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The effect of expansion on high-energy emission from AGN jets

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Abstract: We present a detailed study of the impact of jet expansion on the emission properties of blazars, in particular their gamma-ray lightcurves, based on the notion that the radiation is produced in an emission zone that is travelling down the jet. Using analytical estimates and numerical studies with a particular model of particle energization, we conclude that AGN jets must be very well collimated with opening angles smaller than about 1 mrad, if the emission seen over a few days is caused by an emission zone that travels down the jet. Our findings suggest that either this condition is not met or an unknown very efficient mechanism collimates the jets of blazars.

Introduction

An important question related to the nature of AGN jets is that of collimation and the value of the jet-opening angle. Observations of radio galaxies show that the global opening angle of the jet can be of the order of a degree or smaller [1]. However, direct estimates of the jet-opening angle and the jet-aspect angle based on intensity maps carry a very large systematic uncertainty, as do estimates of the jet Lorentz factor based on superluminal motion [2, 3]. An alternative way of measuring the collimation involves radiation modelling. The monitoring of TeV-blazars indicates that outbursts, that last for weeks or months, consist of successive rapid flares which rise and decay on much shorter timescales down to an hour [4]. In particular in blazars the shortest variability timescale (~ 1 h) of the optical, X-ray, and γ-ray emission mandates an upper limit to the size of the emission region that is around 10^{15} cm for a Doppler factor of $D \simeq 10$.

If the successive flares, that make up an extended outburst, are produced by one emission zone that travels down the jet, then the light curves should carry an imprint of the expansion of the emission zone, which would allow us to infer the jet-opening angle on scales much smaller than the resolution limit of direct observations. Limited though the temporal coverage of the TeV-band observations is, they suggest that the variability timescale does not increase as time passes, which finding we may to constrain the expansion of the jet plasma.

I use generic analytical estimates, complemented with numerical results derived with a specific model of particle energization, to characterize the impact of jet expansion on the emission properties of blazars, thus laying the groundwork for a later statistical analysis of blazar lightcurves. I am specifically considering the expansion of one long-lived emission region that may account for a series of rapid flares in the radiation modelling. Note that this scenario differs from those that assume the existence of new emission zones for each of the rapid flares. We concentrate on situations in which the light travel time within the emission zone is always shorter than the timescales for energy loss. Throughout the paper we use asterisks (*) and diamonds ($^\diamond$) to denote quantities in the host-galaxy frame and the jet frame, respectively. Unmarked quantities are taken in the observer's frame.

Analytical estimates

In this section we present analytical estimates of the minimum variability timescale $\tau_{\rm var,min}$ as a function of the duration of activity $\tau_{\rm obs}$, both taken in the observer's frame. We choose a modest expansion with constant opening angle in the host-galaxy frame. Let the length coordinate along the jet direction of motion be L^*. Then the radius of the jet cross section is

$$R^\diamond = R^* = \psi^* L^* \tag{1}$$

We start at some finite value, $L^*_{\rm min}$, that we can adjust and which for a given opening angle ψ^* would correspond to the initial radius of the jet, $R^\diamond_{\rm min}$. We neglect expansion along the jet axis, so we derive lower limits to the effects of expansion. Consequently we describe the jet plasma as having the geometry of a disk with constant thickness, $d^\diamond$, in the jet rest frame. The observing time is related to the jet position, $L^\diamond$, as

$$\tau_{\rm obs} = \frac{L^\diamond - L^\diamond_{\rm min}}{c\,D} = \frac{L^* - L^*_{\rm min}}{c\,D\,\Gamma} \tag{2}$$

where Γ is the jet Lorentz factor and D is the Doppler factor.

One effect of expansion is that the light travel time across the source increases. The impact on the variability depends somewhat on the radiation mechanism and on the location of particle acceleration, which we assume to operate over the entire cross-sectional area of the emission zone or at least a constant fraction thereof. The strongest lower bound to the jet-frame variability timescale arises then for the SSC emission, whereas those for the other radiation processes can be somewhat weaker. This effect is independent of the model used to describe the acceleration of relativistic particles.

Neglecting the variations in the Doppler factor across the jet, the minimum variability (or delay) timescale on account of causality then is

$$\tau_{\rm var,min} \simeq \frac{1}{D}\,\frac{R^\diamond}{c} = \frac{R^\diamond_{\rm min}}{c\,D} + \Gamma\,\psi^*\,\tau_{\rm obs} \tag{3}$$

which leads to a limit

$$\psi^* \lesssim \frac{1}{\Gamma}\,\frac{\tau_{\rm var,min}}{\tau_{\rm obs}} \tag{4}$$

Related to the causality argument is the fact that the distance to the observer varies across the jet cross-sectional area, so radiation emitted on the far side of the jet takes more time to propagate than near-side emission. Correspondingly, the minimum variability timescale is

$$\tau_{\rm var,min} \simeq \frac{R^\diamond}{c}\,\sin\theta_{\rm obs} \tag{5}$$

$$\simeq \frac{R^\diamond_{\rm min}}{c}\,\sin\theta_{\rm obs} + D\,\Gamma\,\sin\theta_{\rm obs}\,\psi^*\,\tau_{\rm obs}$$

where $\theta_{\rm obs}$ is the angle between line-of-sight and the jet axis and I have used Eq. 2. The limit for the jet opening angle can then be written using the apparent transverse jet velocity, $\beta_{\rm app}$.

$$\psi^* \lesssim \frac{\tau_{\rm var,min}}{D\,\Gamma\,\sin\theta_{\rm obs}\,\tau_{\rm obs}} = \frac{\beta}{\beta_{\rm app}}\,\frac{\tau_{\rm var,min}}{\tau_{\rm obs}} \tag{6}$$

As a second effect expansion also implies that different volume elements effectively propagate in different directions, so the relativistic transformation of their radiation parameters into the observer's system is no longer constant across the jet. If the jet-plasma cloud interacts with a stationary target at some point on its trajectory or energetic particles are injected at a specific point in jet-frame time, then we observe this event earlier on the near side of the jet than on the far side. Again, this is a generic effect that is largely independent of the particle acceleration scenario and only requires that the particle acceleration operates over the entire cross-sectional area of the emission zone or at least a constant fraction thereof. As an example let us consider an infinitesimally brief flarelet at the time $t_c^\diamond$ with a power-law spectrum, so the observed flux from a small volume element of the jet plasma is

$$\delta F = C\,E^{-\alpha}\,D^{2+\alpha}\,\delta\left[t - \frac{t_c^\diamond}{D}\right] \tag{7}$$

where C is a constant. The total observed flux is obtained by integrating over the cross-sectional area of the jet, which can can be written as an angular integration using $dA = L\,d\Omega$. The integral is easiest, if the observer is situated along the jet symmetry axis, so the angle to the symmetry axis is also the angle to the line-of-sight. Then the azimuthal integral is trivial and the polar integral in $\mu_j = \cos\theta_j$ gives

$$F = \frac{2\pi\,C}{t_c^\diamond\,\Gamma\,\beta}\,E^{-\alpha}\,\left(\frac{t_c^\diamond}{t}\right)^{2+\alpha} \tag{8}$$

$$\times\,\Theta\left[t - \frac{t_c^\diamond}{(1+\beta)\,\Gamma}\right]\,\Theta\left[t_c^\diamond\,\Gamma\,(1-\beta\,\cos\psi^*) - t\right]$$

where Θ is a stepfunction. The observer would see the flarelet begin at the time $t_{\rm obs} = t_c^\diamond/(1+\beta)\,\Gamma$

and, in the absence of a cut-off imposed by a finite jet opening angle, measure a decay to one-half of the peak flux after

$$t_{1/2} = t_{\rm obs}\left(2^{1/(2+\alpha)} - 1\right) \simeq 0.26\, t_{\rm obs} \qquad (9)$$

for $\alpha = 1$. The TeV-band light curves of Mrk 501 suggest that the variability time is shorter than a quarter of the duration of activity [4], so the apparent flare duration is most likely limited by the jet opening angle, ψ^*. The flarelet duration would be

$$\frac{\tau_{\rm flare}}{t_{\rm obs}} = \left[\Gamma^2\,(1+\beta)\,(1-\beta\,\cos\psi^*) - 1\right] \qquad (10)$$

which in the limit of small opening angles leads an upper limit to ψ^*,

$$\psi^* \lesssim \frac{1}{\Gamma}\sqrt{\frac{2\,\tau_{\rm var,min}}{\tau_{\rm obs}}}\,. \qquad (11)$$

If one performs the calculation for a finite angle between the jet axis and the line-of-sight, then the resulting limits on the jet opening angle are similarily constraining, largely because the limits depend only on the ratio of the variability timescale and the duration of activity.

A third effect arises from a modification of the energy loss rates and the escape probability of energetic particles in the emission zone. This applies in particular to any synchrotron-self-Compton emission component, for that scales with the density of soft photons and therefore will fall off relative to the total synchrotron flux. For the ratio of the differential source rates we find (with $a = 2$ for isotropic expansion and $a = 1$ for a thin-cylinder geometry with constant thickness)

$$\frac{\dot N_{\rm ssc}}{\dot N_{\rm syn}} \propto \left(\frac{R^\diamond_{\rm min}}{R^\diamond}\right)^a = \left(1 + \frac{\psi^*\,\Gamma\,\tau_{\rm obs}}{\tau_{\rm lc,min}}\right)^{-a} \qquad (12)$$

Noting that

$$\tau_{\rm lc,min} = \frac{R^\diamond_{\rm min}}{c\,D} \lesssim \tau_{\rm var,min} \qquad (13)$$

is the initial light-crossing time, we find the SSC emission to not rapidly fall off compared with the synchrotron component, if

$$\tau_{\rm obs} < \frac{\tau_{\rm lc,min}}{\psi^*\,\Gamma} \;\Rightarrow\; \psi^* \lesssim \frac{1}{\Gamma}\,\frac{\tau_{\rm var,min}}{\tau_{\rm obs}} \qquad (14)$$

External Compton scattering is to first order unaffected, but shows its own variations on account of the slowly changing scattering geometry as the relativistic particles stream down the jet. All other radiation processes that involve interactions with the jet medium will have a diminishing efficacy, for both the plasma density and the magnetic field strength will fall off in the expanding jet.

In the case of a thick target, i.e. if the density of relativistic particles is limited by radiative energy losses, one may not observe a reduction in radiation flux, but only a slowing down of variability because the energy loss timescales become longer. For the most rapid variability of TeV blazars the instantaneous emission is probably not in the thick-target limit, though. The gamma-ray band power is similar to the X-ray power, and therefore the synchrotron loss time is a good proxy of the total energy-loss timescale of relativistic electrons. The observed loss time is related to the observed peak energy of synchrotron X-ray emission, $E_{\rm peak}$, as

$$\frac{\tau_{\rm loss}}{10\,{\rm m}} = \left(\frac{D}{20}\right)^{-\frac{1}{2}}\,\left(\frac{E_{\rm peak}}{\rm keV}\right)^{-\frac{1}{2}}\,\left(\frac{B}{\rm Gauss}\right)^{-\frac{3}{2}} \qquad (15)$$

A thick target is established, if the loss time is much smaller than the variability time scale, which is measured to be as short as 2 minutes in the case of the TeV blazars Mkn 501 [5] and PKS 2155-304 [6]. Pure SSC models feature a low magnetic field strength of the order of 0.01–0.1 G to keep the synchrotron peak frequency low, so even for the most rapidly cooling electrons the variability timescale is similar to the electron energy-loss timescale, thus making the thick-target case unlikely. Any slowing down of variability on account of an increase of the energy loss timescales by jet expansion should therefore be directly observable.

All three signatures of jet expansion scale with the generally unknown jet Lorentz factor and the ratio of the variability timescale and the duration of activity, which is a measurable quantity. Arguments can be made as to how one of these effects can be circumvented in a specific blazar jet model, but it appears exceedingly difficult to evade all three with the same model. Gamma-ray lightcurves of blazars can therefore be used to place constrains on the jet expansion on scales much smaller than those accessible with direct measurements. The important

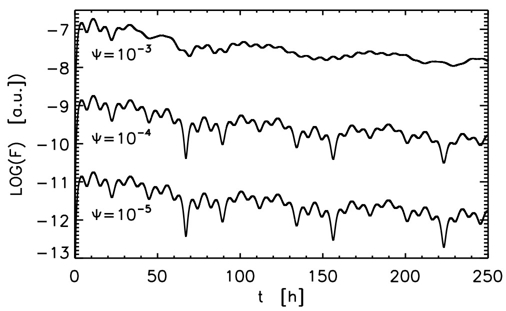

Figure 1: Hypothetical lightcurves at 200 GeV for three different opening angles, all based on the same jet model [7] for a Doppler factor $D = 50$.

observable is $\tau_{\rm var,min}/\tau_{\rm obs}$, where $\tau_{\rm var,min}$ is the variability timescale observed after the source has been active for a time $\tau_{\rm obs}$.

Model-based examples

To illustrate the effect of expansion on actual lightcurves, we have extended a specific blazar model [7, 8] to include expansion. This model involves acceleration by the first half-cycle of a relativistic Fermi process and nothing beyond, in particular no energy transfer from ions to electrons. Figure 1 shows hypothetical lightcurves at 200 GeV for three different opening angles, all other parameters kept constant, including the Doppler factor at $D = 50$ and the initial Lorentz factor $\Gamma_0 = 100$. Variability arises from density fluctuations in the ambient medium, through which we have inserted fluctuations on three different timescales: 7.4 h, 22.2 h, and 74 h in the observer's frame. To be noted from the figure is that after about 200 h the fast variability is no longer present in the lightcurve for $\psi^* = 10^{-3}$, whereas it is preserved for tighter collimation, in line with our analytical estimates above.

Summary

Gamma-ray lightcurves of blazars can be used to place constraints on the jet expansion on scales much smaller than those accessible with direct measurements. The TeV-band lightcurves taken with atmospheric Čerenkov telescopes suggest that AGN jets must be very well collimated with opening angles smaller than about 1 mrad, if the emission seen over a few days is caused by an emission zone that travels down the jet. Our findings suggest that either this condition is not met or an unknown very efficient mechanism collimates the jets of AGN. The GLAST observatory will deliver GeV-band lightcurves of blazars with unprecedented temporal coverage, thus allowing a statistically accurate determination of temporal changes of the variability timescales.

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