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DWARF SPIRALS

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ABSTRACT

We report the discovery of a new class of galaxies, dwarf spirals, that serve as a morphological extension to the Hubble sequence for dwarf galaxies. Although they have a similar morphology to their giant counterparts, the dwarf spirals (dS) are characterized by faint total luminosities ($M_B > -17$), small diameters ($R_{26} < 5$ kpc), low central surface brightnesses ($\mu_0 > 24$ B mag arcsec^{-2}), and low H I masses ($\mathscr{M}_{\rm H\,I} \leqslant 10^9\ \mathscr{M}_\odot$). Most of these dwarf spirals have flocculent or multiple arm spiral patterns, but some have smooth disks, similar in appearance to a dwarf S0's, yet are rich in neutral gas. The combination of small angular size and low surface brightness explains why this class of galaxies was missed in previous cluster catalogs and field surveys. Since cluster catalogs are complete to much fainter surface brightness and smaller angular limits than most galaxy catalogs, yet contain no dS galaxies, we conclude that dwarf spirals are only found in the field. © *1995 American Astronomical Society.*

1. INTRODUCTION

The basic framework for our understanding of the global properties of galaxies is the Hubble sequence, the classification of galaxies into specific morphological types that correlate with some of their integrated physical properties. In fact, the division of galaxies into two primary types (elliptical and spiral) predates our understanding that galaxies themselves were individual units beyond our own galaxy. In 1920's, parallel to his efforts to investigate the distance to galaxies, Hubble developed a set of standard criteria of galaxy morphology (Hubble 1926). The late 1950's saw many refinements and enhancements to the Hubble sequence (Morgan 1959; de Vaucouleurs 1959; van den Bergh 1960). However, by the 1960's, Sandage, in preparing the Hubble Atlas (Sandage 1961), refined the parameters of the Hubble morphological sequence with specific criteria classification and examples of each class into the form we use today. Central to that classification is that there are three main types of galaxies: ellipticals, disks (So's and spirals), and irregulars. Orthogonal to the morphological classes are the luminosity classes ranging from supergiant and giant (I and II) to subgiant and dwarf (IV and V, van den Bergh 1960). In the last decade, as outlined in a series of papers by Sandage, Binggeli, and Tammann (Sandage & Binggeli 1984; Binggeli *et al.* 1985; Sandage *et al.* 1985), the Hubble sequence was extended from giant galaxies to dwarf galaxies based on high-resolution DuPont photographic plates of the Virgo cluster. It was noted in those papers that all morphological classes of galaxies in the current form of the Hubble sequence are represented in the Virgo cluster.

However, the extension of the Hubble sequence from giants to dwarfs was incomplete in that no dwarf spirals with Hubble classes between Sa to Sc were ever discovered [see Fig. 1 of Sandage & Binggeli (1984) and discussion therein]. There were several examples of small Sm types or Im types (for example, see the DDO catalog, van den Bergh 1960), but no evidence for dwarf galaxies that display either a coherent spiral pattern or a distinct bulge and disk structure was ever found. Sandage *et al.* (1985), in an analysis of the luminosity function of spirals in the Virgo cluster, continued this line of argument and demonstrated that no spiral galaxies exist in the Virgo cluster with $M_V < -17$ (we assume $H_0 = 85$ km s^{-1} Mpc^{-1} and a distance to the Virgo cluster of 15 Mpc throughout this paper).

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In this paper we report the discovery of this missing link in the Hubble sequence for dwarf galaxies, dwarf spirals (dS). We present six examples of field dwarf spirals of varying morphological types with radii less than 5 kpc and $M_V > -17$. Their central surface brightnesses are sufficiently low to cause them to have been missed in previous surveys of the field, but not so low that they would have been missed in cluster surveys.

2. OBSERVATIONS

The sample used herein to search for dwarf spirals was selected from a much larger search for dwarf galaxies reported in Schombert *et al.* (1995). That project's goal is to map the large scale structure of dwarf galaxies, of all morphological types, as a test of biased galaxy formation (White *et al.* 1988). A total of 136 dwarf galaxies were discovered from a visual inspection of the Second Palomar Sky Survey J plates (Reid *et al.* 1991). The plates are A or B grade, selected for good surface brightness depth and covering declination zones of the sky that can be observed with the 305 m Arecibo radio telescope. Due to the limited declination range of the Arecibo facility, and the incomplete status of the Second Sky Survey, only 36 fields were examined. All the visual inspection was accomplished by one of us (JMS) and coordinates of each candidate dwarf were taken directly from the plate material.

We observed the dS candidates in our list at 21 cm with the Arecibo 305 m telescope during the 1992 and 1993 observing season. All observations were made with the 21 cm dual-circular feed positioned to provide a maximum gain (8 K Jy^{-1}) at 1400 MHz. The 2048 channel autocorrelator was used and the independent, opposite polarized signals were each divided into two subcorrelators of 512 channels. In order to search a larger velocity space, the secondary local oscillators of each polarization set of subcorrelators were offset on either side of the standard local oscillator frequency of 260 MHz by 8.75 MHz, allowing a total velocity coverage of 8000 km s^{-1}, a velocity resolution of 8.6 km s^{-1}, and some overlap at the band edges. The observations were centered on 4000 km s^{-1}, which avoided detection of the strong galactic hydrogen signal on the low-velocity end, and extended to 8120 km s^{-1}. Observations were made in the total power mode with 5 min on-source and off-source observations. In most cases, only one 5 min on-source integration was required for detection. Wherever possible, the zenith angle was kept less than 14 deg to minimize the degradation of the gain.

Successful detections were later selected for follow-up CCD imaging on the Hiltner 2.4 m telescope located at Michigan–Dartmouth–M.I.T. (MDW) Observatory. We obtained images using either a Thomson 400×576 pixel CCD (0.25 arcsec $pixel^{-1}$) or a Ford–Loral 2048×2048 pixel CCD binned 3×3 (0.51 arcsec $pixel^{-1}$), with exposure times of 25 min or more in both Johnson V and I filters. Details of the optical observations and analysis will be presented in an upcoming paper (Pildis *et al.* 1995).

TABLE 1. Dwarf spirals.

Object	v_0 (km/s)	M_V	R (kpc)	B/D	$V-I$	$\log \mathcal{M}_{\mathrm{H\,I}}$ ($\mathcal{M}_\odot$)	W_{50} (km/s)
D563-4	3384	−17.0	5.1	0.56	0.82	9.35	120
D564-15	3262	−16.5	3.3	0.17	0.78	9.67	148
D577-5	4087	−16.9	4.4	0.44	0.56	9.01	110
D631-8	4340	−16.0	3.0	0.35	0.73	8.80	139
D721-5	5795	−16.9	4.5	0.58	0.50	9.09	110
D774-1	4793	−16.0	5.5	0.42	0.59	9.35	178

3. DISCUSSION

3.1 Properties of Dwarf Spirals

Our claim that a new class of dwarf galaxies exists is based on a combination of their morphological, optical, H I, and kinematic properties. First, all the objects selected as candidate dwarf spirals (dS) have distinct bulge and disk components, both visually and in their surface brightness profiles. While many dwarf irregulars have central concentrations of luminosity, the dS's listed herein have circular bulges similar to those in giant spirals and S0's. These bulges differ slightly from the bulges in giant spirals by being small in size and low in central surface brightness, but they all are red in color, suggesting an old, metal-rich population, and are centrally located. The bulge to disk ratios (B/D) for the sample are found in Table I and range from 0.17 to 0.58. This range is between type Sa's and Sb's in the analysis of B/D ratios by Solanes *et al.* (1989), so these dwarf spirals are distinct from Sd or Sm type systems based on the dominance of their bulges.

Many of the dS candidates also display flocculent or multiple-arm spiral patterns of a design that would certainly have classed them between Sa and Sc solely on their appearance regardless of the presence of a bulge (see Sec. *3.3*). Of the 136 galaxies in our ongoing dwarf survey, we found 6 objects which have a disk and bulge morphology and are solid candidates for classification as dwarf spirals. These candidates and their characteristics are listed in Table I, where column 1 displays the object name, column 2 contains the helocentric velocity in km/s, column 3 contains the V absolute magnitude, column 4 contains the isophotal radius at 26 B mag $arcsec^{-2}$, column 5 contains the bulge to disk ratio based on surface brightness profile fits, column 6 contains the integrated $V-I$ color, column 7 contains the H I mass in $\mathcal{M}_\odot$, and column 8 contains the H I profile width at 1/2 peak in km/s. Figure 1 displays V band CCD frames for two objects. All these galaxies are also available for inspection on the World Wide Web (http://www.astro.lsa.umich.edu/ users/ pildis/ www/ dwarf/ dwarf.html). In terms of appearance, the dS's fall into two types: ones with discernable spiral patterns (4 objects) and ones with extremely low surface brightness (LSB), featureless disks (2 objects).

Second, the optical luminosities and diameters of the dS candidates are much smaller than those of normal disk galaxies. Their typical R_{26} isophotal radii are less than 5 kpc and their total optical luminosities are less than $M_V = -17$. These low optical magnitudes imply that these objects are

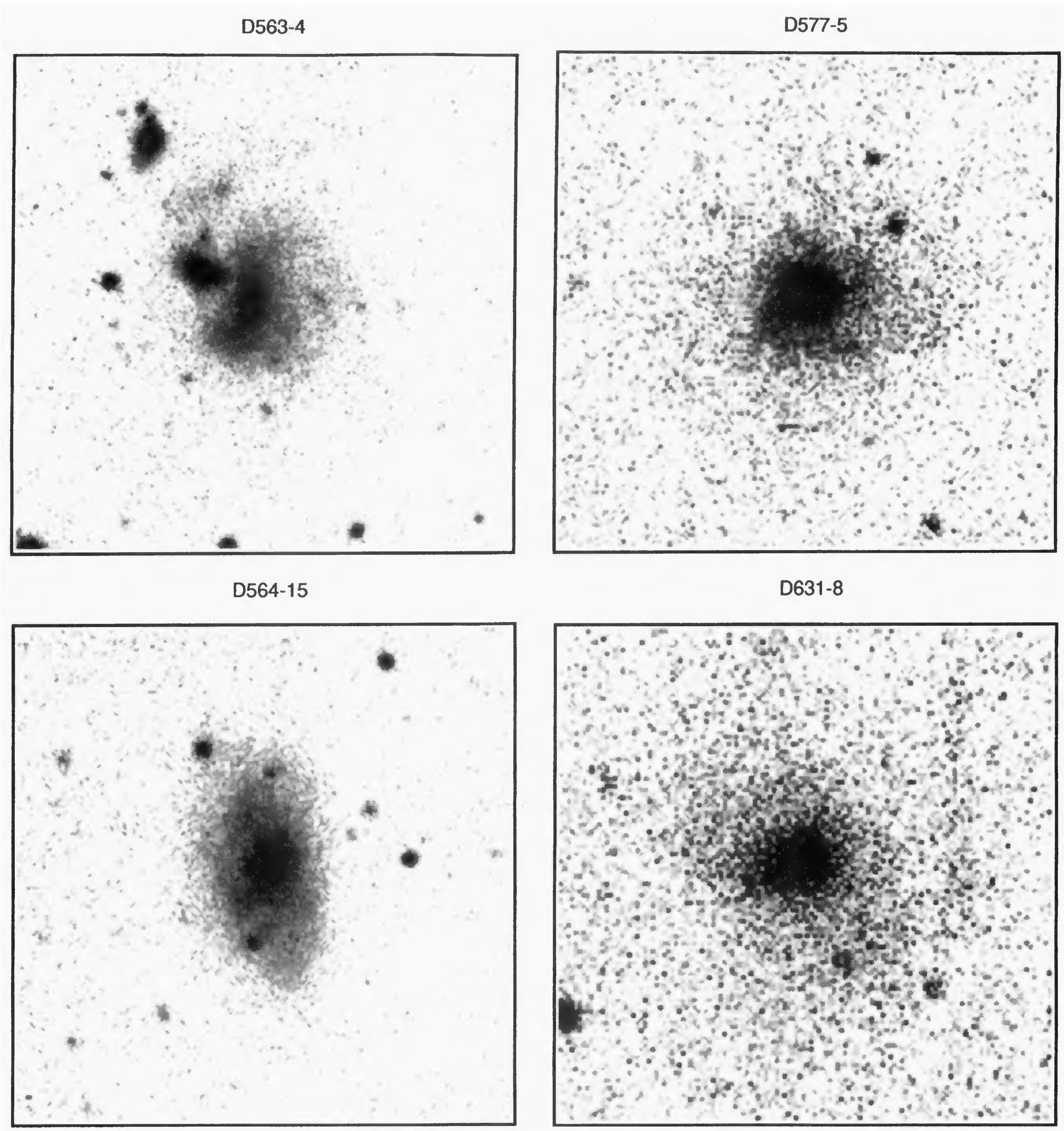

FIG. 1. All six dwarf spiral galaxies are shown. The data are 1200 s V frames taken with the 2.4 m Hiltner telescope of MDM Observatory.

dwarfs based on the criteria used by Sandage *et al.* (1985) in their studies of the galaxy population of the Virgo cluster. With respect to diameter, a search of the UGC catalog (Nilson 1973) finds less than 10 galaxies classed as Sa to Sc with radii less that 6 kpc out of over 3100 spirals in the northern sky (the mean spiral diameter is 24 kpc in the UGC). A similar result is found using the diameter of Virgo cluster spirals from Binggeli *et al.* (1985). Figure 2 displays a comparison of the distribution of UGC diameters based on blue plate material, Virgo cluster spirals and these dS galaxies. The most similar galaxy to our dwarf spirals from previous galaxy catalogs is DDO 122 (van den Bergh 1960), which has an isophotal radius of 5.0 kpc and $M_V=-17.5$. It has a classic two-armed spiral pattern with a weak bulge component, but has many of the same characteristics as our low surface brightness dwarf spirals.

Third, the dS candidates have solid H I detections, indicating a substantial neutral gas content which, aside from morphology, distinguishes them from dwarf S0's discovered by Sandage & Binggeli (1984) in the Virgo cluster. Figure 3 displays the H I profiles and also demonstrates that all of the candidate dS galaxies have double-horned profiles indicative of a rotating disk. This rotation, combined with distinct structural bulge and disk components, is the most compelling evidence for a link between these dwarf spirals and their giant cousins. These new dwarf galaxies are unlike the ir-

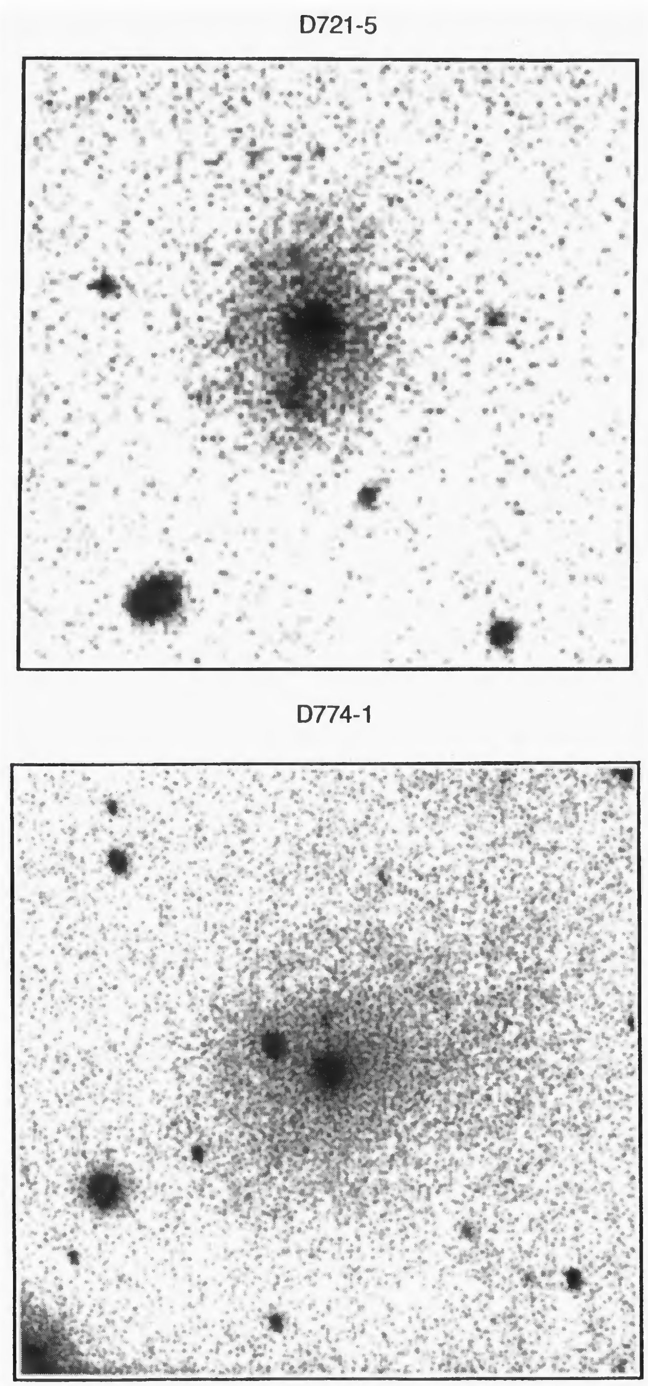

FIG. 1. (continued)

regularly shaped Im and dI class galaxies in that they clearly have a rotationally supported shape. The Sm class galaxies are thought to be disk shaped, rotating galaxies, but they have no evidence of a bulge or central mass concentration as found in these dwarf spirals.

The dS galaxies found in this survey have one common characteristic that explains their lack of detection in other galaxy catalogs: central surface brightnesses below 22 I mag arcsec^{-2}, which corresponds to approximately 23 to 24 B mag arcsec^{-2}. This value is significantly lower in surface brightness than previous, magnitude-limited surveys (see Disney & Phillipps 1983). The UGC, an angular limited catalog, contains several objects within this surface brightness range (Schombert & Bothun 1988) but, since its angular limit is only 1 arcmin, dwarfs of less than 10 kpc in diameter are not found in the UGC beyond 3000 km/s. In the velocity range 1000 to 3000 km s^{-1} there are 700 of the 3100 spirals with known redshifts. Since this is 23% of the sample, it is unlikely that dwarf spirals are undetected in the UGC due to small number statistics. It is more reasonable to assume that their LSB nature makes classification difficult or detection limited.

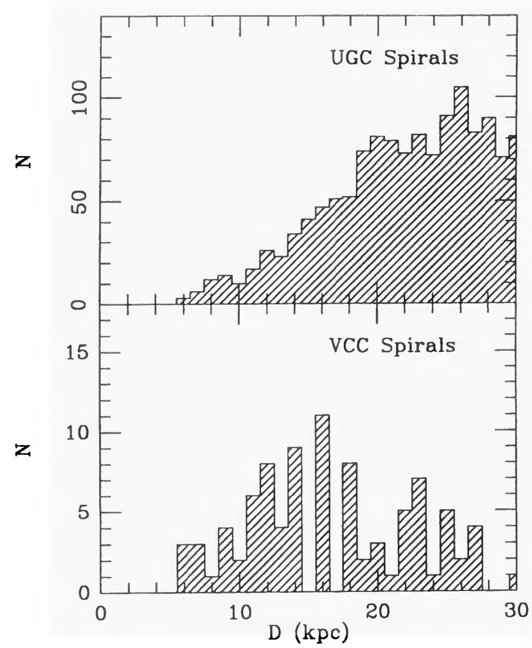

FIG. 2. The distribution of optical diameters in kpc are shown for all spirals (class Sa to Sc) in the UGC with H I detections (3100 galaxies). An H_0 of 85 and a local infall model are used to calculate true distance. The mean value for all spirals is 24 kpc. The bottom figure shows the distribution of spiral diameters from the Virgo Cluster catalogs (Binggeli *et al.* 1985). The dS galaxies in this sample lie between 4 and 9 kpc in diameter.

3.2 Environment

It is highly unlikely that dwarf spirals comprise a major fraction of the total number of dwarf galaxies since they are only a very small fraction of this ongoing dwarf survey. Only 6 candidate dwarf spirals were discovered from the 136 dwarfs found in our survey. Figure 4 shows a redshift map of our current dwarf galaxy survey with the dS galaxies marked (note that the dwarfs trace the same large scale structure as high mass galaxies, in conflict with the predictions from biased galaxy formation theory, see Schombert *et al.* 1995). Of the 34 plates searched (850 sq deg), dS's have an apparent density of 0.011/sq deg vs a density of 0.24/sq deg for giant spirals from the UGC catalog. However, it must be remembered that our survey is not complete in terms of magnitude limits or isophotal diameters. Future digital sky surveys will address the completeness and number counts questions better than our purely visual search.

The central surface brightnesses of dS's are sufficiently low (μ_0<24 B mag arcsec^{-2}) to cause them to have been missed in previous surveys of the field, particularly catalogs such as the UGC which are based on old photographic technology. However, their surface brightnesses are not so low that they would have been missed in cluster surveys, such as

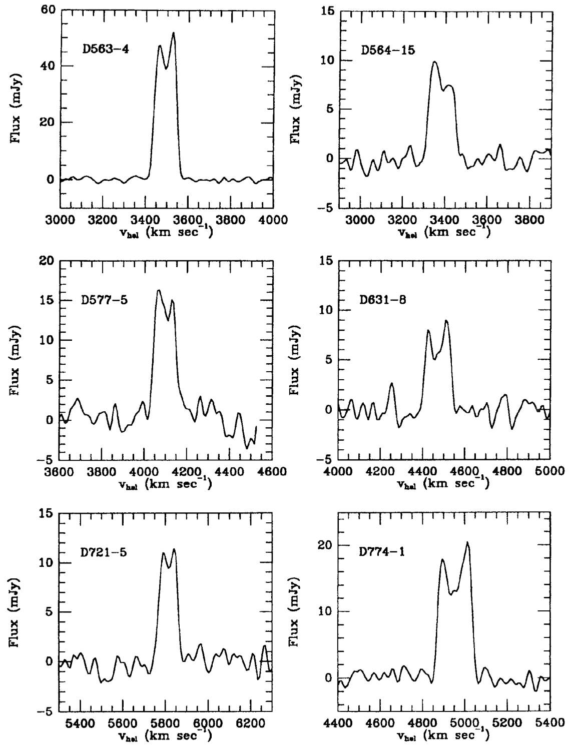

FIG. 3. H I line profiles for all six dS galaxies are shown. Note the double horned shape of each profile that confirms a rotationally supported disk.

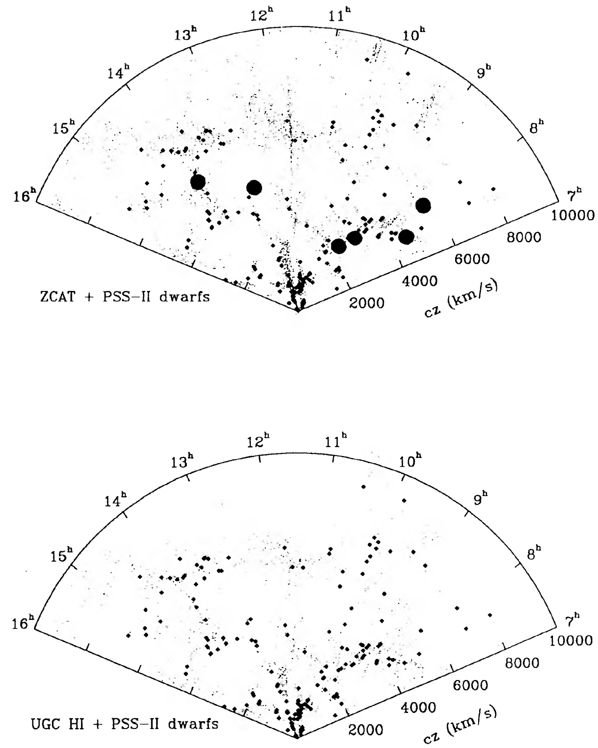

FIG. 4. A redshift cone diagram of our dwarf survey. Normal dwarfs (classes Im, dI, and Sm are marked as solid diamonds, dS's are marked as large circles, CfA survey high mass galaxies are marked as dots). Note how the distribution of dwarfs closely matches the distribution of massive galaxies from the CfA survey, opposite to the predictions of biased galaxy formation.

the DuPont Virgo cluster catalog (Binggeli *et al.* 1985). The Virgo cluster survey revealed galaxies with mean surface brightness well below 26 B mag arcsec^{-2} and would not have missed any of the examples of dwarf spirals found in our survey. Sandage *et al.* (1985) specifically note the lack of dwarf spirals in their survey and, thus, we conclude that dwarf spirals are not found in a rich cluster environment.

If the underabundance of dwarf spirals is real then there are two possible explanations for their rarity, particularly in cluster environments: (1) small disks are extremely fragile and any interaction, or close encounter, would reduce a dwarf spiral into a dwarf irregular (or strip the disk completely to produce a dwarf elliptical from the remaining bulge), or (2) some dwarf disk galaxies have extremely low disk surface densities, rendering the disk invisible (i.e., extremely low rates of past star formation). The second scenario is compelling since it is certainly possible to have many galaxies with detectable bulges, but small, very faint disks, and these objects would only be detected by blind H I surveys. Our dwarf candidates D631-8 and D774-1 are of this nature, for if their disks were slightly lower in surface brightness, they would appear as gas-rich ellipticals. This line of reasoning would argue the merit of an H I survey of the ellipticals from a magnitude limited catalog such as the CGCG. This type of survey would, in effect, be searching for bulges of extremely LSB disks which were mistakenly classified as ellipticals on plate material. However, as noted above, previous cluster surveys would have detected our dwarf spirals and we conclude that a cluster environment inhibits the formation of dwarf spirals, or proves hostile to their survival. This supports the idea that low surface brightness disks not only have low luminosity densities, but low mass densities as well to make them more suspectable to tidal disruption.

3.3 *Spiral Patterns*

Most of the dwarf spirals found in our survey have discernible spiral patterns of either flocculent or multiple arm designs. No grand design patterns were found in our dS's, although the pattern in D563-4 is the closest in the sample to a classic two-armed, symmetric pattern. We note that D563-4 has an apparent companion within the Holmberg radius of the disk which may be tidally inducing the spiral pattern; however, it is unconfirmed by redshift to be physically associated with the primary, and its shape and mean surface brightness would indicate it is a background object. In general, the spiral patterns, as in D564-15 or D577-5, resemble the arm classes 2 or 3 from the Elmegreen and Elmegreen scheme (Elmegreen & Elmegreen 1987). These classes are distinguished by fragmented arms distributed around a low luminosity bulge. However, we note that these disks have central surface brightnesses sufficiently low that exact classification is often subjective and the spiral patterns are more suggestive than precisely defined by bright regions of star formation.

Given that this is a survey targeted at low surface brightness objects, it is not surprising to find a lack of grand design spirals. Typically, grand design spirals are associated with high star formation rates which, in turn, produce very high surface brightness disks. There are no known LSB grand designs in current galaxy catalogs, although there is certainly a range of disk luminosities per spiral type as demonstrated by the various spiral luminosity classes (see the Revised Shapley–Ames Catalog, Sandage & Tammann 1981). Uniformly, LSB disk galaxies have late-type galaxy classes with small bulges and flocculent disks (Schombert & Bothun 1988; McGaugh 1992). The Malin class of giant LSB spirals (Impey & Bothun 1989; Schombert *et al.* 1992), in contrast, have a disk that contains disconnected pieces of a spiral pattern, unlike either grand design or flocculent counterparts. A lack of grand design patterns implies that the star formation in dS's is of local origin rather than driven by some global mechanism, such as a swing amplifier or tidal interactions. This would be in agreement with the current interpretation of star formation in LSB galaxies Schombert *et al.* 1992; McGaugh 1992).

The spiral pattern observed in dS's reflect star formation events and are unlikely to be material waves since the surface densities of these disk are extremely low and the disk colors are quite blue. Blue colors imply a young population, whereas one would expect material waves to be dominated by an old, red stellar population (see Sec. *3.4*). This would imply that the patterns visible in some of the dS's disks are due to some quasistationary driver such as stochastic self-propagating star formation (Seiden & Gerola 1982). The rate of star formation in typical LSB disks is currently low and has been extremely low in the past (SFR$<0.1\ \mathscr{M}_\odot\,\mathrm{yr}^{-1}$, McGaugh 1992); however, even a small enhancement of star formation is noticeable in contrast above the general low surface brightness of the disk. This is confirmed by the fact that several dS candidates, such as D564-15 and D774-1, have spiral patterns which are relatively strong in the V filter, but practically invisible in the I band frames. This behavior has been noted before in giant spirals (Elmegreen & Elmegreen 1984) and indicates that the luminous component that makes up the spiral pattern is composed primarily of young, blue stars. Thus, we conclude that these very weak spiral patterns are caused by very low star formation rates and can only be detected since the old disk population is even lower in surface density, making the contrast between the young and old components high. Since the I band is relatively free of light from H II regions or young massive stars, the lack of spiral patterns in the far red confirms the previous suspicion that the patterns are not density waves.

There is no expectation that a spiral pattern, even a chaotic one, be present in a dwarf galaxy. On the other hand, there is no physical reason to prohibit small disks from being a site for spiral pattern formation, only that a disk implies a sufficiently cold stellar disk (low perpendicular velocity dispersion). Even a small heating of the disk by recent encounters would destroy the disk/bulge appearance, in agreement with our observation that dwarf spirals exist only in isolation. Theoretically, simply reducing the size of a galaxy does not necessarily reduce the spiral pattern by the same scaling. This is evident in dwarf irregulars, which are composed of star forming regions of similar size to those in giant spirals, but not organized into any coherent pattern (Bothun 1986; Hunter *et al.* 1982). On the other hand, the typical spiral pattern, especially in flocculent objects such as these dS's, is tracing star formation through the relatively high surface brightness H II regions. There is no particular theoretical boundary to limit the scale size of the star forming regions, which becomes the typical size of the spiral pattern elements, nor is there a theoretical reason to believe that the size of the spiral pattern is in any manner related to the size of the galaxy. For example, local gravitational instability is determined by the mean gas surface density and, since there is evidence that LSB disks have lower H I surface densities (McGaugh 1992), this reduction in surface density could reflect in smaller star formation regions. This, in turn, could produce a smaller spiral pattern as is evidenced by the dS's. Therefore, dwarf spiral patterns would only occur in galaxies with low gas surface densities which, in turn, produce low star formation rates and low surface brightnesses for the underlying stellar population, which are the same characteristics of our sample.

A comparison of spiral patterns for dwarfs and giants could provide insight into the star formation history of LSB galaxies since, if the spiral pattern is statistically in a steady state, then the individual star formation regions must be quite young to be still recognizable as distinct units. Therefore, the difference in mean surface brightness from the giant spirals to dwarf spirals reflects a real difference in the style of star formation in terms of the properties of the star formation regions. In particular, the optical properties of these dwarf spirals, and other LSB galaxies, indicates that the masses of the star formation regions, rather than age, is responsible for their low intrinsic surface brightnesses (see McGaugh 1992). If the individual features of the spiral pattern are due to star formation from local gravitational instability, then the differences between dwarf and giants are differences in the masses of these local regions and, therefore, the number of stars found in each individual star-forming complex (assuming that the IMF is similar). This supports the hypothesis that LSB disk galaxies have real deficiencies in the mass densities of stars (and perhaps dark matter) rather than concluding that their surface brightness characteristics are due to differences in stellar populations (e.g., a faded, old population).

3.4 Disk Structure

One of the clearest indications that these objects are disk galaxies is the distinct separation of their surface brightness profiles into bulge and disk components. Figure 5 displays both the I band surface photometry and the color profiles in $V-I$ for D563-4 and D774-1. In general, the disk scale lengths for this sample are between 1.0 and 2.5 kpc as compared to 5 kpc for normal spirals. The bulge to disk ratios, listed in Table 1, are normal for Sa to Sb type spirals (Solanes *et al.* 1989), and clearly separates them from the dwarf Sm class or even the small Sd class spirals. Note also that the disk colors are quite blue, with the typical $V-I$ colors between 0.5 and 0.7. This is a common feature to LSB galaxies, in that their colors are not of an old, faded population (i.e, red), but that of a young, star forming population.

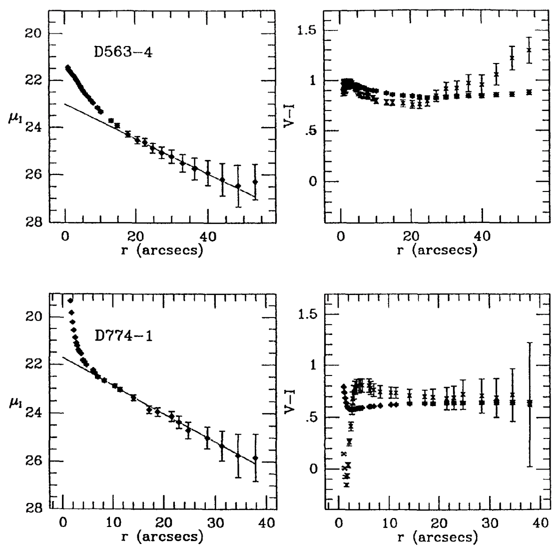

FIG. 5. Surface photometry in the I band and the $V-I$ color profiles for D563-4 and D774-1 are displayed. Dashed lines are exponential fits to the outer disks. Solid symbols are integrated colors, crosses are differential colors.

However, a young population should be rich in massive stars and, therefore, high in surface brightness, which is in contradiction with the observed surface brightnesses. The most reasonable explanation for this behavior is to invoke an evolutionary scenario where the visible population is relatively young with no underlying old population to dilute the colors. This implies that the visible population is the first epoch of star formation, though one that formed in a very low density environment, and that these types of galaxies are ones with extremely quiescent star formation histories in general. This does not necessarily indicate that the galaxies are not of recent origin, for they may have had gravitational identities originating in the normal galaxy formation epoch of $z>8$ but with a first epoch of star formation in very recent times (see McGaugh 1992). The dS objects selected here have similar characteristics with other LSB disk galaxies and are assumed to be an continuation of that particular sequence of galaxies types.

While the detected spiral patterns of the dS's in this study are typically low in surface brightness and flocculent in style, D631-8 and D721-5 have no discernible spiral patterns in our deep CCD frames. They do have distinct bulge and disk components and are included in our discussion since they have a disk galaxy morphology. These objects could also be classified as dwarf S0's, since there is no discernible features in their disks. However, this classification would be in conflict with the large amount of H I detected in these galaxies and their B/D ratios that are consistent with later type spirals. Several examples of dwarf S0's are found in the Virgo cluster (Sandage & Binggeli 1984), but most are edge-on systems with redshift uncertainties. The best example is IC 783, a face-on galaxy with a smooth disk similar to D631-8 and D721-5, but of much higher surface brightness then the objects typical for our sample. It does not appear that dS's can evolve into cluster dwarf S0's due to the differences in their surface brightnesses. The lack of a spiral pattern may be due to insufficient S/N in our CCD frames. No pattern is discerned in our deepest frames; however, with central surface brightnesses below 22 I mag arcsec^{-2}, it becomes a moot point to resolve a pattern contrast that involves such a small amount of the disk material. For all practical definitions in terms of mass or luminosity, the disks are smooth and featureless. We note that the colors of these featureless disks are same as other LSB galaxies, meaning disk colors that are not red as with an old population ($V-I=1.5$), but typically with the colors of a young to intermediate population ($V-I=0.5$).

It is unclear how much of the physical meaning of the Hubble sequence for giant galaxies carries over into the dwarf sequence. For example, there is a strong relation between spiral structure and the global properties of a giant disk galaxy in that the properties of the spiral arms (e.g., pitch angle) are correlated with the bulge to disk ratio and fractional H I content (Sandage 1961). This implies that the presence of a dominant bulge affects—either directly or indirectly—the spiral pattern, such that large-bulge galaxies have more orderly spiral patterns (e.g., Sa type galaxies). There are insufficient numbers of dwarf spirals to draw any conclusions to their global properties. However, the Toomre stability criterion, and the fact that weak spiral patterns are seen in such small galaxies with very low surface, densities, implies that dwarf disks must be much colder than giant spirals (i.e., the radial velocity dispersion is significantly lower than our own galaxy). No direct measurements of the radial velocity dispersions of LSB galaxies have been made to date.

No bar structures are present in this small sample of dwarf spirals, with the possible exception of D563-4, which has an elongated bulge. One difficulty in identifying bars is that the central bulges of the dwarf spirals are much lower in luminosity density then their giant counterparts. It is unclear from the isophotes what constitutes a bar shaped structure or just a random elongation due to low contrast. The lack of strong bars could indicate that dwarf spirals have halos that are massive relative to their low density disks, in order to prevent instability which leads to bar formation. In addition, small stable disks, such as these dwarfs, are a challenge to dark matter theory since a disk of less than 2 kpc scale length will require only a very small radial velocity dispersion to become unstable. Therefore, a very cold population is required to stabilize the disk, yet a hotter disk could explain the lack of star formation despite a large neutral gas supply. A hotter disk would lower the cross section of molecular cloud collisions which, in turn, would lower the massive star formation rate. A fuller understanding of the kinematic properties of dwarf spirals would lead to insights to disk stability and the star formation history of LSB galaxies.

4. CONCLUSIONS

This paper presents evidence for a new class of dwarf galaxies with spiral and/or disk features. Aside from spiral patterns and rotation, dwarf spirals are characterized by low central surface brightnesses and small sizes. It is interesting to note that in the last decade both the largest spirals (Malin

1, Impey & Bothun 1989) and the smallest (this paper) were discovered during searches in the realm of LSB objects. Both the largest and the smallest spirals have definite characteristics (luminosity, mean surface brightness, spiral pattern style) which separate them from normal spirals, but their similarities as a structural class suggest a continuum between the types. We note that the discovery of these new galaxies was the serendipitous result of a small, visual survey for dwarf galaxies. But a visual search is inherently plagued with selection effects and no attempt is made in our survey to reach a specific limiting magnitude or isophotal threshold. The goal of our primary project did not require any particular limits since its only purpose was to locate large numbers of undiscovered dwarfs as chosen by morphology (i.e., the candidates appeared to be dwarf-like in the velocity range of 1000 to 10 000 km/s) to serve as test particles in mapping large scale structure.

Of the three main parameters to a galaxy's structure (total luminosity, scale length, and characteristic surface brightness), the surface brightness values are the physical parameters least quantified in galaxy catalogs. Most catalogs present apparent isophotal diameters and rough magnitudes, but measurement of an accurate surface brightness requires 2D imaging. Previous photometric catalogs (e.g., RC2, de Vaucouleurs *et al.* 1976) used aperture photometry from which an apparent magnitude is measured, an isophotal diameter is interpolated from a curve of growth, and then a mean surface brightness is derived from an aperture magnitude divided by aperture area. Although this is a total measure of a galaxy's mean surface density, it is highly inaccurate if the galaxy is composed of multiple components, such as a bright bulge and a faint disk. Due to this limitation in our galaxy catalogs with respect to actual measured surface brightness values, it is impossible to estimate the impact of surface brightness limits on the nature of such catalogs. Preliminary studies in this area (Disney & Phillipps 1983; McGaugh 1993) have demonstrated that assumed conclusions with respect to the surface brightness values of galaxies, such as the Freeman hypothesis that spiral galaxies all have the same central surface brightness (approximately $\mu_B=21.75$ B mag arcsec^{-2}), are mostly inaccurate and based on a strong biasing in our galaxy catalogs to list objects with central surface brightness greater than the typical night sky value. It is also very difficult to estimate the impact of sky brightness biasing on our understanding of the range of galaxy forms or if there are significant numbers and types of galaxies yet to be discovered, such as these dwarf spirals.

One unplanned outcome to future digital sky surveys will be increased quantification to morphological classification. With full 2D imaging formation it will be possible to directly link physical parameters, such as surface brightness and isophotal diameters, to morphological details. Digital surveys with their vastly increased S/N and greater dynamic range will also broaden the scope of galaxy classification, bringing new emphasis to the fainter LSB features in the halos and cores of galaxies. Given the discovery of many new types of galaxies with very low surface brightnesses (i.e., these dwarf spirals and their Malin cousins), exploring the nature of galaxies from space platforms, which are free not only of the distortions and absorption of the atmosphere but also its natural brightness, will no doubt mean significant changes in our present assumptions about the range of galaxy structure and form.

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