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A NEW LIMIT ON THE MASS-TO-LIGHT RATIO OF THE HALO OF NGC 4565

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ABSTRACT

K-band (2.2 μm) photometry is reported for selected positions near the minor axis of the edge-on spiral galaxy NGC 4565. If the "dark matter" implied by the rotation curve is in the form of a spherical halo, its mass-to-light ratio is $M/L > 38$ (2 σ lower limit) in solar *K*-band units. The faintest known main-sequence star, VB 10, has a mass-to-light ratio of $M/L \approx 34$. In addition, the *K*-band data suggests a $(V-K)$ color gradient for the central bulge of this galaxy.

Subject headings: galaxies: stellar content — galaxies: structure

I. INTRODUCTION

The determination of the mass of a typical galaxy has been a matter of some interest and controversy since the work of Hubble (1936) and Zwicky (1937). Modern thinking on the subject began to coalesce with the seminal papers of Einasto, Kaasik, and Saar (1974) and Ostriker, Peebles, and Yahil (1974), who proposed that the bright parts of galaxies are surrounded by extended spherical halos of dark matter in which most of the mass of galaxies resides. The halo hypothesis received critical support from the discovery of flat rotation curves of spiral galaxies beyond their bright central regions, using both 21 cm radiation (Roberts and Rots 1973; Krumm and Salpeter 1977) and visible wavelengths (Rubin, Ford, and Thonnard 1978). A review of the current evidence on galaxy masses is given by Faber and Gallagher (1979).

Although flat rotation curves do not require that the dark matter in galaxies be spherically symmetric, there are several arguments which support this hypothesis. Ostriker and Peebles (1973) found that galactic disks were unstable to bar formation unless stabilized by a substantial spherical halo. Tubbs and Sanders (1979) calculate that warps in the disks of galaxies would not persist if most of the mass was in the disk. Finally, Monet, Richstone, and Schechter (1981) argue from star counts that much of the mass interior to the Sun in our own Galaxy is in a spherical population. In all that follows, we assume that most of the mass implied by rotation curves is in the form of a spherical halo.

The dynamical evidence does not indicate the form of the dark matter; however, a natural hypothesis is that it is in the form of dim, low-mass stars. Several groups of workers (Freeman, Carrick, and Craft 1975; Hegyi and Gerber 1977; Spinrad *et al.* 1978; Davis, Feigelson, and Latham 1980; Hohlfeld and Krumm 1981; Hegyi 1981) attempted to detect the faint light which these stars would emit, without success. Their work restricted the presumed halo population to have a net mass-to-light ratio larger than that of an M5 dwarf. Since late M-type dwarves emit most of their light in the infrared, we undertook the present observations at 2.2 μm (*K* band) where current detectors appeared good enough to detect a halo of even the dimmest main-sequence stars.

We observed NGC 4565, a nearly edge-on Sb galaxy close to the Virgo cluster in both position ($12^h33^m, +26°$) and redshift ($V \sim 1200$ km s^{-1}). Its distance is taken to be 18.4 Mpc, as inferred from its group association assuming a Hubble constant of 50 km s^{-1} Mpc^{-1} (Faber and Gallagher 1979). Krumm and Salpeter (1977) measured the 21 cm rotation curve to be constant at $V_{\rm rot} = 254$ km s^{-1} out to 11'.6 from the center. This implies a halo mass density of 1.2×10^9 r^{-2} $M_\odot$ kpc^{-3}, where r is in kpc.

The previous optical observations of NGC 4565 (Hegyi and Gerber 1977; Spinrad *et al.* 1978; Davis, Feigelson, and Latham 1980; Hamabe and Kodaira 1980) provide accurate photometry which traces the steep falloff in brightness of the bulge component out to a radius of about 5'. The consistency of these measurements with each other and with other measurements of the central region of the galaxy, along with a discussion of the interpretation of the brightness profile, has been provided by Kormendy and Bruzual (1978) and Kormendy (1979).

II. OBSERVATIONS

K-band ($\lambda = 2.2$ μm; $\Delta\lambda = 0.43$) photometric measurements of NGC 4565 were made in 1981 February and April with the 1.3 m telescope and InSb detector at Kitt Peak National Observatory. We observed six

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positions near the minor axis using a 1′ focal plane aperture for a total integration time of 252 minutes. A fast (8 Hz), chopping secondary allowed us to subtract foreground emission by comparing the main beam to the average of two reference beams located 13′ away in directions parallel to the disk of the galaxy. The 6 primary beams and 12 reference beams are shown superposed on a Palomar Sky Survey red print in Figure 1 (Plate L1). Care was taken that none of these beams contained stars or galaxies down to the limit of the plate. In addition, we observed the center of the galaxy and minor axis points 20″, 40″, and 60″ away to the southwest with an aperture of 23″ in diameter.

III. DATA ANALYSIS AND DISCUSSION

The data were taken in blocks either 10 or 20 minutes long. The standard deviations of these data sets were computed and found to vary by about a factor of 3 in a manner correlated with the absolute brightness of the night sky. The distribution within each set was examined to determine that it was approximately Gaussian. There was, however, one point which differed from the mean by 8 standard deviations. Another data point was contaminated by a bright object which passed through the beam, as observed on the TV monitor. With these exceptions, corresponding to 4 minutes of integration time, all the data on the galaxy are used in the analysis. Inclusion of these points would make a negligible difference in the final conclusion.

The data sets taken at the same galaxy position were averaged, with each set assigned a weight inversely proportional to its variance. The results are presented in Table 1. Small corrections, to account for stars along the chop path, have been applied to three of the points. In all cases these corrections were less than or equal to one-third of the standard deviations of the mean for these points.

TABLE 1

2.2 MICRON INTENSITIES AT SELECTED POSITIONS

Beam Position[a]	Beam Diameter	Intensity (10^{-20} ergs cm^{-2} s^{-1} Hz^{-1} sr^{-1})
0 center	23″	$+1.92 \pm 0.04 \times 10^4$
20″ SW	23″	$+6.80 \pm 0.04 \times 10^3$
40″ SW	23″	$+8.23 \pm 0.44 \times 10^2$
60″ SW	23″	$+1.07 \pm 0.72 \times 10^2$
112″ SW	1′	$+36.1 \pm 9.6$
137″ NE	1	$+5.7 \pm 10.0$
168″ NE	1′	$+5.1 \pm 9.6$
200″ SW	1′	$+0.2 \pm 22.9$
213″ NE	1′	-13.9 ± 12.4
244″ SW	1′	-4.2 ± 9.4

[a]Beam position is indicated by radial distance from the center of the galaxy and its location (northeast or southwest) relative to the plane of the disk.

If a luminous halo surrounds the galaxy, then at large radii the surface brightness of the galaxy should be dominated by the shallow $I \propto 1/r$ characteristic of a mass distribution which produces a flat rotation curve. This is in contrast to the observed V-band surface brightness of the spheroidal component (central bulge and its extension) where $I \propto r^{-2.5}$ (Kormendy and Bruzual 1978). The final K-band luminosity profile is plotted in Figure 2 along with the expected contributions of the bulge, as inferred from the V-band measurements of Hamabe and Kodaira (1980), and a hypothetical spherical halo consisting of M8 dwarves.

a) *Color Gradient*

In order to translate the V-band profile to 2.2 μm we applied a correction $(V - K) = 3.15$ which was obtained from a fit to the inner three points. This value is consistent with typical galaxy colors found in other studies (Aaronson 1978). It is clear that, even in the absence of a luminous halo, the data imply the bulge component is bluer at larger radii. Several authors (Strom *et al.* 1976; Frogel *et al.* 1978) have found evidence for gradients in $V - K$ in E and S0 galaxies. Strom *et al.* (1976) found a decrease in $V - K$ of 0.3–0.5 mag over the central arcminute or so of the minor axes of three different galaxies. These authors explained the trend as the effect of decreasing metallicity (with radius) of the

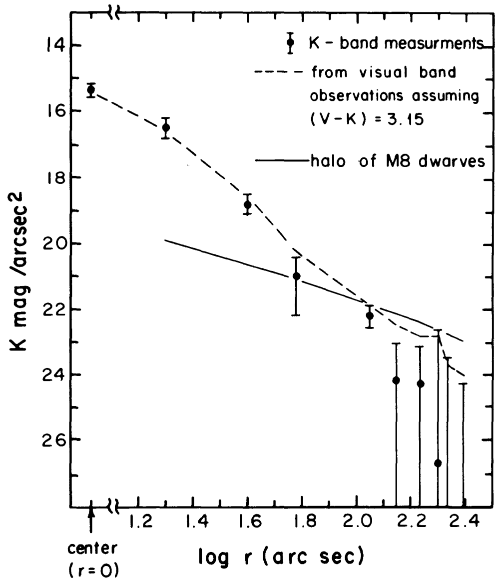

FIG. 2.—Graph of K-band surface brightness vs. distance from the center of NGC 4565. The error bars are $\pm 1\ \sigma$ of the mean, except for the upper limit at $\log r = 2.33$, which is $+2\ \sigma$. For the innermost three points, the error bars represent the combination of photometric and positional uncertainty. The dashed line shows the V-band measurements of Hamabe and Kodaira (1980) translated to K, using $V - K = 3.15$. The line changes slope several times in the outer portion since our measurements did not all lie on the minor axis. The solid line shows the expected brightness of a halo of M8 dwarves.

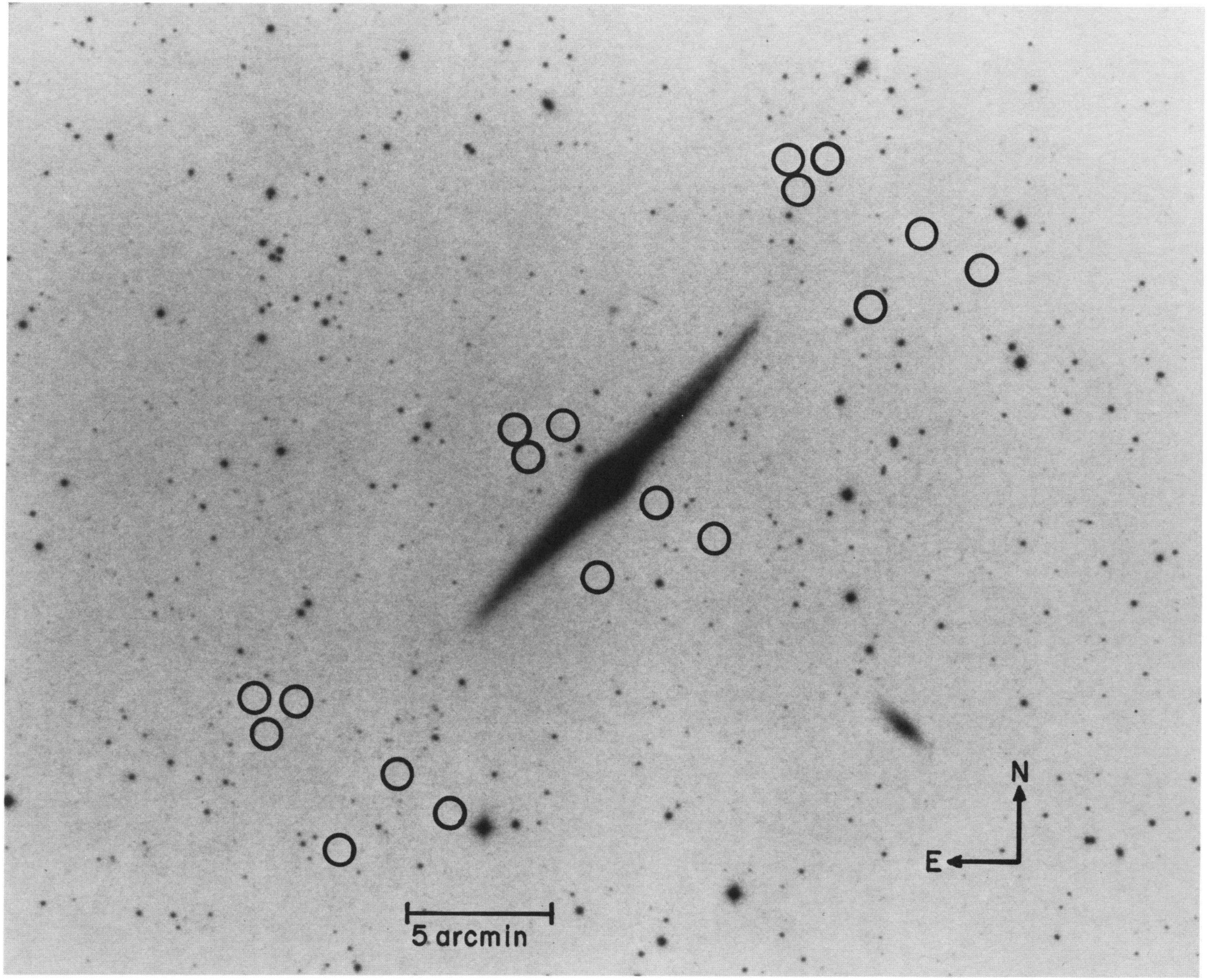

FIG. 1.—Positions of object and reference beams near NGC 4565, for $r \geq 112''$, superposed on a portion of the Palomar Observatory Sky Survey red plate. The circles are 1′ in diameter.

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stars which supply the light. Rieke and Lebofsky (1979) note that while this is a plausible explanation, it has not yet been conclusively demonstrated that some variation of the mix of spectral types of stars could not also be contributing to the effect. For comparison, a fit to our inner three points ($r \leq 40''$) gives $(V-K) = 3.15(+0.15, -0.18)$, while a fit to the six outer points ($r \geq 112''$) gives $(V-K) = 2.42(+0.31, -0.43)$, or a decrease of $0.73(+0.46, -0.36)$.

b) *Halo M/L*

The M8 halo curve in Figure 2 was calculated from the halo mass density given above and the following properties of the star W359, which we take to be a canonical M8 dwarf: $m = 0.1\ M_\odot$ (estimated, Graboske and Grossman 1971); $M_{\rm bol} = 12.1$; $M_V = 16.6$; and $M_K = 9.1$ (Greenstein, Neugebauer, and Becklin 1970). It is clear from this figure that a halo composed of such stars is too luminous to be consistent with the data. (The slight curvature of the halo curve results from a correction made to account for the sensitivity of the reference beams to an extended halo.)

Because of the uncertainty in the $(V-K)$ color of the extended bulge, we are unable to make reliable corrections to the data for this component. However, an upper limit to the luminosity of a halo component can be obtained by fitting the expected luminosity curve to the uncorrected values of the outer points. A least-squares fit to the five outer data points ($r \geq 137''$) to a function of the form $I = b/r$ gives

$$b = 5.9 \pm 34.9 \times 10^6\ L_\odot\ \text{kpc}^{-2},$$

where r is in kpc and $L_\odot$ is the K-band solar luminosity. When combined with the projected mass density inferred from the rotation curve ($3.75 \times 10^9\ r^{-1}\ M_\odot$ kpc^{-2}; r in kpc) we arrive at a 2 σ lower limit on the mass-to-light ratio of the halo of $M/L \geq 49.5$ in solar K-band units. For comparison, the mass-to-light ratio of W359, $M/L \sim 19$, is 5.5 σ below the measured value.

The halo mass-to-light ratio computed above depends inversely on the distance to the galaxy. Estimates range from 8.1 Mpc (de Vaucouleurs 1975) to 24 Mpc, computed from the recessional velocity, 1200 km s^{-1} (Krumm and Salpeter 1977), and a Hubble constant of 50 km s^{-1} Mpc^{-1}. Expressed in terms of D, the distance to NGC 4565, the 2 σ lower limit on the halo mass-to-light ratio becomes

$$M/L \geq 38\left(\frac{24\ \text{Mpc}}{D}\right).$$

It is of interest to compare this value with the mass-to-light ratio of the faintest known main-sequence star, VB 10 (Van Biesbroeck 1961), which has $M_{\rm bol} = 13.1$, $M_V = 18.9$, and $M_K = 9.9$ (Greenstein, Neugebauer, and Becklin 1970). Stellar evolution calculations by Graboske and Grossman (1971) and Straka (1971) indicate that the mass of VB 10 is $m \approx 0.085\ M_\odot$ and is a good candidate for the lowest mass that can stabilize on the main sequence. Using this value for the mass, $(M/L)_{\rm VB\ 10} \approx 34$, which is below the 2 σ lower limit for the halo even if D is as large as 27 Mpc.

Also for comparison, the mass-to-light ratio of UV Cet, the dimmest main-sequence star for which a mass has been measured ($m = 0.109\ M_\odot$), is $M/L \approx 22$ (Veeder 1974; Popper 1980).

c) *Disk Correction*

The mass density used above was derived from the rotation curve and an assumption of spherical symmetry. No account was taken of the mass in the galactic disk. Dekel and Shaham (1979) have modeled the disk as a mixture of neutral hydrogen and K2 stars of total mass $1.4 \times 10^{11}\ M_\odot$ and computed new values for the mass density of the halo. Since these corrections change the mass-to-light ratio by less than 5%, we have ignored them.

d) *Background Stars and Galaxies*

We have considered the possibility of contamination by stars and galaxies which are either too dim or too red to appear on the Palomar red plate. Using the predicted star counts of Bahcall and Soneira (1981), we have estimated the effect of all stars with red magnitudes greater than 19 (a rather conservative value of the plate limit) and conclude that there is less than a 5% probability that such stars in the reference beams would result in an effect as large as one-tenth the 2 σ limit quoted above.

If the plate limit for galaxies is taken to be $M_R = 18.5$ and the $(R-K)$ color is assumed to be 2.1 (that of a K7 star), then no single galaxy below the plate limit can cause an effect as large as one-tenth the 2 σ limit. The total integrated light per beam can be calculated from number counts as a function of limiting magnitude (e.g., Butcher and Oemler 1978; Tyson and Jarvis 1979). The expected flux corresponds to ~ 17 K mag per beam, which is much less than the standard deviation of the mean for each beam position. Furthermore, one would expect some cancellation of this signal by similar signals in the reference beams.

We conclude that it is unlikely our results are significantly contaminated by background stars and galaxies.

IV. CONCLUSIONS

On the basis of K-band measurements of the luminosity profile of NGC 4565, we have set a 2 σ lower limit on the mass-to-light ratio of any halo component (whose surface brightness is proportional to $1/r$) of $M/L \geq 38$ in solar units at K band. This value is larger than that of the dimmest known main-sequence star, VB 10, for which $M/L \sim 34$. VB 10 is suspected to be the smallest star which can stabilize on the hydrogen burning main sequence. If this theoretical conjecture is correct, we conclude that the dominant halo component does not consist of main-sequence stars.

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