THE ASTROPHYSICAL JOURNAL, 247:L5–L9, 1981 July 1

OPTICAL EMISSION FROM THE EXTENDED RADIO SOURCE 3C 277.3 (COMA A)

GEORGE K. MILEY[1] AND TIMOTHY M. HECKMAN[1]
Sterrewacht Leiden, The Netherlands

HARVEY R. BUTCHER
Kitt Peak National Observatory[2]

AND

WIL J. M. VAN BREUGEL[1]
Sterrewacht Leiden, The Netherlands
Received 1980 December 29; accepted 1981 March 13

ABSTRACT

Optical emission has been detected both from the radio jet and from the outer lobe regions of the radio galaxy 3C 277.3 (Coma A) at a redshift of 0.0857. Two optical *continuum* knots are seen in the jet, the brighter of which is found to be 14% polarized with the magnetic vector along the jet. Intense optical emission *lines* have been observed from the knot region of the jet and from regions near the peripheries of the radio lobes. Evidence is presented that this line-emitting gas, which extends over distances of 60 kpc, is related to the depolarization of the radio continuum. The emission-line strengths in the brightest optical knot indicate densities of $\sim 10^3$ cm^{-3}, temperatures of $\sim 10^4$ K, and a total mass of line-emitting gas $\sim 10^6 M_\odot$. Photoionization is probably the dominant ionizing mechanism in this knot. The extended emission-line gas is moving at a few hundred kilometers per second with respect to the nucleus. The origin of this gas and the possibility of using its velocity distribution to trace the kinematics of the relativistic plasma are discussed.
Subject headings: polarization — radio sources: extended — radio sources: galaxies

I. INTRODUCTION

Since the discovery of extragalactic radio sources, a study of their physics has been hindered by the limited information that can be derived from radio continuum observations alone. During the last few years, it has become clear that optical emission is frequently associated with extended radio sources (for references see Miley 1980). Evidence for a direct relationship between extended radio emission and optical emission-line radiation is more meager.

Here we report a case of a detailed coincidence between extended radio continuum structure and optical line emission. We have detected emission lines from the radio galaxy 3C 277.3 (Coma A) at a redshift of 0.0857 (Schmidt 1965). The emission lines extend over a distance of about 60 kpc ($H = 75$ km s^{-1} Mpc^{-1}), and their spatial intensity distribution is closely correlated with the radio structure.

II. OBSERVATIONS AND REDUCTION

The radio emission of 3C 277.3 (Bridle *et al.* 1981) shows a typical double-lobed structure with a hot spot at its northern boundary. The southern lobe emerges from the nucleus as a knotty, jetlike feature at P.A. ≈ 155°, then bends to the southwest and flares out.

We have obtained deep optical images of this source with the Kitt Peak National Observatory (KPNO) video camera system on the 4 m Mayall telescope (Butcher, van Breugel, and Miley 1980). Since the images clearly revealed optical counterparts of the knots in the radio jet, further observations were carried out.

First, polarization information was obtained using four Polaroid filters alternating behind the *B* filter. These data were reduced, assuming the 18.5 mag galaxy 27″ to the southwest of 3C 277.3 to be unpolarized.

Second, to search for optical line emission, we observed the source using the high-gain video spectrometer (HGVS) together with the Ritchey-Chrétien spectrograph on the 4 m telescope. Spectral information was obtained along a 2″ × 166″ slit which was oriented with a P.A. of 155°, i.e., roughly along the radio axis. A lower dispersion spectrum covered a 1336 Å band centered at 4181 Å, with a spectral resolution (FWHM) of 8.6 Å. The second spectrum had higher dispersion and covered a 340 Å band centered at 5291 Å, with a spectral resolution of 2.2 Å. The data were reduced and calibrated using the procedure described by Heckman *et al.* (1981*a*).

Finally, a spectrum of the brightest optical knot (K_1, see below), covering the band from 4500 to 7500 Å with ~8 Å resolution, was obtained with a 3″ aperture using the Intensified Reticon Spectrograph on the 2.3 m (90 inch) telescope of the Steward Observatory.

[1] Visiting Astronomer, Kitt Peak National Observatory.

[2] Operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

III. CONTINUUM RESULTS

Figure 1 (Plate L1) is a reproduction of our blue image of 3C 277.3 with the central galaxy removed. The principal radio features are indicated using the nomenclature of Bridle *et al.* (1981). The first knot in the jet, K_1, is clearly present and appears slightly resolved. This is probably the "blue knot near the identification" of 3C 277.3 previously noted by Goodson, Palimaka, and Bridle (1979). Much weaker optical emission is found coincident with the second radio knot K_2. In addition to the two knots, a number of other interesting features are visible.

After applying a 20% correction for [O II] λ3727 emission in the filter passband (see below), the continuum flux densities from the two knots at 6.67×10^{14} Hz were found to be 23 ± 5 μJy and 3.7 ± 1.0 μJy, respectively. Together with the 5 GHz fluxes derived by Bridle *et al.* (1981), these data imply radio-optical spectral indices for the knots of 0.56 ± 0.03 for K_1 and 0.75 ± 0.03 for K_2. These agree well with the values found for the three other cases of radio-optical jets listed by Butcher, van Breugel, and Miley (1980) which range from 0.65 to 0.72.

Our optical polarization data give a degree of polarization of 14% ± 3% in P.A. 71° ± 6°. This percentage is comparable with that seen in the M87 jet (Schmidt, Peterson, and Beaver 1978), and the inferred magnetic field direction is along the jet, as is often the case in strong radio jets (Fomalont *et al.* 1980; Potash and Wardle 1980). The measured optical polarization, together with the emission-line data reported below, provide strong evidence that the radio depolarization is, in fact, related to the optically observed thermal gas.

The detection of polarized optical emission from the knots in 3C 277.3 and the observed radio-optical spectral indices reinforce the conclusions of Butcher, van Breugel, and Miley (1980) that a continuous nonthermal synchrotron spectrum, extending from 10^9 to 10^{15} Hz, may be a general property of jets. Because the lifetimes of relativistic electrons that radiate optically are only a few thousand years, the new observations also provide further evidence that localized particle acceleration is widespread in radio sources.

IV. LINE RESULTS

a) Relationship to Radio Emission

The part of our spectral data covering the [O III] λ5007 line is shown in Figure 2, in which extended

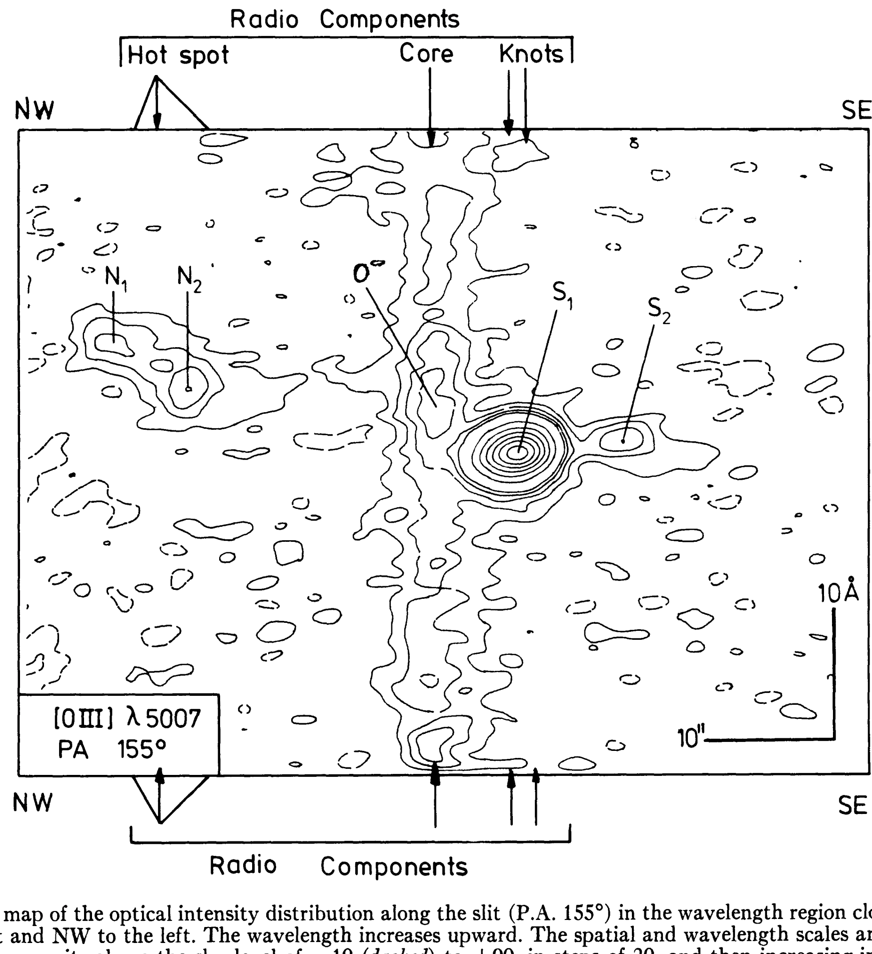

FIG. 2.—A contour map of the optical intensity distribution along the slit (P.A. 155°) in the wavelength region close to the [O III] λ5007 line. SE is to the right and NW to the left. The wavelength increases upward. The spatial and wavelength scales are indicated. Intensity contours are in arbitrary units above the sky level of −10 (*dashed*) to +90, in steps of 20, and then increasing in steps of 100. Various features in the data are designated by letters, and the position of radio components visible in the map of Bridle *et al.* (1981) are shown.

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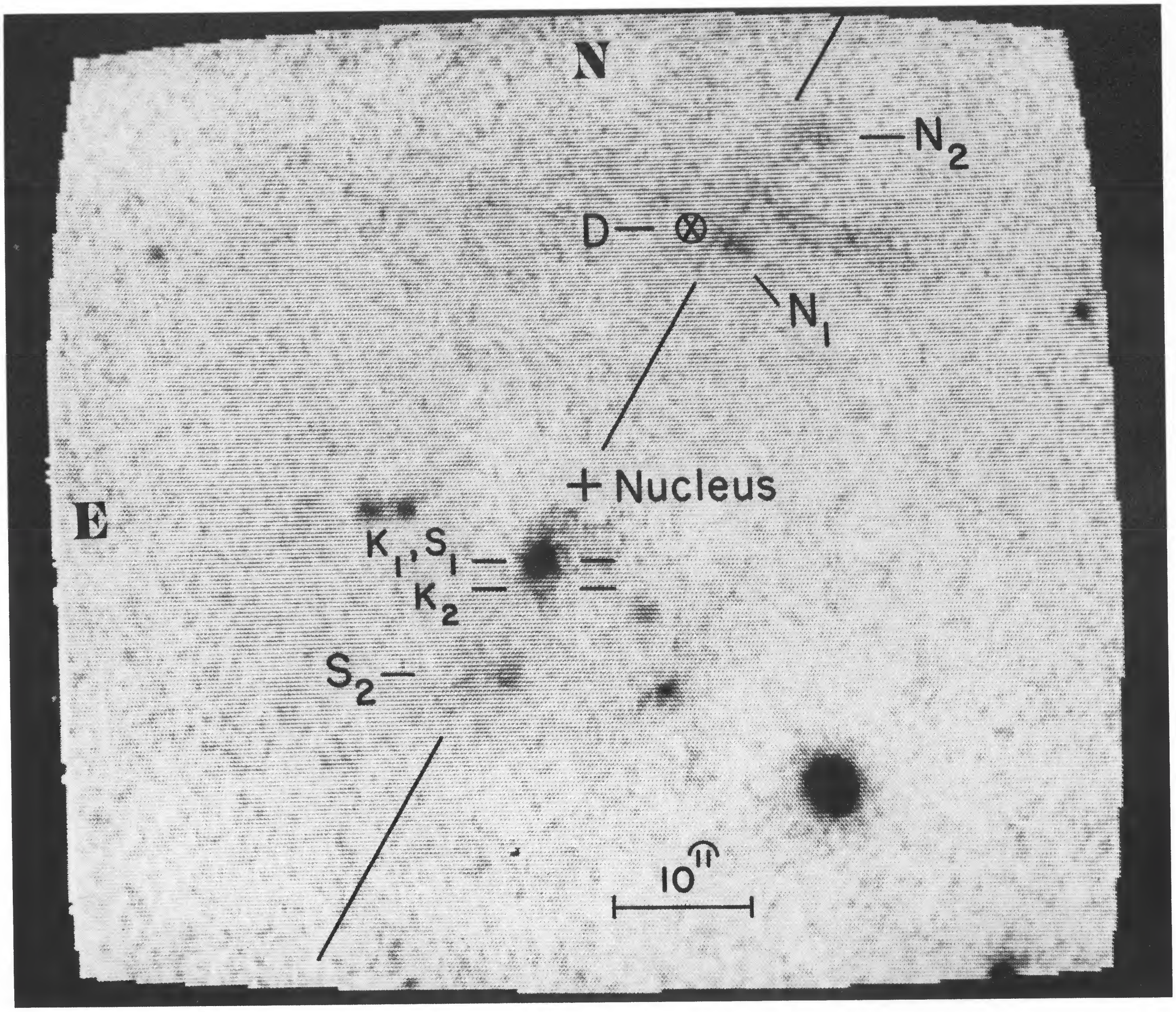

FIG. 1.—Image of a 75″ × 75″ field around 3C 277.3 in the *B* passband. These data have been corrected for distortion, and the central elliptical galaxy has been removed by subtracting a Hubble profile fitted to its outer light distribution. The principal features of the radio source K_1, K_2, and D are indicated by using the designations of Bridle *et al.* (1981). Also, the path of the slit used in our spectroscopic study is shown, together with positions of the detected line features S_1, S_2, N_1, and N_2.

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[O III] emission can be clearly seen. This arises from both sides of the nucleus O, with the strongest peak S_1 coinciding well in position with K_1, the first of two knots on the radio map, and the northern features N_1 and N_2 overlapping the edge of the northern radio lobe. The correspondence in the spatial distributions of the radio continuum and the optical line is also clear in the case of [O II] λ3727. This can be seen in Figure 3, which shows intensity profiles along the slit for the [O III] λ5007 and [O II] λ3727 lines, together with a profile in the same position angle of a 3″ wide slice taken through the radio map.

Further information was obtained by comparing the spatial distribution of the emission lines with that of the radio polarization. A highly polarized region (polarization ≈ 20%) is apparent on the radio map between the nuclear core and the northern hot spot (Bridle *et al.* 1981). This is marked on Figure 3. Elsewhere along the path through the source defined by the slit, no significant radio polarization was observed; the upper limit for the northern hot spot is less than 1%. This indicates the existence of a rough anticorrelation between the line emission and radio polarization and suggests that the radio emission is depolarized by thermal plasma associated with the gas which is responsible for producing the visible emission lines. On the most simple assumptions regarding geometry and equipartition, the radio source would be depolarized at 5 GHz for a product of thermal electron density n_e, filling factor ϕ, and path length $dl \gtrsim 10^{19.5}$ cm^{-2}. Our measured values for n_e and the mass of ionized gas in K_1 (see below), coupled with the size of K_1 as estimated by Bridle *et al.* (1981), imply a value of $n_e\phi dl$ for the clumpy emission-line gas that is consistent with this limit.

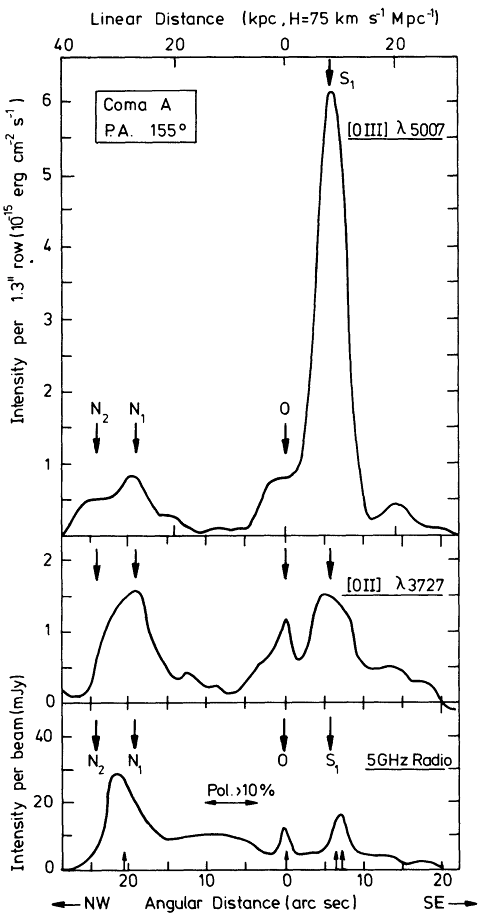

FIG. 3.—Intensity profiles along the slit direction of [O III] λ5007, [O II] λ3727, and the 5 GHz radio continuum (Bridle *et al.* 1981). The contribution of the nuclear optical continuum has been subtracted from the line data. To mimic the effective optical aperture (slit width + seeing), the radio intensity profile has been taken through a 3″ slice along P.A. 155°. Positions of the line features are indicated by downward arrows, and the radio features D, C, K_1, and K_2 by upward arrows. Also indicated is the region along this intensity profile for which significant radio polarization ($\gtrsim$10% per 2″ × 1″ beam) was observed.

b) Line Ratios

Besides [O III] λ5007 and [O II] λ3727, some other lines which were detected in our spectra are [Ne III] λ3869, Hγ, Hβ; [O I] λ6300, Hα; [N II] λλ6548, 6584; and [S II] λλ6717, 6731 (details to be published elsewhere). Several conclusions can be drawn from these data:

1. The relative intensities are fairly typical of those commonly seen in extranuclear line emission (Balick and Heckman 1979) and resemble those seen in the radio galaxies Cen A (Osmer 1978), Virgo A (Ford and Butcher 1979), 3C 120 (Baldwin *et al.* 1980), and NGC 7385 (Simkin and Ekers 1979).

2. Comparison of the [O III] λ5007 data with the [O II] λ3727 data suggests that the knot K_1 has a higher ionization state than other parts of the source.

3. The upper limit to the intensity ratio of [O III] λ4363 to λ5007 + λ4959 in the knot K_1 implies an electron temperature of $T_e \lesssim 17{,}000$ K.

4. The ratio of the λλ6717–6731 [S II] lines in K_1 indicates a density $n_e \approx 10^3$ cm^{-3}, implying a gas pressure of $\sim 10^{-9}$ dynes cm^{-2}. This is ~10 times larger than the corresponding equipartition pressure in the radio plasma (Bridle *et al.* 1981). However, this latter value is poorly determined due to the large uncertainty in the knot's radio structure. We derive a luminosity in Hβ of $\sim 10^{41}$ ergs s^{-1} for the gas sampled by our slit, implying a mass of ionized gas of $M_{H^+} \approx 10^9\, n_e^{-1}\, M_\odot$. If $n_e \approx 10^3$ cm^{-3} everywhere, as in K_1, then $M_{H^+} \approx 10^6\, M_\odot$.

c) Velocities

Figure 4 shows the velocity as a function of distance along the slit. The velocities are plotted relative to that of the nucleus, and since the nuclear [O III] line is broad (FWHM ≈ 450 km s^{-1}) and relatively weak, the zero point of velocity is uncertain by ~100 km s^{-1}. Several points are apparent from the velocity information in Figure 4.

1. Despite the uncertainty in the velocity of the gas in the nucleus (the zero point in Fig. 4), we conclude that the gas to the south is approaching and the gas to the north is receding.

2. The velocities relative to the nucleus of a few

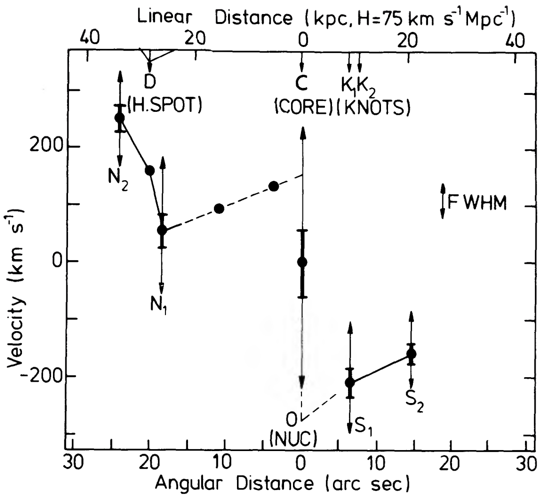

FIG. 4.—The velocity of the [O III] emitting gas as a function of distance along the slit, measured with respect to the nucleus. The peak intensities are shown by filled circles, their uncertainties by thick lines, and the FWHM points by thin lines and bars. The high signal-to-noise peaks are jointed by solid lines, and the noisier peaks by dotted lines. Also indicated is the FWHM corresponding to the instrumental resolution (122 km s^{-1}). Note that the uncertainties in the peaks are about 25% of the FWHM. The zero point of velocity is taken to be 25,730 km s^{-1}.

hundred kilometers per second are similar to those observed for the extended emitting gas in the radio galaxies Cen A = NGC 5128 (Osmer 1978), Virgo A = M87 (Ford and Butcher 1979), and NGC 7385 (Simkin and Ekers 1979).

3. The general shape of Figure 4, close to the nucleus, is suggestive of a galaxy rotation curve, and the velocities are typical of galaxy rotational velocities. However, it is not possible from these data to tell whether the gas is rotating, flowing outward, or infalling.

4. Close to the radio hot spot at the northern edge of the source, the velocity of the gas increases sharply.

5. The inferred mass of the ionized gas ($\sim 10^6 M_\odot$) and velocities of $\sim$300 km s^{-1} imply a kinetic energy of 10^{54} ergs. This compares with a minimum energy of $\sim 10^{58}$ ergs in the *relativistic* plasma, derived using equipartition arguments.

V. DISCUSSION

The new observations provide strong evidence that a line-emitting gas coexists intimately with the relativistic plasma responsible for the radio emission in 3C 277.3. The nature of this gas and its relationship with the relativistic plasma is intriguing. Before discussing the origin of the gas, we shall consider mechanisms for heating and ionizing it.

Shock heating requires relatively high temperatures ($\sim$40,000 K; e.g., Dopita 1978), and our limit of $<$17,000 K rules it out for knot K_1.

Photoionization is a strong possibility since enough Lyman photons to explain the observed Hβ luminosity of K_1 would be produced by extrapolating our measured B-continuum flux density for K_1 into the ultraviolet with a spectral index of 1.1. Thus, the continuum radiation, which has a radio-optical spectral index of $\sim$0.56, is sufficient to photoionize the knot, even if it steepens considerably into the ultraviolet.

The emission-line spectrum of the gas associated with K_1 is significantly different from that of the gas elsewhere in the source (relatively large ratio of [O III] λ5007 to [O II] λ3727). Thus conclusions concerning the form of energy input to the gas near K_1 do not necessarily apply to the rest of the gas. Statements about the ionizing mechanism elsewhere in the source must await a more complete investigation of the emission spectrum.

It is crucially important to establish the origin of the line-emitting gas and its relationship to the radio source. One possibility is that the thermal plasma is a preexisting gas bound to the galaxy and "lit up" by the outward-moving radio source. However, the sudden increase in velocity observed near the northern boundary of the radio source would be difficult to understand on this hypothesis.

A more fascinating alternative is that the gas is being carried outward with the relativistic plasma responsible for the radio emission. There is evidence that this phenomenon occurs on a much smaller scale in some other active galaxies (e.g., Heckman *et al.* 1981*a*, *b*). Since we have shown that the energy necessary to power the 3C 277.3 radio source is probably much larger than the kinetic energy of the ionized gas, one might reasonably expect the relativistic plasma to dominate the dynamics. If the outward-flowing plasma were confined by ram pressure and continuously supplied with momentum, the increase in velocity near the northern boundary of the radio source might well be caused by a sharp decrease in the density of the confining medium.

Within this picture, the velocity pattern close to the nucleus would be interpreted as indicating that deceleration of the gas is occurring, perhaps by collision with a dense, ambient medium. It is then suggestive that the region where the southern radio jet bends and flares out coincides with the knots K_1 and K_2. The velocity change across the knots and the bend in the radio morphology suggest that here the outflowing radio plasma is being decelerated and redirected. The kinetic energy liberated in this process might well power the localized particle acceleration needed to produce the enhanced synchrotron emission and the relatively large optical-to-radio flux ratio observed from the knots.

If the relativistic and nonrelativistic plasmas are comoving, we would be in the fortunate situation of being able to infer the kinematics of the radio source from the velocity field of the thermal gas. The observations would then imply a kinematic age for the radio source (size/velocity) of $\sim 10^8$ yr, consistent with synchrotron lifetime arguments. Interpreted in this way, our observations of 3C 277.3 would indicate that outflow velocities in extended radio sources are highly subrelativistic. Similar low outflow velocities have been inferred from studies of the morphologies of extended radio jets (e.g., Miley 1980; van Groningen, Miley, and Norman 1980).

It is clear that further observations relating to the dynamics, depolarization processes, and particle acceleration mechanisms in 3C 277.3 may provide unique insights into the extragalactic radio source phenomenon.

We thank Allen Bridle, Ed Fomalont, Jay Palimaka, and Tony Willis for access to the radio data before its publication. This work was partially supported by NATO grant 1828.

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Harvey R. Butcher and Wil J. M. van Breugel: Kitt Peak National Observatory, P.O. Box 26732, Tucson, AZ 85726

Timothy M. Heckman: Steward Observatory, University of Arizona, Tucson, AZ 85721

George K. Miley: Sterrewacht Leiden, Postbus 9513, 2300 RA Leiden, The Netherlands