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OPTICAL SPECTROPHOTOMETRY OF THE M87 JET AND ITS ENVIRONS

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ABSTRACT

Spectrophotometry of the brightest knots in the M87 jet shows a gradual steepening of the spectral index from $\alpha = 0.66$ in the IR to 0.92 over 0.46—0.7 μm, rather than the abrupt steepening ($\Delta\alpha \sim 1$) previously reported. Together with *IUE* and *Einstein* data in the literature, this suggests a spectral break of amplitude 0.6 ± 0.1 near 3000 Å and a maximum electron energy in a single power-law distribution near 300 GeV.

No emission lines are seen in the jet to an equivalent-width limit of 1.0 Å, giving an emission measure below 20 cm^{-6} pc. Any ionized gas near the jet, over a very wide range of density, must be hot (10^6–10^7 K). The Hα + [N II] filament projected nearest the jet shows no anomalies in ionization level compared with other such filaments. Attention is called to the possibility that the nuclear emission lines are powered by photoionization from the active nucleus.

Subject headings: galaxies: individual — galaxies: jets — galaxies: nuclei — radiation mechanisms — spectrophotometry

I. INTRODUCTION

Among the most spectacular manifestations of nuclear activity in galaxies are jets, which give direct evidence of collimated flows of energy (and perhaps significant mass as well). Such structures are commonly observed at radio frequencies, but few cases have been identified optically. The brightest example was also the first to be discovered, that in M87 (Curtis 1918).

Considerable data have been accumulated on this jet. Various investigations have dealt with polarization, spatial structure, photometric properties, and the search for spectral features. This paper reports new spectrophotometry of the jet and its surroundings and implications of these data for physical models of the jet.

A brief review of some of the jet's observed properties may be useful. At optical and radio wavelengths the emission is dominated by a series of discrete knots, or complexes, of sub–arc second scale (e.g., de Vaucouleurs and Nieto 1979; Biretta, Owen, and Hardee 1983). The spectra of these knots are very well expressed as power laws, with a spectral index from 6 cm to 0.8 μm of $\alpha = 0.66$ (in the sense $S_\nu \propto \nu^{-\alpha}$; Smith *et al.* 1983). Some photometric studies (e.g., Kinman, Grasdalen, and Rieke 1974) have suggested a strong break in this spectrum in the near-infrared, with an optical value near $\alpha = 1.7$. Confirmation of such a break would be important in understanding the energetics and physical environment in the jet; the break frequency gives an estimate of the maximum electron energy in the power-law distribution and the lifetime (hence streaming length) of the particles as radiators. The optical spectrum of the jet is essentially featureless (e.g., Sulentic, Arp, and Lorre 1979). A new search for emission features was warranted because of the recent availability of linear detectors with high dynamic range (CCDs) and the potential utility of emission lines as diagnostics of the local physical conditions and velocity field.

II. OBSERVATIONS

The jet of M87 was observed spectroscopically using the Cryogenic Camera at the 4 m telescope. This device consists of a 512 × 800 TI CCD at the focus of an evacuated f/1 Schmidt camera, with a grism as the dispersing element for spectroscopy. The grism used has 300 lines mm^{-1}, giving a spectral range of 4600–7900 Å at 3.25 Å per pixel and resolution of about 20 Å. The scale along the slit is 0$''$.84 per pixel. The total exposure was 1260 s, broken up into individual 180 s segments to avoid charge-transfer or saturation problems at the nucleus. The slit was 2$''$.5 wide and was set to the jet position angle of 290°.8 given by de Vaucouleurs and Nieto (1979); alignment with the nucleus and prominent knots in the jet was checked using a rear-slit viewing TV. Flat-field and line-lamp calibration exposures were taken immediately after the observations. The dynamic range, as shown by the strongest and weakest features seen, exceeds 500:1, from the nucleus to a pair of emission knots in the "counterjet" (Arp 1967). As Ford and Butcher (1979) note, Arp's "counterjet" properly refers to a pair of rather diffuse Hα filaments. The emission features observed here are distinct in being discrete, condensed, and within $\sim 1''$ of exact alignment with the jet; one appears in Figure 1 of Ford and Butcher, but they are not otherwise included in that study. The spectra of these objects and their implications for modeling the jet are discussed in § IV.

The images were converted to arrays of flux (F_λ) as a function of wavelength and position by use of the RV package at the KPNO IPPS to remove distortions in both directions and rebin the data into a linear wavelength scale. A mean sky spectrum, from rows near either end of the slit, was subtracted from the entire frame. A small amount (less than about 1% of the peak) of galaxy light remains in the "sky" spectrum, but has no effect on these results. Conversion to

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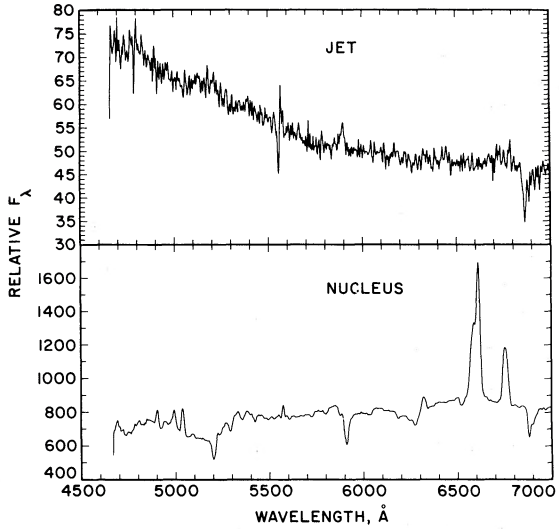

FIG. 1.—Spectra of the nucleus and jet of M87. The jet spectrum has been summed over a 2".5 × 11".2 slit, after removal of starlight continuum.

relative flux units was performed through observations of the spectrophotometric standard HZ 2 (Oke 1974) on a previous night, at the same air mass (1.51) as the M87 observations.

To obtain a spectrum of the jet free of contamination by the stellar component of M87, the spectrum was flipped about the nucleus (as found from the emission-line peak), shifted to match peak positions along the slit (to 0.5 pixel or better), and subtracted from the original spectrum. This procedure should remove the effects of line-strength gradients, requiring only that the starlight be symmetric about the nucleus in the slit plane.

For measurement, one-dimensional spectra of the nucleus and jet were extracted from the reduced data frames, summing over widths of 5–13 pixels. Tests on stellar images showed that 5 pixels (4".3) is the minimum width needed to retain accurate spectrophotometric information, because of the detector's change in focus with position along the spectrum. A 13 pixel width (11".2) was used to sum the spectra of all knots in the jet, for the most accurate available integrated jet spectrum. The photometric scale of this spectrum is good to about 7400 Å; redward of this, atmospheric absorption and large image spread along the slit (at the detector) make photometry very unreliable. The nuclear and integrated jet spectra are shown in Figure 1.

In a search for ionization induced by the jet's UV continuum, new observations were undertaken of the Hα + [N II] filament just north of the jet (Ford and Butcher 1979). In the absence of their original data, new videocamera frames were obtained in Hα + [N II] and the continuum at the 2.1 m telescope to determine the offsets needed to observe the filament. These were scaled, aligned, and the difference taken to yield a pure emission image, as done by Ford and Butcher. The peak-intensity point of the nearest emission filament was measured (1".6 north and 5".0 east of the brightness peak of the jet), and this position observed spectrophotometrically using the image dissector scanner at the 1.5 m UM-UCSD reflector on Mount Lemmon. The spectral range covered was 3700–6900 Å, using 4".7 circular apertures and a resolution of 15 Å.

III. THE OPTICAL CONTINUUM OF THE JET

At all wavelengths for which spectroscopic information is available, the spectrum of the jet (and each constituent knot) is close to a power law. The index of this power law is well defined and constant at 0.66 longward of 0.8 μm (Stocke, Rieke, and Lebofsky 1981; Smith *et al.* 1983). The extension of this power law to higher energies has remained unclear. Photometric studies by Kinman, Grasdalen, and Rieke (1974) suggested a much steeper slope ($\alpha \sim 1.7$) in the *UBV* passbands. A spectroscopic check on this result is of value because of the crucial role played theoretically by the frequency and amplitude of any change in the power-law index. The *UBV* data were very sensitive to any systematic problems in subtracting the starlight contribution; spectroscopic results yield an internal check on this, through the appearance of residual spectral features if an improper subtraction is performed.

The integrated jet spectrum in Figure 1 was used to measure a spectral index from 4600–7400 Å; the large extraction aperture of 2".5 × 11".2 should include all light from the jet and provide the highest photometric accuracy available in these data. Zero galactic reddening toward M87 will be explicitly assumed, following Burstein and Heiles (1978); nonzero reddening (de Vaucouleurs and Buta 1983) would make the true spectral index flatter than that observed. A least squares fit gives a spectral index of 0.92, with a formal error of 0.03. Additional errors might arise in the processes of flux calibration and galaxy subtraction. Errors in fitting the flux calibration curve will have only local effects over a few hundred angstroms, since the software forces the correct value at each standard (Oke 1974) wavelength. Over the observed wavelength range, differential refraction should not affect the jet data, especially as the slit was nearly vertical on the sky; the starlight continuum may have small systematic errors relative to the standard star because of its more nearly uniform light distribution, but this should be removed in galaxy subtraction. The residuals from the power-law fit, with maximum amplitude about $\pm 8\%$, are consistent with an origin in the calibration curve. Since the spectral index fit was done over a long wavelength range, the effects of these "ripples" are included in the formal error above. From the strengths of the Mg *b* band and Na D in the stellar spectrum, limits may be set on any residual starlight contamination in the jet spectrum. A prominent residual is visible in Figure 1 near 5900 Å, suggesting a slight oversubtraction of stellar continuum. Comparison with the nuclear spectrum shows, however, that this feature lies only on the blue half of Na D at the redshift of M87 and probably results from a combination of the instrumental line-profile changes along the slit and night-sky residuals at zero velocity. Using the red edge of the Mg + Mg H band at 5165 Å, a clear limit of 10% (at 5200 Å) residual starlight continuum in the jet may be set. This translates to an additional error of ± 0.05 in spectral index. Considering these errors together yields an optical spectral index of $\alpha = 0.92 \pm 0.06$ for the jet as a whole. Properties of individual knots are not considered here; their spectra do not seem grossly different, based on radio and IR measures and optical images.

Comparison with radio/IR measurements indicates that there is a gradual steepening of the spectrum, but not a dramatic ($\Delta\alpha = 1$), sudden break in the spectral region covered

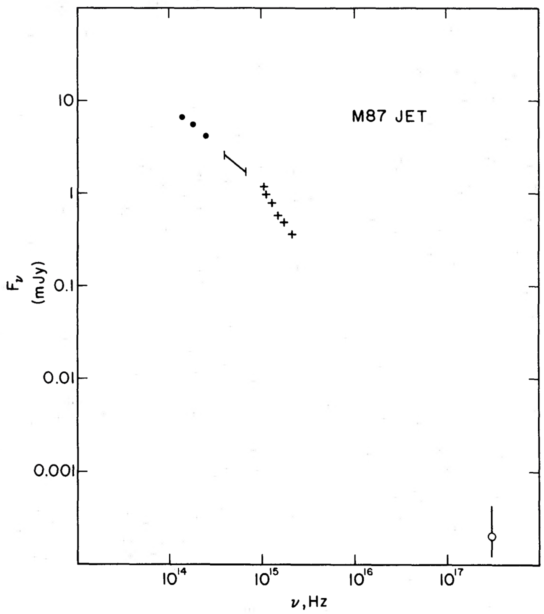

FIG. 2.—Composite spectrum of the M87 jet from 10^{14}–4×10^{17} Hz. Filled circles are from Smith *et al.* (1983); the solid line is the best fit power law from this work; crosses are from the *IUE* measures of Perola and Tarenghi (1980) rebinned into 300 Å intervals; and the open circle is the *Einstein* measurement (Schreier, Gorenstein, and Feigelson 1982). A discrete break appears near 10^{15} Hz ($\sim$3000 Å).

by these observations. The overall spectral shape may be examined by combining the present data with the IR measurements from the references above (summed over the whole jet), the *IUE* data of Perola and Tarenghi (1980), and the *Einstein* measurement at an effective frequency of 4×10^{17} Hz (Schreir, Gorenstein, and Feigelson 1982). The absolute flux scale of the present data was adjusted to match the near-IR data. The resulting spectrum is plotted as Figure 2. The X-ray measurement clearly implies a steepening or break in the spectrum below 4500 Å. This may appear in the *IUE* data at about 3000 Å; observations at high spatial resolution with the Space Telescope will be needed to address this properly. The uncertainties in the *IUE* data are large, because of poor statistics and background subtraction; a simple connection between the *IUE* and *Einstein* data gives a spectral break of $\Delta\alpha = 0.66$. The minimum break may be obtained by connecting the blue end of the present observations with the X-ray point, giving $\Delta\alpha = 0.51$. These values are reasonable limits for the amplitude of the spectral break, unless additional high-energy structure is present in the spectrum (such as a discrete Compton-scattered X-ray component). They are also within the limiting values expected for synchrotron radiation given off by ensembles of electrons (with a power-law energy distribution) being continuously replenished ($\Delta\alpha = \frac{1}{2}$) or in which injection ceased at some time in the past ($\Delta\alpha = 0.78$ for a low-frequency $\alpha = 0.6$; see Pacholczyk 1977). In a continuous-injection model, the break will occur if there is a high-energy cutoff in the electron distribution; the break frequency may be related to this energy and the local magnetic field by assuming that it is approximately the single-electron peak frequency for this energy (e.g., Ginzburg and Syrovatskij 1965). For the case of a break at 3000 Å ($\pm 20\%$) appropriate to the jet, the maximum electron energy in a single, continuous power law is 300 GeV (in which case the X-rays would arise as a superposition of the high-energy tails of each particle energy).

This cutoff frequency implies a characteristic lifetime against synchrotron losses for optically radiating electrons of 10^3 yr (for $B = 10^{-4}$ gauss) to 30 yr ($B = 10^{-3}$ gauss), for pitch angles such that $\sin \alpha = 0.7$. In a simple picture of the jet as a group of point sources of electrons in which the structure of each knot, or complex, is determined by the particle lifetime, streaming distance for this lifetime, and magnetic field geometry, the optical knots would appear significantly smaller than they do in the radio. That the dimensions at each frequency appear idential (Nieto and Lelièvre 1982) suggests that the jet structure is almost entirely governed by the field geometry, and that the field either is quite high (resulting in very short lifetimes and streaming distances) or is capable of confining the particles both along and across the jet. One picture which gives such results has a pinch instability (e.g., Hardee 1982) sufficiently developed to cause a magnetic mirror effect at the end of each jet knot. For a pinch of linear ratio f, the condition for magnetic reflection of particles of Lorentz factor γ is approximately

$$\gamma \leq (f^2 - 1)^{1/2} , \tag{1}$$

following Jackson (1975). The high values of γ for optically emitting electrons, of order 10^6, require such strong pinching and extreme magnetic fields between the knots that their confinement would be difficult by mechanisms heretofore examined (e.g., Biretta, Owen, and Hardee 1983). Field structure does appear to play an important role, from the optical-radio structural comparison and the coherent field in the inner part of the jet found from radio polarization measurements (Owen, Hardee, and Bignell 1980).

IV. LIMITS ON LINE EMISSION AND COOL GAS NEAR THE JET

In the presence of a nonthermal continuum such as that emitted by the jet knots, optical emission lines are sensitive indicators of the presence of gas at temperatures below about 10^5 K over a wide range of densities. In the case of M87, the properties of any such cool gas would be of special interest because of the possibility of seeing its interaction with the (presumably) moving knots, the known presence of both cool and hot (10^6–10^7 K) gas elsewhere in M87, and the hope of measuring significant velocities of gas entrained at some fraction of the jet's velocity. Previous work by Baade and Minkowski (1954) and by Sulentic, Arp, and Lorre (1979) showed that no strong emission lines are present in the jet spectrum. The present observations were obtained primarily to search for lines too weak to have been detected in previous work.

As can be seen in Figure 1, no emission features have been detected. The limit for narrow lines (<700 km s^{-1}) is at an equivalent width of 1.0 Å, approximately corresponding to a flux less than 7×10^{-16} ergs cm^{-2} s^{-1} integrated over the slit area ($2''.5 \times 4''.2$ minimum $= 2.4 \times 10^{-10}$ sr) containing the jet. This limit applies to all emission lines in the observed wavelength range that might be expected in astrophysical plasmas: Hα, [O III] λ5007, and [N II] λ6584 are the strongest lines normally seen in such cases. No features appear that might be such lines at redshifts within ± 0.3.

Deriving a value for the maximum allowed emission measure from this limit requires an assumption about the distribution of the gas (or the solid angle over which emission would actually have been measured). The most straightfoward is that in which the gas is assumed to be uniformly distributed across the slit; this gives a value from Hα of $\mathrm{EM} = \int n_e^2 dL = 20\ \mathrm{cm}^{-6}$ pc; any patchiness in the emission-line distribution would lower this limit. This is far below the values appropriate to H II regions, and comparable only to diffuse galactic Hα emission (1–5). Alternatively, this may be expressed as a limit on the filling factor of cool gas in the cylindrical volume about the jet of radius 1″.2 = 130 pc, namely, $2 \times 10^{-2} n_e^{-2}$ for n_e in cm^{-3}. To be in pressure equilibrium with the X-ray gas at $nT \sim 10^7\ \mathrm{cm}^{-3}$ K, gas of 10^4 K must have $n_e \sim 10^{-3}$; under such conditions its filling factor would be less than 10^{-8}. The most physically reasonable interpretation of this limit is that the jet has not entrained or generated sufficient cool gas to avoid its ablation by the hot X-ray gas over the jet's lifetime.

Limits on any broad Balmer emission are necessarily less sensitive than those for the narrow emission just discussed. Such emission might, for example, be present if the jet knots are analogous to active nuclei (which has been suggested on the basis of continuum shape; Sulentic, Arp, and Lorre 1979). The equivalent width limit for broad Hα is roughly 1 Å × (width/700 km s^{-1}), or a maximum of 7 Å for a width of 5000 km s^{-1} (an extreme value for Seyfert nuclei). This is more than an order of magnitude lower than the values found in active nuclei (Shuder 1981; Yee 1980), so a direct analogy to objects with broad-line regions does not seem appropriate. A similar comparison with BL Lac objects also cannot be pressed very far, because of the complex and highly resolved nature of the radio emission (Biretta, Owen, and Hardee 1983).

Observations of line emission in the vicinity of the jet have been examined as possible constraints on jet properties. If the nearest Hα + [N II] filament were at its projected distance from the jet and the jet spectrum showed no break, the ionization parameter (for $n_e = 10^2\ \mathrm{cm}^{-3}$) due to the jet would be of order 10^{-3}. The spectrum observed at this position shows no difference from the other positions reported by Ford and Butcher (1979), giving an excess of ionization parameter $\Delta U \lesssim 10^{-3.5}$. Because of the unknown geometry, a negative result here gives no useful information.

The two emission regions ("counterjet") seen opposite the jet appear at a higher level (by about a factor 3) than the limit on emission in the jet. Thus they are not matter in an exact duplicate of the jet rendered unseen by a Doppler shift; such a situation has already been rendered untenable by the lack of a true counterjet in the radio and optical in searches with high dynamic range.

Further properties of these objects are of interest. In both cases [N II] λ6583/Hα ∼ 1.5, [S II] λλ6717 + 6731/Hα ∼ 1.0, and the [S II] lines are approximately in the low-density limit ($n_e \lesssim 200\ \mathrm{cm}^{-3}$ at 10^4 K). Crude radial-velocity measurements relative to the nucleus give +100 and +300 km s^{-1} for the inner and outer knots (37″ and 54″ from the nucleus, respectively). Further data will be needed to learn whether these motions are related to M87's nuclear activity, because of two shortcomings in these data. Increased velocity resolution is clearly desirable; the shifts seen are only 1–2 pixels here and could be due in part to changes in Hα/[N II] because the lines are not completely resolved. More critically, the precise positions of the emitting knots with respect to the slit are not known; since they are essentially unresolved spatially (from the Ford and Butcher 1979 images), a misalignment of object and slit could introduce spurious velocity shifts. This could be as much as 130 km s^{-1} for the image scale, slit width, and seeing during these observations. Use of precise knot positions or a slit narrower than the seeing disk will be necessary to improve on these velocity measures.

The emission-line ratios of the emission knots show them to be of low ionization, quite similar in this respect to the extensive Hα filaments and to the nucleus itself. This spectrum does not show [O III], but at the nuclear line ratios it would not be detectable. These objects have some of the properties (luminosity, line ratios, and semistellar appearance) expected of supernova remnants. They would, however, be unusual in several ways. It would be unlikely for two to be seen in a single slit setting unless the supernova rate in M87 is very high for an old population. Also, the fact that most of the interstellar medium in M87 seems to have very high temperatures means that the expanding shell would meet the ambient medium subsonically, rather than supersonically as in the usual Sedov case. Thus the emitted spectrum of such a remnant might be much weaker, and of different ionization, than those of galactic counterparts. Line width measurements will be relevant here.

A final spectroscopic point worth stressing is that the emission spectrum of the nucleus is very typical in line ratios of the low-ionization (Liner) class (Heckman 1980), and that such spectra are at least as well fitted by dilute power-law photoionization as by shock models (e.g., Keel 1983). In this case, significant contributions to the ionization might come from knots in the jet as well as any nuclear source hidden optically in the starlight. At a density $10^3\ \mathrm{cm}^{-3}$, appropriate for the nucleus, the ionization parameter $U \equiv n$ (ionizing photons)/n (particles) due to the brightest jet knots alone (assuming $\Delta\alpha = 0.5$ to connect optical, UV, and X-ray spectral measurements) is of order $10^{-5.5}$, nearly two orders of magnitude lower than that needed to account for the nuclear emission-line ratios (e.g., Ferland and Netzer 1983). Such an ionization parameter can be plausibly attributed to the central point source measured by de Vaucouleurs and Nieto (1979) at $B = 16.76$, or 0.34 times the (blue) intensity of the brightest knots measured here. The long-slit spectrum and emission-line images give a radius for the nuclear emission region of about 2″.5 (270 pc); this implies that most of the nucleus gas has $U \sim 10^{-3.8}$ if the nuclear source has a nonthermal spectrum similar to that of the knots; this rises to $10^{-3.4}$ if the nuclear source has a straight power-law spectrum (with no break) as far as the He II Lyman limit. It is at least plausible to assume that the *nuclear* emission lines in M87 are powered directly by the active nucleus. Spectroscopy at high spatial resolution (0″.5 or better) will be needed to search for the flat continuum and ionization gradients expected in this picture.

V. CONCLUSIONS

New optical spectrophotometry of the jet in M87 has yielded a spectral index from 4600–7400 Å of $\alpha = 0.92 \pm 0.06$. In combination with radio, IR, and X-ray data, this suggests a spectral break of moderate amplitude ($\Delta\alpha \sim 0.6$) near 3000 Å, rather than an abrupt ($\Delta\alpha \sim 1$) break near 6000 Å as previously suggested. The range of values allowed for the amplitude of a near-UV spectral break brackets those expected in straightforward synchrotron theory under physically quite different conditions; UV measurements will be necessary to firmly resolve the behavior of the integrated spectrum, and probably any differences among the knots. The presence of a spectral break at 3000 Å ($\pm 20\%$) and the excellent agreement of optical and radio structures in the jet suggest a rather high (10^{-3} gauss or greater) or closed field. Confinement of the jet remains the most outstanding problem in its study.

No emission features have been detected in the jet. Since even the steepest allowed UV spectrum of the jet contains a substantial number of Lyman continuum photons, this is interpreted as a real lack of optically visible ($T \lesssim 10^5$ K) gas. Any gas present near the jet has presumably been heated to temperatures appropriate for X-ray observations. Weak emission features do exist exactly opposite the jet; further study is needed to see whether these bear any relation to the jet or the active nucleus. The emission-line spectrum of the nucleus itself has an ionization level and luminosity consistent with photoionization by the active nucleus itself, if the central excess light has a spectrum similar to those of the jet knots.

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