LIMITS ON THE DOPPLER FACTOR IN RELATIVISTIC JETS BY MEANS OF GAMMA-RAY OBSERVATIONS

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ABSTRACT

We present in this paper a new, simple and potentially useful method for constraining the kinematical parameters of relativistic jets based on gamma-ray spectral measurements of Active Galaxies. The application of this method to the Quasar 3C273 leads to a value of the Doppler factor of 3-4. This corresponds to jet parameters of $\Gamma > 2$ and $\Theta < 15^\circ$ in good agreement with the values estimated independently from radio observations of superluminal motion. For the particular case of 3C273, our results are also compared to those given by a similar technique based on the comparison of the X-ray observational data with the synchrotron self-Compton prediction from radio measurements. The application of the proposed technique to a significant sample of active galaxies as a result of future gamma-ray surveys of the sky is briefly discussed, particularly with respect to possible ways to constrain the cosmological constants H_0 and q_0.

1. INTRODUCTION. A recent investigation (1) of the attenuation of gamma-rays in the vicinity of Active Galactic Nuclei (AGN) as a result of photon-photon absorption, based on the simplified picture in which the emission was considered isotropic and at rest with respect to the observer, showed that some classes of objects, namely Quasars and BL Lac's, are generally opaque to photons of energies greater than 1 MeV. Emission is possible, however, for progressively higher gamma-ray energies provided that a certain degree of collimation exists for the associated photons.

Such a treatment, whilst correct in principle, cannot be employed if Active Galaxies have relativistic jets beamed at a small angle toward the Earth. In this case, the photon-photon absorption optical depth as calculated in the observer rest frame must be modified to take into account relativistic Doppler effects.

2. FORMULATION. We have considered a simple jet model having only an approaching component with a single bright blob of material moving relativistically at some angle to our line of sight. To take into account the combined effects of Doppler blueshifting of the gamma-ray photons and of relativistic beaming, the size of the emitting region must be decreased while the brightness of the source as well as the energies of the interacting photons must be increased by suitable powers of the Doppler factor $\delta = [\Gamma(1-\beta\cos\theta)]^{-1}$, where $\Gamma = (1-\beta^2)^{-1/2}$, β is the velocity of the jet in units of the speed of light and θ is the angle between the line of sight to the source and the jet axis. Extensive details of this kind of analysis are given in (2) and the reader is referred to this paper for the relevant formulae.

Using the formalism of (1) and including the appropriate factors of δ we derive the following expression for the photon-photon absorption optical depth in a relativistic jet:

$$\tau_{\gamma\gamma} = 3.5\ 10^{-28}\ f(\alpha)\ \frac{Lx}{R}\left(\frac{2m^2c^4}{E_\gamma}\right)^{-\alpha}\left(\frac{1+z}{\delta}\right)^{3(\alpha+1)}$$

where all quantities refer to the observer rest frame. Lx (erg/sec) is the source X-ray luminosity, R(cm) the source size as measured by the variability timescale, E_γ (KeV) the energy of the interacting gamma- ray photons and α the source energy spectral index in the X-ray band. For Lx taken over a fixed energy interval, $f(\alpha)$ is a slowly varying function of α.

If a cut off is observed in the gamma-ray spectrum of an active galaxy at a given photon energy E_γ (> 1 MeV) as a result of the photon- photon absorption process, $\tau_{\gamma\gamma}$ can be set to unity and a direct estimate of the Doppler factor can be made.

3. DISCUSSION. At the present time there is a lack of gamma-ray observational data on a meaningful sample of AGN, so that numerical evaluations of δ by this means will have to await a suitable extragalactic gamma-ray survey. However, an estimate of the Doppler factor for a number of known gamma-ray emitting AGN can be made on the basis of the few available observational data. With the exception of 3C273, we find that for all objects so far detected at gamma-ray energies (NGC4151, MCG8-11-11, NGC1275, and CEN A (2)) δ <1, which indicates that relativistic beaming of the high energy radiation is not required.

For the Quasar 3C273,using values of $\alpha = 0.4$, Lx=1.1 10**46 and R=1.3 10**15 as observed in the 2-10 KeV energy range (3,4), we find that δ lies between 3 & 4 for an assumed gamma-ray cut-off at energies of between 1 and 50 MeV. This corresponds to $\Gamma > 2$, $\theta < 15°$ and $\beta > 0.87$. That is,according to the model the beam is at least mildly relativistic and is pointed within 15 degrees to our line of sight. The precise values depend ,albeit marginally,on the choice of the Hubble constant. For H_o=100 Km/sec Mpc, δ is reduced to values ranging between 2-3.

3C273 has been a principal object of study by VLBI,since the first development of this technique and studies of its compact structure quickly showed it to be a'superluminal radio source' (5). In this class of sources,the apparent velocity v/c of the jet as measured with the VLBI technique is related to the angle θ to the line of sight and to the velocity of the moving material in the jet frame by:

$$v/c = \beta \sin\theta / (1 - \beta\cos\theta)$$

To account for an observed apparent velocity as large as 10.6 (a value scaled to our adopted value of H , (5)),this equation requires that $\theta < 11°$, $\Gamma > 10$ and $\beta > 0.99$ in agreement with the values obtained from the application of the gamma-ray method. Therefore evidence for bulk relativistic motion in the 3C273 jet comes from both superluminal motion and X/gamma-ray measurements. Only by combining these two techniques,is it possible to calculate unique values for the jet parameters: for H_o=50 and taking δ =3-4 and v/c=10.6,we find Γ =15-20 and $\theta = 8°-9°$.

The method proposed here can also be compared to the technique first applied by Marscher et al. (6) and recently employed by a number of authors (7,8,9),which is based on the comparison of X-ray observational data with the synchrotron self-Compton predictions from radio measurements. Unwin et al.(10) have recently applied this technique to the specific case of 3C273 and have deduced lower limits to the Doppler factor of the knots in the jet. At least one knot (the closest to the unresolved core) must be moving relativistically with $\delta > 2.5$, $\Gamma > 1.4$ and $\theta <$ 25°. For the core,the observational parameters are not sufficiently accurate to put constraints on the kinematics of the innermost region of the jet. In particular ,the self absorption spectral turnover of the core as well as its angular size must be measured with high precision before stronger limits to θ and Γ or β may be deduced.

One should note that the value of δ obtained by the X/radio comparative method represents a lower limit on the Doppler factor of the jet since other X-ray emission mechanisms can be operating in the source. A similar situation exists for the case of the gamma-ray technique which, however, has the advantage of relying only on a measurement in a single waveband. In both cases estimates on the Doppler factor carry a certain degree of error due to uncertainties in the parameter evaluation and therefore both methods should be used in a complementary and comparative way.

A future gamma-ray survey of extragalactic objects with instrumentation of adequate sensitivity and broad band spectral resolution which operates for photon energies above 0.1 MeV will be significant for the study of relativistically beamed gamma-ray sources. In particular, it will be possible to determine upper limits to the cosmological parameters H_0 and q_0 ,by observing a large sample of AGN at X/gamma-ray energies so that the minimum bulk Lorentz factor Γ needed to explain the observations can be calculated. The same group of objects have then to be monitored at radio frequencies by a dedicated VLBI array in order to determine the jet apparent velocity and consequently Γ . After averaging over angles of ejection relative to the line of sight, the mean ratio between the two values of Γ can be determined as a function of H_0 and q_0 . Objects at the same redshift would yield a limit on the Hubble constant while objects at different redshifts would allow a limit on q_0 to be placed.

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