraction of its energy). Such energetic photons will interact subsequently with the background radiation

(*) At a temperature above 10^8 the group velocity of a wave in the plasma is much closer to c than the velocity given by formula (1), which is valid for nonrelativistic temperatures only. Thus, a much larger column density Nl, would be needed in order to produce the observed time lags, and these, in turn, demand a larger length l.

to form electron-positron pairs. If the matter around the core is sufficiently dense, a relativistic blast wave is produced (Blandford and Mc Kee [1976]); in this sense, the radio wave dispersion we have proposed would correspond to the initial stages of the blast, prior to the interaction with the surrounding medium.

Finally, it is worth mentioning that the Thompson scattering in the plasma would be negligible if γ is very large. The mean free path for Thompson scattering exceeds the thickness of the shell if

$$l'N' = lN < \sigma_T^{-1},$$

where $\sigma_T = 6.65 \times 10^{-25}$ cm^2. From equation (7) it follows that this last condition is always fulfilled if $\gamma > 2 \times 10^3$.

III. DISCUSSION AND CONCLUSIONS

The observations of very short term (days) radio-variability are unique, until now, for the cases of BL Lac and OJ 287. Simultaneous observations at two or more different frequencies have been carried out since May 1967 till December 1973 for BL Lac (Medd *et al.* 1972; Andrew 1973; Altschuler and Wardle 1975; and Ekers *et al.* 1975) and from January 1970 till December 1973 for OJ 287 (Andrew *et al.* 1971; Altschuler and Wardle 1975). The most extensive monitoring has been recently published by Andrew *et al.* (1978). Their data include observations till December 1976. There is no conclusive evidence of correlation betwen radio and optical variability and recent X-ray observations of the BL Lac objects MK 421 and MK 501 (Giacconi 1978) indicate that there is no correlation between radio and X-ray fluxes. These results lead one quite naturally to two important conclusions.

First, that the phenomena at different wavelengths may be produced by independent components in the source; and second, that the very rapid radio "spike" activity must be a highly localized type of event.

Very long baseline interferometric observations made by Kellermann *et al.* (1977) have shown that this might very likely be the case for BL Lac, since it can be resolved in two separate components. The small component has dimensions of about 1 pc by 0.4 pc. This appears rather large when compared with the typical time scale of long-term variability and certainly much too large when compared with the time scale of short term variability. Nevertheless, observations made with higher resolution may well show the existence of yet smaller components, or that the variability arises in only a localized part of a component. In either case the expanding ultrarelativistic diluted plasma discussed previously would surround the component of the core responsible for the observed variability. The delays produced by dispersion of plasma of the type discussed above depend on the frequencies that are compared. Hence, it should be possible to check the model in the future if simultaneous observations at other near frequencies (e.g., 8 GHz) of the same type of phenomena become available.

BL Lac is by far the best studied object of this type. It would be important to carry out VLBI observations of other objects (especially OJ 287) and to search for radio "spikes" from 0048-09, an object which is very similar to OJ 287 and BL Lac but has been less observed.

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