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BLUE COMPACT DWARF GALAXIES IN THE VIRGO CLUSTER: H I AND *IRAS* DATA AND UPPER LIMITS ON PROTO–DWARF GALAXIES

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ABSTRACT

Blue compact dwarf (BCD) galaxies in the Virgo Cluster Catalog (VCC) are studied, using existing optical data, our H I observations (both previously published and new), and co-added *IRAS* data. In addition, we establish upper limits on the number of optically invisible H I clouds within the VCC survey area. We find that our BCDs lie mainly in two clumps: a low heliocentric velocity clump within the central core, which is most likely the same physical association as that formed by the low-velocity spirals that are thought to be falling through the cluster core from behind, and a diffuse cloud centered on the W group, behind and to the south of the cluster core. Our BCDs tend to have rather large H I profile widths; at constant width, the BCDs are comparable to other dwarf irregular galaxies in blue luminosity and H I flux, but the BCDs are significantly smaller (by a factor of 2 or 3) in optical diameter. We suggest that luminosity in a BCD is redistributed rather than increased from that of an Im galaxy of similar size or mass.

About one-third of the BCDs were detected at 60 or 100 μm by *IRAS* after co-addition, mostly at intensities just above the threshold sensitivity. This is a larger detection rate than for other dwarf galaxies at a comparable distance. The correlations of far-infrared (FIR) luminosity against optical and H I properties suggest that the FIR luminosity of BCDs is dominated by emission from the star formation regions, and that their interstellar medium is deficient in dust only by a modest factor of 2 or 3 compared with normal spiral galaxies. We do not find any significant number of H I clouds in the VCC area without accompanying optical emission. This absence of proto–dwarf galaxies, coupled with the presence of significant dust in observed BCDs, argues that most, if not all, of the Virgo BCDs must have experienced star formation prior to the current burst.

Subject headings: galaxies: interstellar matter — infrared: sources — radio sources: 21 cm radiation — stars: formation

I. INTRODUCTION

Dwarf irregular galaxies (morphological types Sm and Im) have long been considered to be laboratories of the star formation process (see reviews by Gallagher and Hunter 1984; Hunter and Gallagher 1986; and references therein). Evidence cited for high star formation rates in irregular galaxies includes their blue color, proportionately large H I content, chaotic appearance due to large H II regions, and lack of a dominant Population II component. While some of the largest of these galaxies show rotation curves not unlike those of spiral galaxies (Hoffman, Salpeter, and Helou 1986; Tully *et al.* 1978; Huchtmeier, Seiradakis, and Materne 1980; Krumm and Burstein 1984; Comte, Lequeux, and Viallefond 1985; Skillman, Terlevich, and van Woerden 1985; Briggs 1986; Skillman and Bothun 1986; Bottema, Shostak, and van der Kruit 1986; Hummel, Dettmar, and Wielebinski 1986; Skillman *et al.* 1987), at the extreme low-mass end of their distribution the irregulars show little rotation, and their dynamics are dominated by turbulent motions (Sargent, Sancisi, and Lo 1983; Sargent and Lo 1985; Brinks and Klein 1985; Morras and Bajaja 1986). A plausible theory of the structure and evolution of dwarf irregular galaxies is the stochastic self-propagating star formation (SSPSF) scenario of Gerola and Seiden (1978). This model (and earlier work by Searle, Sargent, and Bagnuolo 1973) suggests that dwarf irregulars should evolve in a bursting mode, with short-lived episodes of intense star formation activity alternating with quiescent periods of longer duration for smaller galaxy size (Gerola, Seiden, and Schulman 1980; Comins 1984).

The existence of the blue compact dwarf (BCD) morphological class finds a natural explanation in the SSPSF scenario. BCDs, as defined on a purely morphological basis by Sandage and Binggeli (1984, hereafter SB), are modeled after the "isolated H II regions" of Zwicky (1966), Markarian (1967), Sargent (1970), Sargent and Searle (1970), and Huchra (1977*a*, *b*). Thuan and Martin (1981) defined "blue compact dwarf galaxies" to be galaxies that appear almost stellar on the Palomar Sky Survey, comprising single H II regions with an enveloping galaxy of exceedingly low surface brightness (or none at all). SB have extended this definition to include objects comprising several such H II knots in a common low surface brightness envelope. In the SSPSF scenario, these would be the dwarf galaxies that are currently undergoing an intense star formation episode. (In what follows we will refer to this somewhat loosely as a "BCD episode.") On the quantitative side, however, there are severe puzzles on the relation between BCDs and the lower surface brightness classes of dwarf irregulars. We summarize these puzzles, and some other questions and controversies, as follows:

1. While we shall concentrate on the "pure" BCD galaxy type in the Binggeli, Sandage, and Tammann (1985, hereafter BST) scheme, it is not clear to what extent this corresponds to the "extreme" i0 type of Loose and Thuan (1985, hereafter LT), which shows no evidence for a more extended enveloping disk of older stars. One question we shall address statistically is whether the single optical diameter *a* measured by BST corresponds to the underlying whole galaxy or only to a smaller region currently undergoing a concerted burst of star formation. A related question asks whether the BCD phenomenon represents a large increase in the total optical luminosity L_B of the galaxy or merely a "redistribution." We shall address these questions by way of averages of the ratios of L_B to neutral hydrogen mass M_H and of L_B to the "indicative" total gravitational mass M_T.

2. Apart from purely stochastic events, are bursts of star formation in gas-rich dwarfs particularly sensitive to the galaxy's environment? Because the Virgo Cluster has both an overall density gradient and appreciable subclustering, we can ask two separate questions: Is the ratio of BCDs to other dwarf irregulars (*a*) positively or negatively correlated with the galaxy number density or (*b*) strongly varying from one subgroup to another? Question *b* is related to a generalization of a suggestion by Silk, Wyse, and Shields (1987, hereafter SWS) for galaxies in a group or "cloud" of groups: Can some dynamic or hydrodynamic event, triggered throughout a whole region by collapse or interactions, ignite bursts of star formation in many galaxies simultaneously? Since galaxy groups in general are forming at about the present epoch, and there is evidence (Tully and Shaya 1984) that some clouds are falling into the Virgo Cluster at the present, we may be living in a "specially preferred epoch" as SWS suggest.

3. A number of related questions concern the duration of a BCD episode, the average number N_b of BCD episodes in the Hubble time, and the "typical" value of the average abundance $\bar{Z}$ of heavy elements in a present-day BCD. Kunth and Sargent (1986) have pointed out that the measured values Z_m (about 1/3 to 1/30 of solar) refer only to the ionized gas around stars which are close to the element-producing regions, so that $\bar{Z} \ll Z_m$ if we are indeed witnessing a first-generation burst ($N_b = 1$). Theoretically, the main question is whether N_b is small and $\bar{Z} \ll 0.3\ Z_\odot$ for *most* BCDs, or whether there is a wide spread in the distributions of N_b and $\bar{Z}$. Observationally we can ask two related questions: (*a*) Is the ratio of far-infrared emission L_{FIR}, obtained from *IRAS* data, to the optical luminosity L_B particularly small for BCDs—as it would be for $\bar{Z} \ll 0.3\ Z_\odot$? (*b*) Are there many H I–rich, but optically invisible, proto–dwarf galaxies in the Virgo Cluster? If $N_b = 1$ were common, one would expect an appreciable number of similar gas clouds with $N_b = 0$ and therefore very low optical luminosity.

We have obtained Arecibo[1] H I data for all BCDs listed in the Virgo Cluster Catalog of BST. These data allow us to estimate the reservoir of gas available for star formation and to determine dynamical properties of the individual galaxies, and (along with new Palomar redshifts from Schulte-Ladbeck and Cardelli 1988 and Helou and Schombert 1989) to identify which BCD candidates are genuinely Virgo objects according to their redshifts, and which are background. The redshifts also allow us to sort out how BCDs fit into the overall structure and dynamics of the Virgo Cluster. This sample of objects in Virgo, most presumably at a common distance, complements the all-sky survey of Thuan and Martin (1981). In § II we review the optical properties of BCDs both in and outside Virgo. In § III we discuss the spatial and velocity distribution of Virgo BCDs, and in § IV we analyze the H I and dynamical properties deduced from our observations.

In § V we discuss *IRAS* observations of the Virgo BCDs in comparison with a sample of bright spirals in Virgo and an all-sky sample of dwarf irregulars (Helou 1985). Various correlations of IR, H I, and optical properties are presented. We can also set quite stringent upper limits on the number density of H I clouds in Virgo that have not yet suffered their first burst of star formation, using the many OFF-beams and signal-free portions of ON-beams that we have accumulated in our ongoing studies of the spiral and dwarf galaxies in the area. These upper limits are determined in § VI.

We conclude in § VII with an assessment of the implications of these results for the SSPSF and other galaxy formation scenarios, and some speculations on how some of the puzzles raised here might be resolved, and in § VIII with a summary.

II. REVIEW OF OPTICAL PROPERTIES OF BLUE COMPACT DWARFS

In Paper I (Hoffman, Helou, and Salpeter 1988) we reviewed the properties of irregular and dwarf irregular galaxies, excluding BCDs. We binned together a number of types on the SB classification scheme into three categories: Sdm and Sm into "Sm"; ImIII, ImIII–IV, ImIV (and the brighter half of all other Im galaxies for which no luminosity class was given) into ImBr, and the lower surface brightness Im galaxies, including ImIV–V and ImV, into ImFt. An overall summary of many of the properties (modified from Paper I) is given in Figure 1.

BCDs, in the SB classification scheme, are distinguished optically by their high surface brightness, in contrast to dwarfs of type Sm or Im. The prototypes of the class are the "extragalactic H II regions" of Sargent and Searle (1970). In the SB scheme the class is extended to include objects comprising "a few bright knots ... frequently embedded in an envelope of low surface brightness. The knots resemble large H II regions (30 Doradus type)." When the knots lie within a galaxy extended enough and resolved enough to be otherwise classified Sm or Im, SB have given the galaxy a composite type S... /BCD or Im.../BCD. We consider these separately in this section but will omit them in the rest of this paper. Objects classified as "... or BCD" or "BCD or merger" by BST will be binned together with pure BCDs and will hereafter be referred to simply as BCD.

Gallagher and Hunter (1986, hereafter GH) have obtained *UBV* colors for a subsample of the Virgo dwarf irregulars, including some BCDs. Although the subsample is not statistically complete, it was not preselected for any known factor affecting color and represents a significant fraction of all dwarf irregulars in the BST survey area. Table 1 gives mean $U-B$ and $B-V$ colors, standard deviations σ, and standard deviations in the mean σ_m for the 34 Sm and Im, 12 S... /BCD and

[1] The Arecibo Observatory is part of the National Astronomy and Ionosphere Center, which is operated by Cornell University under a management agreement with the National Science Foundation.

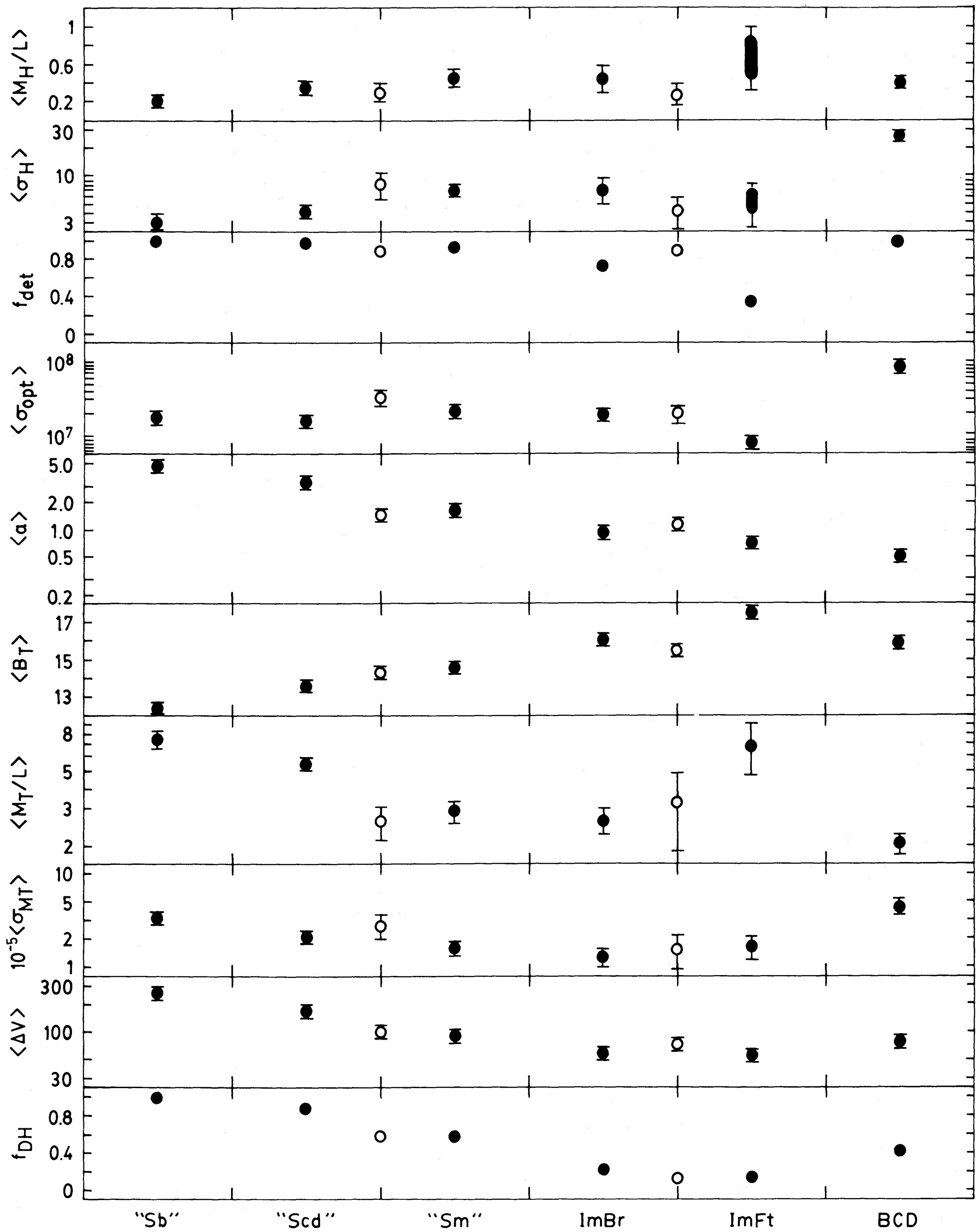


FIG. 1.—Mean optical, H I, and dynamical properties as a function of morphological type. See text (§ II) for explanations of the various quantities. The open circles adjacent to "Scd" and "ImBr" represent "S . . . /BCD" and "Im . . . /BCD" types, respectively. The oblong symbols for properties related to H I mass (*top two panels*) extend from the mean value with undetected galaxies counted as the full upper limit to the mean assuming zero flux for nondetections. Galaxies known (from H I or optical redshifts) to lie in the background are excluded. The units employed are, for ΔV, km s^{-1}; for $\sigma_{\rm MT}$, $M_\odot$ kpc^{-2}: for M_T/L, solar units; for a, arcmin; for $\sigma_{\rm opt}$, $L_\odot$ kpc^{-2}; for $\sigma_{\rm H}$, 10^{-4} Jy km s^{-1} arcsec^{-2}; for $M_{\rm H}/L$, solar units.

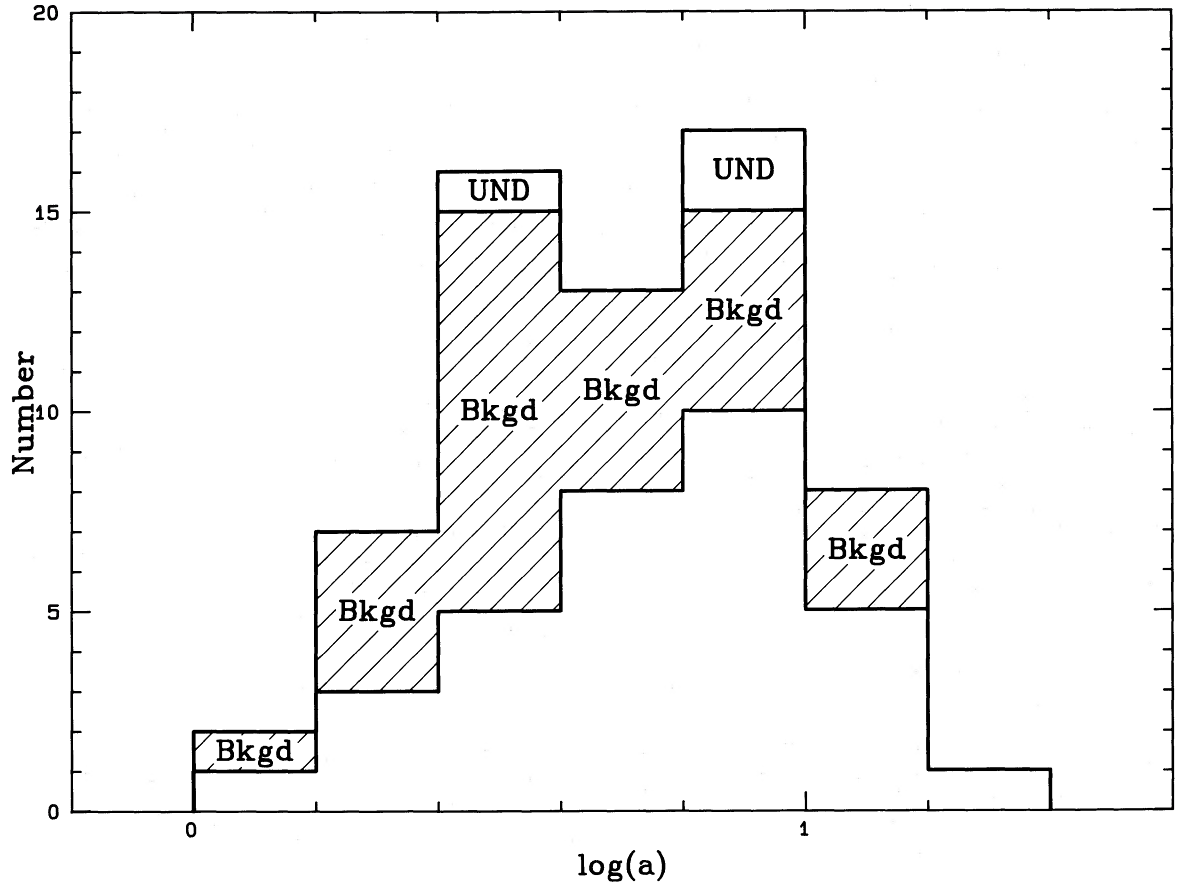


FIG. 2a

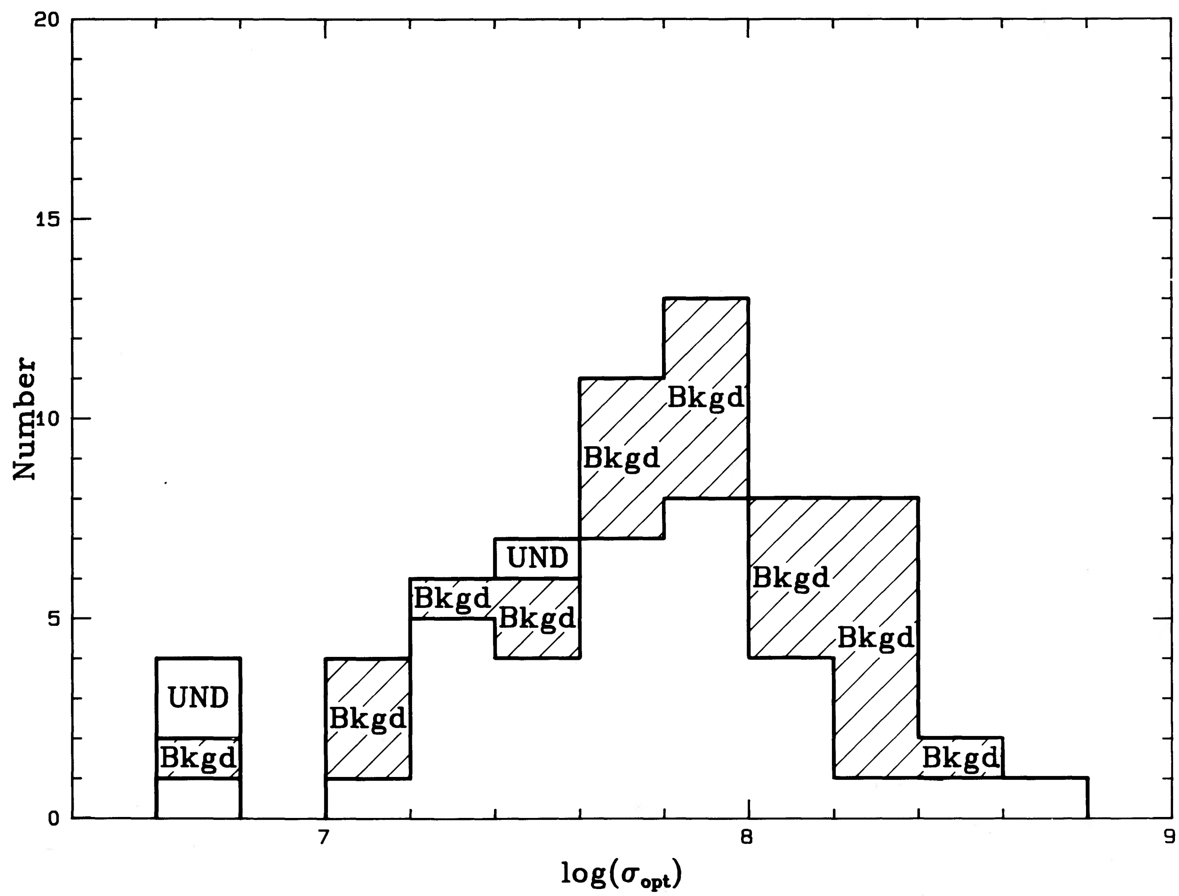


FIG. 2b

FIG. 2.—Histograms for comparison of Virgo BCDs, background BCDs (*labeled Bkgd and hatched*), and undetected BCDs (*UND*). (*a*) Optical diameter, in units of 0.′1. (*b*) Optical surface brightness, in units of $L_{\odot}$ kpc^{-2}.

TABLE 1

UBV COLORS FROM GALLAGHER AND HUNTER 1986

Type	Number	⟨B−V⟩ Magnitude	σ	σ_m	⟨U−B⟩ Magnitude	σ	σ_m
Sm, Im	34	0.49	0.17	0.03	−0.08	0.20	0.03
S, Im . . . /BCD	12	0.53	0.16	0.05	−0.09	0.16	0.05
BCD	11	0.46	0.10	0.03	−0.32	0.26	0.08

Im.../BCD, and 11 "pure" BCDs in the GH sample. Although the bluest of the BCDs and the reddest irregulars would stand out, $B-V$ in Table 1 is essentially the same for all three classes. For the S, Im.../BCD types, $U-B$ is quite similar to that for S, Im, but the "pure" BCDs are considerably bluer in $U-B$. This difference is due mainly to four very blue BCDs (BST 0144, BST 0428, BST 0802, and BST 1313), which are not otherwise distinguished.

Figure 1 shows that, in most mean properties, S . . . /BCD is similar to "Sm," and Im.../BCD is similar to ImBr. This includes the diameter a (as defined by BST and discussed in Paper I) and the apparent blue magnitude B_T, with mean surface brightness at most marginally higher for each "mixed" category than for the corresponding type without the /BCD qualifier. From here on we omit all S.../BCD and Im.../BCD entirely. For the remaining BCDs the mean diameter a in Figure 1 is appreciably smaller than for any other type, the mean B_T is comparable to that for the ImBr category, and so the mean surface brightness $\sigma_{\rm opt}$ is larger by a factor of 3 than for any other type (including true spirals). The important question of diameters and surface brightness for BCDs is illustrated further in Figure 2, which gives the distributions for these two quantities, and in Figure 3, which plots luminosity ($\propto -0.4\ B_T$) against diameter.

LT, working from CCD images, have subdivided the BCD class into four types depending on the regularity of the high surface brightness region and of the low surface brightness enveloping galaxy. The vast majority of the CCD images obtained by LT show a low surface brightness outer halo of either elliptical or irregular shape; however, LT find a few

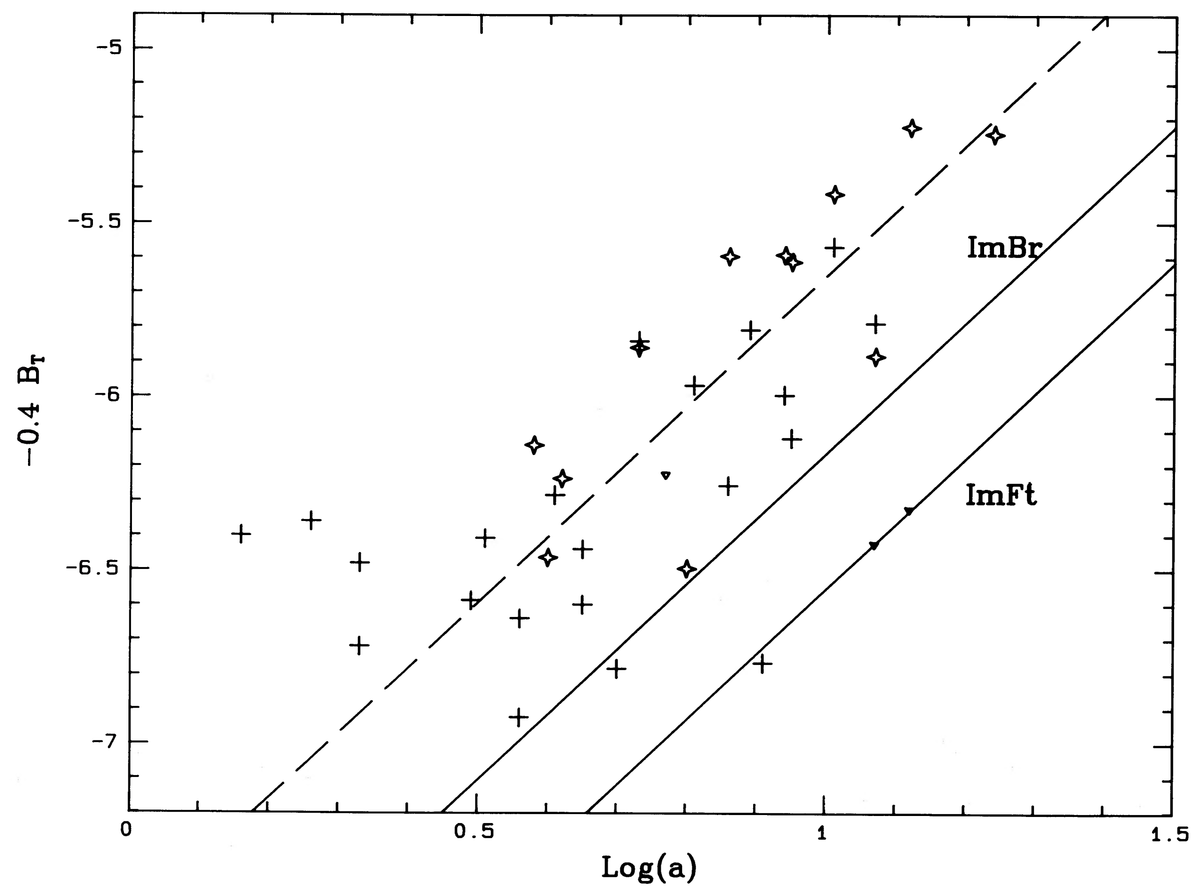


FIG. 3.—Luminosity-diameter diagram for BCDs, with lines representing the best fit to these data (*dashed*) and separately for ImBr and ImFT. The slopes of all three lines are constrained to be the same as for the entire sample of Sm–ImV. Small triangles represent galaxies which were undetected in H I; galaxies detected in the background of the cluster are omitted. Galaxies represented by plus signs were detected only in H I; four-pointed stars indicate detection both in H I and FIR.

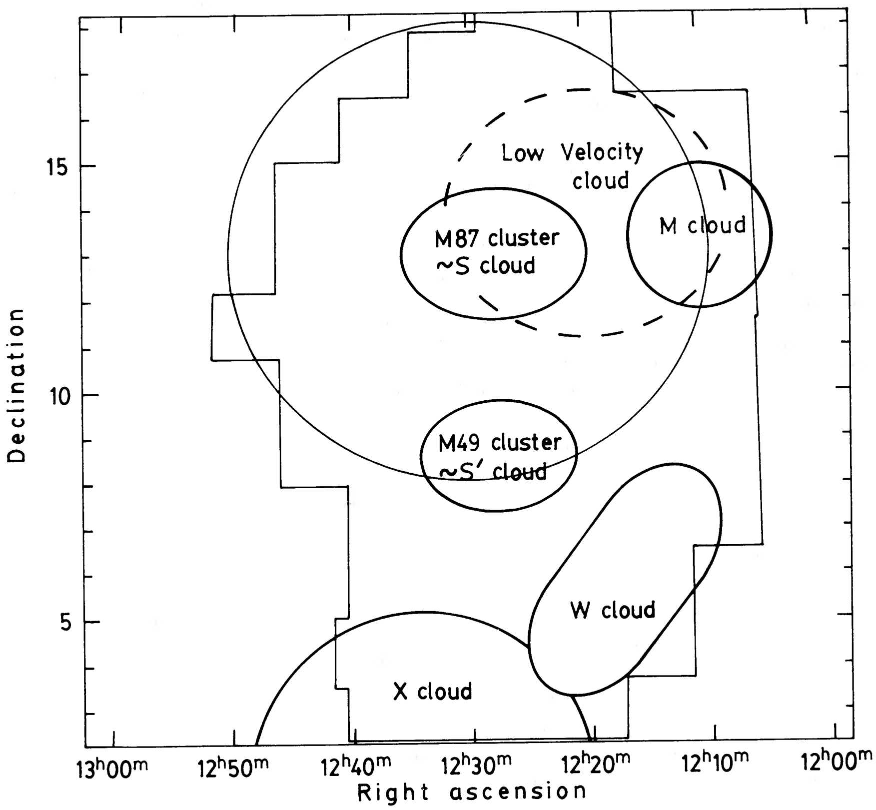


FIG. 4*a*

FIG. 4.—Maps of the Virgo Cluster area showing the positions on the sky of (*a*) various groups and clouds within the cluster, (*b*) BCDs, (*c*) dwarf irregulars, (*d*) spirals Sab–Sd, and (*e*) early types S0, E, and dE. The circle represents the 5° cluster core and distinguishes our IN and OUT samples; the irregular boundary is the BST survey limit. Velocities are coded as follows: *triangles:* $V_\odot < 300$ km s^{-1}; *squares:* $300 < V_\odot < 1900$ km s^{-1}; *circles:* $1900 < V_\odot < 3000$ km s^{-1}. The size of the symbol is directly related to luminosity. Dots represent galaxies with unknown velocities.

objects of type i0, with no outer low surface brightness halo even in the CCD image. We will consider these i0 objects to be "extreme BCD," the "purest" examples of the BCD phenomenon. The distributions of a and $\sigma_{\rm opt}$ in Figure 2 are quite continuous but very broad, and the bottom end of the distribution in a presumably corresponds to the "extreme BCD" category.

Figure 3 shows a broad, continuous scatter diagram for luminosity versus diameter; straight lines with slope 1.89 (determined from the best fit for the entire sample of late spirals and non–BCDs in Paper I), representing ImBr and ImFt, lie along the lower right envelope of the BCD points. Objects known to be in the background ($V_\odot > 3000$ km s^{-1}) have been excluded from the diagram. The dashed line is the best-fit linear relation for the BCDs alone, constrained to have the same slope. To summarize the data in Figure 3: (1) At comparable L_B, BCDs tend to have diameters a half as large as ImBr galaxies; (2) the scatter in L_B versus a is very large, so that the "best-fit" slopes are not very significant; but (3) for large a, the upper envelope in Figure 3 is very nearly parallel to the best-fit line. We present complementary H I data in § IV and shall argue (see § VII) that a, as given by BST, is mainly determined by the star formation regions and *not* by the lower surface brightness enveloping galaxy.

III. SPATIAL AND VELOCITY STRUCTURE OF BLUE COMPACT DWARFS IN THE VIRGO CLUSTER AREA

The area covered by the BST catalog extends well to the south of the core of the Virgo Cluster. For some environmental comparisons we shall consider a circle of radius 5° (centered on R.A. = 12^h30^m, decl. = 13°) as a nominal dividing line. Figure 4*a* shows this nominal circle and schematic outlines (*solid curves*) of a number of concentrations of various galaxy types on which there is at least rough agreement between various research groups (see, in particular, Binggeli, Tammann, and Sandage 1987; de Vaucouleurs and Corwin 1986; Tully and Shaya 1984). The "M87 cluster," or "S cloud," is the central core, rich in early-type galaxies; the "M49 cluster," or "S′ cloud," is richer in spiral galaxies and has a similar (slightly higher) mean redshift. The "X cloud," or "Virgo II cloud," on the northern edge of the southern extension is less uniquely defined but contains a number of spirals at velocities ~1500 km s^{-1}, larger than the Virgo core velocity (~1100 km s^{-1}; all velocities heliocentric). Some of these redshifted spirals appear to be *closer*, not farther, than the Virgo core (Tully and Shaya 1984), providing some evidence for current infall into the Virgo Cluster. The "Low-Velocity Cloud" (hereafter LVC, shown with a dashed boundary in Fig. 4*a*) contains galaxies with low (or negative) heliocentric velocities. The "W cloud" and "M cloud," as outlined by large galaxies, are rich in early-type galaxies, have mean velocities ~2200 km s^{-1}, and are definitely behind the Virgo core. We shall return to the spatial distribution of BCDs (Fig. 4*b*) and its relation to these clouds, but we first discuss the velocity distribution.

All BCD objects in our sample, taken from BST, have been observed in the 21 cm line at Arecibo Observatory. Observations of those having $B_T \leq 17.0$ are reported in Hoffman *et al.*

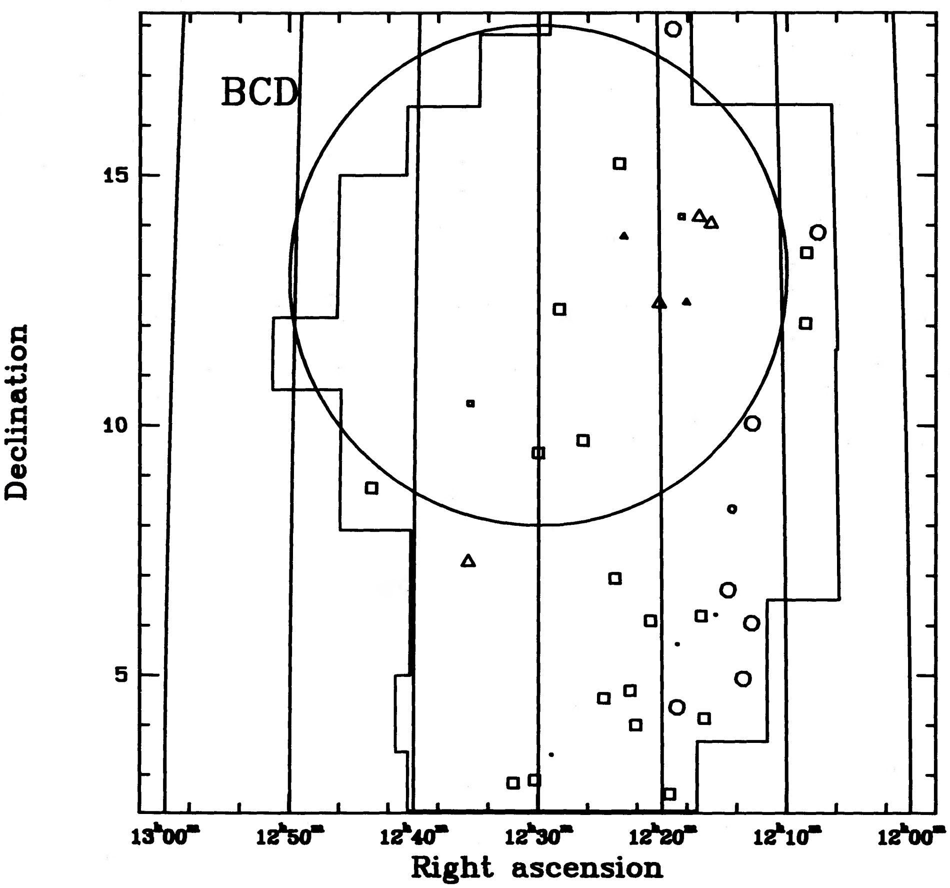

BCD
Declination
15
10
5
13h00m
12h50m
12h40m
12h30m
12h20m
12h10m
12h00m
Right ascension

FIG. 4b

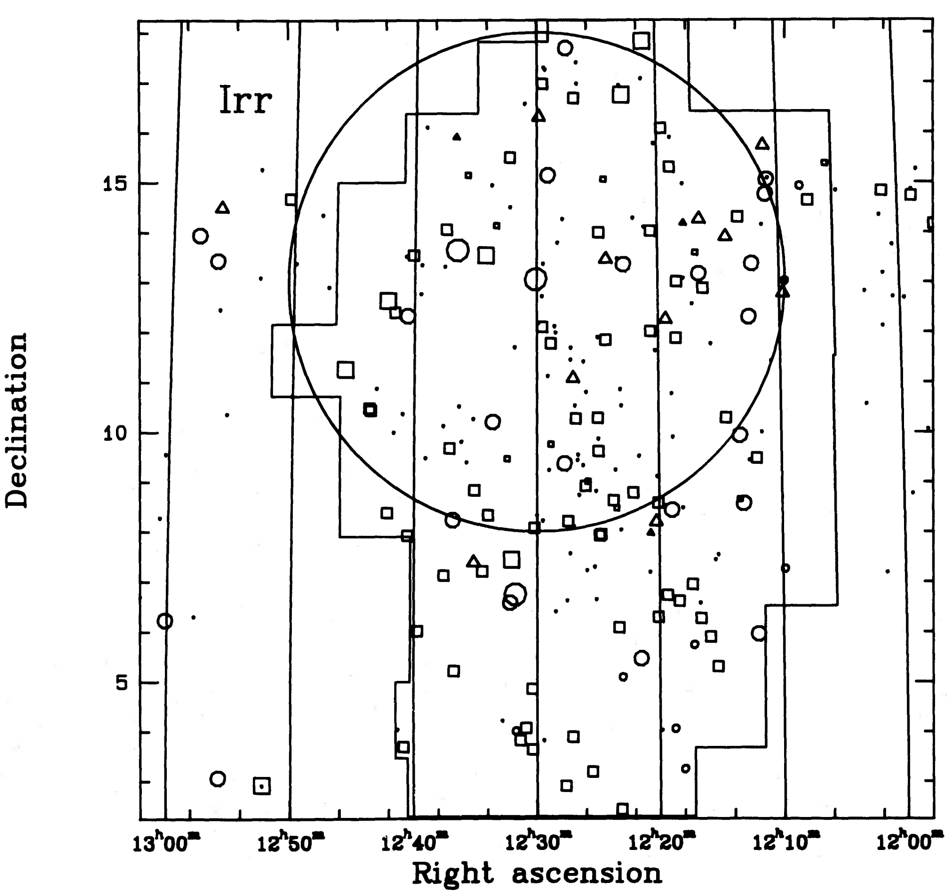
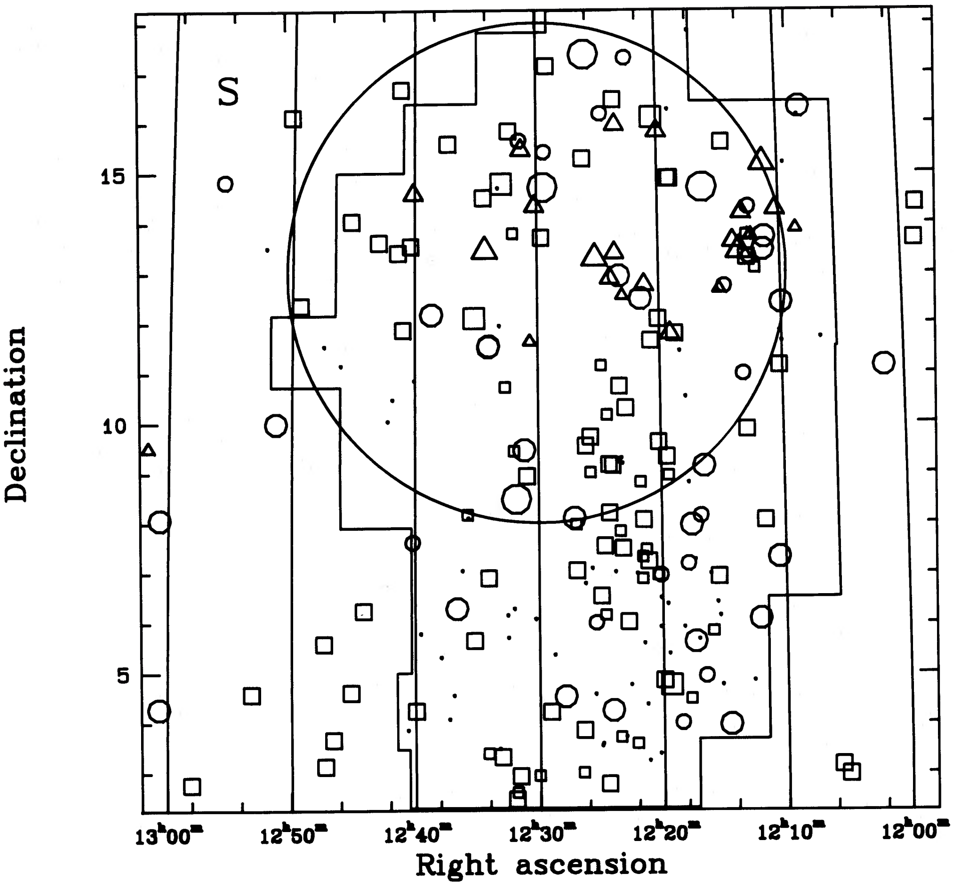
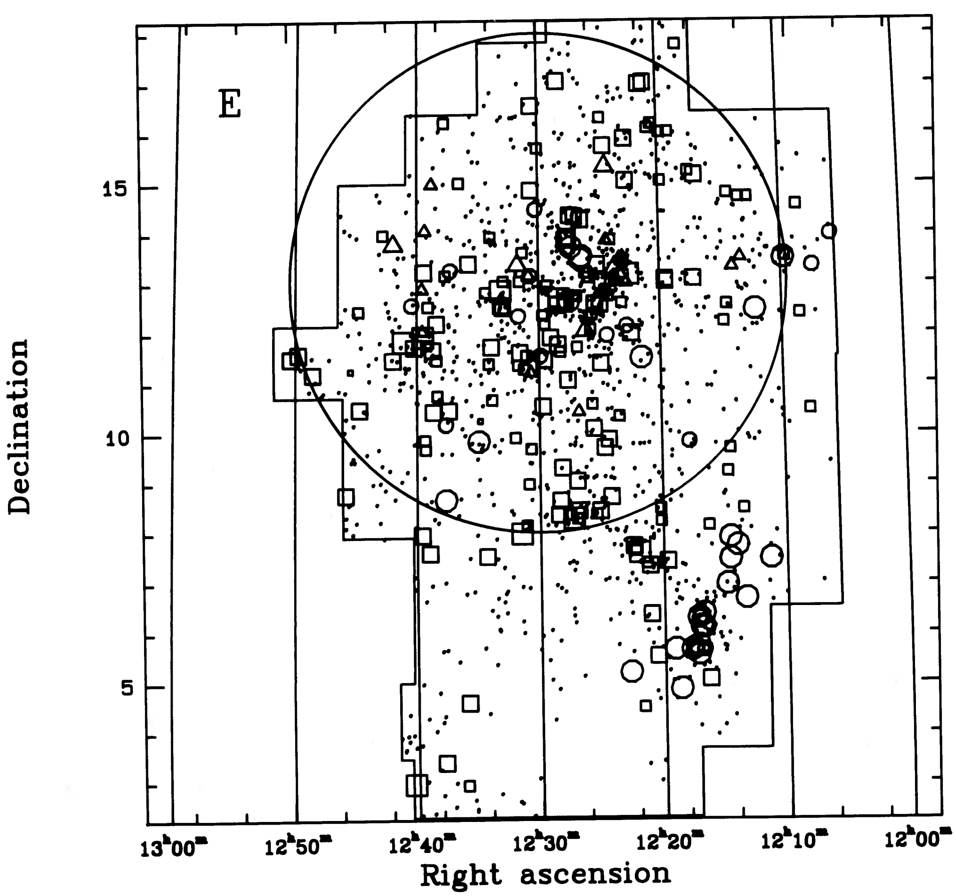

Irr
Declination
15
10
5
13h00m
12h50m
12h40m
12h30m
12h20m
12h10m
12h00m
Right ascension

FIG. 4c



S
Declination
15
10
5
13h00m
12h50m
12h40m
12h30m
12h20m
12h10m
12h00m
Right ascension

FIG. 4d



E
Declination
15
10
5
13h00m
12h50m
12h40m
12h30m
12h20m
12h10m
12h00m
Right ascension

FIG. 4e

(1987, hereafter HHSGS); the observations of the fainter objects will be reported in a forthcoming paper. Of the 64 BCD objects in BST, we detected 39, or 61%; eight of these had velocities uniformly distributed between 3000 and 9000 km s^{-1}. (We call these "background.") Two additional objects (members of LVC) have optical velocities near zero; they were undetected in H I, probably because of confusion with Galactic H I. In all figures and statistics presented here, these two galaxies are omitted from the sample for all quantities involving H I fluxes or upper limits, but are otherwise considered to be Virgo BCDs. Optical redshifts are now available for all but three of the objects still undetected in H I (Schulte-Ladbeck and Cardelli 1988, hereafter SC; Helou and Schombert 1989, hereafter HS). All of those objects have been found to lie in the background, most well beyond $V_{\odot} > 10{,}000$ km s^{-1}. Because Virgo BCDs are expected to have strong emission lines, HS argue that the three objects with unknown redshift are all either at very high redshift or that they are different in nature from the other BCDs. (Two of the three are among the lowest surface brightness objects called "BCD" in BST.)

Disregarding from now on all galaxies with $V_{\odot} > 3000$ km s^{-1}, we have 11 BCDs within the nominal circle (IN) with mean velocity (547 ± 170) km s^{-1} (standard uncertainty in the mean), a velocity distribution similar to that for the nucleated dE's studied by Bothun and Mould (1988). In the OUT region we have 22 BCDs with mean velocity (1683 ± 117) km s^{-1}. By comparison, for the Irr galaxies from Paper I (combination of "Sm," ImBr, and ImFt) we have 60 IN galaxies with mean velocity (1137 ± 100) km s^{-1} and 46 OUT galaxies with mean velocity (1422 ± 105) km s^{-1}. The IN/OUT number ratios and the spatial distributions shown in Figures 4*b* and 4*c* show BCDs to be even less centrally concentrated than Irr galaxies. (See also Iovino, Melnick, and Shaver 1988.) In Paper I we found that Irr galaxies have a spatial distribution similar to that of true spirals in their lack of concentration, but slightly more "spotty."

The BCDs, however, show a *spectacularly* spotty distribution when the spatial data (Fig. 4*b*) and the velocity histograms (Fig. 5) are considered together and in comparison with the subgroups of the Virgo Cluster (Fig. 4*a*):

1. There are rather few BCDs in the densest part of "phase space," the region of the Virgo Cluster core (M87 cloud) with velocities near the cluster mean. Also on the negative side, the somewhat less dense northeast half of the IN circle contains 21 detected Irr galaxies but *no* detected BCDs.

2. On the positive side, we have strong concentrations of BCDs in just two of the six subgroups indicated in Figure 4*a*. One of these is the cloud of low and negative heliocentric velocity galaxies in the IN region (LVC), which is probably falling into the cluster core from beyond (see Fig. 2*a* of Tully and Shaya 1984). The other spectacular concentration in phase space coincides (at least loosely) with the W cloud in the

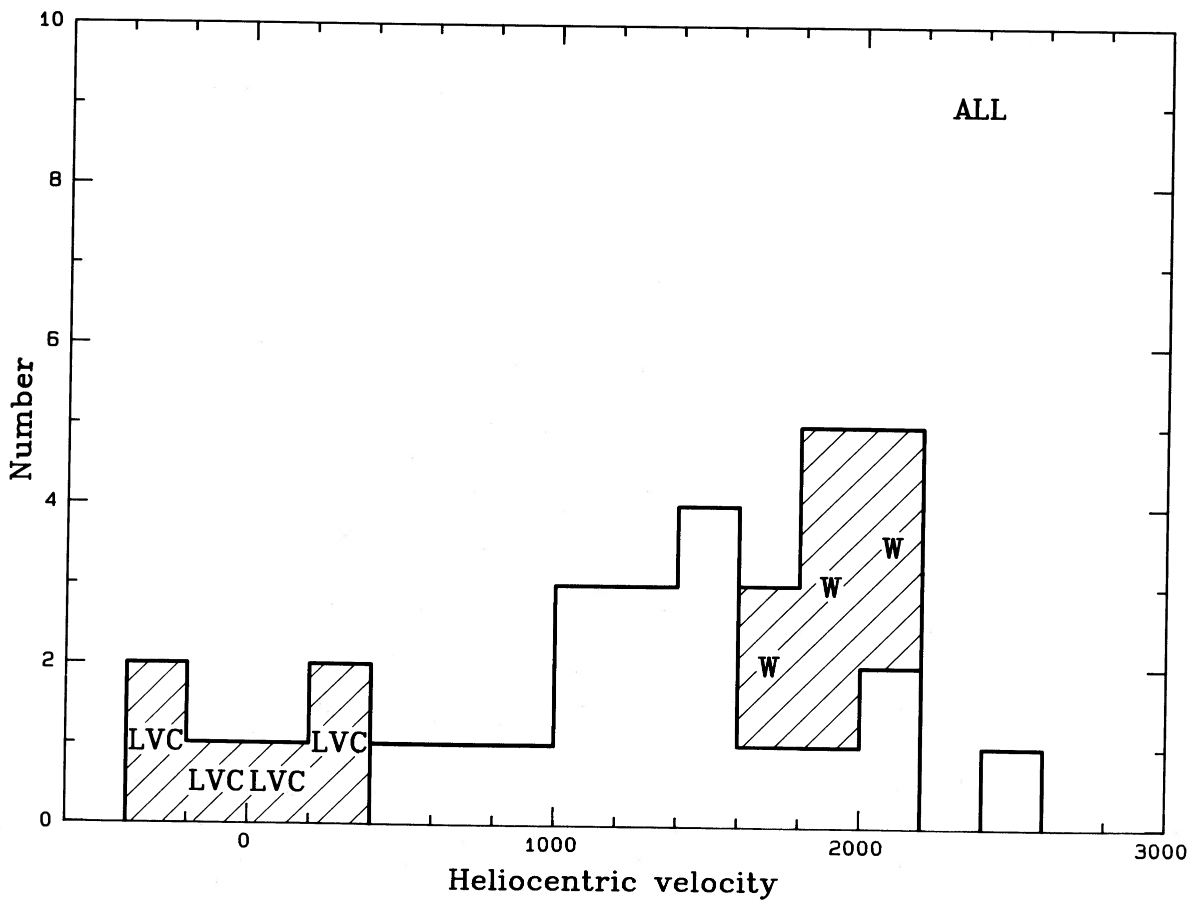


FIG. 5*a*

FIG. 5.—Velocity histograms for the BCDs, (*a*) for the entire BST area; (*b*) IN, $\theta < 5°$; (*c*) OUT, $\theta > 5°$. BCDs in the Low Velocity Cloud are shown hatched and labeled LVC; those in the W cloud, hatched and labeled W.

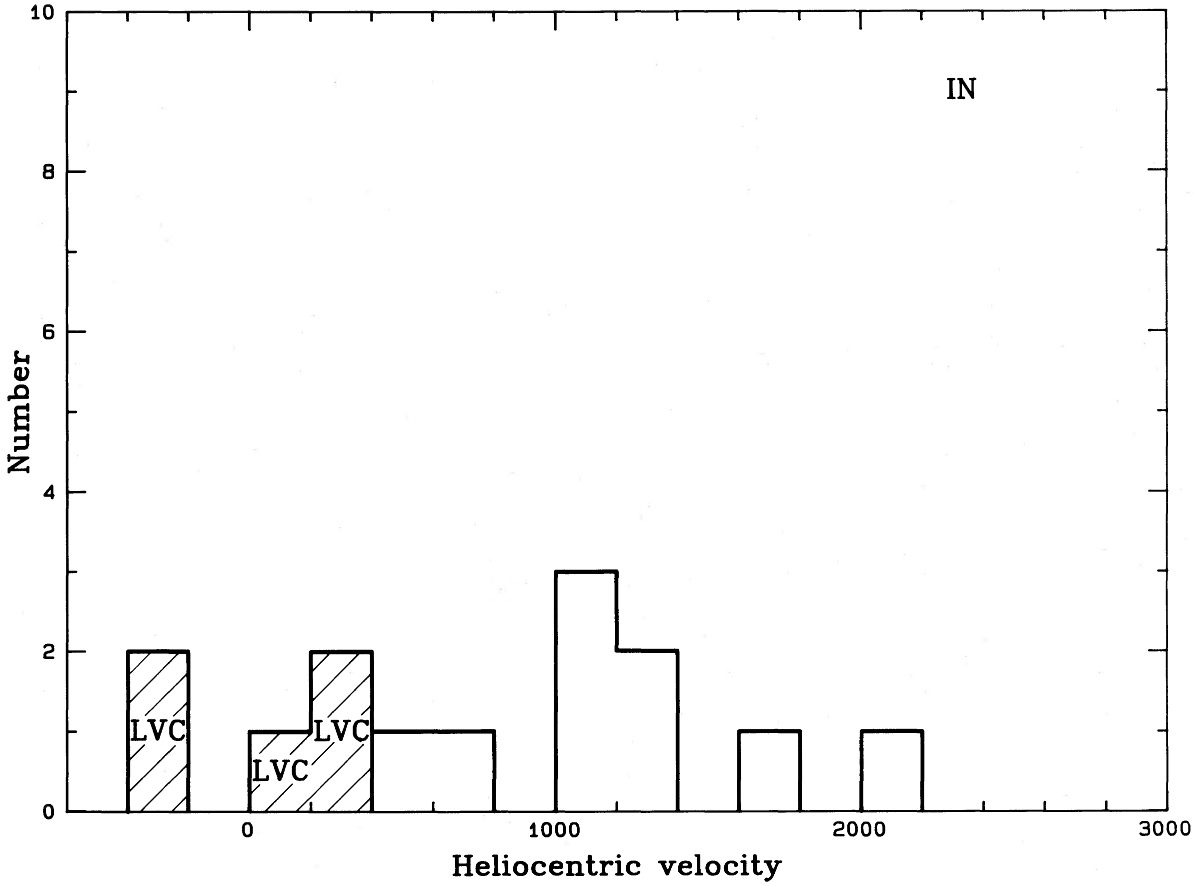

IN
LVC
LVC
LVC
Number
Heliocentric velocity

FIG. 5*b*

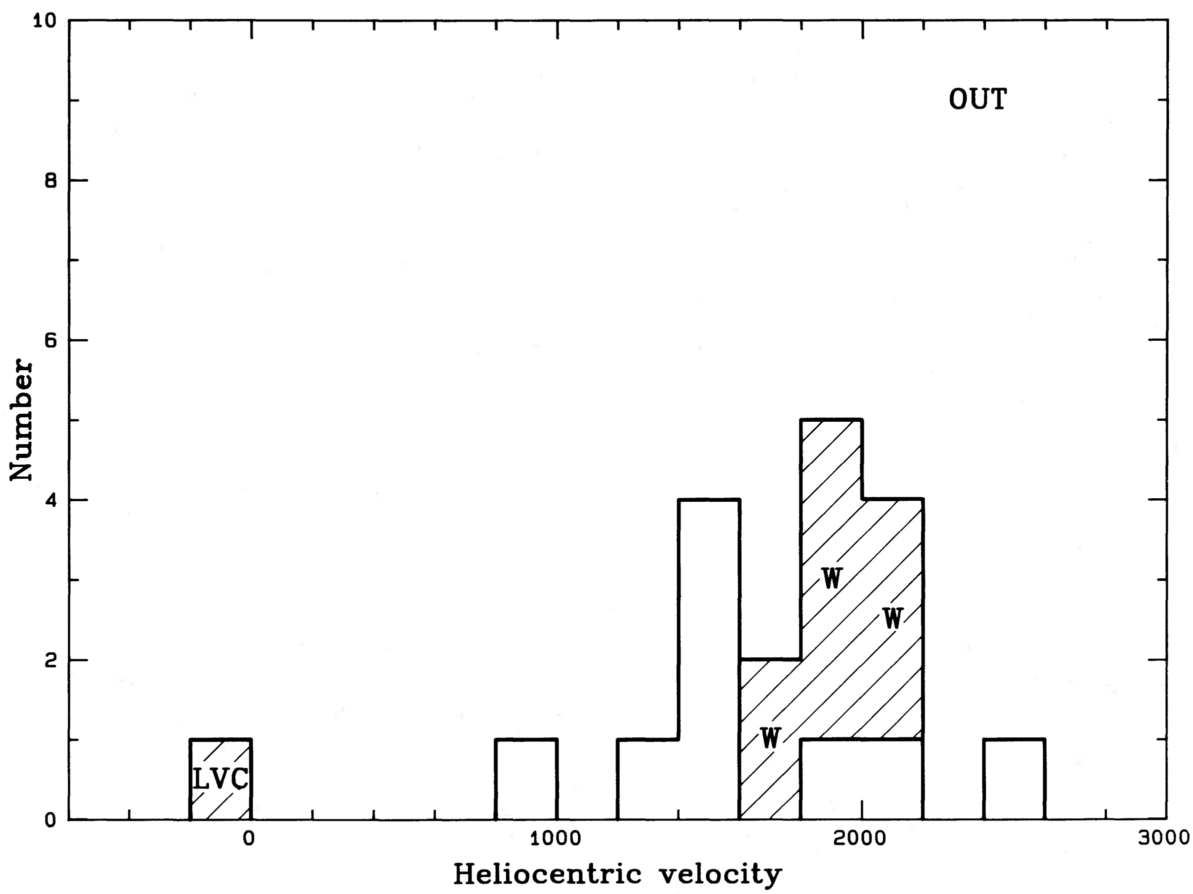

OUT
LVC
W
W
W
Number
Heliocentric velocity

FIG. 5*c*

TABLE 2

NUMBERS OF GALAXIES IN TWO DECLINATION AND THREE VELOCITY RANGES

TYPE	DECLINATION (degrees)	$V_{\odot}$ (100 km s^{-1}) <15	15–22	22–30
RSA	<7	1	7	5
BCD	<7	2	9	0
Irr	<7	4	8	2
RSA	7–14	13	2	4
BCD	7–14	2	0	0
Irr	7–14	18	7	3

southwest corner of the OUT region. There are 11 detected BCDs with $12^h10^m <$ R.A. $< 12^h25^m$ and decl. $< 7°$; 10 of these are in the W cloud area shown in Figure 4*a*. The velocity distribution makes this clump more spectacular still: nine of these 10 BCDs have velocities in the rather narrow range $1500 < V_{\odot} < 2200$ km s^{-1} (mean ~ 1850 km s^{-1}), approximately the lower half of the velocity range of the W cloud. The two BCDs in the far south, near 12^h30^m, just outside our W cloud boundary, also have $V_{\odot} \sim 1800$ km s^{-1}. These statistics are further illustrated in Table 2, which gives data for a strip having $12^h10^m <$ R.A. $< 12^h25^m$, both for the relevant area, decl. $< 7°$ and for a "control region" to the north. The table gives the numbers of BCD and Irr galaxies in three velocity ranges, and for the bright galaxies in the RSA catalog (Sandage and Tammann 1981) for comparison: Only the BCDs show the strong concentration to the middle velocity and lower declination range. Our Tully-Fisher analysis (see § IV) on the 22 spiral and Irr galaxies in the W cloud area gives a mean distance ~ 1.7 times larger than the mean distance of the Virgo core, compatible with the distance to the early-type members (Binggeli, Tammann, and Sandage 1987; de Vaucouleurs and Corwin 1986) of the W cloud itself.

To summarize: We have 33 detected BCDs (always excluding those in the background, with $V_{\odot} > 3000$ km s^{-1}) in the whole BST area, not much fewer than the number of detected Irr galaxies (106). However, the distribution of the BCDs in angular position–velocity space is extremely "spotty," so that most of the BCDs are members of a small number of "special" clouds. The two most striking are (1) a lower velocity, southern portion of the W cloud and (2) a southwest and "blueshifted" (possibly infalling) cloud (LVC) superposed on the Virgo core. We shall conjecture in § VII that the present epoch may be "special" for these "special clouds" and that other regions (both in and out of the cluster area) may contain only about one BCD per 10 irregulars. (For example, the "west window" in HHSGS, containing portions of the Leo groups, has only one detected BCD for 11 detected Irr galaxies). We found BCDs to be underabundant in the dense Virgo core, and also in the less dense northeast corner of the BST survey area.

IV. NEUTRAL HYDROGEN AND DYNAMICAL PROPERTIES OF VIRGO BLUE COMPACT DWARFS

A comparison of our H I results for Virgo BCDs with those of noncluster BCDs obtained by Thuan and Martin (1981) was given in Paper I. The two samples appear to be quite similar in their distance-independent properties. For properties that depend on distance we assume as in Paper I that all OUT galaxies with $V_{\odot} > 1900$ km s^{-1} (always excluding $V_{\odot} > 3000$ km s^{-1}), along with those having $1600 < V_{\odot} < 1900$ km s^{-1} in the W cloud area, lie (on average) a factor of 1.6 more distant than the Virgo Cluster itself.

In Figure 1, compare first the mean properties which do *not* depend on diameter *a* for BCDs—the mean of the ratio of H I mass to blue light, M_H/L_B; the detection fraction f_{det}; the blue magnitude B_T; the mean velocity width (at 50% of peak) ΔV; and the fraction of H I profiles with double-horned (as opposed to Gaussian) shapes—with those for the ImBr type (which is typical of the average for the combined grouping Irr = "Sm" + ImBr + ImFt). All are *roughly similar* for the two groups. For the detected BCD galaxies, we find a mean value of the absolute velocity width (uncorrected for inclination) $\langle \Delta V \rangle = 76 \pm 7$, a value somewhat larger than for Irr in general (about halfway between that for "Sm" and ImBr). Mean values for various other quantities are given in Table 3. Scatter plots of some of these quantities for individual BCDs are given in Figures 6, 7, and 8, which compare the logarithm of blue luminosity ($-0.4B_T$) with the logarithms of the H I flux and the velocity width ΔV, which we take to be an indicator for total dynamical mass M_T despite some suggestions that the outer halo of H I is still infalling (Vigroux, Stasinska, and Comte 1987; Loose and Thuan 1986). We have "corrected" the profile width as in HHS by assigning to each BCD the mean ($\frac{2}{3}$) of $\sin^2 i$ for a population distributed uniformly in $\cos i$ (*i* is the inclination angle). The very irregular shape of the BCDs precludes any determination of the inclination from the optical image (see § V). The solid line in each of the three figures is the fit to all spirals plus irregulars. The dashed lines are best fits for the BCDs, constrained to have the same slope as the solid lines. Here also the mean properties for the BCDs appear similar to those for Irr galaxies, but the scatter is larger (partly because we do not have inclination corrections). These results are compatible with those of Thuan (1985) for BCDs outside the cluster environment.

By contrast, there is a strong discrepancy between BCDs and Irr's in correlations which involve the measured optical diameter *a*, as shown in Figures 3, 9, and 10. As discussed in

TABLE 3

MEAN QUANTITIES FOR BCDs, OTHER IRREGULARS, AND SPIRALS

Type	$\langle a \rangle$ (kpc)	$\langle L_B \rangle$ ($10^8 L_{\odot}$)	$\langle M_H \rangle$ ($10^7 M_{\odot}$)	$\langle \Delta V_C \rangle$ (km s^{-1})	$\langle M_T \rangle$ ($10^8 M_{\odot}$)	$\langle \sigma_{opt} \rangle$ ($10^6 L_{\odot}$ kpc^{-2})
Sb–Sbc	33.2 ± 4.0	1790 ± 410	260 ± 115	329 ± 21	1110 ± 250	18 ± 2
Sc–Sd	22.4 ± 1.4	815 ± 135	193 ± 31	216 ± 9	359 ± 58	16 ± 1
"Sm"	10.8 ± 1.0	228 ± 89	93 ± 38	113 ± 8	44 ± 9	21 ± 3
ImBr	6.1 ± 0.4	57 ± 6	19 ± 3	78 ± 5	14 ± 3	19 ± 2
ImFt	4.8 ± 0.4	16 ± 3	9 ± 2	75 ± 10	12 ± 4	8 ± 1
All Im	5.4 ± 0.3	36 ± 4	14 ± 2	77 ± 5	13 ± 3	13 ± 1
BCD	4.1 ± 0.4	82 ± 15	32 ± 7	96 ± 9	15 ± 4	84 ± 18

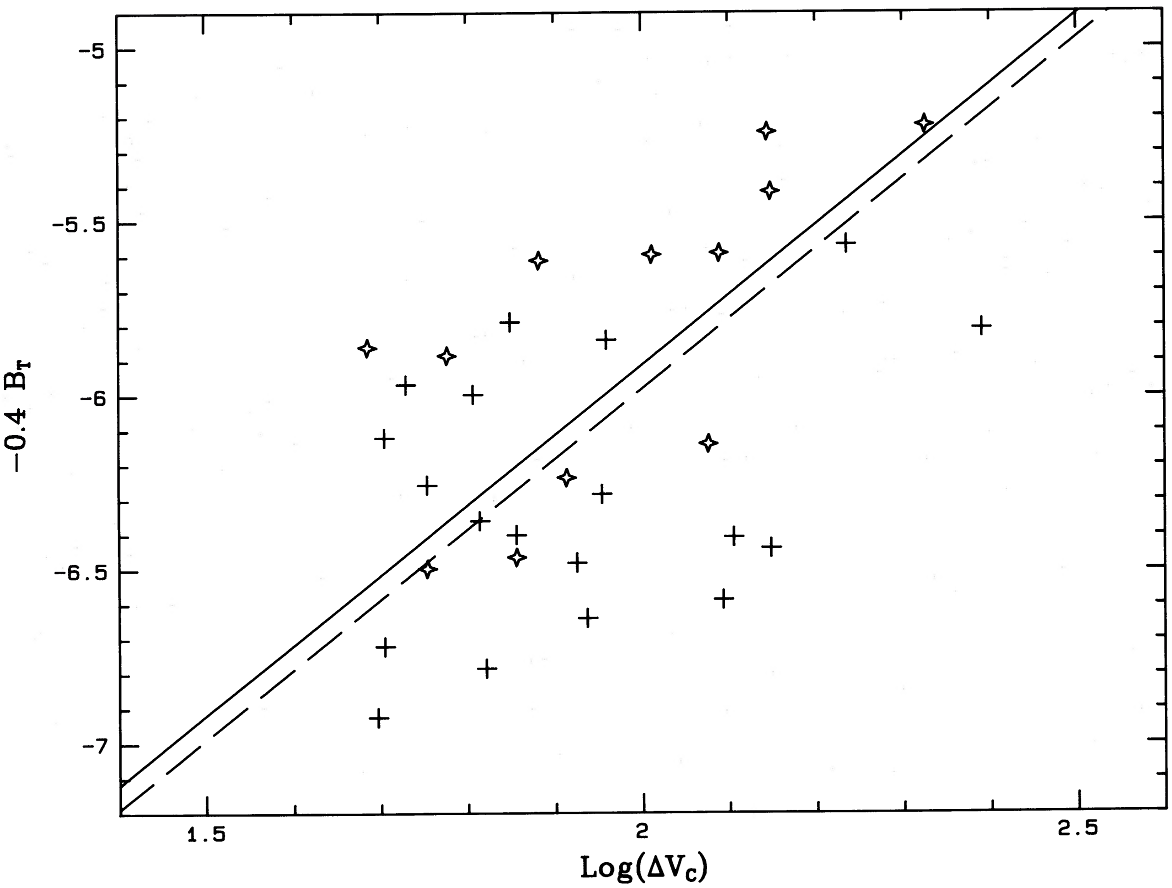


FIG. 6.—Tully-Fisher diagram, log luminosity ($\propto -0.4B_T$) vs. log profile width, for BCDs. Symbols are the same as in Fig. 3. The solid line is the best-fit relation for all spirals plus dwarfs, from Paper I; the dashed line is the best-fit line for BCDs, constrained to have the same slope.

§ II for the blue luminosity L_B, the main features for $M_{\rm H}$ and the corrected profile width ΔV_C versus a are that (1) the BCDs tend to have much smaller a, by factors of 2.6 and 1.9 at common H I flux and common ΔV_C, respectively; (2) the scatter is very large; but (3) the upper envelopes of the scatter diagrams are approximately parallel to the best-fit line for the spiral + Irr sample.

Table 3 gives mean values for the velocity width ΔV_C, diameter a, blue (L_B) and H I luminosities, indicative dynamical mass M_T (defined as in Paper I), and optical surface brightness $\sigma_{\rm opt}$, using the relative distance assignments discussed above. Note that ΔV_C and M_T can be given only for detected galaxies; those means for ImFt are misleading because only the brightest and presumably most massive galaxies were detected. For M_H, half the upper limits for undetected galaxies were included in the mean. The uncertainties given in the table are standard uncertainties in the mean; the true uncertainties are no doubt larger for most quantities, since the distributions are non-Gaussian. We summarize the overall comparison of the detected BCDs with other irregulars as follows: (1) Mean BCD quantities related to absolute dynamical mass (ΔV_C) and gas mass (H I flux) are comparable to those for ImBr, or to all irregulars as long as the more massive "Sm" galaxies are included along with ImBr and ImFt. (2) For a given value of ΔV_C, the luminosity L_B and H I flux are normal (although with large scatter), i.e., BCDs are *not* overluminous. (3) For given ΔV_C, the observed diameter a for BCDs is smaller than for other irregulars by a large and variable factor between unity and about 3.5 (about 2 on average).

V. *IRAS* OBSERVATIONS OF VIRGO BLUE COMPACT DWARFS

The entire sample of 64 BCDs in the BST catalog of the Virgo area now has co-added *IRAS* data (Helou *et al.* 1988, hereafter HKMB). Of these, 23 are detected at 60 μm, 19 at 100 μm, and 17 at both wavelengths. For galaxies detected in at least one of these two wavelength bands we use the flux combination $L_{\rm FIR}$ (HKMB) to characterize the far-infrared emission:

$$L_{\rm FIR} = 1.26 \times 10^{-14}[2.58 f_\nu(60\ \mu{\rm m}) + f_\nu(100\ \mu{\rm m})]\ {\rm W\ m^{-2}}\ ,$$

where f_ν is the flux in janskys for a detection and half the upper limit for a nondetection. Only one detection at each of 12 and 25 μm is found. We will discuss the correlation of $L_{\rm FIR}$ with optical and H I luminosities below, but concentrate first on FIR detection statistics.

The FIR detection fraction does not discriminate between the BCDs in the Virgo redshift range and the background objects. Of the 28 "background" objects known to have $V_\odot >$ 3000 km s^{-1}, 15 were detected by *IRAS*; of the 33 BCDs with $V_\odot < 3000$ km s^{-1} (considered to be Virgo supercluster members), 13 were detected. The three objects still without redshifts were all undetected in the FIR. For the 33 BCDs with known $V_\odot < 3000$ km s^{-1}, a four-pointed star in Figures 3 and 6–10 denotes a FIR detection, while a plus sign denotes a nondetection. The FIR detection probability is positively correlated with blue luminosity, optical diameter a, and H I flux; it is less well correlated, but still positively, with profile width ΔV.

If the high surface brightness of BCDs is due to the same interstellar radiation field which drives FIR emission (Helou 1985; Bothun, Lonsdale, and Rice 1988), one would expect a strong positive correlation between $L_{\rm FIR}$ and optical surface brightness. Let $\sigma_0 = B_T + 5 \log a$ and $\sigma_1 = B_T + 2.5 \log (ab)$, where a is the optical major diameter as above and b is the optical minor diameter; σ_0 is thus a measure of the "nominal face-on" blue surface brightness and σ_1 of that *observed.* Figure 11 shows, for the Virgo redshift BCDs, no correlation between detection in FIR and either surface brightness. This presumably is another artifact of our uncertainty over whether the optical diameter a measures only the high surface brightness patch or a larger diameter low surface brightness halo.

IRAS co-additions are not yet available for the other types of Virgo dwarf irregular (Sm and Im, jointly called Irr here) galaxies. Compilations from other parts of the sky by Helou (1985), Hunter *et al.* (1986), and Thronson and Telesco (1986) indicate that these low surface brightness types of dwarfs have smaller ratios $L_{\rm FIR}/L_B$ than either BCDs or normal spirals. However, we can make some comparisons of $L_{\rm FIR}/L_B$ between BCDs and normal spirals in the Virgo area. The relevant histograms are given in Figure 12. In spite of various uncertainties, we have an important qualitative conclusion: The ratios $L_{\rm FIR}/L_B$ for BCDs in the Virgo Cluster area are comparable to those for normal spirals, *not* particularly small as would be expected if all BCDs were young objects (see § VII).

We can attempt a similar comparison for the ratio $L_{\rm FIR}/M_{\rm H}$. Figure 13 shows scatter plots of log $M_{\rm H}$ versus log $L_{\rm FIR}$, separately for IN and OUT. BCDs undetected in H I or in FIR are shown at their upper limits, with arrows pointing in the appropriate directions. A line of constant $M_{\rm H}/L_{\rm FIR}$ is shown for reference. While the BCDs do appear to fit without discontinuity onto the low-luminosity end of the $M_{\rm H}$-$L_{\rm FIR}$ correlation (we will need co-added *IRAS* data for the fainter spirals and Irr galaxies, to be sure), it is evident that the ratio $L_{\rm FIR}/M_{\rm H}$ is smaller for IN BCDs than for IN spirals. For OUT galaxies, the situation is not so clear cut. Table 4 gives relevant statistical information: the median $L_{\rm FIR}/M_{\rm H}$ for spirals is close to the upper quartile for BCDs. (In this table, IN spirals are weighted by a factor of 0.5 to account for the unequal IN/OUT ratios of numbers of spirals versus number of BCDs.) $L_{\rm FIR}/M_{\rm H}$ tends to be about a factor of 2 or 3 smaller for BCDs than for spirals. This may seem paradoxical, since we concluded that $L_{\rm FIR}/L_B$ is "normal" and that the L_B-$M_{\rm H}$ relation for BCDs fits roughly on the "normal" relation from Im to true spirals; however, the paradox is likely to be resolved by the fact that for the "normal" sequence from ImFt to giant spirals, the ratio $M_{\rm H}/L_B$ decreases with increasing L_B but is smaller for BCDs than for all other irregulars, including Sm galaxies. The bias caused by the H I deficiency of the IN galaxies and the fact that BCDs have a smaller fraction IN than do the spirals is removed by the weighting scheme used in Table 4.

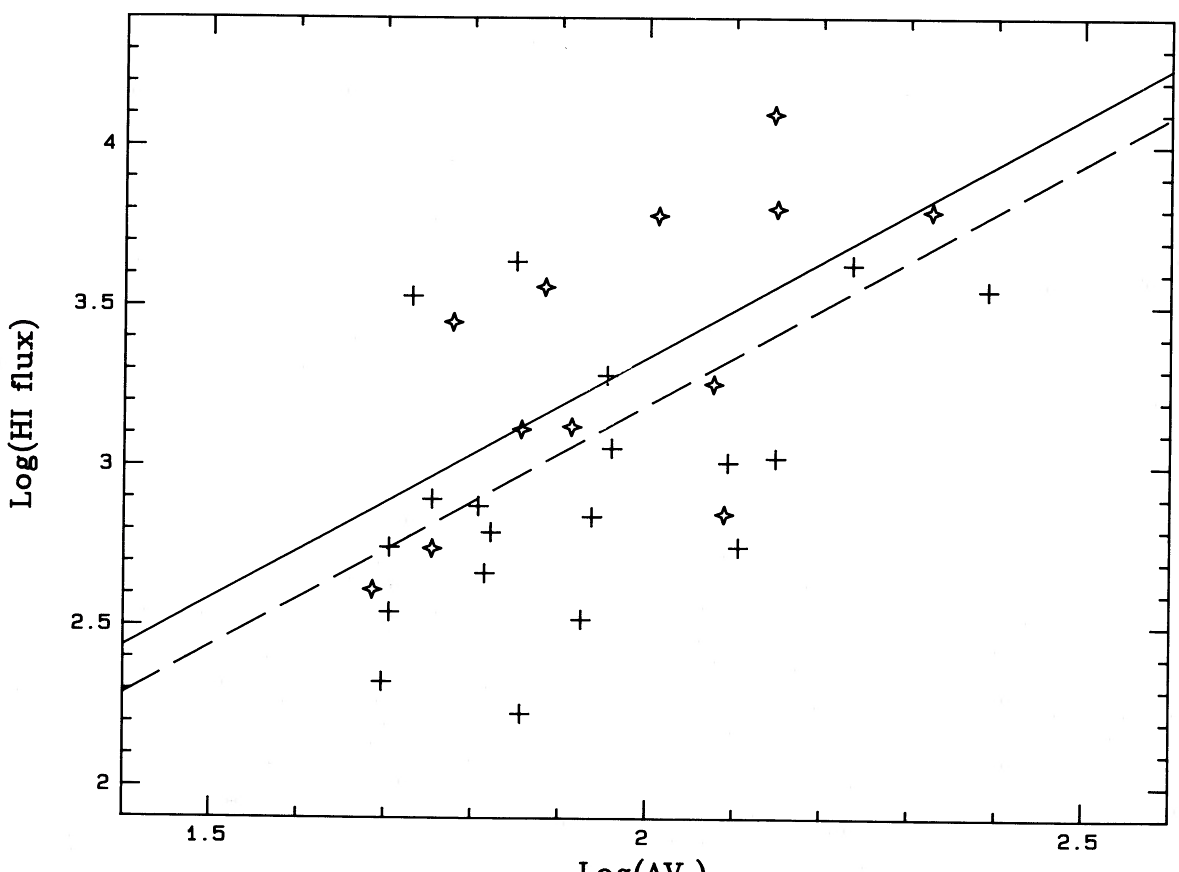


FIG. 7.—H I flux vs. corrected profile width plot corresponding to Fig. 6

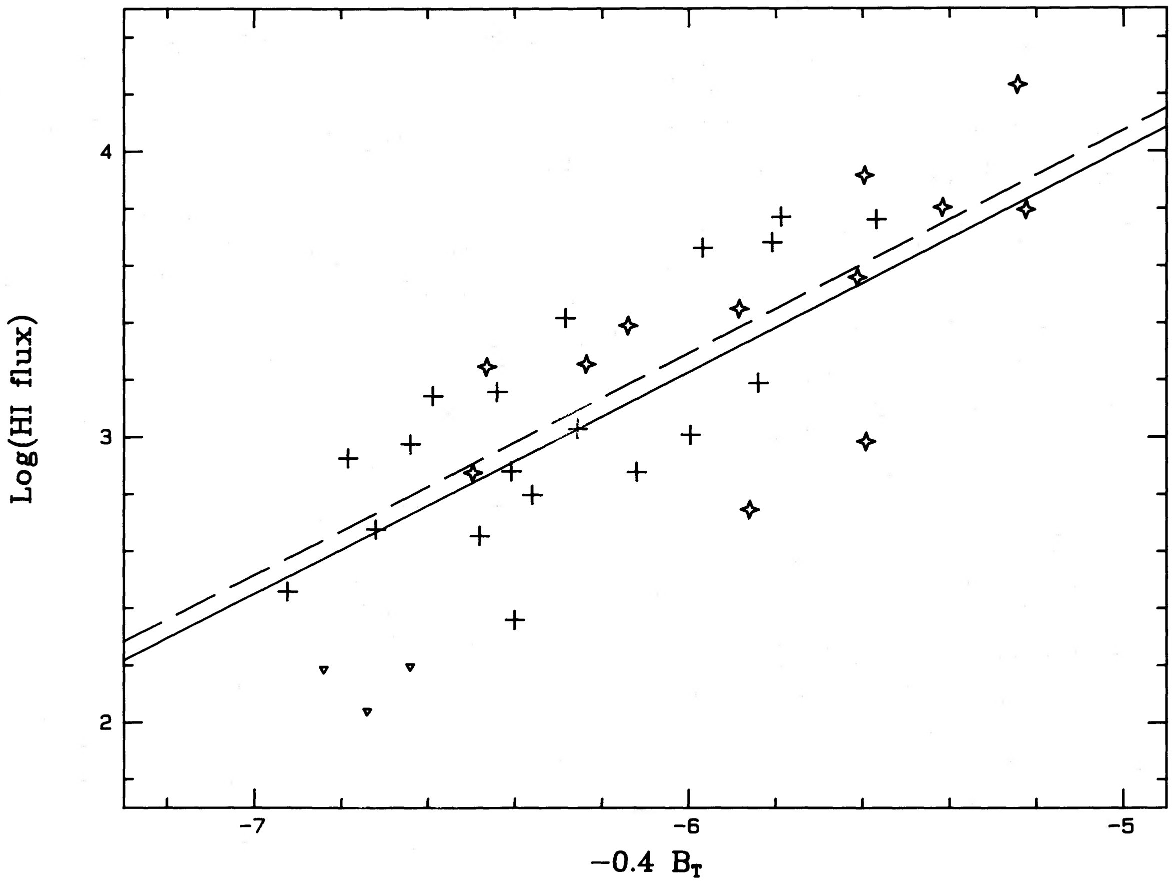


FIG. 8.—H I flux vs. luminosity for BCDs. Small triangles represent the upper limits for undetected BCDs, and background BCDs are omitted. As in Fig. 6, the solid line is the best fit for all spirals plus dwarf irregulars; the dashed line is the best-fit relation for BCDs, constrained to have the same slope. Symbols are the same as in Fig. 3.

Histograms of the 60 μm/100 μm color ratios for BCDs and bright spirals are given in Figure 14. Upper limits on the 100 μm fluxes are shown with arrows pointing in the appropriate direction; BCDs undetected in both bands are omitted from the figure, as are all background objects. Detected BCDs are clearly warmer in their 60 μm/100 μm ratios than spirals by $\sim 30\%$ in the median. In § VII we will argue that this is consistent with L_{FIR} coming mainly from the star formation region in the BCDs rather than from the cooler H I envelope.

VI. OPTICALLY INVISIBLE NEUTRAL HYDROGEN CLOUDS: UPPER LIMITS

In the course of our Arecibo H I surveys of Virgo Cluster spirals and dwarf irregular galaxies (Helou *et al.* 1981; Giovanardi, Krumm, and Salpeter 1983; Helou, Hoffman, and Salpeter 1984, hereafter HHS; HHSGS; Hoffman *et al.* 1989, hereafter HLHSW), we have inevitably also acquired sensitive data on the presence (or absence) of optically unidentified, relatively

TABLE 4

STATISTICS OF FIR/H I RATIO

Sample Selection	Threshold log R	Number with FIR/H I $< R$	Number with FIR/H I $> R$	Number Undecided
Spirals, weighted	−0.15	12	34.5	0
BCD, $V_{\odot} < 3000$	−0.15	7	9	18
BCD, $V_{\odot} > 3000$	−0.15	0	11	11
BCD, V unknown	−0.15	0	0	3
Spirals, weighted	0.13	23	23.5	0
BCD, $V_{\odot} < 3000$	0.13	14	6	14
BCD, $V_{\odot} > 3000$	0.13	4	10	8
BCD, V unknown	0.13	0	0	3
Spirals, weighted	0.50	35.5	11	0
BCD, $V_{\odot} < 3000$	0.50	27	1	6
BCD, $V_{\odot} > 3000$	0.50	5	6	11
BCD, V, unknown	0.50	0	0	3

isolated H I clouds within a significant fraction of the Virgo Cluster volume. For the most part our data have been beam-switched, so that each spectrum contains information on *two* 3'.2 beams. Any H I that happens to lie in the direction of the OFF beam would show up as a negative signal in our final spectrum; and a cloud lying within 1'.6 or so of the ON direction would be recorded as a second positive signal as long as its velocity did not coincide with that of the targeted galaxy.

Three kinds of unidentified H I clouds would be of interest for discussion related to dwarf irregular galaxies: (1) the continuation of the ImFt sequence of BST to even smaller dynamical mass, luminosity, and H I mass, i.e., the faintest end of the ImV class or an even fainter "ImVI" class (Tyson and Scalo 1988); (2) any ordinary dwarf irregulars that should have been classified about ImIV but were somehow missed in compiling the BST catalog; and (3) genuine "*proto*–dwarf irregular galaxies," i.e., objects with dynamical mass and velocity width ΔV corresponding to *somewhere* in the Irr sequence (a distribution of ΔV also similar to that for BCDs). Being *proto*galaxies, these last objects would have much smaller L and (slightly to much) larger H I mass than a corresponding "ordinary" dwarf irregular. The Tyson and Scalo (1988) model would be similar to this. The detailed compilation in Paper I shows that we can say little about category 1 from our observing runs so far, because our detection probability was low for ImV. For category 2, on the other hand (ImIV and larger), the detection probability was quite good, and for most members of category 3 the H I mass would be even larger and the detection probably would be essentially 100%, if the Arecibo beam happened to be pointed within half a beamwidth of the object.

There are a number of H I surveys which give stringent upper limits on the frequency of optically invisible H I clouds for regions other than the Virgo Cluster (Krumm and Brosch 1984; Kerr and Henning 1987; Hulsbosch 1987; Phillips, Lewis, and Terzian 1989; see references in each for earlier surveys). Here we give similar upper limits on the frequency of proto–dwarf galaxies in Virgo, where we have the advantage of statistics on the numbers of dwarf irregulars identified in a systematic optical study.

In observing 287 dwarf galaxies, including the 64 BCDs, 156 spirals (Sab–Sd) and 43 early-type (S0 and Sa) galaxies, we have accumulated approximately 1640 ON/OFF pairs. The "volume" searched by each pair is about $2\pi(1'.6)^2 W$, where W is the velocity width of the spectrum: 2000 km s^{-1} for objects with a previously known velocity, and 3600 km s^{-1} for those for which we made a velocity search. The total volume searched is therefore 1.68×10^4 deg^2 km s^{-1}, or 3.4% of the total volume in the BST survey area which covers 140 deg^2 with a velocity range of -600 to 3000 km s^{-1}. With a typical rms noise $f_{\rm rms} \sim 1.5$ mJy in our spectra, we set a conservative upper limit on the flux for nondetections at $4f_{\rm rms} \times 50$ km s^{-1} ~ 300 mJy km s^{-1}. For a nominal Virgo distance of 21.9 Mpc this gives an H I mass limit of $3 \times 10^7\ M_\odot$. We have in fact noted a number of serendipitous signals, both positive and negative, but most of these occur in association with larger galaxies. In HHS we noted seven positive signals which can be interpreted

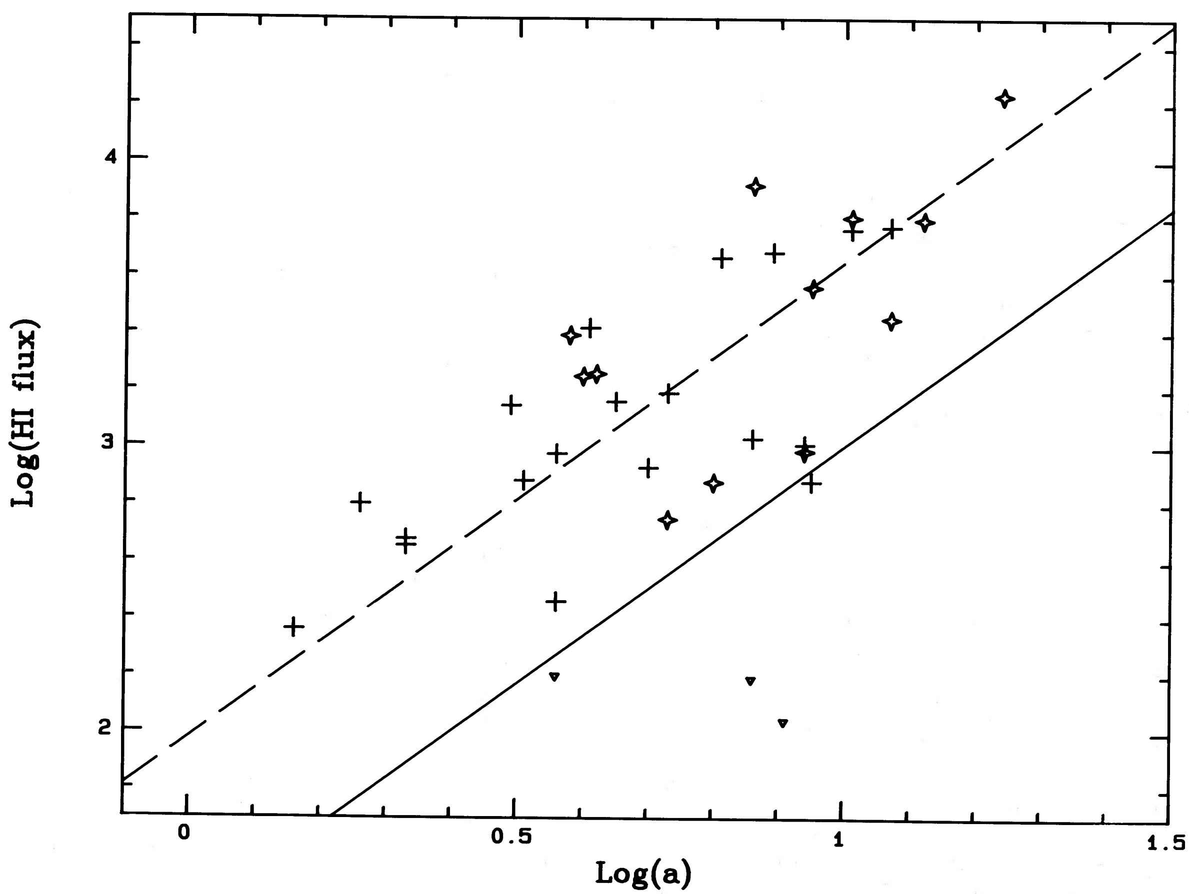


FIG. 9.—H I flux vs. optical diameter plots corresponding to Fig. 8

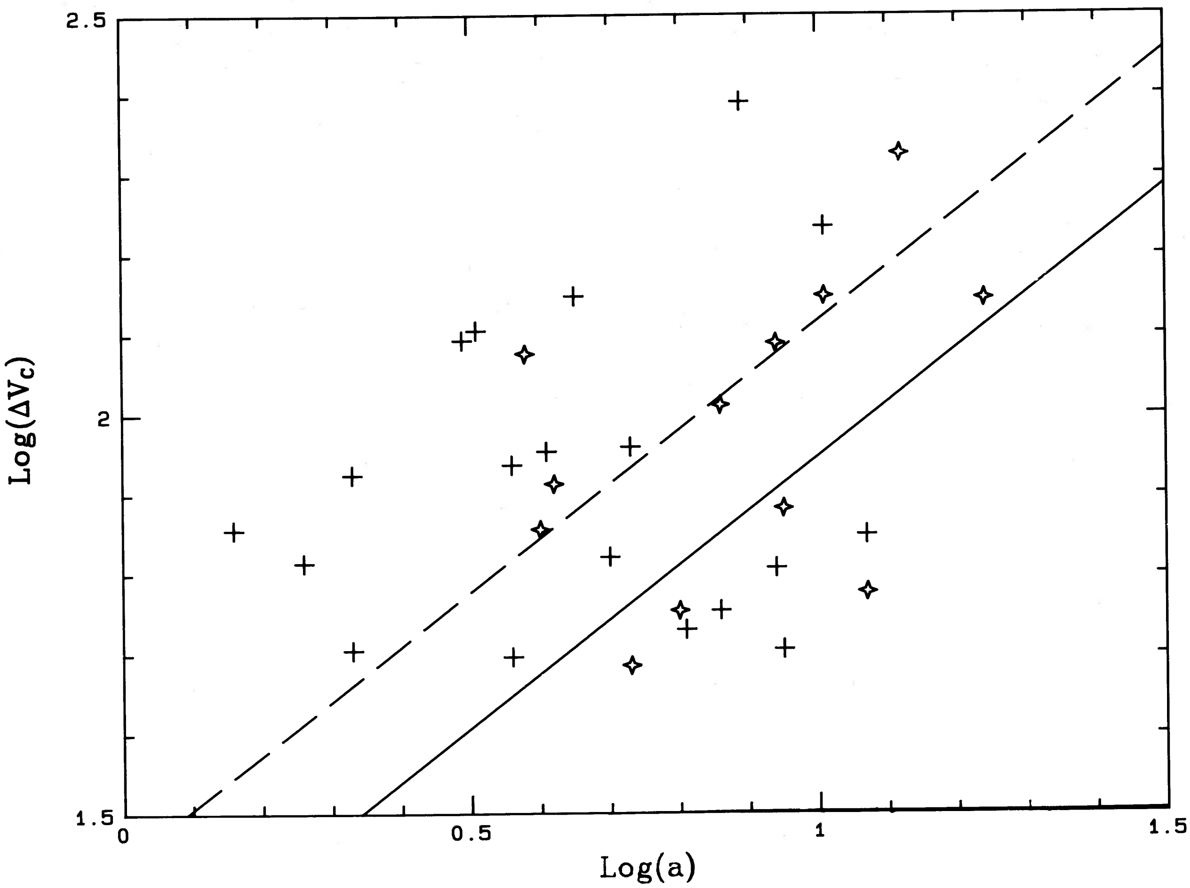


FIG. 10.—Tully-Fisher diagram, log profile width vs. log optical diameter, for BCDs. The lines and symbols have the same meanings as in Fig. 6. The equation for the solid line, which represents the best fit in all spirals plus non–BCD irregulars, was given incorrectly in Paper I; the correct equation is $\log a = -1.880 + 1.477 \log (\Delta V_c)$.

as close dwarf companions of known spiral galaxies. Two of these (companions of NGC 4523 and IC 755) can be clearly identified with dwarfs cataloged by BST (and others); two more (companions of NGC 4273 and NGC 4519) are not cataloged by BST, but candidate objects can be seen at the indicated positions on the POSS prints. Positive features in the maps for the NGC 4067, NGC 4416, and NGC 4758 are most easily interpreted as being due to low surface brightness dwarf galaxies superposed on the images of the program spirals. In each of those three cases, the extra signal is quite narrow (<50 km s^{-1}) and within 200 km s^{-1} of the velocity of the program spiral. In HLHSW we add one more case: the spectrum for NGC 4533 has a pronounced feature to the side of the galaxy's profile, which may be related to BST 1559.

Above and beyond those positive features, we have noticed 28 ON/OFF pairs showing negative features that could be signals in the OFF beam. Fourteen of these 28 proved to be spurious, or due to terrestrial interference. In 13 cases we are able to identify a previously observed spiral or dwarf as the source of the emission in the OFF beam. The one remaining case, in the OFF beam for BST 1032, was confirmed with a follow-up observation in 1987 July. The feature has $V_\odot = 1858$ km s^{-1}, $\int S\,dV = 1.85$ Jy km s^{-1}, and $\Delta V_{50} = 178$ km s^{-1}. The position is about 8′ SW of NGC 4352, an H I–rich SmIII galaxy, and about 9′ west-northwest of DDO 137, a SmIV galaxy that appears to be tidally interacting with NGC 4532. This feature is evidently real, but it has a much larger velocity width than we would expect for a faint dwarf galaxy; it may represent tidal plumes in the pair NGC 4532/DDO 137 or a real intergalactic gas cloud analogous to the one in Leo (Schneider *et al.* 1983).

In summary: We have plenty of serendipitous rediscoveries of known galaxies, a few H I detections of close dwarf companions to known galaxies, and one massive, optically invisible H I cloud moderately close to a pair of interacting gas-rich spirals. Having seen none, we can rule out the presence of more than ~ 3 optically invisible, isolated H I–rich dwarf galaxies with $M_{\rm H} \gtrsim 3 \times 10^7\ M_\odot$ in a "volume" one-thirtieth of the total BST "volume." We thus have an upper limit of about 100 for the entire BST survey area.

VII. DISCUSSION

a) Galaxy Diameters, Masses, and Surface Brightness

Many of the Magellanic and dwarf irregular galaxy types, including S . . . /BCD and Im . . . /BCD (in the notation of BST) but excluding "pure" BCD, fit in with current views of stochastic star formation: as surface brightness and luminosity decrease along the sequence Sm, ImIII, ImIV, ImV, the average rate of star formation per unit gas mass decreases and the process becomes more sporadic (Gerola, Seiden, and Schulman 1980; Matteucci and Chiosi 1983; Comins 1984). For the fainter of these classes, the average rate corresponds to a fairly

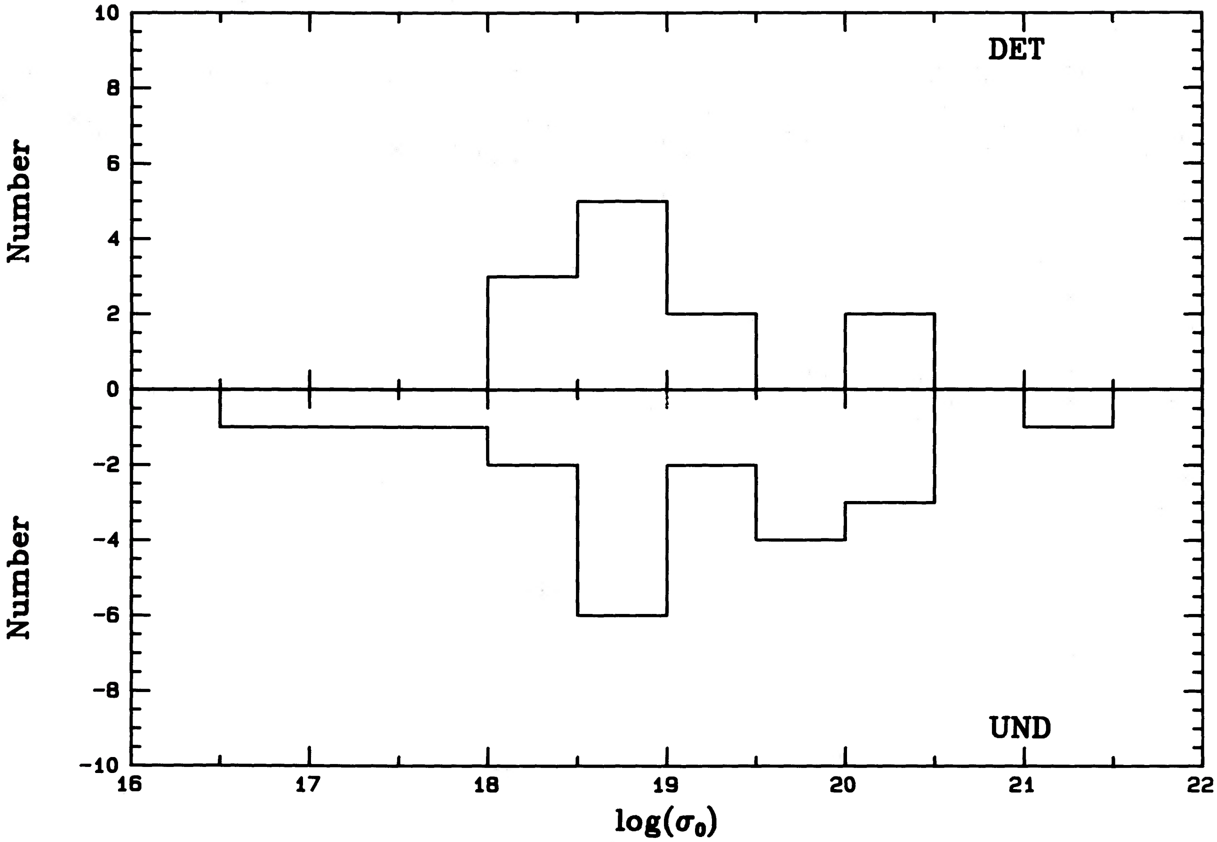


FIG. 11a

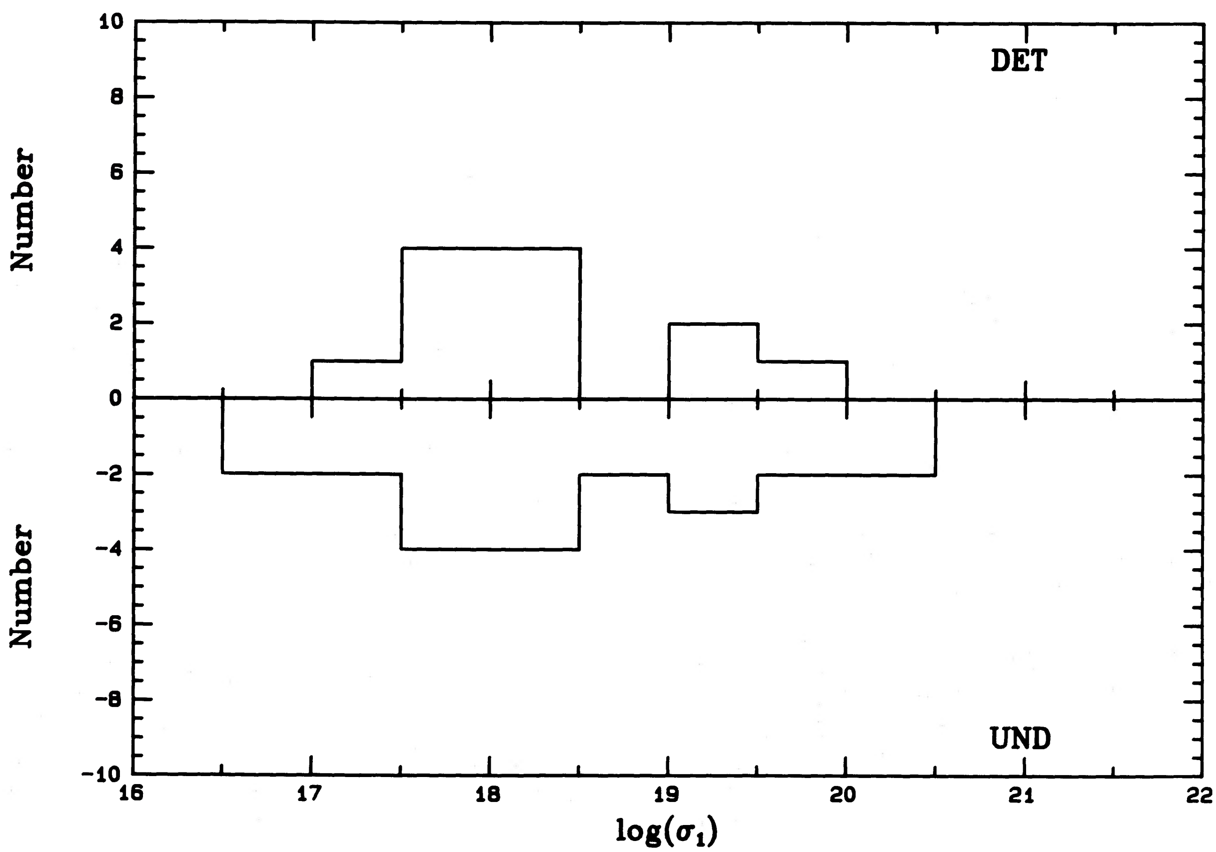


FIG. 11b

FIG. 11.—Histograms of surface brightness for BCDs, for those detected (*DET*) and undetected (*UND*) by *IRAS* separately. The surface brightnesses σ_0 in (*a*) and σ_1 in (*b*) are defined in § IV.

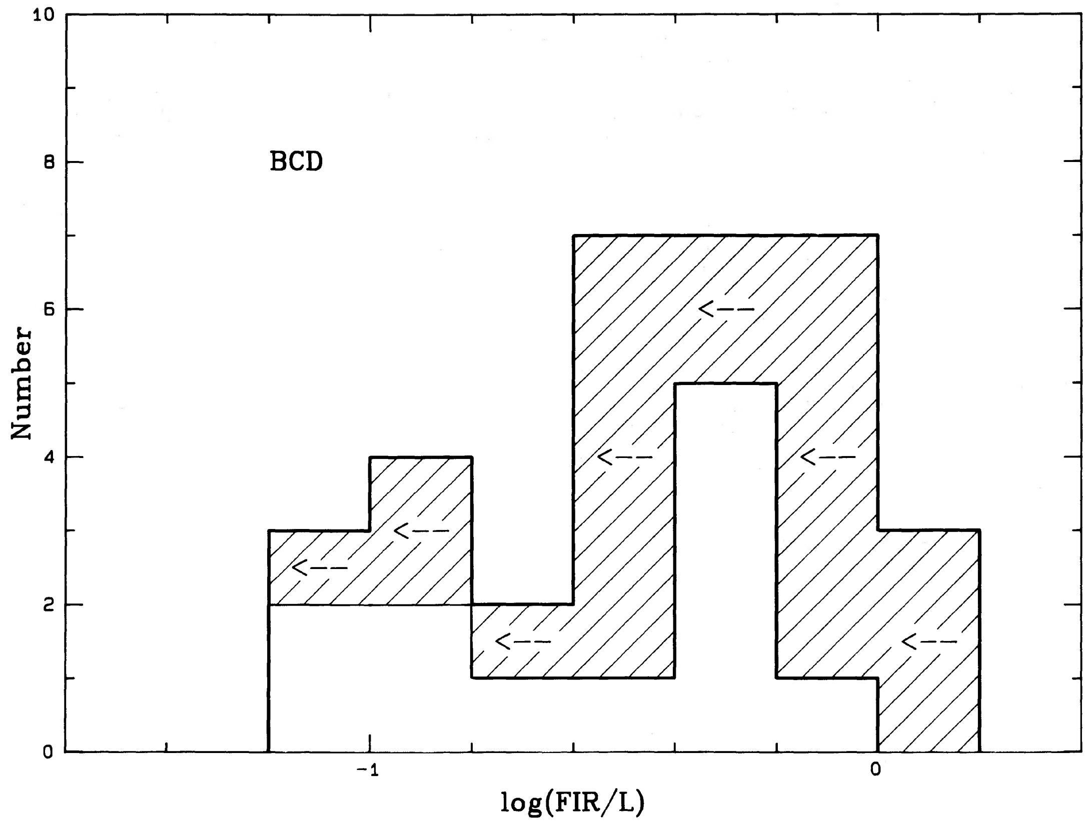


FIG. 12a

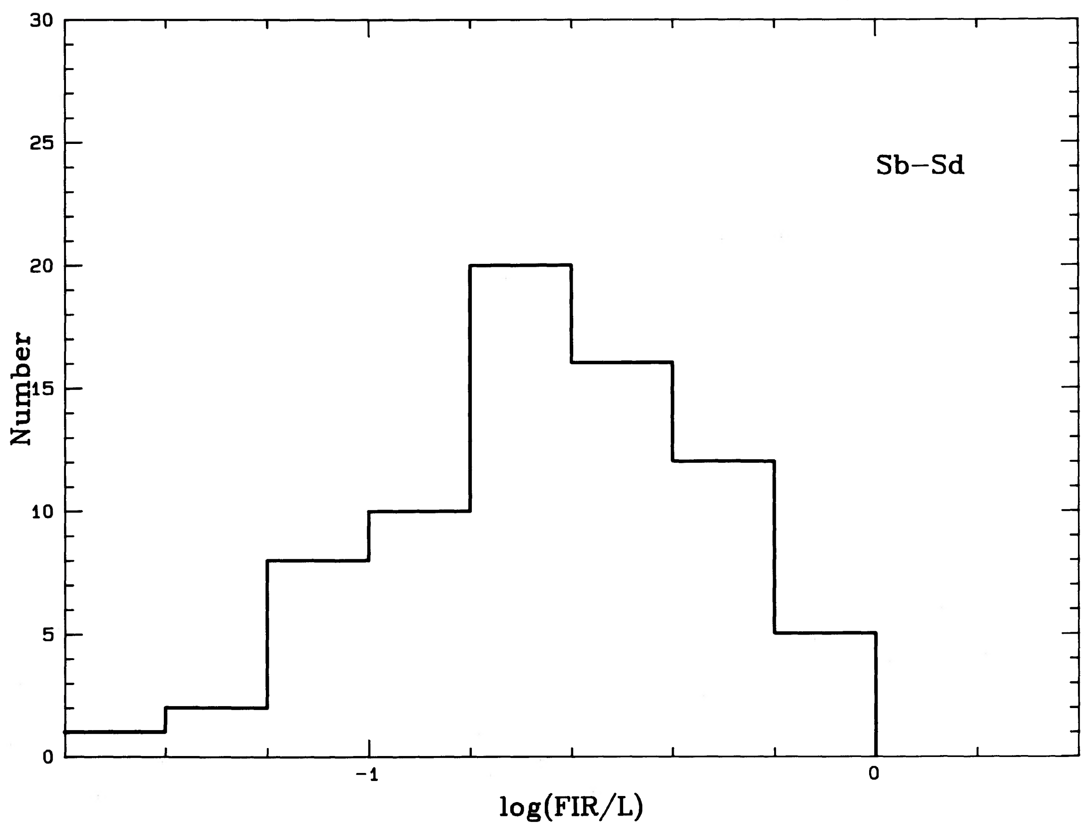


FIG. 12b

FIG. 12.—Histograms of the logarithm of the ratio of FIR to blue luminosity, for (a) BCDs and (b) spirals. The hatched portions of the BCD histogram represent galaxies undetected in FIR.

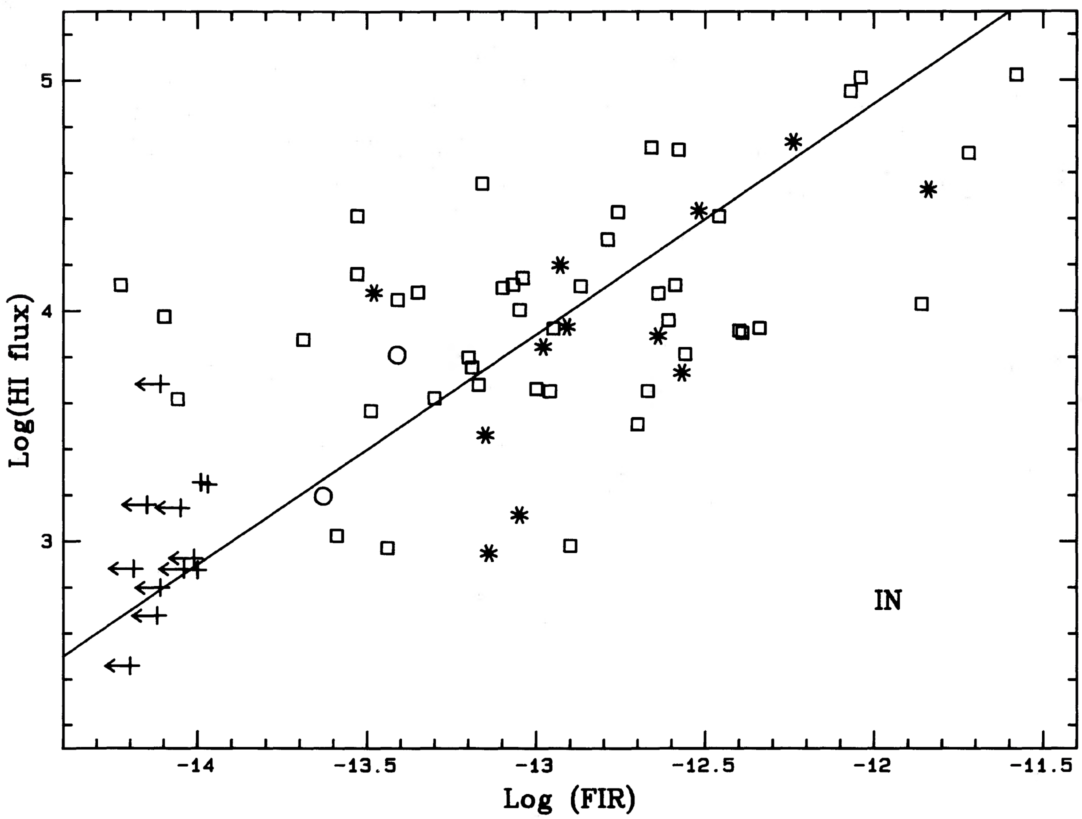


FIG. 13*a*

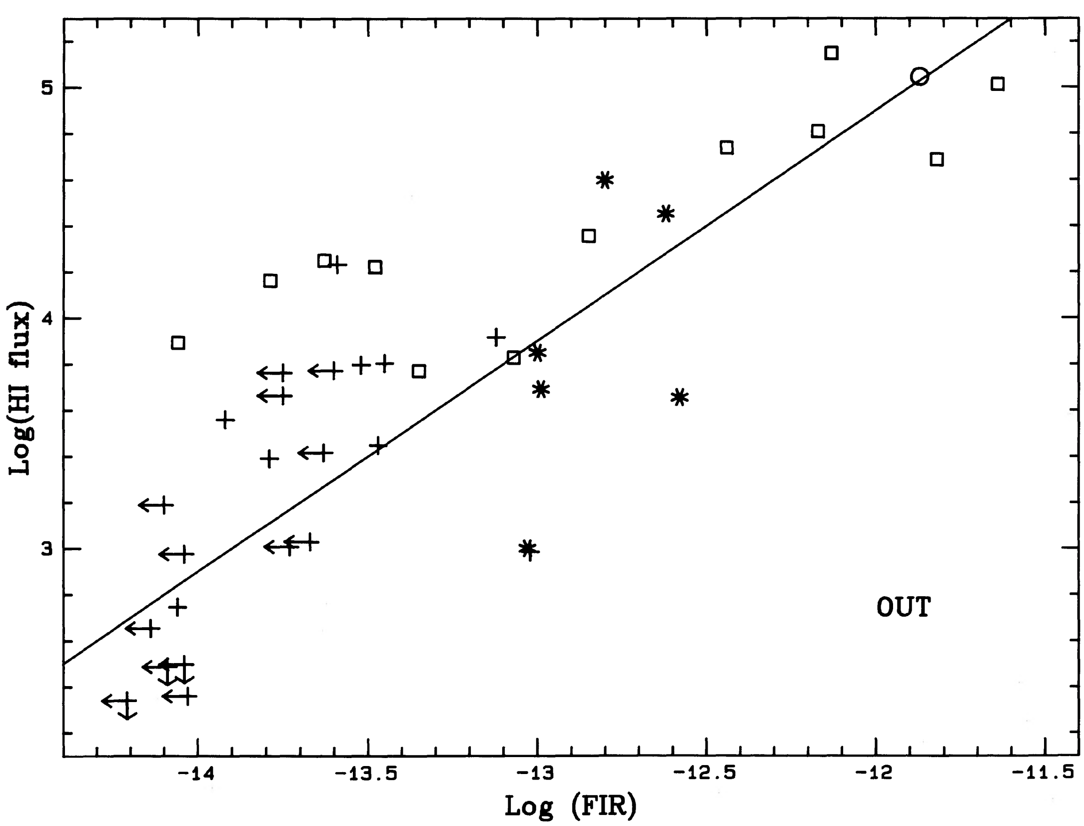


FIG. 13*b*

FIG. 13.—Scatter plots of log (H I flux), in mJy km s^{-1}, vs. log L_{FIR} as defined in the text. (*a*) Galaxies inside the 5° core (IN); (*b*) galaxies outside (OUT). Different symbols are used for Sb–Sbc (*asterisks*), Sc–Sd (*squares*), Sdm–Sm (*circles*), and BCD (*plus signs*). Galaxies undetected in one or both fluxes are shown at their upper limits, with arrows in the appropriate directions. The line represents constant L_{FIR}/M_H, for reference.

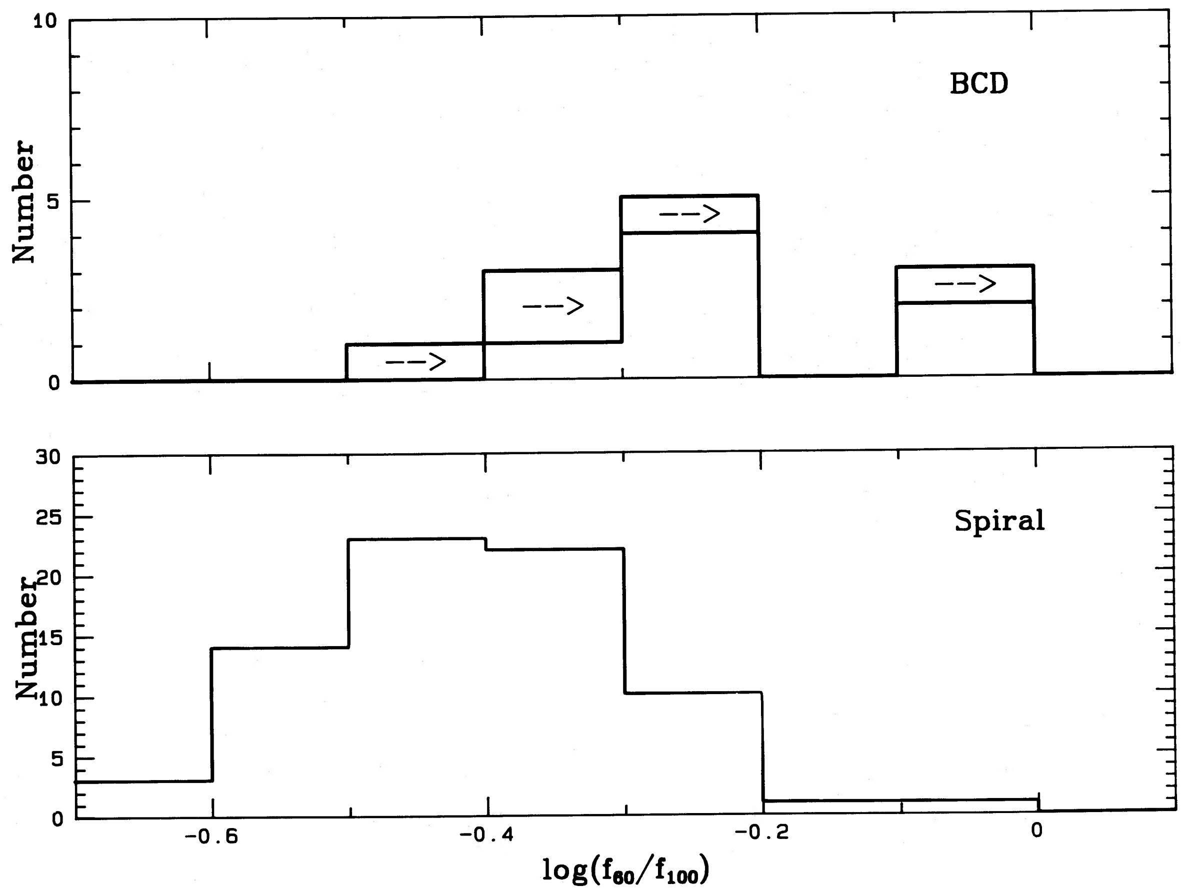


FIG. 14.—Histograms of the 60 μm/100 μm color ratios for detected BCDs (*upper panel*) and bright spirals (*lower panel*). BCDs detected in only one of the two bands are indicated with arrows pointing in the appropriate direction according to whether the ratio is an upper or a lower limit.

small fraction of gas converted into stars per 10^{10} yr, and there is no sign of an older stellar population from an initial phase of intense star formation (Gallagher, Hunter, and Tutukov 1984; Hunter and Gallagher 1985, 1986). For a given morphological type, the BST catalog shows a large scatter in blue surface brightness and luminosity and Kunth *et al.* (1985) cite evidence for star formation bursts aligned in order from redder to bluer in some blue Irr galaxies. Both of these observations are in keeping with the idea of sporadic star formation.

There has been some controversy as to whether the morphological sequence Sm to ImV is partly an evolutionary sequence or only a mass sequence (Hunter and Gallagher 1986; Gallagher and Hunter 1984; and references in each). The dynamical data in Paper I argue in favor of the latter: the H I profile width ΔV should be an indicator of total dynamical mass M_T in spite of any infalling halo (Vigroux, Stasinska, and Comte 1987; Loose and Thuan 1986), which can contribute at most a small fraction of the total H I mass given the steep-sided nature of many of our H I profiles. We showed in Paper I that ΔV, and hence M_T, decrease steadily (with some individual deviations) all the way from Sm to ImV.

The extreme class of pure BCDs ("blue compact dwarf galaxies") is obviously associated with a current burst of star formation, but there are controversies on the details. In particular, the optical diameters a (as defined in BST) tend to be very small and the corresponding surface brightness high, and there are two opposing models: (1) the galaxy might be intrinsically small both in diameter *and* mass M_T, with the burst of star formation "lighting up" the whole galaxy, or (2) the measured diameter a could refer only to the region of intense current star formation, with the enveloping galaxy appreciably larger but of such low surface brightness as to be missed on the du Pont plates of BST. The results summarized in § IV argue strongly against model 1 and for model 2: both for the velocity width ΔV_C, an indicator for the total mass M_T, and for the hydrogen mass $M_{\rm H}$, the distribution and mean values for the BCDs are similar to those for the whole distribution of morphological types from Sm through the Im classes. For these relatively large masses, the measured diameters a are then small and poorly correlated with other quantities, as would be expected for stochastic star formation regions.

The large values of $M_{\rm H}$ for BCDs argue against BCDs being star formation episodes associated with dE's (Bothun *et al.* 1986; SWS), since dE's are gas-poor (HHS; Bothun *et al.* 1986; Impey, Bothun, and Malin 1988). The large values of $M_{\rm H}$ and ΔV, coupled with the upper limits in § VI, also argue against another model in which BCDs are occasional star formation bursts over the whole extent of a separate class of galaxies which have small diameters but large masses: after the burst subsides, the measured diameter would be even smaller, but non–BCD Irr galaxies with large ΔV and small a are not observed, nor are optically invisible clouds with the required hydrogen masses. It has been suggested that many dwarf irregulars have been missed because they have either very small radius (Tyson and Scalo 1988) or very small surface brightness (Impey, Bothun, and Malin 1988; Phillipps, Davies, and Disney 1988). While this could affect number counts drastically, § VI shows that such objects could not have enough H I to be relevant for BCD evolution.

Model 2 states that the surface brightness is very low outside the star formation region in an extreme BCD. An extreme explanation would be that a BCD is a "first generation" of star formation in an otherwise "proto"-galaxy. We give arguments against this hypothesis in the next two subsections and favor *recurrent* bursts of star formation in small portions of dwarf irregulars. The dimming outside the burst region might be due to (1) intervals of $\gtrsim$a few times 10^8 yr between bursts plus (2) an initial mass function with few stars below about 3 $M_\odot$, say (stellar lifetimes a few times 10^8 yr).

b) "*First Generation*" *Galaxies and a* "*Special Epoch*" *for Clouds of Galaxies*

Let N_b be the number of BCD bursts during the last 10^{10} yr in a single Irr galaxy, and let t_b be the duration of one burst. If N_b were approximately constant, and if there were no "special epochs," the fraction g_B of dwarf irregulars in the BCD phase at any instant would be

$$g_B \sim N_b t_b / 10^{10} \text{ yr} . \tag{1}$$

Although early estimates for t_b were $\lesssim 10^7$ yr, the dynamical time scales for propagation of star formation are longer (Scalo and Struck-Marcell 1986; Struck-Marcell and Scalo 1987), and a galaxy may still have a BCD-like appearance up to $\sim 2 \times 10^7$ yr after a burst (Israel 1988). Including this "cooling-off" period in t_b, we provisionally adopt $t_b \sim 3 \times 10^7$ yr.

Next we consider the possibility that N_b varies considerably (Davies and Philipps 1988), and that the present is a "special epoch" for some galaxy clouds. Although rich galaxy clusters and the inner core of the Virgo Cluster must have formed a considerable time ago, typical galaxy groups may be in the process of "forming" just now (SWS), and some "clouds" of galaxies are only just now falling in toward the Virgo Cluster core (Tully and Shaya 1984). Dynamical time scales for groups and clouds are of order 10^9 yr, and we consider a scenario where some fraction f of dwarf irregulars have had little activity for the first $\sim 10^{10}$ yr, but for these galaxies the current $\sim 10^9$ yr is a special epoch for star formation. With N_b bursts during this epoch, equation (1) is replaced by $g'_B \sim N_b/30$. The extreme assumption of $N_b \sim 1$ has been invoked at least for a few galaxies like I Zw 18 (see below), but we can now give an upper limit to f on this assumption: If a fraction f of the 33 detected BCDs in Virgo are undergoing their first generation of star formation now, then about $f \times 33 \times 30$ will do so later and are now gas-rich, star-poor proto-dwarf galaxies. Each proto-dwarf would have at least as much hydrogen as a BCD (mean $M_{\rm H} \sim 3 \times 10^8\ M_\odot$; see Table 3), and considerably more if mass loss due to galactic winds is important during the first burst (Matteucci and Tosi 1985; Vader 1987; Wyse and Silk 1985). In § VI we gave an upper limit of about 100 gas clouds (down to an even smaller H I threshold) for Virgo. We thus have $f \gtrsim 0.1$, so that "first generation" galaxies may account for a few extreme cases such as I Zw 18 but not for an important fraction of the BCDs we see.

With $N_b > 1$, nonbursting galaxies must be visible dwarf irregulars, and the observed fraction of Irr galaxies in the BCD phase then gives us an estimate for N_b. We saw in § III that the LVC and W cloud have a higher than typical fraction of BCDs and may indeed be in a "special epoch" with $g'_B \sim \frac{1}{3}$. With an assumed epoch duration of $\sim 10^9$ yr, this gives $N_b \sim 10$. For the "nonspecial" parts of Virgo, the fraction is $g_B \sim 1/10$, giving $N_b \sim 30$.

An alternative model (SWS) supposes that a BCD results from infall of H I onto a dE during the collapse of a galaxy group or cloud. This does not violate the upper limits in § VI in an obvious way, since the protogalaxy is without gas over most of its life. Nevertheless, there are two weaker arguments against this version: (1) By analogy with high-velocity clouds near our Galaxy, it is likely that the accreting gas would be already neutralized when it has approached to within ~ 10 kpc of a dwarf elliptical galaxy. It must take $\gtrsim 10^8$ yr (~ 10 times the burst duration) for the gas to shrink down to the observed BCD size. These shrinking gas clouds would still be unresolved by the Arecibo beam and should therefore be detectable, but their predicted number, $\sim 10 \times 33$, exceeds our upper limit of ~ 100. (2) The W cloud at least has a few massive S0 galaxies in the same spatial and velocity region as the BCD/W cloud. Assuming that the two do indeed occupy the same physical space, since the accretion rate is proportional to the square of the galaxy mass, the massive S0 galaxies should be anomalously gas-rich, which does not seem to be the case (Chamaraux, Balkowski, and Fontanelli 1986).

c) *Chemical Abundance Measurements*

For a number of BCD and non-BCD dwarf irregular galaxies, various estimates of the gas abundance Z of heavy elements (mostly oxygen) have been made (Thuan 1985; Kunth and Sargent 1986; Campbell, Terlevich, and Melnick 1986; Zamorano and Rego 1986; Skillman *et al.* 1988; Axon *et al.* 1988). Except for DDO 155 = GR 8, the values for non-BCDs are only moderately low and are comparable to the Magellanic Cloud values, $Z \sim 0.1$–$0.3\ Z_\odot$. There are few abundance data for BCD galaxies in the Virgo Cluster, but elsewhere BCD abundances Z_m have been measured in the ionized gas, presumably in the star-forming regions of the BCDs. I Zw 18 has the lowest measured abundance, $Z_m \sim 0.03\ Z_\odot$, the same as DDO 155, but most other BCDs have larger abundances, comparable to those for non-BCD dwarf irregulars, whereas most dwarf ellipticals have lower values. However, Kunth and Sargent (1986) have pointed out that the mass involved in star formation in a present-day BCD burst is a very small fraction of the total gas mass M_g of the galaxy ($\sim M_g/300$, say), and that the heavy elements produced may be spread over as little as ~ 20 times more mass of ionized gas. If we were witnessing the "first generation" of BCD episodes, the average abundance $\bar{Z}$ for the whole galaxy could then be much smaller (by a factor ~ 15, say) than Z_m. We have already given arguments in the last subsection for the typical number N_b of bursts per BCD galaxy being $\gtrsim 10$, rather than $N_b \sim 1$. We now present some more qualitative arguments, based in part on our *IRAS* data.

d) *IRAS Results and the Dust-to-Gas Ratio*

The *IRAS* data discussed in § V led to the following conclusions: (1) the ratio of the far-infrared to blue luminosity, $L_{\rm FIR}/L_B$, is about the same for BCDs and spirals; (2) the FIR colors of BCDs are somewhat warmer than those for spirals; and (3) $L_{\rm FIR}/M_{\rm H}$ is smaller for BCDs than for spirals by a factor of 2 or 3. We infer from these results that the dust-to-gas ratios are smaller for BCDs than for spirals, as follows: We assume that (*a*) dust and gas are well mixed in both morphological classes (or at least mixed in comparable fashion), and the properties of the dust are similar; (*b*) the various phases of the interstellar medium (molecular, atomic, ionized) are in similar proportions; and (*c*) the relative spatial distributions of gas and heating sources are comparable. Observation 1 above suggests that these assumptions are not drastically wrong. We then conclude that the dust-to-gas ratio must be roughly proportional to $L_{\rm FIR}/M_{\rm H}$, and is therefore smaller for BCDs than for spirals by a factor of 2 or 3.

One way to avoid the preceding conclusion would be to postulate that BCDs contain substantially more dust, but that much of the dust remains too cold for it to have been observed by *IRAS*. Observation 2, however, implies just the opposite, that dust is *warmer* in BCDs. Another way out would be to suppose that less heating radiation is available to the dust in BCDs. While $L_B/M_{\rm H}$ is greater in spirals than in BCDs by perhaps 50% (see Fig. 1), the luminosity per H atom in the U band (where heating is more efficient) is comparable, since at similar B the BCDs are brighter than spirals at U by about 0.6 mag. Warmer colors for BCDs also are consistent with a greater heating intensity than for spirals; the model in Helou (1986) would infer from those colors that more than half the FIR emission in BCDs originates in dust exposed to a radiation field at least 10 times more intense than the radiation field in the solar vicinity. With comparable (or greater) heating flux per H atom in BCDs, the only way to end up with a reduced rate of conversion of UV into IR photons is to have less dust per H atom in BCDs than in spirals. If the dust is more concentrated around heating sources in BCDs than in spirals, the dust deficiency in BCDs could be even larger.

There have been some suggestions that the FIR emission in BCDs is *dominated* by that from material in the immediate vicinity of the star formation region. Young *et al.* (1986) and Leggett, Brand, and Mountain (1987) cite the strong $L_{\rm FIR}$/CO correlation in spirals as evidence that $L_{\rm FIR}$ is associated at least in part with molecular clouds. A study of extinction in I Zw 36 (Viallefond and Thuan 1983) suggests that the dust is most likely in molecular clouds around the star formation region, with relatively little in the H I envelope. Kunth and Sevre (1985), Wynn-Williams and Becklin (1986), and Wunderlich, Klein, and Wielbinski (1987) confirm that the strong FIR–radio continuum correlation, found by Dickey and Salpeter (1984), Helou, Soifer, and Rowan-Robinson (1985), and de Jong *et al.* (1985) for spirals, extends to (at least non-Virgo) BCDs. The contributions from the thermal and nonthermal components appear to differ between the two morphological samples, however (Klein, Wielebinski, and Thuan 1984; Sramek and Weedman 1986; Thuan 1986), and the details remain controversial.

Consider some BCD galaxy in Virgo with $M_{\rm H} \sim 3 \times 10^7$ $M_\odot$ and $L_B \sim 10^8$ $L_\odot$ (a ratio $M_{\rm H}/L_B$ slightly larger than for a spiral). There is still considerable uncertainty in the stellar initial mass function in a BCD episode, and hence in the production of UV photons and of heavy elements (Lequeux *et al.* 1981; Viallefond and Thuan 1983; Kunth and Sargent 1986; Scalo 1987). However, one possible model for a single episode producing the blue luminosity would convert slightly less than 10^5 $M_\odot$ into stars in slightly less than 10^7 yr, and could enhance the heavy-element abundance over a gas mass of $\sim 3 \times 10^6$ $M_\odot$, say, by an amount of perhaps $\Delta Z \sim 0.05$ $Z_\odot$. Consider now two opposite extreme models: (1) There have been $N_b \sim 20$ bursts (e.g., Israel 1988) so far, yielding a uniform abundance of $\bar{Z} \sim 0.1$ $Z_\odot$, and (2) the present burst is the first, so that the average $\bar{Z} \sim 0.005$ $Z_\odot$. In model 1 it seems reasonable that the *IRAS* ratio $L_{\rm FIR}/L_B$ should be comparable to that for a normal spiral (and $L_{\rm FIR}/M_{\rm H}$ slightly smaller); the overall abundance Z is down by only a factor of 5, and the dust/gas ratio should be down by not much more. Compared with a spiral, the BCD starlight is of shorter wavelength in the mean and the absorption efficiency per dust gain is higher, so that the two effects should compensate for each other. It is also reasonable that the observed CO emission relative to H I should be $\sim$0.1 times that for a spiral, as observed (Tacconi and Young 1987). However, it seems unlikely that one could get anywhere near enough dust grains in model 2 to produce the observed $L_{\rm FIR}/L_B$ ratio: the overall abundance of grain-producing elements is down by another factor of $\sim$4 even in the burst region, and there is not enough time for the canonical grain production mechanism, the outflow from stars of intermediate mass. (One would have to invoke good grain production efficiency in supernova ejecta.) Furthermore, the 90% of the galaxy's gas mass outside the burst region would be essentially without dust grains, in addition to being weakly irradiated, and could not contribute to the absorption/reemission.

VIII. SUMMARY

We have studied correlations between various properties of the BCD galaxies in the Virgo Cluster, using new H I data for the entire sample of BCDs along with data for all Irr and spiral galaxies in the Virgo Cluster Catalog (BST); upper limits on the number and mass of H I clouds not cataloged by BST; *IRAS* data on BCDs and bright spirals in Virgo; and previously cataloged optical data (BST; GH). On the observational side, we have found the following:

1. BCDs have the least centrally condensed, but most highly subclustered, distribution in position and velocity. Two clouds in particular, one of low and negative heliocentric velocity galaxies superposed on the cluster core (LVC), and another in the general vicinity (both in position and velocity) of the W group, are favored. Other subgroups have few BCDs.
2. At constant mass (as indicated by H I profile width ΔV_C), BCD galaxies are comparable to non–BCD irregulars in both blue luminosity L_B and H I flux; they are, however, significantly smaller in diameter a by a factor of 2–3 than Irr galaxies of the same L_B, H I flux, or ΔV_C.
3. For BCDs alone, L_B and a are reasonably well correlated only for the largest and brightest; for $B_T \gtrsim 15.7$ there is essentially no correlation. Correlations involving ΔV_C are relatively weak, at least in part due to our lack of information on BCD inclinations. H I flux and L_B are well correlated for the brightest objects ($B_T \lesssim 14.5$). There is also a reasonably good correlation between H I flux and a for those with H I flux $\gtrsim 800$ mJy km s^{-1}. The distribution of ΔV_C and H I flux shows that BCDs in Virgo have masses comparable to those for Magellanic irregulars; their L_B is not anomalously large for their mass.
4. About one-third of the BCDs were detected by *IRAS* at 60 μm or 100 μm, mostly at intensities just above the threshold sensitivity. The *IRAS*-detected objects are mainly those with larger L_B and a. The warm *IRAS* colors suggest that $L_{\rm FIR}$ is dominated by emission from the star formation regions.
5. We detected no optically invisible H I clouds, even though the Arecibo telescope would be quite sensitive to proto–dwarf galaxies.

We have suggested the following theoretical interpretations:

1. When a dwarf irregular galaxy has a strong star formation episode (temporarily becoming a pure BCD), its optical

luminosity is redistributed rather than increased. One possibility is that a strong BCD episode is more likely when normal star formation has been quiescent for an unusually long time.

2. It is not clear whether the number ratio of BCDs to ordinary dwarf irregulars depends appreciably on the environment, but the ratio is particularly large in two Virgo subgroups and only $\sim 1/10$ for other subgroups. The BCD–rich subgroups may be in a "special dynamic epoch" of duration 10^9 yr or so.

3. We interpret the relatively low $L_{\rm FIR}/M_{\rm H}$ ratios for BCDs to mean that their dust-to-gas ratios are deficient compared with those for spiral galaxies, but only by a modest factor of 2 or 3. This, and our failure to detect any "proto-dwarf" H I clouds, suggests that first-generation BCD episodes must be rare. There is considerable uncertainty (and controversy in the literature) regarding the duration t_b of a BCD–like burst, the number N_b of bursts, and the resulting chemical abundances Z. To explain the relatively high rate of occurrence of BCDs in Virgo, we favor rather large values for all three: $t_b \sim 3 \times 10^7$ yr, $N_b \sim 10$–30, and $Z \sim 0.3\ Z_\odot$.

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