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UBVRIHKL PHOTOMETRY OF THE CENTRAL REGION OF M31

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ABSTRACT

The nuclear region of M31 has similar brightness distributions, $I(r)$, in BVR and $K(2\ 2\ \mu)$ wavelengths. No non-thermal infrared excess exists in the nucleus of M31 above our limit of detection.

A pronounced variation of $U - B$ exists across the central $\pm 60''$ (± 200 pc) which is not present in $B - V$ or redder colors. $U - B$ changes from 0.79 at the center to 0.60 at $r = \pm 60''$. Variation of the stellar luminosity function or metal abundance with distance from the center is a possible explanation, but neither is proved by the present data. Similar small-scale color gradients exist in M32, M81, and NGC 7331.

The absolute energy distribution $I(\lambda)$ shows a broad maximum which extends between 0.45 μ and 1 μ and decreases sharply on either side of the plateau. The broad-band multicolor data generally agree with the scanner data of higher spectral resolution which is available in the interval $0.33\ \mu < \lambda < 1.1\ \mu$.

The surface brightness of M31 at 2 2 μ averaged over the central ± 13 pc ($7''.62$ diameter) is 2.2×10^{-28} W m^{-2} Hz^{-1} per square second of arc. This is fainter by a factor of 2.4 than the 2.2 μ surface brightness of the Galactic center averaged over the equivalent linear diameter. The $I(r)$ profile for M31 and the Galaxy is similar over the central ± 400 pc—a fact which, combined with the higher surface brightness of the Galaxy, suggests that the Hubble type for the Galactic system is closer to an early Sb than to an Sc of the M33 or NGC 2403 type.

I. INTRODUCTION

The surface brightness of the central ± 2 minutes of arc of M31 has been measured along an east-west line and along the major and minor axes in the spectral interval $0.36\ \mu \leq \lambda \leq 3.4\ \mu$. The purpose was fourfold: (1) A test can be made for the presence or absence of a non-thermal infrared excess (peaked at the nucleus), such as that found in Seyfert galaxies (Pacholczyk and Wisniewski 1967) and QSOs (Low and Johnson 1964; Oke, Neugebauer, and Becklin 1969). Similar $I(r)$ distributions in the infrared and at shorter wavelengths would be evidence against such an excess, since it is known that nearly all continuous radiation in M31 shortward of $\lambda \simeq 0.9\ \mu$ is thermal (i.e. due to stars). (2) Comparison of the infrared brightness distribution of the Galactic nucleus (Becklin and Neugebauer 1968, hereinafter called Paper I) with M31 and other galaxies can provide information on the Hubble classification of our Galaxy. (3) Evidence for differences in the stellar content of the nucleus and the adjacent bulge population of M31 would exist if the spectral energy distribution were shown to vary in a systematic way with wavelength and with distance from the nucleus. (4) The energy distribution $I(\lambda)$ of the nucleus over an extended wavelength interval provides, among other things, (a) constraints on the stellar composition of synthetic luminosity functions (Wood 1966; Spinrad 1966, 1967; Morgan 1967; Johnson 1966), (b) data necessary for calculations of infrared K-corrections important in cosmology, and (c) information to estimate the density of thermal infrared background radiation in the Universe (Sandage and Tammann 1966).

A preliminary discussion of $I(r)_{2.2\,\mu}$ for M31 was given in Paper I (Fig. 10), where it was shown that the half-power widths of the surface brightness distributions are similar for M31 and the Galactic system. We present the data in this paper, together with new measurements of $I(r)$ in the UBV and R band passes for M31 and a few data in UBV for M32, M81, and NGC 7331.

II. *UBVRK* SURFACE BRIGHTNESS MEASUREMENTS

The infrared observations (*IHKL* magnitude system) were made at the Cassegrain focus of the 60-, 100-, and 200-inch telescopes at Mount Wilson and Palomar using the dual-beam photometer described in Paper I. Corrections to the original data were required to obtain the true $I(r)$ function because the reference beam was not completely free from the extended radiation due to M31, although the reference region always had a considerably lower surface brightness than the nucleus.

The 60-inch observations, made with a measuring beam of 47 seconds angular diameter, are least affected because the reference beam was further from the nucleus than at the 100- and 200-inch reflectors owing to the smaller scale of the Cassegrain field. The reference beam was 7 minutes of arc north of the main beam, and the preliminary zero-intensity level was taken, in order to make comparisons with the limited data on the galactic center, 20 minutes to the east. The actual intensity at this position, applied as a correction to the observed ratio signal, was estimated from the $I(20')/I(0)$ ratio observed in blue light as described later. The added intensity resulted in corrections of 3 per cent of the peak intensity (at the nucleus) and 20 per cent at $r = 150$ seconds of arc.

Observations with the 100-inch were made with a resolution of 7.5 seconds angular diameter. The reference beam was 130″ south of the nucleus, and the preliminary zero level was taken 150″ west. Corrections for an intensity zero at infinity amounted to 7 per cent at the nucleus. The 200-inch observations were made with a 5″.0 resolution (diaphragm diameter). The correction corresponding to the $I(\infty) \rightarrow 0$ condition amounted to 7 per cent of the measured value at the nucleus.

The corrected data are listed in Tables 1 and 2. The 2.2 μ brightness distribution was sampled along an east-west line to a distance of $r = \pm 35''$ with the 200-inch, to $r = 50''$W with the 100-inch, and $r = 145''$E with the 60-inch. The 0.88, 1.65, 2.2 and 3.4 μ data were reduced to the I, K, and L zero points by observations of standard stars (Johnson *et al.* 1966; Becklin 1968). Mean errors were estimated from the internal consistency of the multiple integrations obtained at each point of the galaxy. The surface brightness, expressed as K/square seconds of arc, is also listed.

The $UBVR$ data are listed in Tables 3 and 4. The observations were made at the prime focus of the 200-inch, using angular resolutions of 4″.86 and 7″.62 (diameter). An S20 photomultiplier was used for the 1967 (Table 3) observations with filters described elsewhere (Sandage and Smith 1963). Data in Table 3 were obtained along an E-W line, which differs by 52° from the direction of the major axis. The 1959 observations (Table 4) were made along the major and minor axes with a 1P21 multiplier. The sky positions for all observations were taken alternately 1°N and 1°S of the nucleus—regions which have a negligibly small contribution from M31 (de Vaucouleurs 1958, Figure 3; Lyngå 1959).

III. SURFACE BRIGHTNESS AS A FUNCTION OF *r*

Figure 1 shows the variation of surface brightness within $\pm 30''$ of the nucleus. The high-resolution data have been summarized by Kinman (1965). They represent the corrected observations of Redman and Shirley (1957), Thiessen (1955), and Johnson (1961), and are shown as a solid line. The angular resolution of this photographic material is $< 1''$. Kinman's photoelectric B-values, obtained with a diaphragm of 5″.57 (diameter)

TABLE 1

2.2μ DATA SAMPLED ALONG AN E-W LINE

200-INCH: SEPTEMBER 6/7, 1966

CIRCULAR DIAPHRAGM 5".00 DIAMETER

r	K	ϵ	K/□"	ϵ	r	K	ϵ	K/□"	ϵ
0".0E	8.57	±0.12	11.80	±0.12					
1.1E	8.69	.13	11.92	.13	1".1W	8.62	±0.12	11.85	±0.12
3.2E	9.12	.14	12.35	.14	3.2W	8.97	.13	12.20	.13
5.3E	9.47	.15	12.70	.15	5.3W	9.34	.14	12.57	.14
7.4E	9.72	.16	12.95	.16	7.4W	9.44	.15	12.67	.15
9.6E	9.72	.16	12.95	.16	9.6W	9.74	.16	12.97	.16
11.7E	9.68	.16	12.91	.16	11.7W	9.84	.16	13.07	.16
13.8E	9.87	.16	13.10	.16	13.8W	10.03	.16	13.26	.16
16.0E	9.84	.16	13.07	.16	16.0W	10.12	.16	13.35	.16
18.1E	10.07	.16	13.30	.16	18.1W	10.12	.16	13.35	.16
20.2E	10.04	.16	13.27	.16	20.2W	10.17	.16	13.40	.16
35".0E	10.43	±0.20	13.66	±0.20	35".0W	10.47	±0.20	13.70	±0.20

TABLE 2

2.2μ DATA SAMPLED ALONG AN E-W LINE

100 inch: September 12, 1968 Circular Diaphragm 7".5 Dia					60 inch: August 19, 1965 Circular Diaphragm 47" Dia				
r	K	ϵ	K/□"	ϵ	r	K	ϵ	K/□"	ϵ
0	8.05	±0.08	12.18	±0.08	0	4.96	±0.08	13.32	±0.08
5"W	8.49	.11	12.62	.11	5"E	5.04	.09	13.40	.09
10 W	8.90	.13	13.03	.13	15 E	5.06	.09	13.42	.09
15 W	9.25	.16	13.38	.16	25 E	5.21	.09	13.57	.09
20 W	9.10	.15	13.23	.15	35 E	5.53	.09	13.89	.09
30 W	9.65	.25	13.78	.25	45 E	5.68	.10	14.04	.10
40 W	9.85	.25	13.98	.25	55 E	6.06	.10	14.42	.10
50 W	9.75	±0.25	13.88	±0.25	65 E	6.18	.11	14.54	.11
					75 E	6.31	.13	14.67	.13
					88 E	6.56	.15	14.92	.15
					115 E	6.76	.15	15.12	.15
					145 E	6.88	±0.20	15.24	±0.20

24.2 SW	13.54	1.04	0.61	17.75	48.3 NW	14.21	1.02	0.61	18.40

TABLE 3

UBVR DATA SAMPLED ALONG AN E-W LINE

200 INCH: NOVEMBER 25/26, 1967

CIRCULAR DIAPHRAGM 7".62 DIAMETER

r	V	U-B	B-V	V-R	B/□ "	r	V	U-B	B-V	V-R	B/□ "
0".00	11.34	0.78	1.04	0.93	16.53	9".1 E	12.11	0.71	1.00	0.89	17.26
6.0 E	11.93	0.82	0.97	-	17.05	3.0 E	11.48	0.78	1.02	0.90	16.65
12.1 E	12.26	-	1.06	0.90	17.47	0.00	11.34	0.78	1.02	0.92	16.51
18.1 E	12.53	0.75	1.05	0.91	17.73	6.0 W	11.89	0.78	1.02	0.91	17.06
24.2 E	12.77	0.69	0.94	0.84	17.86	12.1 W	12.30	0.72	1.03	0.91	17.48
30.2 E	12.86	0.63	1.03	0.91	18.04	18.1 W	12.52	0.72	1.03	0.92	17.70
27.2 E	12.73	0.67	0.97	0.88	17.85	24.2 W	12.68	0.70	1.00	0.90	17.83
21.1 E	12.57	0.67	1.00	0.89	17.72	30.2 W	12.82	0.67	1.02	0.87	17.99
15.1 E	12.37	0.68	1.02	0.88	17.54						

TABLE 4

UBV DATA ALONG MAJOR AND MINOR AXES

200 INCH: NOVEMBER 25/26, 1959

CIRCULAR DIAPHRAGM 4".86 DIAMETER

r	V	B-V	U-B	B/□ "	r	V	B-V	U-B	B/□ "
	Along Major Axis				48.3 SW	14.08	1.02	0.60	18.27
0".00	12.03	1.10	0.79	16.30	72.5 SW	14.48	1.01	0.57	18.66
24.2 NE	13.58	1.04	0.66	17.79	96.6 SW	14.82	1.02	0.58	19.00
48.3 NE	14.16	1.02	0.63	18.35	120.8 SW	15.06	0.99	0.56	19.22
72.5 NE	14.52	1.04	0.59	18.73		Along Minor Axis			
96.6 NE	14.83	1.02	0.58	19.02	24.2 SE	13.71	1.05	0.61	17.93
120.8 NE	15.13	1.01	0.62	19.31	48.3 SE	14.14	0.92	0.56	18.23
24.2 NE	13.63	1.03	0.66	17.83	24.2 NW	13.60	1.02	0.67	17.79
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

using the Lick 120-inch reflector, are open triangles. The B-data from Table 3 are closed circles, while the 2.2 μ observations in Table 1 are plotted as open circles with error bars and are normalized to the B-scale by adopting $\langle B - K\rangle = 4.44$ mag. The random errors of the triangles and closed circles are generally smaller than the symbols.

Kinman's observations were made along the major axis. That there is no appreciable systematic difference between these data and our observations along an E-W line is evident from the agreement of the solid line and the closed circles for $r > 8''$. The same conclusion applies to the *UBV* data in Table 4, taken along the major and minor axes. Only a slight difference, if any, exists along these two directions to $r \simeq \pm 25''$, suggesting that the axial ratio b/a is close to 1.0 in this region of M31. The data are consistent with $b/a > 0.9$ for $r < 20''$ derived by de Vaucouleurs (1958, Fig. 6).

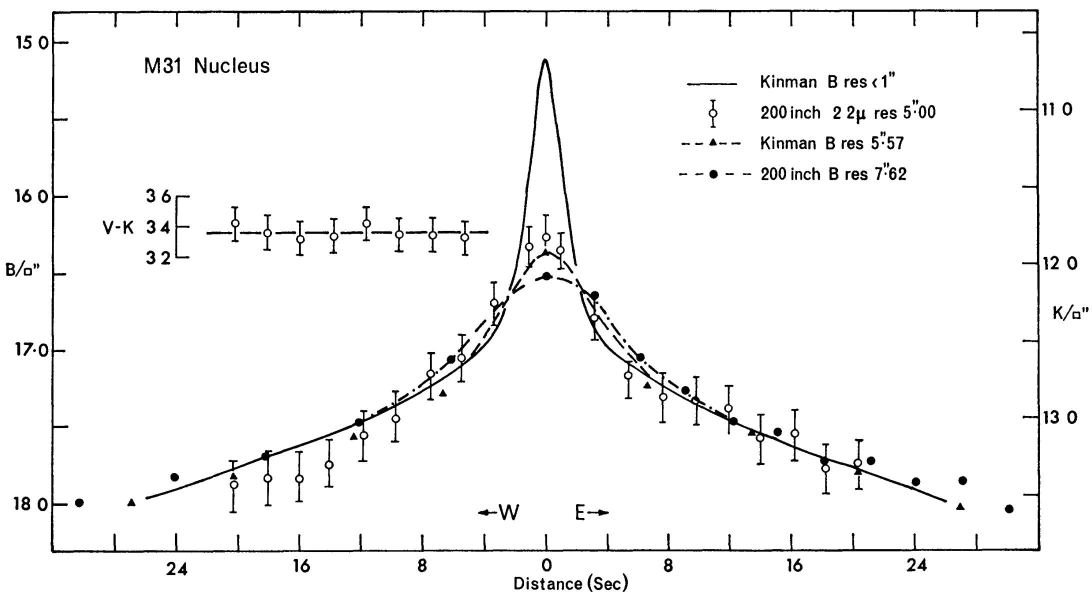

FIG. 1.—Surface brightness of the central region of M31 observed with different angular resolutions. Kinman's data refer to positions along the major axis. Our 2.2 μ and B-data were obtained along an E-W line. Variation of $V - K$ with distance from the center is shown in the insert.

The effect of different angular resolution for $r \lesssim \pm 8''$ is seen in Figure 1, where the profile obtained with the poorest resolution ($7\overset{''}{.}62$) is faintest at the nucleus and has the broadest width near $r = \pm 4''$.

There appears to be no systematic difference in $I(r)$ between the 2.2 μ and the B-data, although the argument is circular at the ± 10 per cent level because, as previously mentioned, the $I(r)_B$ function itself was used to correct the zero point of the infrared data—a procedure which tends to force agreement of the $I(r)$ shapes. However, even the original uncorrected data show conclusively that there is no appreciable infrared excess near the nucleus ($r = \pm 4''$) of M31 relative to the profile further out. A quite conservative limit is $I(0)/I(20'')_{2.2\,\mu} \div I(0)/I(20'')_B \lesssim 1.2$. But the actual limit must be much lower, as shown by Figure 2, where the surface brightness in K is plotted to $\pm 145''$ using the 60-inch data in Table 2. Here the correction for $I(\infty) \rightarrow 0$ was small over the range $35'' < r < 100''$, and the shape of $I(r)$ is nearly independent of the $I(r)_B$. The fact that the 60-inch data merge smoothly with the 100- and 200-inch observations near $r = 30''$ is evidence that a possible infrared excess is below our limit of detection and that our correction procedure does not effect this conclusion. The point is emphasized by the following comparison.

The lines in Figure 2 have not been fitted to the 2.2 μ data, but are *calculated* using the best fit to the B-data along the major axis given in Table 4 and shown in Figure 3. The $I(r)$ profile in Figure 3 has been compressed in Figure 2 along the abscissa by

$$\frac{r}{a} = \left(\frac{1 - e^2}{1 - e^2 \cos^2 \theta}\right)^{1/2},$$

which is the equation of the radius vector which makes a central angle θ with the major axis of an ellipse of eccentricity e, where $b/a = (1 - e^2)^{1/2}$. The adopted axial ratios of the set of isophotes that give the lines in Figure 2 are $b/a = 1.00$ at $r = 0$, $b/a = 0.90$ at $r = 15''$, $b/a = 0.78$ at $r = 60''$, and $b/a = 0.68$ at $r = 120''$. These agree with those

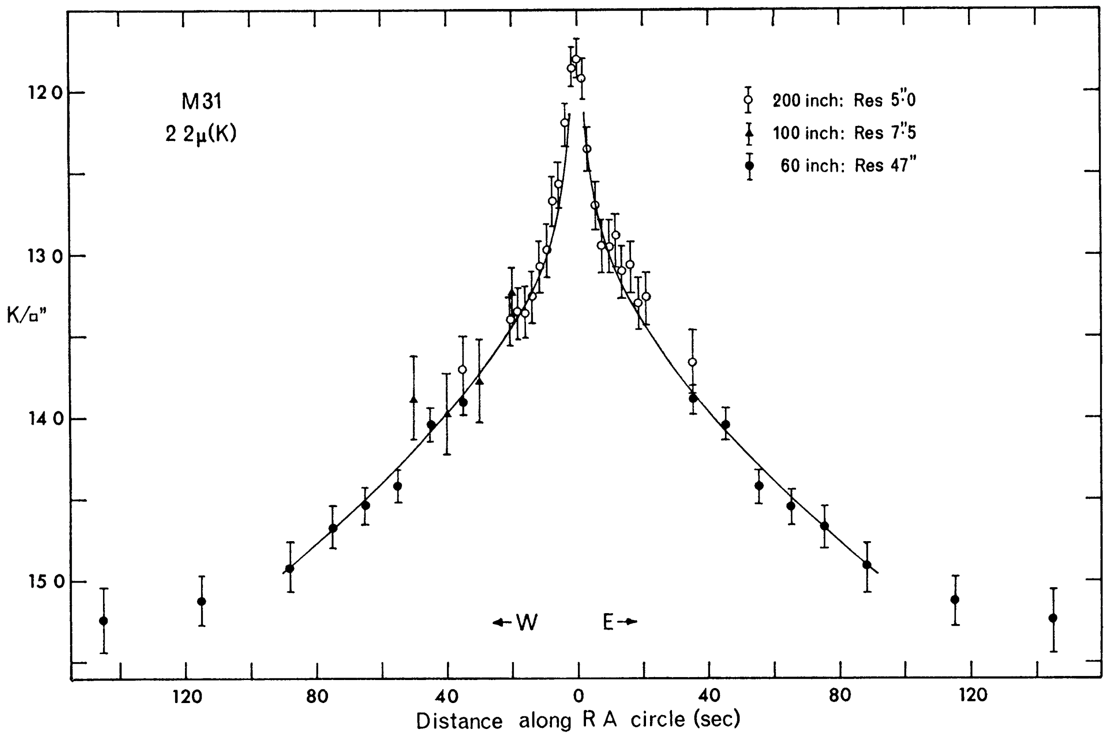

FIG. 2.—Surface brightness profile in the K (2.2 μ) band pass. Lines are calculated from the profile in Fig. 3 by the method in the text. The 60-inch data, obtained only on the east side, have been plotted symmetrically on the west.

given by de Vaucouleurs (1958, Fig. 6) for $r < 60''$, but our last point at $r = 120''$ is 10 per cent lower in b/a. We consider this to be satisfactory agreement. The fact that the calculated lines in Figure 2 fit the 2.2 μ observations made with the 60-inch where the correction for the $I(0) \to \infty$ is small at $r = 60''$ is taken to mean that $I(r)_{2.2\,\mu}$ is the same as $I(r)_B$ over the entire range of the data to better than ± 10 per cent.

IV. COLOR VARIATION ACROSS THE NUCLEUS

The variation of color with distance from the nucleus is shown at the top of Figure 3. We should emphasize that the plotted $U - B$, $B - V$, and $V - R$ colors were not obtained by a subtraction of two steeply varying profiles, but were measured at each discrete r-value without moving the photometer between the U, B, V, and R measurements. Therefore, the colors should have no errors that arise from the steep intensity gradient.

The most unexpected feature of Figure 3 is the pronounced variation of $U - B$

across the central $\pm 40''$ of M31, *a variation which is not mirrored in $B - V$ and $V - R$.* The lack of variation of $V - K$ is also evident, but here the data are less certain for two reasons. (1) $V - K$ was not measured directly, but was obtained by subtraction of the K-profile in Figure 1 (averaged between the east and west sides) from the V-profile using the smoothed $I(r)$ data of Table 3. (2) The $I(r)_K$ profile is not completely independent of the $I(r)_V$ or $I(r)_B$ profile because of the correction procedure to make $I(\infty) \rightarrow 0$.

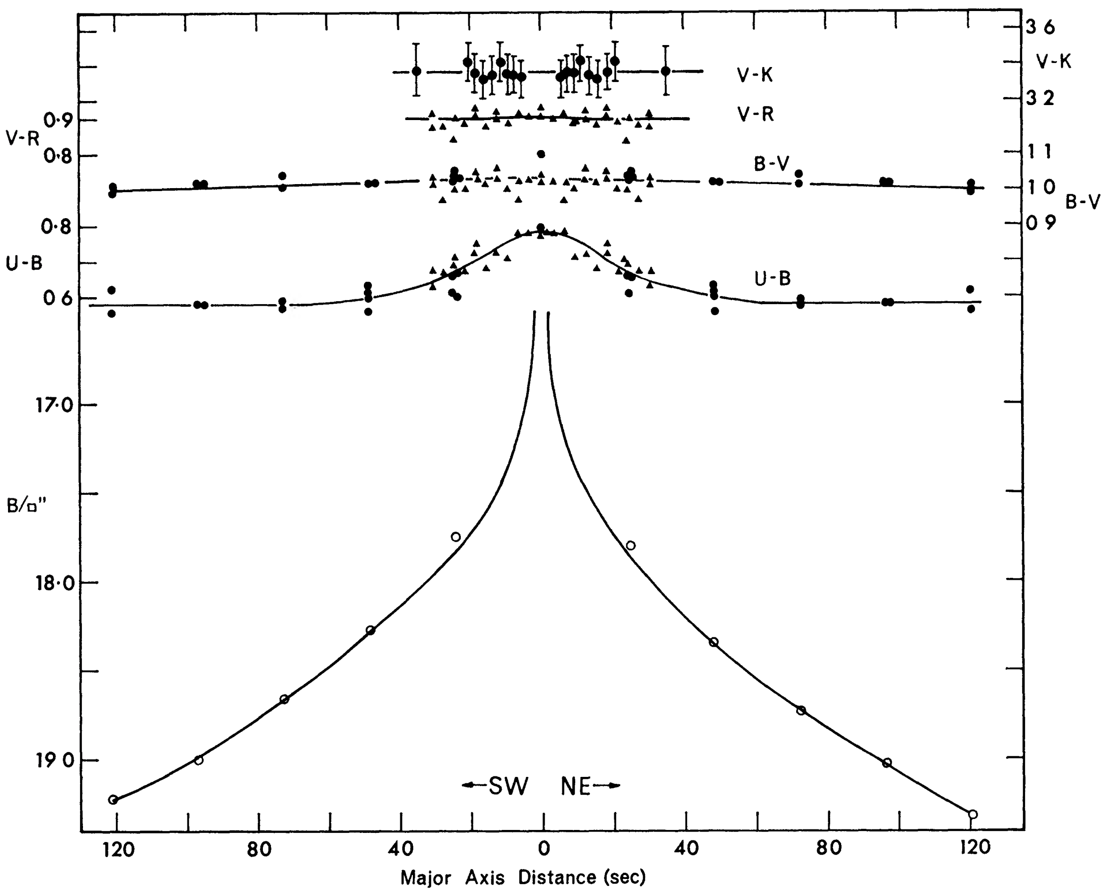

FIG. 3.—The profile in B observed with a resolution of 4".86 along the major axis Variation of color with distance from the nucleus is plotted from data in Tables 3 and 4. Color data have been double-plotted to increase the weight and ensure symmetry, although there is no evidence in the original data for asymmetry.

The existence of color gradients across the face of E, S0, and the central lens of Sa and Sb galaxies is well known from the work of de Vaucouleurs (1961), Tifft (1963), and others. In typical cases discussed by de Vaucouleurs (1961, Figs. 9 and 10), the integral value of $U - B$, measured through apertures of increasing diameter centered on the galaxies, changes from 0.60 at $A/D(0) = 0.2$ to $U - B = 0.50$ at $A/D(0) = 1.0$, where $D(0)$ is the diameter of the entire galaxy on a standard isophotal system and A is the diameter of the measuring aperture. Although these changes are for integral colors, which differ from our measurements made with a diaphragm of fixed diameter, it is clear that the phenomenon discovered by Tifft and de Vaucouleurs is on a very much larger scale than that shown in Figure 3. In M31, $A/D(0) \simeq 1.0$ corresponds to $r \simeq 5000''$ and is far beyond the borders of the diagram. The much smaller scale variation given by our data is limited to a radius of only 200 pc centered on the nucleus, corresponding to

$A/D(0) \leq 0.02$. The observed color change differs from the larger scale variation in two respects: (1) the gradient in $U - B$ is much steeper, and (2) it is wavelength dependent, disappearing below our limit of detection longward of $\lambda \simeq 4500$ A.

Two possible explanations for the phenomenon are (1) a gradient in the "mean spectral type," i.e., a change of the luminosity function such that the stellar radiation has a lower "mean temperature" closer to the center, or (2) a radial gradient in the stellar metal abundance causing line-blanketing differences which affect $U - B$ more strongly than the redder colors.

In the first case, a change from $U - B = 0.79$ to $U - B = 0.60$ would require parallel changes of $\Delta(B - V) = 0.06$, $\Delta(V - R) = 0.03$, and $\Delta(V - K) = 0.10$ (Johnson 1964, Table 3) if the light comes predominantly from luminosity class III giants near K0. If the light comes predominantly from dwarfs, a change of $\Delta(U - B) = 0.19$ requires $\Delta(B - V) = 0.10$, $\Delta(V - R) = 0.11$, and $\Delta(V - K) = 0.10$ (Johnson 1964, Table 5).

From the work of Wood (1966), Morgan (1967), and Spinrad (1966, 1967) it seems likely that light in the U and B band passes comes mostly from giants, while redder light has an appreciable dwarf component. But until we know which component changes toward the center, we cannot estimate the compound color variation. However, a minimum predicted color change of $\Delta(B - V) = 0.06$ and $\Delta(V - R) = 0.03$ due to this cause seems secure. These changes are considerably larger than the observed values of $\Delta(B - V) = 0.01 \pm 0.02$ and $\Delta(V - R) = 0.00 \pm 0.02$ in Figure 3.

In the case of variable line blanketing as a function of radius, the expected color changes for a given $\Delta(U - B)$ depend on the slope of the blanketing lines in the various colors, and these cannot be properly estimated owing to the composite nature of the stellar spectrum. If we were dealing with a sample of dwarfs of identical spectral type, the ratio $\Delta(U - B)/\Delta(B - V)$ due to blanketing is ~ 3.3 near $B - V = 1.0$ according to a previous study (Wildey *et al.* 1962). This value has been confirmed by Johnson, MacArthur, and Mitchell (1968). Sandage and Smith (1963) give relations in $\Delta(V - R)$ which can be extrapolated to derive $\Delta(U - B)/\Delta(V - R) \simeq 4.1$, again for dwarfs near $B - V = 1.0$.

Similar calculations for giants have not yet been made. However, it is likely that the blanketing vector in color-color diagrams has a steeper slope for giants than for dwarfs, as evidenced by the larger $\Delta(U - B)$ for giants which occur in the same clusters as dwarfs of known $\Delta(U - B)$ (Sandage unpublished data for four globular clusters). An estimate from the available data is $\Delta(U - B)/\Delta(B - V) \simeq 4$ and $\Delta(U - B)/\Delta(V - R) \simeq 5$ for giants near $B - V = 1.0$. The predicted color changes due to blanketing in M31 would then be $\Delta(B - V) = 0.05$, $\Delta(V - R) \simeq 0.04$, and $\Delta(V - K) \simeq 0.04$ (Sandage and Smith 1963) if $\Delta(U - B) = 0.19$. Again the predicted change in $B - V$ and $V - R$ is larger than that observed, and the explanation is not conclusive. But we have neglected the composite nature of the spectrum in these estimates. Contamination by a non-varying component could possibly reduce the predicted color effects, but at present we have insufficient information to build an adequate model.

In view of the discrepancies of both explanations, it is important to confirm the observational results in Figure 3. We plan to reobserve M31 next season with narrow-band interference filters to improve the accuracy, and to study the wavelength dependence more completely. But confidence that the effect is real is increased by evidence of a similar phenomenon in M32, M81, and NGC 7331 from data obtained in 1959, 1961, and 1962 given in Table 5. A strong $U - B$ color gradient exists in M32, with a suggestion that $B - V$ changes by half as much, but the data are fragmentary and must be increased. The $U - B$ for M81 changes by about 0.20 mag over a range of $r = 48''$. NGC 7331 shows an even larger variation of $\Delta(U - B) \simeq 0.26$ mag for $r = 24''$.

Whatever the explanation may be, it seems reasonable to conclude that there is a negligible exchange of stars between the central 200 pc of M31 and regions farther out

TABLE 5

PHOTOMETRY OF NUCLEI OF M32, M81 AND NGC 7731 PLUS A FEW MEASUREMENTS ALONG THE MAJOR AXIS

Date	Tel	r	Diaphragm diameter	V	B-V	U-B	V/□"
			M32				
Nov 25/26, 1959	200"	0	12".19	10.50	1.01	0.45	15.67
" "	"	0	12.19	10.53	1.04	0.42	15.70
" "	"	24.2 S	12.19	14.14	0.95	0.23	19.31
			M81				
Oct 10/11, 1961	200"	0	4".86	12.29	1.13	0.70	15.46
" "	"	0	7.62	11.63	1.12	0.72	15.78
Nov 23/24, 1959	"	0	7.62	11.56	1.16	0.70	15.71
Dec 29/30, 1962	60"	0	24.6	10.14	1.09	0.68	16.83
Nov 23/24, 1959	200"	0	30.6	9.86	1.08	0.66	17.02
Dec 29/30, 1962	60"	0	41.7	9.56	1.07	0.66	17.40
" "	"	0	69.0	9.05	1.06	0.63	17.98
Oct 10/11, 1961	200"	48.3 S	7.62	15.11	1.07	0.52	19.26
Nov 23/24, 1959	"	72.5 N	7.62	15.46	1.02	0.58	19.61
" "	"	72.5 S	7.62	15.31	1.01	0.52	19.46
			NGC 7331				
Nov 23/24, 1959	200"	0	4".86	13.30	1.21	0.72	16.47
" "	"	0	12.19	12.16	1.14	0.69	17.33
Nov 25/26, 1959	"	0	12.19	12.30	1.18	0.68	17.47
Nov 23/24, 1959	"	12.1 N	7.62	14.34	1.05	0.56	18.49
Nov 25/26, 1959	"	24.2 N	7.62	14.94	1.06	0.54	19.09
" "	"	24.2 S	7.62	15.00	1.06	0.47	19.15

TABLE 6

SUMMARY OF UBVR DATA FOR CIRCULAR APERTURES CENTERED ON M31 NUCLEUS: 200 INCH

Date	Diaphragm diameter	V	B-V	U-B	V-R	V/□"
Nov 25/26, 1959	4".86	12.03	1.10	0.79	-	15.20
" , 1967	4.86	12.05	1.05	0.82	0.91	15.22
" , 1959	7.62	11.37	1.11	0.76	-	15.52
" , 1967	7.62	11.34(2)	1.04(2)	0.78(2)	0.93(2)	15.49
" , 1967	7.62	11.34	1.02	0.78	0.92	15.49
" , 1959	12.19	10.59	1.08	0.73	-	15.76
" , 1959	12.19	10.57	1.08	0.73	-	15.74

on a time scale which is short compared with that required to reestablish the color gradient once it is destroyed. If the gradient arises from some property of the stellar radiation, either it is a permanent feature of the galaxy or the quality of the stellar radiation is changing on a *rapid* time scale (such as the manufacture of heavy elements which contaminate the atmospheres), which seems unlikely. If the gradient is permanent, there can be no appreciable orbit-mixing in the lifetime of M31. In this case the stars in the central 200 pc could not then have orbital eccentricities so large so as to take them far into the outer disc.

V. ABSOLUTE ENERGY DISTRIBUTION FOR THE CENTRAL 7″.62 (±13 pc) OF M31

Tables 6 and 7 summarize the *UBVRIHKL* data for M31 obtained with different-sized apertures centered on the nucleus. The surface brightness averaged over the measuring aperture decreases for increasing aperture size due to the steep gradient of $I(r)$. The slope of surface brightness against log (aperture diameter) is the same for the B, V, R, H, K, and L data, which means that all data can be corrected to the same aperture size. Adopting the 7″.62 aperture (0.63 mm at the 200-inch prime focus) as the reference size gives the following surface brightness values in magnitudes per square second: $U = 17.31$, $B = 16.53$, $V = 15.49$, $R = 14.57$, $I = 13.57$, $H = 12.29$, $K = 12.11$, and $L = 11.77$. These can be changed to absolute values (W m^{-2} Hz^{-1} per square second of arc or W m^{-2} A^{-1} per square second of arc) from the calibrations given by Matthews and Sandage (1963), Johnson (1965), and Becklin (1968) with the results shown in Table 8. The color indices of Johnson (1966) have been normalized to $V = 15.49$ for comparison with our values. Johnson gives no probable errors, but it is reasonable to assume they are as large as or larger than ours considering the smaller telescope used.

The energy distributions from these data are given in Figures 4 and 5. Johnson's values are shown as closed triangles; ours, by closed circles. The scanner data of Oke and Sandage (1968) with 50 Å spectral resolution are shown as a heavy solid line, arbitrarily normalized to absolute values by an eye-fit to the broad-band points. The agreement of all data seems generally satisfactory to about ±0.1 mag. Johnson's values would agree more closely with ours if we had normalized the two sets at I rather than V.

A comparison of the M31 distribution with K0 III and M0 III stars is shown in Figure 5, all data normalized to the V-point. As previously known, the galactic continuum shortward of $\lambda \simeq 6000$ Å agrees well with that of K0 III stars, but is considerably brighter at longer wavelengths. Analysis of selected intensity ratios in both the continuum and the absorption lines has led Wood (1966), Spinrad (1966, 1967), and others to conclude that appreciable light for $\lambda > 5000$ Å comes from dwarfs later than K0. We have not used our data to discuss synthetic luminosity functions because the methods of Wood and Spinrad are much more powerful than those which rely on broad-band photometry alone. We only remark that the composite nature of the M31 radiation is evident in Figure 5 by the divergence of $F(\nu)$ from that of a single stellar spectral type.

VI. COMPARISON OF THE SURFACE BRIGHTNESS OF M31 AND THE GALACTIC SYSTEM

The mean intrinsic surface brightness of the Galactic system at 2.2 μ, averaged over circular apertures corresponding to diameters which range from 1 pc (21 seconds of arc for a distance of 10 kpc) to 60 pc (1236″), were given in Table 7 of Paper I. These were not corrected for the condition $I(\infty) \rightarrow 0$, and are therefore too small. In Paper I the intensity-zero for the data on the Galactic system was adopted to be at R.A. (1950) = 17^h40^m, decl. (1950) = $-29°00'$, which is 1970 seconds of arc from the Galactic nucleus at R.A. = $17^h42^m.5$, decl. = $-28°59'.4$.

To obtain an approximation correction to the Galactic data, we assume that $I(r)$ has the same linear scale in M31 and the Galaxy. The adopted distance modulus of M31 is

TABLE 7

IHKL PHOTOMETRY FOR M31 NUCLEUS

Date	Diaphragm	Tel.	*I*	*H*	*K*	*L*	*I*/square sec of arc	*H*/square sec of arc	*K*/square sec of arc	*L*/square sec of arc
1966 September 6–7	5″0	200	10.1±0.10	8.88±0.15	8.57±0.12	. . .	13.33±0.10	12.11±0.15	11.80±0.12	. .
1968 September 12	7.5	100	. .	8.22±0.10	8.05±0.07	. . .	.	12.33±0.10	12.16±0.07	.
1968 September 13	15	100	. .	6.96±0.12	6.82±0.12	6.54±0.20		12.58±0.12	12.44±0.12	12.16±0.20
1966 September 6	15	200	.	. . .	6.93±0.15	.		. .	12.55±0.15	. .
1968 September 13	30	100	. .	5.85±0.10	5.69±0.10	5.30±0.17		12.97±0.10	12.81±0.10	12.42±0.17
1965 August 19	47	60	. .	. . .	4.96±0.08	. . . . .	. .	. . . .	13.32±0.08	. . . . . .

$(m - M)_0 = 24.25$, which follows from the work of Baade and Swope (1963) on the cepheids, together with the calibration of the P-L-C relation from Sandage and Tammann (1968), as revised toward brighter values by 0.05 mag in a recalibration (Sandage and Tammann 1969). This modulus gives a distance of 708000 pc to M31, or a distance ratio of 70.8 with the Galactic center.

The assumed zero-position of intensity in Paper I corresponds to $r = 27''.8$ in M31. The intensity at this point relative to the center of M31 can be read from the solid curve in Figure 1, which has a resolution of less than 1″. This is the appropriate curve because the observations of the Galactic center have at least this equivalent resolution. The shape of a modified $I(r)$ function that should correspond roughly to that measured in Paper I was obtained by subtracting the intensity at $r = 27''.8$ from all intensities for $r < 27''.8$. The new $I'(r)$ was integrated numerically to obtain intensities within various aperture diameters. The unmodified curve was also integrated, and the ratio of intensi-

TABLE 8

SURFACE BRIGHTNESS OF M31 AVERAGED OVER A CIRCULAR AREA OF 7″.62 DIAMETER CENTERED ON THE NUCLEUS

Color	⟨λ⟩ (μ)	This Paper: log $F(\nu)$ ($Wm^{-2}Hz^{-1}$ per sq sec of arc)	This Paper: log $F(\lambda)$ ($Wm^{-2}A^{-1}$ per sq sec of arc)	Johnson: log $F(\nu)$ ($Wm^{-2}Hz^{-1}$ per sq sec of arc)	Johnson: log $F(\lambda)$ ($Wm^{-2}A^{-1}$ per sq sec of arc)
U	0 36	−29 66± 008	−18 29± 008	−29 60	−18 23
B	0 44	−28 97± 008	−17 79± 008	−28 96	−17 78
V	0 55	−28 60± 008	−17 61± 008	−28 60	−17.61
R	0 70	−28 36± 008	−17.57±.008	...	...
I	0 88	−28 04± 04	−17 47±.04	−28 14	−17 57
J	1 25	...	...	−28 03	−17.75
H	1.65	−27 90± 04	−17 85± 04	...	...
K	2 2	−28 04± 04	−18 25± 04	−28 11	−18 32
L	3 4	−28 22± 08	−18 80± 08	−28 43	−19 02

ties was calculated as a function of aperture size. The ratios to correct Table 7 in Paper I are 1.07 at 1 pc (20″.6 for the Galaxy, 0″.29 for M31), 1.12 at 2 pc (41″.2 G, 0″.58 M31), 1.20 at 5 pc (103″ G, 1″.45 M31), 1.31 at 10 pc (206″ G, 2″.9 M31), 1.52 at 20 pc (412″ G, 5″.8 M31), 1.86 at 40 pc (824″ G, 11″.6 M31), and 2.27 at 60 pc (1236″ G, 17″.4 M31). Consequently, the corrected 2.2 μ surface brightness of the Galactic center, averaged over the central diameter of 540 seconds of arc, corresponding to 7″.62 in M31 (or 26 pc), is 9.4×10^{-18} W m^{-2} Hz^{-1} $sterad^{-1}$ or 2.2×10^{-28} W m^{-2} Hz^{-1} per square second of arc. This is to be compared with 9.1×10^{-29} W m^{-2} Hz^{-1} per square second of arc at 2.2 μ for M31 averaged over the same diameter as given in Table 8. Therefore, the Galactic center is brighter by a factor of 2.4 than M31 if the correction for absorption adopted in Paper I is used. To force agreement would require that the absorption at 2.2 μ at the Galactic center should be decreased by 1 mag, which would reduce the visual absorption from $\Delta M = 27$ ($\tau = 25$) to $\Delta M = 17$ ($\tau = 15.6$) at 0.55 μ. This seems unlikely by the arguments in Paper I unless independent evidence were available that the Galactic center radiates like the nucleus of a Seyfert galaxy (Paper I, Fig. 11). Barring this possibility, it is likely that the nuclear surface brightness of M31 is smaller than that of the Galaxy by about 1 mag.

This result, together with the similarity of the shape of $I(r)$ given in Figure 10 of

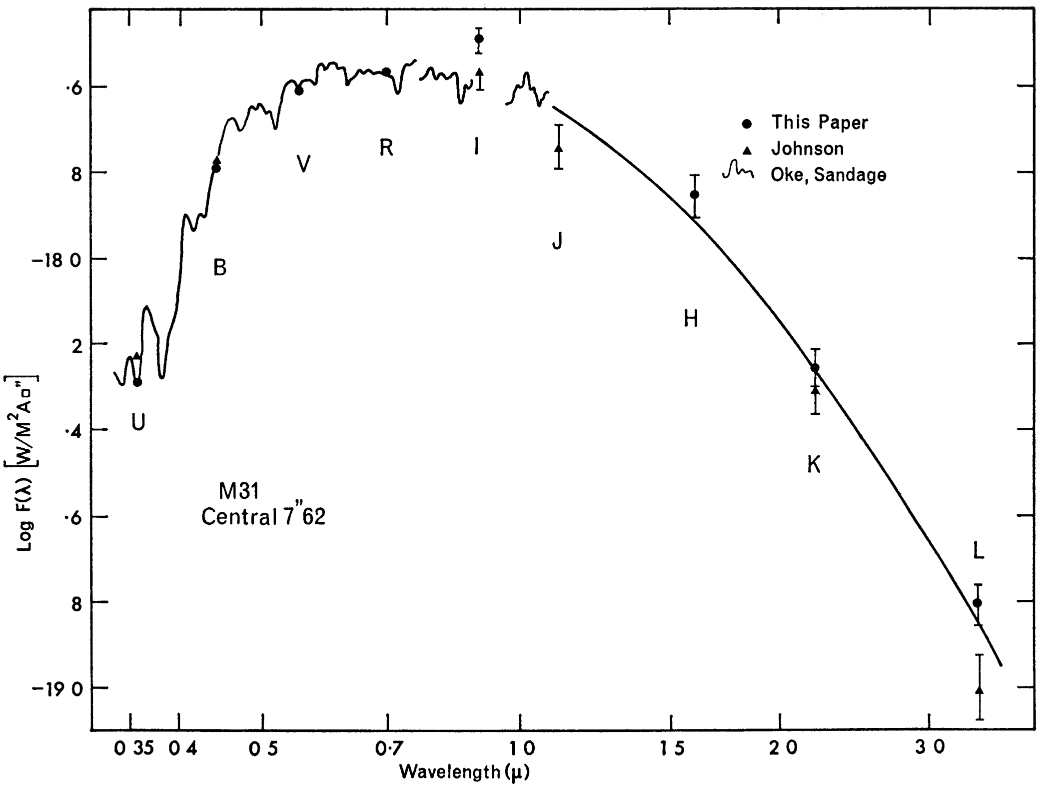

FIG. 4.—Absolute energy distribution per unit wavelength interval averaged over the central 7″.62 (diameter) of M31. Surface brightness is expressed as W m^{-2} A^{-1} per sq sec of arc. Data of higher spectral resolution of Oke and Sandage are shown for comparison.

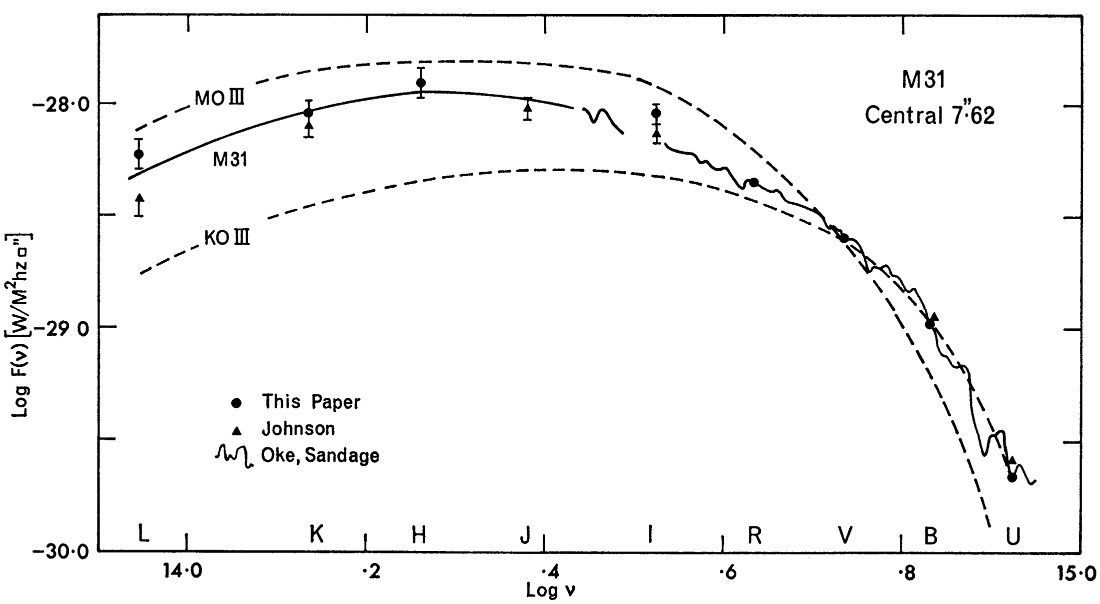

FIG. 5.—Absolute energy distribution per unit frequency interval. Coding is same as in Fig. 4

Paper I, suggests that the Hubble type classification of the Galactic system is closer to early Sb than to Sc as in M33 or NGC 2403.

Note added in proof.—It has been brought to our attention that McClure and van den Bergh (1968, *A.J.*, **73**, 313) have also discussed the problem of the population of the nucleus.

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