HI CLOUDS BEYOND THE GALACTIC DISK

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Abstract Recent observations in the 21cm line with the Green Bank Telescope have changed our view of the neutral interstellar medium (ISM) in several ways. The new data show that in the inner parts of the Milky Way the disk-halo interface is composed of many discrete HI clouds. The clouds lie in a layer more than one kpc thick and follow Galactic rotation. Their origin and evolution is unknown. In the outer Galaxy, the new data show that the high-velocity cloud Complex H is likely a satellite on a retrograde orbit interacting with some extended component of the Milky Way's ISM. These observations place new constraints on models of the ISM and are directly related to the work of Don Cox and Ron Reynolds.

1. Introduction

This paper is about two topics close to the interests of Don Cox and Ron Reynolds: the structure of the ISM at the disk-halo interface, and a high-velocity HI cloud which appears to be interacting with the gaseous Galactic halo. The discoveries discussed here were made with the new 100 meter Green Bank Telescope (the GBT), whose sensitivity, dynamic range, and angular resolution make it a fabulous tool for Galactic 21cm HI observations. We are just now beginning to feel its impact in interstellar and Galactic studies.

2. HI That Came Up From the Disk

It has been known for some time that there are significant amounts of HI far from the Galactic disk that can be observed in 21cm emission and optical/UV absorption lines (e.g., Lockman 1984; Lockman, Hobbs & Shull 1986; Savage 1995). Until now, however, its structure has been unknown. Figure 1 shows GBT observations of the HI in the Galactic plane and lower halo around longitude 20°. In these new data the transition zone between the neutral disk and the halo is seen to be populated with neutral clouds. A typical halo cloud in a sample studied near $\ell = 29°$ (Lockman 2002) has a size of a few tens of pc, an HI mass of a few tens of solar masses, and $N_{HI} = 2 \times 10^{19}$ cm^{-2}, though clouds have a large range in all of their properties. The HI lines from the clouds have a typical width of 12 km s^{-1}, but some lines are so narrow that

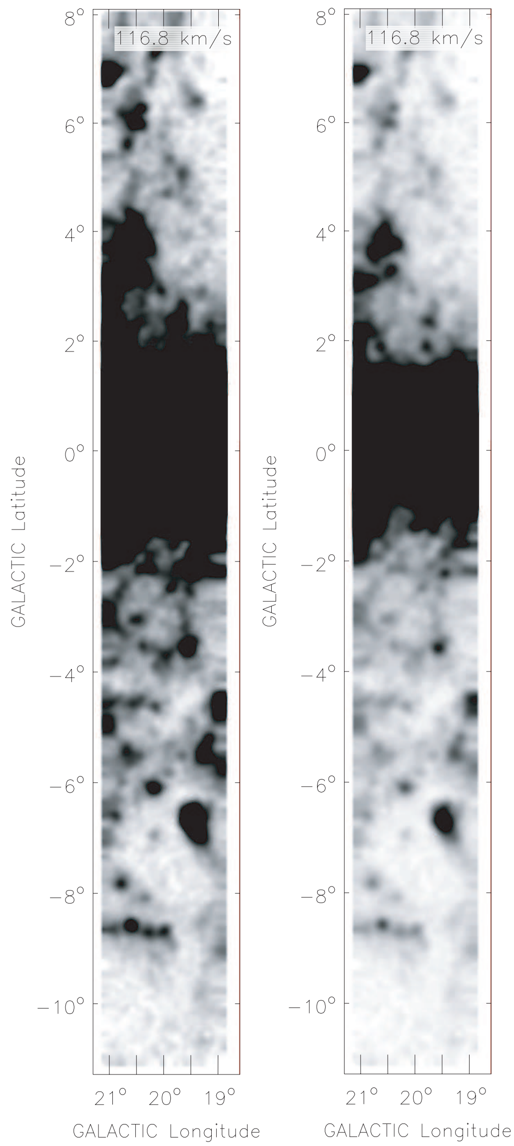

Figure 1. GBT observations of HI near longitude 20° at $V_{LSR} = 116.8$ km s^{-1}. The two panels show identical data plotted on different intensity scales: the left panel to emphasize fainter emission, the right panel to emphasize the brighter. The angular resolution of the observations is $9'$ and observations were made on a $3'$ grid with an integration time of 5 seconds per point. At the velocity shown here one degree in either coordinate corresponds to a linear scale of about 140 pc. Some of the clouds are more than one kpc from the Galactic midplane, and cloud-like structures persist quite far down toward the disk.

components within the clouds must have $T < 1000$ K. It is common to find halo clouds with two line components — one broad and one narrow — at the same velocity, implying that there is HI at two distinct temperatures. This state is possible for diffuse HI at some pressures (Field, Goldsmith & Habing 1969).

These clouds have kinematics which are dominated by Galactic rotation even when they are more than 1 kpc from the plane. Their connection to events in the disk thus seems secure. Yet to what are they connected? Are they formed from neutral gas thrust upward by supernovae (e.g. Heiles 1984; Norman & Ikeuchi 1989; de Avillez & Berry 2002)? Or are they the return products of a Galactic fountain: cool clouds condensing from the very hot gas in the halo (Shapiro & Field 1976)? In either case the clouds consist of material that began in the disk.

The HI clouds are denser than their surroundings by orders of magnitude so they must be falling toward the plane like rocks: the free-fall time is ~ 50 Myr. Yet they are fairly diffuse objects, and have too little mass in HI to be bound gravitationally. Unless confined, these clouds will dissipate on a time scale $Diam/\Delta v \sim 2$ Myr. The halo clouds may be in pressure equilibrium with the Reynolds Layer of H^+ or with the halo of very hot gas. At 1 kpc from the plane the average densities $\langle n(HI)\rangle \approx \langle n(H^+)\rangle$ within a factor of two (Dickey & Lockman 1990; Reynolds 1997) but both species probably have a small filling factor. Magnetic fields may have a role in the maintenance of the halo clouds, as they may for high-velocity clouds (Konz, Brüns & Birk 2002).

Study of the HI clouds is just beginning, and only a few have been observed at high angular resolution. In the existing data the halo clouds do not look as if they are simply the denser peaks in a continuous medium but appear to be isolated objects, and I suspect that they are stable for periods larger than their sound-crossing time. They seem to be genuine interstellar “clouds”.

Is the long search for interstellar clouds finally over?

For 50 years the diffuse ISM has been described as containing ‘clouds’: discrete objects with distinct boundaries in position and velocity (e.g., Munch 1952). Yet such clouds have never been observed. The only structures seen in HI emission which fit that description have peculiar velocities — the high- and intermediate-velocity clouds — and are not associated with the Galactic disk. HI emission studies sometimes find blended filaments and portions of sheets (Kulkarni & Heiles 1988), but no clouds.

Now, in the GBT data, there are hundreds of diffuse clouds, though most are far from the Galactic plane. Has the GBT finally revealed the fundamental structure of the ISM which has been hidden from previous generations of instruments, or is this a population strictly confined to the halo? The data suggest that the situation is not so simple. The HI in our part of the Galaxy — the ISM we look through when doing most extragalactic astronomy — does not appear extremely lumpy. Clouds of the type seen in Fig. 1 would be quite obvious even in older data if some were located at high latitude near the Sun. It is possible that we are being mislead, but local HI just does not seem to decompose into clouds as halo HI in the inner Galaxy (or some fraction of it) does. And yet, as Fig. 1 clearly shows, in the inner Galaxy clouds are observed to fairly low latitudes where they appear to blend together into an indistinguishable mass. Lockman & Stil (2004) present an example of a discrete cloud in the Galactic plane which is observable only because it has a high random velocity and thus lies unconfused in the wing of the HI spectrum. It resembles a McKee & Ostriker (1977) cold cloud core with a peculiar velocity $\sim$ 50 km s^{-1}. It may be an example of the "fast" HI clouds postulated to explain the wings of HI profiles in the Galactic plane (Radhakrishnan & Srinivasan 1980; Kulkarni & Fich 1985). But it is a diffuse cloud nonetheless, that looks like a "halo" cloud, and lies only 14 pc from $b = 0°$. I think that the ISM may have a different structure locally than in the inner Galaxy, where HI clouds with a high cloud-cloud velocity may pervade the disk and the halo.

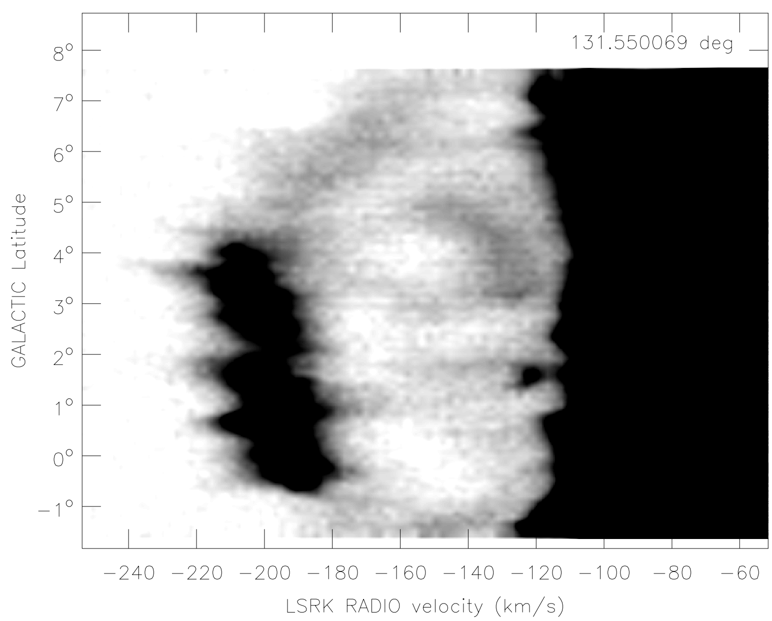

Figure 2. The HI emission from high-velocity cloud Complex H as measured by the GBT. This velocity-latitude cut at $\ell = 131.55°$ shows the cloud with a velocity near -200 km s^{-1}, its velocity gradient with latitude, and diffuse emission connecting the cloud kinematically to the hydrogen in the Galactic disk HI at the right of the Figure.

3. HI Coming Down Onto the Disk

Now we move from gas in normal circular rotation to gas with decidedly unusual kinematics, though I will argue that the kinematics are not pathological. High-velocity HI clouds cover more than one-third of the sky (Wakker & van Woerden 1997). By definition, their velocities cannot be attributed to normal Galactic rotation, but this does not mean that their velocities carry no information on their origin and fate. Complex H, in particular, has a large, organized core, lies in the Galactic plane (so its peculiar motion cannot be attributed entirely to infall), and covers such a large angle that projection effects can be exploited.

Figure 2 shows a velocity-latitude cut through the brighter parts of Complex H at longitude $131.5°$. The figure is overexposed to bring out two key features: (1) the core of the complex has a slope $dV_{LSR}/db = -3$ km s^{-1} deg^{-1} where it crosses the Galactic plane, and (2) there is faint HI emission at velocities between the Complex and the normal disk, connecting the Complex, kinematically, to the Galaxy.

The velocity gradient is a general feature of the Complex, and is important, for although the vertical motion of any object projects to zero velocity LSR where it crosses the Galactic plane, *near* the Galactic plane $dV_{LSR}/db = V_z$. Thus for Complex H the change in V_{LSR} with b is most simply understood as the projection of the vertical velocity component of the Complex: a gradient of –3 km s^{-1} per degree implies $V_z = -170$ km s^{-1}. Complex H is therefore an HI cloud moving to negative Galactic latitude at a substantial velocity. But what of its azimuthal and radial motions? Several lines of evidence now suggest that the circular rotational velocity of the Milky Way is constant at about $V_c = V_0 = 220$ km s^{-1} out to hundreds of kpc from the Galactic center (e.g., Zaritzsky 1999; Bellazzini 2003). If we assume that Complex H is on a nearly circular orbit with a total velocity of 220 km s^{-1}, then both its "anomalous" velocity and the velocity gradient follow naturally if the orbit is inclined, and *retrograde*.

In this model, Complex H is 33 ± 9 kpc from the Galactic center, has an orbital inclination $\approx 45°$, and an overall retrograde motion with a total $V = 220$ km s^{-1} (Lockman 2003). The model reproduces the kinematics of the Complex and the relative location of HI at different velocities (Fig. 2; see also Fig. 1 of Lockman 2003). At 33 kpc from the Galactic center the cloud should be interacting with the extended Galactic disk or halo, explaining why the core of the Complex is shrouded with broad-line gas at a velocity appropriate for material stripped by its passage through the Milky Way. Complex H covers such a large area on the sky that further orbital constraints may be found from the gradient of its V_{LSR} with longitude: the assumption that its orbit is nearly circular might be tested.

Complex H appears to be a satellite of the Milky Way with $M_{HI} \geq 6 \times 10^6 M_\circ$ and a size $> 10 \times 15$ kpc, moving on an inclined, retrograde orbit, which is now passing through the extended Galactic disk (or halo) and being fragmented. It is one of several examples of high-velocity HI clouds which are interacting with a gaseous component of the Milky Way that must extend at least 50 kpc from the Galactic center (Konz et al. 2002; Putman et al. 2003). We are beginning to take advantage of the fact that high-velocity HI clouds can be probes of conditions far out in the halo, messy probes, but probes nonetheless.

4. Questions for Don & Ron (and several others)

This meeting is inspired by the work of Don Cox and Ron Reynolds. For years Don has taught us to think clearly about interstellar physical processes. In a field often sodden with detail, his work stands out for its clarity and focus on the physical facts, and his reviews are full of wisdom (e.g., Cox 1990, 1995, 2000). Ron, the consummate observer, has discovered an entirely new component of the ISM, though it is still ignored by many. He has persisted in making sensitive measurements and pointing out their implications to an often incredulous community (e.g., Reynolds 1989, 1990; Reynolds et al. 1999). I hope that the results presented here will delight and confound Don & Ron in the same way that their work has delighted and confounded me. To this end, and in the spirit of this Tertulia, instead of a summary I will present some questions raised by the GBT data:

1) What produces HI clouds so far from the Galactic disk?

2) Halo HI clouds are exposed to the extragalactic UV radiation field from above and UV leakage from the Galactic disk below. Is there a connection between the halo clouds and the Reynolds layer?

3) What sort of medium is Complex H encountering as it moves along its orbit more than 30 kpc from the Sun? Like the halo clouds, it lacks enough HI to be self-gravitating, so what holds it together?

4) What is the role of magnetic fields in the halo clouds and in Complex H? If the magnetic field is of fundamental importance (as Don reminds us whenever he gets the chance) why can so many of us live comfortable, productive lives while ignoring it almost entirely?

5) If "fast" HI clouds are common at $b \approx 0^\circ$ in the inner Galaxy, is the ISM there fundamentally different from the ISM near the Sun?

6) If the halo clouds are stable for many Myr, how exactly are these turbulent objects confined, even if there is an external medium?

7) Does the ISM know about dark matter, and if so, what does it know?

I suggest that we petition our gracious hosts at the Instituto de Astrofísica de Andalucía to reconvene this group again in Granada in, say, in two years, to see what has become of these questions, and once again participate, with Don and Ron, in fruitful discussions which may lead to their resolution.

Acknowledgments

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References

[1] Bellazzini, M. 2003, MNRAS, (in press: astro-ph/0309312)

[2] Cox, D. P. 1990, in *The Interstellar Medium in Galaxies*, e.g. H.A. Thronson & J.M. Shull, Kluwer, p. 181

[3] Cox, D. P. 1995, Nature, 375, 185 ed. D. Breitschwerdt, M. J. Freyberg, & J. Trümper (Berlin: Springer), 121

[4] Cox, D.P. 2000, Rev.Mex.AA, 9, 14

[5] de Avillez, M.A., & Berry, D.L. 2001, MNRAS, 328, 708

[6] Dickey, J.M., & Lockman, F.J. 1990, ARAA, 28, 215

[7] Field, G.B., Goldsmith, D.W., & Habing, H.J. 1969, ApJ, 155, L149

[8] Heiles, C. 1984, ApJS, 55, 585

[9] Konz, C., Brüns, C., & Birk, G.T. 2002, A&A, 391, 713

[10] Kulkarni, S.R., & Fich, M. 1985, ApJ, 289, 792

[11] Kulkarni, S. & Heiles, C.E. 1988, in *Galactic and Extragalactic Radio Astronomy*, ed. G.L. Verschuur & K.I. Kellermann, Springer, p. 95

[12] Lockman, F. J. 1984, ApJ, 283, 90

[13] Lockman, F. J., Hobbs, L. M., & Shull, J. M. 1986, ApJ, 301, 380

[14] Lockman, F. J. 2002, ApJ, 580, L47

[15] Lockman, F. J. 2003, ApJ, 591, L33

[16] Lockman, F. J. & Stil, J. R. 2004, in press

[17] McKee, C.F., & Ostriker, J.P. 1977, ApJ, 218, 148

[18] Munch, G. 1952, ApJ, 116, 575

[19] Norman, C. & Ikeuchi, S. 1989, ApJ, 345, 372

[20] Putman, M.E., Staveley-Smith, L., Freeman, K.C., Gibson, B.K., & Barnes, D.G. 2003, ApJ, 586, 170

[21] Radhakrishnan, V., & Srinivasan, G. 1980, J. Astr. Ap., 1, 47

[22] Reynolds, R. J., 1989, ApJ, 339, L29

[23] Reynolds, R. J., 1990, ApJ, 349, L17

[24] Reynolds, R.J. 1997, in *Physics of Galactic Halos*, ed. H. Lesch, R-J. Dettmar, U. Mebold & R. Schlickeiser, Akademie Verlag: Berlin, p. 57

[25] Reynolds, R.J., Haffner, L.M., & Tufte, S.L. 1999, ApJ, 525, L21

[26] Savage, B.D. 1995, in *The Physics of the Interstellar Medium and Intergalactic Medium*, ASP Conf. Ser. 80, 233

[27] Shapiro, P.R., & Field, G.B. 1976, ApJ, 205, 762

[28] Wakker B. P., & van Woerden, H. 1997, ARAA, 35, 217

[29] Zaritsky, D.1999, in The Third Stromlo Symposium: The Galactic Halo, ed. B.K. Gibson, T.S. Axelrod, & M.E. Putman, ASP vol 165, p 34

5. Discussion

C. Konz: Do you have any information about the metallicity of Complex H which would support the idea that this complex is not part of the Galaxy?

Lockman: There is no information about abundances in Complex H. To date it has not been detected in any absorption lines at all.

R. Benjamin: You said you have an estimate for the mass loss of Complex H. How long does it have to live assuming it sheds mass at the same rate?

Lockman: Gas that is decelerated from Complex H by 50 km s^{-1} or more will blend in velocity with the much brighter Galactic disk emission and be almost impossible to detect, so my estimates are very uncertain. That being said, it appears that the mass in the HI tail of the Complex is equal to that in the compact core. I suspect, though, that its mass loss is episodic rather than continuous.

C. Heiles: You derive properties of halo clouds by assuming spherical geometry. What if the objects are extended cylinders along the line of sight? With such cylinders the only locations where you could see them are those where the cylinders happen to be lined up. Well-known examples of such effects are the optical filaments in the Cygnus loop, which are sheets seen edge-on. In your case, you see “clouds” connected by “filaments” – just what you’d expect if they were filaments twisting in the wind.

Lockman: First, the clouds *look* quasi-spherical, even those which we have resolved with the VLA. Many of them have well-defined edges in both position and velocity, though not all. The other point is that the clouds often have narrow lines indicating cool gas. The HI structures in the halo which look like filaments always have broad lines. Thus I believe that most of the halo clouds are not simply products of some projection effect.