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Cold Atomic Gas in the Milky Way

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Abstract. In this review, I consider a number of basic questions about cold Galactic H I: What are the physical properties of the cold atomic phase, and how are they maintained? How much mass is there in the cold H I and in the other phases in the disk? Are the true populations of H_2, cold H I, and warm H I distinctly separated from each other in temperature-density space, or do some phase properties overlap? What is the geometric structure of cold interstellar clouds? What is the phase structure? What brings these structures about? What is the role of cold H I in the phase dynamics of the interstellar medium, in star formation, and in the evolution of the Galaxy as a whole? Some of these questions have more complete answers than others at the present time. I conclude with a few comments on the directions of current research and desirable future observations.

1. Introduction

Evidence for cold interstellar matter (Hartmann 1904; Wolf 1904; Barnard 1907; Slipher 1909) and considerations of a multiphase interstellar medium (Strömgren 1939, 1948) both predate the advent of H I 21cm line observations, but it is with the opening of this radio window that our understanding of the Galactic ISM has blossomed. The power of H I line studies arises from the ubiquity of H I emission for spatial and kinematic mapping and from the utility of measuring gas properties from H I absorption. The temperature variation of neutral atomic hydrogen was first demonstrated via the phenomenon of H I self-absorption (Heeschen 1955). Widely different "warm" and "cold" temperature regimes were subsequently revealed by interferometric H I absorption studies toward continuum sources (Clark 1965; Radhakrishnan et al. 1972). The multiphase picture implied by these H I observations was consistent with the theoretical paradigm of cold clouds pressure-confined by a warmer intercloud medium (Spitzer 1954, 1956; Field et al. 1969). Elaborations on this model (Cox & Smith 1974; McKee & Ostriker 1977; Cox 1981) have added both hot and warm ionized phases to the mix. More recently, the concept of discrete phases has been brought into question by both observations (Heiles 2001) and theory (Gazol et al. 2001). But discreteness aside, an ever-growing array of multiwavelength observations attests to the *existence* of a large range of temperatures and densities in interstellar gas (though some question the interpretation of H I line widths in this regard; see Verschuur & Peratt 1999).

The current discrete phase view is essentially that of McKee & Ostriker (1977), though disagreements remain over volume filling fractions and the importance of different mechanisms contributing to them. The major components, labeled in reference to the dominant species of hydrogen (H II, H I, or H_2), are hot ($\sim 10^6$ K) and warm ($\sim$8000 K) ionized gas, warm ($\lesssim$ 8000 K) and cold ($\sim$80 K) neutral atomic gas, and very cold ($\sim$ 10 K) molecular gas. The atomic phases are often called the hot ionized medium (HIM), warm ionized medium (WIM), warm neutral medium (WNM), and cold neutral medium (CNM). The hot and warm phases comprise an "intercloud medium" of low-density ($\lesssim$ 1 cm^{-3}) gas filling most of the interstellar volume, while the colder phases inhabit "clouds" of denser ($\gtrsim$ 10 cm^{-3}) gas with a filling fraction of no more than a few percent in spiral arms near the Galactic midplane and less elsewhere (for more details, see, e.g., Reynolds 1992; Kulkarni & Heiles 1988; Shull 1987; Spitzer 1978).

The cold atomic phase, the subject of this review, is worth studying for a number of reasons, including: (1) it contains a large fraction of the total gas mass in the Galactic disk; (2) it is often found in quiescent regions along with the molecular gas that star formation requires; and (3) considerable fine-scale structure is seen in cold H I that may offer a glimpse into the workings of interstellar turbulence and magnetic fields. I will briefly address a few primarily observational aspects of cold H I below. But the field of 21cm line studies is vast, and the reader is strongly encouraged seek elsewhere for much more information. I recommend starting with the many excellent contributions to these proceedings.

2. Observing Cold H I

Warm H I gas is found over most of the sky (Kulkarni & Heiles 1988), and its contribution to the 21cm spectrum must be disentangled from that of the cold H I for the latter to be investigated properly. Separating the two requires solving the radiative transfer equation $dT_B/d\tau = T_B - T_S$, where T_B represents brightness temperature, T_S is spin (excitation) temperature, and τ is optical depth. Since these quantities are undetermined functions of position along the line of sight, an exact solution is not obtainable. Instead, geometric approximations must be employed, i.e., discrete, isothermal component representations where the number of components is small enough for available constraints to allow a solution (numeric, nonisothermal models are a variation on this theme in which the properties of many isothermal cells are geometrically related).

The two-component discrete representation, though very simplistic, is useful for illustrating some basic principles:

$$T_B \;=\; T_S \left(1 - e^{-\tau}\right) \;+\; T_{bg}\, e^{-\tau} \;, \tag{1}$$

where T_{bg} is the background brightness, and T_S and τ apply to the foreground cloud. An emission feature results for the case $T_S > T_{bg}$, while for $T_S < T_{bg}$, we have absorption. Cold H I gas can be observed in both emission and absorption, the latter against both continuum and H I backgrounds. Figure 1 shows examples of all three manifestations.

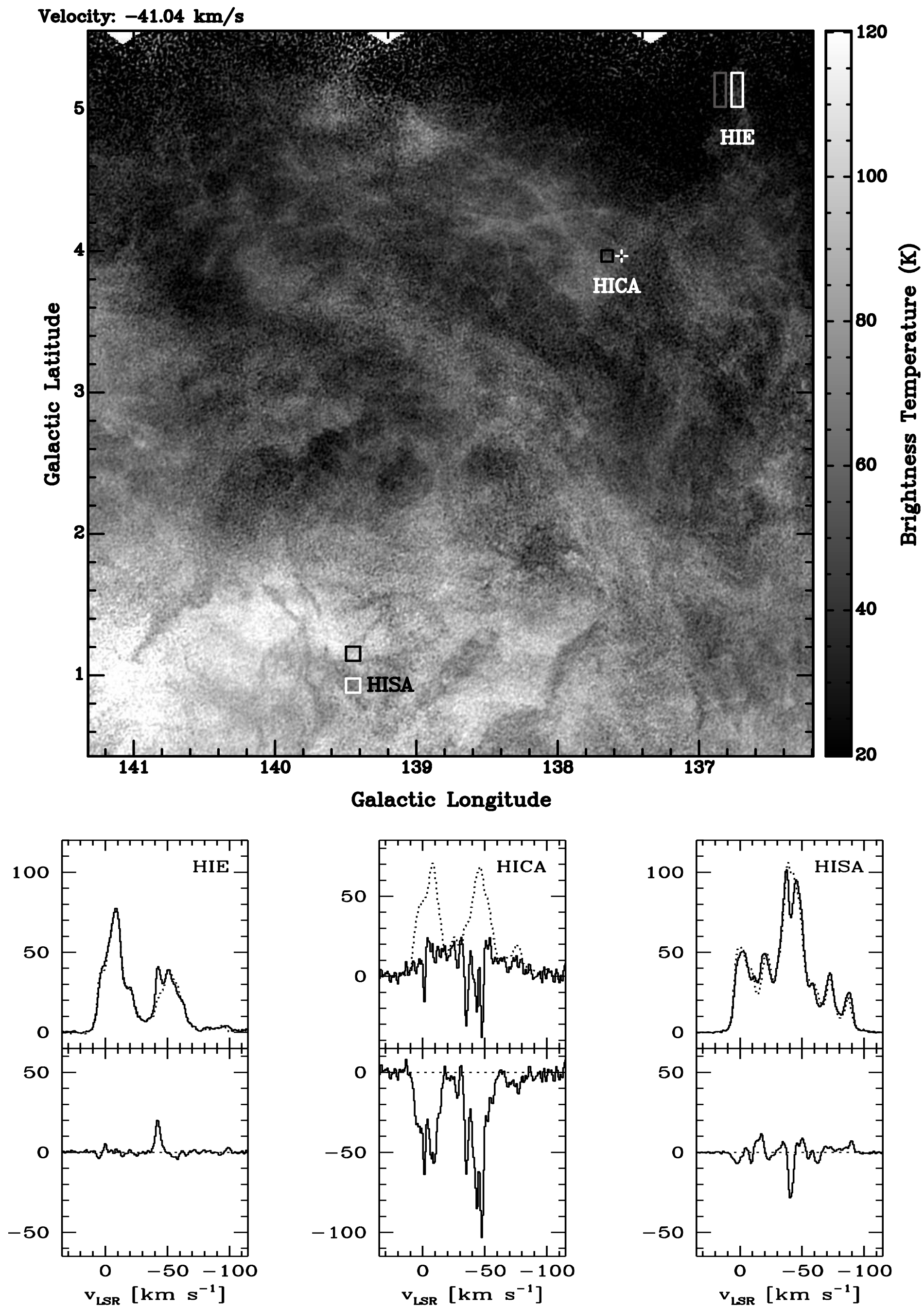

Figure 1. Three examples of cold atomic gas features: H I emission (HIE), H I continuum absorption (HICA), and H I self-absorption (HISA). The top panel shows a 21cm line channel map with ON (light) and OFF (dark) spectral extraction positions marked. The upper spectral panels give ON (solid) and OFF (dashed) brightness temperatures; lower panels plot ON-OFF differences. All spectra use the same vertical stretch. The data are from the Canadian Galactic Plane Survey (CGPS; Taylor et al. 2002).

2.1. H I Emission (HIE)

Since H I emission (HIE) is practically everywhere, it is excellent for mapping. Unfortunately, warm and cold gas are mingled together in HIE. At the line center, $\tau = CN/(T_S \Delta v)$, where N is column density, Δv is line width (FWHM), and $C = 5.2 \times 10^{-19}$ cm^2 K km s^{-1} for a Gaussian profile (Dickey & Lockman 1990). Applying the relation $\tau \propto T_S{}^{-1}$ to Equation 1 demonstrates that the brightness of the foreground cloud is insensitive to T_S if $\tau \ll 1$ and is proportional to T_S otherwise. Consequently, cold HIE is not conspicuous in brightness terms, and it must be identified by spectral linewidth instead: warm H I has widths of $\sim 20\,\mathrm{km\,s^{-1}}$ (FWHM $= 0.215\sqrt{T}\,\mathrm{km\,s^{-1}}$; Spitzer 1978), so features much narrower than this are presumably cold H I, even if turbulent broadening of several $\mathrm{km\,s^{-1}}$ is present, as it often is.

Narrow HIE features are fairly common (even in external galaxies: Braun 1999), but nearly all require either ON-OFF spectral differencing (Figure 1) or Gaussian decomposition (Verschuur & Schmelz 1989; Pöppel et al. 1994) to extract them from the general H I "soup". For the first, the feature must have reasonably clear spatial boundaries; for the second, it must have little or no spectral blending to ensure a unique solution. Since many sightlines satisfy neither criterion, maps of HIE-extracted CNM gas, however laboriously produced, are likely to have patchy sampling.

In addition, though T_{bg} can be estimated from OFF spectra or Gaussian analysis, both T_S and τ are unknowns in Equation 1, so the gas properties are usually not well constrained. The minimum gas temperature is T_{bg}, and the maximum is set by the linewidth, but there must be relatively little nonthermal broadening for this maximum to be interesting. Very high S/N data can also be used to constrain τ with the line *shape*, but this requires almost ideal circumstances to work (Rholfs et al. 1972; Knapp & Verschuur 1972).

2.2. H I Continuum Absorption (HICA)

Absorption studies of CNM gas have an immediate advantage over HIE studies: the inverse dependence of line opacity on temperature ensures that cold clouds absorb more efficiently than warm clouds. In fact, in the simplistic 2-component geometry of Equation 1, only clouds with $T_S < T_{bg}$ can absorb at all! We must be careful here, since the relevant T_{bg} is the intrinsic background brightness before beam dilution, and few sightlines are adequately described by 2 components. Still, H I absorption has great utility for screening cold from warm gas if treated properly.

The phenomenon of H I absorption against continuum sources (HICA) was first observed by Hagen et al. (1955) and has been widely exploited since to study the properties of Galactic H I (e.g., Radhakrishnan et al. 1972; Dickey et al. 1978; Mebold et al. 1982; Kalberla et al. 1985; Stark et al. 1994; Heiles & Troland 2002). Most analyses compare H I spectra ON and OFF the continuum source, presuming the same H I gas is present in both sightlines (the exception is HICA studies on angular scales smaller than the source, where T_S remains indeterminate, e.g., Faison & Goss 2001). In the 2-component example (Equation 1), the ON-OFF brightness difference is $T_{bg} e^{-\tau}$, allowing a direct solution for τ, and subsequently T_S. More careful treatments consider the effects of WNM gas in the sightline, which can otherwise lead to significant biases in T_S (Kulkarni & Heiles 1988).

As with many observations, high angular resolution is desirable, in this case to minimize beam dilution effects and to observe H I emission as close to the source as possible. A more fundamental limitation on the otherwise powerful HICA technique is the pointlike, isolated nature of most continuum backgrounds. This sparse and uneven sampling hobbles HICA mapping efforts at present, though future instrumentation with improved sensitivity at small angular scales may amend this by increasing the population of usable sources.

2.3. H I Self-Absorption (HISA)

The other form of H I absorption, H I self-absorption (HISA), complements HICA in many ways. The H I background is more smoothly distributed than most HICA backgrounds, enabling true mapping, and its lower intrinsic intensity (typically ~ 100 K) provides a more direct filter for CNM gas than HICA (some of the absorbing gas can have $T_S > T_{bg}$, but it must be outweighed by colder gas in the radiative transfer). At the same time, HISA has many of the same problems as HIE: features can be difficult to identify and extract unambiguously, background emission is estimated rather than measured directly, and T_S and τ are only separable in Equation 1 for the unusual case of the foreground cloud extending beyond the sightline boundaries of the emission background. In addition, HISA requires a minimum background level, while cold HIE searches do not, and distinguishing true HISA from mere HIE gaps requires a degree of angular and spectral sharpness greater than that of most cold HIE (Gibson et al. 2000). Both of these limit HISA's mapping ability relative to HIE. However, HISA's $T_S < T_{bg}$ filter is a significant advantage over HIE for finding CNM gas, and HISA can map the CNM distribution in ways HICA cannot.

Despite this mapping potential, the majority of past HISA studies have been either targeted surveys (e.g., Knapp 1974; McCutcheon et al. 1978) or investigations of individual clouds (e.g., Hasegawa et al. 1983; van der Werf et al. 1988, 1989; Feldt 1993; Montgomery et al. 1995). Small areas of the Galactic plane have been surveyed with Arecibo (Baker & Burton 1979; Bania & Lockman 1984), but it is only within the past few years that large-area Galactic plane synthesis surveys have enabled detailed, systematic mapping investigations of CNM gas. I will discuss a few results from one such effort (Gibson et al. 2000, 2002) along with other CNM findings below.

3. Cold H I Properties

3.1. Pressure

Traditional (steady-state) models of the ISM are built around the idea of pressure equilibrium, which applies when the system is able to smooth out pressure imbalances faster than they can accumulate, i.e., the sound crossing time is much less than heating/cooling timescales or the mean time between disruptive events such as shocks. Under a constant thermal pressure, the ideal gas law $P/k = nT$ implies dense gas will be cold and tenuous gas will be warm. The relative balance between different heating and cooling mechanisms over these (T, n) ranges then dictates where $dP/dn > 0$ and stable phases can occur: the equilibrium of CNM gas is thought to be governed largely by photoelectric heating of dust grains and cooling from the fine-structure lines of carbon (Wolfire et al. 1995). The latter are collisionally excited, so that careful line balance analyses are able to extract both n and T and infer a thermal pressure. Such investigations find $10^3 \lesssim nT \lesssim 10^4$ cm^{-3} K, with averages of a couple to a few thousand (Jenkins et al. 1983; Wannier et al. 1999; Jenkins & Tripp 2001).

This is not the whole picture however. The pressures of cosmic rays and magnetic fields are comparable to the thermal pressure (Spitzer 1978), turbulent pressure is several times greater (Heiles 1997), and the total hydrostatic pressure of the ISM is $\sim 3 \times 10^4$ cm^{-3} K (Boulares & Cox 1990)! While this *total* pressure might be relatively constant, equilibrium of the thermal component is not guaranteed, which could be bad news for the discrete phase picture.

3.2. Other Properties

Where T_S and τ can be extracted from 21cm H I line measurements, the column density N is readily obtained (§2.1). Volume density n cannot be found directly from H I observations, but must be inferred, e.g., as $n = P/(kT)$, or $\langle n \rangle = N/\Delta s$, where Δs is the thickness of the feature along the sightline; the accuracy of such methods depends upon the input assumptions (e.g., $\Delta s = \Delta\theta \times$ distance).

Perusal of a number of past HICA studies (Radhakrishnan et al. 1972; Dickey et al. 1978; Mebold et al. 1982; Kalberla et al. 1985; Stark et al. 1994) gives broad T_S ranges of $\sim 20 - 800$ K, with most less than ~ 200 K, and densities of $n \sim 5 - 50$ cm^{-3} (Kalberla et al. 1985). Targeted HISA studies (Knapp 1974; van der Werf et al. 1988; Feldt 1993) give lower temperatures of $\sim 5 - 60$ K and higher densities, though often much of the gas is H_2 rather than H I. A broader-based HISA study (Gibson et al. 2002) that uses both of the n equations above to solve the radiative transfer equation (Gibson et al. 2000) finds the general HISA population to be characterized by ($T_S \sim 70$ K, $n \sim 60$ cm^{-3}) in the Perseus arm and ($T_S \sim 40$ K, $n \sim 120$ cm^{-3}) in the Local arm, both with some scatter, and assuming purely atomic gas; colder, denser values obtain if H_2 is present. The difference between arms is not physical, but instead results from the smaller length scales visible locally for a fixed angular resolution, which allows the $\langle n \rangle = N/\Delta s$ method to "see" denser, colder gas.

3.3. Discrete Phases?

Until fairly recently, our picture of the ISM has been dominated by models with discrete phases. Is the CNM actually a discrete phase? The (T, n) properties of diffuse atomic and translucent molecular clouds are known to overlap (Dickey & Lockman 1990). Some of the HICA and HISA temperatures listed above approach those of canonical molecular clouds, and very cold H I is also seen in emission (Knapp & Verschuur 1972). In some HISA cases, the cold H I is arguably a trace population in cold H_2 (van der Werf et al. 1988; Feldt 1993). On the CNM/WNM side, a new HICA study (Heiles 2001; Heiles & Troland 2002) claims a substantial amount of gas in the previously-presumed unstable regime of $T_S \sim 500 - 5000$ K, corroborating earlier suspicions about HIE linewidths between typical CNM and WNM ranges (Heiles 1989; Verschuur & Magnani 1994).

Numerical models incorporating turbulence and other nonthermal elements (Vázquez-Semadeni et al. 2000; Gazol et al. 2001) suggest that interstellar clouds may be transient rather than stable objects, and gas moves through formally unstable (T, n) domains continually. Some even posit a continuum of phases in which gas properties are scale-dependent functions of turbulent energy dissipation (Norman & Ferrara 1996). Observational tests of these predictions are crucial. Current evidence indicates that completely discrete phases with well-defined (T, n) values are not the reality, but it remains to be seen how prevalent interphase gas is: are the phases preferred modes in a (T, n) continuum where gas tends to linger, like stars in the stable parts of the Hertzsprung-Russell diagram, or are there no modes at all — just artifacts of our observational biases?

4. Structure

4.1. Cloud Geometry

Despite the lingering appeal of Pythagorean aesthetics, most cold HIE gas does not congregate in conveniently spherical clouds (Heiles 1967), and the same appears true for HICA (Deshpande et al. 2000) and HISA (Figure 1). Instead, filamentary and sheetlike structures predominate: some as parts of coherent shell features (Kulkarni & Heiles 1988), many as stochastic entities that can be characterized with power-law angular power spectra over many size scales (Green 1993; Stanimirovic et al. 1999; Dickey et al. 2001). Few of these structures are gravitationally bound, so their shapes are instead influenced by environmental factors like local pressure, thermal and bulk velocity fields (much cold H I may be born in cooling shocks), radiation, turbulence, and magnetic fields. The self-similar multiscale nature of observed H I structures, as well as the oft-overlooked possibility that many apparent structures may result from chance sightline superpositions or velocity fluctuations instead of density enhancements, makes the empirical definition of "clouds" problematic and raises serious concerns for similarly simplistic theoretical models.

4.2. CNM - H_2 Phase Relations

The phase structure of cold H I also appears complicated. The classic onion-skin view of McKee & Ostriker (1977), broadened to include molecular gas, would have cold H_2 cloud cores, surrounded by CNM gas (perhaps with an intermediate photodissociation region), then WNM, WIM, and HIM gas in progression. Depending on local conditions, some of the end-phases might be absent, but H_2 should be found with cold H I. However much HISA does not seem to be associated with CO emission, the common proxy for H_2, nor CO with HISA (Peters & Bash 1987). Figure 2 compares Perseus arm ^{12}CO $J = 1 - 0$ emission (Heyer et al. 1998) with HISA extracted from the CGPS dataset (Gibson et al. 2002). There is no correlation of CO and HISA line strengths, and though some structures display an association of the two that exceeds random expectation, many more show only CO or HISA, but not both. A very large, very cold Outer arm HISA feature has also been found with no detected CO emission (Knee & Brunt 2001). Such results imply at least one of the following: (1) HISA is a poor tracer of cold H I; (2) CO is a poor tracer of H_2; (3) H_2 and cold H I are largely

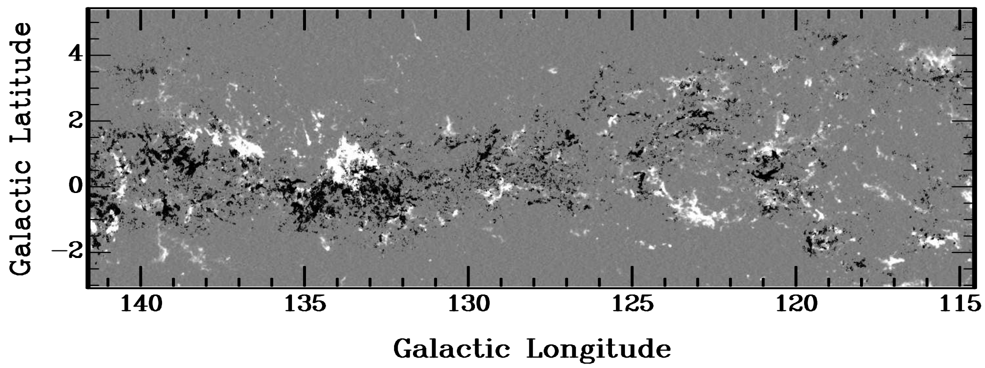

Figure 2. Map of ^{12}CO and HISA spatial distributions over a 25° slice of the Galactic plane. The two line intensities have been integrated over Perseus arm velocities and summed; CO is positive (light) and HISA is negative (dark). The CO data are from the FCRAO Outer Galaxy Survey (Heyer et al. 1998). The H I data are from the CGPS.

independent of one another. Certainly HISA cannot trace all cold H I, since it requires special conditions to manifest and to be identified (§2.3). Likewise, CO may not trace all H_2, especially in diffuse clouds with poor UV shielding (Reach et al. 1994; Meyerdierks & Heithausen 1996). Whether these detection biases are adequate to explain the sheer indifference of the CO and HISA for one another in Figure 2 remains unclear.

5. The Global Role of Cold H I

5.1. Mass Budget

The amount of material in the various gas phases of the ISM is a function of the time evolution (or statistical equilibrium) of the system, including feedbacks with star formation, evolution, and death. Consequently, the ISM mass budget is of great interest in constraining theoretical models. Current indications are that cold H I represents a significant fraction of the ISM mass. Reynolds (1992) gives these surface density estimates for our part of the Galaxy: HIM ~ 0.04, WIM ~ 0.46, WNM ~ 0.73, CNM ~ 0.73, and $H_2 \sim 0.42$ mg cm^{-2}. Though already respectable, the CNM and H_2 portions may be greater if mass is hidden in optically thick H I as HISA or in diffuse H_2 clouds untraced by CO. However, Dickey & Lockman (1990) estimate that HIE line integrals assuming optically thin gas miss only $10 - 30\%$ of the H I mass.

A HISA census is underway to check this estimate (Gibson et al. 2002). Preliminary results give HISA/HIE column density ratios of order ~ 0.1 for purely atomic gas. These findings are consistent with Dickey & Lockman (1990), but they are subject to change as the HISA identification and analysis software is fine-tuned. At some level, mass will always be missed, because the HISA algorithms can only identify the most conspicuous features with reasonable confidence. In addition, the total H I + H_2 mass traced by HISA will be greater

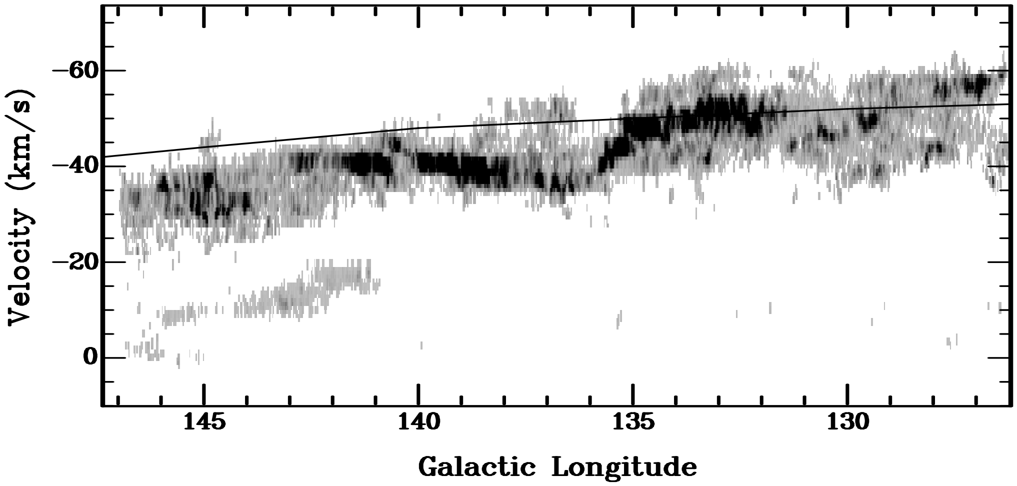

Figure 3. Position-velocity (ℓ, v) map of τ_{HISA} integrated over $-3^\circ < b < 5^\circ$. The intensity scale is linear. The gray features are "ambient" weak HISA, which occurs nearly everywhere the HIE background is bright enough to reveal it, filling most Perseus arm velocities near -40 km s^{-1} and some Local arm velocities near -10 km s^{-1}. Blank areas lack detected HISA but may still contain cold H I. The dark features are strong HISA, which has a more concentrated distribution that may be related to spiral structure. The curve marks the predicted velocity of gas just behind the Perseus arm shock (Roberts 1972).

if the HISA features contain molecular gas (Gibson et al. 2000). The molecular composition of HISA clouds is not well known at present (§4.2).

5.2. Distribution

The space distribution of cold H I is important for theories of Galactic structure and phase structure in the ISM. Some HICA studies have examined the CNM distribution vs. distance from the Galactic center (e.g., Garwood & Dickey 1988), but detailed mapping remains untackled, primarily because of fundamental difficulties in measuring distances to H I features. Though differential rotation models are often used for this purpose, they take little or no account of noncircular motions that can alter the picture significantly. For example, simple rotation models imply that HISA should be common in the inner Galaxy and rare in the outer Galaxy, since the same radial velocity applies to two distances inside the solar circle but only one outside, and HISA needs a background. But HISA is actually common in the outer Galaxy (Gibson et al. 2000).

Figure 3 shows that the Perseus arm is filled with low-level HISA but also contains numerous complexes of stronger HISA. The former can be explained as stochastic (T, v) departures in a turbulent medium, but the latter require something larger and more coherent, such as a spiral density wave. An intriguing possibility is that these strong HISA features are tracing cold H I immediately downstream of the Perseus arm shock, where the compressed H I is cooling rapidly on the way to forming molecules and new stars; the background in this case is the H I further downstream, where it may have been reheated by star formation. The match between the HISA velocities and those predicted by Roberts' (1972) shock model is admittedly imperfect, but this may result naturally from structural inhomogeneities that the model does not address (Binney & Tremaine 1987). HISA has also been found in the inner Galaxy near another possible arm shock (Minter et al. 2001). If this phenomenon is real and widespread, it offers a serious opportunity to test spiral density wave models inside the Milky Way.

6. Future Directions

We live in a marvelous era for 21cm astronomy, with many exciting surveys and new instruments appearing all the time. The three current Galactic plane H I surveys have greatly increased the power of HIE, HICA, and HISA studies, as has the use of parallel multiwavelength data. New and improved instrumentation like the Expanded VLA, the Large Adaptive Reflector, and the Square Kilometer Array promise further and welcome enhancements of our capabilities; the present GPS efforts are up against a sensitivity wall in H I. What should we do with these new tools? Bigger "wave buckets" are certainly nice: the SKA could reproduce the CGPS in a few days at $1'$ resolution or in a few years at $3''$ resolution. But the whole sky at $1''$ would take $\sim 10^3$ years! So we can't do everything.

Smart intensive surveys will be important though, especially if their power combines synergistically. For example, we could merge optical/IR and radio point source surveys to map our galaxy properly at last, with no dependence on kinematic models. Space-based parallax surveys are coming of age: *GAIA* will measure distances out to *tens of kpc*, and successors will go further. Ultimately, we may have a complete 3-D census of the entire Galactic stellar population (in the infrared), but a few million stars will do nicely for a start. A massive optical interstellar absorption survey toward such trig-parallax stars would be one way to go, but we might do better with the dust-free 21cm line — the SKA will be a HICA machine, with an unprecedented source density on the sky (also useful for Faraday and Zeeman surveys!). We can map gas properties on a finely sampled grid: use nearby flare stars with known parallaxes for cloud and arm structure studies, and build up from there to Galaxy-wide scales with brighter Galactic and extragalactic sources.

7. Summary

Cold H I contains a large fraction of the ISM gas mass, but it is difficult to study directly in emission. Absorption methods are more fruitful, but they include their own pitfalls that must be carefully evaluated. CNM gas has excitation temperatures of $\sim 50 - 100$ K and volume densities of $\sim 50 - 100$ cm^{-3}, with significant scatter outside these ranges; the CNM may in fact blend with the adjacent H_2 and WNM phases, but the amount of blending is not known. Morphologically, the CNM is composed of filaments or sheets on many different scales, which along with projection and velocity effects makes identifying "clouds" problematic. The phase structure of CNM clouds is variable. Many appear free of CO emission, but it's possible they have H_2 that is not traced by CO. The CNM population revealed by H I self-absorption is everywhere at low opacity levels and may be tracing spiral arm shocks at higher opacity levels. If so, these CNM clouds may probe a key stage of the Galactic star formation cycle. Current H I 21cm line surveys and those that can be envisioned with planned instrumentation hold great promise for addressing many of these issues more thoroughly.

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