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THE SMITH CLOUD: A HIGH-VELOCITY CLOUD COLLIDING WITH THE MILKY WAY

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ABSTRACT

New 21 cm H I observations made with the Green Bank Telescope show that the high-velocity cloud known as the Smith Cloud has a striking cometary appearance and many indications of interaction with the Galactic interstellar medium. The velocities of interaction give a kinematic distance of 12.4 ± 1.3 kpc, consistent with the distance derived from other methods. The Cloud is >3 × 1 kpc in size, and its tip at $(l, b) \approx 39°, -13°$ is 7.6 kpc from the Galactic center and 2.9 kpc below the Galactic plane. It has $>10^6\ M_\odot$ in H I. Its leading section has a total space velocity near 300 km s^{-1}, is moving toward the Galactic plane with a velocity of 73 ± 26 km s^{-1}, and is shedding material to the Galaxy. In the absence of drag, the Cloud will cross the plane in about 27 Myr. The Smith Cloud may be an example of the accretion of gas by the Milky Way that is needed to explain certain persistant anomalies in Galactic chemical evolution.

Subject headings: Galaxy: evolution — Galaxy: halo — ISM: clouds — ISM: individual (Smith Cloud)

1. INTRODUCTION

High-velocity clouds (HVCs) cover as much as 40% of the sky and have been hypothesized to be the remnants of the formation of the Milky Way, products of a Galactic fountain, material stripped from the Magellanic Clouds, satellites of the Milky Way, and objects in the Local Group (Wakker & van Woerden 1997; Blitz et al. 1999; Braun & Burton 1999; Lockman et al. 2002; Maller & Bullock 2004; Connors et al. 2006). Several have distance determinations that place them in the halo of the Galaxy with $M_{\rm H\,I} \sim 10^6$–$10^7\ M_\odot$ (Thom et al. 2007; Wakker et al. 2007, 2008). Some have a cometary morphology and kinematics suggesting that they are interacting with an external medium (Mirabel & Morras 1990; Brüns et al. 2000; Brüns & Mebold 2004; Peek et al. 2007).

The Smith Cloud (Smith 1963) is a large, coherent H I feature that is also called the Galactic center–positive complex (Wakker & van Woerden 1997). Its velocity of +100 km s^{-1} is only slightly larger than permitted by Galactic rotation at its location $(l, b \approx 39°, -13°)$, and Smith concluded that it was most likely part of the Milky Way disk. In recent years, however, it has been classified as a high-velocity cloud because it lies far beyond the main H I layer (Lockman 1984; Wakker & van Woerden 1997). It has been interpreted variously as a cloud expelled from the disk (Sofue et al. 2004) or the gaseous component of the Sgr dwarf spheroidal galaxy (Bland-Hawthorn et al. 1998). We have made an extensive survey of the Smith Cloud in the 21 cm H I line using the Green Bank Telescope, whose angular resolution and sensitivity promised new insights into this system. In particular, we hoped that, because of its large angular size, we might be able to measure its transverse velocity (e.g., Brüns et al. 2001; Lockman 2003). A complete discussion of the observations will appear elsewhere. Here we present the initial results on the Cloud's physical properties and motion.

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2. OBSERVATIONS AND DATA REDUCTION

The Smith Cloud was observed in the 21 cm H I line using the Robert C. Byrd Green Bank Telescope (GBT) of the NRAO. Spectra were measured in both linear polarizations over a velocity range of 500 km s^{-1} centered at +50 km s^{-1} LSR with a channel spacing of 1.03 km s^{-1} and an effective velocity resolution of 1.25 km s^{-1}. Spectra were acquired by in-band frequency-switching while moving the telescope in Galactic latitude or longitude, sampling every 3′ in both coordinates. In all, more than 40,000 positions were measured over an area of ~140 deg^2. Spectra were edited and calibrated, a third-order polynominal was fit to the emission-free channels, and the data were gridded into a cube with 3.5′ cell spacing. The rms noise in the final data cube is typically 90 mK of brightness temperature in a 1 km s^{-1} channel. The on-the-fly mapping and gridding degraded the angular resolution somewhat from the intrinsic 9.1′ resolution of the telescope to an effective resolution of 10′–11′.

3. THE SMITH CLOUD

Figure 1 shows the GBT H I image of the Smith Cloud at $V_{\rm LSR}$ = 100 km s^{-1}. The Cloud has a cometary morphology with a bright compact "tip" and a more diffuse "tail." Its appearance suggests that it is moving toward the Galactic plane at a 45° angle and is interacting with the Galactic interstellar medium (ISM). Direct evidence of this interaction is given in Figure 2, which shows the H I emission in velocity-position coordinates along a cut through the minor axis of the Cloud. The center of the Cloud has a velocity near +100 km s^{-1}, well-separated from the Galactic H I, but at its edges the lines are broadened and shifted toward the velocity of the Galactic ISM at $\lesssim$+35 km s^{-1}. We interpret this as ram pressure stripping of the Cloud edges. The Cloud's interaction with the Galactic ISM is shown further in Figure 3, a position-velocity slice along the major axis of the Cloud following a track marked by the arrows to the upper right and lower left in Figure 1. There are

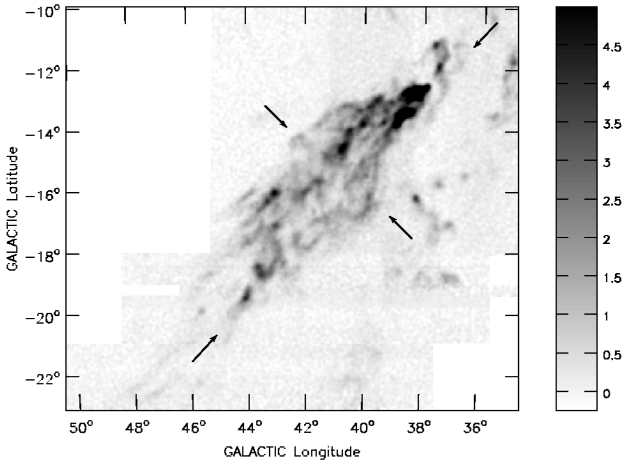

FIG. 1.—GBT H I image of the Smith Cloud at $V_{LSR} = 100$ km s^{-1} showing the cometary morphology that strongly suggests that the Cloud is moving to lower longitude and toward the plane and that it is interacting with the Galactic ISM. Arrows mark the tracks of the velocity-position slices of Figs. 2 and 3.

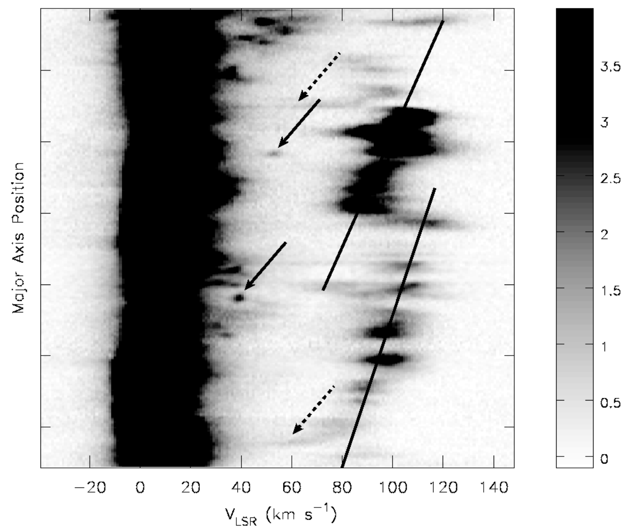

FIG. 3.—GBT H I velocity-position slice through the major axis of the Cloud at the location of the arrows in Fig. 1. Marks on the vertical axis are every 157.5′. Along this track, there are H I clumps at low velocity that match the gaps in the main Cloud. The clumps have likely been stripped from the Cloud. Two are marked by the solid arrows. Two line wings that form kinematic bridges between the Cloud and Galactic gas are marked by the dotted arrows. The main part of the Cloud shows systematic velocity gradients from the changing projection of its space velocity with respect to the LSR. The tilted lines show the expected run of V_{LSR} with position for $V_{tot} = 296$ km s^{-1} (upper part of the Cloud) and $V_{tot} = 271$ km s^{-1} (lower part). The Cloud consists of at least two coherent kinematic pieces.

kinematic bridges between the Cloud and Galactic emission (several are marked with dotted arrows), as well as clumps of H I (two are marked by solid arrows) at velocities $\lesssim 40$ km s^{-1} that correspond to gaps in the Cloud. The clumps are likely material stripped from the Cloud.

4. DISTANCE TO THE CLOUD

Portions of the Smith Cloud appear to have been decelerated by the ambient medium through which it moves, and we use this to estimate a distance to the Cloud. The GBT data show disturbances in Galactic H I attributable to the influence of the Smith Cloud at $V_{LSR} \geq 35$ km s^{-1} but not at $V_{LSR} \leq 0$ km s^{-1}. If the Smith Cloud is interacting with Galactic gas whose normal rotational velocity is in this range, it implies that that the Cloud has a distance in the range 11.1 kpc $< d_k <$ 13.7 kpc, the "far" kinematic distance for a flat rotation curve with $R_0 = 8.5$ kpc and $V_0 = 220$ km s^{-1}.

There are other determinations of the distance. The brightness of diffuse Hα emission from the Cloud and a model for the Galactic UV flux give either 1 or 13 kpc (Bland-Hawthorn et al. 1998; Putman et al. 2003). Recently, Wakker et al. (2008) have bracketed the distance by looking for the Cloud in absorption against several stars, finding 10.5 kpc $< d \leq$ 14.5 kpc. The three methods give identical results, and we adopt the kinematic distance $d = 12.4 \pm 1.3$ kpc for the remainder of this Letter.

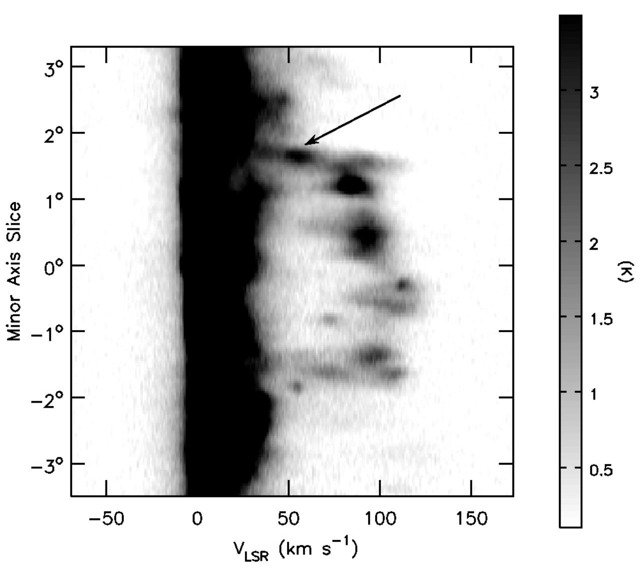

FIG. 2.—GBT H I velocity-position slice through the Smith Cloud along a track through the minor axis of the Cloud (marked by arrows in Fig. 1). The edges of the Cloud show a sharp gradient in velocity from $V_{LSR} \sim 100$ km s^{-1} to the lower velocities of Galactic H I. We interpret this as evidence of the interaction between the Cloud and the gaseous halo of the Milky Way. The arrow marks the decelerated ridge shown in Fig. 4.

5. PROPERTIES OF THE CLOUD

The Smith Cloud lies in the inner Galaxy below the Perseus spiral arm, $R = 7.6$ kpc from the Galactic center. The properties of the Cloud obtained from the GBT data are presented in Table 1. The brightest H I emission at $l, b = 38.67°, -13.41°$ is near the Cloud tip. The H I mass of $10^6\ M_\odot$ is a lower limit because the Cloud appears to consist of multiple fragments

TABLE 1
H I PROPERTIES OF THE SMITH CLOUD

Property	Value
l, b (deg)	38.67, −13.41
Distance (kpc)	12.4 ± 1.3
R (kpc)	7.6 ± 0.9
z (kpc)	−2.9 ± 0.3
T_b (K)	15.5
Δv (km s^{-1})	16.0
N_{HI} (cm^{-2})	5.2×10^{20}
V_{LSR} (km s^{-1})	99 ± 1
H I mass ($M_\odot$)	$>10^6$
Projected size (kpc)	3 × 1

NOTE.—All but integral quantities apply to the direction of greatest N_{HI} at the position $l, b = 38.67°, -13.41°$.

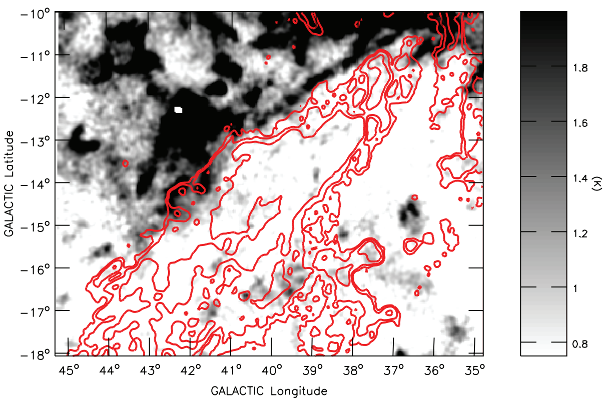

FIG. 4.—H I in a 1 km s^{-1} wide channel at 51 km s^{-1} (*gray scale*) with superimposed contours of the Smith Cloud showing the ridge of gas resulting from the encounter of the Cloud with the Galactic halo. We believe that the lower velocity ridge is material stripped from the Cloud. The Cloud emission is integrated over 90–145 km s^{-1}, and the contours are drawn at 7, 14, and 35 K km s^{-1}.

spread over a wide area, not all of which are covered in the GBT map. It probably contains a significant mass in H$^+$ as well (Wakker et al. 2008). The H I line width Δv (FWHM) varies from $\leq$10 km s^{-1}, in a band from the Cloud tip down along the major axis, to >20 km s^{-1}, in the Cloud's tail and at its edge, where the sight line through the Cloud intersects regions with a great spread of velocity (see, e.g., Figs. 2 and 3). The Cloud as a whole is not self-gravitating, and even the most compact components have only 1% of their virial mass.

There are narrow, unresolved ridges of intermediate-velocity H I with $N_{\rm H\,I} = 2 \times 10^{20}$ cm^{-2} at the edge of the Cloud (Fig. 4, also marked with the arrow in Fig. 2). There is some cool gas in the ridge, especially toward the tip of the Cloud, but in general the lines from the ridge are broad, with Δv = 10–20 km s^{-1}. The ridge contains orders of magnitude more gas than would be expected for material swept up by the passage of the Cloud through the Galactic halo at a distance of a few kiloparsecs from the plane (Dickey & Lockman 1990; Howk et al. 2003), but it has an $N_{\rm H\,I}$ comparable to that of the Cloud. The ridge is most likely material that has been ram-pressure-stripped from the Cloud.

From the GBT data, we find that the edge of the Smith Cloud is unresolved along the region of interaction, implying a size <35 pc. The ridge and the edge of the Smith Cloud do not overlap on the sky, and both have unresolved edges where they are closest, suggesting that we are viewing the interaction at a very favorable angle. The decelerated clumps marked in Figure 3 have $N_{\rm H\,I}$ = 1–2 $\times$ 10^{19} cm^{-2} and H I masses of 200–400 $M_\odot$. The lower velocity clump is unresolved with a size <35 pc, whereas the higher velocity clump is elongated with a size <35 pc $\times$ 130 pc. The line widths are narrow, 4 and 5.4 km s^{-1}, respectively, indicating that the clumps contain gas no hotter than 350 K.

6. TRAJECTORY

The Smith Cloud covers a large area on the sky, and we can hope to derive its complete space motion from its morphology and the systematic change in $V_{\rm LSR}(l, b)$ with position if local effects like drag are small. For a system centered on the Galactic center,

$$V_{\rm LSR} = \left[R_0 \sin l \left(\frac{V_\theta}{R} - \frac{V_0}{R_0}\right) - V_R \cos(\ell + \theta)\right] \cos b + V_z \sin b, \quad (1)$$

where V_θ, V_R, and V_z are velocity components in the direction of Galactic rotation, outward, and vertically toward the north Galactic pole. The angle θ is measured from the Sun-center line in the direction of Galactic rotation. With the Smith Cloud, we have the exceptional circumstance that all distances and angles are known, and so, with measurements of $V_{\rm LSR}(l, b)$ and the angle of the Cloud's motion (assumed to be along its major axis), we can solve for the individual velocity components and calculate the total space velocity $V_{\rm tot} \equiv (V_\theta^2 + V_R^2 + V_z^2)^{1/2}$.

The H I profiles from the Smith Cloud have complex shapes, and a full discussion of the Cloud's kinematics is beyond the scope of this Letter. As an initial step, we have taken the velocity of the brightest H I in each pixel, averaged this over square-degree regions along the major axis of the Cloud from (l, b) = 36°–11° to 48°–23°, and solved for the velocity components. The results are shown in Figure 3. The main Cloud has two kinematic groups, each of which shows the regular velocity pattern expected from the projection effects of the motion of a coherent object. Table 2 summarizes the results, where the quantity $V_{\rm ISM}$ is the velocity of the Cloud with respect to a corotating ISM at its location, and the uncertainties reflect the scatter in both the data and the 45° ± 10° assumed angle of motion of the Cloud across the sky. With $V_{\rm tot} \approx 300$ km s^{-1}, the Cloud is bound to the Galaxy. Its motion is prograde, somewhat faster than the Galactic rotation, with an outward radial velocity $V_R \sim 100$ km s^{-1}. The compact Cloud tip is moving toward the plane with a velocity $V_z = 73 \pm 26$ km s^{-1}, whereas the more diffuse trailing structure appears to have a much lower vertical velocity of 8 ± 11 km s^{-1}.

TABLE 2
KINEMATICS OF THE SMITH CLOUD

Location	V_R (km s^{-1})	V_θ (km s^{-1})	V_z (km s^{-1})	$V_{\rm tot}$ (km s^{-1})	$V_{\rm ISM}$ (km s^{-1})
Tip	94 ± 18	270 ± 21	73 ± 26	296 ± 20	130 ± 14
Tail	129 ± 6	220 ± 11	8 ± 11	271 ± 6	130 ± 5

NOTE.—V_R is the velocity outward from the Galactic center, and $V_{\rm ISM}$ is the total velocity of the Cloud with respect to the corotating Galactic ISM at its location.

From its current position and velocity, we calculate the Cloud's orbit in the potential of Wolfire et al. (1995). Assuming that drag is not significant, it will cross the Galactic plane at a distance $R \approx 11$ kpc from the Galactic center in about 27 Myr. Retracing its orbit into the past (again neglecting drag), the Cloud reached perigalacticon at R = 6.9 kpc some 12 Myr ago, was never more than 3.6 kpc below the Galactic plane, and actually passed through the plane, from above to below, at R = 13 kpc about 70 Myr ago. The current orbit is tilted only ≈30° to the Galactic pole, so we probably view the Cloud at a large angle to the plane of the sky, with its tail closer to us than its tip. These results will likely be modified as we understand the Cloud's structure in more detail, but the conclusion that large portions of the Smith Cloud move coherently seems secure.

7. DISCUSSION

All the data on the Smith Cloud are consistent with the model of a $10^6\ M_\odot$ H I cloud the size of a dwarf galaxy on track to intersect the Galactic plane. We know more about this particular HVC than any other. Its total space velocity of ≈300 km s^{-1} implies that it is bound to the Galaxy and that the components that are not greatly slowed by drag from the Galactic halo should reach the plane in 27 Myr at a location about 11 kpc from the Galactic center. Its trajectory is rather flat and mostly prograde, and it may have passed through the Galactic plane once before some 70 Myr ago. The Cloud now consists of two coherent kinematic components, as well as material decelerated to much lower velocity.

Studies of Galactic chemical evolution have uniformly concluded that the Milky Way is not a "closed box" but must accrete low-metallicity gas, possibly supplied by HVCs (e.g., Friel et al. 2002; Matteucci 2004; Romano et al. 2006; Putman 2006). The collision of an HVC with the disk has also been invoked to explain the largest H I supershells as well as the Gould Belt (Tenorio-Tagle et al. 1987; Mirabel & Morras 1990; Comeron & Torra 1994). Although there are HVCs that show evidence of interaction with the Milky Way halo (Brüns & Mebold 2004), there are only a few known to be interacting with the Galactic disk (Lockman 2003; McClure-Griffiths et al. 2008), and these are located in the outer parts of the Galaxy, far from the main star-forming regions. The Smith Cloud is exceptional in that it is entering the Milky Way at $R \lesssim R_0$.

At its current distance of ~3 kpc from the Galactic plane, the Cloud is probably encountering a mix of warm H^+ and 10^6 K gas with a total density in the range 10^{-3} to 10^{-4} cm^{-3}, although Galactic H I clouds at this height are not out of the question (Lockman 2002; Howk et al. 2003; Benjamin 2004; Pidopryhora et al. 2007). We find several Smith Cloud clumps with $M_{\rm H\,I} \approx 100\ M_\odot$ that have been decelerated by >50 km s^{-1}, suggesting that the ambient ISM is irregular with large density variations. The nature of the Cloud's interaction with the ISM will depend on its internal properties, which are not yet known, but the Smith Cloud shows every evidence of being disrupted and may not survive much longer as a coherent structure.

Does this cloud have a Galactic or extragalactic origin? Is the Smith Cloud a true high-velocity cloud? Its H I mass is in the range of HVCs like complex c, Complex H, and the Cohen Stream (Lockman 2003; Wakker et al. 2007, 2008), and, given its estimated orbit, it is hard to envision an event that would accelerate more than $10^6\ M_\odot$ of material to such a high space velocity with a significant radial component. However, an extragalactic origin is somewhat problematic as well. If it were extragalactic, then it is puzzling that the orbit is tilted by only 30° from the Galactic plane, is prograde, and differs from the ambient ISM by only 130 km s^{-1}. Kinematically, then, it might appear to be more of an intermediate- than a high-velocity cloud, but presumably its orbit must have been affected by drag well before the current epoch (Benjamin & Danly 1997). Its internal kinematics suggest that it has already fragmented (Fig. 3). A key observational datum is the Cloud's metal abundance to establish exactly what kind of gas it is depositing in the Galaxy. For this Letter, we have analyzed only a fraction of the information in the GBT H I spectra. A more detailed analysis of the GBT data and additional measurements of this extraordinary and beautiful object are underway.

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Facility: GBT

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