THE ASTROPHYSICAL JOURNAL, **209**:389–394, 1976 October 15

SURFACE PHOTOMETRY OF THE SPIRAL GALAXY IC 2233 AND THE EXISTENCE OF MASSIVE HALOS

J. S. GALLAGHER
School of Physics and Astronomy, University of Minnesota

AND

H. S. HUDSON
Department of Physics, University of California, San Diego
Received 1976 March 12

ABSTRACT

Using beam-switching to cancel the sky background, deep *BVi* photometric measurements have been obtained near the edge-on Scd galaxy IC 2233. No halo component is detected to a level of ~1 percent of the disk surface brightness. For a concentrated model (half-intensity isophote smaller than the disk radius), the halo M/L must exceed 100 if it is to meet minimally the Ostriker and Peebles criterion for stabilizing a cold disk of stars.

Subject headings: galaxies: individual—galaxies: photometry — galaxies: structure

I. INTRODUCTION

Recently there has been increasing speculation that the optical components of spiral galaxies are imbedded in dark, massive halos. This concept receives theoretical support from the apparent instability of numerical models for "cold" galactic disks (Toomre 1964; Ostriker and Peebles 1973; Miller 1974), which led Ostriker and Peebles to suggest that such disks are stabilized by "hot," and heretofore undetected, halo components. These halos would have high mass-to-luminosity ratios, as would be required if all double galaxies and groups of galaxies are to be gravitationally bound (cf. Einasto, Kaasik, and Saar 1974; Ostriker, Peebles, and Yahil 1974; Turner 1976; also see Burbidge 1975 for criticisms of this interpretation).

Despite the many attractive aspects of the halo hypothesis, direct observational confirmation is lacking. Attempts to detect the halo component of various external galaxies (Davis 1975; Freeman, Carrick, and Craft 1975) have thus far been unsuccessful;[1] observations of halo stars in our Galaxy (Weistrop 1975; Schmidt 1975) indicate that the stellar component of a massive halo has 10–50 times less than the necessary mass. Optical rotation curves for spirals do not indicate significant undetected mass in the interior regions of disk galaxies (Nordsieck 1973). Rotation curves derived from 21 cm H I observations *may* remain flat at large (>30 kpc) galactic radii, which would be consistent with the presence of an extended mass distribution (Rogstad and Shostak 1971; Roberts 1975). However, the masses required need not be as large as those hypothesized by Ostriker and Peebles (1973).

In this paper we present optical observations designed to detect directly, within certain experimental constraints, a luminous halo in an extragalactic system. For a thin disk of stars to be stabilized by a massive halo, the mass of the halo *interior* to the disk must be comparable to the total disk mass (Ostriker and Peebles 1973). The desirable criteria for a candidate galaxy with which to test the optical visibility of such a halo are then (1) an edge-on, thin disk with no indication of a bar or other instability; (2) no spheroidal component on Palomar Sky Survey prints; (3) high disk surface brightness; and (4) available physical parameters. IC 2233 was chosen for this study as it is one of the flattest galaxies known (de Vaucouleurs 1974*a*) and meets criteria (1), (2), and (4). The central surface brightness in a 30″ aperture, corrected for galactic extinction by conservatively assuming $A_B = 0.12\csc|b|$, is $\mu_B = 22.0$ mag arcsec^{-2}. This is quite similar to the extrapolated values for exponential disk components of the galaxies in Freeman's (1970) sample.

II. OBSERVATIONAL TECHNIQUES

In attempting to detect an extended object with low surface brightness, a proper subtraction of the night-sky background is of critical importance. This was accomplished for our measurements by using beam-switching to obtain a reference sky level. The observations were made with the UM-UCSD 1.5 m telescope on Mount Lemmon. Since this telescope is normally used for infrared astronomy, it is equipped with a chopping secondary mirror which allows the beam to be switched between object and reference positions. In practice, galaxy and sky positions were

[1] Spinrad (1976) has obtained marginal detections of red ellipsoidal components in the edge-on-spirals NGC 253 and NGC 4565. In both instances the data are very suggestive, but could be contaminated by an extended disk in NGC 253 (e.g., Burkhead and Burgess 1973) or the nuclear bulge of NGC 4565 (cf. de Vaucouleurs 1974*b*).

TABLE 1

JOURNAL OF OBSERVATIONS

Date	Detector System*	Visual Sky Brightness
1975 February 17–18...........	AC System and RCA 31034#1	High
1975 November 2–3, 6–7.......	Pulse Counting System and RCA 31034#1	High
1976 January 29–30............	AC System and RCA 31034#2	Normal

* The newer photomultiplier tube, RCA 31034#2, was considerably more sensitive at I than the previous tube (#1).

switched at a rate of 5 Hz for an integration period of 10 s. The telescope was then driven so that the object appeared in the alternate beam. This three-beam switching technique cancels gradients in the sky background to first order, and suppresses time fluctuations slower than the chopping frequency.

Table 1 gives a journal of observations. For the February and January runs, the photomultiplier output was processed using a lock-in amplifier which was synchronized with the chopping frequency. In this mode, only the brightness difference between the two beam positions is measured. The November data were obtained with a pulse-counting system which gave brightnesses for both the object and sky positions as well as their difference. In both cases, errors were determined from the statistics of multiple observations.

Transformations between instrumental magnitudes and BV magnitudes were obtained through observations of standards listed by Landolt (1973). Only a few standards were observed at I. Thus this transformation is poorly determined, and we have therefore designated magnitudes at this color by i. Because of problems with gain variations, the February data may contain a zero-point error of up to 0.1 mag, although the internal consistency is about 0.05 mag. November and January observations of standards were repeatable to ~0.01 mag.

III. RESULTS

Photometric measurements of IC 2233 are summarized in Table 2. In all cases the beam was chopping north-south, and reference positions were free from stars visible on the Palomar Sky Survey red prints. Figure 1 shows the positions sampled on a reproduction from the Sky Survey. The upper limits at positions 3, 4, and 5 were set by taking 3 times the standard deviation of the mean. To a level of ~1 percent of the surface brightness of the disk, no extended component was detected. Integrated magnitudes are on the system used by de Vaucouleurs and de Vaucouleurs (1964) in the *Reference Catalog of Bright Galaxies* (hereafter RCBG).

We have also attempted to measure the intensity distribution across the disk by sampling positions near the galaxy with a 28″ circular diaphragm. The resulting profile, shown in Figure 2, is in agreement with one's visual impression from both the red and blue Sky Survey prints: the edge of the disk shows an extremely steep intensity gradient. This is a common feature (at least in visual light) in many edge-on spirals as can be seen on several of the isodensity plots in Kormendy and Bahcall (1974) as well as the surface photometry by Davis (1975) and that by Freeman, Carrick, and Craft (1975).

TABLE 2

PHOTOMETRY OF IC 2233

Position	Location	Beam Throw (arcmin)	Aperture Diameter (arcsec)	B	V	i	No Filter*	μ_B	μ_V	μ_i	μ_{none}*
1........	Centered	2.3	28	15.15	14.65	14.41	−10.54 (−12.8)†	22.12	21.62	21.38	3.57 (−5.8)†
2........	30″ N along disk	2.3	28	16.52	16.04	...	...	23.49	23.01	...	...
3........	50″ SW of Position 1	4.6	53	>18.4	...	...	> −7.3	>26.8	...	...	> +1.1
4†.......	2′.1 W of Position 1	4	53	>18.9	...	>16.8	> −9.0	>27.2	...	>25.2	> −0.6
5†.......	1′.6 W of Position 1	4	53	...	...	>17.4	...	...	...	>25.8	...
6........	Sky‡	...	...	...	...	...	...	21.2	19.9	18.4	...
	Entire Galaxy (Holmberg)	...	...	13.36§	...	...	...	...	...	...	...
	Entire Galaxy (RCBG)	...	...	13.45	12.96	12.72‖	...	...	...	...	...

* Instrumental magnitude, $m = -2.5 \log$ (counts). Since an RCA 31034 photomultiplier tube was used, no filter will have an effective wavelength longward of 6000 Å for a red source.

† Observations made with lock-in amplifier system; the data at Position 5 were obtained on 1976 January 30 when the sky brightness was low.

‡ Sky brightness refer to data taken in 1975 November.

§ Magnitudes converted to RCBG $B(0)$ system following Roberts (1969).

‖ Estimated from measured $V - i$.

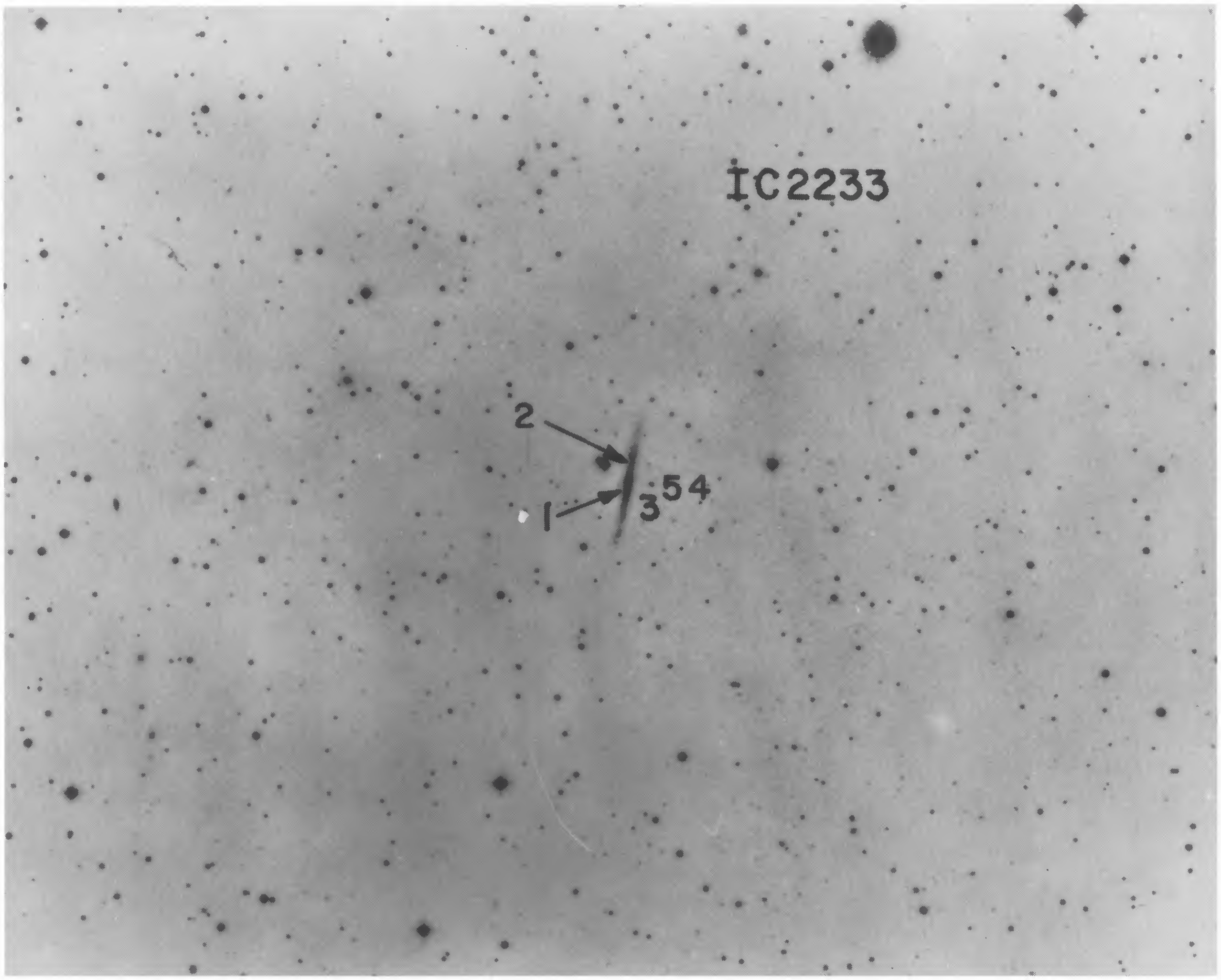

FIG. 1.—Positions sampled in IC 2233 are shown on a reproduction from the red print of the *National Geographic–Palomar Sky Survey*. The numbers refer to the observations in Table 2.

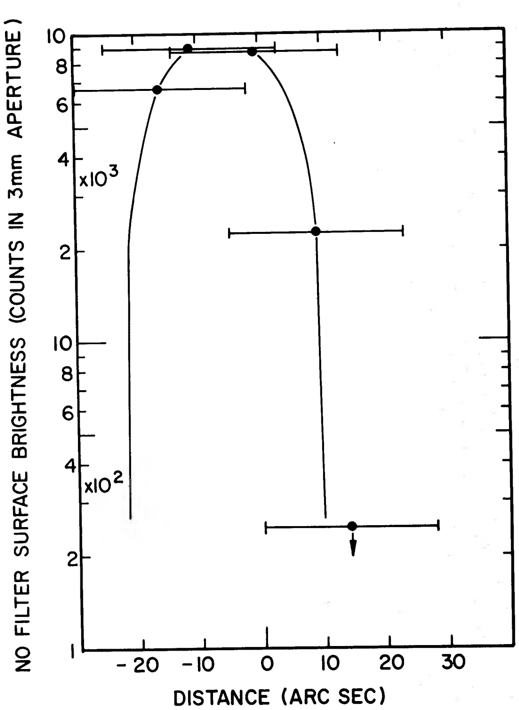

FIG. 2.—A cross section of the IC 2233 disk 35″ south of the nucleus with a 30″ circular diaphragm and no filter. The steep gradient at the edge of the galaxy is also apparent in Fig. 1. The east-west coordinates are relative to the position of the nucleus.

IV. LIMITS FOR THE HALO OF IC 2233

Following the disk stability argument, we wish to consider limits on the luminosity of a halo interior to the disk, $r_H \leq R_D$. Let $\mu(H)$ be the lower limit to the halo surface brightness in mag arcsec^{-2} as given in Table 2. The integrated magnitude $m(H)$ of the halo will then be

$$m(H) \gtrsim \mu(H) - 2.5 \log [g\pi R^2{}_D(\text{arcsec})] - f\,. \quad (1)$$

Here g is a geometrical factor depending on the concentration of the halo and f is a correction for beam cancellation which could occur if the halo were very extended.

A simple limit for $m(H)$ can be found by assuming a uniform model which has $g = 1$ and $f = 0$. Physically equation (1) would then correspond to a King (1966) model with low central concentration, large core radius, and a peak surface brightness below the detection threshold. If $\mu(H)$ is limited by beam cancellation, equation (1) then gives only an upper bound to $m(H)$. The "disk radius" of a galaxy is not a well-defined property. A photometric radius taken from the $D(0)$ given in RCBG yields $R_D = 0\rlap{.}'8$, Holmberg (1958) gives $R_D = 3\rlap{.}'5$, and an estimate from the Sky Survey $R_D = 2'$. Adopting $R_D = 2'$, Table 3 gives some limits for $m(H)$ based on the uniform model for the case of no beam cancellation.

Elliptical galaxies and the nuclear bulges of normal spiral galaxies are highly concentrated. For such

TABLE 3

UPPER LIMITS FOR HALO MAGNITUDES

Position	Color	Models (R_D = 2 arcmin) $g = 1, f = 0$	$g = 0.1, f = 0$
3.........	B	$m(H) > +15.2$	$m(H) > +17.7$
	No filter*	> -10.5	> -8.0
4.........	B	$> +15.6$	...
	i	$> +13.6$	...
	No filter*	> -12.2	...
5.........	i	$> +14.2$	...

* Instrumental magnitudes; magnitudes at these two positions differ since different amplifier systems were used in the February and November runs.

systems, King's (1966) models require a core-to-tidal-radius ratio of $r_t/r_c \approx 100$. If halos have dimensions on the order of 100 kpc (Ostriker and Peebles 1974; Turner 1976), then $r_c \approx 1$ kpc is representative for a concentrated model. Adopting $D = 7$ Mpc for IC 2233 (Fisher 1975; see below), then r_c will subtend an angle of $0\rlap{.}'5$. Reference beam cancellation will still be negligible ($f = 0$), and for position 3, $I(r) \approx I_0\, r^{-1.4} (r > r_c)$, which gives $g \approx 0.1$. The halo luminosity limit is then reduced, as is shown in Table 3.

Finally, one could assume that the halo has a core radius on the order of the disk radius. In this instance, reference-beam cancellation can become important. Such a model cannot be rigorously excluded by our data, although we consider it unlikely and note that the mean sky brightness agreed well with measurements made at other positions, and was the same in all three beam positions.

For the purposes of discussion, we adopt $B_H \gtrsim 16$ as representative of the data in Table 3. The integrated magnitude of the galaxy is $B = 13.4$ (Table 2); thus $(M/L_B)_{\text{Halo}} \gtrsim 11\ (M/L_B)_{\text{disk}}$. Physical parameters for IC 2233 can be derived from the H I observations of Fisher (1975), who finds a velocity of 560 km s^{-1} and a velocity width of 180 km s^{-1}. By using the relationship between 21 cm velocity width and absolute magnitude developed by Tully and Fisher (1975), the distance to IC 2233 is 7 Mpc. Although this distance is adopted for the purposes of discussion, the redshift allows a distance of up to 11 Mpc (for $H = 50$). For $D = 11$ Mpc all values of M/L would be increased by a factor of 1.6. The width of the 21 cm line can also be used to estimate the mass of the system, and following Roberts (1968), $M = 4 \times 10^9\ M_\odot$.

We will assume that this mass refers to both the disk and halo components; if a minimal stabilizing halo exists, $M_{\text{disk}} \approx 2 \times 10^9\ M_\odot$. Using the data in Table 2, we have scaled the position 1 measurements to estimate the total magnitude of the disk in the various filters. A similar procedure was applied to the halo upper limits by scaling with our conservative limit of $B_H > 16$. Table 4 gives a summary of basic physical parameters.

The limits in Table 4 for halo M/L can be considered quite conservative, provided the halo component is

TABLE 4

PHYSICAL PARAMETERS FOR ADOPTED HALO MODEL*

Parameter	Disk	Halo ($r \leq R_D$)
$L_B/L_\odot$..........	3.4×10^8	$< 3.1 \times 10^7$†
$L_i/L_\odot$..........	8.1×10^8	$< 2.2 \times 10^8$
$L_{opt}/L_\odot$‡........	$\sim 5 \times 10^8$	$\lesssim 7 \times 10^7$
$M/M_\odot$..........	$2\text{–}4 \times 10^9$	$> 2 \times 10^9$ (assumed)
$(M/L)_B$..........	6	$\gtrsim 70$
$(M/L)_i$..........	2.5	$\gtrsim 20$
$(M/L)_{opt}$........	~ 4	$\gtrsim 30$

* For this comparison, no corrections were made for galactic or internal extinction.

† All limits represent 3 σ as determined from the data fluctuations.

‡ Refers to measurements with no filter. These were converted to magnitudes by assuming $M_{opt} = V - 1.0$, i.e., we have basically corrected for an increase in bandpass.

somewhat concentrated ($r_c \leqslant 5$ kpc). In all instances, the mean signal at the halo position was less than 1 σ. Thus, to a lower level of confidence, all of the M/L values for the halo could be increased by a factor of 2 or 3. If the halo component were to consist of low-mass main-sequence stars, then $(M/L)_i \geqslant 20$ is a rather strict limit [e.g. for a 1/2 $M_\odot$ dwarf, $(M/L)_i \approx 5$ (Allen 1973)].

V. CONCLUSIONS

No halo component is detected for the flat, edge-on spiral IC 2233 to a level of about 1–5 percent of the central disk surface brightness at wavelengths of 4000–8000 Å. Conservative upper limits for concentrated halo models then require blue mass-to-luminosity ratios to exceed ~ 100 in solar units. This is consistent with the null results obtained in other attempts to detect halo components optically.

Since, for example, white dwarfs have $M/L > 100$ at both B and i, it is always possible to produce an optically undetectable dark halo, especially if the concentration is low. However, in view of the continued lack of direct detections of halo components and the absence of dynamical evidence for large amounts of unseen mass in individual galaxies (cf. Burbidge 1975), it must be considered increasingly improbable that *all* spiral disks are stabilized by massive halos.

We would like to thank Dr. H. Spinrad and Dr. R. Fisher for communicating unpublished observations, and Dr. E. P. Ney for several discussions about surface photometry. The pulse-counting photometer could not have been constructed without the technical assistance and advice of A. Knutson and J. Stoddart of the University of Minnesota and Dr. D. J. Taylor of the University of Nebraska-Lincoln. J. S. Gallagher thanks the University of Minnesota Graduate School for a grant supporting this research. The Mount Lemmon facility is supported in part by the National Science Foundation.

REFERENCES

Allen, C. W. 1973, *Astrophysical Quantities* (3d ed.; London: Athlone).
Burbidge, G. 1975, *Ap. J.* (*Letters*), **196**, L7.
Burkhead, M. S., and Burgess, R. D. 1973, *A.J.*, **78**, 606.
Davis, M. 1975, *A.J.*, **80**, 188.
de Vaucouleurs, G. 1974*a*, in *IAU Symposium No. 58, The Formation and Dynamics of Galaxies*, ed. J. R. Shakeshaft (Dordrecht: Reidel), p. 7.
———. 1974*b*, in *IAU Symposium No. 58, The Formation and Dynamics of Galaxies*, ed. J. R. Shakeshaft (Dordrecht: Reidel), p. 335.
de Vaucouleurs, G., and de Vaucouleurs, A. 1964, *Reference Catalog of Bright Galaxies* (Austin: The University of Texas Press) (RCBG).
Einasto, J., Kaasik, A., and Saar, E. 1974, *Nature*, **250**, 309.
Fisher, J. R. 1975, private communication.
Freeman, K. C. 1970, *Ap. J.*, **160**, 811.
Freeman, K. C., Carrick, D. W., and Craft, J. L. 1975, *Ap. J.* (*Letters*), **198**, L93.
Holmberg, E. 1958, *Medd. Lunds Astr. Obs.*, Ser. 2, No. 136.
King, I. R. 1966, *A.J.*, **71**, 64.
Kormendy, J., and Bahcall, J. N. 1974, *A.J.*, **79**, 671.
Landolt, A. U. 1973, *A.J.*, **78**, 959.
Miller, R. H. 1974, *Ap. J.*, **190**, 539.
Nordsieck, K. H. 1973, *Ap. J.*, **184**, 735.
Ostriker, J. P., and Peebles, P. J. E. 1973, *Ap. J.*, **186**, 469.
Ostriker, J. P., Peebles, P. J. E., and Yahil, A. 1974, *Ap. J.* (*Letters*), **193**, L1.
Roberts, M. S. 1968, *A.J.*, **73**, 945.
———. 1975, in *IAU Symposium No. 69, Dynamics of Stellar Systems*, ed. A. Hayli (Dordrecht: Reidel), p. 331.
Rogstad, D. H., and Shostak, G. S. 1971, *Astr. and Ap.*, **13**, 99.
Schmidt, M. 1975, *Ap. J.*, **202**, 22.
Spinrad, H. 1976, private communication.
Toomre, A. 1964, *Ap. J.*, **139**, 1217.
Tully, R. B., and Fisher, J. R. 1976, preprint.
Turner, E. L. 1976, preprint.
Weistrop, D. 1975, *A.J.*, **80**, 303.

J. S. GALLAGHER: School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455

H. S. HUDSON: University of California, Department of Physics, P.O. Box 109, La Jolla, CA 92037