THE ASTROPHYSICAL JOURNAL, 237:L65–L69, 1980 May 1

INTERNATIONAL ULTRAVIOLET EXPLORER OBSERVATIONS OF M87

F. BERTOLA AND M. CAPACCIOLI
Asiago Astrophysical Observatory, University of Padova

A. V. HOLM
Computer Science Corporation, Silver Spring, Maryland

AND

J. B. OKE
Hale Observatories.[1] California Institute of Technology
Received 1979 September 4; accepted 1980 January 25

ABSTRACT

The *International Ultraviolet Explorer* (*IUE*) has been used to obtain a spectrum of M87 in the 1150–2000 Å spectral range. When combined with a commissioning team spectrum obtained in the 2000–3200 Å region and multichannel spectrometer observations obtained with the 5 m Hale telescope, the absolute spectral energy distribution from 1300 to 10,000 Å is obtained. The flux density drops rapidly in the UV, reaches a minimum at 2200 Å, and then increases sharply between 2200 and 1300 Å. It is shown that this turnup is not a consequence of scattered light in the instrument. It is also shown that this 1300–2200 Å radiation comes from an extended source which probably is made up of hot horizontal-branch stars, although one cannot rule out the possibility that the hot stars are on the upper main sequence. The ratio of hot stars to cool stars is different in M87, M31, and M32. There is good evidence in the UV for an emission line of C IV; a few other emission lines may also be present. The relative strengths of C IV, Hβ, and [O III] $\lambda\lambda$4959, 5007 are consistent with those seen in planetary nebulae but [O II] λ3727 is much too strong.

Subject headings: radio sources: galaxies — spectrophotometry — ultraviolet: spectra

I. INTRODUCTION

The elliptical galaxy M87 (NGC 4486) is of particular interest to astronomers because (*a*) it is relatively nearby and bright, (*b*) it has a remarkable optical jet which is polarized, and (*c*) it is a strong radio and X-ray source. The recent discovery that it probably has a massive object at its center makes it of even more interest. For all of these reasons it was placed on a list of objects to be observed in the ultraviolet, using the *International Ultraviolet Explorer* (*IUE*).

II. OBSERVATIONS

A spectrum of the nuclear region of M87 was obtained on 1978 July 30 at the Villafranca ESA ground station using the short-wavelength camera (SWP) of *IUE*. The wavelength range covered was from 1150 to 1950 Å, and the exposure time was 400 minutes, nearly the maximum possible in one 8 hour shift. Because the source is faint, the low-resolution mode (with a resolution of 6 Å) was used along with the 10″ × 20″ entrance aperture. This entrance aperture is the equivalent of a 10″ diameter circular aperture trailed in one direction by 10″. The nucleus was set and centered on the aperture using the fine error sensor (FES) while guiding was done using a nearby star. The guiding accuracy is estimated to be better than 1″. The position angle of the elongated direction of the entrance aperture was −25° on the sky. It can easily be verified that the brightest knots of the jet lie well outside the entrance slot.

In Figure 1 we present the net spectrum obtained with the short-wavelength camera. The reduction was done using the standard techniques available with *IUE*. The conversion to absolute flux is based on the first official calibration curve issued by ESA and NASA on 1978 November by Bohlin and Snijders (1978). This spectrum, which had been processed with incorrect Intensity Transfer Functions, was corrected with the 3 Agency 4th file method. The average values of f_λ in a selection of wavelength intervals are listed in Table 1 and plotted in Figure 2.

A similar spectrum of the nuclear region of M87, viewed with the long-wavelength camera (LWP), which covers the range from 2000 to 3100 Å, had already been obtained during the commissioning phase (Boksenberg *et al.* 1978). Since no detailed spectrum is shown by them, we have only the points plotted in their Figure 10. Since the absolute flux calibrations during the commissioning phase were very uncertain, we have used the following procedure to try to put their fluxes on the current accepted absolute flux scales. More recent observations of NGC 4151 made with the LWR camera by one of the authors (J. B. O.), and converted to absolute fluxes using a recent calibration (Bohlin and Snijders 1978), were compared with the corresponding fluxes obtained during the commissioning phase (Boksenberg *et al.* 1978) using the LWP camera.

[1] Operated jointly by the Carnegie Institution of Washington and California Institute of Technology.

This comparison was used to generate correction factors to convert commissioning phase LWP fluxes to newer LWR fluxes; these correction factors decrease the fluxes given by Boksenberg *et al.* by up to a factor 2. The fluxes for M87, corrected in the above fashion, are listed in Table 1 and shown in Figure 2.

In the visual wavelength range an absolute spectral energy distribution was obtained with the multichannel spectrometer (MCSP) on the Hale 5 m telescope. The fluxes were measured through a 14".1 diameter circular aperture centered on the nucleus while the sky was measured 26" east or west of the nucleus. This automatic sky measurement still has a significant contribution from the galaxy which must be removed. This was done by also measuring the true sky at a limited number of wavelengths several arcmin from M87; these produced wavelength-dependent corrections of 7–18%.

It is also necessary to adjust these observations so that they represent the same area on the galaxy as the 10" × 20" *IUE* aperture. This was done by using the luminosity profile of M87 by Young *et al.* (1978) and integrating over the 10" × 20" aperture and the 14".1 diameter MCSP aperture. This indicated that the MCSP fluxes should be increased by 8%.

The final fluxes are shown in Figure 2. The band-passes are 80 Å for $\lambda < 5700$ Å and 160 Å for $\lambda > 5700$ Å. It is apparent that the fluxes from the SWP camera, the LWP camera, and the visual fluxes provide an essentially continuous curve from 1300 to 10,500 Å. The striking result is the turnup in flux below 2200 Å.

TABLE 1

CONTINUUM FLUX DENSITY FOR M87

Wavelength Range (Å)	Camera	F_λ (10^{-15} ergs s^{-1} cm^{-2} Å^{-1})
1240–1294	SWP	8.6±0.9
1295–1350	SWP	7.2±0.7
1351–1405	SWP	7.8±0.7
1406–1460	SWP	7.2±0.7
1461–1516	SWP	7.0±0.7
1517–1571	SWP	7.2±0.7
1572–1626	SWP	4.5±0.6
1627–1681	SWP	5.6±0.6
1682–1736	SWP	5.0±0.6
1737–1772	SWP	6.5±0.6
1794–1848	SWP	4.9±0.5
1849–1904	SWP	3.9±0.4
1905–1958	SWP	3.4±0.6

Wavelength (Å)	Camera	F_λ[a] (10^{-15} ergs s^{-1} cm^{-2} Å^{-1})
2170	LWP	2.4±2.1
2390	LWP	2.8±0.7
2480	LWP	4.9±0.6
2580	LWP	3.3±0.4
2680	LWP	4.4±0.4
2780	LWP	4.8±0.4
2880	LWP	6.3±0.8
2980	LWP	9.6±0.9
3060	LWP	10.5±0.9
3180	LWP	14.4±1.9

[a] Data derived from Boksenberg *et al.* (1978), their Fig. 10.

III. TESTS FOR SCATTERED LIGHT

Before accepting the energy distribution shown in Figure 2, it is necessary to check that scattered, long-wavelength light is not important, since we are dealing with a very red object. Indeed, spectra of planets and very cool stars taken with the short-wavelength camera can extend below the wavelength where the camera sensitivity becomes negligible, indicating that some scattered light is present. To check the scattered light level we have obtained two spectra of Capella (α Aur). Ground-based photometry and *OAO 2* spectra (Code and Meade 1979) show that Capella has an energy distribution in the 2900–5500 Å region which agrees well with that which has been derived here for M87. This makes it a good model to test the contribution of scattered light at shorter wavelengths. Fluxes were derived for Capella from the *IUE* spectra for regions of apparent continuum between 2500 and 1225 Å.

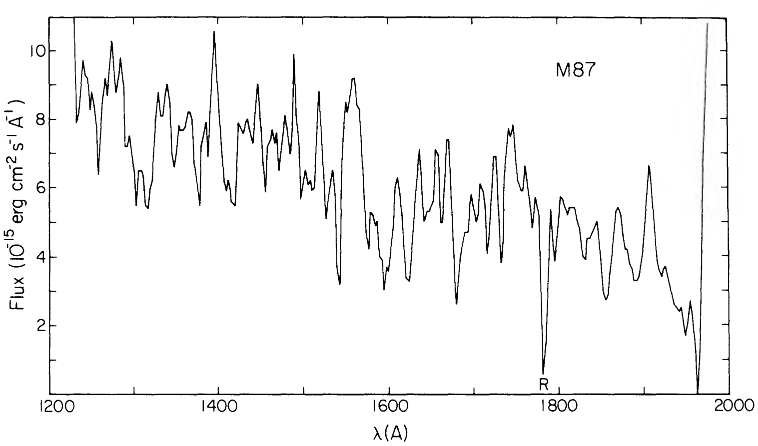

FIG. 1.—Net spectrum of the nucleus of M87, taken with the *IUE* SWP low-resolution camera through the 10" × 20" aperture. Exposure time is 400 minutes. A region affected by a reseau mark is marked by *R*. A three-point running mean smoothing has been applied.

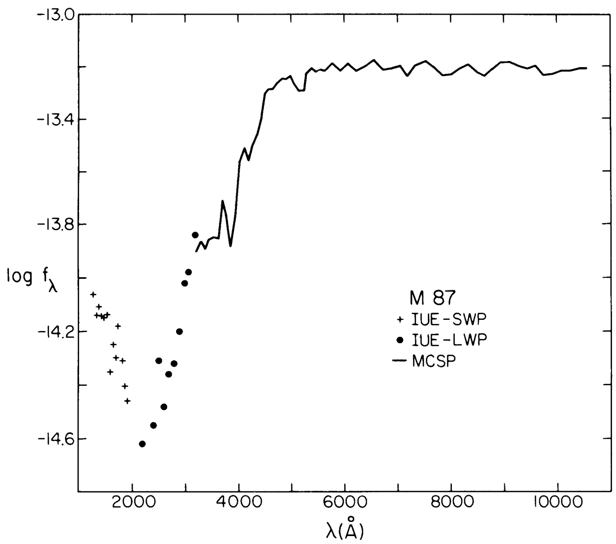

FIG. 2.—Visual and UV energy distribution of the nucleus of M87. *Continuous line*, Palomar multichannel data. *Plus signs*, *IUE* SWP (this paper). *Solid dots*, *IUE* LWP from Boksenberg *et al.* (1978). Fluxes f_λ are in ergs cm^{-2} s^{-1} A^{-1}.

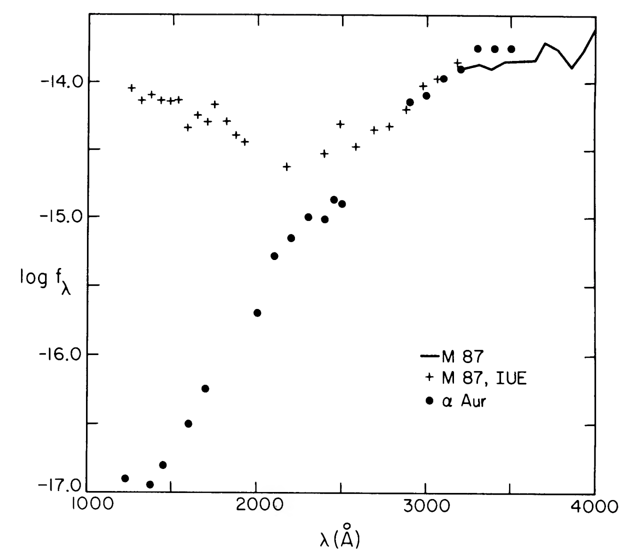

FIG. 3.—The solid dots show the energy distribution log f_λ for Capella (α Aur) based on *IUE* and *OAO 2* observations, but scaled to the visual magnitude of M87. Also shown are the M87 observations made with *IUE* (*plus signs*) and the multichannel spectrometer (*continuous line*). The very different behavior below 2200 Å in the two objects shows that the M87 UV fluxes are intrinsic and not a consequence of scattered light.

These, together with the *OAO 2* fluxes longward of 2900 Å, are scaled by the difference between the *V*-magnitudes for M87 and Capella and plotted on Figure 3. In the worst possible case all the fluxes from Capella at 2000 Å and shortward could be scattered light. Therefore, the observed flux in M87 can be at most 10% scattered light at 2000 Å and 0.2% at 1200 Å. In fact, there is reasonable agreement between the *IUE* and *OAO 2* at all wavelengths longer than 2000 Å so that the scattered light probably contributes much less than the upper limits given above. Thus the energy distribution in Figure 2 is intrinsic to M87.

IV. THE UV LUMINOSITY PROFILE OF M87

Since the spectrum of the nucleus has been obtained with a slot whose length is 20″, and since the Galaxy was held fixed in the slot during the exposure, one can obtain interesting information about the 1200–2000 Å UV light distribution in the nuclear region of the galaxy. In order to derive a luminosity profile, the counts in each row of pixels perpendicular to the direction of the dispersion were plotted. The background was determined using the counts on both sides of the exposed spectrum and interpolating between them with a second-order polynomial. Mean intensity points were then derived for rows of pixels parallel to the dispersion and in symmetrical positions relative to the central point. These means, obtained from pixels corresponding to 1530–1660 Å and 1660–1790 Å agree quite well. They are plotted in Figure 4. The galaxy has been detected over almost the whole length of the slit.

An SWP spectrum of the star BD +3°1011 (kindly provided by P. Bernacca), exposed to the same level as the M87 spectrum, was used to derive the instrumental profile at the center of the *IUE* larger aperture. The profile extended over only five pixels and is shown in the left part of Figure 4. The dashed line in this figure is the Gaussian fit with $\sigma = 1.2$ pixels (2″.4). The accurate deconvolution of the *IUE* M87 luminosity profile cannot be performed precisely since the point-spread-function is not known over the whole aperture; a qualitative estimate shows that its effect is negligible for our purpose. In order to compare the UV luminosity profile with the optical one, we have plotted in the right-hand side of Figure 4 both the deconvolved M87 UV profile (full line) and the visual profile (broken line) derived from that of Young *et al.* (1978) derived by geometrically integrating over the *IUE* aperture. The agreement is excellent and shows that the radiation in the 1300–2200 Å spectral region is distributed in the same way as the visual radiation; it is not a point source.

V. EMISSION AND ABSORPTION LINES

Our SWP spectrum of M87 is very noisy so that only the strongest spectral features can be detected. Fortunately, a second SWP long-exposure spectrum, taken by G. Perola and M. Tarenghi, was kindly shown to us, for comparison purposes. Only features clearly present in both spectra were accepted as possibly real. Several emission lines appear to be real or suspected; they are listed in Table 2 along with equivalent widths and line intensities. These latter are uncertain by at least 50%. It should be noted that Lα is within the geocoronal Lα line and cannot therefore be detected. A search was made for absorption lines with the effort being directed toward those lines which would be present in the spectra of early B–type stars (the continuum in the 1200–2000 Å region fits a blackbody at 30,000 K). Absorption at λ1300 (mainly Si III) may be present, but there is no evidence for any absorption at λλ1394, 1402 (Si IV), and λλ1548, 1550 (C IV) is masked by possible emission.

VI. DISCUSSION

The continuum flux of M87 from 2500 to 10,000 Å matches that expected of stars with temperatures of about 4200 K, i.e., the cool stars which dominate the light from elliptical galaxies. Below 2000 Å the rapid increase in flux can be formally represented by a blackbody with a temperature of 30,000 K. Such a turnup has been observed in other galaxies (including M87), in the central bulge of M31, and in some globular clusters by *OAO 2* (Welch and Code 1972; Code and Welch 1979). The first question is whether the turnup in M87 is related to the massive object at the center (Young *et al.* 1978; Sargent *et al.* 1978), or a general property of elliptical galaxies. Since the luminosity profiles in the UV and visual agree with each other, this implies that the far-UV radiation is extended, and therefore it is a property of the stellar radiation and not of a central massive source, which would require a point UV source. Moreover, since the UV excess is observed through the *OAO 2* 10″ aperture, which contains 25 times as much visual flux as the *IUE* large aperture, this phenomenon must apply to a large fraction of M87. Adopting the view that the UV radiation is related to the stellar component, then, as discussed by Code and Welch, it is a question of whether this radiation comes from hot O- and B-type stars or

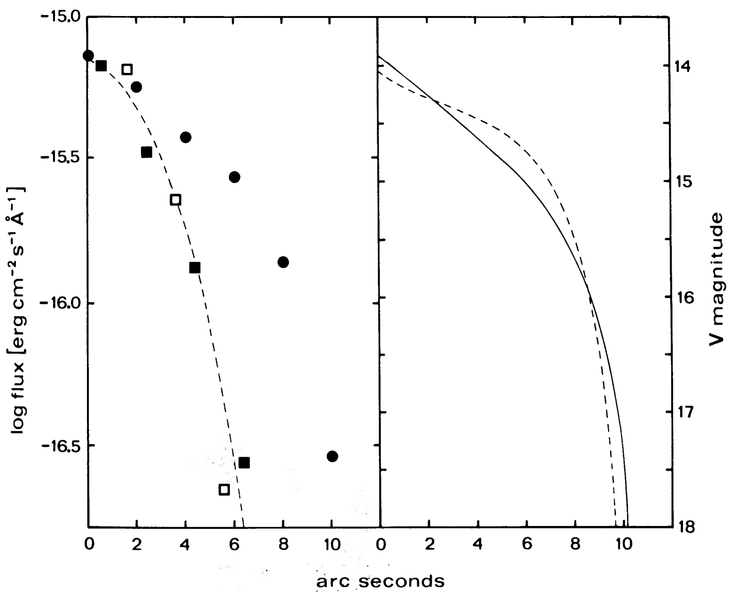

FIG. 4.—*Left panel*, mean luminosity profile of the nuclear region of M87 in the *IUE* short-wavelength range folded with respect to the peak brightness (*dots*). Squares give the two sides of the instrumental *IUE* profile as derived from a star, scaled to the peak brightness of M87. The dashed line is a formal fit with a Gaussian function with $\sigma = 1.2$ pixel. The scale in abscissa has been computed adopting a 2″.0 pixel size in the spatially resolved image. *Right panel*, comparison between smoothed representation of the UV profile of M87 (*continuous line*) and visual profile (*broken line*) (Young *et al.* 1978) geometrically integrated to match *IUE* resolution. The former has been scaled to give the same total flux as the latter within the 10″ × 20″ aperture.

TABLE 2

EMISSION-LINE INTENSITIES

Rest Wavelength (Å)	Ion	E.W. (Å)	Line Intensity (10^{-14} ergs s^{-1} cm^{-2})	Remarks
1393, 1402.....	Si IV, O IV]	5	2.5	Probable
1548, 1550.....	C IV	18	8.7	Almost certain
1749..........	N III]	10	4.4	Probable
3727..........	[O II]	35	6.0[a]	
4861..........	Hβ	1.6	0.8[a]	
4959..........	[O III]	6.5	3.3[a]	

[a] Based on the spectrum by Arp (1979) with very uncertain aperture corrections applied.

from the hot horizontal-branch stars expected in old evolved populations. The fact that the *OAO* observations also show a turnup in the far-UV in globular clusters favors the view that the horizontal-branch stars produce the radiation; but it is not clear even in globular clusters that there are no main-sequence OB stars.

It is of interest to compare the *IUE* fluxes for M87 with those for M31 and M32 (Johnson 1979). There is a progressive change in the wavelength of the minimum flux in the UV which appears to be caused by varying amounts of hot stellar radiation relative to that from the cool stars. The relative hot-star contribution is greatest for M87, a factor 2.5 smaller in M31, and a further factor 2.5 smaller in M32. The difference between M31 and M87 is qualitatively similar to that found by Code and Welch (1979). These differences presumably reflect the ratio in population of hot stars, either horizontal-branch or main-sequence, to cool-giant and main-sequence stars.

We next consider the question of emission lines in the far-UV spectrum of M87. Emission lines of H I, [O II], and [O III] are seen in the visible; very uncertain estimates of the line intensities based on an observation by Arp (1979) are given in Table 2.

To see whether the estimated line intensities are reasonable we can be guided by models or observations of planetary nebulae.

The models for planetary nebulae and UV observations reported by Bohlin, Harrington, and Stecker (1978) suggest relative line intensities for [O III], Hβ, and C IV which agree well with those measured for M87. The [O II] line in M87 is, however, too strong by nearly a factor of 10; also, the UV lines other than C IV are much stronger than predicted.

We gratefully acknowledge the assistance of the *IUE* Observatory staffs in both Europe and the United States in the acquisition and reduction of these data. This work was supported by the National Aeronautics and Space Administration under grant NSG 5243.

A first draft of this *Letter* has been prepared while one of us (F. B.) was visiting California Institute of Technology, using a grant of the Italy-United States Science Cooperation Program.

REFERENCES

Arp, H. C. 1979, preprint.
Bohlin, R. C., Harrington, J. P., and Stecker, T. P. 1978, *Ap. J.*, **219**, 575.
Bohlin, R. C., and Snijders, M. A. J. 1978, *NASA IUE Newsletter*, No. 2.
Boksenberg, A., *et al.* 1978, *Nature*, **275**, 404.
Code, A. D., and Meade, M. R. 1979, *Ap. J. Suppl.*, **39**, 195.
Code, A. D., and Welch, G. A. 1979, *Ap. J.*, **228**, 95.
Code, A. D., Welch, G. A., and Page, T. L. 1972, *Scientific Results from the Orbiting Astronomical Observatory*, ed. A. D. Code (NASA SP-310), p. 559 (CWP).
Johnson, H. M. 1979, *Ap. J.* (*Letters*), **230**, L137.
Sargent, W. L. W., Young, P. J., Boksenberg, A., Shortridge, K., Lynds, C. R., and Hartwick, F. D. A. 1978, *Ap. J.*, **221**, 731.
Welch, G. A., and Code, A. D. 1972, *Scientific Results from the Orbiting Astronomical Observatory*, ed. A. D. Code (NASA SP-310), p. 541.
Young, P. J., Westphal, J. E., Kristian, J., Wilson, C. P., and Landauer, F. P. 1978, *Ap. J.*, **221**, 721.

F. Bertola and M. Capaccioli: Osservatorio Astronomico, 35100 Padova, Italy

A. V. Holm: *IUE* Science Operation Center, Code 685/CSC, Goddard Space Flight Center, Greenbelt, MD 20770

J. B. Oke: Department of Astronomy 105-24, California Institute of Technology, Pasadena, CA 91125