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The Compact Structure of Blazars at High Frequencies

Alan P. Marscher

Institute for Astrophysical Research, Boston University, 725 Commonwealth Ave., Boston, MA 02215, USA

Abstract. VSOP-2 will provide a quantum leap in angular resolution at 43 GHz. Whether we can make use of this technological breakthrough depends critically on whether everything from the core of the jet to the central engine is opaque at this frequency. I argue that current data from the VLBA indicate that the core is often a physical structure rather than the location in the jet where the optical depth becomes unity. New superluminal knots identified by their polarization position angle are sometimes seen upstream in 43 GHz VLBA images. X-ray and γ-ray flares in BL Lac occur both as a knot propagates down a region with helical magnetic field and when it passes through the core. This bodes very well for the ability of VSOP-2 to explore the most interesting regions of blazar jets.

1. Introduction

The prospect of an antenna in high Earth orbit capable of joining ground-based VLBI arrays at 43 GHz is an exciting one for studies of blazar jets. The angular resolution of ~ 40 μas that this can provide will allow us to examine in exquisite detail features that are only barely resolved in our current images. It will also probe the region of the jet upstream of the core if any millimeter-wave emission is produced there and can reach us without severe attenuation from absorption. Whether that is the case depends on the nature of the core. My collaborators and I have been exploring the structure, polarization, and time variability of blazar jets with the VLBA at 43 GHz for 13 years. Over the past ten years, we have combined this imaging at a resolution of ~ 100 μas with polarization monitoring at shorter millimeter and optical wavelengths. Our analysis of this rich dataset suggests that we can in fact see new superluminal knots upstream of the core before they pass the core and proceed down the jet. Furthermore, we find that, in at least one case, an optical to γ-ray outburst occurred just before a new knot appeared upstream of the core. The indications are therefore very positive for the ability of VSOP-2 to explore the inner secrets of relativistic jets.

2. The Nature of the Core

There are various possible physical reasons for a bright, compact feature to appear at the upstream end of a jet. Because the underlying geometry of a jet is a cone, the core could be the $\tau \sim 1$ surface, i.e., the densest region whose radiation at the observed frequency ν is not strongly cloaked by absorption (Blandford & Königl 1979). Here, τ is the optical depth. In this case, the position of the core should move toward the central engine at higher frequencies (Königl 1981; Marscher 1980). This effect is reported in some extragalactic jets (e.g., Lobanov 1998), but is not seen in others (e.g., Mittal et al. 2006). We can explain cores with similar positions at two frequencies if the jet contains multiple bright stationary features, a situation that is common in blazar jets (Jorstad et al. 2001, 2005). The core would then be either the $\tau \sim 1$ surface or the first stationary hotspot downstream of that surface, whichever is more intense.

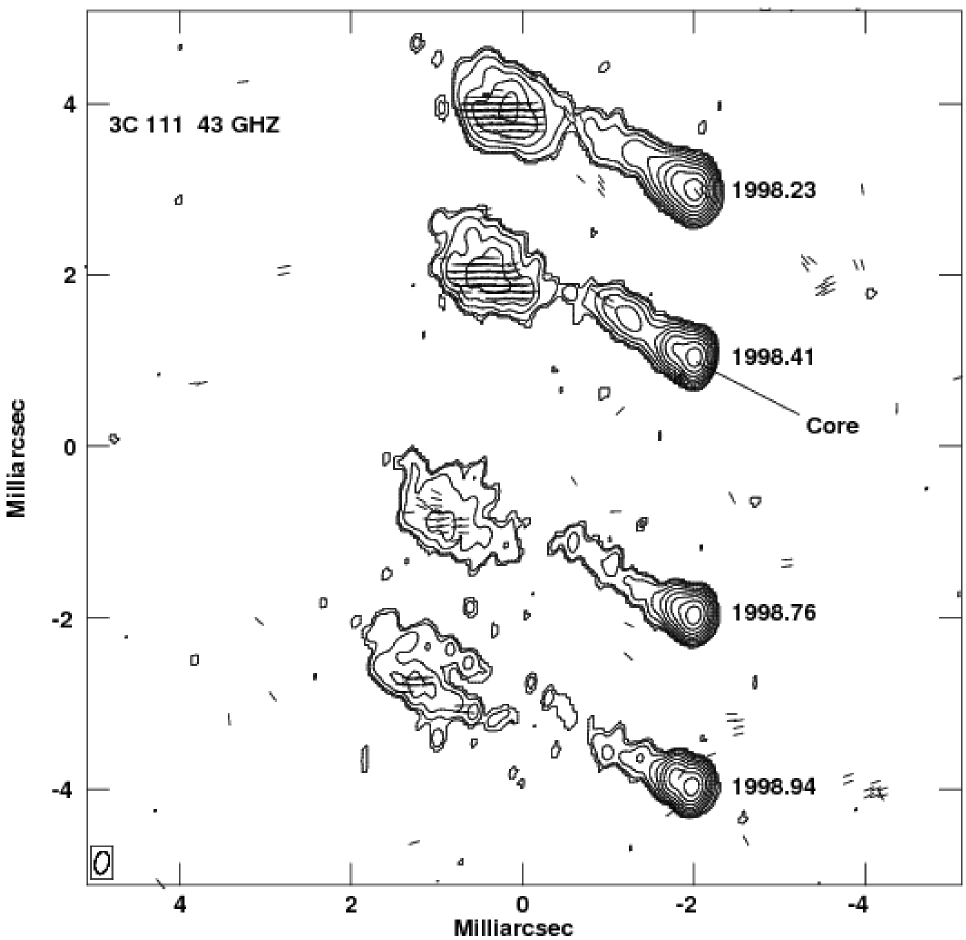

Figure 1. Series of 43 GHz VLBA images of the radio galaxy 3C 111. The core is indicated. An extended emission region is seen moving superluminally toward the east-northeast. Contours correspond to 0.25, 0.5,..., 64% of the peak intensity of 0.82 Jy beam^{-1}. Polarization sticks indicate direction of the electric vector and are scaled at 0.025 Jy beam^{-1} per milliarcsec.

If the core is the $\tau \sim 1$ surface, there is little hope to image the portions of the jet that lie upstream of it unless we observe with VLBI at frequencies higher than the self-absorption turnover in the spectrum, generally $\nu \gtrsim 50$ GHz and in many cases much higher (Impey & Neugebauer 1988; Bloom et al. 1999). But if, for example, the core is a standing shock wave (perhaps a conical recollimation shock; Daly & Marscher 1988; Gómez et al. 1995; Bogovalov & Tsinganos 2005), there can be a region between the $\tau \sim 1$ surface and the core that is accessible at somewhat lower frequencies if the angular resolution is high enough. There is observational support for the notion that in some jets the core is a conical shock that compresses a chaotic ambient magnetic field in the passing plasma. The polarization structure expected in this case (Cawthorne 2006) agrees with that found in some cores of blazars (Jorstad et al. 2007).

Jets in which the core is a standing conical recollimation shock, with turbulent jet plasma flowing through it, should possess some well-defined polarization characteristics. The core should be weakly polarized at 43 GHz, with fluctuations in both degree and position angle of polarization χ. In support of this, the cores in polarized intensity VLBA images at 43 GHz have degrees of polarization of order several percent or less (Lister & Smith 2000; Marscher et al. 2002b; Lister & Homan 2005; Jorstad et al. 2005, 2007). In addition, the expected rapid variability of the polarization has been detected in blazars observed during intensive campaigns. The strongest result thus far is for the quasar 0420−014 (D'Arcangelo et al. 2007). The optical polarization position angle χ(opt) rotated by about 140° over 10 nights, while χ(43 GHz) rotated by about 80°, in step with the optical rotation, over a segment of the same time interval. The fluctuations in χ as well as degree of polarization agree with variations expected when many cells of randomly oriented magnetic field pass through the emission region for a restricted time period (Jones et al. 1985; Jones 1988). Besides indicating the nature of the core, the synchronous variation of χ(opt) and χ(43 GHz) demonstrates that the emission at 43 GHz and in the optical bands is co-spatial. The co-spatiality is only partial, however: the degree of polarization at 43 GHz is lower than that in the optical band, so there must be an additional, essentially unpolarized emission component at 43 GHz. Nevertheless, the observations imply that most of the optical radiation comes from the millimeter-wave core rather than from farther upstream in the jet.

3. Knots Upstream of the Core

If the core is something other than the $\tau \sim 1$ surface, we should be able to see knots propagating from closer to the central engine before they reach the core. This, of course, requires both that the knots form upstream of the core and that electrons can be energized in this region. If the knots are shocks, they can either form near the base of the jet if there is an abrupt and substantial increase in either the velocity or pressure of the flow, or farther downstream if the change is more gradual. An example of the latter would be an increase in velocity such that the Lorentz factor changes from Γ_1 to Γ_2 over a time t, where the relative velocity $\beta_{\rm rel}$ is greater than the local sound speed. In this case, the fluid steepens into a shock over a distance (in our frame) $\sim ct/(\beta_2 - \beta_1)$. As an example, if $\Gamma_1 = 10$ ($\beta_1 = 0.9950$), $\Gamma_2 = 20$ ($\beta_2 = 0.99875$), and $t = 1$ day, the shock will form at a distance of ~ 0.2 pc. The relative speed in this case is $\beta_{\rm rel}c = 0.60c$, which is a bit higher than the sound speed of 0.577 in a plasma with energy density much greater than its rest-mass energy density. Hence, a weak shock can form even in this extreme case.

How far away is the core from the black hole? This is a question that cannot be answered by observing most blazars, since nearly all the observed emission originates in the jet. Radio galaxies with jets viewed from the side can potentially do this, but then we have no assurance that what appears as the core in these objects is the same physical structure as the core in a jet pointed toward us. There are, however, a few objects that are hybrids, with blazar-like jets seen at radio wavelengths and X-rays that arise from the central engine. In one of these, the radio galaxy 3C 120, my collaborators and I (Marscher et al. 2002a) found that there is a time delay of ~ 60 days between dips in X-ray flux and the passage of superluminal knots through the core. After taking into account the apparent superluminal motion and projection, we can say that the core lies at least 0.4 pc from the black hole.

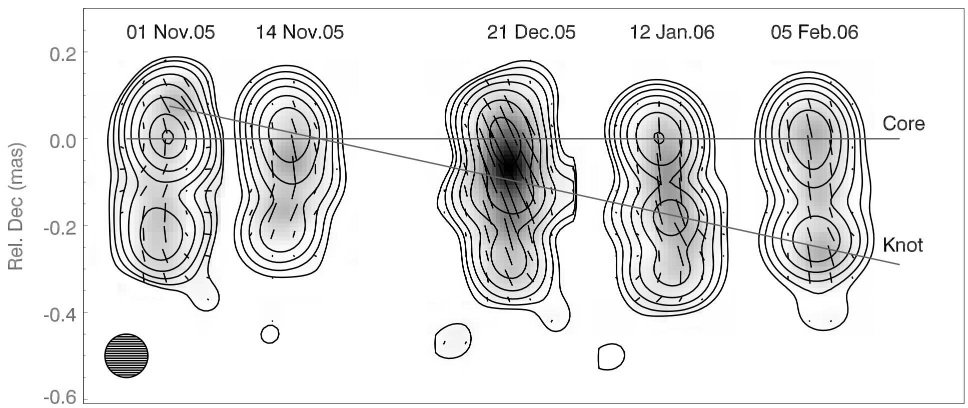

Figure 2. Sequence of VLBA images of BL Lac at 43 GHz during and after the double outburst in late 2005. A superluminal (5.0c) knot, identified by its unique polarization position angle, is first seen upstream of the core before it passes the core and continues downstream. The contours represent total intensity and start at 0.5% of the peak, 2.30 Jy beam^{-1}. The gray scale indicates polarized intensity, which has maximum value of 0.215 Jy beam^{-1} (on 21 Dec. 2005). The polarization sticks are oriented along the direction of the local electric vector.

During 3 years of bimonthly VLBA monitoring of 15 blazars and radio galaxies, (Jorstad et al. 2005) found an example of a distinct polarization direction from emission slightly upstream of the core in OJ287, followed by the same polarization position angle appearing in a superluminal knot downstream of the core. More recently, my collaborators and I have followed some blazars with more frequent sampling. We found that in BL Lac a knot with a distinct polarization direction first appeared upstream of the core and then propagated through the core and down the jet at an apparent speed of 5c (see Fig. 2). As Figure 3 shows, a major outburst in optical, X-ray, and possibly TeV γ-ray flux occurred before the knot appeared on the VLBA images (Marscher et al. 2008).

A second optical and X-ray outburst occurred as the knot passed through the core. Near the peak of the first flare, the optical polarization direction rotated by 240°. We interpret this in the same manner as Kikuchi et al. (1988): a knot followed a spiral path as it moved through a region with a tight helical magnetic field. We identify this region of helical field as the zone where the jet is accelerated and collimated (Vlahakis & Königl 2004; Vlahakis 2006).

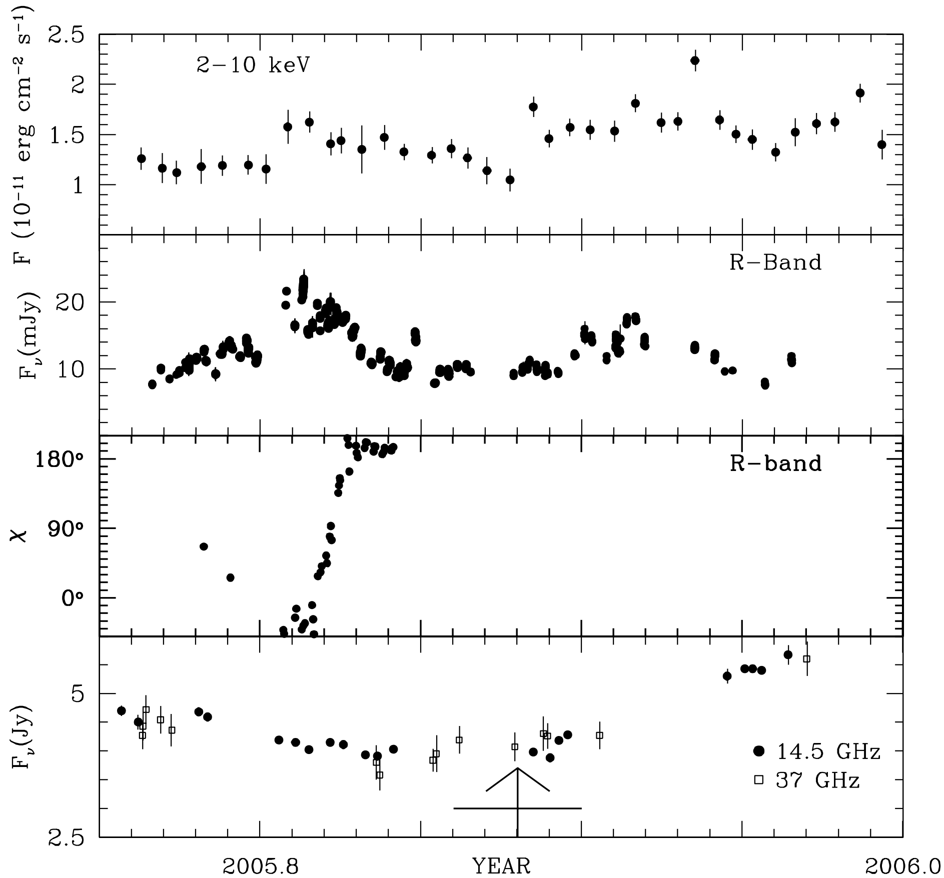

Figure 3. X-ray, optical, and radio flux, as well as optical polarization position angle χ(opt), vs. time for BL Lac in late 2005. The time when the superluminal knot was coincident with the core is marked by an upward arrow.

4. Conclusions

In cases in which the core is the site in the jet where the optical depth at 43 GHz is unity, the extra resolution allowed by VSOP-2 will only be adequate to see details in that region. However, there is mounting evidence that, in at least some blazars, the core is a physical structure such as a standing conical shock. In these cases, VSOP-2 has the possibility of probing the region between the core and the acceleration and collimation zone of the jet. Furthermore, we know that at least some of the optical, X-ray, and probably γ-ray emission comes from the core region that VSOP-2 will be able to image. I look forward to many exciting discoveries that this will provide!

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