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The evolution of GHz-peaked-spectrum radio sources

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Abstract. Observations of extended radio emission in some GPS sources suggest that they may not be a young version of the classical doubles. The compact source would be confined by the presence of a dense medium in the center of the galaxy. The existence of such a dense environment is supported by the observation of disturbed optical morphologies indicating galaxy-galaxy interaction or mergers. A simple model is formulated to calculate the velocity of advance of the jet as it propagates in a cloudy medium. Different forms of interaction of the jet with the clouds are studied as well as the distribution of gas and clouds on scales smaller than 1 kpc around the central engine. It is found that the age of these GPS sources is of the same order as that of the extended radio sources and that the jet propagates either by scattering clouds or by drilling its way through them.

Key words: quasars: general – galaxies: jets

1. Introduction

Extragalactic radio sources are observed with a wide range of size spanning from tens of parsec up to megaparsecs and with a variety of morphological forms and spectral shapes. Different classification schemes are possible depending on which aspect is chosen to describe them. Thus, one has extended and compact sources according to their size, double, triple or core-jet according to the emission distribution in radio maps and flat or steep spectrum, simple convex, or complex spectrum. Usually one designates compact those sources that are observed at sub-arcsecond to arcsecond scale. Two classes of compact sources are of particular interest. They are Compact Steep-spectrum Sources (CSS) and Gigahertz-Peaked-Spectrum (GPS) radio sources.

The first are compact objects of sub-galactic dimensions with angular size $\lesssim 1$ arcsec. They have a steep high frequency spectrum, the spectral index being $\gtrsim 0.5$, hence the name, Compact Steep-spectrum Sources (Pearson et al., 1985; Fanti et al., 1989, 1990). The morphological structure resembles that of the more extended radio sources, and on scales of tens to hundreds milliarcsec, they show a double, triple, and core-jet structure.

On yet smaller scales we find the Gigahertz-Peaked-Spectrum (GPS) radio sources of typical extent of a few tens to hundreds of parsecs. Their name derives from the fact that they have a simple convex spectrum peaking around a few GHz (Gopal-Krishna et al., 1983; Spoelstra et al., 1985; Gopal-Krishna & Spoelstra, 1993). Those associated with quasars show a complex morphology in VLBI maps while sources associated with galaxies are double or triple radio sources (Phillips & Mutel, 1980, 1981; Mutel & Hodges, 1986). They have a steep spectrum at high frequencies and their low frequency spectral turnover is believed to be due to synchrotron self absorption in a compact component with a large magnetic field (Hodges et al., 1984; Mutel et al., 1985; Baum et al., 1990; O'Dea et al., 1991). They have an extremely high luminosity of order 10^{45} erg s^{-1} similar to that of many quasars. Other important properties of the GPS have been described and summarized by O'Dea et al. (1991) and recent optical observations by de Vries et al. (1995) provide identification for several GPS radio sources and in a few cases, new redshifts have been measured.

The subclass of compact sources that exhibit a double-lobed structure is called compact double (CD) and has components with similar spectral shape and flux density (Phillips & Mutel, 1982). In contrast to what happens to asymmetric sources, this symmetric structure indicates that they are not Doppler-boosted. Even so, they have luminosities comparable to the luminous, edge-brightened, extended double sources. Phillips & Mutel (1982) suggested that they are young, scaled down versions of the classical double sources of Fanaroff-Riley class II type. Although recent observations have shown that some apparent compact doubles are in fact asymmetric core-jet sources, Wilkinson et al. (1994) have confirmed the existence of a class of objects that they call Compact Symmetric Objects (CSO). They present two-sided ejection on scales of ~ 100 pc and are intrinsically very luminous since there is no indication of relativistic beaming. The CSOs would be associated with subclass CD of the GPS objects.

Apart from the different scale size, there are many similarities between the GPS sources and CSS. It has been suggested that the CSS sources are just larger versions of the GPS sources with the latter evolving in time into the CSS (Mutel & Phillips,

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1988). Other authors however believe that the CSS sources are of sub-galactic size because they become trapped near the galactic center due a high density medium that they would encounter there (Fanti et al., 1990; O'Dea et al., 1991). Recently Fanti et al. (1995) have studied a sample of double-lobed CSS with linear sizes of a few kpc, which in analogy with the name CSO, they named MSOs (Medium-sized Symmetric Objects). They conclude that these are young objects with ages of $\sim 10^6$ years and are the precursors of the extended double radio sources.

We have presented a model (Carvalho, 1985) in which we show that the properties of the CD sources are consistent with the "youth scenario". With ages less than 10^4 yr and having a sub-galactic extent of < 1 kpc, the CD's are very young radio sources that evolve into extended FR II radio sources on time scales of $10^6 - 10^8$ yr. O'Dea et al. (1991) suggested that this scenario also would apply to most GPS sources with galaxy identifications. Mutel & Phillips (1988) used this model to show that there exists an evolutionary sequence from compact doubles (CD) to compact steep-spectrum sources (CSS) to extended classical doubles.

More recently, Readhead et al. (1996a) proposed a classification scheme for symmetric sources based on their linear size. According to this the CSO would be objects < 1 kpc, the MSO would have sizes in the range $1 - 15$ kpc while they have called the more extended sources (> 15 kpc) "Large Symmetric Objects" or LSO. These three classes all have common properties, that is, high luminosity, symmetric structure and are manifestations of the same type of objects seen at different epochs of their evolution, as has already been proposed by Carvalho (1985) and Mutel & Phillips (1988). The work by Bicknell et al. (1997) adopts the view that the GPS and CSS sources and CSO are the same sort of object and proposes a single model which explain their radio spectra and optical emission.

There are, however, indications that at least a fraction of the GPS sources may not be as young as initially thought. For instance, Baum et al. (1990) detected extended emission on scales of tens of kpc from the nucleus of 0108 + 388. Other observations by Stanghellini et al. (1990) showed that about 20% of the GPS sources present a diffuse extended radio emission though more recent results indicate that this number could be lower, in the range $5 - 10\%$ (Stanghellini et al., 1997). Baum et al. (1990) proposed that in these sources the nuclear activity is a recurrent phenomenon, the diffuse emission being the relic of a previous activity while the compact GPS source would be the product of a renewed activity of the host galaxy. Another possibility is that the galaxy has suffered a recent and sudden increase in the gas density near the center due to an interaction or merger with a gas rich companion. The radio source has been smothered by the dense and clumpy gas that keeps the source confined to the nuclear region. In that case the GPS sources would not be young objects but have ages comparable to the extended doubles.

Indeed, recently Stanghellini et al. (1993) have made CCD images of a group of GPS sources and found disturbed optical morphologies and the presence of dust, suggesting that mergers and galaxy-galaxy interaction play an important role in these objects. A more recent analysis made by O'Dea et al. (1996) of a sample of forty GPS radio galaxies shows that 57% of them have distorted isophotes. They found that a large fraction of the GPS sources exhibits evidence for interaction and/or mergers. This corroborates the hypothesis that this subclass of GPS sources is confined in the dense nuclear region. Saikia et al. (1995) have investigated the symmetry parameters of a sample of CSSs and compared with those of extended sources. They found strong evidence of intrinsic asymmetry in the environment in many sources and on all scales. The effect, though, is more pronounced in the small objects where the jets propagate through an asymmetric medium probably suffering collisions with dense clouds. The existence of such a cloudy environment has recently been well establish by de Vries et al. (1997) through the discovery of the alignment between the optical and radio emission in CSS sources.

On the other hand, De Young (1991) showed, through hydrodynamical simulations of the interaction of a jet with a dense cloud, that this can be an efficient way to decelerate the jet. Following the encounter with a heavy intergalactic cloud, the jet velocity decreases drastically while the cloud is partially destroyed by the jet. Therefore, the propagation of the GPS sources in a very cloudy medium will be slow and consequently the age will be larger than that deduced from a uniform medium (O'Dea et al., 1991). We have recently developed a very simple analytic model for the jet propagation in a clumpy medium (Carvalho, 1994). A rough estimate of the age, taking the propagation velocity of the jet to be constant, already indicates values of around 10^6 yr, which is of the same order as the age of the extended sources. Here we shall discuss a more detailed model taking into account the variation of the propagation velocity with the distance from the central object, different modes of interaction of the jet with the clouds and other aspects of the jet propagation. We compare three forms of motion of the jet, namely scattering by heavy clouds (Model A), drilling through the clouds (Model B) and propagation in a dense uniform medium (Model C). As we shall see, the real situation is more likely to lie between Models A and B. In Sect. 2 we study the propagation of the jet in a medium filled with clouds and describe two of the models. In Sect. 3 we give the basic expressions of the jet motion in a homogeneous medium. Sect. 4 examines the matter distribution around the center of the galaxy and in the near intergalactic medium, while in Sect. 5 the age of the GPS sources is calculated using the proposed models. Finally, in Sect. 6 we give the main conclusions.

2. Jet Propagation in a Clumpy Medium

The interaction of an extragalactic jet with dense clouds has been studied by De Young (1991, 1993) through a series of hydrodynamical simulations. As we said previously, we shall try to build an analytical model that, in spite of its simplicity, is able to describe the phenomenon reasonably well. We shall investigate two possibilities, the first one being that during the collision both the cloud and jet behave as if they were solid bodies and are scattered one by the other (Model A). In that case one can treat the problem as an elastic shock.

The second possibility (Model B) is that the jet crosses the cloudy medium by drilling its way through the clouds. One may expect this seeing that the jet cross-section is in many cases much smaller than the cloud cross-section and thus, the low density and high velocity stream of particles will just penetrate the much heavy cloud without affecting too much its structure or moving it from its initial position. Of course the real situation should be a compromise between the two extremes just described although, as we argue below, it resembles the first one more closely.

2.1. Model A: Jet-cloud scattering

That the clouds are partially deflected by the jet can be seen from the numerical simulations by De Young (1991), although they refer to clouds at a distance of a few kpc from the galaxy, the scale being bigger than the one envisaged here. For a cloud large compared with the size of the jet, during the first moments of the collision we see that the behavior of the cloud is approximately that of an almost rigid body being struck by a much smaller mass. After some time, the part of the cloud that has interacted more directly with the jet suffers considerable erosion. By then, the cloud has already moved a distance greater than its radius perpendicularly to the jet trajectory and the path of the jet is almost free. If the size of cloud is of the same order as the jet radius, although considerable erosion takes place at a much early time, the cloud still moves aside. It is thus reasonable to assume as a rough approximation that the interaction between the jet and cloud can be described as an elastic shock.

Let us suppose that in the uniform intercloud medium the jet propagates with velocity V_j determined by the balance between the ram pressure and internal pressure. We shall assume a spherical shape for the cloud and that it is initially at rest. If its mass is M and m is the mass of the jet that takes part in the collision, the velocity of the cloud after the collision will be

$$V = \frac{2}{1+\mu} V_j \cos\theta. \tag{1}$$

Here $\mu = M/m$ and θ is the angle between the velocity V and the direction of propagation of the jet. In order to estimate the mean velocity of the jet going through many encounters like these with a cloud, we must first calculate the characteristic time τ of the collision. Since this is essentially the time it takes for the cloud to move a distance equal to $R_c - b$, where b is the impact parameter and R_c its radius, we have

$$\tau \simeq \frac{R_c}{V} \frac{R_c - b}{b}.$$

From Eq. (1) we obtain

$$\tau \simeq \frac{\mu R_c}{2V_j \cos\theta} \frac{R_c - b}{b}, \tag{2}$$

where we assumed that the cloud is much heavier than the jet, that is, $\mu \gg 1$.

The masses entering in μ are the mass of the cloud $M = 4\pi R_c^3 m_H n_c/3$ and that of the jet, which can be estimate from the expression $m \simeq \pi R_j^2 m_H n_j V_j \tau$. Here R_j and n_j are respectively the radius and density of the jet, n_c the cloud density and m_H is the mass of the hydrogen atom. Substituting M and m in (2) we obtain the collision time

$$\tau \simeq \tilde{\alpha} \frac{R_c^2}{R_j V_j} \left(\frac{n_c}{n_j}\right)^{\frac{1}{2}}, \tag{3}$$

The factor $\tilde{\alpha}$ comes from averaging τ over the values of the impact parameter b from $R_j/2$ to R_c. It is weakly dependent upon the ratio R_j/R_c and, for instance, for $R_j/R_c = 0.02$ we have $\tilde{\alpha} \sim 0.58$.

Supposing now that the jet encounters on average λ clouds per unit length, and under the simplifying assumption that it stays at rest during the collision, which is a good approximation provided $\mu \gg 1$, then the average propagation velocity of the jet is given by

$$V_A = \left[1 + \tilde{\alpha} R_c \lambda \frac{R_c}{R_j} \left(\frac{n_c}{n_j}\right)^{\frac{1}{2}}\right]^{-1} V_j. \tag{4}$$

2.2. Model B: Jet perforates clouds

The second possibility referring to the jet-cloud interaction corresponds to the other extreme situation in which the jet perforates the cloud. In this case the jet is decelerated when going through the cloud just by the fact that the density is increased as compared with that of the ambient medium. Let V_B be the velocity of the jet in a medium filled with clouds whose density is n_c. If the jet encounters λ clouds per unit length, then the average velocity V_B is given by

$$V_B = \left(1 + \frac{\pi}{2} R_c \lambda \left[\left(\frac{n_c}{n_e}\right)^{1/2} - 1\right]\right)^{-1} V_j \tag{5}$$

where n_e is the density of the external medium and the factor $\pi/2$ comes from averaging over all values of the impact parameter. It is interesting to note that the factor $R_c\lambda$ does not depends explicitly on the radius of the cloud (see Eq. (11) below) and therefore, V_B is independent of R_c as well.

As we shall see later in Sect. 5, this situation is not equivalent to the case where the propagating medium, although homogeneous, has a high density equal to the mean density obtained by spreading the clouds uniformly (Model C).

3. Motion of the jet in a uniform medium

Suppose that the jet propagates under ram pressure equilibrium with the external medium. Its velocity V_j in a uniform medium can be calculated from

$$m_H n_e V_j^2 \simeq \frac{1}{3} u,$$

where n_e is the medium density and u the jet internal energy density. If the central engine supplies energy to the jet at a rate L (erg s^{-1}) we have (Scheuer, 1974; Carvalho, 1985)

$$V_j = \left[\frac{2a+1}{3} \frac{L}{m_H c n_e \Omega_o R_o^2}\right]^{\frac{1}{2}} \left(\frac{R}{R_o}\right)^{-a}. \tag{6}$$

Here R is the distance from the center of the host galaxy, c is the velocity of light and Ω_o is the jet solid angle at a reference distance R_o. In the above expression we also take into account a non-linear dependence of the radius of the jet on the distance R according to the law

$$R_j = \left(\frac{\Omega_o}{\pi}\right)^{1/2} R_o \left(\frac{R}{R_o}\right)^a ,$$

where $a \leq 1$ is a free parameter.

It has now been well established that in order to explain the evolutionary sequence in which compact symmetric sources evolve into medium-sized and later into large symmetric objects, some sort of luminosity evolution has to be taken into account (Carvalho, 1985; Fanti et al., 1995; Readhead et al., 1996b). More recently O'Dea & Baum (1997) have studied a combined complete sample of GPS and CSS sources. They concluded that they evolve in a different way than the extended classical doubles as they undergo strong luminosity evolution. However, this is expected to happen for sources larger than $\sim$ 1 kpc or, equivalently, for times greater than $t \sim 10^5$ yr when the luminosity should decrease as $t^{-\delta}$, where δ is a constant. Therefore, this will only affect the compact GPS sources to a small extent and, to avoid the introduction of a new parameter into the model we assume that the power supply L is constant.

Of course, the model is not realistic enough to cope fully with the physics on the parsec scale encountered in compact sources and (6) may give too large a value for the velocity. This is due to the fact that the jet geometry yields an extremely high energy density near the central object because its volume tends to zero. In order to overcome this problem we limit our calculations to a region $R \geq R_m$ and choose R_m = 1 pc. At this distance the velocity attains its maximum value V_M, which for powerful classical doubles is or the order of $\sim \frac{1}{3}c$. Now, if we substitute R_m and V_M into (6) we obtain the minimum value of the jet opening angle at R_o which ensures that V_j is always less than V_M.

Another problem arises at large distances R. Depending upon the value of $a < 1$ and on how fast the density decreases, there could be a region where the jet speed increases with distance from the central object. This happens because, besides encountering less resistance from a medium whose density decreases rapidly, the high collimation of the jet is maintained since a is kept constant. Would there be any observational evidence for such an increa.se of the jet velocity? Indeed, according to Fanti et al. (1995), the linear size distribution for steep spectrum sources can be fitted by a power law of the type $dN/dD \propto D^{-m}$, where $m \simeq 0.65$. This includes compact sources with size $D \gtrsim$ 300pc. They conclude that the expansion velocity of the sources should increase with their size, being proportional to D^m.

Provision has to be made in the model to avoid that the velocity exceeds V_M at larger R. However, due to the form of the gas density distribution that we shall use (Eq. (9) below), this increasing of the jet speed only occurs in a small interval of distances around 100 pc and for $R > 10$ kpc, which is already out of the size range of the compact sources. Therefore, in order to make the model as simple as possible, we just choose Ω such that the velocity is less than V_M for most of the range of values of R and limit it to V_M otherwise. For instance, if for a = 1, Ω_o is calculated by substituting R_m and V_M into (6), for a = 0.5 we have to take Ω_o two times greater than the value calculated in this way.

Finally, the density of the jet n_j can be estimated by equating its internal energy density u to $n_j m_H v_i^2$ and supposing the internal jet speed $v_i \sim c$. We then obtain

$$n_j = \frac{2a+1}{3} \frac{L}{m_H c^3 \Omega_o R_o^2} \left(\frac{R}{R_o}\right)^{-2a} . \quad (7)$$

Apart from a numerical factor of order unity, an identical expression is reached using Eq. (2.1) of Begelman et al. (1984), for the case in which the internal speed is much larger than the speed at which the jet advances through the medium.

4. Matter distribution

Here we discuss the matter distribution of both the uniform and cloudy medium through which the jet propagates as well the density and characteristic size of the clouds. The density distribution of extensive halos around giant elliptical galaxies follows a general law of the type

$$n_e = N_c \left[1 + \frac{R^2}{R_h^2}\right]^{-\beta} , \quad (8)$$

where $\beta \simeq 0.75$ and N_c is the density at the galactic center (Forman et al., 1985). If we put $R_h = 1 - 2$ kpc for the characteristic radius and $N_c \simeq 1\,\mathrm{cm}^{-3}$, then n_e will represent the density distribution around an extended source. This distribution should be appropriate to study the propagation of the jet outside the galactic central regions. It has been used in a simplified form by Fanti et al. (1995) in the case of kiloparsec-sized steep-spectrum sources. However, in the case of compact sources, the distances from the central object are much smaller, of the order of tens of parsec and one expects the density to be higher. Therefore, we add a second, short-scale height component, which enables us to describe the motion of the jet near the galactic center. In this case one would take $N_c \simeq 10^3\,\mathrm{cm}^{-3}$ and a characteristic radius $R_h \simeq 2$ pc. Therefore the density distribution has the form,

$$n_e = 10^3 \left[1 + \frac{R^2}{(2\,pc)^2}\right]^{-\beta} + \left[1 + \frac{R^2}{(2\,kpc)^2}\right]^{-\beta} cm^{-3}, \quad (9)$$

Consider now a cloudy medium surrounding the central object. Not much information exists on the distribution and structure of the clouds. Assuming that the galaxy has suffered an increase in the gas density due to an interaction or merger with a gas-rich companion, we suppose that this gas will form clouds that will be distributed around the central object up to an outer radius R_2. An inner boundary R_1 of the cloud distribution must also exist if the individual clouds are to be stable against tidal forces. If, for instance, the mass of the central object is of the order of $10^8 M_\odot$ the lower limit of R_1 is $\sim$ 3 pc otherwise the density of the clouds will be much greater than $10^8\,\mathrm{cm}^{-3}$.

We shall suppose that the clouds' contribution to the mean density is also given by the general law (8) but with a much smaller value of R_h, around $\sim$ 5 pc and $N_c \simeq 10^{4-5}$ cm^{-3}. We shall call this density n_{ec}. It is given by

$$n_{ec} = 10^{4-5}\left[1 + \frac{R^2}{(5\,pc)^2}\right]^{-\beta} cm^{-3}\ for\ R_1 < R < R_2 \quad (10)$$

and

$$n_{ec} = n_e \qquad \text{otherwise.}$$

The outer radius R_2 of the cloud region can only be estimated roughly and should not be much larger than the galaxy central region. One constraint to R_2 is the total mass present inside the cloudy region. If we take this to be $\sim 10^{9-10} M_\odot$ then for the value of N_c above one must have R_2 in the range $200 - 500$ pc. We therefore take a characteristic value R_2 = 300 pc as a lower limit.

The number of clouds per unit length λ and the internal density of the clouds n_c should be such that the mean density n_{ec} of the ambient medium is achieved. The average number of λ clouds per unit length is then given by

$$\lambda = \left(\frac{m_H n_{ec}}{M}\right)^{1/3}.$$

Since the linear density λ always appears multiplied by R_c we also give the expression

$$R_c\lambda = \left(\frac{3n_{ec}}{4\pi n_c}\right)^{1/3}, \quad (11)$$

where n_c is the particle number density of the cloud. We assume that n_c depends on the distance from the central object. For instance, in the case of dense, self-gravitating clouds, if they were to be stable against tidal disruption, one would have $n_c \propto R^{-3}$. Since other factors also may come into play, we generalize this and use the following parametrization

$$n_c = \tilde{n}\left(\frac{R}{R_1}\right)^{-\gamma} \quad (12)$$

where γ is a free parameter in the range 0-3. The value of $\tilde{n}$ depends on the mass of the central object M_N and of the radius of the inner boundary of the cloud distribution R_1 and it is given by

$$\tilde{n} = \frac{9}{4\pi}\frac{M_N}{m_H R_1^3}. \quad (13)$$

This expression ensure that the cloud will always withstand tidal forces at $R \geq R_1$.

Finally, the radius R_c of the clouds should not be constant so that we allow for a linear increasing with the distance R, that is,

$$R_c = R_{co}\left(\frac{R}{R_o}\right). \quad (14)$$

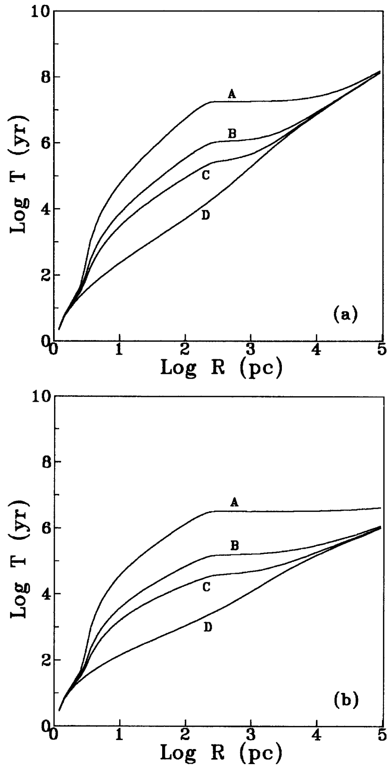

Fig. 1a and b. Age of GPS sources as a function of the jet size. The labels A, B, C and D correspond to the models described in the text. The values of the parameters are γ = 0, $L = 10^{44}$ erg s^{-1}, R_{co} = 8 pc and **a** a = 1 and **b** a = 0.5.

5. The age of the sources

In this section we determine the dynamical age of the sources as a function of its size, that is, the distance R of the hot spot to the central object. This is given by

$$T_i = \int_{R_m}^{R}\frac{dR'}{V_i}.$$

The lower limit R_m = 1 pc is quite appropriate considering that our attention will be focused on compact sources whose size is in the range 20 - 100 pc.

In the case of a cloudy medium, the age of the source when the jet scatters the clouds (T_A) is obtained substituting the velocity V_i in the above expression by Eq. (4). For the case where the jet perforates the clouds the age T_B is obtained by using Eq. (5) for the velocity V_i. In order to evaluate how effective the clouds are in decelerating the jet, we also study the propagation of the jet through a massive but uniform medium whose density is equivalent to that of the clouds (Model C). In this case an age T_C is obtained when the velocity V_i is given by (6) but with the external density n_e being substituted by n_{ec}. Finally, the age T_D of a source propagating through a low density medium is also calculated and should represent the age of an extended source. In this case the velocity is just given by Eq. (6).

In what follows we evaluate the age as a function of the size of the source for different values of the parameters. As far as the

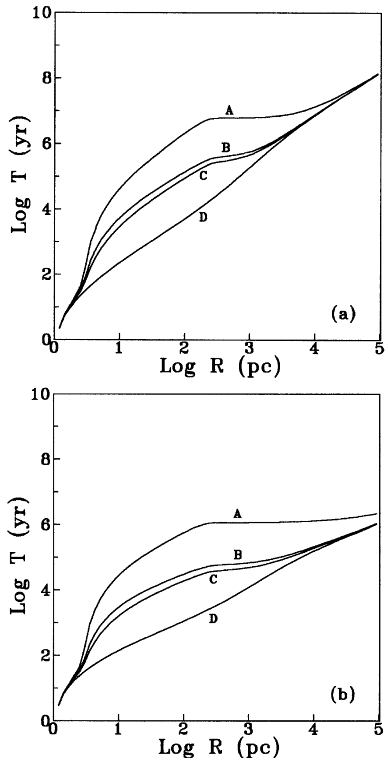

Fig. 2a and b. As in Fig. 1 but for γ = 2.

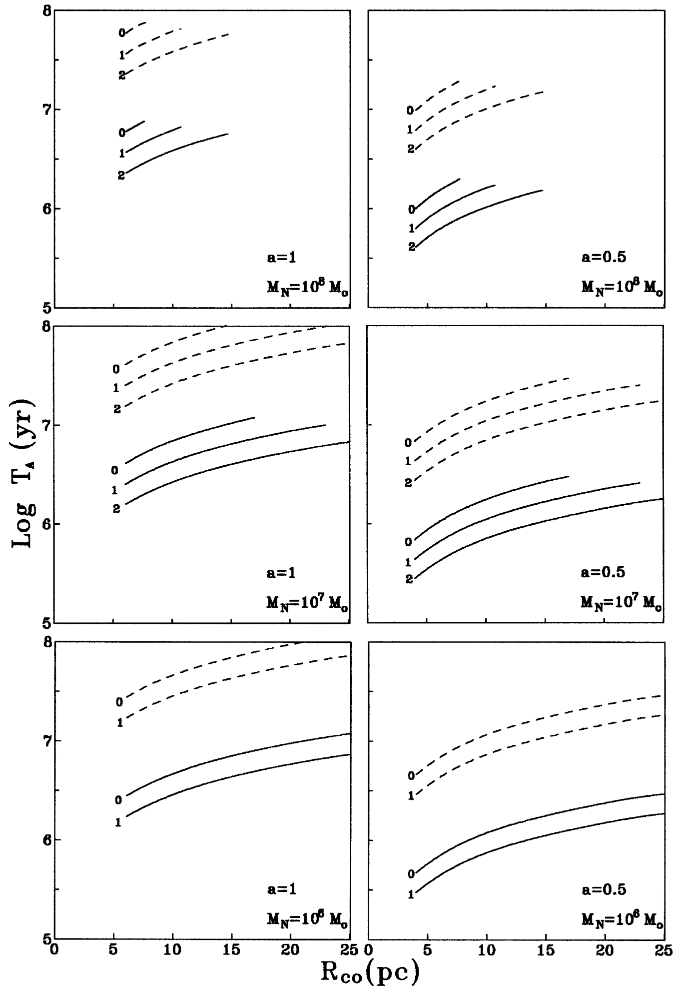

Fig. 3. Age of GPS sources in Model A for R = 100 pc as a function of the radius of the clouds at R_o = 100 pc. The labels 0, 1 and 2 are the values of the parameter γ and solid and dashed lines correspond to L = 10^{44} and 10^{43} erg s^{-1} respectively.

geometry of the jet is concerned we make a = 1 and 0.5, with the parameter determining the density within the clouds γ = 0, 1 and 2. The characteristic luminosity of the central engine L = 10^{43} and 10^{44} erg s^{-1} and its mass M_N = $10^{6-8} M_\odot$. The radius R_{co} of the clouds at the reference radius, which we put R_o = 100 pc, is picked in the range 1 - 25 pc.

Of course, the combination of all these parameters will not always give a physically meaningful picture. For example, it may happen that the number of clouds in the line of sight up to a distance R, that is $N_L(R) = \int_{R_1}^{R} \lambda dR'$, is either too small and there could be no collision of the jet with them, or that it is so large that the clouds will overlap. To avoid this we require that, on the one hand, the jet has encountered at least one cloud when it grows to a size of 20 pc ($N_L(R = 20pc) > 1$) and, on the other hand, that $R_c\lambda$ is always less than 0.5. We also require the ratio between the radius of the jet and that of the cloud to be less than 1/2. Thus, although the parameters are in the range given above, some combinations of them will not appear in the results we give below.

In Fig. 1a and 1b we show the results for a = 1 and a = 0.5 respectively and for γ = 0, L = 10^{44} erg s^{-1}, M_N = $10^7 M_\odot$ and R_{co} = 8 pc. The first thing to note is the effectiveness of the clouds in slowing down the jet. As it enters the cloudy region that lies between 3 and 300 pc the age of the source increases significantly. We see how Model A, in which the jet scatters the clouds, is much more effective ($T_A > T_B$) than Model B where it perforates them. We also note that both Models A and B are better than the uniform, high density model (T_C). For instance, in sources whose distance of the hot spot to the central object is 100 pc, T_A is approximately 5.5×10^6 yr and $T_B \simeq 3.4 \times 10^5$ yr while $T_C \simeq 8.7 \times 10^4$ yr. If there is no density enhancement due to the clouds the age would be $T_D \simeq 5 \times 10^3$ yr. As one would expect, whereas T_A is more than one order of magnitude greater than T_B, Model B gives an age not too different of Model C although still a few times greater.

The ages are generally smaller for a = 0.5 than for a = 1. In Fig. 1b we have for R = 100 pc, $T_A \simeq 1.4 \times 10^6$ yr, $T_B \simeq 7.1 \times 10^4$ yr, $T_C \simeq 1.9 \times 10^4$ yr and $T_D \simeq 1.1 \times 10^3$ yr. The main reason is that the jet with a = 0.5 is more collimated ($\Omega \sim 3.6 \times 10^{-5} sr$) than in the case a = 1 ($\Omega \sim 2.7 \times 10^{-3} sr$) and advances more rapidly trough the medium.

Figs. 2a and 2b show the age respectively for a = 1 and a = 0.5 but now for γ = 2. The ages are smaller by approximately a factor 2.5, being $T_A \simeq 2.1 \times 10^6$ yr and $T_B \simeq 1.3 \times 10^5$ yr for a = 1 and $T_A \simeq 5.6 \times 10^5$ yr and $T_B \simeq 3.0 \times 10^4$ yr for a = 0.5. This illustrates how the radial distribution of the density of the clouds affects the age. From Eq. (12) we see that, if γ = 0, the

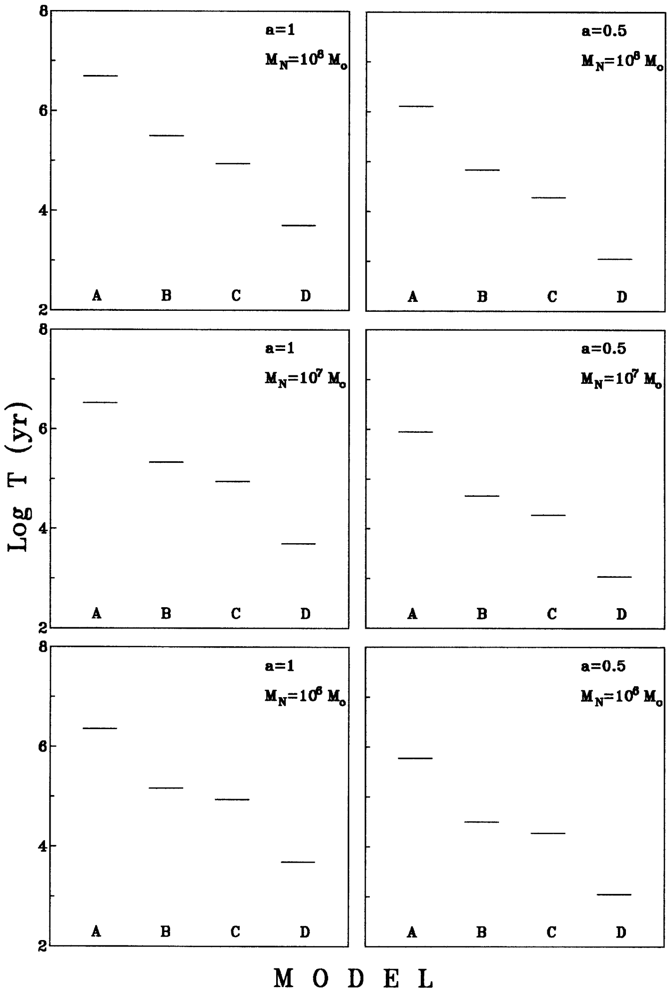

Fig. 4. Age of GPS sources for R = 100 pc in models A, B, C and D described in the text. The parameters are γ = 1, L = 10^{44} erg s^{-1} and R_{co} = 8 pc.

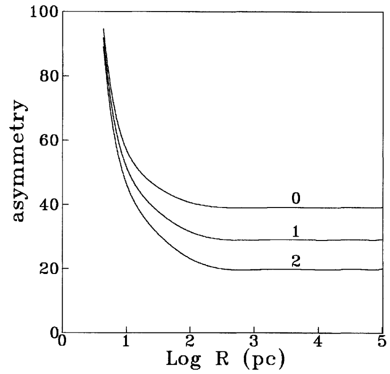

Fig. 5. Fractional fluctuation in the number of clouds with which the jet collides ($100/\sqrt{N}$) as a function of the jet size. Labels 0, 1 and 2 are the values of the parameter γ.

density of the clouds is constant throughout the entire region and they will be more efficient in braking the jet even at large distances from the center. On the other hand, for γ = 2 the clouds become rapidly less dense as R increases and the jet will be able to maintain its velocity much longer, resulting in a lower age. As we mentioned before, this should be a more realistic case since γ = 2 is closer to the theoretical value (γ = 3) for which tidal disruption of the cloud can be avoided. Comparing Figs. 1 and 2 we also observe that the difference between Models B and C becomes less pronounced as the value of γ increases.

Therefore, the group of GPS sources like 0108 + 388 that have, beside the compact structure on the tens of parsec scale, an extended emission suggesting ages $> 10^6$ yr, may well be explained by a model lying between the two extreme cases represented by our Model A and B.

On the other hand, we see that the high-density uniform model (Model C) gives for a = 0.5 ages around 10^4 yr which is compatible with that found by Readhead et al. (1996a) for 2352 + 495. For this "compact symmetric object" that has an overall size 120 pc (R = 60 pc), they estimated an age of 10^4 yr assuming that the jet has a low velocity of 0.02c and is being confined by a uniform cloud 200 pc in radius whose density is $\sim$ 10 cm^{-3}. This is almost equivalent to our Model C where the jet advances at an average velocity of approximately 0.04c between 3 and 300 pc and the density at 100 pc is $\sim$ 12.5 cm^{-3}.

Curves C and D of Figs. 1 and 2 should represent the evolution of more extended ($>$ 15 kpc) sources. Indeed, for R = $10^4 - 10^5$ pc the age is around $10^6 - 10^8$ yr. However, as we have already pointed out in Sect. 3, we did not take into account the variation of luminosity with the age of the source as one must expect after 10^4 yr, that is $\gtrsim$ 1 kpc (Carvalho, 1985; Fanti et al., 1995; Readhead et al., 1996b). Thus, extrapolating the models to sources larger than 1 kpc must be done with caution.

In Fig. 3 we give an overall view of the age of a 100 pc source in Model A as a function of the radius of the clouds at R = 100 pc, that is, R_{co}, and how it depends upon the different parameters. The curves begin or finish at distinct values of R_c to satisfy the constraints mentioned early in this section. As we have already seen, the effect of increasing the parameter γ is to decrease the age of the source. As for the luminosity L, the less powerful the central object is the more the age increases, since according Eq. (6) the jet advances more slowly into the medium. The figure also shows how the mass of the central object affects the age. A large value of M_N allows the existence of denser clouds as suggested by Eqs. (12) and (13), which in turn will decelerate the jet more efficiently. Seemingly, the age goes up if one increases the radius of the clouds as we must expect. Models B, C and D do not depend on the size of the cloud and in Fig. 4 we compare their ages with that of Model A calculated for $R_{co} = 8\,pc$, again for a source whose hot spot is at 100 pc from the galactic nucleus. The figure shows the ages in the various models for a = 1 and a = 0.5 and for M_N varying in the range $10^6 - 10^8 M_\odot$. Here, L = 10^{44} erg s^{-1} and γ = 1.

6. Conclusion

Saikia et al. (1995) have found evidence for a more pronounced intrinsic asymmetry in steep spectrum sources with small linear size. This could be related to the non-homogeneities of the medium in which the jets propagate. In this respect, and if this trend is observed down to the scales of 10-100 pc of the compact GPS sources that we are dealing with, one can speculate whether it has to do with the possibly different number of clouds with which the two jets will collide in their way out from the central object. The asymmetry parameter should be proportional to the fractional fluctuation in the number of clouds dN/N that is equal to $1/\sqrt{N}$. In Fig. 5 we have plotted $100/\sqrt{N}$ as a function of R for $M_N = 10^7 M_\odot$, $R_{co} = 4$ pc and $\gamma = 0, 1$ and 2. We see that for small R the fluctuation is large and decreases as R increases until it reaches an asymptotic value for $R > R_2$, that is, outside the cloud region. This is expected since the number of clouds the jet encounters is small near the nucleus and increases progressively as it advances through the cloudy medium. We conclude that the model predicts that sources of small size ($\lesssim 100$ pc), being confined by a cloudy medium, should present a more accentuated asymmetry than the bigger ones.

The scenario presented here is one in which a subclass of the GPS radio sources can be confined near the nucleus of the host galaxy after an increasing of the gas density around the central engine has taken place, mainly in the form of clouds. The diffuse outer regions observed around some of them are the remains of the extended radio lobes that fade as their energy supply has been interrupted.

We have proposed three models for the motion of the jet near the galactic nucleus. The jet would propagate either by scattering dense clouds (Model A) or by drilling through the clouds (Model B). These turn out to be quite efficient ways to confine the jet with the result that the age of GPS sources smothered in a dense clumpy medium is of the same order as the age of the extended sources. A dense but otherwise uniform medium (Model C) will confine the et less efficiently. We have also discussed how these results are affected by the various aspects of the model like source power, jet opening angle, mass of the central object and radius and distribution of clouds. Although Models A and B are very schematic, they should represent limiting cases and we expect the real situation will lie between these two extremes. They predict that a subclass of GPS object are confined by a cloudy medium and are as old as the extended classical double, having ages of the order of 10^6 yr.

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