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H I PROPERTIES OF DWARF IRREGULAR GALAXIES IN THE VIRGO CLUSTER

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ABSTRACT

A neutral hydrogen survey was carried out at Arecibo on 91 dwarf irregular galaxies, with morphological types Sdm through Im, in and around the direction of the Virgo Cluster. Only nine of these were found to be background galaxies, and 19 remain undetected, i.e., most of the candidate galaxies are indeed members of the Virgo Cluster or Supercluster. The distribution of positions and systemic velocities (compared with large spirals) shows no evidence for mass segregation. The H I depletion for dwarfs in the cluster core is only moderate, no more than for spirals. The magnitude–velocity width correlation is continuous from spirals to dwarfs. Statistics on H I masses agree only partially with a simple stochastic star formation model.

Subject headings: galaxies: clustering — galaxies: structure — stars: formation

I. INTRODUCTION

H I properties have been compiled for dwarf irregular galaxies of various types and at various distances (Fisher and Tully 1975; Tully *et al.* 1978; Thuan and Seitzer 1979; Huchtmeier, Seiradakis, and Materne 1981; Hunter, Gallagher, and Rautenkranz 1982; Davies and Kinman 1984). Dwarf irregular galaxies selected from the Las Campanas optical survey of the Virgo Cluster (Binggeli, Sandage, and Tarenghi 1984; Binggeli, Sandage, and Tammann 1985, hereafter BST) have the advantage of comparable distances and of morphological type assignments in a detailed classification scheme (Sandage and Binggeli 1984, hereafter SB). We report here on an Arecibo H I detection survey[1] for a selection of 91 such galaxies. The 21 cm beam used has a beam width ~ 3′; the optical diameters of the dwarf galaxies are < 2′, and most of the H I is unresolved. We determine the hydrogen flux of each detected galaxy, its systemic velocity $V_\odot$, and its velocity width ΔV.

One aim of the H I study is to "calibrate" the optical classification scheme in SB. For dwarf irregulars (unlike dwarf ellipticals), the variations of surface brightness along the sequence are only moderate, and the classification relies on morphological appearance. We determine the fraction of galaxies, classified as Virgo dwarfs, which in fact are at larger distances, $V_\odot > 4000$ km s^{-1}. We discuss implications for the "stochastic star formation model" (Gerola, Seiden, and Schulman 1980) and for the ram pressure stripping model for H I deficiencies.

II. THE OBSERVATIONS

The BST catalog covers the Virgo Cluster and part of the southern extension; it has 1852 entries. Of these, the late end of the Hubble sequence from Sdm through Sm, Im irregulars, Im/BCD, and BCD has 242 entries (13% of the total). Ninety-one galaxies in this morphological range (see SB) were chosen for this radio study.

The H I observations were made during runs in 1983 March, 1984 January, and 1984 June, using the 305 m Arecibo telescope. The procedures followed and data reductions were essentially as described in Helou, Hoffman, and Salpeter (1984, hereafter HHS). The observations covered the (heliocentric) velocity range from $V_\odot = -600$ to $+8000$ km s^{-1}. All new observations reported here have a single Arecibo beam centered at the central position of each galaxy as determined by SB. The comparison data for bright spirals are from HHS and use the total galaxy fluxes determined by mapping. The hydrogen line width ΔV is the width at 50% of peak flux, for dwarfs just as for the bright spirals in HHS. We use the *uncorrected* B_T magnitudes and blue diameters, taken from BST for dwarfs and from de Vaucouleurs and Pence (1979) for bright spirals. Galaxies with $V_\odot < 3000$ km s^{-1} and within 5° of the Virgo Cluster center (R.A. = $12^{\rm h}27^{\rm m}.6$, decl. = 12°56′) are assumed to lie at a common distance of 21.9 Mpc (Sandage and Tammann 1976, 1982). Outside 5°, we tentatively assume that galaxies with $V_\odot < 2125$ km s^{-1} lie at

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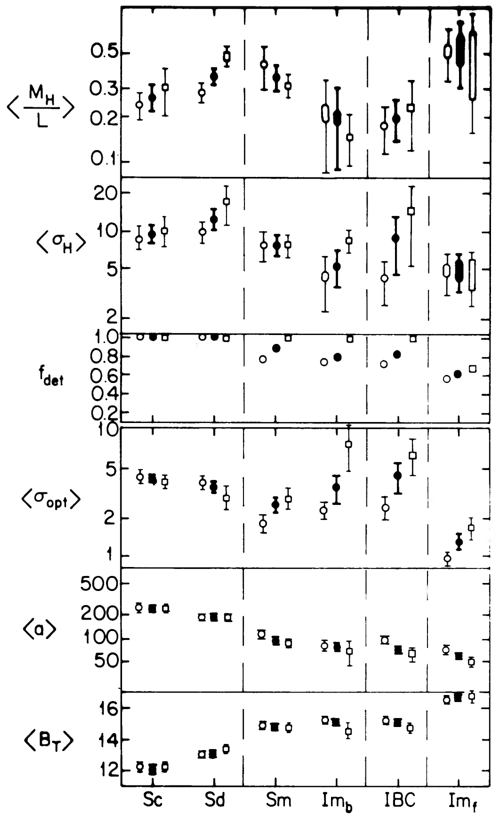

FIG. 1

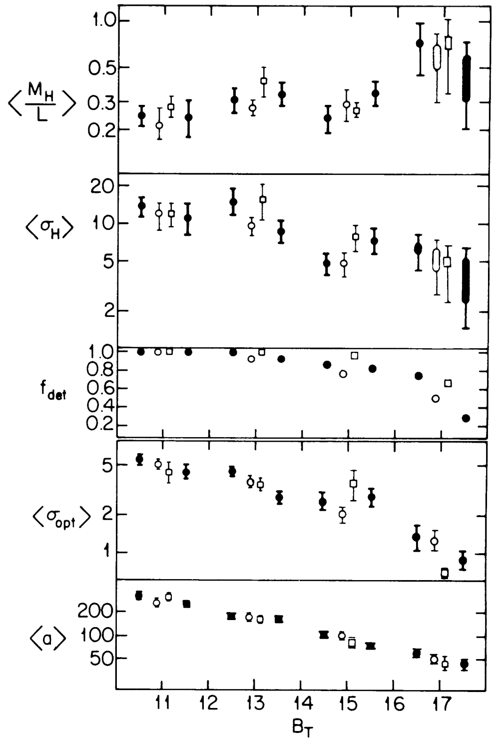

FIG. 2

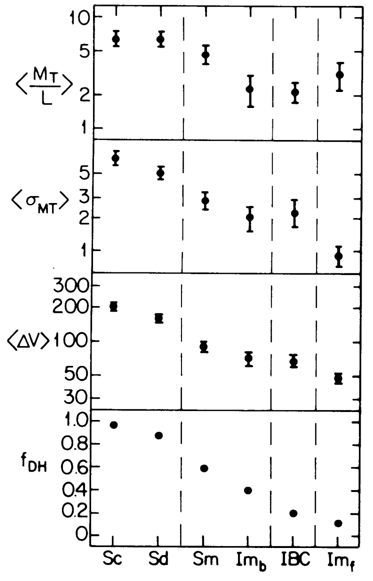

FIG. 3

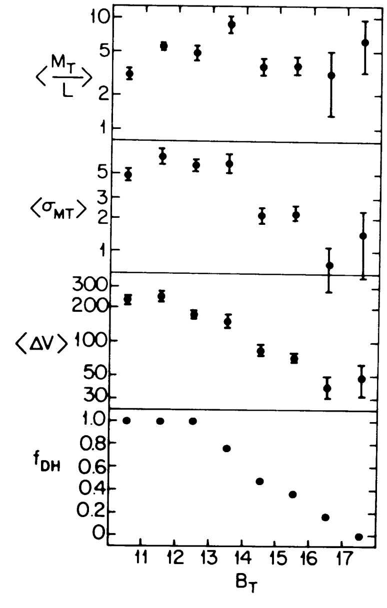

FIG. 4

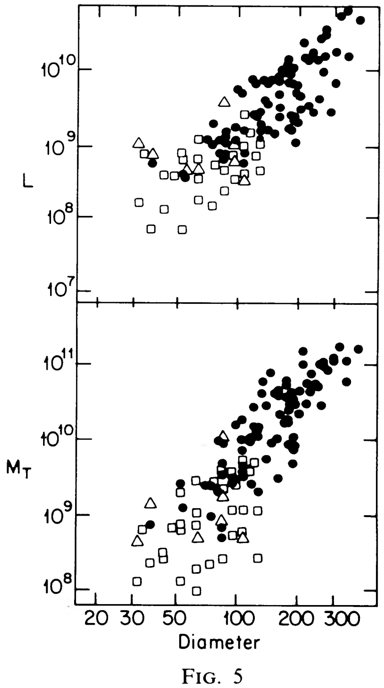

FIG. 5

the cluster distance and those with $3000 > V_\odot > 2125$ km s^{-1} lie at twice the cluster distance, i.e., at 43.8 Mpc from Earth (just inside the supercluster). This assumption affects five bright spirals but only one dwarf. Galaxies with $V_\odot > 4000$ km s^{-1} (nine dwarfs and one spiral) are considered as background and are not included in the statistics below (we detected no galaxies between 3000 and 4000 km s^{-1}).

III. H I PROPERTIES AND MORPHOLOGY

Various mean properties as a function of morphological type (after some binning) are displayed in Figure 1. The first two bins (for comparison only) contain late-type regular spirals: Sc denotes Sc I plus Sc II galaxies, Sd = Sc III plus Sd. The assignments for the four "dwarf" bins are: Sm = Sdm + Sm (21 galaxies), $\mathrm{Im_b}$ = Im II + Im III/IV (18 galaxies), $\mathrm{Im_f}$ = Im IV to Im V (30 galaxies), and IBC = BCD (blue compact dwarfs) + any dwarf containing blue compact patches (15 galaxies). If the bins $\mathrm{Im_b}$ and IBC are omitted, the remaining bins (including the late-type spirals) form an uncontroversial one-dimensional sequence with mean optical major diameter a and optical surface brightness $\sigma_{\mathrm{opt}} = 4L/\pi ab$ decreasing monotonically from left to right and optical (blue) magnitude B_T increasing monotonically. As discussed by SB, the IBC galaxies do *not* fit into any one-dimensional sequence: Their position in Figure 1 was assigned according to their mean major diameter a, but both σ_{opt} and B_T are brighter than interpolation along the a-sequence would suggest (the empirical situation is intermediate for the "bright irregulars," $\mathrm{Im_b}$). The equivalent statistics are plotted against B_T in Figure 2.

Of the 91 dwarf galaxies in our list we detected 63 in the velocity range appropriate to the Virgo Supercluster ($V_\odot <$ 3000 km s^{-1}) and only nine at large redshifts ($V_\odot > 4000$ km s^{-1}). Omitting these nine galaxies, the fraction f_{det} of galaxies detected in our H I survey with $V_\odot < 3000$ km s^{-1}, plotted in Figures 1 and 2, is quite large except for the faintest bin ($\mathrm{Im_f}$). Only 19 of the dwarfs remain undetected, and many of these are likely to be hydrogen-poor members of the Virgo Supercluster (see the IN–OUT comparison below). We thus have one gratifying conclusion: Relatively few of the galaxies classified as Virgo Cluster dwarfs are misclassified bright galaxies in the distant background; the morphological separation works!

Two different measures of the hydrogen mass M_{H} per galaxy are displayed in Figures 1 and 2: the mean mass-to-light ratio $\langle M_{\mathrm{H}}/L \rangle$, where L is the blue luminosity corresponding to B_T, and a "mixed surface density of hydrogen mass" $\sigma_{\mathrm{H}} = 4M_{\mathrm{H}}/\pi ab$, where a and b are the *optical* major and minor diameters. Undetected galaxies are *included* in the averages. Omitting the bins $\mathrm{Im_b}$ and IBC at the moment, we see that $\langle M_{\mathrm{H}}/L \rangle$ *increases* and σ_{H} *decreases* slightly from Sm to $\mathrm{Im_f}$ in Figure 1. For IBC galaxies $\langle M_{\mathrm{H}}/L \rangle$ is relatively small, presumably because the bright patches increase L. The value of σ_{H} for IBC galaxies may be slightly *larger* than interpolation between Sm and $\mathrm{Im_f}$ would predict, but the discrepancy is not yet statistically significant. In Figure 2 we find a nonmonotonic pattern, but an average trend for $\langle M_{\mathrm{H}}/L \rangle$ to increase and σ_{H} to decrease slightly with increasing B_T.

For each detected galaxy we measure the velocity width ΔV and assign the spectrum to either "double-horned" (DH, similar to integral spectra for edge-on spirals) or "Gaussian." The mean values for ΔV and f_{DH}, the fraction of spectra assigned as DH, are plotted against morphological type in Figure 3 and against magnitude in Figure 4 (averages here refer to detected Virgo galaxies only). We define an "apparent inclination angle" i by the standard Hubble-Holmberg formula, $\cos^2 i = [(b/a)^2 - 0.04]/0.96$ and assume an inclination-corrected ΔV_0 (in units of km s^{-1}) of the form

$$\Delta V_0^2 = \Delta V_{\mathrm{obs}}^2 + \left(\Delta V_{\mathrm{obs}}^2 - 25^2\right)\left(\mathrm{cosec}^2 i_> - 1\right), \qquad (1)$$

where $i_>$ is the larger of i and a constant i_c. The quantity 25 (km s^{-1}), slightly smaller than the smallest ΔV_{obs}, includes the contribution from random motions. Although we do not expect a thin rotating disk, we found *empirically* that the variance about the mean $\log \Delta V_0$–B_T relation is a minimum for $\sin i_c = 0.4$. We define a "total indicative gravitational mass" M_T for each detected galaxy by the relation $M_T = \Delta V_0^2 a/8\,G$, where a is the optical diameter. We plot the mean ratio of total indicative mass to luminosity, $\langle M_T/L \rangle$, and the equivalent surface density $\sigma_{MT} = 4M_T/\pi ab$ against morphological type in Figure 3 and against B_T in Figure 4. Figure 5 gives scatter diagrams of optical diameter a versus M_T and L.

IV. EFFECTS OF ENVIRONMENT AND MASS SEGREGATION

A simple overall test of the effect of the Virgo Cluster environment on gaseous galactic disks is to compare galaxies within 5° of the cluster center with galaxies outside this circle.

FIG. 1.—Mean optical and H I properties vs. morphological type. The binning is described in § III. The units are: for B_T, magnitudes; for major diameter a, arc seconds; for optical surface brightness σ_{opt}, $10^7\ L_\odot$ kpc^{-2}; for H I surface brightness σ_{H}, 10^{-4} Jy km s^{-1} arcsec^{-2}; for H I mass-to-light ratio M_{H}/L, $M_\odot/L_\odot$. f_{det} is the fraction of galaxies detected in each bin. The elongated symbols stretch from the mean value adopting the *full* upper limit for H I flux for undetected galaxies, to the mean adopting zero flux for those objects. Solid symbols represent means for the total sample; the open circle to the left represents the mean for IN galaxies only; the open square to the right represents the mean for OUT galaxies alone.

FIG. 2.—Mean optical and H I properties vs. blue magnitude B_T in bins 1 mag wide. Symbols and units are as for Fig. 1, except that IN and OUT means are displayed only for 2 mag wide bins.

FIG. 3.—Properties derived from the H I profile shape and width vs. morphological type for detected galaxies only. f_{DH} is the fraction exhibiting double-horned profiles. The observed line width at 50% of peak flux, ΔV, is in units of km s^{-1}; indicative mass surface density σ_{MT} in units of 10^5 $M_\odot$ arcsec^{-2}; and the indicative mass-to-light ratio M_T/L in solar units.

FIG. 4.—Same as Fig. 3, but displayed vs. B_T in 1 mag wide bins

FIG. 5.—Scatter diagrams of luminosity L and indicative mass M_T (solar units) vs. diameter in arc seconds. Closed circles represent Sc through Sm; open squares, $\mathrm{IM_b}$ and $\mathrm{Im_f}$; and open triangles, IBC.

This IN–OUT comparison, for each of our four dwarf morphological bins, is given in Figure 1 for the detection probability $f_{\rm det}$, the mean values $\sigma_{\rm H}$, $M_{\rm H}/L$, a, and $\sigma_{\rm opt}$ (with equivalent comparisons in Fig. 2). For the dwarf irregulars $f_{\rm det}$ is larger for the OUT galaxies than the IN galaxies for each morphological and each magnitude bin (also suggesting that most of the undetected galaxies are cluster members). The resultant $\langle \sigma_{\rm H} \rangle$ is also larger OUT than IN by varying factors $F_{\sigma {\rm H}}$, with the average $F_{\sigma {\rm H}}$ over all dwarf types about 2.4. This excess is statistically significant but not particularly large. Unexpectedly, $\sigma_{\rm opt}$ is also larger OUT than IN for the dwarfs (but *not* for regular spirals), so that $\langle M_{\rm H}/L \rangle$ is *not* appreciably different IN versus OUT.

For considerations of mass segregation, we compare the kinematic properties of dwarf galaxies with bright (and presumably massive) spirals: Here we restrict "dwarfs" to $B_T \geq 14.00$, and define "bright spirals" to be types Sb through Scd, restricted to $B_T < 12.50$. The numbers of "dwarfs"/"bright spirals," including undetected galaxies, are 50/21 for the IN group and 29/10 for the OUT group. The corresponding velocity dispersions are 728 km s^{-1}/785 km s^{-1} (IN) and 563 km s^{-1}/409 km s^{-1} (OUT), excluding $V_\odot > 2125$ km s^{-1}. Our data show *no* significant difference between dwarfs and spirals in the distribution of positions nor of $V_\odot$.

V. DISCUSSION

The simplest model for the various SB morphological types postulates a *one-dimensional* sequence all the way from giant Sc galaxies (Sc I) to "true" faint dwarf irregulars (Im V), with a tight correlation between optical major diameter a, corrected velocity width ΔV_0, and the total mass M_T of a galaxy, but large variations in luminosity L because of the stochastic star formation. The mean relations in Figure 5 are indeed continuous over a wide range of parameters: The simplest "single power-law" fit to our data in Figure 5 (all the way from Sc I to Im V), $M_T \propto a^\gamma$, gives $\gamma = 2.9 \pm 0.4$; the equivalent power-law fit for luminosity is $L \propto a^\delta$ with $\delta = 2.0 \pm 0.1$. Although M_T/L correlates little with magnitude (our Fig. 4 and Davies and Kinman 1984), it seems to decrease slightly with decreasing diameter a ($M_T/L \propto a^{0.9 \pm 0.4}$). The observed variance of $\log L$ about its mean relation is fairly large as expected, but the variance of $\log M_T$ is even larger (measuring errors or intrinsic?)!

The mean variations of hydrogen properties are weak and complex: Both $\sigma_{\rm H}$ and $M_{\rm H}/L$ increase from Sc to Sd, and from $B_T = 11$ to $B_T \approx 13$ or 14; omitting $B_T = 14$ to 16 (or Im$_{\rm b}$ to IBC), $\sigma_{\rm H}$ decreases slightly and $M_{\rm H}/L$ increases slightly toward the right in Figures 1 and 2 (the minima in $M_{\rm H}/L$ for IBC and for $B_T \approx 14.5$ mainly reflect the luminosity increase due to the bright compact patches). Both positive and negative effects have been predicted for the correlation between the star formation rate and the hydrogen density. It is perhaps physically significant for the dwarfs that the small increase of $\sigma_{\rm H}$ for the optically bright IBC is statistically quite insignificant!

For regular spirals of given type both the "mixed" hydrogen surface density $\sigma_{\rm H}$ and the hydrogen diameters are smaller inside the Virgo Cluster core (circle of radius 5°) than outside (Haynes, Giovanelli, and Chincarini 1984), as expected for ram pressure stripping. Dwarfs have smaller escape velocities, and one expects ram pressure stripping to be even more important. For our dwarf sample $\sigma_{\rm H}$ is indeed smaller inside the core than outside, qualitatively as expected, but quantitatively we have a big puzzle: The effect of position on $\sigma_{\rm H}$ is not very large, and the optical surface brightness $\sigma_{\rm opt}$ unexpectedly shows a similar effect! As a consequence the observed effect of position on $M_{\rm H}/L$ is comparable for dwarfs and spirals, unlike the simplest predictions. A possible explanation might be a clumpy intergalactic medium, which makes ram pressure stripping "all or nothing," independent of escape velocity.

Finally, some observational evidence *against* mass segregation in the Virgo Cluster: If most of the invisible mass required for the cluster core were associated with individual giant galaxies, dwarf galaxies should have a small tendency for larger distances from the center and, at a given distance, for larger dispersions of systemic velocities (Farouki, Hoffman, and Salpeter 1983). The observed dispersions are not significantly larger for dwarfs than for giants, and the spatial distributions are similar. If the invisible mass is distributed in smaller chunks, mass segregation is not expected.

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