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The Doppler crisis in TeV blazars and its possible resolutions

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Different observers have estimated drastically different bulk Lorentz factors and Doppler factors for the jets of the TeV blazars, depending on the method used. On the one hand, rapid variability at high energies on timescales of a few minutes and fits to the spectral energy distributions (SEDs) imply large Doppler factors approaching 100. On the other hand, jet morphologies, kinematics, and brightness temperatures measured from parsec-scale imaging with the Very Long Baseline Array (VLBA) imply at most modest Doppler boosting. Such modest Doppler boosting is also suggested by unification arguments. This so-called Doppler crisis may indicate the presence of structured jets in these sources, with different regions of different Lorentz factors, for example, a fast spine and a slower layer. We discuss the constraints on such structured jet models from our latest observations of these sources with the VLBA.

Keywords: Active galactic nuclei; blazars.

1. Introduction

A variety of recent work in blazar astronomy (for example, Ref. 1) has revealed that there may be only two fundamentally distinct types of relativistic jets from these sources:

(1) Weak jets resulting from inefficient accretion modes in low-excitation radio galaxies (LERGs) that are seen as high-frequency peaked BL Lac objects (HBLs) when viewed nearly end-on.
(2) Powerful jets from standard accretion disc systems in high-excitation radio galaxies (HERGs) that are seen as flat-spectrum radio quasars (FSRQs), or as low or intermediate-frequency peaked BL Lac objects (LBLs or IBLs), when viewed nearly end-on.

A key parameter describing any relativistic jet is the jet Doppler factor.[a] While estimates of the jet Doppler factors for the powerful jets tend to be relatively consistent, estimates of the Doppler factors of weak-jet sources can be wildly discrepant depending on the method and the wavelength used, a phenomenon nicknamed the "Doppler crisis".[2] The discrepancy becomes particularly apparent when considering

[a]The Doppler factor $\delta = 1/(\gamma(1-\beta\cos\theta))$, where θ is the viewing angle, $\beta = v/c$, and $\gamma = (1-\beta^2)^{-1/2}$ is the bulk Lorentz factor.

the constraints on the Doppler factor that are obtained when observing at very high-energy gamma-rays. To date, about 46 HBLs have been detected at TeV energies by atmospheric Cherenkov telescopes such as H.E.S.S., MAGIC, and VERITAS; these are the so-called TeV blazars. The Doppler crisis indicates that these intrinsically weak jets from the TeV HBLs are likely to be more complex in their internal structure than their more powerful cousins; in this brief review we investigate the evidence and the proposed mechanisms for this.

2. High Doppler Factor Estimates

High Doppler factor estimates for the TeV blazars arise either from fits to the multiwavelength spectra (e.g., Refs. 3, 4, 5), or from constraints imposed by rapid variability. When fitting multiwavelength spectra, the emission model used is important, and the highest Doppler factors are typically obtained using the one-zone synchrotron self-Compton (SSC) model. Some TeV blazars vary in TeV gamma-rays on timescales as short as a few minutes; causality and opacity arguments then imply Doppler factors approaching 100.[6–8] Various specific fast variability scenarios have been considered, but all invoke highly relativistic motion of the gamma-ray emitting plasma.[9–12]

3. Low Doppler Factor Estimates

3.1. *VLBI Imaging*

Many of the low Doppler factor estimates for these sources come from imaging studies; such imaging provides constraints on jet parameters independently of those obtained from spectral fitting or variability arguments. The only way to directly image blazar jets on the parsec-scale is in the radio with VLBI. We have been conducting an observing campaign to produce multi-epoch parsec-scale images of every TeV HBL north of $-40°$ declination without prior VLBI data, using the Very Long Baseline Array (VLBA). Most TeV HBLs are too faint (correlated flux densities as low as 5 mJy) to be included in other large VLBA programs such as MOJAVE, so separate dedicated observations are needed. We recently published first epoch images of twenty new TeV blazars,[13] and kinematic analyses of multi-epoch images is ongoing. Images and calibrated data are available at the project website.[b] A sample VLBA image from this campaign is shown in Figure 1.

Our prior VLBA studies indicated the absence of rapidly moving features in the jets of TeV HBLs; jet components were either nearly stationary or slowly moving ($<\sim 1c$).[14] The latest distribution of apparent jet speeds,[c] including eight previously unpublished sources, is shown in Figure 2. These new measurements will be discussed further in a forthcoming publication. With the new apparent speeds, a

[b] www2.whittier.edu/facultypages/gpiner/research/archive/archive.html
[c] The apparent jet speed $\beta_{app} = \beta \sin\theta/(1 - \beta\cos\theta)$.

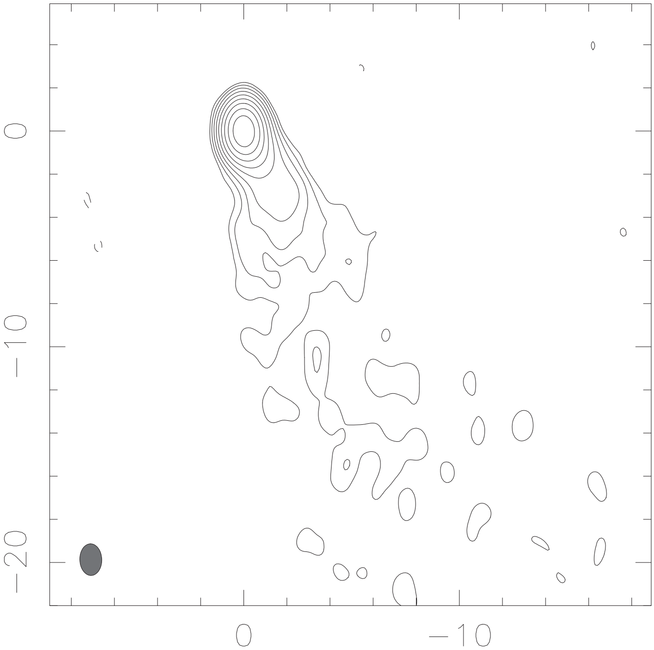

Fig. 1. VLBA image of RGB J0710+591 at 8.4 GHz from 2015 Apr 30. Axes are in milliarcseconds. The lowest contour is three times the rms noise level of 22 μJy beam^{-1}, other contours are each a factor of two higher. The peak flux density is 31.5 mJy beam^{-1}. The beam is 1.47 by 1.02 mas at a position angle of 1.6°.

mildly superluminal tail to the distribution is now evident for the first time; however, the majority of the TeV HBLs have peak apparent speeds of only about $1c$. Other studies confirm this dearth of fast-moving components, even after powerful flares.[15] If such slow apparent speeds are combined with the high Doppler factors implied by the TeV data to solve for Γ and θ, then very small viewing angles ($\theta << 1°$) result. Such small viewing angles imply tiny opening angles, huge linear sizes, and huge numbers of parent objects, showing that the combination of *both* high Doppler factor and slow apparent speed in the same jet region is unphysical. If we instead assume realistic viewing angles of a few degrees, then the observed apparent speeds imply only modest Lorentz and Doppler factors of a few.

If the VLBI core can be resolved, then the brightness temperature of the core also provides an indicator of the amount of Doppler boosting. Measurements of core brightness temperatures in TeV HBLs[13] do not actually require *any* Doppler boosting to reduce their values below measured intrinsic limits.[16] Other indicators of low Doppler factors and Lorentz factors in TeV HBLs from VLBI imaging include measurements of core to extended flux ratios[17], and jet morphologies consisting of large opening angles and patchy uncollimated structure beyond a few parsecs from the core, suggestive of low-momentum outflows (see Figure 1). The lack of detection of counterjets in the VLBI images for any TeV HBL[13,18] requires that the Doppler

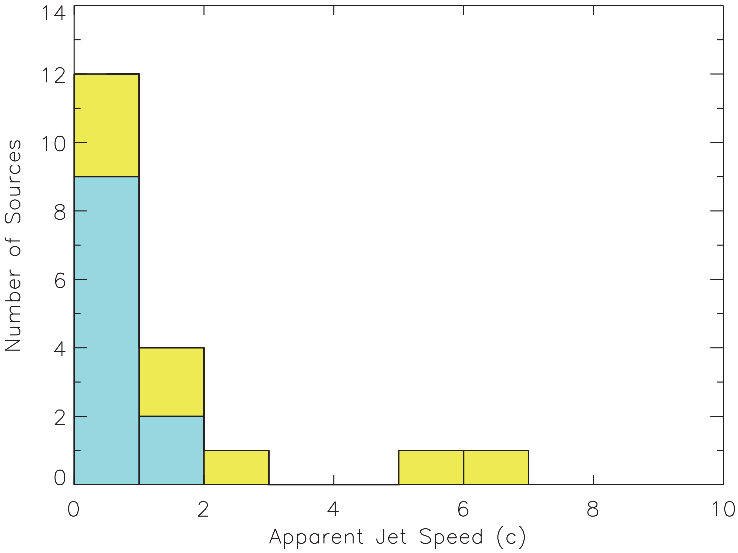

Fig. 2. Histogram of the fastest apparent jet speed in each of the 19 TeV HBLs studied in our program to date. New sources with previously unpublished speeds are shown in yellow (8 sources). Sources previously published in Ref. 14 are shown in blue (11 sources).

factor cannot be arbitrarily low, and values of δ and Γ of a few are most consistent with the combined VLBI data.

3.2. *Unification*

Work attempting to unify weak-jet sources such as HBLs with their putative FR I parent objects also requires lower Doppler factors and Lorentz factors than those implied by the TeV observations. Debeaming a prototypical HBL such as Mrk 421 using a single high Lorentz factor results in an object well outside the range of measured FR I properties.[19] Overall, the population of weak-jet sources (HBLs) follow a debeaming curve in the ($\nu_{\rm peak}$,$L_{\rm peak}$) plane that is much shallower than that of the strong-jet sources.[20] Such a shallow debeaming curve requires a jet with velocity gradients (e.g., a jet with a Lorentz factor that decreases from 15 to 3).[20] Similarly, boosting up the observed properties of an FR I sample results in reasonable 'blazar' properties only when a relatively low Lorentz factor of $\Gamma \sim 3$ is adopted.[21]

4. Possible Resolutions

An obvious resolution to the Doppler crisis is for multiple Doppler factors to co-exist in the same jet on parsec scales through jet velocity structures. One such structure is a jet that decelerates along its length.[22] In such a jet, the fast inner part sees blueshifted photons from the slower outer part, reducing the high Lorentz factor required in the fast portion. This is a general feature of models with velocity structures; radiative interaction among the different regions allows the SED to be reproduced without the extremely high Lorentz factors and Doppler factors characterizing single-zone models. Another possible velocity structure is a transverse one with a fast central spine and a slower outer layer. Such structures are expected to form from interaction of the jet with the external medium in weak-jet sources.[23] Radiation from spine-layer jets has been considered by Ref. 24, and they show that radiative interaction between the spine and layer naturally decelerates the spine, producing both radial and transverse velocity structures in the same jet, and physically motivating the deceleration posited by Ref. 22.

If such spine-layer jets are present in the TeV HBLs, then the layer is expected to dominate the radio emission due to its SED shape, even with a lower Doppler factor than the spine.[24] An observational signature of this in VLBI images would be a limb-brightened transverse profile for the jet. We are actively searching for such structures in our current VLBA observations, and we reported two such profiles among the twenty new sources analyzed in Ref. 13. We note that spine-layer structures may be difficult to detect in VLBI images even if they are present; observations must both resolve the region in the radial and transverse directions, and have sufficient sensitivity to faint jet structure. Limb-brightened intensity profiles may also be produced by other mechanisms, such as a helical magnetic field.[25]

Numerous other possible jet velocity structures have also been proposed (some to model a single source) that we cannot describe in detail in this brief review. These include models consisting of multiple blobs,[26] fast moving "needles" within the main jet,[9] "minijets" powered by magnetic reconnection events,[10,27,28] faster moving leading edges of blobs,[29] and many turbulent subregions within the jet.[11,30]

5. Conclusions

A consistent picture may be emerging that resolves many of the problems associated with the Doppler crisis in TeV blazars. In this picture, the intrinsically weak-lined AGN (the LERGs) have inefficient accretion modes that produce weak jets. Weak jets favor the interaction of the jet walls with the external medium, forming a slow layer. Radiative interaction between the spine and the layer decelerates the spine, and eventually disrupts the jet. Such jets would dominate the X-ray and TeV-selected samples because selection in these bands favors rare high-synchrotron peak sources, which are drawn from the low end of the luminosity function where the source density is largest.[1] Continuing analysis of our ongoing VLBA observations will reveal if high-resolution imaging of the full set of TeV HBLs supports this general picture, and will help to clarify the role of other specific models.

Specifying the nature and extent of velocity structures in TeV HBLs is also critical for quantifying any possible neutrino production from these jets. The TeV blazars have been postulated as a potential source of the PeV neutrinos detected by

IceCube,[31] and such emission may be greatly enhanced by any spine-layer velocity structures that are present.[32]

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