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Accretion Onto the Milky Way: The Smith Cloud

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Abstract. Active gas accretion onto the Milky Way is observed in an object called the Smith Cloud, which contains several million solar masses of neutral and warm ionized gas and is currently losing material to the Milky Way, adding angular momentum to the disk. It is several kpc in size and its tip lies 2 kpc below the Galactic plane. It appears to have no stellar counterpart, but could contain a stellar population like that of the dwarf galaxy Leo P. There are suggestions that its existence and survival require that it be embedded in a dark matter halo of a few 10^8 solar masses.

Keywords. Galaxy: evolution, Galaxy: formation, Galaxy: halo, galaxies: ISM

1. Introduction

The puzzle of the origin of high velocity clouds (HVCs) is still with us more than 50 years after their initial discovery (Muller *et al.* 1963), and despite the enormous progress made in the past decades in understanding their distances, size, mass, metallicity, covering fraction, and ionization state (e.g., Wakker & van Woerden 1997; Lockman *et al.* 2002; Fox *et al.* 2006; Wakker *et al.* 2008; Thom *et al.* 2008; Shull *et al.* 2009; Putman *et al.* 2012; Lehner *et al.* 2012). HVCs are now known to exist around nearby galaxies in a population that extends at least 50 kpc from the host system (Thilker *et al.* 2004; Grossi *et al.* 2008; Westmeier *et al.* 2008; Putman *et al.* 2009). The possibility that *some* HVCs may be intra-group or even intergalactic, or associated with dark matter halos, or tracers of faint dwarf galaxies, cannot be excluded (e.g., Blitz *et al.* 1999; Braun & Burton 1999; Adams *et al.* 2013). Except for the Magellanic Stream, the origin of even the most well-studied HVC is completely unknown.

2. The Smith Cloud

Perhaps the most exceptional HVC is the Smith Cloud (Smith 1963), first identified in observations at 35′ resolution where it shows some head-tail structure, as do about 10% of Milky Way HVCs (Brüns *et al.* 2000). Observations with the 100 meter Green Bank Telescope (GBT) at 9′ resolution reveal a spectacular cometary cloud, showing extensive evidence of interaction between the cloud and the gaseous halo of the Milky Way (Lockman *et al.* 2008). Figure 1 shows an HI image from new unpublished GBT observations (Lockman *et al.* 2016). The new data reveal some previously unknown cloud components symetrically placed aside the main body of the cloud, as well as a very extended "tail".

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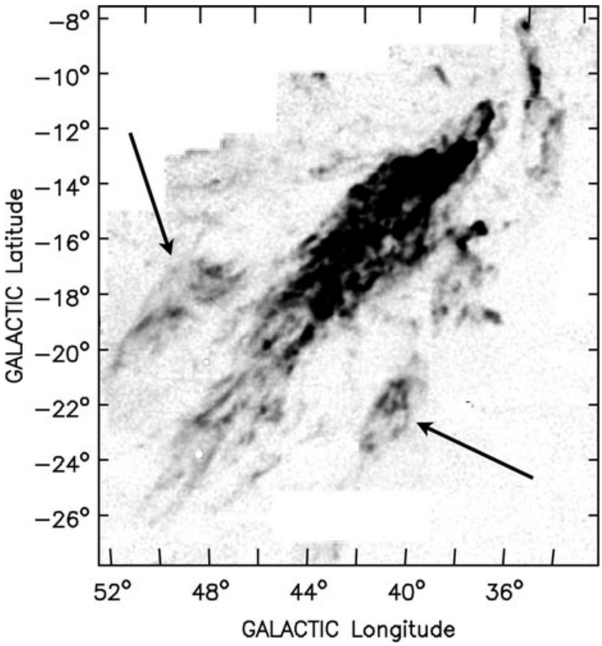

Figure 1. The Smith Cloud in HI from new unpublished observations with the GBT. The two features marked with arrows have the appearance of having been shed by the cloud as it moves toward the Galactic plane; each contains $\sim 5 \times 10^4$ $M_\odot$.

Much is now known about the Smith Cloud. Its distance has been estimated from three independent techniques, which agree quite well (Lockman *et al.* 2008). Measurement of interstellar absorption lines against stars at varying distance provide the strongest constraint (Wakker *et al.* 2008). Basic properties of the cloud are listed in Table 1.

Faint Hα emission detected from the cloud suggests that it contains as much ionized as neutral gas (Bland-Hawthorn *et al.* 1998; Putman *et al.* 2003; Hill *et al.* 2009). From a study of the rotation measure of background AGN, Hill *et al.* (2013) deduce the presence of a magnetic field with an amplitude 8 μG in the decelerated parts of the cloud. New data, currently being analyzed, should improve both of these estimates.

There is no obvious stellar counterpart to the cloud. Stark *et al.* (2015) looked for young stars but did not find a statistically significant excess toward the cloud compared to adjacent areas. Contamination by the Milky Way at the low latitude of the cloud makes this work difficult, however, and Stark *et al.* emphasize that they cannot rule out a stellar population like that of Leo P, a dwarf galaxy with a similar HI mass and $M_V = -9.4$ (McQuinn *et al.* 2013).

3. Interaction

Evidence of interaction with the Milky Way abounds. The overall morphology of the Smith Cloud suggests that it is moving towards the Galactic plane and enountering the Galactic halo, shedding pieces of itself as it goes. The tip of the cloud at $z \approx -2$ kpc is closer to the Galactic plane than the top of some HI superbubbles (Pidopryhora *et al.* 2007). The densest portions of the cloud lie closest to the Galactic plane while the “tail”, 10° further from the plane, is much more diffuse. There is kinematic evidence of the interaction as well. Figure 2 shows a velocity-position cut across the center of the cloud. The main body of the cloud is distinct from Galactic HI, but there are kinematic

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Table 1. Smith Cloud Properties

Distance[1,2]	12.4 ± 1.3 kpc
R_{gal}	7.6 ± 1.0 kpc
z	-2.2 kpc
size	$\approx 3 \times 1$ kpc
M_{HI} [2]	2.0×10^6 $M_\odot$
M_{H+} [3]	$> 1.0 \times 10^6$ $M_\odot$
$B_{\|\|}$ [4]	8 μG

Notes: 1) Wakker *et al.* 2008. 2) Lockman *et al.* 2008, 2016. 3) Hill *et al.* 2009. 4) Hill *et al.* 2013.

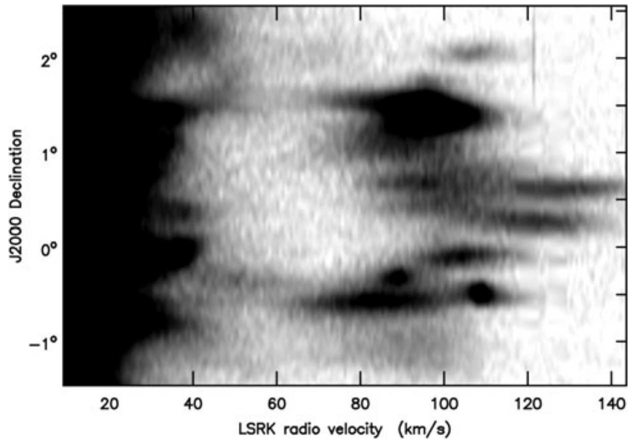

Figure 2. Position-velocity cut across the minor axis of the Smith Cloud. The main part of the cloud lies at $V_{LSR} \approx 100$ km s^{-1}, but its edges show kinematic "bridges" to the lower-velocity Galactic gas, indicating that portions of the cloud are decelerating and being accreted by the Galaxy.

"bridges" between the cloud edges and lower-velocity disk/halo gas. Here we see direct evidence that portions of the cloud have been decelerated and are now blending with the Galaxy. There is also a ridge of decelerated gas conforming to the upper edge of the cloud (see Figure 4 of Lockman *et al.* 2008). Several holes in the main body of the cloud at $V_{LSR} \approx 100$ km s^{-1} correspond to ~ 100 $M_\odot$ HI clumps at ~ 50 km s^{-1} lower V_{LSR}, suggesting that pieces of the cloud have broken away and been decelerated by the medium it is encountering. There seems to be no doubt that the Smith Cloud is being destroyed by its interaction with the Milky Way and is losing gas to the Galaxy. A similar pattern of accretion is observed in the HVC Complex H (Lockman 2003).

4. Trajectory and Progenitor

Lockman *et al.* (2008) used the change of V_{LSR} along the cloud's major axis to estimate a trajectory and found that the cloud has a total space velocity ≈ 300 km s^{-1}, well below the escape velocity of the Milky Way. While this analysis was based on early data and does not include the full extent of the cloud in Fig. 1, there seems little doubt that the cloud's largest velocity component is in the direction of Galactic rotation – as it interacts with the Milky Way it therefore adds angular momentum to the disk.

It is likely that the main body of the cloud was never more than 4 kpc from the Galactic plane and its "tail" is considerably closer to us than its head, though its exact orientation with respect to the plane of the sky is unknown. There is even evidence for

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a extended component of the cloud ahead of the main body (Lockman 2012). Clarifying these points is clearly important to understanding the origin and fate of the cloud.

Simulations suggest that clouds falling into the Milky Way halo are easily disrupted (Putman *et al.* 2012 and references therein), so given its striking appearance, evidence for interaction, and rather modest total space velocity, a natural question is why the Smith Cloud has survived as long as it has. One answer, first proposed by Nichols & Bland-Hawthorn (2009) and presented in more detail by Nichols *et al.* (2014) is that the Smith Cloud is the baryonic component of a dark matter sub-halo. A dark matter halo $\sim 3 \times 10^8$ $M_\odot$ is sufficient to stabilize the cloud core while not massive enough to induce significant star formation, which is not observed. This model may be entirely consistent with the Smith Cloud being a dwarf galaxy similar to Leo P, but a dwarf whose accretion and disruption by the Milky Way are now being witnessed at close range.

The Smith Cloud is an extraordinary object whose study may illuminate many aspects of the growth and evolution of galaxies.

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