DETECTION OF H I ASSOCIATED WITH THE SCULPTOR DWARF SPHEROIDAL GALAXY

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ABSTRACT

Neutral hydrogen (H I) has been detected in the Local Group dwarf spheroidal galaxy Sculptor with the 64 m Parkes single-dish telescope and mapped with the Australia Telescope synthesis array. Most of the detected H I is in two clouds ~15°–20° away from the optical center. The gas is observed at the same systemic velocity as the stars, but at ~125 km s⁻¹ away from the Magellanic Stream components in that region. A lower limit to the H I mass of 3.0 × 10⁴ M☉ is derived from the synthesis observation for an (MHI/LB) ≃ 0.02. This amount of H I is compatible with mass loss expected from normal giants, even if only 10% of the gas is retained by the galaxy in its neutral form.

Key words: galaxies: dwarf — galaxies: individual (Sculptor) — ISM: H I — Local Group — techniques: interferometric

1. INTRODUCTION

It is generally believed that the dwarf spheroidal (dSph) companions of the Galaxy and of M31 are completely devoid of a detectable interstellar medium (ISM) and, in particular, neutral hydrogen (e.g., Da Costa 1994). Previous attempts to detect H I in these galaxies (Knapp, Kerr, & Bowers 1978; Mould et al. 1990; Koribalski, Johnston, & Otrupcek 1994) have been carried out with the NRAO 91 m and 41 m and the Parkes 64 m single-dish telescopes; these studies were only able to set upper limits of ~10⁻⁵–10⁻⁴ M☉ for the H I content of eight of the nine dSph companions of the Milky Way. Thuan & Martin (1979) set limits on the H I content of two of the lower luminosity dSph systems near M 31 (And I and And III).

The only ambiguous detection near the Milky Way was the Sculptor dSph system. Knapp et al. (1978; their Fig. 1) identified H I while observing Sculptor; they noted that “it is therefore (remotely) possible that the galaxy is embedded in the gas cloud at ±120 km s⁻¹.” In the end, they dismissed this possibility, because the optical velocity of Sculptor was believed to be ~200 km s⁻¹ at that time. Subsequent optical radial velocity studies of individual stars in Sculptor have shown its systemic velocity to be ~110 km s⁻¹ (Queloz, Dubath, & Pasquini 1995), quite close to the H I velocity reported by Knapp et al. (1978). Hence, in retrospect it appears that Sculptor was the first dSph system in which neutral gas was detected; however, because of the initial suggestion that the H I was not associated with the galaxy, this result has been largely forgotten.

The ISM of dSph and dSph-like systems may be considerably more complex than is generally believed (see Mateo 1998 for a more extensive discussion). Johnson & Gottesman (1983) and Young & Lo (1997a) found complex H I distributions associated with the more luminous dSph-like M 31 systems NGC 185 and 205. In each case, the gas is distributed asymmetrically about the optical galaxy. 21 cm detections have also been reported in the remote Phoenix galaxy (Carignan, Demers, & Côté 1991), a system sometimes mentioned as a transition system between dwarf irregular (dI) and dSph galaxies (van de Rydt, Demers, & Kunkel 1991; van den Bergh 1994). Oosterloo, Da Costa, & Staveley-Smith (1996) found an H I cloud near the even more remote Tucana dSph galaxy, but concluded that the gas is more likely a high-velocity cloud (HVC) associated with the Magellanic Stream (MS); this will remain speculative until an optical radial velocity for this galaxy is obtained.

Sculptor is one of the closest of the Milky Way satellites, at a distance of 88 kpc (Kaluzny et al. 1995). Its angular size (40') is comparable to that of the apparently largest dSph system (after Sagittarius), Fornax. The distribution of stars along the horizontal branch (HB) and the observed mean metallicity of Sculptor imply that the bulk of the stars in the galaxy have ages similar to those of the relatively young globular clusters found in the outer halo (Kaluzny et al. 1995). The existing color-magnitude diagrams (CMDs) do not reveal a strong intermediate-age population (Da Costa 1984; Aaronson 1986), contrary to what is seen in Fornax or Carina (Stetson 1997; Hurley-Keller, Mateo, & Nemec 1998). In contrast, the substantial spread in metallicity seen in Sculptor (Da Costa 1988; Kaluzny et al. 1995) suggests that its star formation history may have been rather complex. Da Costa (1984) and Grebel, Roberts, & van de Rydt (1994) have noted a significant number of blue stars...
above Sculptor's main-sequence turnover. While Da Costa identified them as blue stragglers, it is quite possible that these stars represent a small but significant younger population. Grebel et al. (1994) argue strongly that a second star formation episode has occurred in Sculptor, possibly triggered by the external accretion or internal accumulation of gas.

The radial velocity of Sculptor has been established by Queloz et al. (1995) to be 109.9 ± 1.4 km s⁻¹, confirming previous determinations of 109.2 ± 4.5 km s⁻¹ by Aaronson & Olszewski (1987) and of 107.4 ± 2.0 km s⁻¹ by Armandroff & Da Costa (1986). The velocity dispersion, derived from their sample of 23 K giants, was found to be 6.2 ± 1.1 km s⁻¹, for a global mass-to-light ratio ~9 ± 6 (M/L_☉). The physical parameters of Sculptor are summarized in Table 1.

There is ample, growing evidence that other galaxies in the Local Group exhibit complex star formation histories, but the relationship to their ISM remains unclear (see, e.g., Mateo 1998). As noted, Carina and Fornax have complex star formation histories, but no detected ISM. Three more distant and isolated objects, Phoenix (d ≤ 400 kpc), Tucana (d ≤ 900 kpc), and Antlia (d ~ 1.15 ± 0.1 Mpc), share many of the properties of the bona fide dSph systems. However, photometric studies (Canterna & Flower 1977; Ortolani 1988; van de Rydt et al. 1991; Whiting, Irwin, & Hau 1997) have shown that Phoenix and Antlia possess stellar populations that seem to share properties of the populations found in both dSph and dI galaxies.

The growing evidence of complex star formation histories in virtually all dwarf galaxies, including those with little or no detectable ISM, suggests that we do not yet understand the relationship between the stellar and gaseous components of these deceptively simple-looking systems (Mateo 1998). Because Sculptor is so close, and because of its past (though unappreciated) detection at 21 cm, we have obtained new H I observations of the galaxy to study its ISM component in more detail. The new radio observations are described in § 2; these include single-dish H I observations using the Parkes 64 m telescope, synthesis H I mapping done with the Narrabri Australia Telescope Compact Array (ATCA), and CO observations obtained with the Swedish-ESO Submillimeter Telescope (SEST) in Chile. In § 3, we analyze in detail the content and distribution of the H I gas mapped with the ATCA, while in § 4 we speculate about the possible origin of the detected gas in Sculptor. We end with a summary of our principal results and our main conclusions in § 5.

## 2. Observations

### 2.1. Single-Dish Parkes Observations

We observed Sculptor with the Parkes 64 m single-dish telescope (Table 2) to confirm the detection reported by Knapp et al. (1978). These new data were obtained in 1992 January. The flux calibrator PKS 1934–638 was used to measure a mean system temperature during the run of T_m ~ 50 K with a half-power beamwidth (HPBW) of 14.9 ± 0.2. The 8 MHz bandwidth, centered at 300 km s⁻¹, was divided in 1024 channels for a channel width of 1.65 km s⁻¹ and a full-velocity coverage of [−544, 1144] km s⁻¹.

A total of 100 minutes integration was accumulated on Sculptor, which, after averaging the 12 individual 500 s observations, resulted in a spectrum with an rms noise of 0.013 Jy. This sets a 3 σ detection limit of ~100 M_☉ at the distance of Sculptor. As we discuss in more detail below, we obtained a clear, strong detection of Sculptor with these observations. In addition to Sculptor, we also obtained new observations of the relatively recently discovered Sextans dSph (Irwin et al. 1990). Contrary to the Sculptor observations, we did not detect H I toward Sextans. Our 3 σ upper limit for the neutral hydrogen content is 130 M_☉ for any gas that might be located within the Parkes beam. For both galaxies, the Parkes telescope was centered directly on the optical centroids of the galaxies during these observations.

### 2.2. ATCA Synthesis Mapping

After confirming the earlier H I detection by Knapp et al. (1978), we decided to try to map Sculptor with the 375 m configuration of the ATCA on 1992 October 2 (Table 3). For these observations, we obtained a total of 8.2 hr of integration on source, in blocks of 35 minutes and separated by 5 minute integrations of PKS 0042–442 for phase and amplitude calibration purposes. The absolute intensity scale was set by a 30 minute observation of PKS 0407–658, which we assumed to have a flux density of 14.4 Jy at our

## Table 1

| Parameter                           | Value   |
|-------------------------------------|---------|
| Morphological type                  | Sph     |
| R.A. (J2000.0)                      | 1 00 09.4 |
| l (deg)                             | −33 42 33 |
| b (deg)                             | −83.16  |
| Galactocentric distance (kpc)       | 87.5 ± 6 |
| Isophotal major diameter, D_s      | 40      |
| Core radius, r_c (arcmin)          | 5.8 ± 1.6 |
| Tidal radius, r_t (arcmin)         | 76.5 ± 5.0 |
| Major-axis P.A. (deg)              | 99 ± 1  |
| Proper-motion P.A. (deg)            | 40 ± 24 |
| Abundances [Fe/H]                   | [−2.2, −1.6] |
| Absolute magnitude, M_p            | −10.0  |
| Total luminosity, L_p (L_☉)        | 1.5 × 10^6 |
| Absolute magnitude, M_v            | −10.7  |
| Total luminosity, L_v (L_☉)        | 1.6 × 10^6 |
| Optical velocity, V_o (km s⁻¹)      | 110 ± 1.4 |
| Galactocentric velocity, V_{GCE} (km s⁻¹) | 77     |

**Note:** Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

a De Vaucouleurs et al. 1991.

b Kaler et al. 1995; at this distance 1' ~ 25.5 pc.

c Irwin & Hatzidimitriou 1995.

d Schweitzer et al. 1995.

e Queloz et al. 1995.

## Table 2

| Parameter                         | Value               |
|-----------------------------------|---------------------|
| Dates of observations             | 1992 Jan 25–30      |
| Flux calibrator                   | PKS 1934–638        |
| System temperature, T_m (K)       | ~50                 |
| Primary beam at half-power (FWHM) (arcmin) | 14.9 ± 0.2 |
| Bandwidth (MHz)                   | 8.0                 |
| Central velocity (km s⁻¹)         | 300                 |
| Velocity range (km s⁻¹)           | [−544, 1144]        |
| Channel width (kHz)               | 7.8 (1.65 km s⁻¹)   |
TABLE 3
PARAMETERS OF THE ATCA H i OBSERVATIONS

| Parameter                                      | Value |
|------------------------------------------------|-------|
| Date of observations                           | 1992 Oct 2 |
| Integration time on source (hr)                | 8.2   |
| Configuration (m)                              | 375   |
| Baselines                                      | 10 [61 m, 459 m] |
| Flux calibrator                                | PKS 0407 - 658 |
| Phase calibrator                               | PKS 0042 - 442 |
| System temperature, \( T_{\text{sys}} \) (K)    | \( \sim 35 \) |
| Primary beam at half-power (FWHM) (arcmin)     | 33    |
| Bandwidth (MHz)                                | 7.4   |
| Channel spacing (no smoothing) (kHz)            | 7.8 (1.65 \( \text{km s}^{-1} \)) |
| Channel spacing (after Hanning smoothing) (kHz) | 15.6 (3.3 \( \text{km s}^{-1} \)) |
| FWHM of synthesized dirty beam (arcsec)        | 205 \( \times \) 86 |
| FWHM of restored cleaned beam (arcsec)         | 240 \( \times \) 240 |
| Rms noise in channel maps (full resolution/no cleaning) (mJy beam\(^{-1}\)) | 2.5 |
| Rms noise in channel maps (after cleaning/convolved) (mJy beam\(^{-1}\)) | 3.3 |
| Conversion factor, 240" \( \times \) 240" beam (equivalent to 1 mJy beam\(^{-1}\) area) (K) | 0.01 |
| Map gridding (arcsec pixels)                   | 30 \( \times \) 30 |

observing frequency. Normally, the full array comprises six antennas; however, data from the sixth antenna located \( \sim 6 \) km from the array center was discarded during the reduction stage, since no flux could be seen in the longest baselines. This left 10 baselines with the remaining five antennas, which spanned a baseline range of 61 to 459 m. With this configuration it is possible to detect structures up to \( \sim 22 \). With the ATCA 22 m antennas, the FWHM of the primary beam is \( \sim 33' \). The mean system temperature during the run was \( T_{\text{sys}} \approx 35 \) K. A bandwidth of 7.4 MHz was used with a channel spacing of 7.8 kHz, for a velocity resolution of 1.65 \( \text{km s}^{-1} \).

The synthesis data were edited and calibrated using the NRAO Astronomical Image Processing System reduction software package. A bandpass calibration was applied using the PKS 0407 – 658 data and the continuum was subtracted by fitting a straight line to the real and imaginary parts of line-free channels in the UV plane and subtracting the fit from the data. The images were then computed using natural weighting for the UV data (higher weight to the
shorter baselines), which gives maximum sensitivity while decreasing the spatial resolution by about a factor of 2. During the process of generating the radio image, the data were also Hanning smoothed in velocity, thus decreasing the velocity resolution to 3.3 km s\(^{-1}\). The full-resolution data cube has a synthesized beam of 205\(^\circ\) \times 86\(^\circ\) and an rms noise in each channel of 2.5 mJy beam\(^{-1}\). The CLEANed data cube, restored with a synthesized beam of 240\(^\circ\) \times 240\(^\circ\), has a noise of 3.3 mJy beam\(^{-1}\). The channel maps of the CLEANed data cube are shown in Figure 1. One can see already in these maps that most of the detected signal is located away from the center of the image. As with the Parkes observations, the ATCA pointing corresponded to the optical centroid of Sculptor.

2.3. SEST CO Observations

Sculptor was observed with the SEST (Table 4) in the \(J = 1\rightarrow 0\) line emission of \(^{12}\)CO at 115 GHz in 1997 January. The Schottky receiver and good weather conditions yielded system temperatures 370 K. The low-resolution acousto-optical spectrometer (LRS2) was used as the back end, with a bandwidth of 1088 MHz and a frequency resolution of 1.4 MHz (3.6 km s\(^{-1}\)), centered on a heliocentric velocity of 110 km s\(^{-1}\). A detailed description of SEST can be found in Booth et al. (1989).

Antenna temperatures were calibrated using the chopper wheel method, and relative calibration uncertainties were estimated to be about 10%. The beamwidth at this frequency is 43\(^\circ\). The observations were made in a double beam-switching mode with a throw of 12\(^\circ\) and a scan integration time of 120 s. Integrations were performed at five distinct locations on the galaxy, corresponding to the off-center \(\text{H} I\) peaks in both the northeast and southwest components, as well as on the inner edges of the \(\text{H} I\) clouds, since this is very often where CO is detected in dE systems (see, e.g., NGC 185 and 205 in Young & Lo 1997a). The spectra were co-added and smoothed in various ways to try to detect any CO emission but, regardless of the methods employed, no emission was found at any of these locations. Spectra of all the observed positions were then added together, yielding an average spectrum representing a total integration time of 15.5 hr, with an rms noise level of 2.1 mK. The 3 \(\sigma\) CO brightness temperature limit is therefore \(T_{mb} < 9.0\) mK, after beam efficiency corrections (taking \(n_{mb} = 0.7\) for the SEST at 115 GHz), corresponding to a CO integrated intensity \(I_{CO} = \int T_{mb} dV < 0.2\) K km s\(^{-1}\).

3. ANALYSIS OF THE \(\text{H} I\) DATA

3.1. \(\text{H} I\) Content

Figure 2 shows the average spectrum of the 100 minute Parkes integration at the central position of Sculptor. From it, a systemic velocity of 112 ± 3 km s\(^{-1}\) was derived, very close to the optical velocity of 110 ± 1.4 km s\(^{-1}\). The detected flux of 5.7 Jy translates into an \(\text{H} I\) mass of \(\sim 1.0 \times 10^4\ M_\odot\), at the distance of Sculptor. Since, as will be seen below, a large fraction of the \(\text{H} I\) probably lies outside the HPBW of the Parkes beam, this mass estimate should only be considered as a lower limit of the total \(\text{H} I\) content of Sculptor.

Figure 3 shows the global profile from the AT synthesis observations. Notice that the systemic velocity from this spectrum is slightly different than the Parkes spectrum: 102 ± 5 km s\(^{-1}\). This already suggests that a considerable fraction of the gas detected by the synthesis observations is different from the gas seen in the single-dish observation. This can be seen more clearly in Figure 4, where the two spectra have been superposed. The integrated ATCA profile gives a total detected flux of 17.3 Jy km s\(^{-1}\), which implies a total detected \(\text{H} I\) mass of \(3.0 \times 10^4\ M_\odot\) at the adopted distance of Sculptor.

![Global Profile](image)

**Fig. 2.**—Global profile from the single-dish Parkes observations. From this profile we derive \(V_{sys} = 112\) km s\(^{-1}\) and \(M_{\text{H} I} \simeq 1 \times 10^4\ M_\odot\).

![Global Profile](image)

**Fig. 3.**—Global profile from the AT synthesis observations. From this profile we derive \(V_{sys} = 102\) km s\(^{-1}\) and \(M_{\text{H} I} \simeq 3 \times 10^4\ M_\odot\).
3.2. H I Distribution

Figure 5 shows the H I surface density map for the gas detected by the synthesis observation. It can be seen that most of the H I is located within two distinct clouds located 15'–20' from the optical center. It is quite likely that a large fraction of the gas present in this map was not detected in our single-dish observations with the 149 Parkes beam centered at the optical position. Moreover, a large fraction of the gas is also outside the HPBW of the primary beam (~33') of the ATCA antennae; thus, even if the data in Figure 5 were corrected for primary-beam attenuation, this single-field observation will have missed any gas located further out from the center of the galaxy. Given the observed distribution of gas in Sculptor, it is at least plausible, and we believe probable, that more extended H I gas is present.

There is also another reason (already mentioned in § 2.2) that suggests that this observation may not have detected all the flux present. The diameter of the detected clouds is ~20', which is close to the largest structures (~22') that can be detected with the shortest baseline (~60 m) of the 375 m ATCA configuration we employed. Shorter baselines are needed to detect larger structures, if they exist. Thus, the 3.0 × 10^4 M_☉ of H I detected within the primary beam by the ATCA observation should also be considered as a lower limit. Another indication that the ATCA observations have not detected all the flux can be seen in Figure 4, which shows that there is some flux seen around 125 km s^{-1} in the single-dish observations that is not seen in the interferometric data.

The fact that most of the H I sits at the edge of the optical component of Sculptor is illustrated even more clearly by the H I radial profile shown in Figure 6. This distribution is reminiscent of what has been observed in some extreme dI
systems. Puche & Westpfahl (1994) summarized the situation in low-mass systems such as Sextans A, Holmberg I, and M81dwA as follows: “Very little gas remains in the central regions of the galaxies. The inner limit of the H I shell nearly coincides with the optical radius of the galaxy. The outer extent of the H I shell is about 1.5 times the optical radius.” This is a nearly perfect description of what we have observed in Sculptor, though a complete H I shell has not yet been mapped.

3.3. H I Kinematics

The map of the isovelocity contours for the detected H I is shown in Figure 7. The mean radial velocities for the three clouds are \(98 \pm 8\) km s\(^{-1}\) for the northeast cloud, \(119 \pm 2\) km s\(^{-1}\) for the central cloud, and \(104\) km s\(^{-1}\) \(\pm 11\) for the southwest cloud. It is difficult to determine conclusively whether the H I clouds are in rotation around the main body of the galaxy. This might be surprising, since no hint of rotation has been found in any dSph systems that have adequate data (Mateo 1994), with the exception perhaps of Ursa Minor (Hargreaves et al. 1994). It is equally difficult to determine with any certainty whether the clouds in Sculptor are systematically expanding or contracting from or toward the galaxy center. What makes the interpretation of the kinematic data difficult is that we have no independent constraint on the true orientation parameters of the galaxy and even less on the origin or orientation of the gas. The various different possibilities will be discussed in the next section.

The H I velocity dispersion map is shown in Figure 8. The mean dispersions for the three clouds are \(4.3 \pm 2.5\) km s\(^{-1}\) for the northeast cloud, \(2.3 \pm 1.2\) km s\(^{-1}\) for the central cloud, and \(3.8 \pm 2.2\) km s\(^{-1}\) for the southwest cloud, with the exception of a small region (dark area around 00\(^{h}\)59\(^{m}\)30\(^{s}\) and \(-33^\circ 52'00'\)) where \(\langle \sigma \rangle \approx 15 \pm 2\) km s\(^{-1}\). While the
mean velocity dispersion of $\sim 4 \pm 2 \text{ km s}^{-1}$ of the gas in the outer parts appears to be smaller than the stellar velocity dispersion of $\sim 6 \pm 1 \text{ km s}^{-1}$ observed in the center (Armandroff & Da Costa 1986; Queloz et al. 1995), they are still comparable within the quoted errors.

4. DISCUSSION

In trying to understand the properties of the ISM in Sculptor, we must try to reconcile the following principal characteristics of the galaxy and its relation to the Milky Way. First, Sculptor is presently located relatively close to the Milky Way, and its perigalactic distance is even closer ($\sim 60 \text{ kpc}$; Irwin & Hatzidimitriou 1995; Schweizer et al. 1995). Consequently, it is possible (see §4.2) that tidal effects have played some role in producing the observed distribution of gas in the galaxy. This may help reconcile why gas that may be of an internal origin is located so close to the edge of the optical image of the galaxy. Because Sculptor is relatively close, one must also carefully consider the possibility that the detected gas may not be associated with Sculptor, but is instead a high-velocity cloud from the Magellanic Stream or some other complex that happens to be present in this part of the sky.

4.1. Internal Origin

Is it possible to account for the neutral gas seen in Sculptor from mass loss in normal giants? The most likely internal sources of gas that can be realistically retained in the vicinity of Sculptor are winds from evolved stars on the red giant and asymptotic giant branches, and gas expelled during the planetary nebula phase of intermediate-age and old stars. Since the central regions of dSph galaxies appear to be devoid of neutral gas (Knapp et al. 1978; Mould et al. 1990; Koribalski et al. 1994; this paper), and since they reveal no obvious signs of dust or molecular gas (with the exceptions of NGC 185 and NGC 205, both of which are sometimes considered ultraluminous dSph systems; Young & Lo 1997a; Mateo 1998), a supernova would eject most, if not all, of the existing gas from a galaxy as small as Sculptor (Mac Low & Ferrara 1998), as well as its own ejecta. Any supernovae would simply complicate the gas-retention problem; if a galaxy such as Sculptor is to retain gas from internal sources, the more sedate (and slow) sources of gas must dominate the generation of the ISM.

As summarized by Mould et al. (1990), the total mass-loss rate expected from normal evolution is about $0.015 \text{ M}_\odot \text{ yr}^{-1}$ per $10^9 L_{\odot, B}$. For Sculptor ($L_B \sim 10^7 L_{\odot}$, Mateo
1998), this implies a total return of $1.5 \times 10^5 M_\odot$ Gyr$^{-1}$. At this rate, it would take $\sim 200$ Myr to produce the observed amount of $\text{H} \text{I}$ seen in Sculptor even if all of the ejected gas is retained by the galaxy and is converted to neutral H, neither of which is probably correct. If we assume that the mass distribution in Sculptor is more extended than the light (Da Costa 1994), the escape velocity may be as much as 3.0 times larger than the central dispersion of 6.6 km s$^{-1}$, or about 20 km s$^{-1}$, or may be as only about twice the central dispersion, or about 13 km s$^{-1}$, if the mass follows the light distribution. The velocity spectrum of red giant winds extends somewhat above even this upper limit, suggesting that up to 80% of the gas from such winds can be lost from the galaxy. Thus, the rejuvenation time of the ISM from internal sources must be considerably longer than 200 Myr.

For our purposes, the key point is that it should take from 200–1000 Myr to build up the amount of gas seen in Sculptor, and even longer if a significant fraction of the gas is in molecular form (observations of dE's suggest that there could be as much mass in $\text{H}_2$ as in $\text{H} \text{I}$; Wiklind, Combes, & Henkel 1995). Since most of the star formation seems to have taken place between 8 and 10 Gyr in Sculptor (Da Costa 1984), it would have produced a gas reservoir of $\sim 3.0 \times 10^3 M_\odot$. So, only 10% of this need be retained in its neutral form to account for the $\text{H} \text{I}$ detected by the present observations.

Of course, for other dSph galaxies in which $\text{H} \text{I}$ is not detected, these same arguments should apply; for these systems, the problem shifts to how the gas is lost or is otherwise made unobservable. Galaxies such as Fornax (Stetson 1997; Demers, Mateo, & Kunkel 1998) and Carina (Smecker-Hane et al. 1994; Mighell 1997; Hurley-Keller et al. 1998), which show clear evidence of star formation episodes even within the last few Gyr, show as yet no evidence of neutral gas, at least in the central regions. In these cases, perhaps there simply has not been enough time to generate a reservoir of gas. But what about Ursa Minor, Draco, Sextans, and Leo II? These galaxies contain no significant populations younger than the youngest stars found in Sculptor. If Sculptor could retain gas from red giants and planetary nebulae, why didn't these? Have we looked in the right place?

4.2. Tidal Effects

Another possibility is that the gas was removed from the outer parts of Sculptor by tidal forces from the Milky Way during its last perigalactic passage $\sim 10^8$ years ago (Irwin & Hatzidimitriou 1995). This theory is based on the fact that while the central 10' of Sculptor (i.e., the optical core) has zero ellipticity, outside this region, the ellipticity smoothly increased to the asymptotic value of $\sim 0.3$ (Irwin & Hatzidimitriou 1995). This picture is similar to numerical simulations of dSph galaxies that are tidally disrupted, where material is ejected ahead of and behind the satellite (e.g., Allen & Richstone 1988; McGlynn & Borne 1991; Moore & Davis 1994; Piatek & Pryor 1995; Oh, Lin, & Aarseth 1995; Kroupa 1997). Is it a coincidence that the position angle of the proper motion measured by Schweitzer et al. (1995) of $40^\circ \pm 24^\circ$ happens to be almost exactly the position angle defined by the two $\text{H} \text{I}$ clouds (see Fig. 5)?

Tidal effects could produce two clouds symmetrically distributed on both sides of the optical center. Moreover, when stars (and gas) are detached from the host galaxy, they continue to follow their host's galactic orbit for several galactic years before dispersing beyond the host's tidal radius (Oh, Lin, & Aarseth 1994).

With few exceptions, the dSph galaxies of the Local Group are clustered around the Milky Way and M31, while the dI galaxies are more evenly distributed throughout the group (Mateo 1998). This certainly suggests that the proximity of a massive galaxy may have played an important role in determining the structural and kinematic properties of dSph systems. The removal of their gas by tidal effects may be one of the important results of these encounters, though whether this can explain our observations of Sculptor remains unclear.

4.3. Gas Falling Back or Expanding?

A number of authors have at various times suggested that dSph systems may be the remnants of extremely low luminosity dI galaxies that have been depleted of gas by their initial or subsequent star formation episodes, or perhaps by tidal effects (e.g., Ferguson & Binggeli 1994; but also see Mateo 1998 and references therein). This scenario is supported by the fact that large expanding cavities surrounded by dense shells are found in the neutral interstellar medium of many dI galaxies that were observed with sufficient resolution (Puche & Westpfahl 1994). The energetics of the gas suggest that these structures are plausibly created by stellar winds and supernova explosions from the young dI stellar populations ( Larson 1974; Dekel & Silk 1986).

The largest dwarfs, such as Magellanic irregular systems (e.g., IC 2574, Martimeau, Carignan, & Roy 1994; Holmberg II, Puche et al. 1992), contain several such shells. However, in the smallest dwarfs (e.g., Holmberg I and M81dWA, Westpfahl & Puche 1994; Leo A, Young & Lo 1996), only one large, slowly ($v_{exp} \approx 5$ km s$^{-1}$) expanding shell usually dominates the ISM. The expansion and contraction of the entire ring- or shell-like ISM of these small galaxies is interpreted as being the result of burst(s) of star formation that took place in those systems.

dSph systems, such as Sculptor, are in the same mass range as the low-luminosity dI galaxies ($M_\odot \approx -10$), and a similar process may have taken place. Soon after the primordial burst of star formation, most of the ISM could have been expelled from the inner regions of the galaxy by stellar winds and supernova explosions, stopping star formation. Depending on the energy released in the initial burst, and the total mass of the system, some of the gas may be falling back into the galaxy, giving the $\text{H} \text{I}$ a ringlike appearance. The ring size would depend on the parent galaxy mass, the strength of the initial burst, and time. In the case of Sculptor, because of the missing short spacings of the present observations, which do not perceive structures larger than $\sim 22'$, it is possible that we are only seeing the two regions of highest surface density. Perhaps most difficult for this interpretation is the lack of any obvious, recent stellar population that may have ejected the gas. As in the tidal scenario, we must suppose that the gas, if ejected by star formation processes, has been able to stay associated with Sculptor and remain in the outer parts of the galaxy since its last burst.

The $\text{H} \text{I}$ gas observed in a galaxy like Phoenix could have another origin. Van de Rydt et al. (1991) found that this system has an intermediate population of blue stars with an age of $\sim 1.5 \times 10^8$ yr along with an old, globular cluster-like population. If that last burst of star formation is
responsible for the observed H I location, and if we assume a constant expansion velocity of 5 km s\(^{-1}\) (as estimated in extremely low mass DIs systems), most of it should be found around \(\sim 750 \text{ pc} (\Delta \approx 400 \text{ kpc})\), which corresponds to \(\sim 6.5\) on the sky. In recent VLA observations of Phoenix (Young & Lo 1997b), an H I “cloud” was found at about the right distance west of the center. However, it is difficult to know if that gas, detected at about \(-23 \text{ km s}\)^{-1}, is truly associated with Phoenix, since no optical velocity is available.

If the same kind of calculations are applied to Sculptor, the radius where the H I is found would imply that the most recent burst of star formation would have taken place about 10\(^8\) years ago. Could the blue stars observed by Da Costa (1984) and Grebel et al. (1994) around magnitudes 21 to 23 be the tip of such a population? The deepest existing CMD of Sculptor (Da Costa 1984) tells us that the most recent burst of star formation in the galaxy occurred more than 5–8 Gyr ago, but these data are strictly from a small region near the center of Sculptor. Thus, while this scenario appears highly unlikely, deeper CMDs over a much larger portion of Sculptor are needed to determine if a recent burst of sufficient magnitude has occurred in this system. If such a population were found, it could potentially explain the location and amount of detected gas. If no young stars (or too few) are present, it becomes immediately more likely that if the observed H I came from an internal source, the gas had to have been produced during an initial burst of star formation in Sculptor (then remained in the vicinity of the galaxy for nearly a Hubble time), or else slowly accumulated from giant winds and planetary nebulae as described above.

4.4. External Origin

A large H I cloud was recently detected near the distant dSph galaxy Tucana (Oosterloo et al. 1996). Because the position of the cloud does not coincide well with the optical galaxy, and because the total gas mass inferred at Tucana’s distance is rather large (\(> 10^8 M_\odot\)), these authors argued that the detected gas is more likely to be an HVC associated with the MS (Mathewson, Cleary, & Murray 1974). Could the same thing be happening with Sculptor? This is a reasonable possibility: Sculptor is close to the south Galactic pole, where the MS has a complex structure and several velocity components (Haynes & Roberts 1979). However, the highly symmetric distribution of the gas in Sculptor relative to the optical image of the galaxy, and the nearly perfect velocity correspondence between the radio and optical observations, suggest strongly that in Sculptor’s case we are not dealing merely with an optical/radio illusion. Instead, the proximity of HVCs suggests that Sculptor may have actually accreted gas—or is in the process of doing so—from external clouds.

There is circumstantial evidence supporting the notion that dSph galaxies may be accreting gas of external origin. In Carina, Smecker-Hane et al. (1994) argue for a large age spread, yet a surprisingly small spread in abundance. This is in striking contrast to Leo I, which has a complex star formation history (Lee et al. 1993) and a broad giant branch indicative of a large abundance spread. This behavior makes somewhat more sense if the gas that formed distinct generations of stars in these galaxies was accreted or captured from distinct clouds with their individual—and therefore, random—mean abundances. Wakker & van Woerden (1997) review the observations of HVC in the halo; their summary of past surveys suggest that many small, low column density, and distant clouds could still be hidden throughout the Galactic halo.

The low velocity dispersions that make it difficult for dwarfs to retain much of an ISM from internal sources also seem to limit the feasibility of capture from outside sources even more severely. The dispersion in the halo is 10–20 times higher than in dwarfs such as Sculptor, so very little gas could be captured in a random collision. The other possibility is that the galaxies and clouds follow more ordered motions. Lynden-Bell & Lynden-Bell (1995) have recently reviewed the possibility of kinematically and spatially related streams of objects in the Galactic halo; they conclude that some such streams may exist, but Sculptor in particular does not seem to be associated with any stream containing any other galaxies or halo clusters. Indeed, a measurement of the proper motion of Sculptor (Schweitzer et al. 1995) seems to rule out its association with all previously identified galaxy streams. Nonetheless, these results do not rule out that Sculptor may be located in a stream of H I clouds—the lack of distance information for the clouds makes it impossible to constrain the existence of such streams. If galaxies such as Sculptor (and Carina, Fornax, and Leo I, when they were forming stars) did, in fact, accrete gas from an external source, this would seem to be the only way—contrived as it is—of doing so.

5. SUMMARY AND CONCLUSIONS

We have obtained Parkes single-dish and ATCA synthesis observations of the Sculptor dSph galaxy, and have clearly detected H I associated with this galaxy. Our principal results include:

1. The single-dish observation has detected \(1.0 \times 10^4 M_\odot\) of H I at a systemic velocity of \(112 \pm 3 \text{ km s}^{-1}\), which is similar to the mean velocity of the stellar component.

2. The synthesis observation allows to set a lower limit to the total H I content of \(3.0 \times 10^4 M_\odot\). The mean velocity of the gas detected with the ATCA is \(102 \pm 5 \text{ km s}^{-1}\).

3. Most of the detected gas is located in two clouds symmetrically distributed 15°–20° to the northeast and southwest of the optical center. This distribution and good velocity coincidence with the optical component of Sculptor virtually guarantees that the gas is truly associated with the galaxy.

4. The facts that a large fraction of the detected H I is outside the 33' HPBW of the ATCA antennas, and that the sizes of the detected H I clouds (\(\sim 20'\)) are close to the theoretical largest structures (\(\sim 22'\)) that can be seen by the 375 m array configuration, suggest that much more H I may be present in Sculptor, but was missed by the present observations. The masses derived from the interferometric observations should thus be considered as lower limits.

5. The amount of H I detected is \(\sim 10\%\) of the estimated mass loss from normal giants during the main epoch of star formation 8–10 Gyr ago.

6. Tidal effects caused by the proximity of the Milky Way may have played a role in the observed distribution of the gas.

7. The detected H I could be either gas expelled in the original burst of star formation that is falling back onto the system, or gas expelled in a more recent burst of star formation that would have taken place \(\sim 10^8\) years ago. However, since there is as yet no clear evidence for such a young stellar population in Sculptor, the first alternative is only
The H I masses are clearly lower limits. It is possible that mapping larger areas around these systems will reveal a much larger quantity of gas. If this is the case, this would lend support to the suggestion that some dSph systems may be remnants of extreme dI galaxies that have been stripped of their gas by tidal effects or star formation bursts. If this stripping/ejection scenario is correct, H I should also be observed at large radii in the other dSph systems. Since the observations used to derive the upper limits given in Table 5 were centered on the optical images of the galaxies, it remains entirely possible that other dSph systems contain large quantities of neutral gas that has so far escaped detection.

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TABLE 5

| Name          | $M_V$ | $R_{GC}$ (kpc) | $L_{tot}$ ($L_\odot$) | $M_{HI}$ ($M_\odot$) | ($M_{HI}/L_\odot$) | References |
|---------------|-------|-----------------|-----------------------|----------------------|-------------------|------------|
| Fornax        | -13.0 | 120             | $1.4 \times 10^7$     | $< 10^4$             | ...               | 1          |
| Leo I         | -11.5 | 198             | $3.4 \times 10^6$     | $< 10^4$             | ...               | 1          |
| Sculptor      | -10.7 | 87.5            | $1.6 \times 10^6$     | $\geq 3.0 \times 10^4$ | 0.02              | 2          |
| Phoenix       | -9.9  | $\leq 400$      | $7.6 \times 10^5$     | $1.0 \times 10^5$    | 0.07              | 3          |
| Leo II        | -9.6  | 207             | $5.9 \times 10^5$     | $< 10^4$             | ...               | 1          |
| Tucana        | -9.5  | $\leq 900$      | $5.3 \times 10^5$     | $1.5 \times 10^4$    | $\leq 3$           | 4          |
| Sextans       | -9.2  | 83              | $4.1 \times 10^5$     | $< 130$              | ...               | 5          |
| Carina        | -8.6  | 85              | $2.4 \times 10^5$     | $< 10^3$             | ...               | 6          |
| Ursa Minor    | -8.4  | 64              | $2.0 \times 10^5$     | $< 280$              | ...               | 1          |
| Draco          | -8.3  | 72              | $1.8 \times 10^5$     | $< 68$               | ...               | 2          |
| Sagittarius   | ...   | 16              | ...                   | ...                  | ...               | 1          |
| Antlia        | ...   | 1150            | ...                   | ...                  | ...               | 1          |
| Leo A         | -13.9 | 2200            | $5.3 \times 10^7$     | $8.1 \times 10^7$    | 1.5               | 7          |
| Sextans A     | -13.8 | 1320            | $4.8 \times 10^7$     | $5.8 \times 10^7$    | 1.2               | 8          |
| M81 dw A      | -11.0 | 3250            | $3.6 \times 10^6$     | $1.1 \times 10^7$    | 3.0               | 9          |
| GR 8          | -10.6 | 1100            | $2.6 \times 10^6$     | $2.0 \times 10^7$    | 0.8               | 10         |
| NGC 205       | -15.7 | 850             | $1.6 \times 10^8$     | $4.3 \times 10^5$    | 0.003             | 11         |
| NGC 185       | -13.8 | 600             | $2.8 \times 10^7$     | $1.0 \times 10^5$    | 0.004             | 11         |

* Irwin & Hatzidimitriou 1995.

b Kaluzny et al. 1995.

c Ibata, Gilmore, & Irwin 1995.

d Whiting, Irwin, & Hau 1997.
