OPTICAL OBSERVATIONS OF RADIO JETS

Wil van Breugel and George Miley
Sterrewacht Leiden, The Netherlands
Harvey R. Butcher,
Kitt Peak National Observatory, Tucson, AZ 85726 USA.

INTRODUCTION

Over the past several years a considerable body of evidence has accumulated, suggesting that extended radio sources are powered quasi-continuously from the nuclei of their parent galaxies. This view is supported by the recent discovery that several radio galaxies have narrow radio jets which connect their active nuclei with the large radio lobes and which often extend for several tens of kiloparsecs. Because of their presumed association with the energy transport outward from the active nuclei, radio jets are at present being intensively studied with high-resolution radio techniques.

The closest galaxy known to have a radio jet is the giant elliptical M87 (e.g., Wilkinson 1974), and in this case there is a well-known optical counterpart (e.g., Curtis 1918; de Vaucouleurs, Angione and Fraser 1968), This optical jet is highly polarized (Baade 1956), implying that at least part of the emission is non-thermal. This and the good agreement between the optical and radio structure suggests that these features are closely related.

Because of its potential importance to the physics of radio galaxies, we have undertaken a search for additional examples of optical jets which are associated with radio jets (Butcher, van Breugel and Miley 1979). We have begun the search with four galaxies known to have strong radio jets: 3C 66 B (Northover 1973), 3C 31 (Burch 1977), NGC 315 (Bridle et al. 1979) and 3C 449 (Perley, Willis and Scott 1979).

To search for these optical jets we have employed the Kitt Peak ISIT vidicon video camera on the 4 m Mayall telescope (Robinson et al. 1979) using a broad-band blue filter (effective wavelength 4500 Å, FWHM 900 Å). Our strategy in searching for possible optical jets in the data has been to subtract a smooth representation of the background stellar light of each galaxy, and then to examine the flattened data for features which stand against the background.

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RESULTS

1. 3C 66 B

This source has been studied at high resolution and at several radio frequencies by Northover (1973). It has a high intensity radio jet emanating from the nucleus toward the northeast.

After subtracting symmetric Hubble profiles, optimized to fit the stellar light distribution of the galaxy in the northeast quadrant, an optical jet is readily evident in each of our broad-band (blue) exposures. It extends to a radius of 16", beyond which it disappears into the noise. Within 8" (3 kpc)+, the optical jet (as well as the radio jet) is significantly brighter than further from the galaxy. This part of the jet is shown in Figure 1. The general correspondence with the 5 GHz map of Northover, 1973, is excellent, although the resolution and noise in the optical data preclude the certain identification of individual knots. As in M87, the optical flux density of this jet is slightly less than would be predicted by an extrapolation of the radio frequency spectrum into the optical. The integrated flux density for the jet in the blue is F_B = 9 μJy.++

2. 3C 31

High-resolution observations at 5 GHz of this source have been made and discussed by Burch (1977). A strong radio jet is seen to emerge from the nucleus in position angle 341°.

The optical jet is not immediately apparent in our optical image. Instead, a ring of absorbing material is seen to encircle the nucleus at a radius of about 3". Fortunately however, the axis of symmetry of the dust lane coincides with the minor axis of the galaxy's stellar light component and to search for an optical jet we have removed the symmetric component of the galaxy light.

The result is shown in Figure 2. The jet is plainly visible, extending out to 5" (1.5 kpc) from the nucleus in precisely the position angle of the radio jet and coincident with a region of strong radio emission (beyond which the radio jet broadens systematically). We derive an integrated flux density in the blue for the jet of F_B = 6.2 μJy. Again this flux is less than one would predict from an extrapolation of the radio spectrum and also slightly less than the scaled flux from the M87 jet.

3. NGC 315 and 3C 449

For the radio jet in the giant radio galaxy NGC 315 (Bridle et al.

+ A value for H_o of 75 km s^{-1} Mpc^{-1} will be used throughout.

++ Conversion to B magnitudes may be made via the formula $B = 8.98 - 2.5 \log F_B$, F_B in Jansky (1 Jy = 10^{-26} W m^{-2} Hz^{-1})

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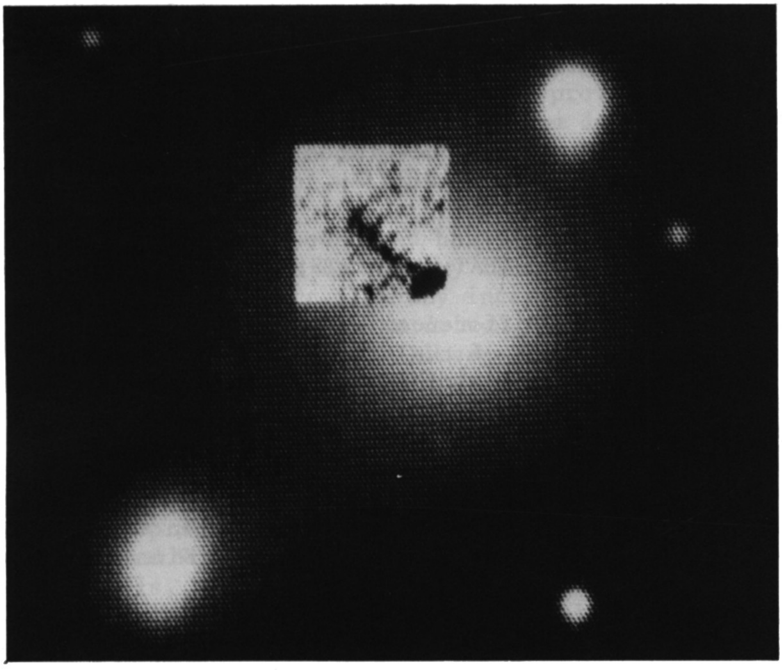

Fig. 1. The bright inner part of the optical jet in 3C 66 B, reinserted into the original data. The inserted region has had its background starlight subtracted and its relative contrast greatly enhanced.

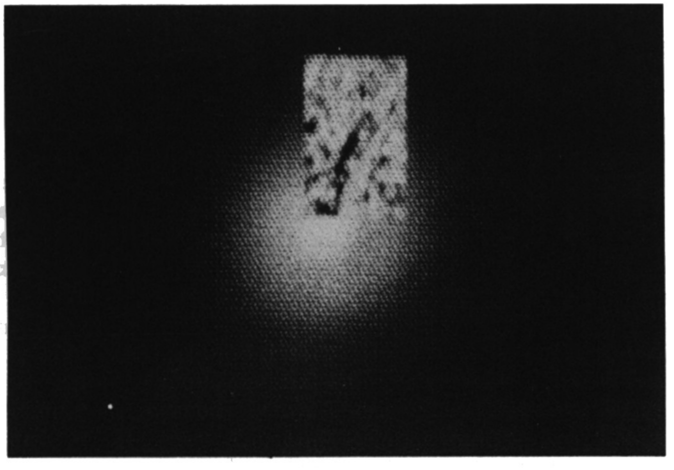

Fig. 2. The background subtracted image of the optical jet in 3C 31, reinserted into the original data. Its contrast is greatly enhanced relative to that of the galaxy.

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1979), and the two radio jets in 3C 449 (Perley et al. 1979) no optical counterparts have been detected and we derive integrated flux density limits of $F_B < 3.2$ μJy and $F_B < 2.5$ μJy respectively.

In NGC 315 we find several discrete absorption clouds and in 3C 449 there is evidence of absorbing matter apparently absorbing the nucleus much like that seen in 3C 31.

INTERCOMPARISON OF GALAXIES THAT HAVE JETS;

Although significant differences in radio-optical spectral indices exist, it is remarkable that of the five galaxies with radio jets that have been surveyed, the spectral indices for three of them differ by less than 0.1 and imply spectra only slightly steeper than those at radio frequencies; the limits we derive for NGC 315 are consistent with this. This implies that the spectra of the jets probably extend continuously from 10^9 to 10^{15} Hz and are almost straight. (Note, however, that the spectrum of the knots in the M87 jet may steepen either in the optical (Ables and Kron 1973) or in the infrared (Kinman et al. 1974)).

Of course the statistics are not yet significant, but there are some additional trends which are suggestive. Relatively larger jet luminosities and flatter radio-optical spectra seem to be associated with larger total optical and radio luminosities and with smaller radio jet "gaps" (the distance from the galactic nucleus at which the radio jet turns on, Perley et al., 1979).

RELATION TO PHYSICS OF JETS

1. Amount of Energy Being Conducted to the Lobes.

A dependence of the observed intensity of a jet on the flux of energy being transported outward would be consistent with the tendency of the jets with relatively high optical power to be associated with larger total radio luminosities. These more luminous sources have presumably had a larger integrated activity in the past and must therefore be supplied with more energy. From the radio luminosity of the cores, there is no evidence that the galaxies are more active at present, but the highly energetic processes required to generate optical radiation in the jets may vary sporadically, as a result of unsteady nuclear activity (Rees 1978).

2. Efficiency of the Energy Transport

It is possible that higher jet luminosities and smaller radio gaps indicate a lower efficiency of energy transfer (see also Perley et al., 1979). In a source where the energy transport is less efficient, most of the energy would be dissipated close to the galaxy, and the corresponding radio source might well be smaller.

Inefficiency may be related to the degree to which the energy transfer is relativistic (Rees 1978) or to the amount of interstellar matter entrained in the beam (Blandford and Königl 1979). Some evidence that the latter mechanism may be important is provided by the tendency of the jet luminosity to depend on the absolute optical magnitude of the galaxy. If optically luminous galaxies have more and denser interstellar matter, the jets might well be caused to radiate more intensely.

Each of the galaxies we observed has a significant amount of interstellar matter and this seems to be very clumped. Because it is highly likely that jets will interact with any interstellar medium, recent models of jets involving shock waves driven into inhomogeneities in the medium (Blandford and Königl 1979) seem particularly appropriate.

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