The Hubble Space Telescope

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HST OBSERVATIONS OF THE JET IN M87

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INTRODUCTION

The EO galaxy M87 harbours the prototypical and most studied example of an optical jet. First observed by Curtis in 1918, it remained little more than a curiosity, until Baade and Minkowski studied it in 1954 and first used the term "jet" to describe the sequence of optical knots extending to about 20" from the nucleus. Since then, the jet has been observed at radio (Owen, Hardee & Cornwell, 1989, Biretta, Stern & Harris 1991), optical (de Vaucouleurs & Nieto 1979, Keel 1988, Fraix-Burnet, Le Borgne & Nieto 1989) and X-rays wavelengths (Schreier, Gorenstein & Feigelson, 1982).

The radio and optical morphologies and polarization structure of the jet are similar (Schlötelburg et al, 1988) to within the resolution limits of the ground based observations. These results are best explained by emission from synchrotron radiation. In addition, the emission detected at x-ray wavelengths in the jet region also suggests that the synchrotron spectrum extends to high frequencies.

OBSERVATIONS

Images of M87 centred on the nucleus and positions along the jet were obtained with the Faint Object Camera (FOC), utilizing the following filters in the f/96 512 x 512 modes: F120M, F140W, F220W (direct and with polarizers POL0, POL60, POL120), F430W (with polarizers only) and F501N. Additionally, a zoomed acquisition image was made with the F372M filter. The exposures were made in fine lock, with an expected tracking accuracy of 0."007.

The F220W exposures were corrected using the Lucy (1974) deconvolution technique to produce the final deconvolved images with minimum beam size 0."2 FWHM. The results of this restoration are shown in Figure 1. This figure shows side-by-side the deconvolved FOC and VLA data. As is easily observed, two FOC frames (each of 11" x 11") are needed to cover the jet which extends for over 20" in length.

The complex structure and the wide range of intensities make it very difficult to display all the features in a single picture. Furthermore, the value of the relative

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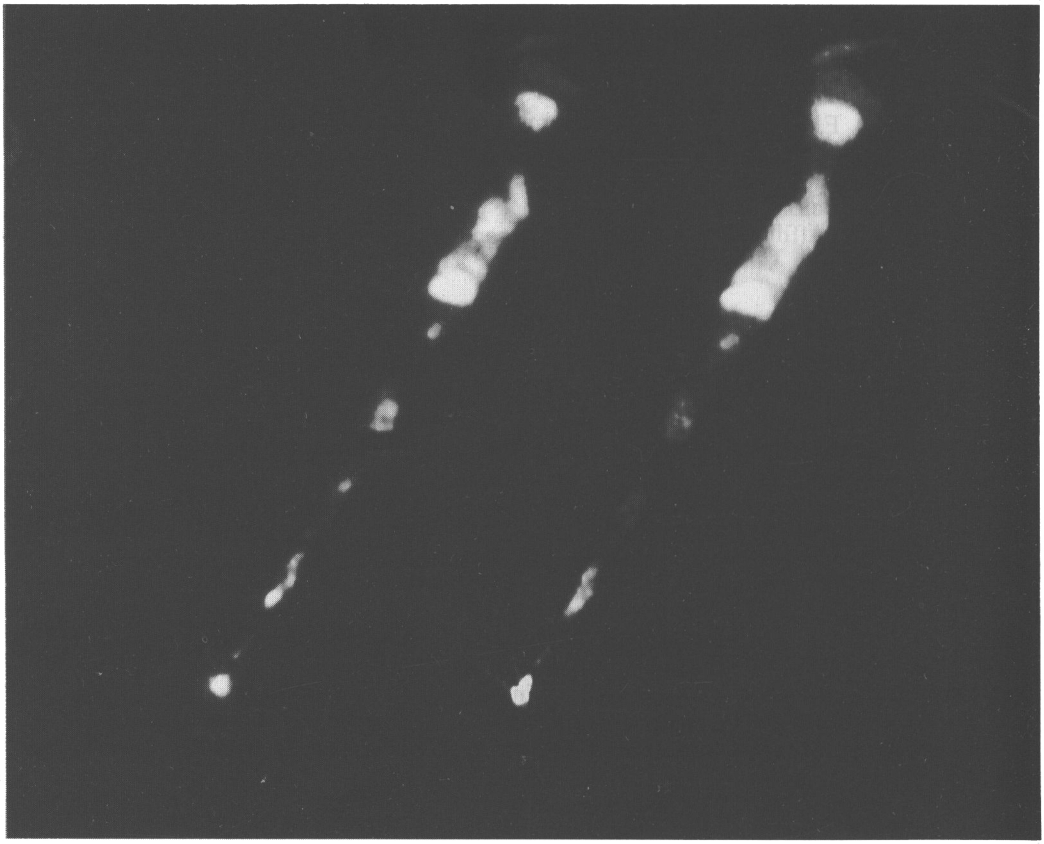
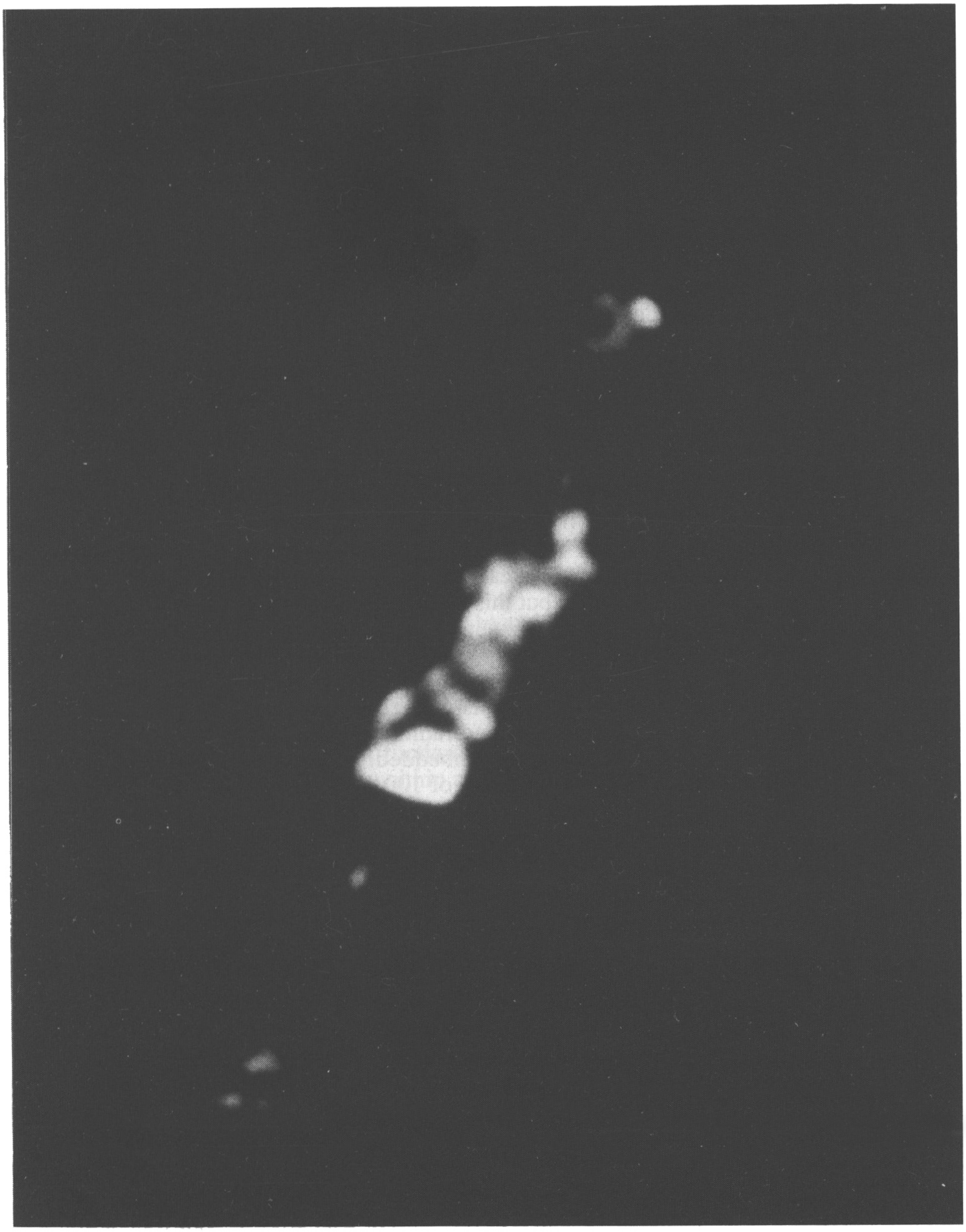
Figure 1



Left. Deconvolved FOC image of the M87 jet. Two FOC images are needed to cover the length of the jet (@ 20"), hence the small gap in the spatial coverage. Right. Deconvolved VLA image kindly supplied by F. Owen and J. Biretta. The images show the remarkable agreement of the ultraviolet and radio observations.



Deconvolved FOC image of Knot A showing detailed filamentary spiral structure and limb brightening.

intensity of the ultraviolet and radio data is arbitrary and was chosen only to show the most prominent features. Detailed intensity comparisons and determination of spectral indices as a function of position along the jet will be carried out in the near future.

The FOC observations demonstrate for the first time that the radio and ultraviolet brightness distribution is generally the same over a scale of about 0."1 or about 10 pc (M87 presents 78 pc arcsec^{-1} at an assumed distance of 16 Mpc).

The FOC data shows that all the prominent optical knots (A,B,C, etc) have now been fully resolved and show the same remarkable structure as the radio data. (See Owen, Hardee and Cornwell, 1989, also for the knot notation). The jet is limb brightened, shows very well-defined edges along its conical structure with an opening angle of ~ 6.5° and has a tight filamentary structure. The appearance of this structure indicates that the filaments are wrapped around the jet with pitch angles of about 30° - 40° between the nucleus and knot I. At knot A, and between knots A and B, the filaments are more tightly wrapped with a pitch angle between 80° and 90° and decreasing from knot A towards knot B. The pitch angle may increase again towards knot C.

Slices taken across the jet at different locations show prominent limb brightening similar, but not identical, to the radio data. Detailed comparisons are beyond the scope of this paper, but this general agreement provides strong evidence in favor of the two fluid model for this jet. (Pelletier & Roland, 1988, Owen, Hardee & Cornwell 1989).

In this scenario, the jet consists of a cone around which one or more bright filaments are wrapped. The optical and radio emission comes mostly from a surface layer in which these filaments are embedded. The synchrotron lifetimes in the ultraviolet are typically only of the order of 100 yr, corresponding to light travel times of about 30 pc. This is comparable to the width and presumably the thickness of the optical and radio strands.

The low emissivity in the jet's core indicates that the energetic particles are not suffering significant synchrotron losses. This is also compatible with the model in which the jet's core has a relatively low magnetic field. In this case, the high-energy particles can be produced in the central black-hole and propagate along the jet's interior in a low magnetic field region, thereby suffering only modest synchrotron losses. As they diffuse across the jet and into the high magnetic field boundary layer, they can produce the optical emission without the need for in situ acceleration.

Several mechanisms can be invoked to explain how the emission from this boundary layer is produced. Non-linear evolution of synchrotron instabilities has been proposed by Bodo et al, 1991, to explain the formation of filaments in jets out of equipartition, such as that in M87, where the energy of the relativistic electrons exceeds that of the magnetic field. They find that in a plasma subject to constant heating, after an initial phase in which the instability growth rate follows the linear model, the instability reaches a quasi equilibrium state on timescales of the order of several synchrotron timescales. This mechanism can explain the formation of filaments of enhanced emission observed in the lobes and jet of M87.

Optical synchrotron emission can also be produced through a diffusive shock acceleration mechanism (Fraix-Burnet, 1991). This process is so efficient that it requires the magnetic field turbulence to be quite low. The source of energy of this turbulence could be the kinetic energy of the jet which can be transferred to the magnetic field (or to the plasma) through the interaction of the jet with the interstellar medium.

The answer to which of the competing mechanisms and scenarios are at work and the determination of the relevant physical parameters will have to wait further detailed analysis of the FOC optical, ultraviolet and polarization data.

CONCLUSIONS

The study of the optical counterparts to radio jets with the Faint Object Camera on board the Hubble Space Telescope has already produced new and unexpected results.

The jet in PKS 0521-36 (Macchetto et al, 1991a) which is the most distant, has been fully resolved. Because of its length, magnetic field configuration and optical morphology, it seems to require reacceleration sites for the optical electrons. These could well be provided by shocks at the site of the brighter knots observed.

For both 3C 66B (Macchetto et al, 1991b) and M87, we have observed, for the first time at optical wavelengths, a filamentary structure which is similar to the radio data. In this case, we conclude that the emission comes from a boundary layer where the filaments and the strong magnetic field are located.

One of the most puzzling, but fundamental, results that must be explained by models of particle acceleration is why within an object, over more than five decades of frequency and a large variation of physical conditions, the old and young electrons have similar spatial distributions, although large differences are observed from object to object.

Our FOC observations of PKS 0521-36, 3C 66B and M87 show that, even with its present aberration problems, the HST is a uniquely important instrument for studying synchrotron jets. Future observations with the HST of other extragalactic jets should provide fundamental information about the nature of collimated activity in galaxy nuclei.

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