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THE GASEOUS TRAIL OF THE SAGITTARIUS DWARF GALAXY

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ABSTRACT

A possible gaseous component to the stream of debris from the Sagittarius dwarf galaxy is presented. We identify (4–10) × 10^6 $M_\odot$ of neutral hydrogen along the orbit of the Sgr dwarf in the direction of the Galactic anticenter (at 36 kpc, the distance to the stellar debris in this region). This is 1%–2% of the estimated total mass of the Sgr dwarf. Both the stellar and gaseous components have negative velocities, but the gaseous component extends to higher negative velocities. If associated, this gaseous stream was most likely stripped from the main body of the dwarf 0.2–0.3 Gyr ago during its current orbit after a passage through a diffuse edge of the Galactic disk with a density greater than 10^{-4} cm^{-3}. This gas represents the dwarf's last source of star formation fuel and explains how the galaxy was forming stars 0.5–2 Gyr ago.

Subject headings: galaxies: individual (Sagittarius Dwarf) — galaxies: ISM — Galaxy: formation — Galaxy: halo — intergalactic medium — Local Group

1. INTRODUCTION

Evidence for the process that formed our Galaxy is found throughout our Galaxy's halo as trails of stars and gas (e.g., Yanny et al. 2003; Putman et al. 2003, hereafter P03). These Galactic building blocks are currently accreting satellites, and the Sagittarius dwarf galaxy (hereafter Sgr dwarf) is one of the closest examples of this process (Ibata, Gilmore, & Irwin 1994). The evidence continues to accumulate showing that contiguous streams of leading and trailing stellar debris are being pulled from the Sgr dwarf as it spirals into the Milky Way (e.g., Newberg et al. 2003; Majewski et al. 2003; hereafter M03). The stars associated with the Sgr dwarf span a wide range of ages, with the youngest population between 0.5 and 2 Gyr old (Layden & Sarajedini 2000; Dolphin 2002; M03). This indicates that within the past Gyr, the Sgr dwarf was forming stars and had a source of star formation fuel.

Neutral hydrogen is a principal source of star formation fuel for a galaxy. Galaxies which contain H I are commonly currently forming stars (e.g., Lee et al. 2002; G. Meurer et al. 2004, in preparation), and those without detectable H I tend to have primarily older stellar populations and thus appear to have exhausted their star formation fuel (e.g., Gavazzi et al. 2002). This is evident in the dwarf galaxies of the Local Group. The stars in the Local Group dwarfs vary from being almost entirely ancient (older than 10 Gyr; e.g., Ursa Minor) to a number of systems that are actively forming stars (e.g., WLM, Phoenix, LMC). The H I content of the dwarfs is summarized by Mateo (1998), Grebel, Gallagher, & Harbeck (2003), and Bouchard et al. (A. Bouchard et al. 2004, in preparation). The majority of the Local Group galaxies with H I have formed stars within the past 2 Gyr, and those with no evidence for recent star formation do not contain detectable H I (e.g., Mateo 1998; Dolphin 2002).

Pointed H I observations of the central region of the Sgr dwarf ($\alpha = -30°25'$, $\delta = 19^{h}00^{m}$ [J2000]; $l = 6°$, $b = -15°$) indicate that our closest satellite galaxy does not currently contain a significant amount of star formation fuel ($M_{\rm H\,I} < 1.5 \times 10^4$ $M_\odot$ [3 σ]; Koribalski, Johnston, & Otrupcek 1994). The search for H I associated with the Sgr dwarf was continued by Burton & Lockman (1999), but they also found no associated gas over 18 deg^2 between $b = -13°$ and $-18\overset{\circ}{.}5$, with limits of $M_{\rm H\,I} < 7 \times 10^3$ $M_\odot$ (3 σ). These results are surprising considering that the Sgr dwarf was forming stars within the last Gyr. Since the orbit of the Sgr dwarf is approximately 0.7 Gyr (Ibata & Lewis 1998), one might expect to find this fuel stripped along the dwarf's orbit, possibly at a location similar to the stellar trail. The trailing stellar tidal tail of the Sgr dwarf has recently been found to extend for over 150° across the south Galactic hemisphere with a mean distance between 20 and 40 kpc from the Sun (M03). Here we present H I data from the H I Parkes All Sky Survey[5] (HIPASS) along the entire Sgr dwarf galaxy orbit to investigate the possibility that a gaseous Sgr trail is also present. The gas detected represents a potential method of tracing the history, makeup, and classification of the Sgr dwarf galaxy, as well as the construction of our Galaxy.

2. OBSERVATIONS

The neutral hydrogen data are from HIPASS reduced with the MINMED5 method (P03). HIPASS is a survey for H I in the southern sky, extending from the south celestial pole to decl. = +25°, over velocities from −1280 to +12,700 km s^{-1} (Barnes et al. 2001). The survey utilized the 64 m Parkes radio telescope, with a focal-plane array of 13 beams arranged in a hexagonal grid, to scan the sky in 8° zones of declination, with Nyquist sampling. The MINMED5-reduced HIPASS data have a spatial resolution of $15\overset{'}{.}5$ and a spectral resolution, after Hanning smoothing, of 26.4 km s^{-1}. The survey was completed with a repetitive scanning procedure that provides source confirmation, mitigates diurnal influences, and aids interference excision. For extended sources, the rms noise is 10 mJy $beam^{-1}$ (beam area 243 $arcmin^2$), corresponding to a brightness temperature sensitivity of 8 mK. The northern extension of the survey, from +2° to +25°, was only recently completed and is presented for the first time here. The noise in these cubes is slightly elevated compared to the southern data (11 mK vs. 8 mK). This may be

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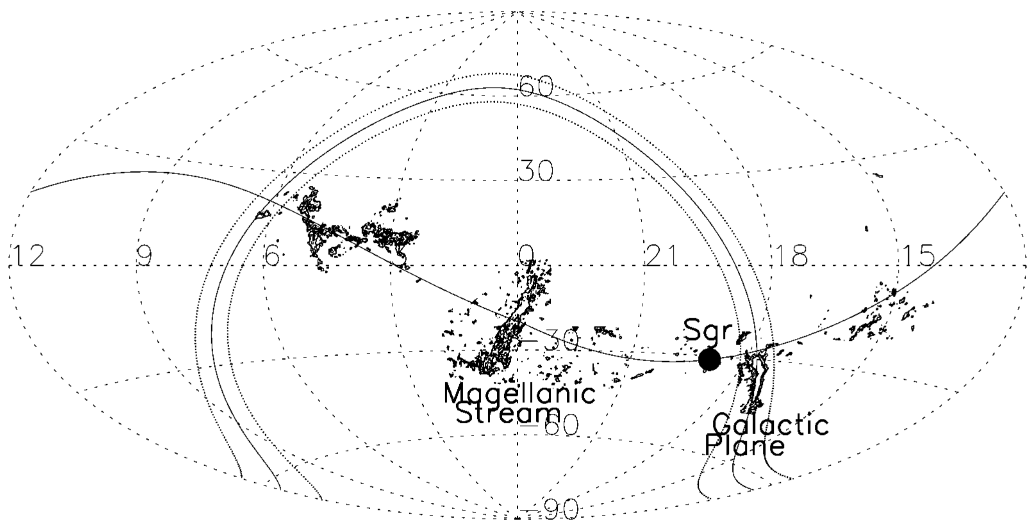

FIG. 1.—Negative high-velocity H I (∼−85 to −400 km s^{-1} [LSR]) along the orbit of the Sgr dwarf galaxy in celestial coordinates. The current position of the Sgr dwarf is shown by the filled circle, and the orbit of the Sgr dwarf (Ibata & Lewis 1998) is plotted as the solid line through this point. The negative-velocity gas attributed to the Magellanic Stream and Galactic plane gas at the Galactic center is labeled. The solid line through the labeled Galactic plane gas indicates $b = 0°$, with the two dotted lines on each side representing $b = +5°$ and $-5°$. The negative-velocity carbon stars extend from approximately $\alpha = 0^{\rm h}$, $\delta = -20°$ to $\alpha = 12^{\rm h}$, $\delta = 20°$ along the Sgr orbit (Ibata et al. 2001). Contours represent column density levels of 0.5, 1.0, 5.0, and 10.0 $\times 10^{19}$ cm^{-2}.

due to a combination of low zenith angles during these observations and an inability to avoid solar interference as effectively.

Integrated intensity maps of the high positive and negative velocity gas (generally $|v_{\rm LSR}| > 80$ km s^{-1}, as long as the gas was clearly separate from Galactic emission) were made for the 24 deg^2 cubes that lie along the Sgr orbit. The positive-velocity cubes had very little emission in them, so we concentrated on the negative-velocity cubes. The noise at the edges of the negative-velocity maps were blanked within AIPS, and the images were then read into IDL to create the map of the entire orbit shown in Figure 1. At 20–40 kpc, the MINMED5-reduced HIPASS data have a sensitivity to clouds of gas with $M_{\rm H\,I} > 80$–$320\ M_\odot$ ($\Delta v = 25$ km s^{-1}; 3 σ).

3. RESULTS

The large-scale H I map, which includes all of the high negative velocity gas along the orbit of the Sgr dwarf, is shown in Figure 1. This plot is in celestial coordinates, as it depicts the main features found along the orbit better than Galactic coordinates. The Galactic plane, the orbit of the Sgr dwarf (Ibata & Lewis 1998), and the current position of the Sgr dwarf are shown. The stream of M giants presented by M03 has quite a broad width (commonly several degrees) along this orbit. The orbit of the Sgr dwarf crosses the Galactic plane at $l \sim 185°$ and $l \sim 0°$, which corresponds to approximately $\alpha = 6^{\rm h}$, $\delta = 25°$ and $\alpha = 18^{\rm h}$, $\delta = -30°$, respectively. At the Galactic center, high negative and positive velocity gas is present; thus we have labeled the negative-velocity H I emission within $\pm 5°$ of the Galactic plane at that location. The Sgr orbit crosses the Magellanic Stream (labeled) at the south Galactic pole, or $\alpha = 0^{\rm h}$, $\delta = -15°$. The majority of the Sgr dwarf orbit does not have both stars and H I gas at high negative velocities, with the exception of the H I gas between $\alpha = 3^{\rm h}$–$4^{\rm h}30^{\rm m}$ and $\delta = 0°$–$30°$, or $l \approx 155°$–$195°$ and $b \approx -5°$ to $-50°$. A close-up of the velocity distribution of these H I clouds in Galactic coordinates is shown in the channel maps of Figure 2.

The M giants of the Sgr stellar stream fill a large percentage of the region shown in Figure 2. This high-velocity H I gas was previously identified as part of the anticenter complexes (ACHV and ACVHV; Wakker & van Woerden 1991) and was discovered almost 40 years ago (e.g., Mathewson et al. 1966), but its relationship to the Sgr dwarf was not previously noted. There are some small negative-velocity clouds along the Sgr dwarf orbit, but apart from the gas labeled in Figure 1, the only other substantial complex of negative-velocity gas along the orbit of the Sgr dwarf is in a region that has predominantly positive-velocity stars (Ibata et al. 2001). This is the group of high-velocity clouds (HVCs) known as complex L, at $\alpha \approx 15^{\rm h}15^{\rm m}$, $\delta \approx -19\overset{\circ}{.}5$. The amount of high positive velocity gas along the orbit of the Sgr dwarf is very limited and not correlated with the position of the positive-velocity stars along the Sgr stellar stream.

Figure 2 shows the gas along the orbit of the Sgr dwarf between $\alpha = 2^{\rm h}$–$5^{\rm h}30^{\rm m}$ and $\delta = 0°$–$30°$ in Galactic coordinates over the velocity range of -380 to -85 km s^{-1} (LSR). The emission extending from -380 to -180 km s^{-1} at $b < -20°$ is orientated along the orbit of the Sgr dwarf and is completely isolated from gas that merges with lower velocity emission. This complex of gas would amount to $M_{\rm H\,I} = 4.3 \times 10^6\ M_\odot$ at 36 kpc, the approximate distance to the stars in the Sgr stream. Other emission that appears in the channel maps includes a distinct filament beginning at $b = -10°$ in the velocity range of -245 to -75 km s^{-1}, which would have a mass of $5.4 \times 10^6\ M_\odot$ at 36 kpc. The gas in both complexes has peak column densities on the order of 10^{20} cm^{-2} at the $15\overset{\prime}{.}5$ resolution of HIPASS and extends to the column density limits of the data (5 $\sigma \sim 3 \times 10^{18}$ cm^{-2}; $\Delta v = 25$ km s^{-1}). There is also a population of clouds appearing at -125 km s^{-1} that merge into intermediate-velocity emission and are not included in Figure 1 for this reason. The distance of 36 kpc was based on the continuous stellar trail presented in M03 at those distances and the matching distance of a population of carbon stars (Ibata et al. 2001). The carbon stars associated with the Sgr dwarf at this position have velocities between -140 and -160 km s^{-1} (LSR; Dinescu et al. 2002; Totten & Irwin 1998; Green et al. 1994).

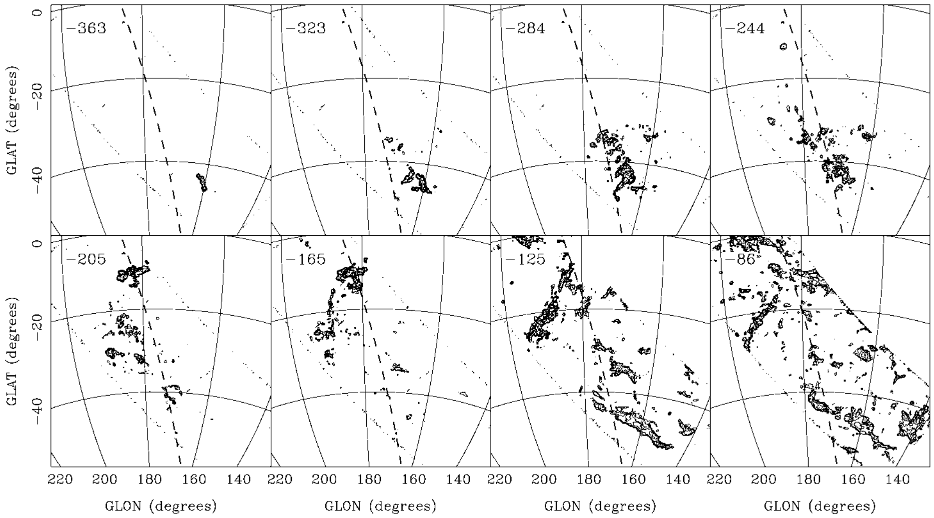

FIG. 2.—Channel maps of the H I clouds found along the trailing stellar stream of the Sgr dwarf in Galactic coordinates with v_{LSR} labeled in the upper left corner. The M giants (M03) extend across this region in a ∼15° band along the orbit of the Sgr dwarf (*dashed line*; Ibata & Lewis 1998). Contours are 0.055, 0.11, 0.22, 0.44, 0.88, and 1.8 K.

4. DISCUSSION

The present orbit of the Sgr dwarf is estimated to be 0.7 Gyr (Ibata & Lewis 1998). Using this orbit, the core of the Sgr dwarf was at the position of the H I complex presented here approximately 0.2–0.3 Gyr ago. It would make sense if the gas was part of the Sgr dwarf 0.3–0.7 Gyr ago, considering the age of part of the Sgr dwarf stellar population (0.5–2 Gyr; Layden & Sarajedini 2000; Dolphin 2002; M03). Not surprisingly, star formation surveys find that those galaxies that are actively forming stars also contain substantial amounts of star formation fuel in the form of neutral hydrogen (Lee et al. 2002; G. Meurer et al. 2004, in preparation). This Letter addresses the issue of when and how the star formation fuel of the Sgr dwarf was stripped from the galaxy.

The gas between −380 and −180 km s^{-1} at $b < -20°$ in Figure 2 is the gas we propose was most likely once part of the Sgr dwarf, as it follows the orbit of the Sgr dwarf and is completely isolated from lower velocity emission that may have a relation to disk gas (e.g., Tamanaha 1995). This gas lies at a position where the Sgr dwarf would have passed through the extreme edge of the Galactic disk, as the Sgr dwarf stellar debris at this position is approximately 40–50 kpc from the Galactic center (M03). We have adopted 45 kpc as the typical distance from the Galactic center at the position of the bulk of the gas. This distance is significantly beyond the typical radius quoted for our Galaxy (∼26 kpc); however, it is possible that an extended ionized disk exists for our Galaxy (e.g., Savage et al. 2003), as found in other systems (Maloney 1993; Bland-Hawthorn, Freeman, & Quinn 1997; Steidel et al. 2002). The passage through an extended disk of our Galaxy, in addition to the tidal forces already obviously at work as evident from the stellar tidal stream, might have been enough to disrupt the H I in the core of the galaxy and cause it to lose all remaining star formation fuel. The gas would be stripped from a galaxy if $\rho_{IGM} v^2 > \sigma^2 \rho_{gas}/3$ (Mori & Burkert 2000; Gunn & Gott 1972). We can use this equation to estimate the density needed at the edge of the disk to strip the gas from the core of the Sgr dwarf. We use a tangential velocity of 280 km s^{-1} for the Sgr dwarf and a velocity dispersion of 11.4 km s^{-1} (R. A. Ibata et al. 2004, in preparation; Ibata & Lewis 1998). If the column densities and size of the H I distribution in the core of the Sgr dwarf were on the order of 5 × 10^{20} cm^{-2} (averaged over the core) and 1 kpc, the typical ρ_{gas} would be 0.16 cm^{-3}. An extended disk density greater than 3×10^{-4} cm^{-3} is then needed to strip the gas via ram pressure stripping. Based on previous estimates of the density of the Galactic halo, this density would be easily achieved in the plane of the Galaxy, 20 kpc from the currently observed edge of the disk. Examples of estimates for the density of the Galactic halo that are consistent with ∼10^{-4} cm^{-3} at distances of 50 kpc and more include: explaining the existence of head-tail clouds that can be associated with the Magellanic Stream (Quilis & Moore 2001); the confinement of the tip of the Magellanic Stream (Stanimirović et al. 2002); the O VI high-velocity absorption line results (Sembach et al. 2003); and the diffuse X-ray emission (Wang & McCray 1993) and dispersion measures for Large Magellanic Cloud pulsars (Taylor, Manchester, & Lyne 1993) when the ionized medium is extended over ∼100 kpc.

Stripping gas from a Galactic satellite by passing it through the edge of the Galaxy's disk was proposed as a possible solution for the origin of the Magellanic Stream by Moore & Davis (1994, hereafter MD94). They invoked an extended ionized disk at 65 kpc from the Galactic center, with column densities less than 10^{19} cm^{-2}, to strip gas from the satellite galaxy. The stripped gas initially has its speed reduced, but the decelerated gas falls to a lower orbit and subsequently attains a higher angular velocity. In order to reproduce the properties and distribution of the Magellanic Stream, MD94 induce a braking effect on the gas with a diffuse medium in the halo, preventing it from rapidly falling into the Galactic potential. Although the H I trail of the Sgr dwarf has a very different structure from the Magellanic Stream, parallels can be made between the MD94 model and the stripping of the Sgr H I clouds. Both of the systems have similar impact velocities and have gas at similar distances from their cores (roughly 50–60 kpc), with similar column densities and velocities. The gas along the Sgr dwarf orbit has slightly higher negative velocities than the carbon stars with velocity determinations in this region, and this may be due to the gas falling into a slightly lower orbit than the stars. The exact predicted position and velocity of the gas relative to the stars will be addressed in a future simulation paper.

At 36 kpc from the Sun, the H I gas between −380 and −180 km s^{-1} at $b < -20°$ has a mass of $4.3 \times 10^6\ M_\odot$. If the filament extending from $b = -10$ to $-25°$ and $v_{LSR} = -245$ to -85 km s^{-1} is included as formerly part of the Sgr dwarf, the total H I mass goes up to 9.7×10^6 $M_\odot$. A typical total H I mass for a dwarf galaxy is on the order of 10^7–10^8 $M_\odot$ (Grebel et al. 2003), so 10^6–10^7 $M_\odot$ of gas originally being associated with the dwarf is certainly plausible and may represent anywhere from the majority to 10% of the Sgr dwarf's original H I mass. Using a total Sgr dwarf mass of 5×10^8 $M_\odot$ (M03), this gas represents 1%–2% of its total mass. The Sgr dwarf most likely originally had more than 10^6–10^7 $M_\odot$ of neutral hydrogen associated with it, as the outer gaseous component would have been the first thing stripped (e.g., Mihos 2001; Yoshizawa & Noguchi 2003). This outer gas would have had column densities between 10^{18}–10^{19} cm^{-2} and most likely has either already dispersed or been ionized, although remnants of this gas may be present as small HVCs along the Sgr dwarf orbit. Since there is currently no H I associated with the core of the Sgr dwarf (Koribalski et al. 1994), and the dwarf has stars that are 0.5–2 Gyr old, the H I gas presented here most likely represents the high column density gas from the core of the Sgr dwarf that was finally stripped when the dwarf passed through the higher density medium in the extended Galactic disk. This is supported by the relatively high peak column densities of the H I gas currently seen ($\sim 10^{20}$ cm^{-2}). For the Sgr H I gas to survive for 0.2–0.3 Gyr (the time since the last passage of the core of the Sgr dwarf), not to mention the Magellanic Stream, which is thought to be more than 0.5 Gyr old, the gas should either be confined by an existing halo medium or associated with significant amounts of dark matter.

5. OVERVIEW

Our Galaxy's halo is made up of numerous streams of satellite debris that trace its formation. The association of H I gas with the Sagittarius dwarf galaxy emphasizes the number of dynamical processes occurring within the Galactic halo. In this Letter we find (4–10) $\times 10^6$ $M_\odot$ of H I gas along the orbit of the Sgr dwarf. This is approximately 1%–2% of the total mass of the dwarf, 10–20 times lower than the H I mass of the Magellanic Stream, and approximately the same H I mass as the leading arm of the Magellanic System (P03). We argue that this H I was the last gas stripped from the core of the Sgr dwarf ~0.2–0.3 Gyr ago as a result of its passage through the extended Galactic disk, with densities greater than 10^{-4} cm^{-3}. This is supported by the agreement in the spatial distribution of the gas and stars along the Sgr orbit, by both components having high negative velocities, the location of the gas relative to the plane of our Galaxy, the relatively high column densities of the H I gas, and the star formation history of the Sgr dwarf. The association of H I gas with the Sgr stellar stream suggests that the dwarf spheroidal classification for the Sagittarius galaxy may need to be reconsidered. It also suggests that slightly offset H I and stellar streams may be a common feature of disrupted satellites in the Galactic halo. With the accretion of this Sgr H I stream, the Magellanic Stream (P03), complex C (Wakker et al. 1999), and possibly other HVCs, there is ample fuel for our Galaxy's continuing star formation and our understanding of the distribution of stellar metallicities (e.g., the G dwarf problem is not a problem). Determining the metallicity, distance, and ionization properties of the H I gas presented here will aid in confirming if this H I gas was indeed stripped from the Sgr dwarf during its current orbit. Since we propose that this is the last gas from the core of the Sgr dwarf, we will also look for molecular gas and dust associated with these clouds. A future simulation paper will address the exact spatial and velocity distribution expected for gas stripped from the Sgr dwarf.

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