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OBSERVATIONS OF THE MASS AND LIGHT DISTRIBUTION OF NGC 5963, AN UNUSUAL LOW SURFACE BRIGHTNESS SPIRAL

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ABSTRACT

NGC 5963 is an unusual member of a class of spiral galaxies characterized by disks of abnormally low surface brightness. The inner region of the galaxy appears to be a vigorous, relatively normal spiral of late type. Exterior to this spiral is a low surface brightness disk in which low surface brightness H II regions define a roughly spiral pattern. From the optical surface photometry and rotation curve reported here, the radial dependence of the local mass-to-light ratio M/L_B is derived. In the inner high surface brightness regions of NGC 5963, $M/L_B \approx 2$; in the outer regions, $M/L_B \approx 18$. Hence, the mass and light distributions in this galaxy are quite clearly not coupled. The star-forming history of the inner and outer regions appears to differ dramatically as well. The observed ratio of [N II]/Hα is unusually high in the inner disk but drops significantly just outside this region. This result suggests that star formation, gas depletion, and element production have proceeded much more rapidly in the inner regions than in the outer regions of the galaxy. Infrared and 21 cm measurements are used to locate NGC 5963 in the H, Δv plane; it appears to lie significantly below the Virgo Fisher-Tully relationship recently reported by Aaronson, Huchra, and Mould.

Subject headings: galaxies: evolution — galaxies: individual — galaxies: photometry

I. INTRODUCTION

The galaxy NGC 5963 is representative of a class of spiral galaxies characterized by unusually low surface brightness disks. A program to study the properties of this class was begun three years ago; the details of our comprehensive observational survey will be published in the near future (Romanishin, Strom, and Strom 1982). However, the results obtained for NGC 5963 seem of sufficient interest to merit earlier, separate publication.

On the blue Palomar Observatory Sky Survey prints, NGC 5963 appears dominated by an oval-shaped nuclear region with a major axis of length $\sim 40''$. Surrounding this region is a barely discernible low surface brightness disk. A deep 4 m U plate (see Fig. 1 [Plate 7]) reveals the inner region to be a high surface brightness spiral subsystem; the outer region appears to be a patchy, open spiral.

We report in this contribution observations aimed at mapping the mass and light distributions in this unusual system. Observations of color, H II region emission-line ratios, and H I content permit further, qualitative discussion of the possible star-forming history of this galaxy.

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II. PHOTOMETRIC OBSERVATIONS

The light and color distributions for NGC 5963 were obtained from the analysis of a U (IIIa-J + UG-2; MP 2382, $t_{exp} = 120$ min) and R (IIIa-F + RG-610; MP 2383, $t_{exp} = 50$ min) plate pair obtained at the prime focus of the Mayall 4 m telescope at KPNO. The plates were traced using the KPNO PDS microdensitometer. The resulting density-position rasters were converted to intensity-position matrices through application of the standard density-to-intensity algorithms written for the KPNO IPPS (see, for example, Strom and Strom 1978). The run of surface brightness distribution with galactocentric distance r was obtained by averaging local values of intensity over a series of elliptical paths of axial ratio $b/a = 0.75$ (characteristic of the bright, inner oval). The procedure is described in detail by Strom and Strom (1978). The instrumental surface brightness values were transformed to the Johnson U and R systems by means of photoelectric aperture photometry obtained with the KPNO 1.3 m and 2.1 m telescopes (see Table 1). From the consistency of the transformations, we estimate the uncertainty of the resulting color transformations to be $\sim \pm 0.05$ mag. In Figure 2 luminosity and color are plotted against r, the distance along the major axis. The luminosity profiles appear to exhibit the following distinct regions:

Within $r = 6''$ (0.5 kpc for $v_{systemic} = 853$ km s^{-1} and $H_0 = 50$ km s^{-1} kpc^{-1}; see § III), there is a hint of a

TABLE 1

PHOTOMETRIC OBSERVATIONS OF NGC 5963

Aperture Diameter (″)	V	$B-V$	$U-B$	$V-R$	KPNO Tel.
13.3	14.23 ± 0.01	0.72 ± 0.01	0.00 ± 0.02	0.74 ± 0.02	2.1 m
35.3	12.98 ± 0.01	0.51 ± 0.03	−0.09 ± 0.03	0.70 ± 0.03	1.3 m
58.6	12.72 ± 0.01	0.55 ± 0.03	−0.12 ± 0.03	0.70 ± 0.03	1.3 m

bulge component. No fit to a de Vaucouleurs law was attempted because the region of bulge dominance is so narrow.

Between 6″ and 23″ (0.5 to 1.8 kpc), the luminosity profile exhibits a "plateau" that mimics the behavior of the "lens" component discussed by Kormendy (1979). For $r > 3$ kpc, the light distribution exhibits a roughly exponential fall-off; the exponential scale length $\beta = 4.0 \pm 0.2$ kpc. The central surface brightness $\mu(0)$ is 23.3 and 22.3 mag arcsec^{-2} in U and R, respectively. From the $U-R$, $U-B$ color-color relations derived for late-type spirals by Romanishin (1980): $U-B = 0.38\,(U-R) - 0.49$; $B-V = 0.38\,(U-R) + 0.14$, we deduce $U-B = -0.1$ at the center of the disk. Hence the uncorrected central surface brightness at B is 23.5 mag arcsec^{-2}. Using standard corrections for Milky Way extinction (Sandage 1972) and for inclination (Freeman 1970), we find a corrected central surface brightness $B(0) = 23.4$ mag arcsec^{-2}. This value is 1.8 mag smaller than the "canonical" value of projected central surface brightness thought typical of disk galaxies (Freeman 1970). The total luminosity of the galaxy (within an isophotal limit of $\mu_U = \mu_R = 28$ mag arcsec^{-2}), expressed in terms of apparent magnitude, is computed as $m_U = 12.61$, $m_R = 11.58$. From these values we estimate $m_B = 12.71$.

The radial color profile derived by subtracting the U and R surface brightness profiles (Fig. 2) shows (a) a relatively red component arising in the small nuclear bulge, (b) a relatively blue lens region, (c) a red region just exterior to the lens, and (d) a blue disk of relatively constant color.

III. ROTATION CURVE AND MASS MODEL

A rotation curve for NGC 5963 was derived from a long-slit spectrogram obtained with the RC spectrograph plus the Carnegie image-tube system on the 4 m telescope. The spectrum (MGS 1703) centered at $\lambda \approx 6600$ Å was taken with a grating yielding a dispersion of 26 Å mm^{-1}. The slit passed through the center of NGC 5963, through the star labeled 1 in Figure 1, and through a selection of H II regions (labeled 2, 5, and 26) which fall along a common radius vector within 5° of the major axis P.A.

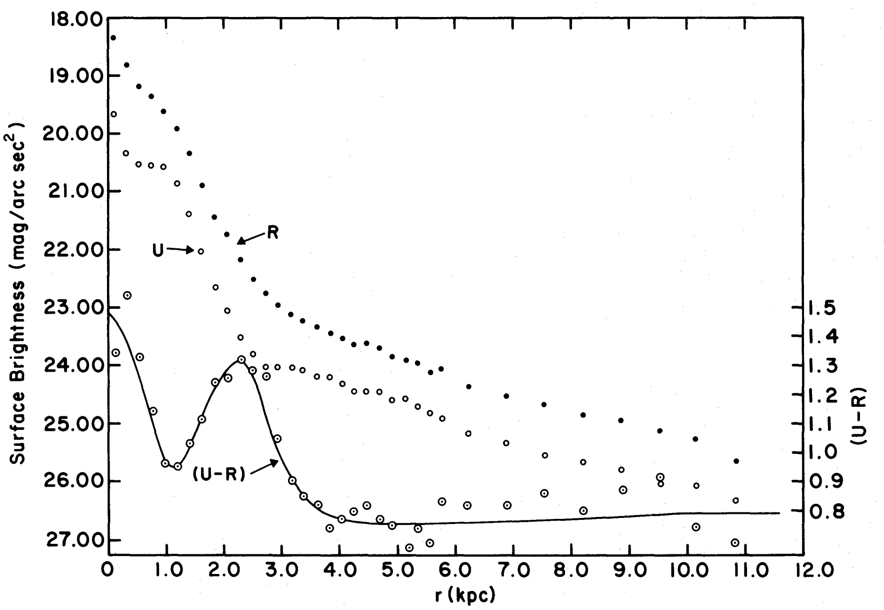

FIG. 2.—A plot of U and R surface brightness against galactocentric distance in kpc; at the assumed distance for NGC 5963, 1″ = 78 pc. Also plotted is the run of $(U-R)$ color with galacticentric distance. Note that the first minimum in $U-R$ occurs just outside the "edge" of the high surface brightness, inner spiral (see Fig. 1).

(see Fig. 1). The latter was estimated to be P.A. = 54° ± 2° for the bright inner regions and P.A. = 49° ± 4° for the outer region. The P.A. of the slit was chosen to be P.A. = 50°.7. The galaxy spectrum, along with a curvature plate obtained at the same mean hour angle of observation, was traced using the KPNO PDS. After conversion to an intensity-position raster, the spectrum was then analyzed using the "RV" program developed for the Kitt Peak IPPS by Goad, Tody, and Phillips (1980). The algorithms in RV permit (*a*) geometrical rectification of the spectrum (to correct for curvature introduced by image-tube focusing optics) (*b*) subtraction of terrestrial atmospheric emission features, and (*c*) automatic centroiding of individual emission lines across the spectrum. From analysis of Hα, [N II], and [S II] emission features, we derived the rotation curve listed in Table 2. Note that the velocities listed represent mean values deduced from a smooth curve passed through the observed points. The listed errors represent the larger of (*a*) the difference of velocities between approaching and receding sides of the disk or (*b*) the scatter in derived velocities in the vicinity of the listed radius. The systemic velocity for the galaxy is 650 ± 10 km s^{-1} (heliocentric), which corresponds to v_{systemic} = 853 km s^{-1} after correction for galactic rotation (de Vaucouleurs, de Vaucouleurs and Corwin 1976). If H_0 is 50 km s^{-1}, the distance to NGC 5963 is 17 Mpc, corresponding to a modulus of 31.15 mag. We deduced the mass distribution from the rotation curve by assuming a standard pure disk model. The Kuzmin (1952) integral was solved in the standard way (see, for example, Rubin *et al.* 1978). The mass distribution thereby derived was, at all radii, increased by a factor of 1.1 (Brandt 1960) to correct for the mass underestimates characteristic of such idealized solutions.

The resulting mass distribution $M(r)$ is given in Table 3. A plot of mass against radius reveals a nearly linear increase in M with r, as might be deduced by inspection of either Table 2 or Table 3. The radial variation of mass-to-light (M/L_B) ratio derived from the values listed in Table 3, the U and R band surface photometry, and the approximate transformation from U and R to B magnitudes are plotted in Figure 3.

TABLE 2

OBSERVED ROTATION CURVE FOR NGC 5963

Galactocentric Distance (kpc)	Velocity[a] (km s^{-1})
0.0	0.0
0.45	65 ± 10
0.75	86 ± 10
0.97	93 ± 5
1.12	102 ± 5
1.20	106 ± 5
1.79	112 ± 5
2.54	120 ± 5
3.28	128 ± 5
4.10	131 ± 5
7.09	131 ± 5

[a] The systemic velocity is 650 km s^{-1} (heliocentric) and 853 km s^{-1} (corrected for galactic rotation); at the assumed distance of NGC 5963, 1″ = 78 pc.

TABLE 3

COMPUTED MASS DISTRIBUTION FOR NGC 5963

Galactocentric Distance r (kpc)	Mass within r ($\times 10^8\ M_\odot$)	Mass between (r − 0.5 kpc) and r
0.5	2.6	2.60
1.0	11.4	8.79
1.5	22.4	11.0
2.0	35.1	12.7
2.5	49.7	14.6
4.0	99.0	16.5
3.0	65.6	15.8
3.5	82.5	17.0
4.0	99.0	16.5
4.5	115.0	16.0
5.0	130.0	15.2
5.5	145.0	14.9
6.0	160.0	14.7
6.5	174.0	14.5
7.0	189.0	14.4
7.5	203.0	14.4

IV. NEUTRAL HYDROGEN OBSERVATIONS

The 21 cm profile for NGC 5963 was observed with the NRAO 91 m telescope as part of a more extensive program to determine the H I characteristics of low surface brightness spirals; the results of that survey will be reported elsewhere (Romanishin *et al.* 1982). The profile plotted in Figure 4, does not appear to be unusual in any way. From the profile, we derive a

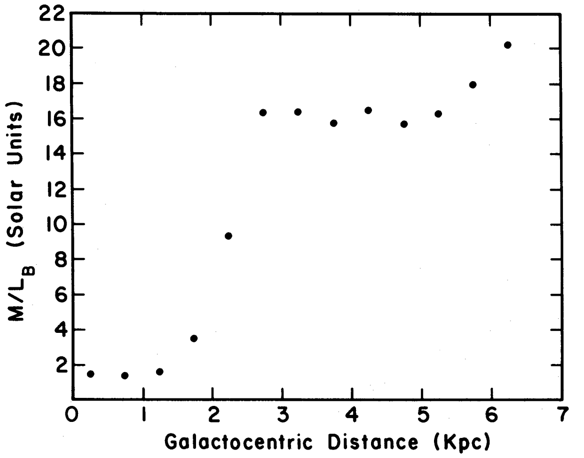

FIG. 3.—A plot of M/L_B against galactocentric distance for NGC 5963. Note that the dramatic rise in M/L_B occurs just exterior to the high surface brightness, inner spiral (see Fig. 1).

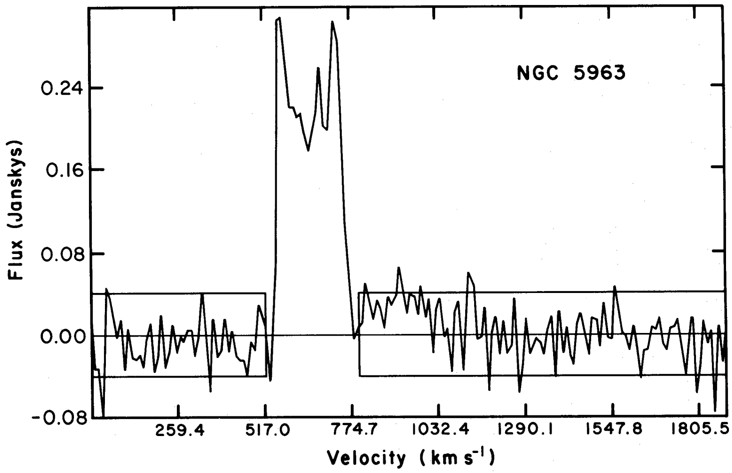

FIG. 4.—A plot of the observed neutral hydrogen profile obtained using the Arecibo telescope

systemic velocity (heliocentric) of 656 ± 10 km s^{-1}, which compares well with the optical value of 650 ± 10 km s^{-1} derived in § III.

The observed full-width at quarter peak intensity is $\Delta v = 206 \pm 10$ km s^{-1} (uncorrected for inclination), which compares with a value $\Delta v(\mathrm{opt}) = 176 \pm 10$ km s^{-1}. The ratio $[\Delta v(\mathrm{radio})/\Delta v(\mathrm{opt})]^2$ is thus 1.37, which is not significantly different from the average value 1.25 quoted by Faber and Gallagher (1979) for a large sample of spiral galaxies. The neutral hydrogen mass derived from this profile is $M_{\mathrm{H}} = 3.6 \times 10^9\ M_\odot$ (see Roberts 1975).

V. DISCUSSION

a) Mass-to-Light Ratio

From inspection of Figure 3, it is clear that the radial variation of M/L_B is discontinuous. In the inner regions of the galaxy ($r \lesssim 1.5$ kpc), $M/L_B \approx 2$, a value characteristic of late-type spirals (Faber and Gallagher 1979). Outside this region, M/L_B rises to a value ~ 18. It is noteworthy that the rapid rise in local M/L occurs just exterior to the lens region, where the disk surface brightness begins to drop rapidly. NGC 5963 therefore provides a dramatic illustration of the conclusion that *the mass and light distributions in disk galaxies are not well-coupled* (see Bosma 1978, for example).

b) Star-Forming History of NGC 5963

The color profile (see Fig. 2) for NGC 5963 suggests two regions in which the ratio of new/old stellar population is high: the lens region and the outer disk.

The blue color of the lens region clearly derives from the vigorous star formation proceeding in the bright H II regions clearly visible in Figure 1. That such a high star formation rate has been characteristic in the past is suggested by the emission-line ratios observed from the lens region.

From the long-slit spectrum discussed in § III, we derived a mean value log [N II]/H$\alpha = -0.16$. This value is larger than all but one of the 40 H II regions studied by Smith (1975). We emphasize that the strong [N II] lines are not confined to the nucleus but extend throughout the bright spiral structure of the lens regions. Typically large values of [N II]/Hα are found in H II regions characterized by low excitation resulting from high metallicity (Searle 1971). We recognize that conditions other than high metallicity can produce high [N II]/Hα ratios. Nevertheless, the unusually high value of [N II]/Hα strongly suggests the possibility of an unusually high metallicity for the lens region of this galaxy. If this interpretation is correct, it in turn suggests that the number of heavy element-yielding, star-forming events has been high and the degree of gas depletion advanced (see Searle and Sargent 1972). Confirmation of these speculations awaits observation of more direct metallicity indicators such as [O III]/Hβ, [O II]/Hβ, and a high spatial resolution map of the H I distribution.

In contradistinction to the lens region, the H II region (labeled "5" in Fig. 1) just exterior to the lens has a value log [N II]/H$\alpha = -0.58$, more than 0.4 dex smaller than that typical of the lens. Hence, if [N II]/Hα is indicative of the metal abundance in the gas, we must conclude that the degree of gas consumption and element production in the low surface brightness disk has been significantly lower than in the lens. Thus the blue color of the disk could arise from a combination of low metallicity and a high fractional contribution of new ($<10^8$ yr) compared with old ($>10^9$ yr) stars.

c) m_{H}/L Ratio

From the integrated apparent B magnitude and the distance modulus quoted in § IV, we derive an absolute B magnitude $M_B = -18.44$. If we make no correction for Milky Way reddening or for internal absorption in NGC 5963, we derive a value $m_{\mathrm{H}}/L_B = 0.97$ if the absolute B magnitude of the Sun is taken to be $M_B = 5.48$ (Allen 1973). If we adopt the Milky Way reddening (for $b = 49°$) and internal extinction appropriate to an Sdm galaxy given in de Vaucouleurs, de Vaucouleurs, and Corwin (1976), $M_H/L_B = 0.70$. This value is approximately twice that of the average for Scd–Sdm galaxies listed by Shostak (1978) and is exceeded by only 20% of the late-type galaxies in his samples.

It would clearly be of interest to obtain a high spatial resolution H I map of NGC 5963. The H II region emission-line ratios discussed in the previous subsection strongly suggest that the higher-than-normal m_H/L ratio of the system derives from the contribution of unprocessed gas in the unusual, low surface brightness outer disk of NGC 5963. If the neutral hydrogen is located in the outer ($r > 1$ kpc) disk, a value of $M_H/L_B \gtrsim 1.5$ would characterize this region. If so, this galaxy might be related to the hydrogen-rich "S0" galaxy discussed by Longmore *et al.* (1979).

d) *NGC 5963 and the Fisher-Tully Relation*

Because of its unusual nature, we felt it would be of interest to locate NGC 5963 with respect to the infrared luminosity-hydrogen line width relationship recently discussed by Aaronson, Huchra, and Mould (1979). If this peculiar object were to fall on the mean (H, Δv) relationship, it would allay the concerns of some regarding possible "cosmic scatter" in that relationship. Consequently, infrared observations were obtained using an InSb system on the KPNO 1.3 m telescope. Measurements taken through a 47″ aperture yielded the following colors: $H = 10.28 \pm 0.03$, $J - H = 0.06 \pm 0.03$, $H - K = 0.16 \pm 0.03$. From the U and R surface photometry and the precepts of de Vaucouleurs, de Vaucouleurs, and Corwin (1976), we estimate a face-on diameter $\log D(0) = +1.38$. This compares with the value of $\log D(0) = 1.52$ listed by de Vaucouleurs, de Vaucouleurs, and Corwin (1976). Discrepancies of this magnitude are not uncommon in our experience, and we prefer to use our value in the discussion that follows. Hence at $\log A/D(0) = -0.5$, $H(-0.5) = 10.28 \pm 0.03$. From the observed redshift of NGC 5963 and a Virgocentric flow model derived from the Aaronson, Huchra, and Mould study (Schechter 1981), we deduce a best-estimate distance for NGC 5963 of 0.8 times the Virgo cluster distance. Hence, at the distance of Virgo, $H(-0.5) = 10.76$ for NGC 5963. From the observed axial ratio $b/a = 0.75$ ($i = 42°$), we can correct the observed neutral hydrogen velocity width for the inclination; $\Delta v(\text{corr}) = 305$ km s^{-1}. We note that as a consequence of the relatively small inclination of NGC 5963, $\Delta v(\text{corr})$ is somewhat uncertain.

Given the Aaronson, Huchra, and Mould relation between $H(-0.5)$ and $\Delta v(\text{corr})$ for Virgo spirals, we expect $H(-0.5) = 9.91$ at the $\Delta v(\text{corr})$ observed for NGC 5963. We conclude that this galaxy falls 0.85 mag *below* the standard relationship. This behavior is typical of a larger class of low surface brightness spiral galaxies and results from the higher values of M/L characteristic of galaxies of this class. A detailed discussion of this behavior will be given elsewhere (Romanishin *et al.* 1982). We note here that the mean M/L_B for NGC 5963 is ~8.1 (computed according to the precepts of Faber and Gallagher 1979) and is nearly twice that characteristic of galaxies of its type. Its location below the Aaronson, Huchra, and Mould relation is consistent with its apparently higher M/L_B.

e) *Further Comments on the Evolutionary Status of NGC 5963*

As a working hypothesis, let us assume that the inner disk of NGC 5963 is comparable with a normal spiral, whereas the outer disk represents an abnormal "add-on." Justification for this hypothesis can be found in the normal M/L_B for the inner disk and the apparently normal position of the inner disk spiral system in the size-luminosity relationship for Virgo spirals (Peterson, Strom, and Strom 1979). The latter statement is based on a Holmberg radius estimated by extrapolating the μ, r relationship for the inner spiral to a $B = 26.5$ mag arcsec^{-2} isophote.

Why should NGC 5963 possess a low surface brightness outer disk? Perhaps the answer lies in the relative isolation of this galaxy. From examination of the Palomar Sky Survey prints, there appear to be no galaxies brighter than $M_B = -16$ within a projected radius of 0.6 Mpc of NGC 5963. The two nearest galaxies *exterior* to this radius are NGC 5907 ($V_0 =$ 780 km s^{-1}) and an anonymous galaxy, A 1535+55 ($V = 859$ km s^{-1}). Five galaxies located within the 0.6 Mpc circle appear, from visual inspection, to be background spirals, although their redshifts are not known.

If NGC 5963 represents an isolated spiral, we speculate that this system was able to retain disk or halo gas located at very large galactocentric distances, whereas such gas has been lost to other, less isolated spirals by virtue of interactions with nearby galaxies. Clearly a good neutral hydrogen map of NGC 5963 would be important in establishing the full extent of the gaseous component as well as in estimating local values of M_H/L_B in the outer disk.

The H II regions in this galaxy also merit further study. First, it would be valuable to confirm our speculations regarding metallicity values in the inner and outer disk regions. Second, we note that not only the outer disk itself but also most of the H II regions located in the outer disk appear to have low surface brightness values. Careful study of the emission-line strength and continuum spectral energy distributions characteristic of these regions might yield important clues regarding the ages and distributions of stellar masses within the OB association responsible for exciting the ionized regions.

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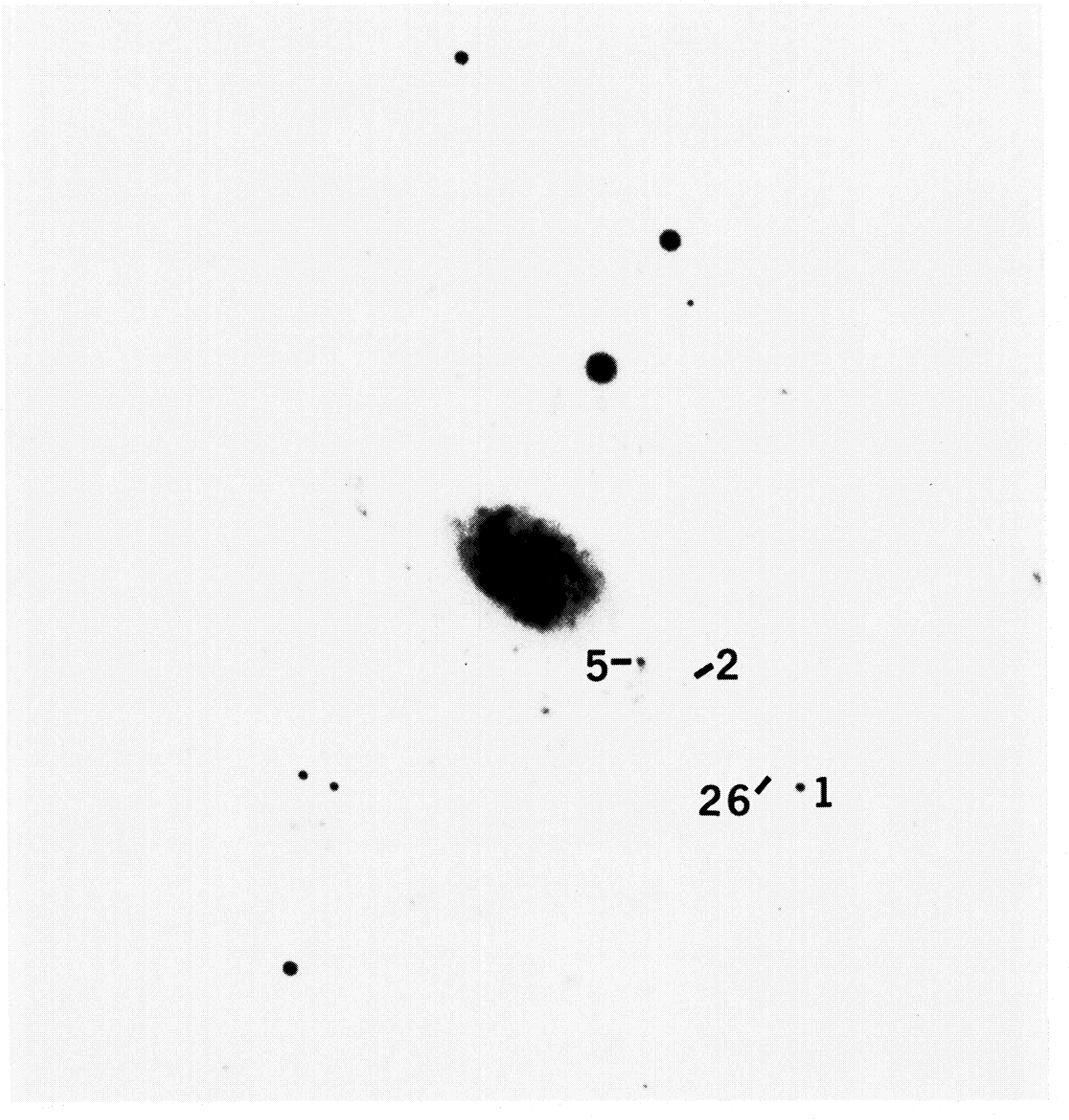

FIG. 1.—A *U*-band photograph of NGC 5963 taken at the prime focus of the Mayall 4 m reflector. Compare the high surface brightness spiral diameter ~25″ = 2000 pc) in the central regions and the low surface brightness disk and spiral pattern in the outer parts of the galaxy. Radial velocities within the galaxy were obtained from a spectrogram taken (nearly) along the major axis and passing through the nucleus, the star labeled 1, and the outer disk H II regions 2, 5, and 26. North is to the top and east to the left. The bright, inner spiral is approximately 25″ in size, as measured along the major axis.

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