POLARIZATION OF THE JET OF PKS 0521—36

W. B. SPARKS
Space Telescope Science Institute

G. K. MILKY
Sterrewacht Leiden; and Space Telescope Science Institute

AND

F. MACCHETTO
Space Telescope Science Institute

Received 1990 June 4; accepted 1990 July 13

ABSTRACT

Optical polarization has been detected from the jet in the radio galaxy PKS 0521—36. Except for M87 and 3C 66B, PKS 0521—36 is the only other radio galaxy whose jet has been measured to be optically polarized. The polarization position angle contrasts with that of M87 but is similar to that of the quasar 3C 273 in that the magnetic field is aligned parallel to the jet. PKS 0521—36 contains a luminous BL Lac type nucleus whose polarization is approximately parallel to the jet. The difference in the observed polarization directions between the PKS 0521—36 and M87 jets may be connected with the presence of this bright optical nucleus. Either the core of PKS 0521—36 is currently more active than M87 or the jet axis is oriented closer to the line of sight.

Subject headings: BL Lacertae objects — galaxies: individual (PKS 0521—36) — galaxies: jets — polarization — radio sources: galaxies

I. INTRODUCTION

Although the existence of optical jets in M87 and 3C 273 had long been known (Curtis 1918; Greenstein and Schmidt 1964), the discovery that radio jets are widespread (e.g., van Breugel and Miley 1978; Miley 1980) established that synchrotron jets play a fundamental role in the energetics of radio sources.

Because optical synchrotron decay times are much less than those at radio wavelengths, optical measurements provide information about more recent particle acceleration within the knots of synchrotron jets. Despite the hundreds of galaxies and quasars now known to possess radio jets, optical jets have still only been detected in a very few cases (e.g., Butcher et al. 1980; Keel 1988) and the optical polarization has only been mapped for M87 (e.g., Schöier, Meisenheimer, and Röser 1988; Fraix-Burnet, Le Borgne, and Nieto 1987) and 3C 273 (Röser and Meisenheimer 1986; Scarrott and Warren-Smith 1987). In addition, Fraix-Burnet, Nieto, and Poulain (1989) report the probable detection of polarized emission in knots associated with 3C 66B.

Here, we present the results of optical polarization observations for the extragalactic jet in the radio galaxy PKS 0521—36. A prominent optical jet had previously been found in this galaxy, as well as a complex extranuclear emission-line region, prompting a number of detailed spectroscopic and morphological studies (Danziger et al. 1979, 1983; Wierlick 1981; Sol 1983; Keel 1986, 1988; Cayatte and Sol 1987; Boisson, Cayatte, and Sol 1989). Keel pointed out that the jet structure is comparable to that in M87, although at a redshift of \( z = 0.055 \) intrinsically more luminous. Here, we show that the optical polarization properties of the jet resemble those of 3C 273, rather than M87.

II. OBSERVATIONS AND REDUCTION

Images were taken on 1989 February 10 with the ESO Faint Object Spectrograph and Camera (EFOSC) at the Cassegrain focus of the 3.6 m telescope at the European Southern Observatory. The light passes through a collimator in which there are two filter wheels. Polarizing filters utilizing HN38 polaroid were mounted in the first filter wheel at position angles 0°, 45°, 90° and 135°, while a standard V filter was mounted in the second wheel.

The high-resolution RCA ESO CCD No. 8 was used as a detector—a thinned, back-illuminated chip with 1024 \( \times \) 640 15 \( \mu \)m pixels corresponding to 0"337 pixel \(^{-1}\). The CCD was used with a gain corresponding to 3.6 electrons per analog-to-digital unit (ADU), and a readout noise of \( \approx 30 \) electrons.

A 1 minute direct V image without polarizers, and four frames of 2 minutes duration using the V filter in combination with each polarizer in turn, were obtained. None of the data were saturated at or near the galaxy. The images all have FWHM \( \approx 1\)". To spatially register frames, an image section to the east of the galaxy \( \approx 1\times2\)" was used in each frame and cross-correlated against the reference V image section. A two-dimensional parabola fitted through the peak of the cross-correlation image provided the shifts, and linear resampling was used to perform the registration. Stars and galaxies within the same image section were assumed to be unpolarized and hence used to derive the relative scaling between each of the frames, as described by Sparks, Paresce, and Macchetto (1989).

The Stokes parameters were obtained as \( Q = 0.5(I_0 - I_29) \) and \( U = 0.5(I_{45} - I_{135}) \), where the prime denotes linearly
matched intensities. The polarized flux is \( I_P = (Q^2 + U^2 - \sigma^2)^{1/2} \), where \( \sigma^2 \) corrects for the biasing effects of errors (Wardle and Kronberg 1974), and the \( Q \) and \( U \) estimates used \( 3 \times 3 \) pixel averages at each image point. An independent check on the validity of the observing and reduction procedures was provided by polarization mapping of R Mon and the jet of M87 using images obtained during the same observing session. The results agreed well with published data.

III. RESULTS

a) The Jet

Figure 1 (Plate L10) shows the sum of all images at high contrast, with a galaxy-subtracted image as Figure 2 (Plate L11) showing the jet. (An empirically derived elliptical model of the galaxy was subtracted; e.g., Sparks et al. 1985.) Figure 3 contours the jet surface brightness, and Figure 4 shows the corre-

![Image](image1)

**Fig. 3.**—Contour map of the PKS 0521–36 jet for comparison with polarization vector field, Fig. 4. Axes are in pixels, 0.337 pixel \(^{-1} \), with contour levels at 3, 4, 9, 22, and 39 au and \( \mu_\nu \approx 26.76-2.5 \) log au. The morphology is identical to the VLA data of Keel (1986) seen at lower resolution, apart from the stellar "red tip" (see text).

![Image](image2)

**Fig. 5.**—Intensity profiles for the jet of PKS 0521–36 for points with polarization S/N > 3; 10 counts correspond to \( \mu_\nu \approx 24.3 \). Solid circles are total intensity after subtraction of a model galaxy, and open circles are polar-

![Image](image3)

**Fig. 6.**—Polarization degree vs. distance from the nucleus in PKS 0521–36 derived from the data of Fig. 5. The curve shows radially binned data and indicates the effect of including lower S/N polarization data. Open circles show the polarization degree without correction for underlying galaxy light.

![Image](image4)

**Fig. 4.**—Vectors showing electric vector position angle and polarization degree with correction for underlying galaxy in the vicinity of the jet. The nuclear polarization vectors are shown without correction for dilution. A polarization of 20% corresponds to 2.5 pixels in the jet, and 8.4 pixels in the nucleus.
48° ± 2°, which indicates a magnetic field within 16° of the jet axis.

Clearly the optical radiation from the jet is highly polarized, as in the well-known jets of M87 (Warren-Smith, King, and Scarrott 1984; Schlöteblie, Meisenheimer, and Röser 1988; Fraix-Burnet, Le Borgne, and Nieto 1989) and 3C 273 (Röser and Meisenheimer 1986; Scarrott and Warren-Smith 1987). The polarization position angle suggests a magnetic field predominantly lying along the jet, even at the position of the bright inner knot which is very reminiscent morphologically of knot A in the M87 jet. By contrast, the most luminous portion of the M87 jet, knot A, has a magnetic field transverse to the jet direction, although elsewhere along the M87 jet the field is primarily parallel to the jet. 3C 273 on the other hand displays a roughly constant polarization of ~15% with magnetic field along the jet; Scarrott and Warren-Smith (1987).

The radio polarization as given by Keel (1986) is high, with a peak polarization ≈ 50%. The lower spatial resolution of the optical data compared to that of the VLA data will act to dilute any fine structure in the polarization position angles. The fact that we measure polarizations as high as the radio suggests that the polarization is not strongly diluted by structure on intermediate scales (0.3'-10').

The "red tip" at the end of the jet ≈ 8° from the nucleus (Keel 1986) is not measurably polarized in this data, P ≲ 0.1, supporting the contention of Keel that it is not part of the jet.

b) The Nucleus

The nucleus of PKS 0521 – 36 has been known to be polarized for some time, as is apparent from its frequent classification as a BL Lac object. Angel and Stockman (1980) reported a 6% polarization in position angle 155° using a 4" aperture. Bailey, Hough, and Axon (1983) found a polarization of ≈ 11% using a 12° aperture, while Brindle et al. (1986) also measured a polarization of 6% using a 4" aperture. Both of these latter found a position angle of polarization of 140°.

It is clear from the imaging polarimetry that the nucleus is significantly polarized. Slight differences in point-spread function between images can cause difficulties in interpreting the polarization images of pointlike objects, so to measure the nuclear polarization we derived simulated aperture photometry for each filter and calculated the nuclear polarization from the resultant aperture magnitudes. Table 1 lists the V magnitude and percentage polarization for several radii within the galaxy. Dilution by unpolarized starlight is apparent in the larger apertures.

For comparison with the measurements cited above, within a 4" aperture we find a linear polarization of 15.5% and polarization position angle 154°, which is very similar to the previous observations. The position angle of polarization indicates a magnetic field roughly perpendicular to the radio source axis, as has been found previously for other quiescent blazars and quasars (Stockman, Angel, and Miley 1979).

c) Discussion

The detection of appreciable optical polarization in the PKS 0521 – 36 jet and its similarity with the radio polarization measurements is strong evidence that the optical radiation from the jet is synchrotron emission and that Faraday rotation effects are not important at wavelengths below the shortest observed radio bands (2 cm).

As pointed out by Keel, the galaxy is similar to M87 in many ways. In particular, the morphology of the jet and in particular the presence of a bright inner luminous "knot," its radio-to-optical colors, and the extranuclear emission-line gas (Boisson, Cayatte, and Sol 1989) resemble those of M87. However, there are also important differences, namely the presence of a bright nonthermal BL Lac nucleus in PKS 0521 – 36 and its location outside a rich cluster like Virgo. Also, the jet length is greater (10 kpc projected length) and overall luminosity higher. The optical polarization data also show significant differences with those of M87. In particular, the most luminous portion of the jet has a polarization position angle at right angles to the corresponding location in the M87 jet. This weakens the argument that the two knots are generically the same, phenomenon, for example, a simple oblique shock.

The polarization directions in the PKS 0521 – 36 jet resemble those in the quasar 3C 273 (Scarrott and Warren-Smith 1987) where the polarization is observed to be perpendicular to the jet, unlike M87 where it is parallel to the brightest knot. In this regard, we note that like 3C 273, PKS 0521 – 36 possesses a luminous nonthermal optical nuclear component. This suggests that the orientation of the optical polarization in jets is related to the apparent luminosity of the optical nucleus which is some 500 times higher in PKS 0521 – 36 (H0 = 50 km s⁻¹ kpc⁻¹). This is the same phenomenon that has long been noted for radio jets (e.g., Bridle and Perley 1984). The orientation of magnetic fields deduced from radio polarization measurements of jets are found to be closely correlated with the luminosity of the radio nuclear cores, with the "weak-core" jets having fields perpendicular to the jets and the "strong-core" jets having aligned fields.

The difference between the apparent nonthermal nuclear luminosities of PKS 0521 – 36 and M87 imply either that the nucleus of PKS 0521 – 36 is currently more active than that of M87 or that the jet axis is oriented closer to the line of sight and is Doppler-boosted by relativistic beaming. To explain the differences in magnetic field orientation in the case where the nucleus is more active, the increased energy flux along the jet would need to translate into enhanced synchrotron emission in regions of the jet where the magnetic field is aligned, while alternatively a different viewing angle may, depending on the detailed field geometry, result in a different projected field direction.

IV. Conclusions

High optical polarization has been measured in the jet and nucleus of PKS 0521 – 36, increasing with distance from the nucleus. This clearly establishes the nonthermal nature of the optical radiation and increases to three the number of known, nearby radio galaxies harboring optical nonthermal jets.

Comparison of detailed optical and radio polarization distributions of this and other optical jets at higher spatial resolutions may constrain possible mechanisms for the production, propagation and evolution of extragalactic synchrotron jets. For this exercise, the Hubble Space Telescope will be essential.
REFERENCES


F. MACCHETTO and W. B. SPARKS: Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218

G. K. MILEY: Sterrewacht Leiden, Postbus 9513, 2300 RA Leiden, The Netherlands

© American Astronomical Society • Provided by the NASA Astrophysics Data System
Fig. 1.—Direct image of PKS 0521 – 36, showing the sum of all the data. The field of view is ≈2.9 × 2.9.

Sparks, Miley, and Macchetto (see 361, L42)
Fig. 2.—As in Fig. 1, but after subtraction of an elliptical model of the galaxy

Sparks, Miley, and Macchetto (see 361, L42)