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HI and Galactic Structure

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Abstract. HI observations in the 21cm line have been a principal tool for investigating the large-scale structure of the Milky Way. This review considers what was learned in the first decade after the discovery of the 21cm line, and how that knowledge has been expanded and refined in subsequent years. Topics include spiral structure, the Galactic nucleus, the thickness of the HI layer, and affairs in the outskirts of the Galaxy. New advances in instrumentation and computing, and a broad attack on problems using information from all wavelengths, are likely to keep HI studies of the Milky Way interesting for years to come.

1. Introduction

Knowledge of the large scale structure of the Galaxy has been the single most important achievement of Galactic 21cm HI studies. The nature of Galactic rotation and the thickness of the disk were discussed in the second paper ever published on 21cm observations, mere months after the discovery (Muller & Oort 1951). The collected information is now vast. Major reviews by Burton (1988; 1992), and by Dickey & Lockman (1990), and the discussion in Binney & Merrifield (1998; hereafter BM98) have covered aspects of this topic with varying degrees of completeness. For this brief review I will narrow the focus by considering what was known of the Galaxy after the first 10 years of 21cm work and how this knowledge has been modified, refined, revised or rejected in the subsequent 40 years. The very center of the Galaxy is a topic of its own and will not be discussed. Although the general features of the Galactic system are now reasonably clear, we still have no consistent and satisfactory understanding of many fundamental aspects of the HI distribution. Only a fraction of the information has been extracted from existing HI surveys, and there remains before us the tantalizing possibility that with a single new insight, a new feature of the Galaxy might be pulled from the data.

2. What Oort Knew in 1961

In April 1961, Jan Oort attended a meeting in Princeton on the topic of the distribution and motion of interstellar matter in Galaxies, and contributed several papers to the proceedings (Oort 1961a, 1961b). The 21cm line had been detected ten years earlier (Ewen and Purcell 1951), but Oort had been thinking about radio spectroscopy for at least a decade before that. During the 1950s, Oort built telescopes in the Netherlands with students and colleagues, parallel work went on in Australia (e.g. Kerr, Hindman & Carpenter 1957) and in a burst of discovery the Galaxy was mapped. Seven years after the first detection of the 21cm line, the IAU had a new coordinate system.

By the Princeton meeting in 1961, the main elements of the picture were in place, derived from observations with an angular resolution of no better than half a degree and usually several times worse. The papers at the meeting are remarkably fresh in many ways, and illustrate the conceptions (and misconceptions) of the time. Here is what Oort knew then:

HI is strongly concentrated to a thin layer. In the inner Galaxy most HI lies in a layer having a FWHM ~ 220 pc with little change in this thickness between about $0.3R_0$ and $0.7R_0$. But outward from the Sun, at $R \gtrsim R_0$, the layer thickens monotonically to the Galaxy's edge.

The HI layer is not only thin, it is flat. In the inner Galaxy the mean deviation from a simple plane is less than 30 pc. However, beyond the solar circle the layer bends into a systematic m=1 warp whose mean distance from the plane can be several kpc, many times the layer's thickness.

It rotates. Galactic HI is primarily in circular rotation, with noncircular components $\lesssim 10$ km s^{-1} or $< 5\%$ of the rotational velocity. The angular velocity of rotation increases toward the Galactic center. The rotational velocity is almost constant inward from R_0 to $0.3R_0$, but then rises to a peak at $R \approx 0.05R_0$.

The Galactic Center is in Sagittarius. Galactic rotation is approximately symmetric about the radio source Sgr A, but the nucleus itself contains many HI features which have large peculiar motions indicative of expansion, for example, the 3-kpc arm. There is evidence for outflow from the nucleus of $1M_\odot\ y^{-1}$.

There are some departures from circular rotation outside the nucleus. High latitude HI has systematic infall, often at large velocity. The rotation curve has small-scale structure, and the northern rotation curve deviates systematically from the southern curve.

HI shows the spiral structure of the Galaxy. But the northern and southern patterns do not match.

There is an HI halo. Considerable HI intensities are found 500 pc from the plane. These have no apparent connection with the known high-latitude continuum features.

These items will be reconsidered in light of current knowledge, but first it is useful to summarize what is now known about HI as a vehicle for learning about Galactic structure.

3. Living with the Limitations: Essential Facts about Galactic HI

The activity of measuring Galactic HI spectra has gone on for fifty years, and a number of properties of the data relevant to their use for discerning Galactic structure are now evident. A more complete discussion of these issues is in Dickey & Lockman (1990; hereafter DL90); many have been known for some time (e.g. Kerr 1969).

Galactic HI is seen in all directions and at all velocities permitted by Galactic rotation given the size of the Galaxy.

The total N_{HI} in any direction depends primarily on its Galactic latitude. We live in an edge-on system and most of the HI is piled up in the plane. Most structure visible in HI at the higher latitudes is likely the consequence of specific events in the life of the Galaxy.

The line brightness temperature does not change much with angular resolution. HI emission has a very steep spatial power spectrum $P(k) \propto k^{\alpha}$ with $\alpha < -2$ (e.g. Green 1993). HI is thus highly correlated from point to point, with most spatial power on the largest spatial scales. HI emission spectra in the Galactic plane change remarkably little as the angular resolution is increased from $36'$ to $4'$ (see Figure 3 of Bania & Lockman 1984).

The dynamic range in an HI emission spectrum is not large. To first order, most of the structure in brightness temperature across a spectrum, especially at low latitude, results from kinematic effects and thermodynamic structure (e.g. self-absorption). "Normal" emission features are highly blended, and efforts to isolate individual HI clouds in emission profiles are usually successful only for clouds which are atypical because of their location or velocity. For these reasons any quantity which depends on slight variations in T_b at different directions, or at different velocities, is likely not to be well constrained.

At low latitudes the HI optical depth is ~ 1 at many velocities. Derivation of volume densities is thus uncertain, and quantities like the HI surface density over the Galaxy will also be uncertain because of the need for an opacity correction (Burton 1992; Dickey 1993).

Velocity crowding can be significant. Galactic rotation projected to the LSR often compresses a considerable distance into a small velocity interval. In the inner Galaxy objects separated by 1 kpc along the line of sight have radial velocities which typically differ by only 5 km s^{-1}. In the outer Galaxy 1 kpc differences may project to < 1 km s^{-1}. Random and non-circular motions will cause systematic distortions in kinematically derived structures.

There are phase transitions in the ISM. In some locations HI is being lost through ionization or is recombining; in other locations it is lost to the formation of H_2 or regained through molecular dissociation. Tracing the Galaxy through observations of HI alone will surely lead to incomplete and probably misleading conclusions.

4. 1961 to 2001: Progress, Revisions, and One Dead End

4.1. Spiral Structure in HI

In February 1970, a "Spiral Workshop" was held at the University of Maryland to resolve some of the differences between the pictures that had emerged to that date. The workshop was attended by Bok, Burton, Kerr, Lin, Lindblad, Mezger, Shu, Weaver, Westerhout and other researchers active in the field (Simonson 1970; 1971).

Kerr discussed the HI arms at length, beginning by saying *"...21 cm emission is the way to study the whole Galaxy..."*, then, after presenting a map of spiral structure (Kerr & Westerhout 1965; Kerr 1969), he discussed a series of qualifications which progressively undermined whatever sense of confidence one might have had in that map. Acknowledging that *"there is so much 21 cm emis-*

sion that we're confused by it", and that *"optical investigations tend to disagree with the 21 cm investigations in many ways"*, Kerr thought that part of the trouble might be because *"the apparent rotation curves are different on the two sides, in the first and fourth quadrants"*, though the cure for this was perhaps worse than the disease: *"the thing we've tended to do so far (quite incorrectly, of course) is to use two different rotation curves for the two sides of the Galaxy."* Even with this "fudge" (not the first or the last in this business, as we will see), the Kerr-Westerhout map does not look much like a spiral galaxy.

At the same meeting Burton showed that it was much easier to reproduce the observed structure in HI profiles with modest streaming motions (consistent with observations, and actually predicted by density-wave theory), than with large variations in the true HI density (Burton 1971, 1976). The converse statement though, is what doomed HI studies of spiral structure in the inner Galaxy: subtle velocity effects can mimic or mask large density differences. To be fair, this problem was known to the early researchers, but they must have hoped that the HI spiral arms would somehow shine through the uncertainties.

It is now generally accepted that evidence of spiral structure in inner Galaxy HI profiles is confused at best, and attempts to derive the spiral structure of the Galaxy from HI spectra have largely been abandoned. While HI can contribute to study of arms in the outer Galaxy, arms in the inner Galaxy seem better delineated in tracers which have a higher arm-interarm contrast, or are less ubiquitous, than HI. Molecular clouds are one alternative species, but these days anyone needing a model of our spiral structure usually turns to ionized gas, either HII regions or diffuse electrons from pulsar dispersion measures (Georgelin & Georgelin 1976; Taylor & Cordes 1993). Models of the large-scale morphology of the Galaxy are tested against the HI data rather than being derived from the data (e.g. Burton 1976; Englmaier & Gerhard 1999).

4.2. The Inner Rotation Curve and the Galactic Center

A triumph of early HI studies was in establishing the location of the Galactic center, whose position can be determined to within a degree or so in longitude from the kinematic symmetry of profile shapes (Oort & Rougoor 1960; Blitz 1994). The HI over a large area around the Galactic center, however, has complex kinematics, which for many years was misinterpreted as structure in the basic rotation curve.

At the Princeton meeting Oort (1961a) presented a Galactic rotation curve whose amplitude fell gently from the Sun toward the Galactic center, then rose abruptly to a narrow peak at $R \sim 0.5$ kpc before falling again. That rotation curve is quite consistent with current models from R_0 down to $R \sim 1$ kpc (e.g. Burton 1992; BM98), but the inner peak is now understood as an artifact of motions induced by a Galactic bar, motions which have about the same magnitude as circular rotation at 0.5 kpc $\leq R \leq$ 1 kpc. When the non-circular component is removed, the Galactic rotation curve looks similar to that of other systems and is in reasonable agreement with the stellar data (Liszt 1992; Burton & Liszt 1993). The rotation curve at $R < R_0$ is thus now fairly well determined, at least to within 10 km s^{-1} or so, which is the magnitude of motions ascribed to streaming and asymmetries (but see §5.7).

The "anomalous" HI features in the Galactic nucleus discussed in Oort's (1961a) review grew steadily in number as more observations were made, until by 1977 there were nearly ten (Table 2 in Oort 1977). More were to follow. There were attempts to explain some of these, especially the 3-kpc arm, in terms of stable orbits rather than expulsion of gas (e.g. Shane 1972; Peters 1975), but these models fit only part of the data and also tended to predict HI features where none were observed. Finally, Burton and Liszt used new data and a full 3-d analysis to show that the kinematics and distribution of *all* the HI emission (and the molecules) in the inner ~ 1 kpc of the Galaxy plausibly arose from gas moving in closed elliptical orbits in a tilted, bar-like system (Burton & Liszt 1978, 1983; Liszt & Burton 1978, 1980, 1996). The HI features which Oort believed were ejecta from the nucleus, as well as much seemingly "normal" HI emission in this area, were revealed to be projections of the symmetric, tilted, elliptical disk. No net expansion or mass flux was needed. A decade later, the bar was observed in starlight at the location and orientation predicted from the HI kinematics (Blitz & Spergel 1991b; Blitz 1993).

Our current picture of the Galactic nucleus is much more satisfying (and far simpler) than the "patchwork of kinematically and morphologically diverse features" (Liszt & Burton 1980) that Oort thought was required. Though there remain many puzzles (see, e.g., BM98), and the region is quite complex, progress has been steady and is likely to continue as more elaborate models are developed and tested against the data (e.g. Fux 1999; Weiner & Sellwood 1999).

4.3. The Surface Density and Size of the Galaxy in HI

The full two-dimensional surface density, $\Sigma_H(R,\theta)$, is unlikely to ever be known well because of non-circular motions and velocity crowding, but there is no fundamental reason why the more robust $\Sigma_H(R)$ could not be determined with reasonable accuracy. The current state of knowledge, however, is disappointing though amusing. Consider the $\Sigma_H(R)$ curve given in Binney and Merrifield's (BM98) excellent book as Figure 9.19, attributed to Dame (1993). It appears quite respectable: nearly flat over most of the Galaxy at 4 $M_\odot$ pc^{-2} with an exponential decline past $R = 17$ kpc. A look back at Dame's paper, though, induces some doubt. His presentation of the same data has the following notes: *"HI at $R < R_0$ [is] derived from midplane number densities given in Burton & Gordon (1978) and constant HI layer thickness of 220 pc (FWHM) given by Dickey & Lockman (1990); values have also been arbitrarily scaled by a factor of 2 to approximately match the value at $R = R_\odot$ (see Liszt 1992)."* The provenance of this curve does not instill confidence in its accuracy.

The situation takes an odder turn for the outer Galaxy, for Dame gives not one, but two possibilities for $\Sigma_H(R > R_0)$, both credited to Lockman (1988) and shown here in modified form as Figure 1. These two estimates were derived (using the old value of $R_0 = 10$ kpc) from identical HI data sets, but with different assumptions about the outer Galaxy rotation curve: the solid line is for a rotation curve which is flat at $R \geq R_0$, while the dashed line adopts the curve of Kulkarni, Blitz & Heiles (1982) which rises linearly by a mere 14% from R_0 to $\sim 2R_0$ then is flat thereafter. Figure 1 was originally constructed to make the point that in the outer Galaxy small differences in the assumptions (specifically in $|dV/dr|$) propagate into large differences in Σ_H, but the size of

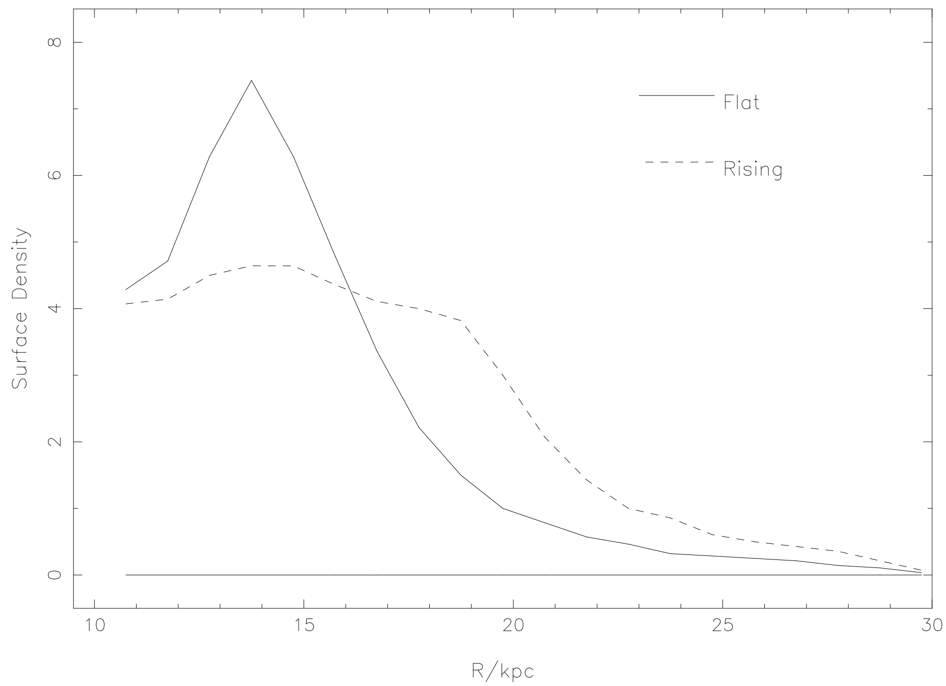

Figure 1. The HI surface density in the outer Galaxy is extremely sensitive to the rotation curve used to derive it. The curves show the implied surface density $\Sigma_H(R)$ in $M_\odot$ pc^{-2} for data from the Weaver & Williams (1973) survey when analyzed using a flat rotation curve (solid line) where $V_{cir} = V_0$ for $R \geq R_0$, and for a rotation curve which rises by about 2 km s^{-1} kpc^{-1} from R_0 to $2R_0$ then is flat thereafter (dashed line). The two rotation curves differ by only a few percent in amplitude at $R = 12 - 15$ kpc. The scale is based on the old $R_0 = 10$ kpc (adapted from Lockman 1988).

the Galaxy in HI also depends on the shape of the rotation curve beyond R_0, as does the total HI mass, which changes by 20% between the two models.

The sensitivity of the surface density to the rotation curve was used by Knapp, Tremaine & Gunn (1978) to make inferences about the size of the HI disk and the form of the curve itself. They were able to limit the size because HI emission does not extend to the maximum velocity permitted by Galactic rotation. But the parameterization of the rotation curve that they adopted would not allow for the result given by the dashed line.

It has been by argued that the rotation curve is probably flat or slightly declining beyond the Sun (Binney & Dehnen 1998), but if $\Sigma_H(R)$ is also to be flat or declining for all $R > R_0$, then an increase in the circular rotation velocity between R_0 and $\sim 2R_0$ seems required, exactly as a naive interpretation of the rotation curve data would suggest (Wouterloot et al. 1990; Merrifield 1992). While it seems certain that the vast majority of Galactic HI lies in the outer Galaxy at $R > R_0$, the actual amount out there is not so well known.

4.4. Scale Height and Mean z in the Inner Galaxy.

The high degree of flatness of the HI layer in the inner Galaxy was noted in the first surveys, and the HI plane was taken to be the best reference for a "Galactic plane" (Blaauw et al. 1960). But interestingly, although the HI layer at $R < R_0$ is thin and flat, it is not completely thin, and it is not completely flat: there is some residual waviness of the mean about the plane (Gum, Kerr, & Westerhout 1960). The deviation of the mean layer from $z = 0$ is only a few tens of pc (Quiroga 1974), but the phenomenon is significant because the deviations are to some extent coherent, and are shared by every Population-I type species in the inner Galaxy, suggesting that the gravitational potential itself may be distorted (Lockman 1977; Spicker & Feitzinger 1986). There is as yet no explanation for the "corrugations", as they are usually called, but they have been detected in other galaxies (Florido et al. 1991).

The scale height also has interesting structure. Oort (1961a) reported that it was approximately constant over much of the inner Galaxy, though somewhat smaller at small R and somewhat larger near the Sun. This has been a matter of theoretical concern, for the scale length of the stellar disk is only a few kpc, and unless supporting forces somehow compensate exactly for the change in the local gravity, the HI layer should thicken significantly from $0.25R_0$ to R_0 (see Ferrara 1993 for a discussion of this point, and an ingenious solution).

In the inner Galaxy the tangent points are unambiguous locations for measuring the thickness of the layer. Malhotra (1995) modeled the emission at the tangent points in the first and fourth quadrants with a single HI component and derived a scale height which is approximately constant between $0.25R_0$ and $0.7R_0$, then rises slightly approaching R_0. Although Malhotra ultimately interprets the data somewhat differently, her Figure 6 indicates that Oort's understanding is still accurate.

The vertical structure of HI in the inner Galaxy has further interesting complexities. Figure 2 shows a velocity-latitude diagram for HI at longitude 10° (all v-b diagrams in this paper use data from the Leiden-Dwingeloo survey of Hartmann & Burton 1997). The tangent point here has $R = 0.17R_0$, certain enough, but the velocity at which the tangent-point gas manifests itself depends on the rotation curve, the velocity dispersion, and the spatial arrangement of the HI. I have calculated the vertical FWHM of the HI emission at three velocities and the results are indicated by barred vertical lines at 180, 190 and 200 km s^{-1}. At this tangent point, the FWHM is not very sensitive to the velocity at which it is measured, having a value of 120 pc at all three velocities (and note the "corrugation" of the HI upward from $b = 0°$).

Figure 3 shows a similar v-b plot at longitude 29°, where the tangent point is at $R = 0.48R_0$. The FWHM is again calculated at three velocities, but here the scale height is very much greater in the line wings than in the brighter emission. This behavior is seen at many longitudes and shows that the Galaxy has an HI component with high velocity dispersion and high scale height which, at low latitudes, stands out only in the line wings (Lockman 1984). The high-dispersion component can be traced many hundreds of pc from the plane and is not encompassed by Malhotra's (1995) single-component model. The gaseous "halo" discussed by Oort (1961b) has now been seen in many species, and in other galaxies, and it poses interesting problems (Lockman, Hobbs, & Shull

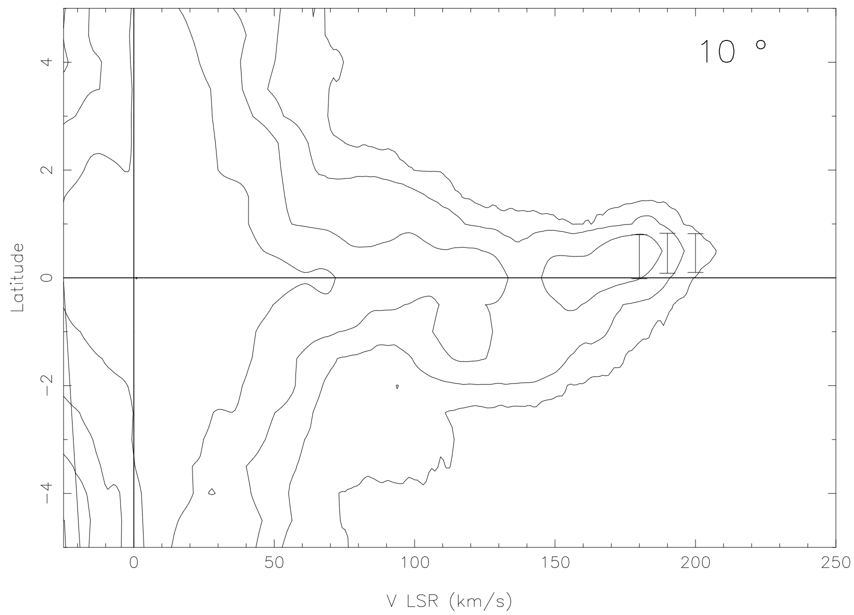

Figure 2. Velocity-latitude diagram for HI at longitude 10°. The vertical barred lines show the FWHM of the emission at velocities 180, 190, and 200 km s^{-1}. The layer has a thickness of about 120 pc independent of the exact velocity at which it is measured.

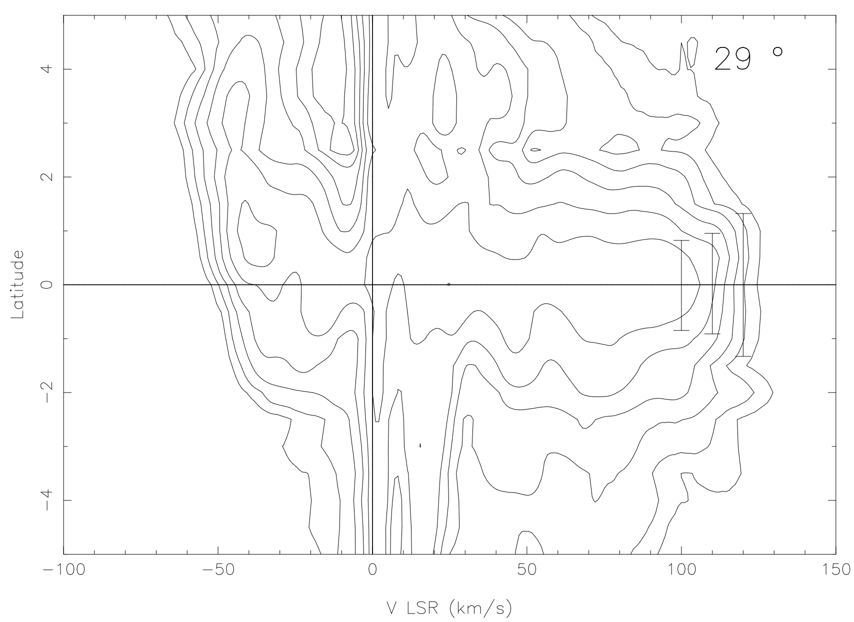

Figure 3. Velocity-latitude diagram for HI at longitude 29°. Vertical barred lines mark the FWHM of the emission at three velocities, and illustrate how gas in the profile wing lies in a much thicker layer than gas at lower velocity. The FWHM increases steadily from 220 pc to 345 pc between 100 and 120 km s^{-1}, though gas at all these velocities must come from nearly the same location.

1986; Savage 1990; Sembach 1997; Ferrara 1993; Sancisi et al. 2001; Benjamin, this volume).

The multiple components of HI in the inner Galaxy are probably responsible for most differences in results between various studies of the HI scale height, for different methods of analysis can emphasize one component over another.

4.5. The Outer Galaxy: Warping and Flaring

There is considerable current interest in HI in the outer Galaxy, stimulated in part by studies of other galaxies and in part by the possibility of using HI as a tracer of dark matter. This brief discussion will not do justice to the current pace of research, especially to the extragalactic and theoretical work.

The Galactic warp is the least well-understood major Galactic structure. Whereas the flatness of the HI layer in the inner Galaxy was recognized as having "fundamental physical significance" (Blaauw et al. 1960) the shape of the warp may be a mere contingency. The description of the warp given by Oort (1961a) is still generally correct, only the scale has changed with use of newer rotation curves (Diplas & Savage 1991; Voskes & Burton 1999). A general review is in Burton (1992). The warping begins at about $1.5R_0$ and is seen in molecular gas as well as many species in UV absorption lines (e.g. Wouterloot et al. 1990; Savage, Sembach & Lu 1995). Emission in the 21cm line remains its best tracer. The conclusion that the Sun lies near the line of nodes of this $m = 1$ warp is generally viewed as an unfortunate coincidence and not as a misinterpretation of something else (e.g. Kuijken & Tremaine 1994).

The dramatic flaring of the HI layer at $R > R_0$, in contrast to the more ambiguous run of scale-height with R in the inner Galaxy, greatly simplifies our understanding of it. As the surface density of the stellar disk decreases in the outer Galaxy, the gas layer should puff up unless its means of support also decreases. This property of HI has in fact been used to measure the disposition of dark matter in the outer Galaxy by Olling & Merrifield (2000), although in their application they assumed total turbulent support for the HI layer, an assumption which has been roundly criticized (Merrifield 1993) when applied to the solar neighborhood (Lockman & Gehman 1991).

The difficulties in a traditional kinematic analysis, and the potential importance of understanding the flaring and warp, led Merrifield (1992) to appeal to geometry and symmetry and derive the scale height and rotation curve simultaneously from the HI data. This approach has its own set of biases and may be susceptible to any ellipticity in the disk, but offers an independent constraint on Galactic parameters (Kuijken & Tremaine 1994).

Warps are now known to be extremely common among galaxies whose HI extends past the optical disk (Briggs 1990; Kuijken & Garcia-Ruiz 2001). There is a tight correlation of HI surface density with the surface density of dark matter implied from the rotation curve (Sancisi 1996; Hoekstra, van Albada, & Sancisi 2001), which has prompted suggestions that the HI is somehow coupled to the dark matter, either materially (Pfenniger, Combes & Martinet 1994) or epistemologically (e.g. Freeman 2001). This area of research is a rare one where Galactic and extragalactic studies are congruent. The region of the warp may be a zone of transition between the disk and the halo; between gas in near-circular orbits, and high-velocity clouds.

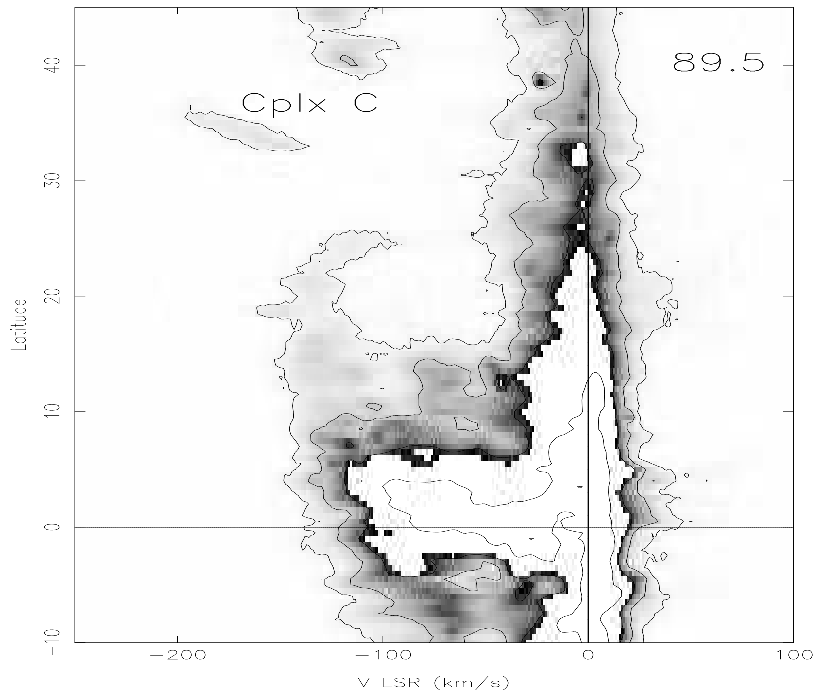

Figure 4. Velocity-latitude diagram for HI at longitude 89°.5. The mean layer warps to higher and higher z with increasing distance from the Galactic center (to negative velocity) and lies more than 20° away from $b = 0°$ at its most extreme. Above the warp, in the same velocity range, is the group of high-velocity clouds called Complex C.

4.6. Anomalous Velocity HI – High-Velocity Clouds

The sky is falling: the low-velocity HI at the Galactic poles is descending gently but systematically at a few km s^{-1}, illustrated by Weaver (1974) in his marvelous Figure 9. There is also intermediate velocity HI falling toward the plane at about -50 km s^{-1} over a large part of the northern sky (e.g. Kuntz & Danly 1996). Both phenomena may be local, related to the bubble of hot gas around the Sun and the relative paucity of HI at high latitude (DL90; Cox & Reynolds 1987). More generally, recent HI surveys show that almost 40% of the sky is covered with anomalous-velocity HI emission ($|V_{LSR}| \geq 100$ km s^{-1}), whose velocity is unlikely to arise solely from Galactic rotation (Lockman et al. 2002). For many years high-velocity clouds were detectable only in HI. They are a source of interest, confusion and dispute. The topic is reviewed by Wakker & van Woerden (1997) and by Putman in this volume, so I will comment only on the possible connection between the high-velocity gas and Galactic structure.

If the Galactic warp extends far enough from the plane, could it be mistaken for a high-velocity cloud? In the v-b plot of Figure 4, distance from the Sun (and from the Galactic center) increases to the left. The HI contours begin to warp away from $b = 0°$ around -40 km s^{-1}, and by -125 km s^{-1} (or $R = 20$ kpc for a flat rotation curve and $R_0 = 8.5$ kpc) the centroid is nearly five degrees above the plane at an implied $z = 1.5$ kpc. The warp then shoots up quite steeply in faint emission at more negative velocity, and appears to be trying to connect up with several high-velocity clouds belonging to Complex C. The fact that the assuredly "Galactic" HI emission at latitudes $\lesssim 20°$ seems to continue toward the high-velocity clouds lying at the same velocity, has led to suggestions that the warp and the high-velocity phenomena are the same, or at least related, though at the sensitivity level of the Leiden-Dwingeloo survey there is no connecting emission. One subclass of high-velocity clouds is generally accepted to be an extension of one of the outer arms of the Galaxy (e.g. Habing, 1966; Haud 1992), but the link between the others and the Galactic disk is more obscure and in many cases implausible.

If most of the positive-velocity high-velocity complexes at $\ell > 180°$ belong to a leading arm of the Magellanic Stream (Putman & Gibson 1999; Sembach et al. 2001), then the vast majority of the high-velocity HI *not* associated with the Magellanic Stream has a negative velocity, and Oort's belief that high-velocity clouds are primarily infalling with respect to the LSR remains correct.

Some of the high-velocity complexes have distances which place them only a few kpc away and thus in the Galaxy's halo (van Woerden et al. 1999). They must give the Galaxy a very ragged edge. The environment around the Milky Way may be not too different from that of other interacting systems where Galactic disks swim in a sea of gaseous debris (e.g. Gibson et al. 2001).

4.7. Galactic Asymmetries

Gas in a circular orbit around the Galactic center will have a velocity $V_{LSR} = R_0 sin(\ell) cos(b)[\Omega(R) - \Omega_0]$. Thus, in the inner Galactic plane, the terminal velocity $V_t(\ell' < 90°)$ should be of equal magnitude but opposite sign to the V_t at the symmetric position $-\ell'$, because in both directions it arises from the same galactocentric radius $R = R_0 sin(\ell)$. It was known in 1961 that the HI deviates from this symmetry at the level of ± 10 km s^{-1}, and that the deviations have some large-scale coherence. Simple fixes to restore the symmetry by applying a radial motion to the LSR (Kerr 1962) do not solve the problem completely (e.g. Kerr 1969; Lockman 1988).

If there is an outer edge to the HI disk which occurs at an approximately constant R_{max} around the Galaxy, there should be another large-scale symmetry in the velocity structure of one wing of all HI profiles, proportional to $sin(\ell)$. The true "outer edge" of Galactic HI can be fairly irregular without distorting the $sin(\ell)$ structure because velocity crowding is so severe at large R that details a few kpc in size are not discernible. But again, the data show clear, systematic deviations from the expected behavior (Blitz & Spergel 1991a).

Asymmetries in the inner Galaxy are probably a manifestation of the bar or other components of the Galactic potential, but the situation at the Galaxy's edge is less certain. The observations may indicate a general asymmetry of the Galactic potential, or give proof that the HI disk is not in equilibrium or is extremely lopsided (Blitz & Spergel 1991a; Kuijken & Tremaine 1994).

5. What Next?

5.1. More, Better, HI data

High angular resolution is not always necessary to resolve large-scale Galactic features, which is why most of what Oort knew in 1961 is still basically correct. As Kerr noted *"in more recent years, new surveys with higher resolving power at Parkes and Green Bank have yielded an enormous amount of new information ... but have not yet greatly improved the understanding of the basic problems"* (Kerr 1969). But consider: one degree corresponds to about 150 pc at the Galactic Center, which gives a few, but only a few, independent points across the HI layer at most locations in the inner Galaxy, and resolves the warping, flaring outer Galaxy HI layer only at $90^\circ \leq \ell \leq 270^\circ$. A 100-meter antenna has a resolution of $\sim 10'$, or 25 pc at the Galactic Center, which is sufficient to resolve the disk but inadequate for individual clouds or the complicated structures in the Galactic nucleus. The angular resolution of $\lesssim 1'$ attained by the synthesis surveys presented elsewhere in this book allows study of structure in the warp in the first and fourth quadrants, though any single spectrum at this resolution may be dominated by small clouds in self-absorption and not by large-scale features. But the current synthesis surveys do not have the sensitivity to detect most halo gas, or most high-velocity clouds, or even to detect the disk in some high-latitude directions. There will be a continued need for different data sets, with different resolution and sensitivity, for different investigations.

A list of major HI emission surveys is given in Burton (1992) and Binney & Merrifield (BM98), to which can be added the southern counterpart to the Leiden-Dwingeloo survey (Arnal et al. 2000), the 140 Foot Telescope survey of the northern Galactic Plane (Lockman & Murphy in preparation), the HIPASS, HIJASS, CGPS, SGPS, VGPS, and IGPS discussed elsewhere in this volume.

5.2. More Computing, More Ideas

The data from all major HI surveys can now be stored and manipulated by relatively inexpensive computers – the type accessible to most astronomers, indeed, to most people with any kind of education. Galactic HI studies have, in principle, become democratized, and those willing to make the effort can test their ideas against the data, and possibly even make a discovery, all in the comfort of their high school classroom, home, or pub. Though all the easy questions have already been asked, the contrast with 1961 could not be more pronounced.

One area where this increase in computing power may pay off is in revealing HI features that cross longitude, latitude and velocity, and do not appear coherent in the traditional projections. Advanced visualization software may remove their obscurity.

5.3. Information from Other Species

The ability of the 21cm line to "see through the dust", which made it of such interest to Oort, is now shared by many other lines in the radio (e.g., Dame, Hartmann, & Thaddeus 2001; Roshi & Anantharamaiah 2001). Fifteen years after Oort's review, major efforts were underway to compare HI with ionized and molecular gas (Burton 1976). These days, observations in the optical and UV, though limited to directions of moderate extinction, contribute increasingly to Galactic structure studies. One recent, striking, result is the detection of the Galactic warp in UV absorption lines toward a distant quasar (Savage, Sembach, & Lu 1995). The data suggest that the metallicity at the Galaxy's edge falls to 0.1 solar, which is the metallicity of some high-velocity clouds. A similar study in another direction shows that the abundances in a high-velocity cloud differ from those in an intermediate-velocity cloud, implying that the two clouds have very different histories (Richter et al. 2001). Current $H\alpha$ telescopes have the resolution in angle and velocity of the early HI surveys (Reynolds, Sterling, & Haffner 2001) and are providing information on the relationship between HI and H^+ above the disk (Reynolds et al. 1995).

These other species may provide critical information to HI studies. A measurement of the HI scale height, for example, will be profoundly misleading if some fraction of the clouds are ionized at high $|z|$, neutral near the plane, but turn molecular at very low $|z|$, yet that behavior is quite possible in environments where the time scale for a phase transition is smaller than the dynamical time (Combes & Becquaert 1997). Another example is high-velocity clouds, which have long been the province of 21cm studies alone. The discovery of a cloud which is predominantly ionized (Sembach et al. 1999) shows that even for high-velocity clouds, HI may be giving us just the tip of the iceberg.

5.4. HI in Absorption

HI emission measurements have made enormous contributions to our understanding of the Galaxy, and it is safe to predict that they will still be important in 50 years, for 21cm emission comes from varied environments and can trace subtle phenomena in all directions. HI absorption measurements have had a more limited impact. The 21cm line can be seen in absorption against bright continuum sources (e.g. Radhakrishnan et al. 1972; Garwood & Dickey 1989), and, sometimes, in self-absorption against background HI emission (e.g. Knapp 1974; Baker & Burton 1979). Self-absorption has attracted recent attention because the high-resolution CGPS has shown that the sky is peppered with cool clouds (Gibson et al. 2000; see also the papers in this volume), but self-absorption requires such special geometry that it seems unlikely that it will yield statistically unbiased information on Galactic structure. Absorption against radio continuum sources, however, is another story.

The sensitivity of absorption surveys is discussed in DL90. There are hundreds of Galactic HII regions which are bright-enough and compact-enough to yield a good HI absorption spectrum in an hour with existing instruments. Their velocities can be derived from recombination lines, and for some, accurate distances can be determined from astrometric observations of associated OH or H_2O masers. Pulsars, supernova remnants and some stars can also serve as targets. Extragalactic continuum sources can be used for measurement of the HI absorption through the entire disk of the Galaxy, analogous to emission measurements.

The current synthesis surveys are beginning to give a sense of what might be possible in mapping the cool HI throughout the Galaxy. It is amusing to consider that, with enough data, it may even be profitable to resume the old search for the HI spiral arms of the Galaxy, only this time not in emission, but in absorption!

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