Improved Searches for HI in Three Dwarf Spheroidal Galaxies

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ABSTRACT

Previous searches for HI in our Galaxy's dwarf spheroidal companions have not been complete enough to settle the question of whether or not these galaxies have HI, especially in their outer parts. We present VLA observations of three dwarf spheroidals: Fornax, Leo II, and Draco, all of which have known stellar velocities. The new data show no HI emission or absorption. Column density limits in emission are 4×10^{18}–7×10^{18} cm^{-2} in the centers of the galaxies. The importance of the new observations is that they cover larger areas than previous searches and they are less plagued by confusion with foreground (Galactic) HI. The apparent absence of neutral gas in the Fornax dwarf spheroidal is especially puzzling because recent photometry shows evidence of stars only 10^8 years old. We discuss whether the VLA observations could have missed significant amounts of HI.

Subject headings: galaxies: individual (Fornax, Leo II, Draco)— galaxies: ISM— galaxies: evolution— Local Group

1. Introduction

Dwarf spheroidal galaxies, the smallest companions of our own Milky Way galaxy, were long thought to be old and dead galaxies devoid of any interstellar medium. They show no sign of current star formation. Furthermore, searches for HI emission from the dwarf spheroidal galaxies (Knapp et al. 1978; Mould et al. 1990; Koribalski, Johnston, & Otrupcek 1994) found no evidence of gas in the galaxies, with one possible exception (Carignan et al. 1998). Optical and UV absorption experiments for Leo I (Bowen et al. 1995, 1997) also detected no gas. Thus, it is commonly assumed that the dwarf spheroidal galaxies have no neutral ISM at all.

However, recent work on color-magnitude diagrams of the Local Group dwarf spheroidals contradicts this picture of old, dead galaxies. Most of the dwarf spheroidals experienced periods of star formation activity at various times from 10 Gyr to 1 Gyr ago (e.g. Smecker-Hane 1997 and references therein; Hurley-Keller, Mateo, & Nemec 1998). The Fornax dwarf spheroidal even seems to contain some very young stars, $\sim 10^8$ yrs old (Stetson, Hesser, & Smecker-Hane 1998). Since star formation requires neutral gas, these facts clearly demonstrate that the spheroidals have had an interstellar medium (ISM) in the past several Gyr or less. This ISM could have existed in the spheroidals for most of their lifetimes, or it could have been captured from some external source such as the Magellanic Stream, high velocity clouds, or a cooling intracluster medium (e.g. Silk, Wyse, & Shields 1987). Regardless of its origin, star formation histories show that the spheroidals had significant amounts of neutral gas in the recent past. Therefore, they might be expected to have an interstellar medium today.

The question of whether there is neutral gas in the dwarf spheroidals has important implications for our understanding of star formation and the evolution of galaxies. If the dwarf spheroidals had neutral gas in the past but they have none now, what happened to the gas? Two popular ideas are that (1) the neutral gas in the spheroidals may have been stripped by interactions with the outer halo of our Galaxy, or that (2) a burst of star formation activity, with attendant supernovae and stellar winds, may have evacuated the neutral gas from the galaxies. Skillman & Bender (1995) discuss some advantages and disadvantages of these ideas. Another possibility might be that if the gas density were lowered, neutral gas could be ionized by the interstellar UV field (e.g. Bland-Hawthorn, Freeman, & Quinn 1997; Bland-Hawthorn 1998). In any case it is clear that the presence or absence of neutral gas in the dwarf spheroidals is an important clue to their history.

The existing data on the HI content of dwarf spheroidals is not complete enough to answer the question of whether they have any neutral gas (Section 2). Therefore, we have conducted new searches for HI in and around the Leo II, Fornax, and Draco dwarf spheroidal galaxies using the VLA's D configuration. These observations cover larger regions than before and limit possible confusion with foreground Galactic HI. Subsequent sections describe what was previously known about the HI contents of dwarf spheroidals, the current observations, and the implications of these new data.

2. Existing Data on the HI Content of Dwarf Spheroidals

It is commonly repeated that dwarf spheroidals have no HI, but an examination of the published results shows that the data are simply not adequate to make this conclusion. The basic problem is incompleteness. HI surveys (Hartmann 1996; Huchtmeier & Richter 1986) have covered a large fraction of the Northern sky or have searched many galaxies, but at poor sensitivity. Searches for optical and UV absorption lines in front of quasars near Leo I (Bowen et al. 1995, 1996) provide extremely low column density limits, but they only probe three points at radii of 3, 5, and 10 times the tidal radius of the galaxy. (In this paper, core and tidal radii for the dwarf spheroidals are taken from the work of Irwin & Hatzidimitriou [1995].) Even the published HI observations (Knapp et al. 1978; Mould et al. 1990; Koribalski et al. 1994) are inconclusive, for reasons described below.

Existing searches for HI in dwarf spheroidal galaxies suffer from two problems. The major problem with existing single-dish observations is that they searched only a small fraction of the galaxies' areas. In the case of the Draco and Ursa Minor spheroidals (Knapp et al. 1978) a beam with a half-power radius of $5'$ was centered on galaxies whose core radii (semi-major axes) are $9'$ and $16'$. Therefore, less than one third of the area inside the core radii of these galaxies has been observed. Similar arguments apply to the Sagittarius dwarf spheroidal, Fornax, and Carina (Koribalski et al. 1994; Knapp et al. 1978; Mould et al. 1990). The small HI mass limits given for these galaxies are commonly misunderstood and misused because they apply only to the small area which has been observed, not to the entire galaxy. Neutral gas could be present in the unobserved parts of the optical galaxies.

Gas could also be present in the outer parts beyond the optical galaxies. Blow-out models (e.g. Dekel & Silk 1986; De Young & Heckman 1994; Mac Low & Ferrara 1997) provide some reasons why gas might be found in the outer parts of quiescent dwarf galaxies instead of in the center. Furthermore, several dwarf galaxies are indeed observed to have HI minima centered on the galaxy and HI rings (or partial rings) outside the optical galaxy. These include M81 dwarf A (Sargent, Sancisi, & Lo 1983; Puche & Westpfahl 1994), Sag DIG (Young & Lo 1997), and even the dwarf spheroidal Sculptor (Carignan et al. 1998). It is not clear whether the blow-out models mentioned above explain the observed HI rings. In any case it cannot be assumed that all of the gas should be in the centers of the dwarfs, where previous searches have been made.

Another problem with single-dish observations of the dwarf spheroidals is that HI gas at velocities close to 0 km s^{-1} could have been overlooked because of confusion with Galactic HI. The best example of how this can happen is the case of the Phoenix dwarf (sometimes referred to as a "transition" galaxy between irregulars and spheroidals). Phoenix was observed with a single-dish telescope (Carignan et al. 1991) and subsequently with the VLA (Young & Lo 1997). The VLA observations detected a cloud of HI at -23 km s^{-1}, but the single-dish observations did not detect the cloud because this velocity lies under partially-subtracted Galactic HI which the VLA resolves away. More recent interferometric observations of Phoenix show even more HI than Young & Lo (1997) found (Carignan 1998, private communication). Knapp's (1978) observations of Fornax and Leo II might also suffer from confusion with Galactic HI. The problem is exacerbated by the fact that the velocity of Leo II was not known at the time the observations were made. Leo II's optical velocity is +76 ± 1 km s^{-1} (Vogt et al. 1995), but at that position the Galactic HI extends out to velocities of almost +120 km s^{-1} (Young & Gallagher 1998). Thus, the detection efforts made to date are limited and cannot give a conclusive answer about whether the spheroidals really have no HI.

3. Observations

We address some of the problems of previous observations by using the NRAO Very Large Array (VLA)[1] to search for HI emission in and around the Fornax, Leo II, and Draco dwarf spheroidal galaxies. For Draco, these VLA observations cover a much larger fraction of the galaxy than has been previously searched. For Leo II and Fornax, these VLA observations suffer much less from confusing local HI emission. One reason that there is less confusion in the VLA images is that most of the local HI emission is simply not detected. Unlike a single-dish telescope, the VLA acts as a high-pass spatial filter. Most of the radiated power from foreground Galactic HI is on relatively low spatial frequencies (large angular scales of degrees or greater). Thus, most of the Galactic HI does not appear in the VLA images. In addidition, spatial mapping allows us to distinguish gas that is probably not associated with the galaxy.

The observational setups are described in Table 1. The observations were made in the D and DnC configurations in 1997–1998. They cover a bandwidth of 1.56 MHz, which gives a usable velocity range of about 290 km s^{-1} centered close to the optical velocity of the galaxy as determined from stellar absorption lines. The velocity resolutions were 2.6 km s^{-1}, based on previous experience detecting HI clouds in the vicinity of the Phoenix and Tucana dwarf spheroidals (Young & Lo 1997; Oosterloo et al. 1996). The primary beam of the VLA at 21cm has a full width at half maximum of $31'$, i.e. a response of 50% at a radius of $15.5'$, and a response of 10% at a radius of $26.4'$ (Napier & Rots 1982). The data were mapped using natural weight and again with a tapering weight function which emphasizes large spatial structures, both before and after continuum subtraction. Continuum emission was subtracted directly from the combined dataset using the task UVLIN in the AIPS package. Table 1 gives the positions, velocity ranges covered, beam sizes, noise levels, and column density limits for these observations. The beam linear sizes are computed assuming

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[1] The National Radio Astronomy Observatory is a facility of the National Science Foundation, operated under cooperative agreement by Associated Universities, Inc.

the distances given in Irwin & Hatzidimitriou (1995).

The phase/pointing centers of the VLA observations, given in Table 1, are quite close to the actual centers of the galaxies. The phase/pointing centers for Leo II and Draco are less than $1'$ away from the galaxy centers given in Irwin & Hatzidimitriou (1995). The Fornax dwarf spheroidal is observed to have significant asymmetrical structure, with the peak stellar density about $6'$ northeast of the centroid of the lowest isophotes (Stetson et al. 1998). The VLA phase/pointing center is between the peak stellar density and the galaxy centroid, about $2'$ southwest of the position of peak stellar density. The center velocities in Table 1 are also within 6 km s^{-1} of the most recently determined heliocentric stellar velocities, which are 53 ± 2 km s^{-1} for Fornax (Mateo et al. 1991), 76 ± 1 km s^{-1} for Leo II (Vogt et al. 1995), and -294 ± 3 km s^{-1} for Draco (Hargreaves et al. 1996).

4. Results

We find no evidence for any HI emission or absorption that can be associated with the dwarf spheroidal galaxies. Sensitivity limits for HI emission are given in Table 1 and are typically 5×10^{18} cm^{-2} at the galaxy center, twice that at the VLA half-power point (radius $15.5'$), and 5×10^{19} cm^{-2} at the VLA 10% power point (radius $26.4'$). The column density limits are given as the column density of a 3σ signal in three consecutive channels. For purposes of comparison, the low column density HI clouds observed near the Sculptor, Phoenix, and Tucana dwarfs peak at 2×10^{19} cm^{-2} (Carignan et al. 1998), 4×10^{19} cm^{-2} (Young & Lo 1997), and 8×10^{19} cm^{-2} (Oosterloo et al. 1996), respectively. We argue in Section 5 that there is not likely to be a significant amount of HI which we have not detected, especially in the centers of the galaxies.

Figures 1, 2, and 3 show isopleth maps of the galaxies (Irwin & Hatzidimitriou 1995) along with the half-power and 10% power circles of the VLA primary beam. Table 1 gives the major axis core radii and tidal radii of these galaxies, taken from Irwin & Hatzidimitriou (1995). For Leo II, the column density limit is 4.3×10^{18} cm^{-2} at the center of the galaxy and 5.2×10^{18} cm^{-2} at the tidal radius of the galaxy. Thus, effectively all of Leo II has been searched at good sensitivity (see also section 5). For Draco, the detection limit is 7.1×10^{18} cm^{-2} at the center of the galaxy, increasing to 8.7×10^{18} cm^{-2} at the (major axis) core radius, and about 7×10^{19} cm^{-2} at the tidal radius. Since the tidal radius of the galaxy is approximately equal to the VLA's 10% power radius, any HI associated with the galaxy would most likely be within the VLA field of view. However, the sensitivity at Draco's tidal radius is probably not good enough to exclude the presence of HI there (section 5). In the case of Fornax, the detection limit is 4.6×10^{18} cm^{-2} at the galaxy center and 7.9×10^{18} cm^{-2}

at the core radius. The galaxy's tidal radius (71′) is much larger than even the VLA's 10%-power radius. Thus, there might still be undetected HI somewhere between the core radius and the tidal radius of Fornax or Draco.

We find some HI emission in the data cubes, but it is undoubtedly from foreground Galactic HI. Galactic emission in these VLA images takes the form of large-scale (∼20′) positive and negative features at velocities near 0 km s^{-1}; the negative features arise because the VLA has resolved out most of the total flux. Figures 4, 5, and 6 show spectra constructed from each data cube and illustrate that the emission features are not associated with the dwarf galaxies in velocity. In the case of the Fornax dwarf the Galactic HI is seen at velocities between 19 and −22 km s^{-1} (heliocentric), with greatest intensities at two peaks at about 9 and −4 km s^{-1}; the galaxy's stellar velocity is +53±2 km s^{-1} (Mateo et al. 1991). Near Leo II, Galactic HI is observed between velocities of 3 and −59 km s^{-1}, with greatest intensities at −2 and −41 km s^{-1}, in agreement with a single-dish spectrum of Leo II (Young & Gallagher 1998). The stellar velocity of Leo II is +76±1 km s^{-1} (Vogt et al. 1995). No Galactic HI is observed in the Draco field. The VLA has effectively removed contamination from Galactic HI at the velocities of the dwarf galaxies, so we conclude that we have not missed any dwarf galaxy emission which is hiding behind Galactic HI.

There are a number of background continuum sources in each of the VLA fields, but no absorption is detected towards any of them. Table 2 presents the positions, peak flux densities, and optical depth limits (3σ) for the brightest continuum sources in each field. The positions quoted are simply those of the brightest pixels and should not be assumed to be more accurate than 0.5 pixel (5″–10″). The last column also gives the distance between the continuum source and the galaxy center. Since none of the continuum sources are particularly bright, the column density limits in absorption are not as meaningful as the limits in emission. For example, the smallest optical depth limit is 0.11 for a source 22′ away from the center of Draco; for this source, the column density upper limit is $N_{HI} < 5.2 \times 10^{17}\, T_S$ cm^{-2}, and a typical spin temperature T_S of 100 K would give column density limits of 5×10^{19} cm^{-2}.

5. Discussion

Interferometers, by their nature, cannot detect very smooth spatial structures. However, it is unlikely that HI in the dwarf spheroidal galaxies has escaped detection by reason of being too smooth for the VLA to detect. The present datasets include baselines as short as 170 λ (20′) for all three galaxies, and the VLA can be expected to image structures as large as 15′ (Perley 1997). At the adopted distances of these spheroidals,

$15'$ corresponds to linear sizes of 520 pc (Fornax), 900 pc (Leo II), and 310 pc (Draco). Thus, HI in the spheroidals could be “resolved out” by the VLA only if it was very smooth on scales smaller than at least 300–900 pc. Such a situation would be highly unusual, as every other galaxy which has been observed in HI emission at high resolution shows small scale structures. Kalberla et al. (1985) found structures as small as 0.5 pc – 1 pc in Galactic HI; a mosaic of HI in the Small Magellanic Cloud shows intricate structure down to scales of 30 pc (Staveley-Smith et al. 1997). If HI structures are due in large part to star formation activity, the dwarf spheroidals might indeed have relatively smooth interstellar media. However, the scales involved, at least 300 pc, are so large that the absence of any structure seems a remote possibility. Furthermore, while smoothly distributed gas could not be detected in emission, it *could* be detected in absorption against the point sources, and no absorption was found.

We consider it possible, but unlikely, that HI could exist in the dwarf spheroidals at column density levels below the sensitivities achieved in these VLA observations, especially in the galaxy centers. HI simply does not seem to exist at low column density levels in the outer parts of galactic systems. Sensitive observations of a spiral galaxy (van Gorkom 1993) show that the HI disk of the spiral cuts off sharply when the HI column density reaches about 10^{19} cm^{-2}. A similar effect is seen in high velocity clouds, where Colgan et al. (1990) observe a tendency for the HI in the clouds to cut off sharply at column densities below $5{\times}10^{18}$ cm^{-2}. Corbelli & Salpeter (1993a, 1993b) and others have argued that these HI cutoffs are probably caused by ionization by the galactic and/or extragalactic UV radiation field. In this picture, hydrogen could not exist in neutral form in the dwarf spheroidals at column densities below about 10^{19} cm^{-2}. (And because of the high spatial resolution of these VLA images, 30–75 pc, the column density of any HI should not be diluted much by a small beam filling factor.) The observed column density limit for Leo II is well below 10^{19} cm^{-2} even beyond the tidal radius of the galaxy; therefore, it is unlikely that Leo II contains significant amounts of HI. For Draco and Fornax, the column density limits rise above 10^{19} cm^{-2} between the core radius and the tidal radius. For these galaxies, it is highly unlikely that there is significant HI within the core radii, but we cannot rule out the presence of HI at column density levels of a few times 10^{19} cm^{-2} between the core radius and the tidal radius.

6. Implications

The stellar population of Leo II is predominantly made up of stars with ages between 7 and 14 Gyr, and the stars in Draco are at least 10 Gyr old (Smecker-Hane 1997 and references therein; Grillmair et al. 1998). However, recent observations of Fornax (Stetson, Hesser, & Smecker-Hane 1998) indicate that there are a number of young stars in that galaxy, so that the absence of neutral gas in the center of Fornax becomes an interesting puzzle. The photometry of Stetson et al. (1998) reveals a large number of bright blue ($B - R < 0$) stars which are interpreted as a young main sequence with an age of only 100 to 200 million years. These young stars are concentrated in the center of the galaxy, with a distribution much like that of the bulk of the stars in Fornax. Figure 7, which is based on the data of Stetson et al. (1998), shows the distribution of the bright blue stars in Fornax and in the VLA field of view.

The young stars in Fornax are concentrated in the center of the VLA field of view; and as little as 10^8 years ago, these stars must have been associated with neutral gas. We infer two possibilities: either (1) the gas that formed the young stars in Fornax is now ionized or molecular, and has not been detected; and/or (2) the neutral gas and the young stars parted company in the last 10^8 years. Perhaps the neutral gas was ejected from the galaxy, as in the popular "blow-out" models (e.g. Mac Low & Ferrara 1998, and references therein). Since the one-dimensional velocity dispersion of the stars in Fornax is 11 ± 2 km s^{-1} (Mateo et al. 1993), gas moving at the escape speed of 38 km s^{-1} would reach the outer edge of the VLA field of view ($26' = 920$ pc) after only 2.4×10^7 yr. Apparently, enough time has elapsed to get rid of the gas which formed the young stars. If neutral hydrogen existed at some point in the past, and then expanded because of blow-out caused by star formation, its column density could drop significantly and it might now exist in an ionized state at very low emission measure. The presence of these young stars and the apparent absence of neutral gas is a puzzle which we cannot resolve at this time.

7. Summary

We present VLA searches for HI in the Fornax, Leo II, and Draco dwarf spheroidal galaxies. No HI was detected in these galaxies, either in emission or absorption. In all three cases the VLA observations cover larger areas than have been previously searched, and for Fornax and Leo II the new data have the important advantage of removing possible confusion with Galactic HI. For Leo II, the column density limit in emission is 5×10^{18} cm^{-2} out to the tidal radius. For Fornax and Draco the column density limits are 4×10^{18} and 7×10^{18} cm^{-2} in the galaxy centers, increasing to 10^{19} cm^{-2} at points between the core radii and the tidal radii. In the Draco dwarf galaxy we also find HI optical depth limits $\tau < 0.1$ towards two continuum sources at 1.9 and 2.4 core radii from the center. From these observations we conclude that there is no significant HI within the tidal radius of

Leo II or in the centers of Fornax and Draco. It will be necessary to observe still larger areas to determine whether there is HI in the outer parts of Fornax and Draco. However, these observations are much more complete than previous ones, and they close important loopholes in assessing the question of whether there is or isn't HI in the spheroidals.

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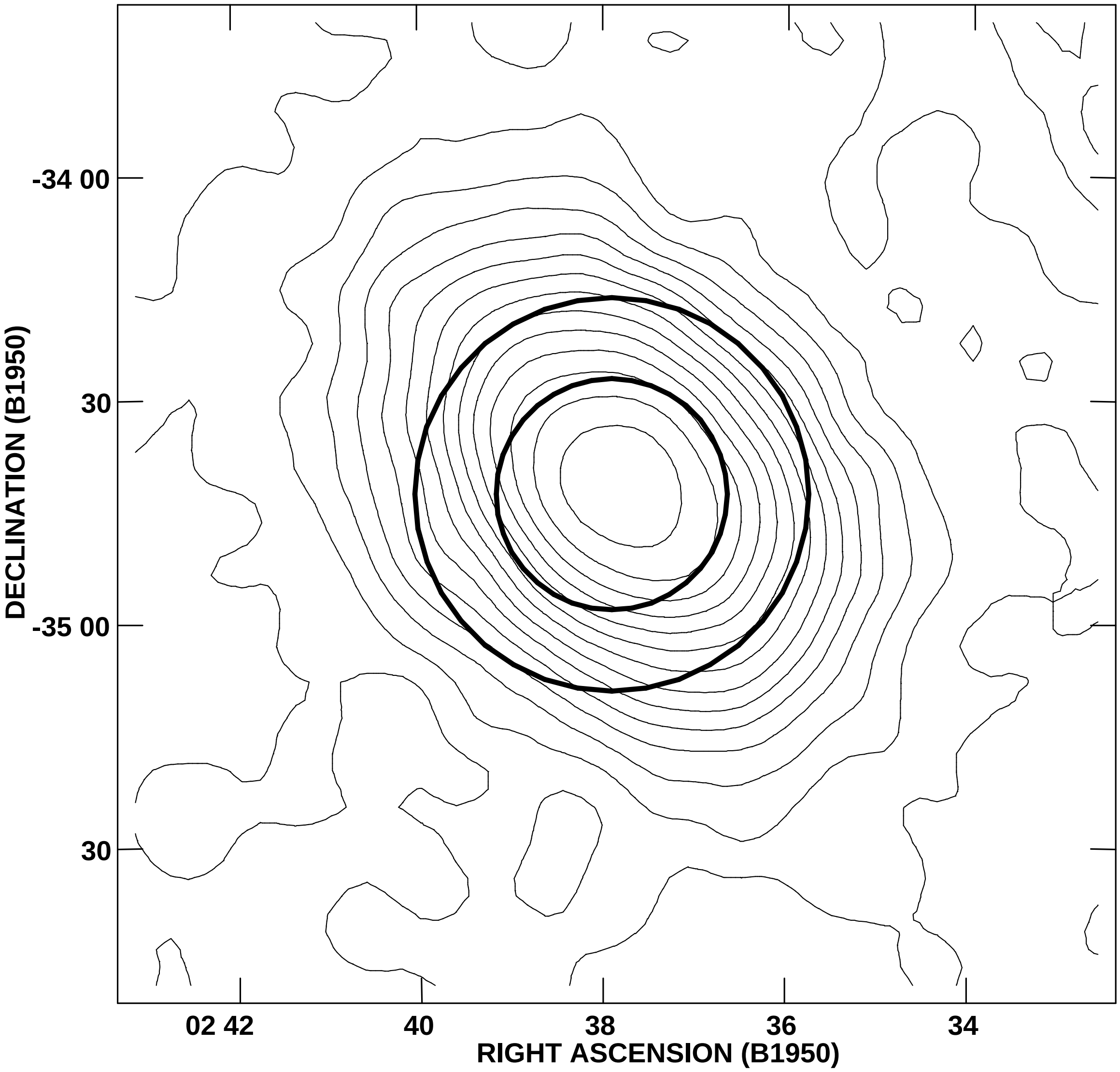


Fig. 1.— Optical extent of the Fornax dwarf spheroidal galaxy compared to the VLA field of view. The light contours show the isopleth map of Irwin & Hatzidimitriou (1995), with the same contour levels described in that paper. The heavy circles show the VLA half-power points (radius 15.5′) and 10% power points (radius 26.4′).

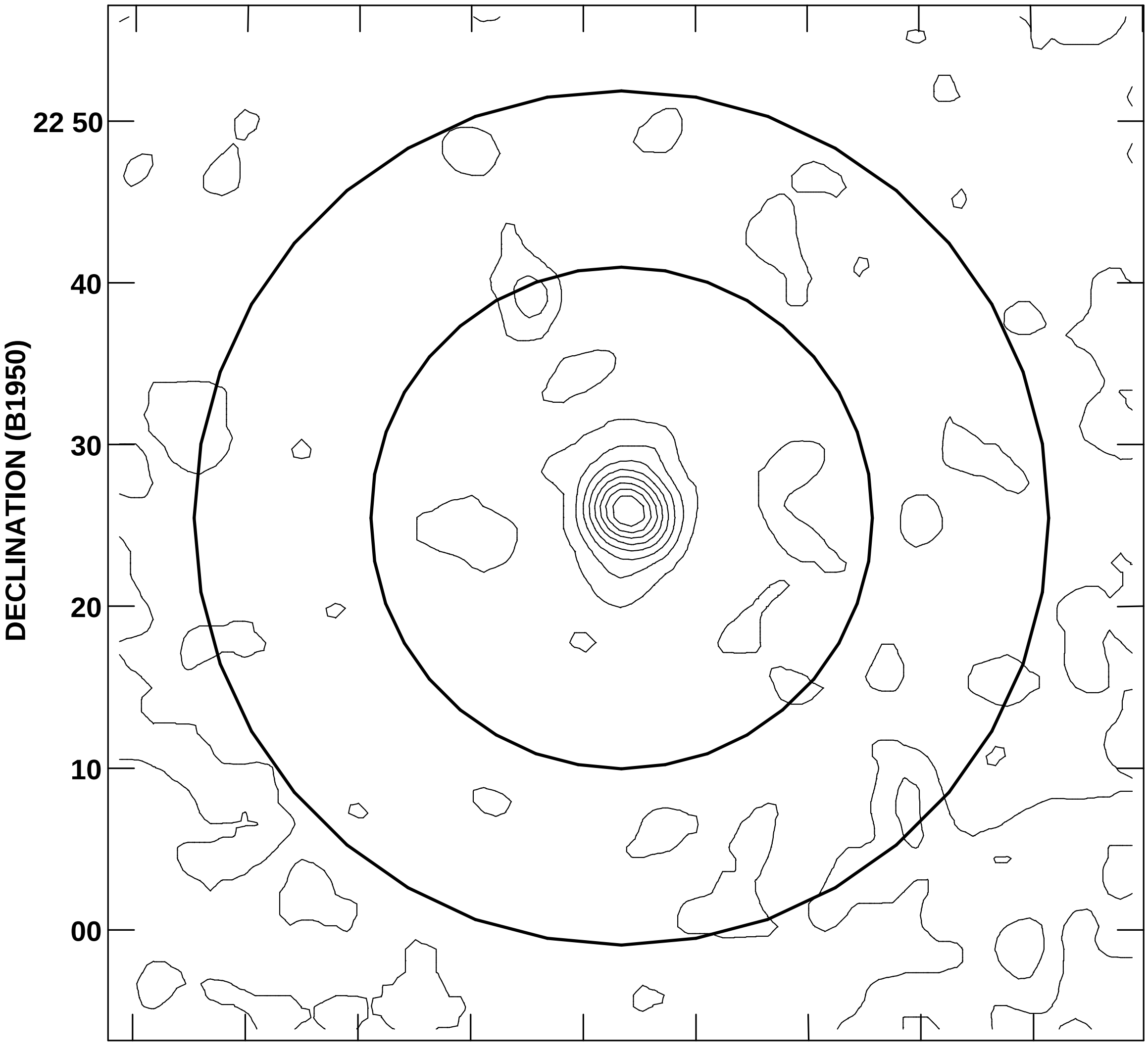
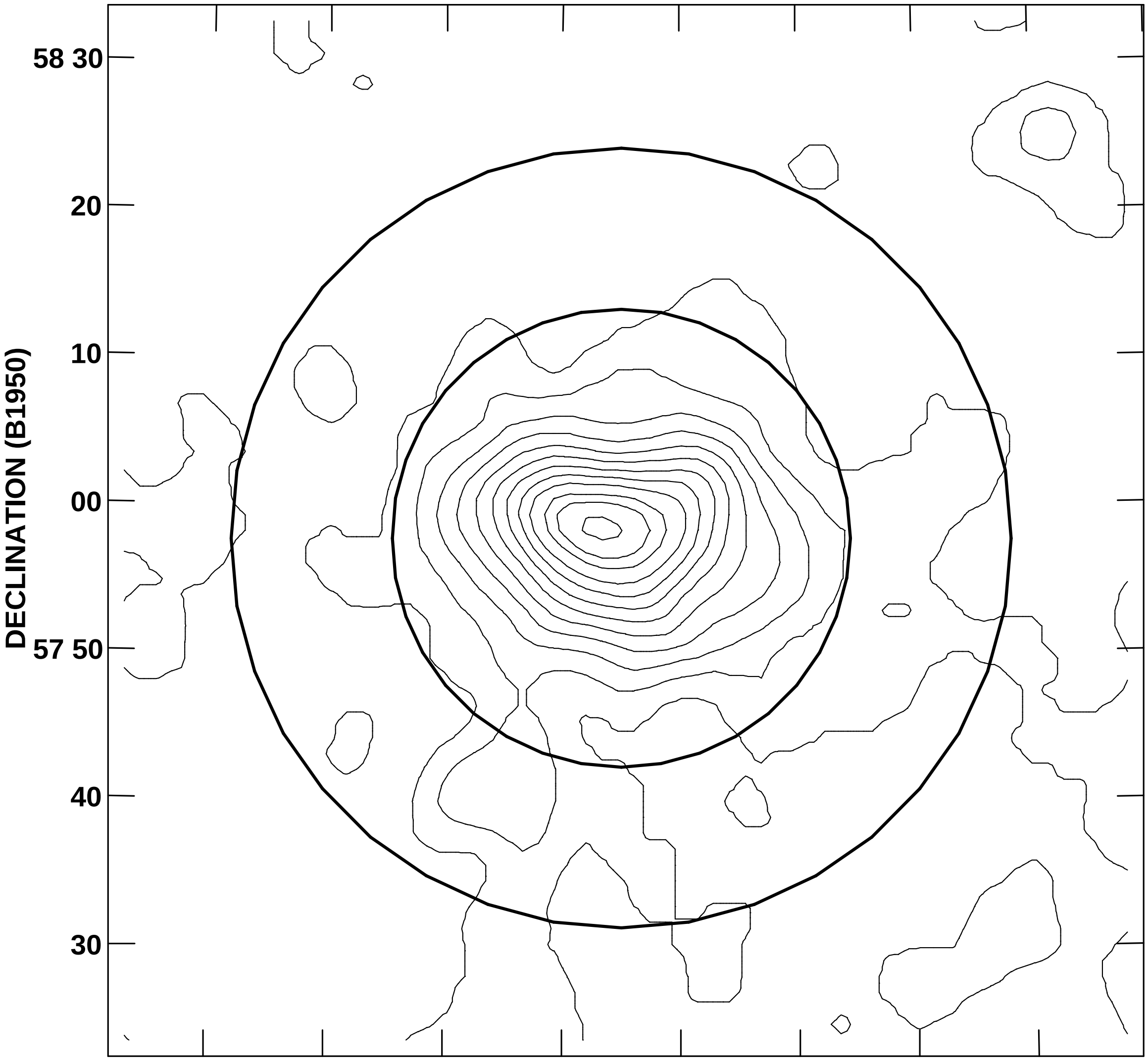


Fig. 2.— Same as Figure 1, for Leo II.



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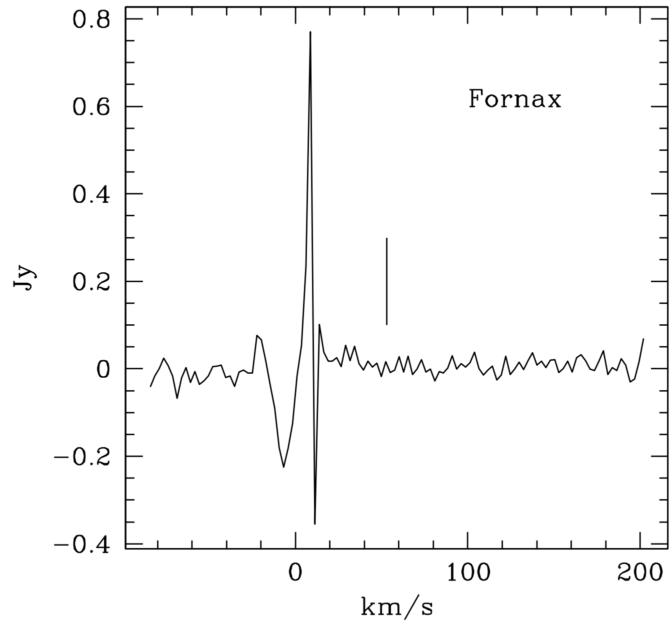

Fig. 4.— Spectrum from Fornax's data cube. This spectrum is a sum over the area inside the half-power point, after correction for the primary beam. The optical velocity of the galaxy is marked with a vertical line. The strong positive and negative features near 0 km s^{-1} (heliocentric) arise from foreground Galactic HI.

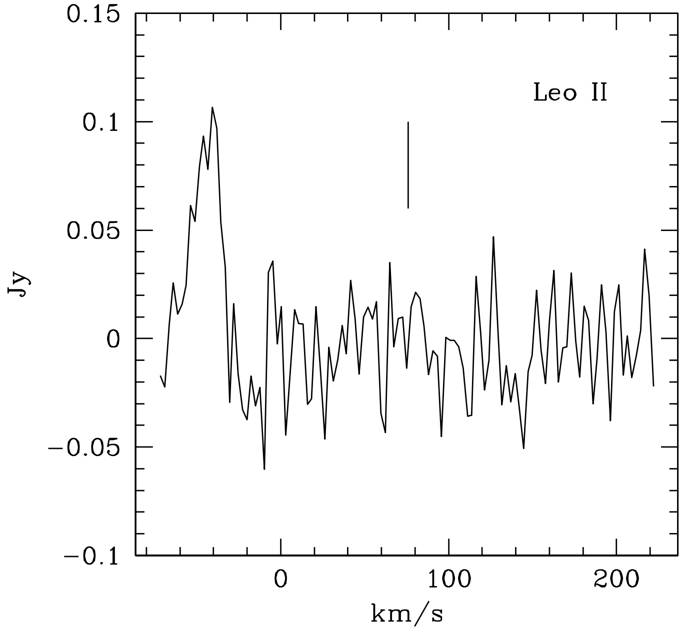

Fig. 5.— Similar to Figure 4, for Leo II. The features at velocities lower than 0 km s^{-1} are caused by Galactic HI.

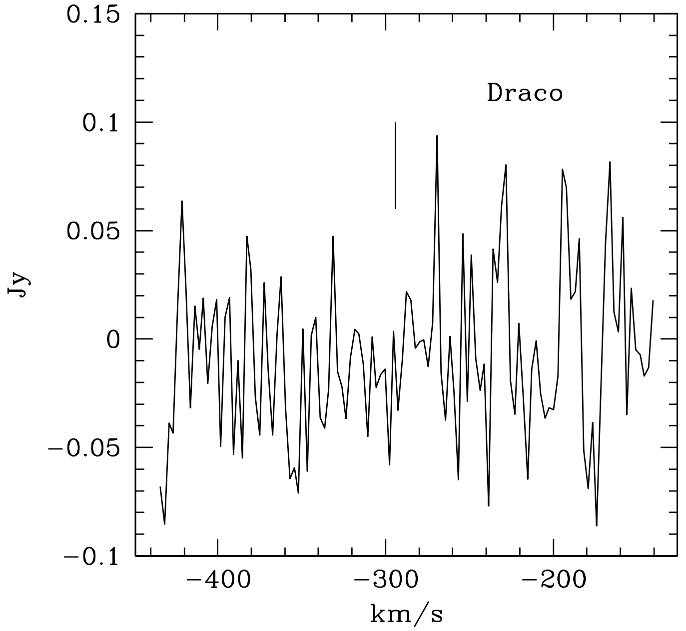

Fig. 6.— Similar to Figure 4, for Draco.

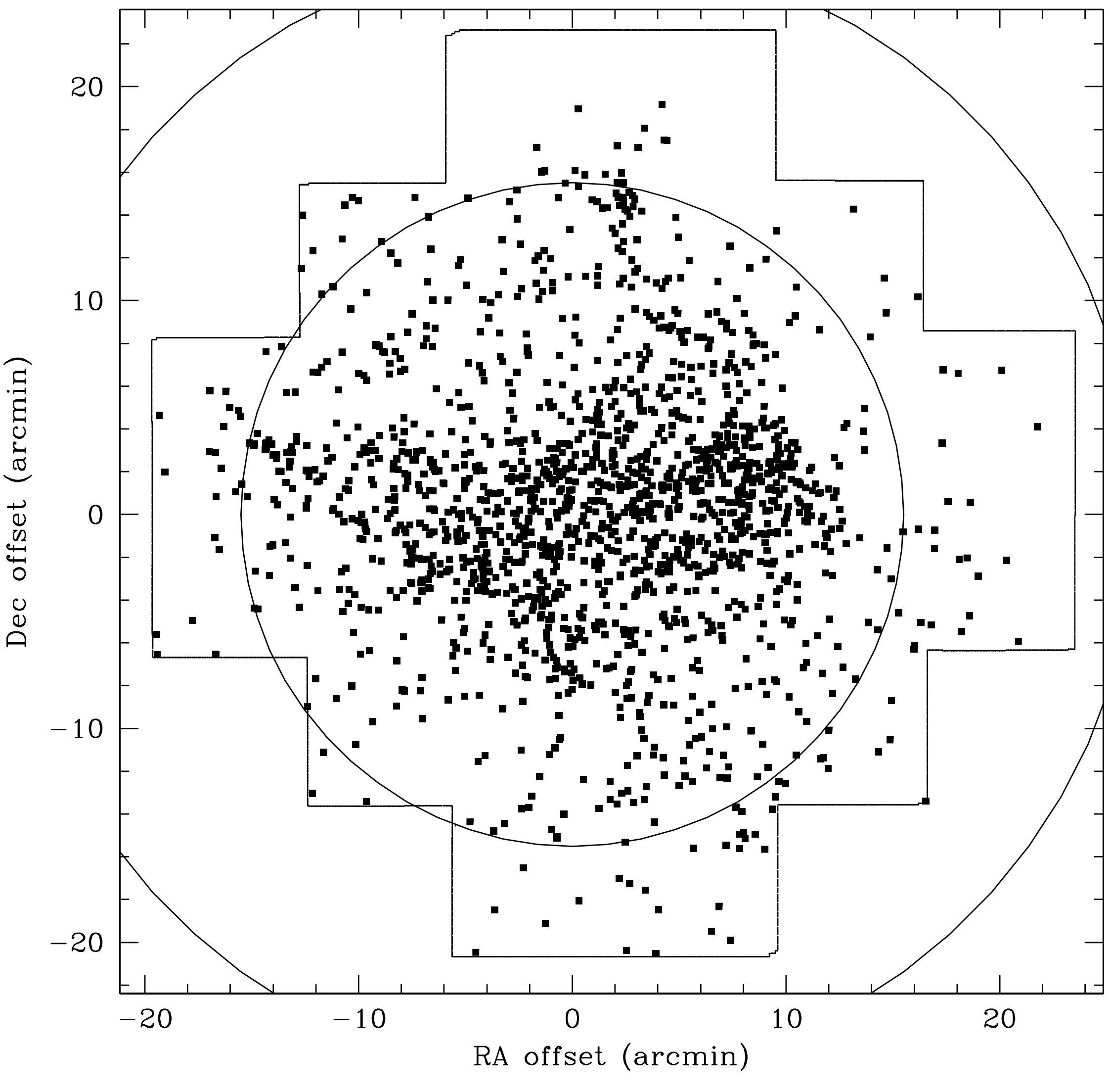

Fig. 7.— Distribution of the bright blue stars in Fornax. Filled symbols show the locations of stars which, in the data of Stetson et al. (1998), have magnitudes $18.5 < (B+R)/2 < 22.0$ and colors $B - R < 0.25$. (These criteria are likely to include some blue evolved stars in addition to massive main sequence stars.) The two circles show the VLA half-power points and 10% power points, and the cross-shaped region is the field observed by Stetson et al. The axis units are arcminutes with respect to the VLA pointing center. North is up and east is to the left, as in Figure 1.

Table 1. VLA Observations of HI in Dwarf Spheroidals

	Fornax	Leo II	Draco
phase center (J2000)	02 39 58.5	11 13 29.2	17 20 18.7
	−34 30 00	+22 09 11	+57 54 48
total time, hr	9.0	5.0	2.0
configuration	DnC	D	DnC
date	15oct97, 19oct97	08jan98	23oct97
phase calibrator	J0240−231	J1120+143	J1634+627
bandpass calibrator	J0137+331	J1331+305	J0137+331
center velocity (km s^{-1})	+55.0	+70.0	−290.0
beam size ($''$)	121×73	75×71	95×67
beam linear size (pc)	70×42	75×71	33×23
rms noise (mJy/beam)	1.58	0.89	1.74
rms noise (K)	0.11	0.10	0.17
N_{HI} limit (cm^{-2})	4.6×10^{18}	4.3×10^{18}	7.1×10^{18}
N_{HI} limit ($M_\odot$ pc^{-2})	0.037	0.035	0.057
distance (kpc)	120±8	207±10	72±3
core radius ($'$)	14	2.9	9.0
tidal radius ($'$)	71	8.7	28

Table 2. Optical Depth Upper Limits for Continuum Sources

Galaxy	No.	RA	Dec	Peak	τ	Distance
		J2000.0		mJy/beam		$'$
Draco	1	17 20 58.8	+57 49 08	32	0.16	8.0
	2	17 19 04.3	+58 04 27	18	0.29	13.6
	3	17 20 51.3	+57 55 18	44	0.12	17.3
	4	17 20 49.8	+57 35 38	19	0.28	19.9
	5	17 18 21.1	+58 10 05	49	0.11	21.6
Leo II	1	11 13 59.4	+21 59 11	8.7	0.30	12.9
	2	11 14 12.3	+21 57 26	14	0.19	16.1
	3	11 12 07.1	+22 10 40	15	0.18	18.5
	4	11 12 15.9	+22 00 40	8.7	0.30	18.8
Fornax	1	02 40 08.2	−34 29 20	12	0.38	1.0
	2	02 39 03.4	−34 36 39	15	0.31	14.7