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FAINT PHOTOMETRY OF EDGE-ON SPIRAL GALAXIES: A SEARCH FOR MASSIVE HALOS

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ABSTRACT

Upper limits have been set to the luminosity from the massive halos of three late-type edge-on spiral galaxies: NGC 2683 (Sb), NGC 4244 (Scd), and NGC 5907 (Sc). The limits resulted from simultaneous photometry in the visual (V) and 2.2 μm (K) photometric bands which is sensitive to both luminosity and color changes along the minor axes of the three galaxies. The mass-to-light ratios for the halo of NGC 5907 are the largest ever recorded: $M/L_V > 2000$ and $M/L_K > 64$ in solar units. The results virtually eliminate the possibility that hydrogen-burning stars comprise more than a fraction of the halo masses. Variations of the $V-K$ colors along and perpendicular to the disks show no sign of population changes toward redder objects at large galactocentric radii.

The nucleus of NGC 5907 contains an unresolved source less than 330 pc in size with a 2.2 μm luminosity of order $5 \times 10^9\ L_{\odot}$, and may be an example of a starburst galactic nucleus overlooked by visual observations.

Subject headings: galaxies: nuclei — galaxies: photometry — stars: formation

I. INTRODUCTION

Massive halos of underluminous matter almost certainly surround most spiral galaxies (e.g., Faber and Gallagher 1979). Many nearby galaxies have constant rotational velocities to radii much greater than the visible disk (Roberts and Rots 1973; Krumm and Salpeter 1977; Rubin, Ford, and Thonnard 1978). These flat rotation curves trace the presence of large quantities of unseen matter which is commonly believed to reside in spheroidal halos extending well beyond the disks. Theoretical requirements on the stability of thin disks (Ostriker and Peebles 1973), as well as the persistence of warps in the outer disks of many spiral galaxies (Tubbs and Sanders 1979), also point to the existence of massive halos. The mass in these halos may be an order of magnitude greater than that in the disks alone.

There are as yet few clues to the nature of the matter. It might consist of elementary particles such as neutrinos or monopoles, or massive condensed objects such as black holes or underluminous stars. Of these possibilities, only stars might be directly observed at present.

Several attempts to observe low-mass stars in galactic halos (Hegyi and Gerber 1977; Spinrad *et al.* 1978; Hohlfeld and Krumm 1981; Boughn, Saulson, and Seldner 1981; Jensen and Thuan 1982) yielded upper limits to the optical and near-infrared light. Some of these studies concentrated on early-type galaxies, since their large visible bulges could be manifestations of extended halos. On the other hand, many late-type spiral galaxies have flat rotation curves, and the lack of bulges permits searches for halos much closer to edge-on disks.

In this paper, we present simultaneous observations in the visual ($V = 5500$ Å) and 2.2 μm (K) photometric bands of three late-type edge-on spiral galaxies: NGC 2683 (Sb), NGC 4244 (Scd), and NGC 5907 (Sc). Both NGC 4244 and NGC 5907 exhibit flat rotation curves well beyond their Holmberg radii, as well as warped H I disks (Sancisi 1976). Spatially resolved H I data do not exist for NGC 2683, but available H I profiles (Rots 1981) are consistent with a flat rotation curve.

In addition to setting limits to the halo intensities, the observations also provide a reliable measurement of the $V-K$ colors of disks. Variations of the color away from the inner disk may reflect population, metallicity, or extinction gradients, and test the suggestion that the population shifts toward redder objects at large distances from the disks (Hegyi and Gerber 1977).

II. OBSERVATIONS

The two-channel photometer, shown in Figure 1, provided simultaneous observations in the V and K photometric bands. An ambient temperature dichroic beam splitter directed light from the telescope onto a photomultiplier and a cooled infrared detector. Both the photomultiplier and infrared detector had matched 5.8 mm focal-plane diaphragms which were spatially aligned by translating the photomultiplier in the focal plane. The photomultiplier was an uncooled Hammamatsu 647-04 with f/16 field optics and a standard V-band filter. The infrared detector was an InSb photovoltaic diode operated at solid nitrogen temperature (~ 50 K) in combination with f/16 field optics and a K-band interference filter (2.02–2.42 μm FWHM).

Observations were made on the nights of 1983 January 15, 18, 21, 23, and 25 and June 2–10 using the 1.5 m University of Arizona/NASA telescope at Mount Lemmon. The 5.8 mm focal-plane diaphragms corresponded to beam sizes of 48″. Scans of standard stars showed the response across the aperture to be uniform to 10% in both channels. The two beams coincided to better than 4″. The secondary mirror oscillated north-south at 5 Hz to provide background cancellation. The chopper throw of $\sim 8'$ was adjusted at each position to avoid stars in the reference beam visible on the Palomar Sky Survey. We also used this photometer during the period of 1982 June–September with the 60 cm Hartung-Boothroyd Cassegrain reflector near Ithaca, New York. These preliminary observa-

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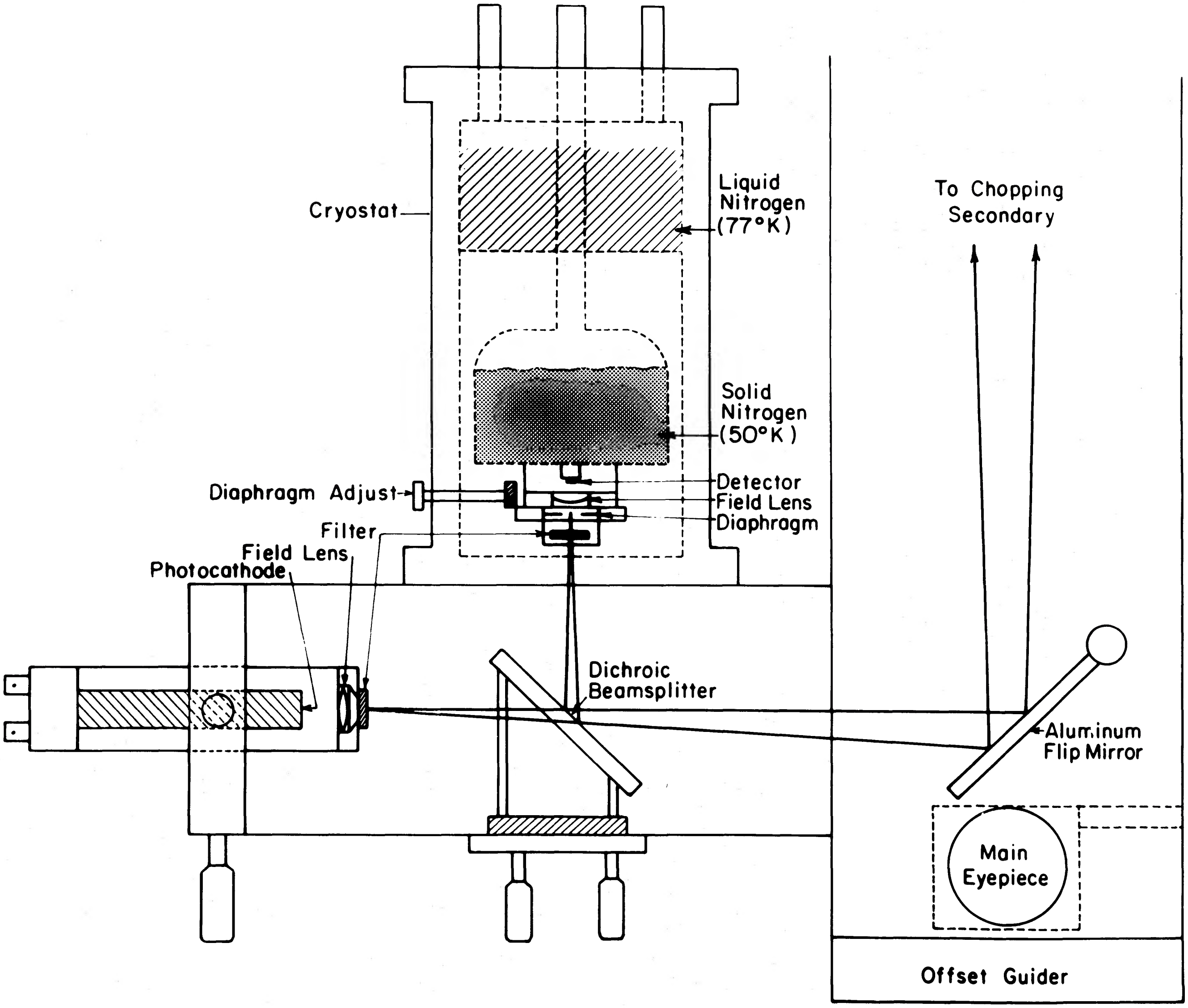


FIG. 1.—Schematic diagram of infrared/optical detection system. Diagram shows visual phototube and cryostat with an infrared detector. Dichroic beam splitter provides simultaneous measurements in visual (V = 5500 Å) and 2.2 μm (K) photometric bands through diaphragms aligned in focal plane of telescope.

tions, with a beam size of 120″, provided an independent confirmation of the results presented here.

A small Z80-based microcomputer digitized and synchronously demodulated the photomultiplier anode current and the infrared detector voltage. Data were taken over 5 minute intervals consisting of pairs of 20 s integrations on the two chopped images. Specifics of the data system, calibration, and method of assignment of uncertainties are described in more detail by Skrutskie, Shure, and Beckwith (1984).

Systematic uncertainties arose due to pointing inaccuracies, telescope drifts, and magnitude calibration/extinction uncertainties. Comparison of separate runs taken on the nuclei of NGC 5907 and NGC 4244 on different nights provides an estimate of these systematic variations. The standard deviation of the mean nuclear magnitudes is 0.07 mag in both photometric bands, establishing the minimum uncertainty for a single measurement. Since the V and K magnitudes at each point were determined simultaneously, the systematic errors for the $V-K$ colors are different from those for the individual magnitudes, mainly because color variations were probably small over the pointing uncertainties of a few arc seconds. The standard deviation of the nuclear colors is 0.05 mag. This value is larger than expected for a simultaneous measurement in V and K, suggesting that most of the variation in the color results from uncertainties in the atmospheric extinction corrections, which were not carefully measured. We choose a value of ± 0.05 mag, as the minimum uncertainty in the $V-K$ colors for all positions.

All upper limits are 3 σ above the mean, except when the mean is less than zero. In this case, the upper limit is conservatively set to 3 σ above zero. Each observation at low light level consists of data from several independent measurements. The uncertainty assigned to these low flux positions (with statistical uncertainties ≥ 0.07 mag) is the greater of either the combined individual uncertainties or the standard deviation of the mean of the separate runs. These two estimates compare rather well for the visual channel, while for the infrared channel the latter is typically larger by a factor of 1.5.

Thermal background noise from the telescope limited the infrared channel sensitivity. The visual channel noise was the

TABLE 1

UPPER LIMITS TO SURFACE BRIGHTNESS[a]

Galaxy	Position	V Band	K Band
NGC 2683	3 NW	25.9[b]	22.0
	3 SE	25.4	22.4[b]
	4 NW	26.0	22.5
	6 SW	26.1	22.3
NGC 4244	1.5 SE	27.0[c]	22.1
	2 NW	27.1[b]	22.5[b]
	2 SE	27.1	22.1
	8 NE	26.8[c]	22.1
NGC 5907	1 NE	26.6[c]	22.0[b]
	1.5 NE	27.5[b]	21.8
	6 SE	26.4[c]	22.6

[a] In mag arcsec^{-2}.
[b] Positions used to compute limits in Table 2.
[c] Greater than 3 σ detections at this position.

result of fluctuations in the night-sky background. Due to the different character of the respective noise sources, the visual channel sensitivity was ~ 5 mag greater than the K-band sensitivity. If the $V-K$ color of the population under study is less than 5, characteristic of M5 and earlier dwarf stars, the V-band measurements establish the limiting halo luminosities. Owing to this disparity between infrared and optical sensitivities, searches for late-type stellar population may be carried out most effectively at optical and near-infrared wavelengths, where photomultipliers can still be used efficiently and thermal background is low.

All three galaxies are inclined nearly 45° to the celestial equator, so positions are expressed in cardinal directions. Figure 2 (Plate 5) provides a reference for each galaxy. Positions are given in terms of a displacement from the nucleus in arcminutes and direction.

Figure 3 shows the surface brightness and color profiles along the major and minor axes of each galaxy. Figure 4 shows similar profiles for several scans through the galactic disk parallel to the minor axis. Table 1 presents the upper limits to the halo intensity in units of magnitudes per square arcsecond at V (μ_V) and K (μ_K) for several positions in each galaxy.

III. DISCUSSION

a) *Limits to Halo Luminosity*

The visual luminosity profiles of galactic disks and bulges are well known (e.g., Hubble 1930; de Vaucouleurs 1959; Kormendy 1977). The bulge is roughly spherically symmetric, and its surface brightness, I, falls steeply with radius, r, as

$$\log I(r) \propto -r^{1/4} . \qquad (1)$$

The disk component falls exponentially, both radially and in the direction perpendicular to the disk when viewed edge-on, although it may drop sharply beyond some maximum disk radius (van der Kruit and Searle 1981). A spherically symmetric halo of the sort needed to produce a flat rotation curve with velocity $V_{\max}$ has a mass density

$$\rho(r) = \frac{V_{\max}^2}{4\pi G} \frac{1}{r^2} , \qquad (2)$$

and should have a surface brightness profile proportional to r^{-1}, assuming a uniform mass-to-light ratio. Such a halo would have a total mass of

$$M_{\rm tot} = 2.3 \times 10^{11} \frac{V_{\max}^2}{(100 \text{ km s}^{-1})^2} \frac{r_{\max}}{(100 \text{ kpc})} M_\odot , \qquad (3)$$

where $r_{\max}$ is the maximum radius of the halo. The radius $r_{\max}$ must be at least as large as the maximum radius of the constant velocity rotation curve, but the upper limit is unknown. Choosing typical values of $V_{\max} = 250$ km s^{-1} and $r_{\max} = 50$ kpc results in a halo mass of $M_{\rm tot} = 7 \times 10^{11}\ M_\odot$.

Integrating the mass density along a line of sight near the nucleus establishes a mass column density through the halo of

$$M(r) = 5.7 \times 10^4 \frac{V_{\max}^2 (\text{km s}^{-1})}{r \text{ (kpc)}} M_\odot \text{ kpc}^{-2} . \qquad (4)$$

This mass column density may be used in combination with the upper limits to the flux in Table 1 to establish lower limits to the mass-to-light ratios M/L_V and M/L_K in the halos. NGC 5907 provides the best limits, since it has the steepest luminosity gradient along the minor axis of the three galaxies observed. The discussion will focus on this galaxy, with the results for NGC 2683 and NGC 4244 presented in Table 2.

NGC 5907 has a maximum rotation velocity of 245 km s^{-1}, implying a halo column density of $3.4 \times 10^9/r$(kpc) $M_\odot$ kpc^{-2} near the nucleus. The infrared observations at position 1 NE, 3.3 kpc from the nucleus, imply 3 σ upper limits for the surface brightness of $1.6 \times 10^7\ L_{\odot K}$ kpc^{-2}. The visual band measurement at 1.5 NE sets a limit of $3.5 \times 10^5\ L_{\odot V}$ kpc^{-2} ($M_{\odot v} = 4.83$, $V-K_\odot = 1.42$). The lower limits to M/L are 64 and 2000, respectively, in solar units. These values vary inversely with the distance to the galaxies. Distances to each galaxy are listed in Table 2 and were derived using velocities from Fisher and Tully (1981), and a Hubble constant of 75 km s^{-1} Mpc^{-1}.

The above result assumes that the halo mass dominates the disk mass in producing the peak H I rotation velocity. In NGC 5907 there is evidence that the sharp cutoff in disk luminosity (van der Kruit and Searle 1981) produces a decrease in the rotation curve at large radii (Sancisi 1976; Casertano 1983). In this case, a rotation velocity of 210 km s^{-1} may be more characteristic of the halo alone, implying M/L_K of 47 and M/L_V of 1500.

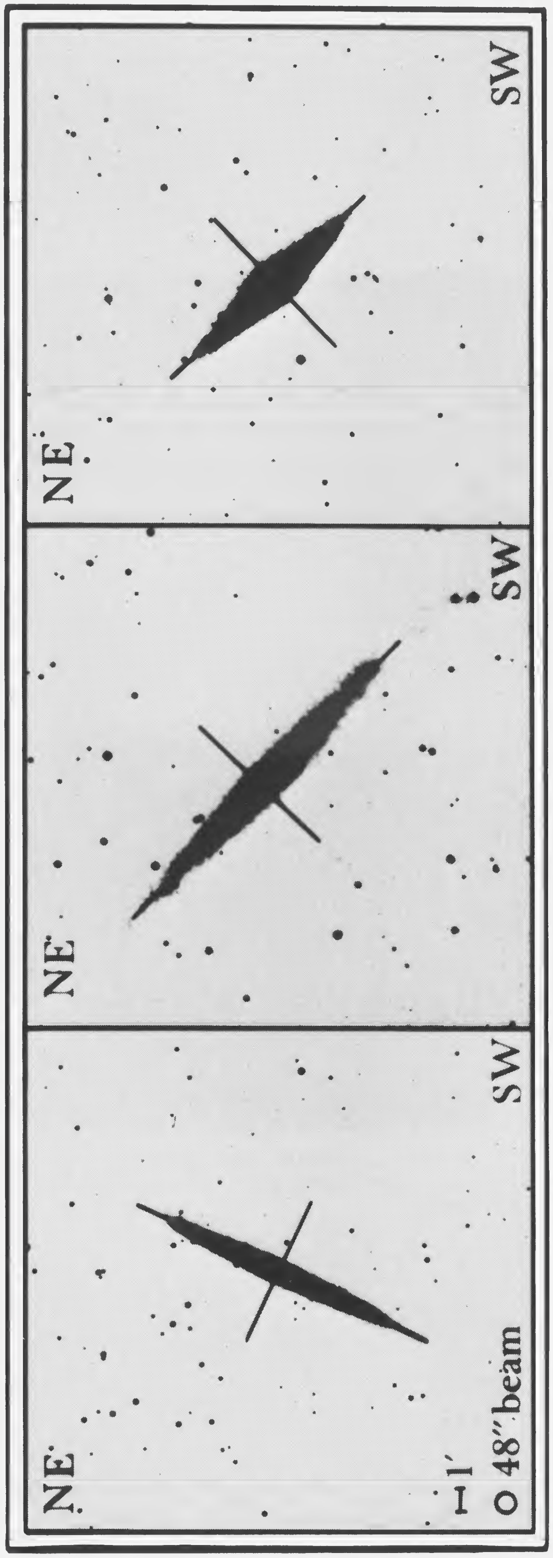
In the galaxies observed, typical limits to M/L_K are of order 60 in solar units, which is much greater than the value of ~ 35

TABLE 2

GALAXY STATISTICS AND RESULTS

Galaxy	Type	$V_{\max}$ (km s^{-1})	Distance[a] (Mpc)	Inclination	$L_{\odot K}$ Halo	$M_\odot/L_{\odot K}$	$L_{\odot V}$ Halo	$M_\odot/L_{\odot V}$
NGC 2683.........	Sb	225	5.0	80°	$<9.5 \times 10^9$	>61	$<1.4 \times 10^9$	>420
NGC 4244.........	Scd	110	3.7	88	$<4.3 \times 10^9$	>33	$<2.2 \times 10^8$	>630
NGC 5907.........	Sc	245	11.4	87	$<1.1 \times 10^{10}$	>64	$<3.5 \times 10^8$	>2000

[a] Velocities from Fisher and Tully 1981. $H_0 = 75$ km s^{-1} Mpc^{-1}.



5907 4244 2683

FIG. 2.—Photographs of galaxies observed. In text, positions are labeled in terms of distance from nucleus in arcminutes and a direction (e.g., 3 SW).

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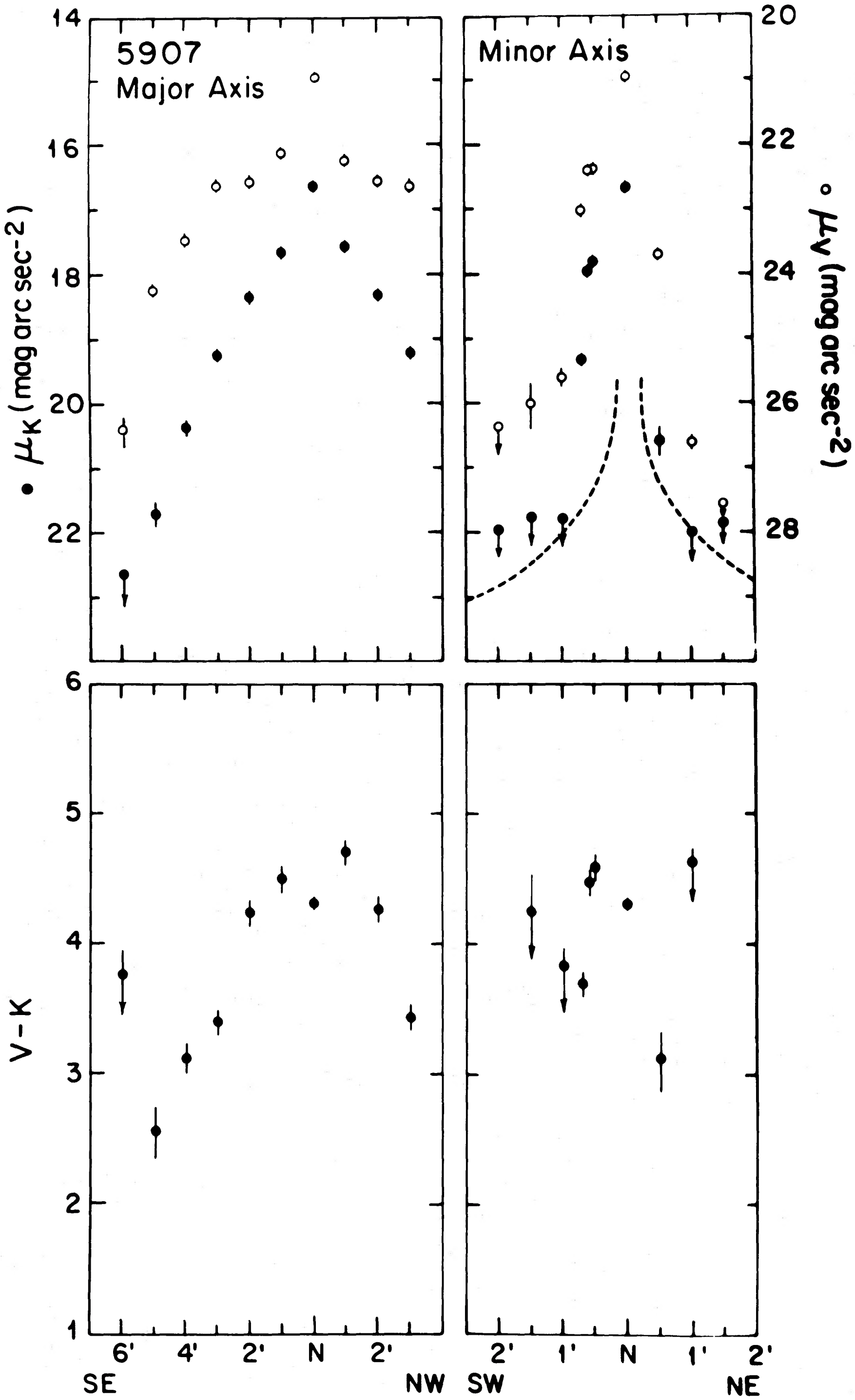

FIG. 3a

FIG. 3.—Major and minor axis profiles for each galaxy observed, with corresponding $V-K$ color plot below. Filled circles are infrared K-band data. Open circles represent V-band data. Error bars are $\pm 1\ \sigma$. Upper limits are $3\ \sigma$. Dashed profiles on minor axis plots represent brightest K-band halos with uniform M/L consistent with upper limits.

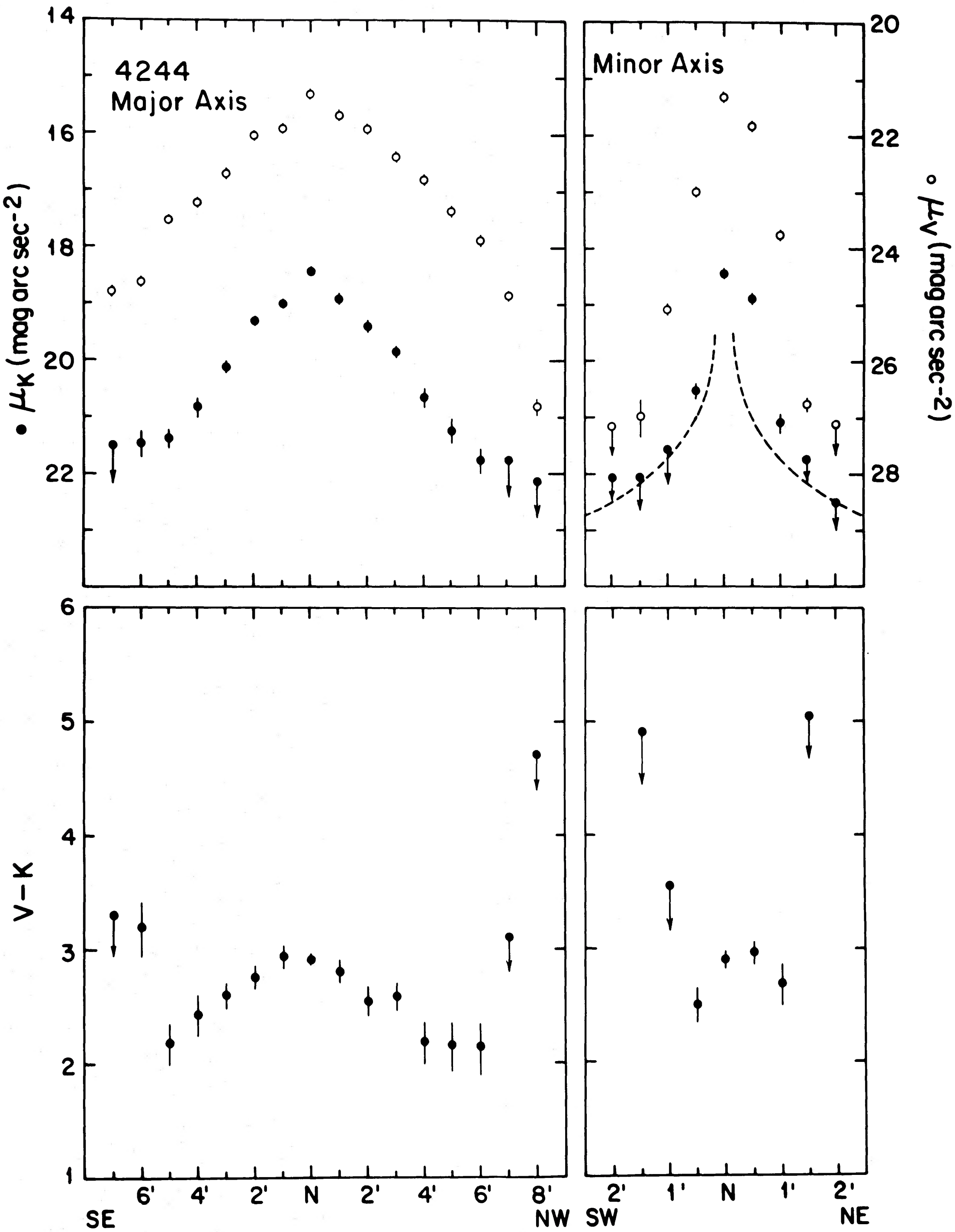
4244
Major Axis
Minor Axis
• μ_K (mag arc sec-2)
∘ μ_V (mag arc sec-2)
V−K
14
16
18
20
22
20
22
24
26
28
6
5
4
3
2
1
6'
4'
2'
N
2'
4'
6'
8'
SE
NW
2'
1'
N
1'
2'
SW
NE

FIG. 3b

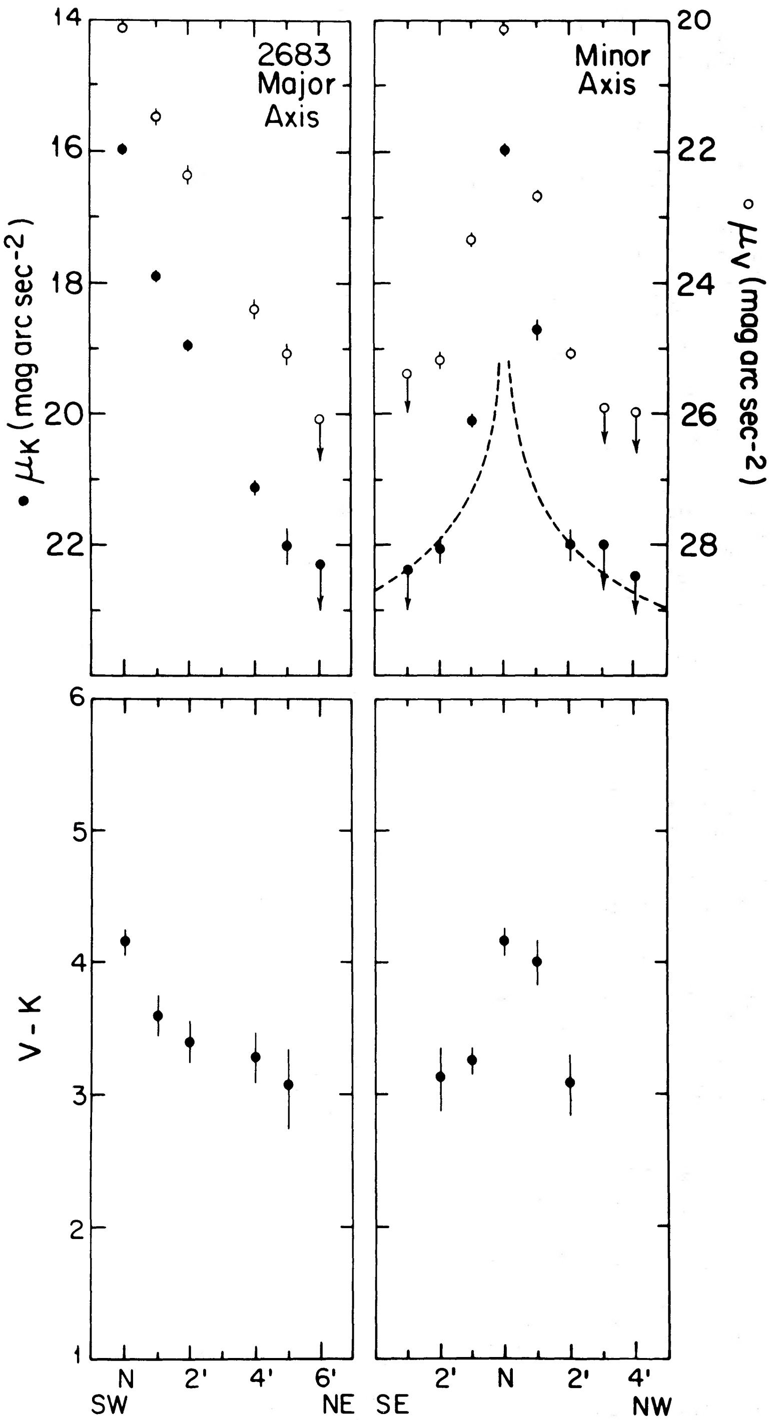
2683
Major
Axis
Minor
Axis
• μ_K (mag arc sec-2)
° μ_V (mag arc sec-2)
V - K
14
16
18
20
22
20
22
24
26
28
6
5
4
3
2
1
N
2'
4'
6'
SW
NE
2'
N
2'
4'
SE
NW

Fig. 3c

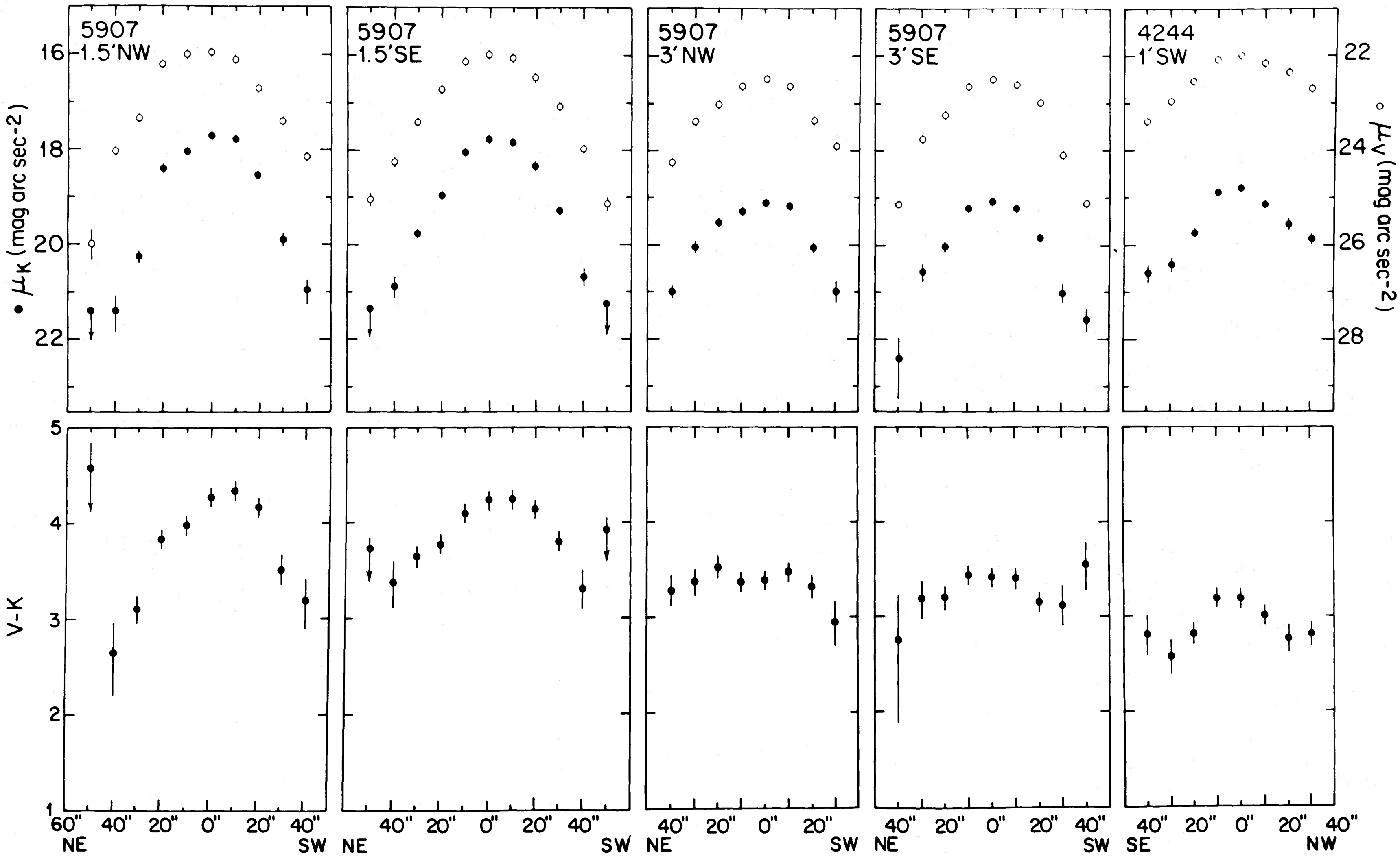

FIG. 4.—Results of scans through disks of NGC 5907 and NGC 4244 parallel to minor axes. NGC numbers and crossing point on major axis are labeled in upper left-hand corners. Positions are labeled in terms of displacement from major axis in arcseconds.

reported for the faintest M dwarf stars with masses of order 0.08 $M_{\odot}$ (Boughn, Saulson, and Seldner 1981). This limit is a factor of 2 greater than the best previous infrared measurements of halo M/L (Hohlfeld and Krumm 1979; Boughn, Saulson, and Seldner 1981). Since the luminosity drops precipitiously for main-sequence stars with masses less than the minimum hydrogen-burning mass of 0.08 $M_{\odot}$ (Stevenson 1978; Nelson, Rappaport, and Joss 1985), this result strongly implies that stars are not the main halo constituent. In addition, the $V-K$ colors in Figures 3 and 4 do not increase (i.e., redden) away from the nucleus. There is no evidence for an extreme late-type stellar population in the halos.

The limit of 2000 to M/L_V is one of the largest values appearing in the literature (see Spinrad *et al.* 1978), and rules out the possibility that the halo is composed of even a small fraction of Population II stars, which have $M/L_V < 10$. This value is a factor of 4 or more greater than that derived for galaxy clusters using virial arguments (Rood and Dickel 1978), and supports the belief that some of the invisible cluster mass may reside in dark galaxy halos. Whether only some small fraction of the halo mass is in the form of stars will remain an open question as long as only upper limits to the halo luminosity are available.

The dashed lines in Figure 3 represent the brightest K-band halo profile with an r^{-1} decline [$\rho(r) \propto r^{-2}$, M/L = constant] compatible with the observed upper limits. If M/L is constant throughout the halo, then the limits to M/L at one position in conjunction with the total halo mass (eq. [3]) set upper limits to the total halo luminosity. For NGC 5907, the halo mass within 50 kpc of the nucleus is 6.9×10^{11} $M_{\odot}$. The corresponding halo luminosity is then 1.1×10^{10} $L_{\odot}$ at K, and 3.5×10^{8} $L_{\odot}$ at V. M8 dwarf stars ($M_V = 16$, $V-K = 7$, $M = 0.1$ $M_{\odot}$) could account for at most 2×10^{11} $M_{\odot}$, or less than one-third the halo mass, based on the infrared limits. It is unlikely that the halo consists entirely of low-mass stars, unless they are of a later type than M8. Since these stars lie close to the mass limit for hydrogen burning, this is improbable. On the other hand, if the halo population is a typical distribution of Population II stars (e.g., Messier 3, mean spectral type F8 III, $M/L \approx 0.8$), the luminous component constitutes no more than 3×10^{8} $M_{\odot}$, based on the V-band limits. In this case, the bulk of the halo must be nonluminous or extremely underluminous matter, with the stars serving only as an insignificant tracer.

Table 2 summarizes these results, as well as the results of similar analyses for the other galaxies studied.

b) $V-K$ Colors: Metallicity and Population Gradients

In principle, the $V-K$ colors within the galactic disk trace metallicity and/or population gradients, but in practice reddening can badly confuse the interpretation. Metallicity gradients are seen in the extinction-free environments of E and S0 galaxies (Strom *et al.* 1976), with a decrease in the observed $V-K$ colors with increasing galactic radius implying decreasing metallicity. Similar metallicity gradients are inferred for spiral galaxies (see Mould 1980 for a review), but population variations and reddening by dust complicate the interpretation.

For an edge-on spiral galaxy with no extinction, the $V-K$ color should increase with increasing vertical distance above the disk, since the youngest (bluest) stars have the smallest vertical scale heights. The data for the minor axis scans, as well as scans parallel to the minor axis, show the opposite trend. Extinction almost certainly dominates the $V-K$ color variations in this case. This result contradicts the suggestion of Hegyi and Gerber (1977) that colors become redder at very large galactocentric distances, although our data do not extend to the same distances.

Along the major axis, the $V-K$ color falls uniformly, suggesting either an increasing metal-poor population, or a decreased amount of dust at greater radii.

c) Nuclear Point Source in NGC 5907

The sharp discontinuity in the minor axis profile of NGC 5907 between positions 0.6 SW and 0.7 SW shows the presence of an unresolved nuclear source. The sharp edges of the beam profile made it possible to set much smaller limits on the size of the source than the beam size of 48″. The source is less than 6″ in size, corresponding to less than 330 pc at 11.4 Mpc. The $V-K$ color is 5.1, assuming the difference in flux between the positions 0.6 SW and 0.7 SW is due entirely to the point source. This small nuclear source is very similar to one detected in another Sc spiral, NGC 253, by Scoville *et al.* (1985). *JHK* photometry and 2.6 mm CO observations suggest that the source in NGC 253 is associated with a star formation rate of 2.3 $M_{\odot}$ yr^{-1} in O, B, and A stars.

The very red color of the nucleus in NGC 5907 probably results from a few magnitudes of visual extinction, A_v, though the edge-on disk. We can estimate A_v by assuming an intrinsic color for the nucleus. A nuclear population of F and K giants, with a typical $V-K$ color of 3.0, implies ~ 2 mag of visual extinction. If recent star formation is responsible for the nuclear source, a $V-K$ color of ~ 0.0 would be appropriate, and would indicate 5 mag of visual extinction. In either case, since reddening at 2.2 μm is an order of magnitude smaller than at visual wavelengths (Becklin *et al.* 1978), the observed 2.2 μm flux is probably within a factor of 2 of its unreddened value. The unreddened source luminosity in the K band is $\sim 5 \times 10^{9}$ $L_{\odot}$. Choosing either an early-type population corresponding to recent star formation or a population of F and K giants implies a mass for the source of order 10^{8}–10^{9} $M_{\odot}$.

This source has many of the characteristics of starburst nuclei seen in other spiral galaxies (Weedman *et al.* 1981), and would have been overlooked in searches for blue galactic nuclei because of the high extinction to the nucleus. Radio continuum observations have set upper limits to the nuclear source radio luminosity of 2×10^{18} W Hz^{-1} at 1410 MHz (Hummel, Sancisi, and Ekers 1984). This luminosity is a factor of 10^{3} less than that for NGC 7714, one of the most active starburst nuclei (Weedman *et al.* 1981), but it is not inconsistent with either a weak or old nuclear starburst. Confirmation could come from a search for infrared and optical emission lines.

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