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IUE SPECTRA OF THE JET AND THE NUCLEUS OF M87[1]

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ABSTRACT

IUE spectra from 1300 to 3000 Å of the jet and the nucleus of M87 are presented. The flux detected with the 10″ × 20″ aperture positioned on the jet is consistent with the extrapolation of the optical power law spectrum ($\lambda^{-0.3}$) of the bright complex of knots A + J + B, plus a contribution of diffuse light from M87.

The spectrum $F(\lambda)$ of the nucleus declines from 3000 to about 2000 Å and then rises again at shorter wavelengths, indicating the presence of two components. The profiles along the slit of the two spectra in the 2000–3000 Å range and in the 1200–2000 Å range are both much broader than the profile of an unresolved source, and the amount of broadening is the same. This shows that both components are diffuse and that their spatial distributions are similar.

An absorption feature due to Mg II λ2800 is seen both in the spectrum of the jet and in that of the nucleus.

Subject headings: galaxies: individual — galaxies: nuclei — ultraviolet: spectra

I. INTRODUCTION

The optical jet in the elliptical galaxy M87 (NGC 4486 = Virgo A) has been regarded since the 1950s as one of the most remarkable peculiarities found in radio galaxies. It looks like a string of knots aligned with the nucleus of the galaxy over a distance from it of about 1 kpc. Its light exhibits a featureless continuum (Baade and Minkowski 1954) with a high degree of polarization (Baade 1956), and is therefore believed to be mainly due to synchrotron radiation. Recently, Sulentic, Arp, and Lorre (1979), besides showing to a high level of sensitivity the absence of any feature in the optical spectrum, present evidence of time variability both in brightness and polarization, obtained by comparing photographs taken 22 years apart. In § III we report the measurement of the far-UV spectrum (from 1300 to 3000 Å) of the brightest portion of the jet made with the *International Ultraviolet Explorer* (*IUE*).

Two *IUE* spectra of the nuclear region of M87 excluding the jet have been published so far. The first, of rather poor quality, obtained in the long wavelength (LW) range (from 2000 to 3000 Å) during the commissioning time, was published by Boksenberg *et al.* (1978). The second, in the short wavelength (SW) range (from 1300 to 2000 Å), was published by Bertola *et al.* (1980). The latter shows a sharp increase of $F(\lambda)$ down to 1300 Å, which Bertola *et al.* (1980) attribute to a population of hot stars distributed in space in the same manner as the cool stars responsible for the visible light. This conclusion is checked, and in fact reinforced, in § IV, by means of two new spectra of comparable quality in the SW and the LW ranges.

II. THE OBSERVATIONS

The observations were all made from VILSPA, using the 10″ × 20″ aperture with the short wavelength prime (SWP) and the long wavelength redundant (LWR) cameras in the low resolution mode. The image label of each spectrum, the date, the exposure time, and the position angle of the entrance aperture are given in Table 1. The first spectrum of the jet in the SW range was actually obtained by us in 1978 July 22, but the image (SWP 2085) was unfortunately spoiled by strong microphonic noise, and is not presented here. When taking the spectrum of the jet, the entrance aperture was positioned as shown in Figure 1 using a blind offset technique. The offset maneuver was started with the slot centered on the nucleus of the galaxy, and measuring the position of nearby stars in the Fine Error Sensor plane before and after the maneuver, we could check the final position of the slot within 1″.

The spectra have been extracted from the line-by-line reproduction of the photometrically and geometrically corrected image (the fourth file in the data tape provided by VILSPA). The net signals have been

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1980ApJ...240..447P

TABLE 1

JOURNAL OF OBSERVATIONS

Image	Date	Exposure	P.A.
M87 jet:			
SWP 3571	1978 Dec. 11	6^h10^m	$-1°$
LWR 3159..........	1978 Dec. 13	6^h30^m	$-1°$
M87 nucleus:			
SWP 4299	1979 Feb. 19	7^h10^m	$-26°$
LWR 3818..........	1979 Feb. 21	3^h50^m	$-26°$

derived by subtracting a smoothed background estimated from strips of image adjacent to the spectra and then converted into absolute fluxes using the calibration curve issued jointly by ESA and NASA in 1978 November (Bohlin and Snijders 1978). Unfortunately our spectra were obtained during a period when an incorrect Intensity Transfer Function was used in the reduction of the SW image. To take care of this, we applied the preliminary recipe prepared at VILSPA (Cassatella and Ponz 1979), which allowed us to work directly on the line-by-line spectrum.

III. THE SPECTRUM OF THE JET

The two spectra SWP 3570 and LWR 3159 were taken with the entrance aperture in the position shown in Figure 1, where the outline of the slot is drawn onto an optical contour map of the jet. The arrows at the top indicate the positions of the various knots along the jet, including the new ones (I, J, K) identified by de Vaucouleurs and Nieto (1979). Only the knots F, I, A, J, B, K, and C are within the aperture. Of these, the complex A + J + B, which dominates in brightness over the rest of the jet, is close to the center.

To investigate the spatial distribution of the source of the UV light, we have derived the profiles of the two spectra perpendicular to the dispersion, that is, along the major axis of the slot. They are shown in Figure 2, together with the profile of a SWP spectrum of a star obtained with an exposure time of 1 hour. Each bin represents a line of pixels in the spectrum and corresponds to 2″.09. The dotted line is the average background level assumed. The two profiles are slightly but significantly broader than that of the star, with about 15% of the net flux lying outside the five central bins, as opposed to 5% in the case of the star. They indicate that the major fraction of the flux comes from an "unresolved" object, identified with the complex A + J + B, to which is added the diffuse contribution of the galaxy and the contribution of the fainter knots F, I, K, and C. The latter, because of the setting of the aperture, should be mostly contained in the five central bins.

The spectrum at full resolution (the points are given in intervals of 2.67 Å in the SW range and 4.42 Å in the

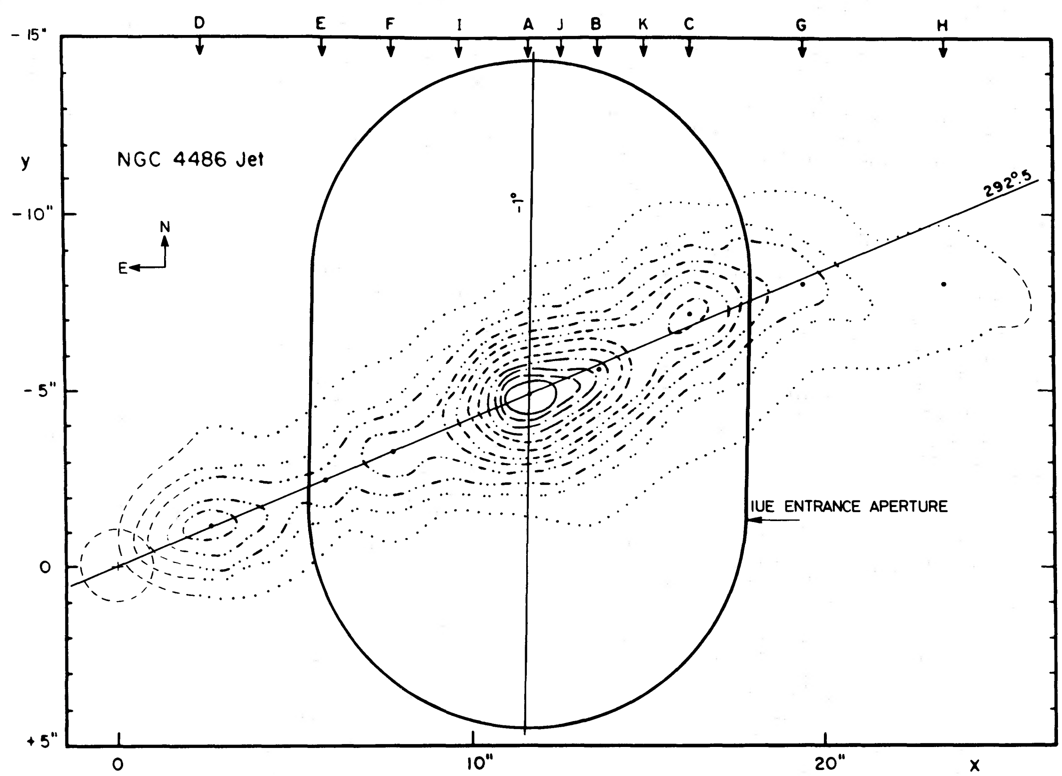

FIG. 1.—The position of the entrance aperture for the spectra of the jet. The isophotes are from de Vaucouleurs *et al.* (1968). The nucleus is at the origin of the coordinates.

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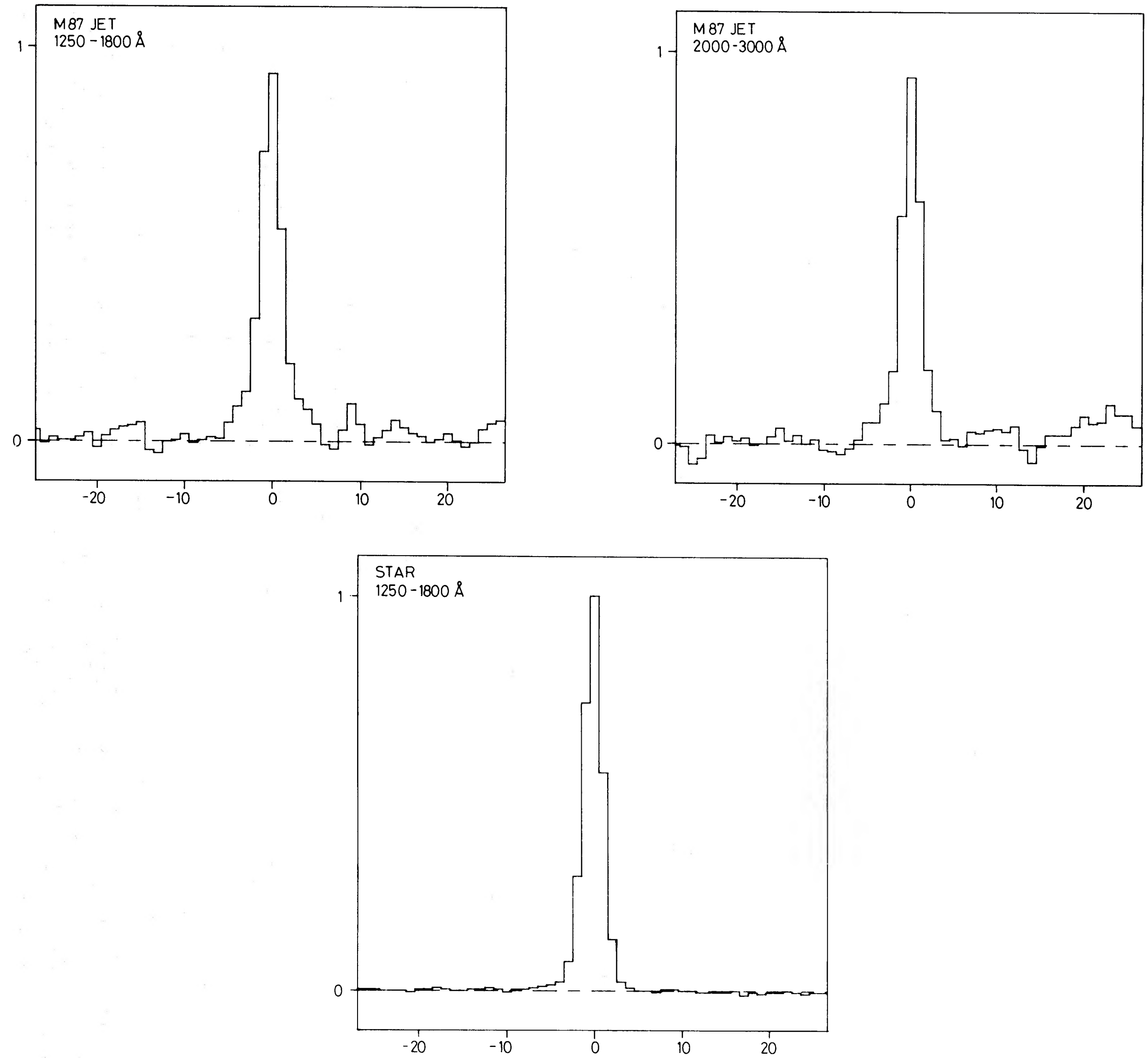

FIG. 2.—Spatial cross sections of the SWP 3571 and LWR 3159 spectra, and of the spectrum of a star. Each bin number in abscissa corresponds to 2″.09.

LW range), obtained by summing the five central lines, is shown in Figures 3*a* and 3*b*. The extra lines containing the wings of the profile were not included, in order to keep the spectrum as free as possible from the numerous spurious features which can be discerned in the background. The fluctuations from point to point are mainly due to the background noise, and their rms value varies from 15 to 30% depending on the wavelength, being lower where the sensitivity is better. When the spectrum is binned in intervals up to 100 Å, there are remarkable deviations from a smooth distribution, which are larger than expected from the rms noise. We have noted, however, that background spectra extracted from the same image and treated in the same way show a similar behavior, and therefore we conclude that those deviations are most likely due to the underlying background, and that our spectrum is consistent with a smooth continuum. The only feature in the spectrum which can be considered real is the Mg II absorption at 2800 Å, and it will be discussed in § V.

The same spectrum, binned in intervals of 75 Å, is shown in Figure 4. The error bars combine the uncertainties due to background noise and fluctuations and to the calibration. The five points between 2000 and 2400 Å are bracketed to indicate that they are extremely uncertain, due to the weakness of the signal in this low sensitivity range of the camera. On the same figure we give the fluxes corresponding to the *UBV* photoelectric photometry of the complex A + J + B

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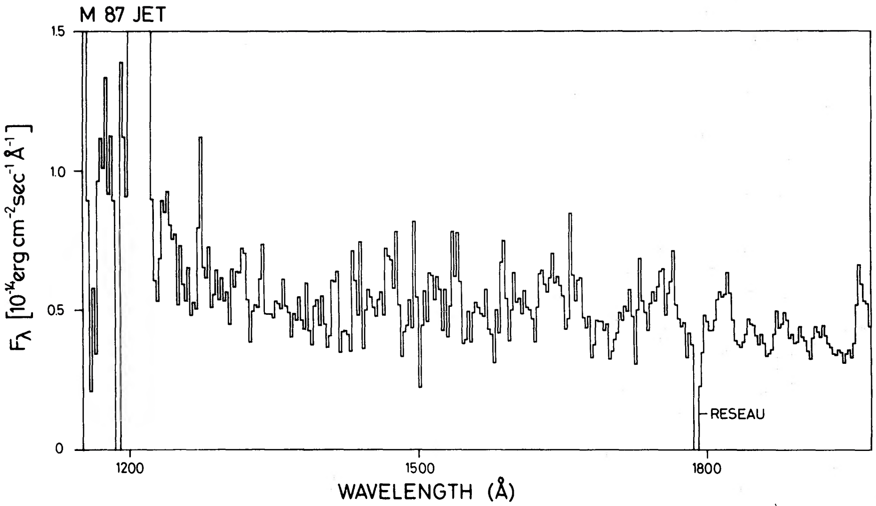

FIG. 3*a*

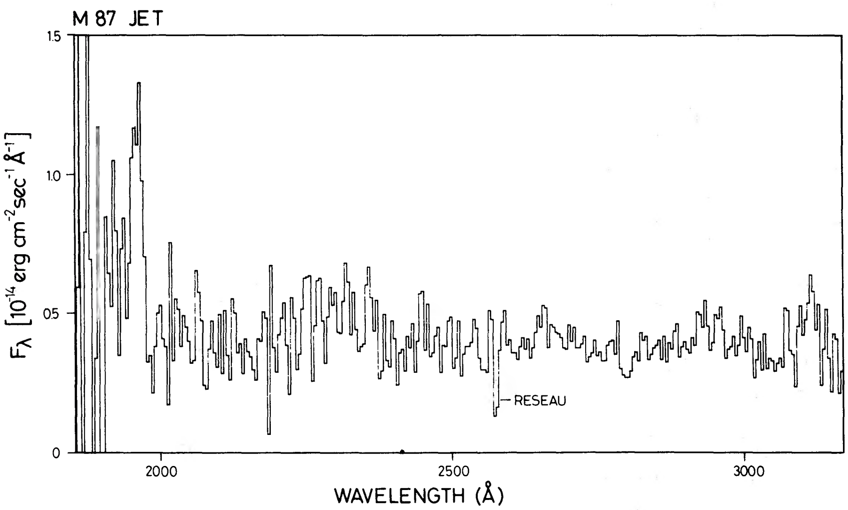

FIG. 3*b*

FIG. 3.—(*a*) Full-resolution spectrum of the jet from image SWP 3571. (*b*) Full-resolution spectrum of the jet from image LWR 3159.

obtained by Kinman, Grasdalen, and Rieke (1974) in 1974 April. The three points are fitted by a power law $\lambda^{-(0.3\pm0.1)}$. De Vaucouleurs and Nieto (1979) measured the blue magnitude of all the knots in the jet on photographs taken in 1964 March. In the figure we give the corresponding flux for the same complex. This is 25% higher than measured by Kinman, Grasdalen, and Rieke (1974), a discrepancy which could be due to a different subtraction of the galaxy light, or, in view of the results obtained by Sulentic, Arp, and Lorre (1979), to the time variability. Our measured flux lies well above the extrapolation of a $\lambda^{-0.3}$ law from either of the two blue magnitudes, and assuming that the UV spectrum of A + J + B is represented by one or the other of these extrapolations, the excess flux amounts to 30–45% of the measured flux around 1500 Å and to 25–45% around 2700 Å.

In order to estimate the contribution from the background light of M87, we make the assumption (which will be justified in the next section) that its UV light has the same spatial distribution as the visual, at least out to a distance from the nucleus comparable to the length of the jet. We then use the UV flux measured with the aperture centered on the nucleus reduced by the ratio of the visual light through the aperture in the two positions. This ratio has been evaluated from the surface photometry in the *V* band given by Young *et al.* (1978). The estimated contribution amounts approximately to 30% around 1500 Å and to 25% around 2700 Å of the flux measured in the five central lines, and accounts, within the uncertainties, for the flux measured in the outer lines. It seems, therefore, that the galactic light is responsible for at least a large fraction of the excess flux, and perhaps for all of it. A direct test

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1980ApJ...240..447P

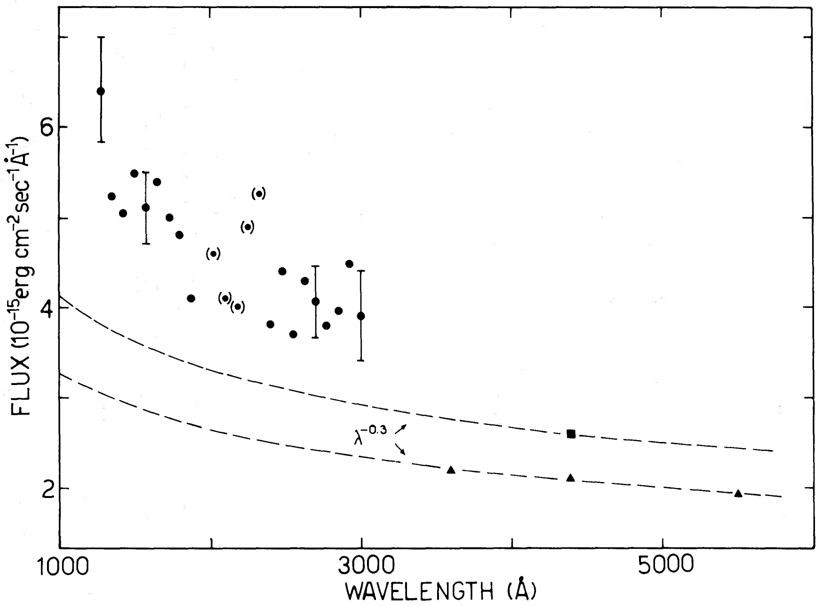

FIG. 4.—Spectrum of the jet binned in intervals of 75 Å. The optical fluxes are from Kinman *et al.* (1974) (*triangles*) and from de Vaucouleurs and Nieto (1979) (*square*).

of this conclusion would be possible by taking a UV spectrum of the galaxy with the entrance aperture in a position symmetrical, with respect to the nucleus, to that shown in Figure 1.

To estimate the contribution of the knots F, I, K, and C, we use the blue magnitudes measured by de Vaucouleurs and Nieto (1979). Their optical flux corresponds to 34% of the total flux from the portion of the jet in the aperture. If these knots had the same spectral slope of A + J + B, they would also account for the excess or a very large fraction of it. We then conclude that, *if* our assumption on the extrapolation of the optical spectrum of A + J + B and our estimate of the diffuse light contribution are correct, the fainter knots should have a ratio of UV to optical light smaller than that of the bright complex. This conclusion stresses the importance of *UBV* photometry also of the fainter knots.

IV. THE SPECTRUM OF THE NUCLEAR REGION

Bertola *et al.* (1980) present and discuss a SW spectrum of the nuclear region of M87 obtained with the 10″ × 20″ aperture centered on the galaxy nucleus, which they combine with a LW spectrum obtained

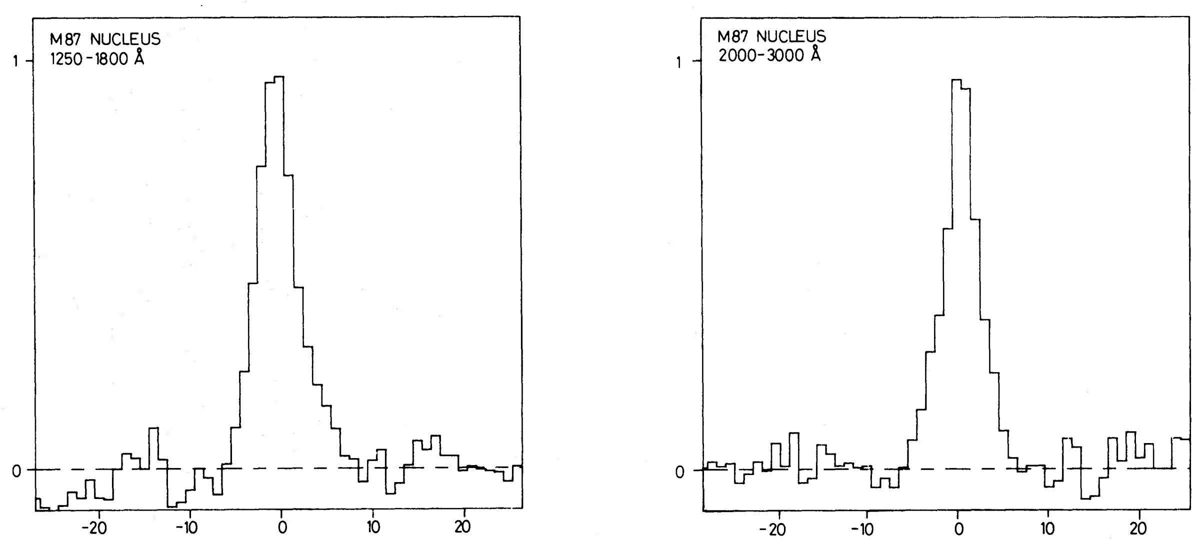

FIG. 5.—Spatial cross sections of the SWP 4299 and LWR 3818 spectra

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1980ApJ...240..447P

during the commissioning period (Boksenberg *et al.* 1978) and a multichannel spectrometry from 3000 to 10000 Å made with the 5 meter Hale telescope. The spectral distribution $F(\lambda)$ in the optical is approximately flat from 10000 to 5000 Å, and declines rapidly afterwards. This decline continues in the UV down to a minimum at about 2200 Å, which is then followed by a rise of a factor about 3 from 2200 to 1300 Å. The flux measured in the 2000–3000 Å region appears as the pure continuation of the spectrum of the cool stars which dominate in the optical. One of the main conclusions of their paper is that the turnup below 2200 Å is due to a population of hot stars (with a nominal temperature around 30,000 K) which are distributed in the nuclear region of M87 in the same manner as the cool stars. This conclusion is based on the analysis of the profile of the spectrum across the dispersion, which appears consistent with the distribution of the visual light in the entrance aperture derived from the surface photometry of Young *et al.* (1978).

This important conclusion could be checked directly by comparing the profiles of the SW and the LW spectra, but unfortunately the quality of the focus was not under control during the commissioning time. We have obtained two spectra, a SW and a LW one, with an equivalent quality of the focus, and their profiles are shown in Figure 5. They are both much broader than those of the jet spectra (Fig. 2), where an "unresolved" component dominates, and are very similar to each

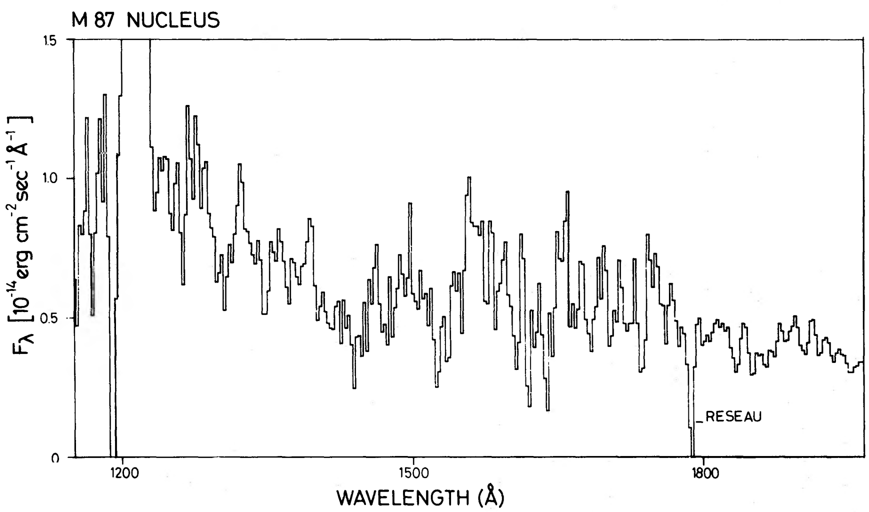

FIG. 6*a*

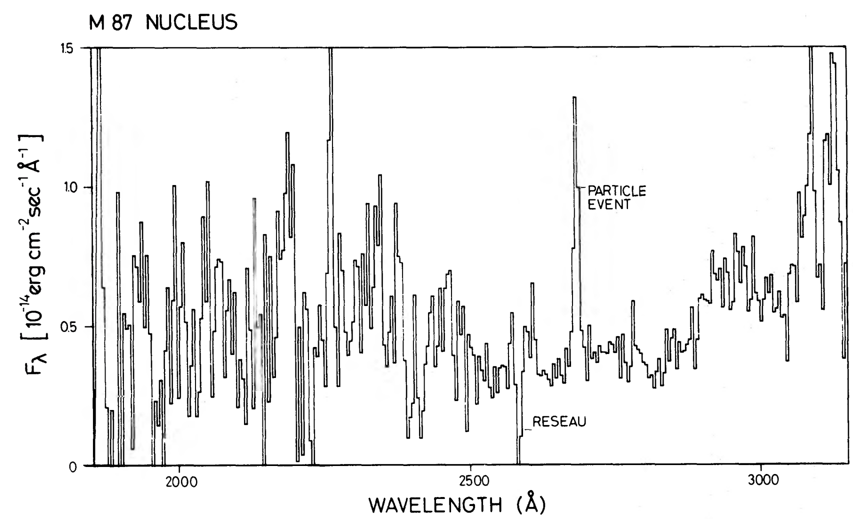

FIG. 6*b*

FIG. 6.—(*a*) Full-resolution spectrum of the nucleus from image SWP 4299. (*b*) Full-resolution spectrum of the nucleus from image LWR 3818.

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1980ApJ...240..447P

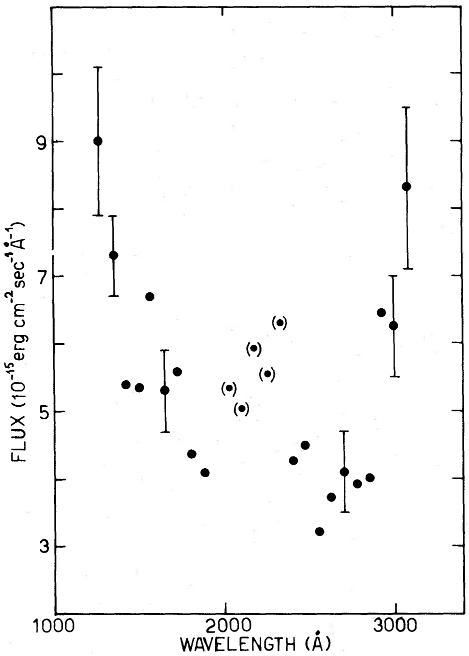

FIG. 7.—Spectrum of the nucleus binned in intervals of 75 Å

other, thus proving directly that the hot and the cool stars have a similar distribution in space. (This also justifies the assumption made in the previous section in estimating the diffuse light contribution to the spectrum of the jet.) In fact, the profile in the SW range looks somewhat broader and asymmetric at the bottom. Because of the setting of the aperture, the asymmetry would be caused by an excess of radiation in the SE quadrant, and therefore has nothing to do with the jet (only the weak knots D and E were within the aperture, and they lie in the NW quadrant). We believe that it is a background effect on the extracted spectrum. It should be noted that the asymmetry is not present in the spectrum taken by Bertola *et al.* (1980), with the aperture in P.A. 25°, and which we have analyzed independently for this effect.

One should consider also the possible contribution from the optical spike at the nucleus of M87 (Young *et al.* 1978; de Vaucouleurs and Nieto 1979), whose *B* magnitude is comparable to that of knot A. If it had also the same spectrum, $\lambda^{-0.3}$, its contribution around 1800 and 2500 Å, where the sensitivity of the cameras is good and the observed spectrum is close to a minimum, would amount to 30–35% of the measured flux. It is practically impossible, however, with the available signal, to discern this contribution in the profiles around those wavelengths.

The full resolution spectrum is shown in Figures 6*a* and 6*b*, and the same binned in intervals of 75 Å is shown in Figure 7. The signal-to-noise ratio is similar to that of the spectrum of the jet, and the same considerations apply for the effect of a nonuniform underlying background. In particular we attribute to such an effect the hump made by the points in brackets.

The SW spectrum (Fig. 6*a*) can be compared with that given by Bertola *et al.* (1980) to evaluate the reliability of the features. This comparison was done already by the authors of that paper.

The LW spectrum (Fig. 6*b*) is shown for the first time at full resolution (the spectrum obtained during the commissioning time is given by Boksenberg *et al.* 1978, in bins of 100 Å; moreover, it is affected by the imperfect calibration then available). It is very noisy, and the only feature which we consider real is the Mg II absorption at 2800 Å. We estimate upper and lower limits of 9 and 3 Å to its equivalent width, by taking the lowest and highest local continuum which can be drawn through the adjacent points. This absorption is present also in the spectra of the nuclei of M31 and M32 (Johnson 1979) and of the globular clusters M15 and NGC 6624 (Dupree *et al.* 1979). In M31, Johnson estimates a W_λ of about 13 Å, and comparable values can be derived from the published spectra of the other objects. It looks as if in the nucleus of M87 this feature were significantly weaker, and this could be due to a partial compensation by emission from the nuclear gaseous component responsible for the optical emission lines (Sulentic, Arp, and Lorre 1979).

V. DISCUSSION

The evidence that the spectrum of the jet extends into the far-UV can be used to argue that the absence of emission lines in its spectrum is probably not due to a lack of ionizing photons. Our measurement is consistent with the extrapolation of the optical spectrum as $\lambda^{-0.3}$ up to 1300 Å. Assuming that this slope is maintained up to the He I limit (504 Å), we adopt the expression given by Penston and Fosbury (1978) to evaluate the expected equivalent width of Hβ:

$$W_\beta \approx 564(9.64)^\alpha\left(\frac{1-0.553^\alpha}{\alpha}\right)\text{Å}\,,$$

which applies when the source of ionizing photons is completely surrounded by optically thick gas. The exponent α is the frequency spectral index, in our case $\alpha = -1.7$, and therefore the maximum expected $W_\beta \approx 12.2$. Although they do not quote upper limits, this quantity is at least one order of magnitude greater than Sulentic, Arp, and Lorre (1979) would have been able to detect in their spectrum of the jet. We then conclude that, unless the UV spectrum cuts off below the Lyman limit, the absence of emission lines is naturally attributed to the absence of gas in the state normally found around the continuum source in QSOs and Seyfert galaxies. This conclusion is the same as the one reached by Boksenberg *et al.* (1978) with regard to the BL Lac object Mrk 421, and strengthens the similarity between the M87 jet and BL Lac objects in general, pointed out by Sulentic, Arp and Lorre (1979).

In § III we noted the presence of Mg II λ2800 absorption in the spectrum of the jet. Upper and lower

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1980ApJ...240..447P

limits to its equivalent width are 11 and 5 Å. This feature is conceivably due in part to the absorption intrinsic to the background light of M87 contaminating the spectrum, and in part to interstellar absorption in our Galaxy. Because of the large uncertainties, it is not worth trying to disentangle the two contributions. We limit ourselves to mentioning, for comparison, that the Mg II interstellar feature in the spectrum of 3C 273, another high-galactic-latitude object ($b = 64\overset{\circ}{.}4$ compared to $74\overset{\circ}{.}5$ of M87), has $W_\lambda = 0.8$–1.6 Å (Ulrich *et al.* 1980).

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