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Beaming and precession in the inner jet of 3C 273

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Abstract. We have investigated the effects of precession in the inner jet of 3C 273 on its beaming properties and high energy emission. We have used all available VLBI data to determine the kinematic evolution of the jet. The position angles, velocities and formation epochs of different superluminal components are consistent with a precessing inner jet. The time-dependence of the Doppler factor for this jet was computed and the implications for the γ-ray emission are discussed. Additionally, the model, when considered along with simultaneous radio and X-ray variability observations, provides an upper bound to the possible values of the Hubble constant ($H_0 < 80\,\mathrm{km\,s^{-1}}$ Mpc^{-1}).

Key words: galaxies: jets – galaxies: quasars: individual: 3C 273 – gamma rays: theory – radio continuum: galaxies

1. Introduction

The existence of relativistic bulk velocities in the inner jets of radio-loud AGNs is a well accepted fact. It is mainly supported by observations of apparent superluminal velocities of the individual features present in the jets and by the inferred brightness temperatures, sometimes exceeding the inverse Compton limit of 10^{12} K (Rees 1966, Blandford & Königl 1979). The occurrence of superluminal velocities requires small angles between the jet and the line of sight, but their actual values depend also on the unknown Lorentz factor γ of the bulk motion of the relativistic flow in the jet.

Beaming was also postulated to explain other characteristics of AGNs, like the relatively low intensity of the measured X-ray fluxes when compared to values predicted for the synchrotron self-Compton emission (see, for instance, Marscher 1987). The ratio of X-ray to radio flux densities in a jet with viewing angle ϕ provides only a lower limit for the Doppler factor $\delta = [\gamma(1 - \beta\cos\phi)]^{-1}$, since other processes could also contribute to the X-ray emission (Walter & Courvoisier 1992). Other sources of uncertainty in the determination of this lower limit are the small number of simultaneous observations at X and radio wavelengths and the lack of knowledge of the exact frequency of radio turn-over as well as of the actual size of the emitting region.

In the last seven years the Energetic Gamma Ray Experiment Telescope (EGRET) on board the Compton Gamma Ray Observatory (CGRO) has detected high energy ($E > 100\,\mathrm{MeV}$) emission from several dozens of flat-spectrum extragalactic radio sources (e.g. von Montigny et al. 1995, Mattox et al. 1997, Punsly 1997). Most of these objects (usually named ‘blazars’) are confirmed superluminal sources and known for displaying strong variability across the entire electromagnetic spectrum (e.g. von Montigny et al. 1997). The γ-ray blazar emission must be generated in the relativistic jet, otherwise $\gamma\gamma$-pair production attenuation should be observed. From the condition of small optical depth for pair production and variability timescales, γ-rays provide an alternative way to estimate a lower limit to δ. Unfortunately, just a few of the detected blazars have measured timescales for variability.

It was shown recently that the kinematic behavior of the superluminal features in some quasars and BL Lac objects like 3C 279 and OJ 287 can be explained in terms of a precessing jet, in which case the Doppler factor of the relativistic flow could vary (due to changes in the viewing angle ϕ) with large amplitudes within the same object (Abraham & Carrara 1998, Abraham 1998). This result was used to explain the apparent periodic variations in the lightcurves of these objects.

Since relativistic beaming is an important ingredient in all models of γ-ray production in blazars (see Urry & Padovani 1995), a detailed knowledge of the kinematic behaviour of the jet in some concrete object, which could be translated into a reliable $\delta = \delta(t)$ curve, would be a powerful tool to test the different theoretical pictures. Such insight of the jet evolution can be obtained from extensive VLBI monitoring of ejected components.

In this paper we use the available VLBI information about the well-studied quasar 3C 273 in order to detect a possible regular ejection pattern which could be related to the precession of the inner jet, and hence to be important to the X and γ-ray emission. We shall show that the data strongly support the existence of a precessing period of 16 years. Using the available radio, X, and γ-ray data we shall obtain lower limits to the Doppler factor at different epochs, and we shall show that the radio and X-ray

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observations, when considered within the context of our model, constrain the Hubble constant to $H_0 < 80\,\mathrm{km\,s^{-1}}$ Mpc^{-1}.

The structure of the paper is as follows: in Sect. 2 we introduce the relevant VLBI radio information that will be used in Sect. 3 for computing the jet parameters. Sect. 4 presents some relevant comments on beaming at different wavelengths in the framework of our model. In Sect. 5 we discuss the implications for the different γ-ray production models proposed for 3C 273. We close with some final comments and a summary.

2. The VLBI jet of 3C 273

3C 273 is one of the most extensively studied extragalactic sources. Detailed observations have been accumulated during almost 35 years, including simultaneous determinations of its spectrum from radio to γ-ray energies (Lichti et al. 1995) and multiwavelengths variability data for equally wide energy ranges (von Montigny et al. 1997).

3C 273 has been also subject to intense VLBI monitoring since Cohen et al. (1971) measured its superluminal expansion velocity. The first hybrid maps were obtained by Readhead et al. (1979) at 10.7 GHz, and from them Pearson et al. (1981) clearly established the existence of superluminal motions in this object. Since then at least ten superluminal components, labelled from C1 to C10 according to the identification epoch, have been detected moving away from the core (e.g. Unwin et al. 1985, Biretta et al. 1985, Cohen et al. 1987; Zensus et al. 1988, 1990; Krichbaum et al. 1990, Abraham et al. 1996). Additional short-lived components almost surely have been missed during the gaps between observations. Superluminal motions can be detected up to a projected distance of $\sim 46\ h^{-1}$ parsecs from the core (Davis et al. 1991). There has been some discussion about whether the motions are ballistic or curved (e.g Zensus et al. 1988, Krichbaum et al. 1990). Analyzes of all available data (e.g. Abraham et al. 1996) show that the velocities of the individual components do not change with time, but clearly vary from one component to another, ranging from 4.9$c\ h^{-1}$ to 7.7c h^{-1}. These results seem to support a picture where the motions are ballistic at least up to distances of 15 mas.

We shall work with the hypothesis that the central engine of blazars ejects plasma at relativistic bulk velocities and relatively small viewing angles (e.g. Blandford & Königl 1979). The plasma is collimated into a jet which can be detected at parsec-scale distances from the unresolved core by VLBI techniques at cm and mm-wavelengths. It is usually thought that the VLBI core is the narrow end of the undisturbed jet flow, while the superluminal components are propagating disturbances like shock waves (e.g. Marscher 1996a,b). The term ‘inner jet’ will be used here to denote this unresolved, optically thick, innermost section of the source through which the relativistic plasma flows towards the extended mas-radio jet.

In Table 1 we summarize the main information for the different superluminal features for which high-quality data are available. We list for each component the superluminal velocity in units of c, the position angle η, the formation time t_0 and the references from which the data were obtained. The superluminal velocities were calculated from the proper motions assuming a Robertson-Walker universe with Hubble constant $H_0 = 100\,\mathrm{km\,s^{-1}}$ Mpc^{-1} and deceleration parameter $q_0 = 0.5$. The quoted errors represent the differences in the values quoted by different authors instead of the smaller formal errors obtained by model fitting the VLBI observations or adjusting straight lines to the velocity data. The position angle η of the individual components varies between $-98°$ and $-135°$. The arcsec radio and optical jet is directed towards $\eta = -138°$, imposing an additional constraint to the precessing jet amplitude. We shall use this information to reproduce the kinematic evolution of the inner jet from which the components were expelled.

Table 1. Superluminal components in the VLBI jet in 3C 273

Comp.	$\beta_{obs}(c)$	η (deg)	t_0 (years)	ref.
C2	7.7 ± 1.0	-130 ± 5	1963.0 ± 1	1,2,3
C3	5.2 ± 0.3	-118 ± 3	1970.2 ± 1	2, 4,5
C4	6.6 ± 1.0	-98 ± 4	1976.4 ± 1	2, 5, 6
C5	7.7 ± 0.5	-115 ± 4	1978.6 ± 1	2, 6
C6	7.3 ± 0.5	-134 ± 4	1980.0 ± 1	2, 5, 6
C7	5.2 ± 0.5	-135 ± 4	1983.6 ± 1	6
C8	5.4 ± 0.5	-124 ± 4	1984.7 ± 1	6
C9	4.9 ± 0.5	-114 ± 4	1988.4 ± 1	6

1: Cohen et al. (1983), 2: Biretta et al. (1985), 3: Zensus et al. (1988), 4: Pearson et al. (1981), 5: Unwin et al. (1985), 6: Abraham et al. (1996)

3. Model fitting: a precessing inner jet

In order to apply the model we shall assume that the inner jet of 3C 273 precesses with constant angular velocity ω, defining a cone of opening angle Ω. Its instantaneous axis is characterized by the viewing angle ϕ and the position angle in the plane of the sky η. Shocks are formed near the origin of the jet and will move outwards in ballistic trajectories with constant superluminal velocities. The viewing and position angles of these features will represent the corresponding angles of the jet at the epoch at which the shocks were formed. Denoting by ϕ_0 and η_0 the corresponding angles of the axis of the precessing cone, we obtain that the jet movement is described by (Abraham & Carrara 1998):

$$\eta(t) = \arctan \frac{y}{x} \tag{1}$$

$$\phi(t) = \arcsin \left[(x^2 + y^2)\right]^{1/2} \tag{2}$$

with

$$\begin{aligned} x \;=\; & (\cos\Omega \sin\phi_0 + \sin\Omega \cos\phi_0 \sin\omega t) \cos\eta_0 - \\ & - \sin\Omega \cos\omega t \sin\eta_0 \end{aligned} \tag{3}$$

$$\begin{aligned} y \;=\; & (\cos\Omega \sin\phi_0 + \sin\Omega \cos\phi_0 \sin\omega t) \sin\eta_0 + \\ & + \sin\Omega \cos\omega t \cos\eta_0 \end{aligned} \tag{4}$$

where the time is measured in the frame fixed at the central source. The viewing angle is not directly observable but it is

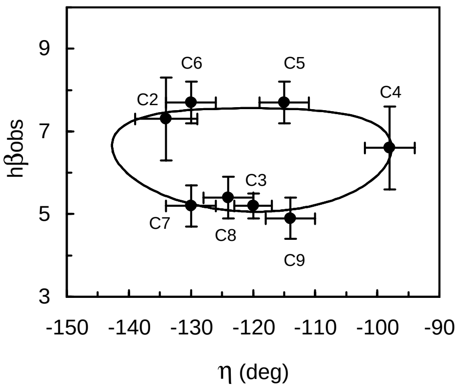

Fig. 1. Apparent velocities of the superluminal features in the jet of 3C 273 (points), scaled by the constant $h = H_0/100$, as a function of their position angles in the plane of the sky. The solid line represents the model fitting of a precessing jet, with the parameters presented in Table 2 for three values of h.

Table 2. Parameters of the precessing model

h	γ	Ω (deg)	ϕ_0 (deg)	η_0 (deg)
0.5	15.4 ± 0.7	2.8 ± 0.2	7.1 ± 0.7	−120 ± 3
0.7	10.8 ± 0.6	3.9 ± 0.5	10.0 ± 0.8	−120 ± 3
1.0	7.7 ± 0.5	5.4 ± 0.8	14.0 ± 1.0	−120 ± 3

related to the superluminal velocity of the components at the ejection time by:

$$\beta_{\rm obs} = \frac{\beta \sin\phi}{1-\beta\cos\phi}, \quad (5)$$

where $\beta = (1-\gamma^{-2})^{1/2}$. The Doppler factor δ will be also a function of time due to the jet movement.

In order to obtain the parameters γ, Ω, ϕ_0 and η_0 of the model, we first fit the data in the $(\beta_{\rm obs}, \eta)$-space. The best fitting, independent of the value of the Hubble constant, is seen in Fig. 1. The set of parameters that fits the data, for several values of the Hubble constant $H_0 = 100h\,{\rm km\,s^{-1}}$ ${\rm Mpc}^{-1}$, are presented in Table 2.

The values of $\beta_{\rm obs}(t)$ and $\eta(t)$ were used to adjust the period in the observer's frame (Fig. 2). The results clearly indicate a period $T \sim 16$ yr. The jet has completed one and a half cycles during the time for which there are reliable VLBI data. The viewing angle is currently increasing and will reach a new minimum towards the year 2011. The previous minimum was in 1995, so if some new superluminal components were ejected close to this epoch, its apparent velocity should be similar to that of C5 (i.e. $\beta_{\rm obs} \sim 8h^{-1}$). Instead, the velocities of components ejected around 2002 should be $\sim 5h^{-1}$.

4. The beaming factor

In Fig. 3 we present the Doppler factor δ as a function of the epoch in the observer's frame for the three models described in Table 2, obtained for different values of h. The large range of δ-values for each model must certainly have consequences in

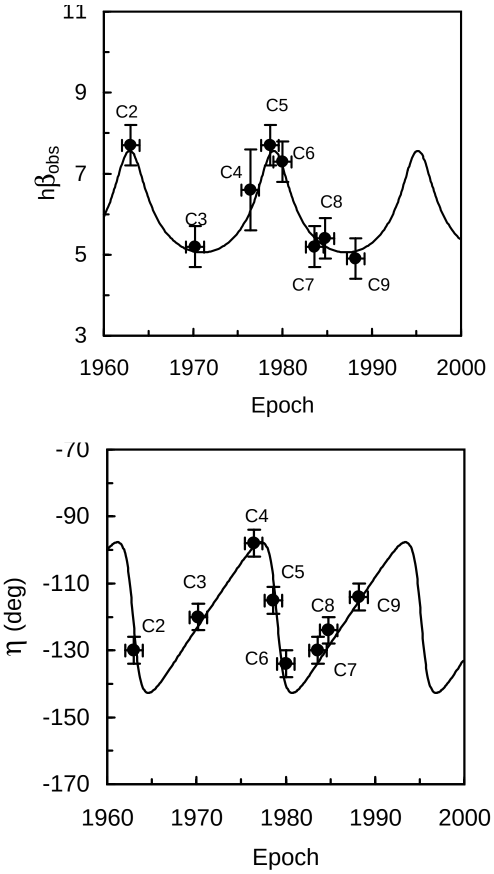

Fig. 2. Apparent superluminal velocities, scaled by the value of $h = H_0/100$, and position angle in the plane of the sky of the superluminal features in the jet of 3C 273 as a function of the epoch at which they were formed. The continuous line represents the result of the models with the precession parameters given in Table 2.

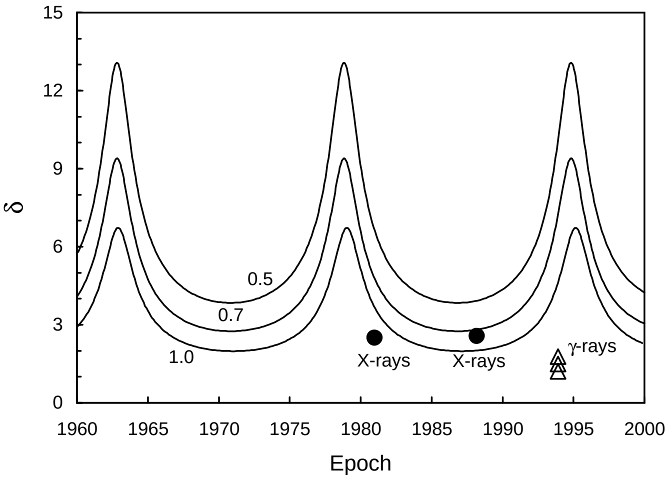

Fig. 3. Doppler factor of the precessing jet as a function of time for different values of the constant $h = H_0/100$ (0.5, 0.7, 1.0), resulting from the models described by the parameters given in Table 2. The two filled circles represent the lower value of δ obtained from X-ray observation, assuming an inverse self-Compton emission process (they are independent of h). The triangles represent the lower limit to δ imposed by the γ-ray observations for the three values of h used by the models. The higher value of h gives to the lower value of δ

the beaming properties of the quasar at all wavelengths, as we shall see in the following discussion.

4.1. *Beaming at radio frequencies*

Due to the relativistic motion in the jet, the flux density is boosted by a factor

$$S(\phi) \propto \delta^{n+\alpha} S_{\rm i} \tag{6}$$

where $S_{\rm i}$ is the isotropic flux density measured in the comoving frame, α is the spectral index, and $n = 3$ for ballistic motion. If the motion is in the form of a continuous flow instead of discrete ejecta, the effect of light travel time results in $n = 2$ (Lind & Blandford 1985).

For optically thin sources $\alpha > 0$, implying that large boosting should be expected; instead, in the optically thick part of the spectrum α can reach the value -2.5 and, consequently, little boosting is obtained for such regions. Moreover, Kellermann (1994) showed that the effect of the blueshift in the self-absorption frequency can even invert the boosting when $n = 2$. We believe that this is the case in the inner jet of 3C 273, where the unresolved core presents a spectrum that increases with frequency, at least up to 100 GHz, as determined by Unwin et al. (1985).

The superluminal features, on the other hand, are optically thin at radio frequencies. It is interesting to notice that the Doppler factor is about three times larger for C5 than for C3, for all values of h, whereas its flux density is not thirty times larger, as expected. The lifetime of C5, however, was 2.5 times shorter than the lifetime of C3, in agreement with the larger Doppler factor. The explanation for the lack of boosting in the flux density lies in the nature of the superluminal features. If they are formed by shocks propagating along the jet, they will evolve through the well-known Compton, radiative, and adiabatic phases, becoming optically thin at lower frequencies (e.g. Marscher 1990). In the latter phase, the intensity of the maximum in the spectrum varies as

$$S_{\rm i}(\nu_{\rm m}) \propto {\nu_{\rm m}}^{-\alpha_{\rm th}} \tag{7}$$

where $\alpha_{\rm th}$ is the spectral index of the optically thick part of the spectrum. Since the flux density in the optically thin part of the spectrum is always smaller than $S_{\rm i}(\nu_{\rm m})$ and the frequency of the maximum in the comoving reference frame is a factor of δ smaller than the observed frequency, we have to introduce an additional factor $\delta^{\alpha_{th}}$ in the observed luminosity. The beamed radiation, in the optically thin part of the spectrum, is therefore given by:

$$S(\phi) \propto \delta^{n+\alpha} \delta^{\alpha_{\rm th}} \tag{8}$$

and the boosting is strongly reduced in accordance with the observations. Notice that this effect is a consequence of the evolutive character of the superluminal features and does not apply to quiescent sources.

4.2. *Beaming and X-rays*

A lower limit to the Doppler factor δ can be obtained from the ratio between the measured X-ray flux and the inverse Compton emission predicted from the synchrotron source. In the simplest homogeneous model, this relation can be written as (Madau et al. 1987):

$$\begin{aligned} \delta \ = \ & f(\alpha) {F_{\rm X}}^{-1/(4+2\alpha)} (h\nu)^{-\alpha/(4+2\alpha)} F_{\rm m} {\nu_{\rm m}}^{(5+3\alpha)/(4+2\alpha)} \\ & \times \theta^{-(6+4\alpha)/(4+2\alpha)} [\ln(\nu_{\rm b}/\nu_{\rm m})]^{1/(4+2\alpha)} (1+z) \end{aligned} \tag{9}$$

where α is the spectral index, $f(\alpha)$ varies between 0.17 and 0.22 for $0.25 < \alpha < 1.0$, $F_{\rm X}$ is the X-ray flux density (in Jy) of the X-ray self-Compton emission at energy $h\nu$ (in keV), $F_{\rm m}$ is the flux density (in Jy) at the turnover frequency $\nu_{\rm m}$ (in GHz), $\nu_{\rm b}$ is the cutoff frequency of the synchrotron spectrum, and θ is the angular diameter of the spherical emitting region. In the case of VLBI components, usually described by elliptical Gaussians, Marscher (1987) recommends the use of:

$$\theta = 1.8(\theta_{\rm a}\theta_{\rm b})^{0.5} \tag{10}$$

where $\theta_{\rm a}$ and $\theta_{\rm b}$ are the FWHM of the major and minor axis, respectively, of the elliptical Gaussians obtained by model fitting.

Unwin et al. (1985) compared the X-ray emission expected from the individual features present in the 10.7 GHz VLBI map of 3C 273 at epoch 1981.1 with the X-rays measured in 1981.02. They found $\delta \sim 1$ for the unresolved core and component C4, but $\delta > 2.5$ was necessary to explain the emission of C5.

Walter & Courvoisier (1992) analyzed simultaneous X-ray and ultraviolet observations obtained between 1984 and 1989 and found an excellent anti-correlation between the X-ray spectral index and the logarithm of the ratio between the X-ray and ultraviolet fluxes. They concluded that this relation strongly supported the inverse Comptonization models, where hot electrons scatter up seed ultraviolet photons. They found, however, two X-ray flares which do not fit the anti-correlation curve. They both occurred a few months before optical and infrared flares were detected, being probably associated to newly formed shocks in the jet. In the light of these results we conclude that the value of δ should have been considerably higher for C5, since Unwin et al. (1985) used the full value of the X-ray emission and a flare at other wavelengths was observed associated to the enhanced X-ray emission, indicating the formation of a new shock, probably C6, which was responsible for most of the additional X-ray emission. This expected high δ value for C5 is in very good agreement with the predictions of our precession model for this epoch.

The X-ray flare described by Walter & Courvoisier, in 1983 Dec, can be associated to the superluminal feature C8 (Botti & Abraham 1988). The highest frequency VLBI observations of this component were made at 22 GHz (Zensus et al., 1990) in 1984.09, when the new feature was still blended to the core. More information is available for the second X-ray flare, observed in 1987 Dec 27. VLBI observations at 3 mm (Bååth et al. 1991) in 1988.21 clearly show a strong feature at a distance of 0.1 mas from the core, with angular size of 0.010×0.118 mas^2. The spectra between 43 and 230 GHz was obtained almost at the same epoch by Matsuo et al. (1989), who showed that the turnover frequency was near 230 GHz. Bååth et al. (1991) estimated the flux density of this component at the turnover to be 10 Jy. Using these data, we find from Eq. (9) that $\delta > 2.6$ for epoch 1988.2. This value is only obtained in our precessing model if $H_0 < 80\,\mathrm{km\,s^{-1}}$ Mpc^{-1}. Since the determination of the Doppler factor is independent of the value of H_0, the predictions of the precessing jet model can be used as an alternative method to constrain the admissible values of the Hubble parameter.

4.3. Beaming and γ-rays

The condition on the Doppler factor to avoid pair-production absorption on lower energy (X-ray) photons in a source with γ-emission varying on timescales t_{v} can be cast in the form (Mattox et al. 1993):

$$\delta \;\geq\; \left[8.9 \times 10^{-4}(1+z)^{-(4+2\alpha)}(1+z-\sqrt{1+z})^{-2}h^2 \times \left(\frac{F_{\mathrm{keV}}}{\mu\mathrm{Jy}}\right)^{-1}\left(\frac{E_\gamma}{\mathrm{GeV}}\right)^{-\alpha}\left(\frac{t_{\mathrm{v}}}{10^5\mathrm{s}}\right)\right]^{-1/(4+2\alpha)}, \qquad (11)$$

where E_γ is the energy of the γ-ray photons and the measured X-ray flux density has been represented by a power law $F(E) = F_{\mathrm{keV}}(E/\mathrm{keV})^{-\alpha}$, with F_{keV} the differential flux density at 1 keV.

At energies $E > 100$ MeV, 3C 273 was first detected by the Cos-B experiment (Swanenburg et al. 1978, Bignami et al. 1981) during 1976.5. EGRET detections occurred in 1991.5 (von Montigny et al. 1993) and 1993.9 (von Montigny et al. 1997). During the latter detection the flux changed by a factor ~ 3 within 43 days; the peak value was at the level of the Cos-B detection. Just upper limits were determined during all remaining EGRET observations (von Montigny et al. 1997). Using the data from the γ-ray burst observed at 1993.9 we get $\delta \geq 1.29$, 1.47, and 1.77 for $E_\gamma \sim 1$ GeV, $t_{\mathrm{v}} = F_{\max}(\Delta F/\Delta t)^{-1} \sim 5 \times 10^6$ s, and $h = 1$, 0.75, and 0.5, respectively. These figures are in accordance with the values expected from our modelling for this epoch: $\delta \geq 4$. However, the first limit, corresponding to $h = 1$, must be rejected according to the considerations of the previous subsection. The constraints introduced by the X and γ-ray emissions at different epochs are marked in the curves shown in Fig. 3.

We would like to emphasize, before discussing the implications of the jet precession for the γ-ray emission, that 3C 273 is by far the object with more extensive temporal VLBI monitoring and, consequently, the best candidate for a study of the possible precession of an inner jet. The knowledge of the amplitude and period of this precession can be very useful to guide future variability observations in those energy ranges where the Doppler enhancement of the inner jet emission is of particular importance.

5. Implications for the γ-ray emission

The energy-density spectrum of 3C 273 obtained from the quasi-simultaneous data of Lichti et al. (1995) shows three maxima. The first one is around 6.7×10^{11} Hz. This emission is interpreted as synchrotron radiation from the jet. A second maximum appears in the UV to soft X-ray region. The strong emission in the optical and UV forms a 'big blue bump' which is almost surely originated in thermal emission from the hot photosphere of the accretion disk that surrounds the central supermassive black hole. The third maximum occurs in the soft γ-ray range, somewhere between 1 and 8 MeV. It has been suggested that this maximum is due to pair annihilation processes in the inner jet (e.g. Romero 1996a,b; Böttcher & Schlikeiser 1996). An additional, not observed maximum has been inferred for the near IR band (Litchi et al. 1995).

Different types of models have been proposed to explain the high energy emission of blazars. In most of them the γ-rays are the result of inverse Compton scattering of lower energy photons by ultrarelativistic electrons and positrons in the initial section of the jet. The origin of seed photons is not clear. They could be synchrotron radiation from the jet (synchrotron self-Compton scattering or SSC; e.g. Königl 1981, Maraschi et al. 1992, Bloom & Marscher 1993 and 1996, Marscher & Bloom 1994, Marscher & Travis 1996), produced by the accretion disk (e.g. Melia & Königl 1989, Dermer et al. 1992, Dermer & Schlickeiser 1993), or emitted by the disk and reprocessed in a nearby halo (probably the broad line region) before the Compton interactions with the relativistic pairs of the jet (e.g. Sikora et al. 1994, Blandford & Levinson 1995). It has been also suggested that inelastic hadron interactions could be an important source of secondary electrons and positrons, and hence responsible for a part of the γ-ray flux (e.g. Mannheim & Biermann 1989).

In the particular case of 3C 273 all these models seem to be capable to fit reasonably well the spectral data (see von Montigny et al. 1997 for a discussion). However, variability data across the spectrum introduces additional constraints.

An analysis of simultaneous UV and X-ray variability observations of 3C 273 led Walter & Courvoiser (1992) to discard the SSC model in the case of this particular source due to the absence of correlations. As we have already mentioned, they found instead anticorrelations that strongly support a picture where the photons of the big blue bump are scattered up to the X-ray band by the electron population. At γ-ray energies, the strong burst in 1993.9 was not accompanied by any significant change in the synchrotron emission (von Montigny et al. 1997) as one would expect from SSC models. The strong burst observed at mm-wavelengths during 1990 was probably related with the formation of the component C10, but at the time of the 1993-burst the radio flux was still in a period of slow decrease and did not display any particular activity that could be clearly related to the γ-ray enhancement.

If the γ-ray emission is produced by Compton upscattering of external seed photons, this kind of variability can be the result of a change in the geometry produced by the precession of the inner jet. In fact, during its movement the jet can 'illuminate' one of the clouds of the broad line region. As a consequence the photon flux from the opposite direction to that of the flow bulk velocity would be dramatically increased. As shown by the numerical computations of Ghisellini & Madau (1996), the synchrotron jet emission reprocessed in the illuminated cloud is by far the dominant contribution to the radiation energy density seen by the jet. If ψ is the angle between the incident photons and the electron or positron directions and α is the optically thin spectral index, then the factor $(1-\beta\cos\psi)^{1+\alpha}$ in the Compton-scattering photon emissivity (see, for instance, Dermer 1995) can be replaced by $2^{1+\alpha}$, which yields in the case of 3C 273 a γ-ray enhancement of a factor ~ 3 as observed, without changes in the physical parameters that characterize the flow, and consequently without changes in the synchrotron emission.

The timescale of the variability and the jet precession velocity can be used to estimate the size of the cloud. The distance from the central source of luminosity $L = L_{44} \times 10^{44}$ erg s^{-1} to the broad line region is $r_{\rm blr} \sim 3 \times 10^{16} L_{44}^{1/2}$ cm (e.g. Peterson 1997). Using the value for the luminosity associated to the hot component of the blue bump of 3C 273 (Lichti et al. 1995) we get $r_{\rm blr} \sim 0.17$ pc, and then the size of the cloud responsible for the γ-ray enhancement results

$$l \sim \frac{t_{\rm var}}{1+z} w r_{\rm blr} \sim 2.6 \times 10^{16} \quad {\rm cm}. \qquad (12)$$

An additional prediction within this framework is that a correlated variability should be observed in the intensity of the emission-line profiles during the γ-ray burst. Unfortunately, there are not at our knowledge simultaneous observations of the emission-line flux of 3C 273 for the period of interest. It would be worthwhile to carry out such studies during future multiwavelength campaigns. In particular, the γ-ray detection of 3C 273 is favoured during the epochs of higher Doppler factor for the inner jet. The next window with $\delta \geq 4$ will commence in year 2009 and will last until 2012.

Finally, it should be mentioned that if the energy-density peak at MeV energies is due to $e^- - e^+$ annihilations in the inner jet, then this peak should shift in energy between 0.62 MeV and 2.12 MeV according to the δ-oscillation. Detailed calculations by Böttcher & Schlickeiser (1996) show that the annihilation radiation dominates over the inverse Compton radiation for pair densities above $\sim 10^9$ cm^{-3}. Such high densities seem to be possible just in the base of the jet and then the MeV emission would be affected by the precession. The significance of the COMPTEL detection of 3C 273 in June 1991 (Williams et al. 1995) and December 1993 (von Montigny et al. 1997) was sufficiently high as to allow a division of the data into the energy bands 0.75–1.25, 1.25–3.0, and 3.0–8.0 MeV. The errors, however, are too large to establish without ambiguity a displacement of the peak from the first to the second energy range between both observations. If the new generation of γ-ray telescopes can detect this displacement, then the electron-positron nature of the inner jet could be clearly set.

6. Comments

Since the optical synchrotron emission from the inner jet does not dominate the overall optical flux of 3C 273, the periodic evolution of the Doppler factor is not necessarily reflected in a periodic lightcurve. Most of the optical emission comes from the accretion disk and the outer optical jet. In this jet, optical variability can be produced by propagating shocks with different Doppler factors (e.g. Marscher & Gear 1985), while orbiting hot spots or other short-term instabilities can generate variability in the disk emission. This could explain why no clear periodicity has been found in the historical lightcurve (Angione & Smith 1985; see, however, Babadzhanyants & Belokon' 1993).

At radio wavelengths, variability can be introduced by shock interactions with particle density inhomogeneities (e.g. Marscher 1990, Romero et al. 1995), turbulence (e.g. Marscher et al. 1992), or curved paths of superluminal knots caused at some distance from the core by Kelvin-Helmholtz instabilities (e.g. Romero 1995) or helical magnetic field configurations (e.g. Roland et al. 1994). In addition, radio outbursts are produced when new superluminal components are ejected (e.g. Krichbaum et al. 1990). All this makes the resulting radio lightcurve very complex. Consequently, periodicity should be hardly identifiable from single dish determinations of the total flux density.

The possible physical mechanism behind a rapid precessing jet has been discussed by Katz (1997). A binary black hole system with an orbital plane inclined respect to the accretion disk can produce a Newtonian-driven precession with a period of a few years. The fact that other blazars like OJ 287 and 3C 279 also present evidence for precessions of their jets suggests that a binary central system could be a rather common ingredient of radio loud AGNs. Recently, Wilson & Colbert (1995) have proposed that mergers or close interactions of host galaxies with massive central black holes could trigger the radio loud phase of the AGN phenomenon. This is in accordance with the old hypothesis by Toomore & Toomore (1972) that many, may be most elliptical galaxies are the result of merging of spirals and the fact that radio loud quasars and blazars are never found in this latter type of hosts.

The underlying galaxy of 3C 273 was first detected by Wyckoff et al. (1980). Deep CCD images obtained by Tyson et al. (1982) confirmed the detection and showed that the galaxy is probably elliptical. Recent emission line observations (Kennicutt 1992, Hippelein et al. 1996) indicate high star forming-rates that suggest a companion galaxy in a starburst phase. New Hubble Space Telescope observations of the host galaxy of 3C 273 could provide additional evidence for a recent merger, and hence for the existence of a binary black hole central source.

7. Summary

We have shown that the different velocities and position angles at the ejection time of superluminal components in 3C 273 can be the effect of an inner jet with a bulk Lorentz factor $\gamma \sim 10.8$ that precesses within a cone of opening angle $\Omega \sim 3.9°$ (for $h = 0.7$), and with a period of ~ 16 years. The Doppler factor varies between 2.8 and 9.4, leading to some concrete predictions on the

γ-ray emission. We think that inverse Compton upscattering of external photons in the inner jet is the most plausible mechanism for the generation of the γ-rays in this particular object. Future high sensitivity observations at MeV energies could provide direct evidence for the $e^{-}e^{+}$-annihilation nature of the peak observed at this band by detecting the shifts of the annihilation line produced by the oscillation of the Doppler factor.

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