Polarization measurements in VLBI

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Since the first successful VLBI polarization measurements in the early 1980's, there has been immense progress in this field from both a technical and astrophysical point of view. A number of the most interesting recent results in polarization VLBI will be discussed. Although many of these have been made possible by the frequency flexibility and instrumental stability of the VLBA, the EVN remains an extremely valuable instrument for polarization work.

1. Introduction

Even the earliest VLBI polarization measurements – made at 6 cm with only four stations on continental US baselines – revolutionized our view of the parsec scale structures of active galactic nuclei (AGN). The reason for this is simple: it is impossible to make sound deductions about the dominant forces acting on the parsec-scale flows probed by VLBI observations without knowledge of the orientation and degree of order of the underlying magnetic (**B**) field associated with the radio synchrotron radiation.

It early became clear that, in most cases, the **B** fields in VLBI jet components are roughly either aligned with or transverse to the local jet direction, and that, to some extent, the **B**-field structure in the VLBI jet depends on the strength of the optical line emission (Gabuzda et al. 1989; Cawthorne et al. 1993). Longitudinal fields were often interpreted as the effect of shear between the jet and a surrounding medium, while transverse fields were usually thought to be associated with compression of the jet plasma by shocks. Independent of details of the interpretation, however, the availability of information about the linear polarization of the VLBI-scale emission dramatically changed our view of the parsec-scale radio emission of AGN.

2. In Quest of Higher Resolution

There has been a definite push toward higher resolution as VLBI polarization techniques have matured. This is quite natural in connection with many astrophysical questions, since it allows more accurate estimation of the properties of individual polarized features, as well as better determination of the relationship between these properties and the jet flow – e.g. the orientation of the polarization position angle relative to the local jet flow direction. Generally speaking, there are two ways to achieve higher angular resolution in VLBI: observing at higher frequency or with longer baselines. The former has been realized by extending VLBI polarization measurements to ever shorter centimeter wavelengths – 7 mm and 1.3 cm are now routine on the VLBA. The latter has been realized through *VSOP* space VLBI polarization observations. Both of these approaches are required if we wish to obtain as full a picture as possible of the physical principles dominating in the relativistic jet flows.

Recent high-frequency polarization observations have revealed a number of interesting features. For example, the 1.3 cm VLBA+Effelsberg total-intensity (I) and linear polarization (P) images of Gabuzda & Cawthorne (2001) confirmed that the polarization position angles χ in the jets of BL Lac objects – AGN with relatively low-luminosity optical line emission – tend to be aligned with the local jet direction θ, and showed that this trend is stronger in these 1.3 cm images than in 6 cm global images: eight of ten jet components with detected polarization had χ aligned with θ to within 12°. Since the degrees of polarization of these features are high enough that they must be optically thin, this implies that the **B** field is *transverse* to θ. In some cases, χ clearly remains aligned with the jet as it curves, providing useful information about the mechanism for forming the transverse **B** field (see the discussion of the *VSOP* results for 1803+784 below).

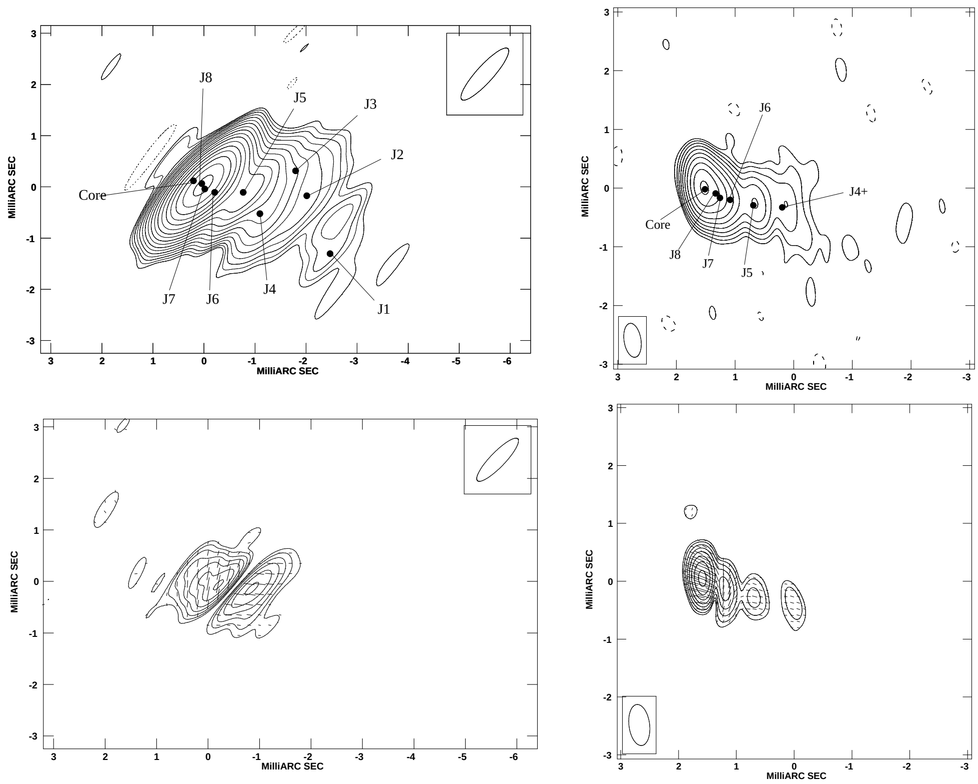

FIGURE 1. Top : 6 cm *VSOP I* (left) and *P* (right) images of OJ 287 on April 4, 1999. Bottom: 1.3 cm VLBA *I* (left) and *P* images of OJ 287 on March 19, 1999. The superposed sticks show the orientation of χ. The *I* and *P* structures in the inner jet correspond very well, and the roughly 90° rotation in the observed core χ orientation is due to the fact that the core is optically thick at 6 cm but optically thin at 1.3 cm (Gabuzda & Gómez 2001a).

Gómez et al. (1999) have obtained 1.3 cm and 7 mm *I* and *P* images of the relatively nearby AGN 3C 120, which clearly show that the core is unpolarized, and that the dominant **B** field in most of the jet is longitudinal. They also provide evidence that several bright jet knots displaced from the main jet ridgeline are associated with interactions between the jet and the surrounding medium. Although the 7 mm images provide higher resolution, the 1.3 cm images follow the jet further from the core, so that they provide information about the jet flow beyond the visible end of the 7 mm jet. Gómez et al. (2000) have recently analyzed the evolution of this source's *I* and *P* structure at 1.3 cm over 16 epochs, providing the most detailed view of parsec-scale structural changes currently available.

In their 1.3 cm and 7 mm VLBI studies of a sample of about 20 AGN, Lister & Smith (2000) considered possible correlations between the optical and high-frequency radio polarization. Their analysis provides evidence for correlations between the optical and radio core degrees of polarization, and also between the optical degree of polarization and the radio core luminosity at 7 mm. This suggests a close link between the optical and compact radio emission, as proposed earlier by Gabuzda, Sitko & Smith (1996) based on a comparison of nearly simultaneous optical and 6 cm VLBI polarization measurements. Such coordinated radio + UV/optical/IR polarization measurements are still rare, and a wealth of information remains to be gleaned from analyses of this sort.

Space VLBI observations provide a unique opportunity to achieve higher angular resolution without losing sensitivity to optically-thin (steep-spectrum) jet emission. *VSOP* polarization observations are now available for about half a dozen AGN (Gabuzda 1999, 2000; Moellenbrock et al. 2000; Gabuzda & Gómez 2001a,b). One of the most striking results is the discovery that the small-scale jet in the BL Lac object 1803+784 is appreciably curved, and that the **B** field in the jet is everywhere transverse, interpreted as evidence for a helical **B** field associated with this jet (Gabuzda 1999; see also Pushkarev & Gabuzda, these proceedings). In the case of OJ 287, comparison of 6 cm *VSOP* images with 1.3 cm VLBA images obtained only two weeks earlier showed a very good agreement between the I and P structures at the two wavelengths – except that χ for the 6 cm and 1.3 cm core components were nearly perpendicular to each other (Gabuzda & Gómez 2001a; Fig. 1). This was interpreted as a consequence of the fact that the core was optically *thick* at 6 cm (so that $\chi \parallel \mathbf{B}$), but optically *thin* at 1.3 cm (so that $\chi \perp \mathbf{B}$): both measurements thus imply that the core **B** is transverse to the direction of the inner jet. It is clear that polarization sensitivity must be an important part of future space VLBI observations (e.g. the proposed *VSOP-2* and *ARISE* missions).

3. Probing the Surrounding Medium

In our eagerness to obtain as high angular resolution as possible, we must not forget the value of relatively low-frequency VLBI polarization observations, which can offer unique information about the medium through which the VLBI jets propagate. There are two reasons for this: (1) Faraday rotation of the plane of linear polarization during passage of radiation through a region of magnetized thermal plasma increases as λ^2, where λ is the observing wavelength; (2) higher-frequency observations will tend to be less sensitive to interactions between the jet and surrounding medium, due to their decreased sensitivity to steep-spectrum jet emission. For this reason, multi-wavelength VLBI polarization observations at "moderate" centimeter wavelengths very nicely complement higher-frequency observations such as those described above.

A number of recent studies have revealed enhanced thermal-plasma densities near the cores of AGN. Taylor (1998, 2000) has reported high rotation measures in the core regions of several quasars, and evidence for variability in the observed rotation measure of the VLBI core of 3C 279 on a time scale of about 1.5 years. Similarly, Reynolds, Cawthorne & Gabuzda (in prep.) have found an enhanced and variable rotation measure in the VLBI core of BL Lac. In the case of 1803+784, there is evidence that the rotation measure is highest near the VLBI core and falls off with distance from the core (Gabuzda, Chernetsky & Cawthorne, in prep.).

All these results suggest the presence of thermal plasma on parsec to sub-parsec scales that is concentrated toward the core region. However, there are also cases in which the rotation measures are highest somewhere in the jet, well separated from the VLBI core. One example is the high-rotation-measure quasar 3C 119: Nan et al. (1999) demonstrated that the Faraday-rotating material is concentrated near a bright component situated at a sharp bend in the jet, suggesting that this bend is the result of a collision between the jet and a dense cloud of thermal plasma. More recently, Gabuzda, Pushkarev &

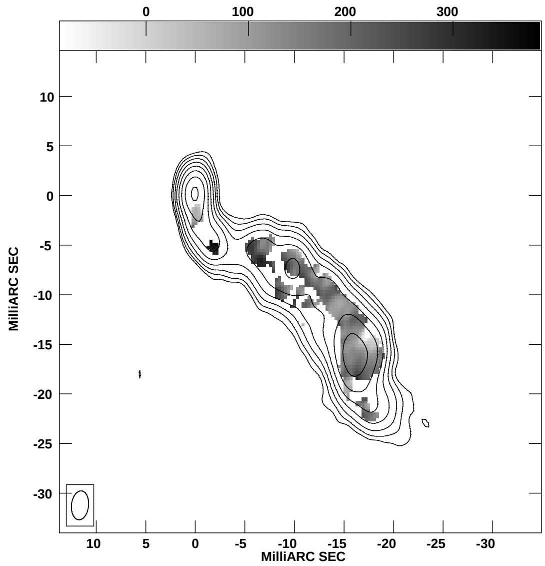

FIGURE 2. 6 cm VLBA I image of 0820+225 with the rotation-measure distribution (in rad/m^2) superimposed. The non-uniformity of the distribution of thermal plasma is evident (Gabuzda, Pushkarev & Garnich, in prep.).

Garnich (in prep.) have discovered the presence of large rotation-measure gradients over the extended, complex VLBI jet of 0820+225 (Fig. 2).

4. The First Circular Polarization Measurements

Recently, the first detection of circular polarization on VLBI scales was reported by Wardle et al. (1998). Circular polarization has now been detected in about 20 AGN (Wardle 2001), and variability of the circular polarization in the VLBI core region of 3C 279 has been reported (Homan & Wardle 1999). The intrinsic degree of circular polarization of incoherent synchrotron radiation is very small, and Wardle et al. (1999) suggest that the most likely mechanism for producing the observed circular polarization is so-called Faraday conversion of linear to circular polarization (Jones & O'Dell 1977). If this is the case, joint analyses of VLBI-scale circular polarization measurements and Faraday rotation/depolarization measurements can provide interesting constraints on the composition of the relativistic jets. Essentially, if appreciable circular polarization is observed in the absence of significant Faraday rotation and depolarization, this implies that the positive charge carriers in the jets must be predominantly positrons rather than protons: the Faraday rotations for positrons and electrons are equal in magnitude and opposite in direction, so that the net rotation/depolarization is zero.

However, Faraday conversion is not the only known mechanism that could give rise to the observed circular polarization. For example, helical **B** field geometries could lead to appreciable circular polarization without accompanying Faraday rotation, due to the superposition of the radiation from the far and near sides of the jet (Wardle 2001); this possibility seems particularly pertinent given growing evidence from linear polarization measurements that helical **B** fields may be common on VLBI scales (Pushkarev & Gabuzda, these proceedings). In addition, it is not clear that coherent mechanisms can be ruled out (e.g. Benford & Lesch 1998). Therefore, the detection of circular polarization on VLBI scales seems to be on firm footing, but the correct interpretation of this result is not yet clear.

5. The Nature of Intraday Variability

Centimeter-wavelength variations in both total and polarized flux density on timescales less than a day – so-called "intraday" variability, or IDV – have been observed in a number of strong extragalactic radio sources (see Wagner & Witzel 1995, for example). It is not yet clear what fractions of such variations are intrinsic and extrinsic; i.e., due to refractive scintillation in the interstellar medium (Rickett 1986, Heeschen et al. 1987, Rickett et al. 1995). It seems clear that the most extreme IDV is dominated by scintillation (Kedziora–Chudczer et al. 1998; Dennett-Thorpe & de Bruyn 2000), however, it is difficult to explain all the variations in this way. The situation is further complicated by the fact that the source sizes implied by the most extreme variability are small enough that we would probably expect the sources to *both* scintillate and show rapid intrinsic variability.

It is of interest to study IDV with the highest possible resolution, in order to better isolate the regions in the source that are varying and determine their parameters. Polarization sensitivity is also highly desirable, since the amplitude of P variations often appreciably exceeds that for the corresponding I variations. Gabuzda et al. (2000a,b, 2001) have analyzed polarization IDV observed during several VLBI polarization experiments jointly with simultaneous integrated I and P measurements obtained with the Very Large Array. The combination of simultaneous VLBI and integrated data is very powerful: the sensitive VLA observations provided a means to monitor the I and P fluxes of the sources, while the VLBI data made it possible to pinpoint the location of varying component(s).

In a number of cases, it has been possible to demonstrate that integrated polarization IDV occurred in the VLBI core (e.g. 0735+178: Gabuzda, Wardle, & Roberts 1989; 0917+624: Gabuzda et al. 2000b; 2131-021: Gabuzda et al. 2001). In the case of 2155–152, only one of two polarized VLBI components varied, while the other remained constant (Gabuzda et al. 2001). The most surprising result was the detection of polarization IDV in 0716+714 about 30 mas from the VLBI core (Gabuzda et al. 2000a): the presence of sufficiently compact structures so far from the VLBI core was quite unexpected. These results suggest that IDV can occur in compact features on a fairly wide range of scales, and that there must be an appreciable intrinsic component to the variability. There is every reason to believe that future joint VLBI and integrated polarization observations of rapidly varying sources will continue to provide useful constraints on mechanisms for IDV.

6. The EVN and Polarization VLBI

I would like to conclude with a few words about the role of the EVN in current and future polarization VLBI observations. Although there is no doubt that the VLBA is a powerful tool for polarization VLBI, the EVN antennas are still extremely valuable instruments in this field. Here are a few reasons why this is true.

- EVN observations make it possible to **probe intermediate scales** between milliarcseconds and arcseconds, about which relatively little is known.
- **Global polarization VLBI observations** involving the most sensitive EVN antennas provide a wide range of sensitive baselines for high quality imaging.
- Sometimes, the **sensitivity** of individual antennas is a key issue – the ability to detect polarization directly on individual baselines is crucial for some astrophysical problems. For example, the detection of polarization IDV on scales of tens of milliarcseconds in 0716+714 (Gabuzda et al. 2000a) would have been impossible with the VLBA alone (key information was provided by the short, sensitive Effelsberg–Medicina baseline).

• **Simultaneous integrated** I **and** P **measurements** with the Westerbork array and MERLIN can facilitate reliable calibration of the polarization angles.

The first pilot experiments employing frequency switching at the Effelsberg and Medicina antennas and the Westerbork array were carried out in May–June 2000. Thus, multi-frequency global experiments are now starting to become possible for the first time. With time, frequency agility should become available on more EVN antennas, increasing the coverage attainable with such observations and making them more routine.

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