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# The Neutral Medium

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**Abstract**

We consider the physical conditions of the neutral medium within, and in the environments of, galaxies. The basic physical and morphological properties of the neutral medium within galaxy disks are now quite well-constrained. Systematic variations in temperature and phase-balance (of cool versus warm neutral gas) are indicated as a function of both radius and $z$-height. Interestingly, the cool medium line-widths are observed to be dominated by turbulent energy injection within cells of 10 pc to 1 kpc size. Deep new observations reveal that 5–10% of the neutral medium is associated within an extended halo which rotates more slowly and experiences radial inflow. Much of this component is likely to be associated with a "galactic fountain" type of phenomenon. However, compelling evidence is also accumulating for the importance of tidal disruption of satellites as well as continuous accretion (of both diffuse and discrete components) in fueling galaxy halos and disks. Continued fueling is even observed on scales of 100's of kpc in galaxy environments, where the neutral component is likely to be merely a trace constituent of a highly ionized plasma.

## 1 Introduction

Although the neutral interstellar medium, as traced by the 21 cm emission line of atomic hydrogen, is often imagined to be a rather homogenous environment, this is really not the case. The neutral medium, essentially by definition (if we adopt, say, a 50% or greater neutral fraction), occupies the regime between the ionized medium on the one hand and the molecular medium on the other. Within this regime, equilibrium gas kinetic temperatures vary from some $10^4$ K to as low as 10 K. Even the boundaries of the neutral regime are somewhat indistinct, since trace atomic components (as low as 1 % or less by number) are often still the most effective observational probes of both highly ionized plasmas as well as predominantly molecular regions. In this short review we will consider the entire neutral regime as well as some of these boundary zones, first from a theoretical perspective and then an observational one.

## 2 Predicted Thermodynamics, Phase Balance and Temperature

A critical concept to appreciate is the fact that atomic hydrogen can exist in pressure equilibrium in two distinct thermodynamic phases, the so-called cool neutral medium (CNM) and the warm neutral medium (WNM). These are much more than merely slightly warmer or cooler regions of interstellar space. They are distinct phases which are separated by a phase transition, that can perhaps best be visualized by considering the phase transition between liquid water and water vapor near the earth's surface. A similar density contrast, of about a factor of 100, is associated with both of these phase transitions. The concept of an interstellar cloud, should then have somewhat more meaning to the reader. Although still diffuse by earthly standards, these are much more substantial than the medium within which they are immersed.

Physical conditions in the neutral medium have been the subject of a series of analyses going back to the pioneering work of Field (1965), continuing with Draine (1978), Shull & Woods (1985) and most recently with Wolfire et al. (2003). A wide variety of heating and cooling mechanisms play a role in determining the temperature and phase balance of the neutral medium, but as soon as even moderate metal abundances are attained, the heating is dominated by photo-electric emission from dust. Cooling, on the other hand remains sensitive to the particle density, with Ly$\alpha$ emission dominating at low densities (below about 1 cm$^{-3}$) and C II emission at high. Equilibrium solutions have a characteristic tilted "S" shape when plotted in the pressure – volume density plane, as seen for example in Fig. 7 of Wolfire et al. (2003). Thermodynamically stable solutions are those with a positive slope in these figures, while the negative slopes correspond to unstable conditions. Small temperature perturbations will lead parcels of gas to migrate from regions of negative slope to those of positive slope.

The simple picture that emerges is that the WNM/CNM phase balance is driven largely by the local ambient pressure. At ambient pressures typical of galactic disks ($P/k$ of a few hundred to as much as 10000 cm$^{-3}$K) the WNM and CNM can coexist in pressure equilibrium, while at even lower pressures the WNM will dominate and at higher pressures it will be the CNM.

The timescale for equilibrium to be achieved has been determined by Draine (1978) for quite a wide range of conditions to be about $n \cdot \tau \sim 10^6$ cm$^{-3}$yr. If ambient conditions (principally the pressure) vary more rapidly than this, then equilibrium will not be achieved and a broader range of conditions can be expected. In practice, one can then expect a wider range of temperatures to be encountered at a given location in a galaxy, than simply the two intercept points of a line of constant pressure with the tilted "S" equilibrium curves.

High resolution numerical simulations of the interstellar medium typically show little evidence for a simple bimodal gas temperature distribution (eg. de Avillez & Breitschwerdt 2004). This may reflect the simplified treatment of the gas thermodynamics in the simulations, but may also reflect the moderately short timescales for strong pressure modulation of much of the medium.

However, there are some predicted global trends which can be sought in observational data. A general decrease of the thermal pressure is expected as a function of both radius, $R$, and $z$-height within disk galaxies. This should give rise to a systematically changing phase balance as function of both $R$ and $z$. At low $R$ and $z$ we expect the CNM to dominate, while at high $R$ and $z$ it should be the WNM. Further, the pressure gradient as function of $R$ might give rise to a systematic change in the median CNM temperature.

In any case, the detailed thermodynamic analyses have shown that essentially independent of the gas temperature, density and phase the neutral medium has an associated electron density, $n_e \sim 0.01$ cm$^{-3}$ (eg. Wolfire et al. 2003). This residual ionization is crucial in providing coupling of the neutral medium to magnetic fields (which are after all the focus of this conference).

## 3 Observed Thermodynamics, Phase Balance and Temperature

While the emission brightness of the 21 cm line of neutral hydrogen gives an unambiguous indication that some atomic gas is present along a line-of-sight, it does not always provide a direct constraint on the gas temperature or even the total column density, in view of the unknown opacity. The best constraints on physical conditions come from observations of both HI absorption and emission from essentially the same line-of-sight. Such data have been accumulated for both the solar neighborhood of the Galaxy and different portions of the M31 disk by Braun & Walterbos (1992). The solar neighborhood data show a very tight correlation of HI absorption opacity, $\tau$, with emission brightness, $T_B$, that can be well-modeled with a two phase ISM, although with about a factor of two variation in the CNM temperature (100±50 K). The data for the M31 disk is much sparser and noisier but shows a similar trend. These data further show a systematic trend for the $\tau$–$T_B$ curves at increasing galacto-centric radii to be offset to higher CNM temperatures.

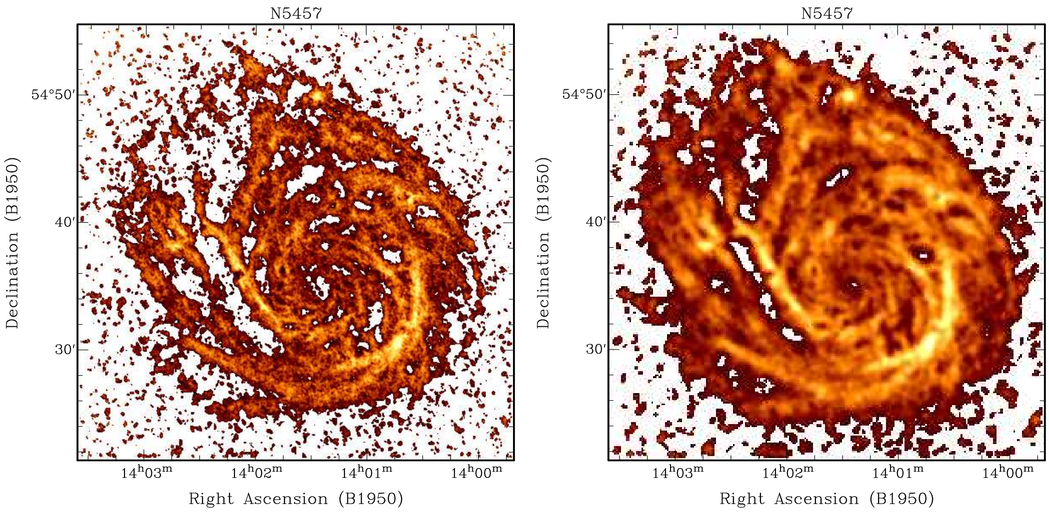


Figure 1: Integrated HI emission in the nearly face-on galaxy NGC 5457. With high angular resolution **(left)** a network of high brightness CNM filaments can be detected that is marginally resolved at 150 pc and 5 km/s. Such filaments are confined to the star-forming disk of the galaxy, where they have a ~15% surface covering factor and account for more than half of the HI mass. With further spatial smoothing **(right)**, much fainter diffuse emission is detected between the filaments and out to much larger radii consistent with the WNM phase.

Similar conclusions follow from high resolution HI imaging of many nearby galaxies by Braun (1995, 1997). Such imaging studies reveal a CNM network of high brightness temperature filaments that is marginally resolved at about 150 pc and 5 km/s resolution in face-on systems. This is superposed on a much fainter background of diffuse, higher line-width emission that is consistent with arising within the WNM. These components are contrasted in Fig. 1 for NGC 5457, seen at 9 arcsec resolution on the left and after smoothing to 25 arcsec resolution on the right. When the CNM has been marginally resolved it displays a peak observed brightness temperature which increases systematically with galacto-centric radius from some 50 K at small radii to about 200 K at the edge of the star-forming disk. Several spot measurements of HI absorption toward background radio sources confirm that this trend reflects an increase in the nominal CNM kinetic temperature which is closely traced by the observed peak brightness temperature. The implication of this correspondence is that the typical HI opacity in the filaments is greater than unity. The surface covering factor of the CNM filaments varies somewhat from galaxy to galaxy but is typically some 15% inside of the star-forming disk, and essentially 0% at larger radii. These filaments account for 60–90% of the total HI inside the star-forming disk, but since the diffuse WNM continues to much larger radii, the global CNM fraction is only some 35–70%.

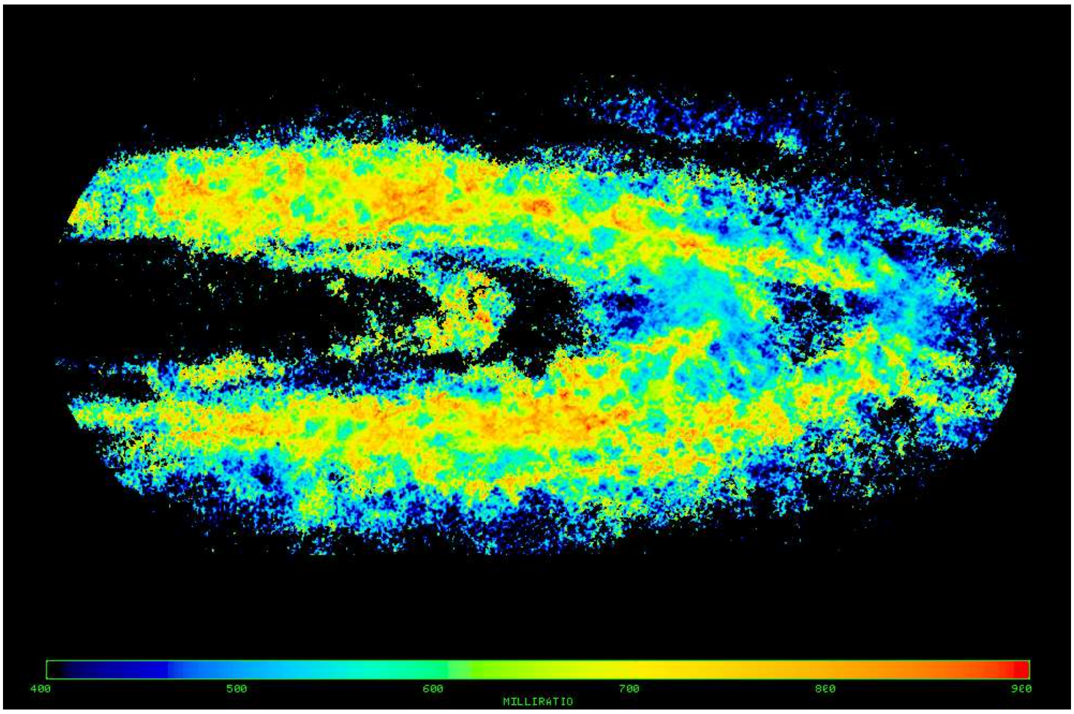


Figure 2: The distribution of HI linewidth in the north-east half of M31. Regions of high linewidth form a filamentary network which appears to be organized and powered by massive star formation events.

Studies of the shape, rather than just the strength, of HI emission lines have also provided insights into the role and origin of turbulence in the neutral interstellar medium. The high brightness line profiles of CNM filaments are found to be highly non-Gaussian in shape (Braun 1997, 1999). Although the line cores are rather narrow, they are associated with extremely broad wings ($\sim$100 km/s FWZI), which can be well-fit with Lorentzian distributions. Just as the CNM itself is organized into a highly filamentary system, so it is also the case with the regions of high HI line-width. This phenomenon is clearly seen in Fig. 2 for the north-east half of M31. Even though the inclination of the M31 disk is so high (almost 80°) that the CNM filaments become highly blended when seen in total intensity, they are readily distinguished in this image of HI line-width. Regions of high HI line-width are organized into a frothy system of bubbles and filaments on scales of 10 pc up to about 1 kpc. Many of the shell-like structures are associated with recent sites of massive star formation as traced by H$\alpha$ emission and broad-band optical detection of stellar associations.

## 4 Predictions for Galaxy Disks, Halos and Environs

Quantitative predictions of neutral medium structures and topologies within galaxy disks and halos are only beginning to emerge from recent high resolution 3-D simulations (eg. de Avillez & Breitschwerdt 2004) of $\sim$1 kpc$^2$ regions. Up to this point, most predictions had been fairly qualitative and been based primarily on the so-called "Galactic Fountain" (Shapiro & Field 1976) and "chimney" models (Norman & Ikeuchi 1989). Even now, it has not been possible to simulate a complete realistic galaxy disk and halo in three dimensions. This is becoming increasingly urgent as widespread detections of halo gas with peculiar kinematics are being made (as we will see below).

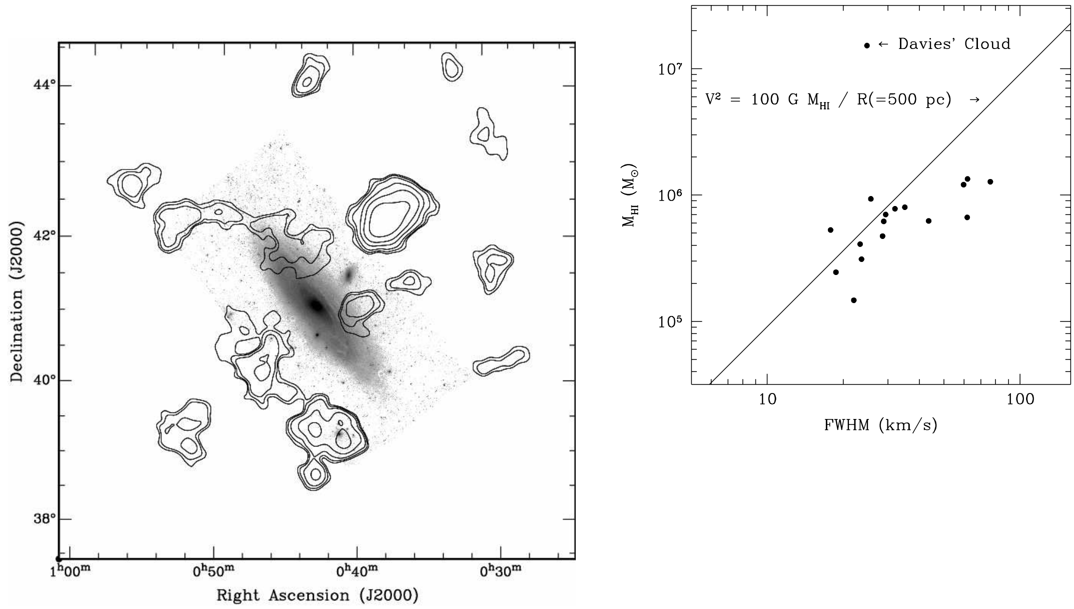


Figure 3: Contours of H I column density **(left)** for discrete and diffuse high-velocity H I in the M31 GBT field, after masking out emission from the inclined, rotating disk; at 0.5, 1, 2, 10, and $20 \times 10^{18}$ cm$^{-2}$, overlaid on a V band image of M31. Observed H I mass versus FWHM line-width **(right)** for discrete clouds near M31. Line-width was measured globally for each cloud. Also plotted is the anticipated relationship between H I mass and line-width for gravitationally confined clouds. To first order, our FWHM measurements appear consistent with the hypothesis that the objects are dark matter dominated, assuming a dark matter to H I mass ratio of 100:1 and a characteristic size of 0.5 kpc for each H I cloud core.

Various authors (eg. Maloney 1993, Corbelli & Salpeter 1994, Dove & Shull 1994) have considered what should occur at the edges of galaxy disks, where the intergalactic radiation field leads to a rapid decline in the neutral fraction. Below a critical column density of $\log(N_{HI}) \sim 19.5$, there should be an exponential decline in the neutral fraction from essentially unity down to about 3% by $\log(N_{HI}) \sim 18$. This marks the transition between the optically thick and optically thin regime for the penetration of ionizing intergalactic radiation. Ironically, the neutral fraction remains almost constant at even lower column densities, once the optically thin regime has been reached. However, in many ways this transition marks the effective "edge" of disk galaxies in HI, since current observations only rarely have the sensitivity to reach column densities below $\log(N_{HI}) \sim 19$.

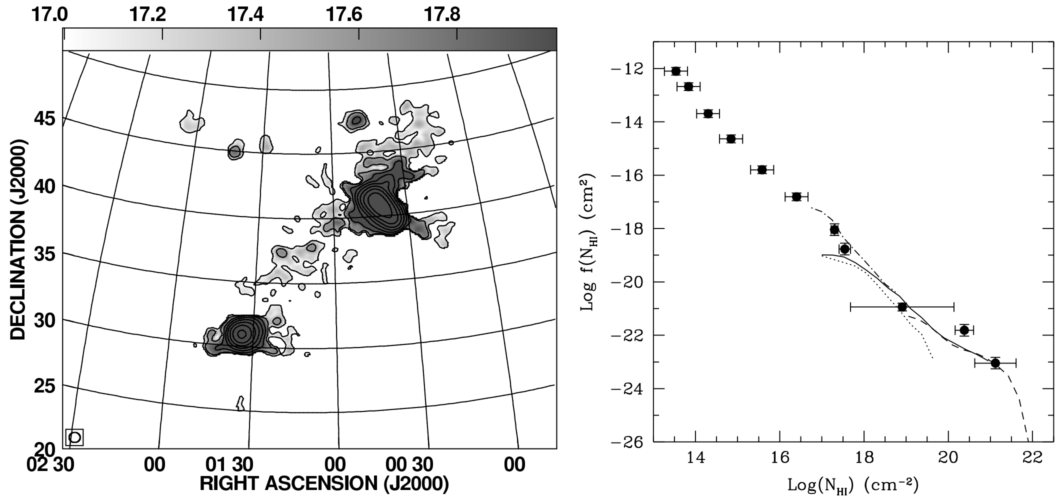


Figure 4: Integrated HI emission **(left)** from features which are kinematically associated with M31 and M33. The grey-scale varies between $\log(N_{HI}) = 17 - 18$, for $N_{HI}$ in units of $cm^{-2}$. Contours are drawn at $\log(N_{HI})$ = 17, 17.5, 18, ... 20.5. M31 is located at (RA,Dec) = (00:43,+41°) and M33 at (RA,Dec) = (01:34,+30°), The two galaxies are connected by a diffuse filament joining the systemic velocities. The distribution function of HI column density **(right)** due to M31 and it's environment. The data from three HI surveys of M31 are combined in this figure to probe column densities over a total range of some five orders of magnitude. The dashed line is from the WSRT mosaic (Braun et al. 2005) with $1'$ resolution over 80×40 kpc, the dotted and solid lines from our GBT survey (Thilker et al. 2004) with $9'$ resolution over 95×95 kpc and the dot-dash line from the wide-field WSRT survey (Braun & Thilker 2004) with $48'$ resolution out to 150 kpc radius. The filled circles with error-bars are the low red-shift QSO absorption line data as tabulated by Corbelli & Bandiera (2002).

But galaxy disks, typically associated with $\log(N_{HI}) \sim$ 18–22, only account for about 1/3 of the cosmic baryons in the nearby universe. A further third is apparently associated with more diffuse systems of ongoing filamentary accretion in the range $\log(N_{HI}) \sim$ 14–18. The final third of local baryons likely resides in a very diffuse photo-ionized phase and is associated with $\log(N_{HI}) \sim$ 12–14. This breakdown in three column density regimes is determined from high resolution numerical simulations of structure formation over cosmic time (eg. Davé et al. 1999, 2001). These simulations suggest that in the intermediate regime of $\log(N_{HI})$, a large fraction of the gas resides in the so-called "warm-hot intergalactic medium" or WHIM, a condensed shock-heated phase with temperature in the range, $T \sim 10^5$–$10^7$ K. This simple picture is complicated by the growing suspicion that the gas accretion process may well occur in two rather different regimes (eg. Binney 2004, Keres et al. 2004). Low to moderate mass galaxies ($M_{Vir} < 10^{12} M_\odot$) may experience primarily "cold-mode" accretion ($T \sim 10^{4.5}$ K) along filaments, while only more massive systems may be dominated by the more isotropic "hot-mode" accretion ($T \sim 10^{5.5}$ K).

## 5 Observations of Galaxy Disks, Halos and Environs

A series of very deep studies of the HI distribution in galaxies of various inclinations is beginning to reveal widespread evidence for components with peculiar kinematics at large $z$-heights. One of the first of these studies was that of NGC 2403 by Fraternali et al. 2002. But more recently NGC 891 (Fraternali et al. 2005), NGC 253 (Boomsma et al. 2005a) and NGC 6946 (Boomsma et al. 2005b) have all been subjected to very sensitive imaging. What these studies are revealing is that between 5 and 10% of the total HI mass in the studied galaxies is distributed in an extended "halo" component with an exponential scale-height of a few kpc. In the most extreme cases, the gas has been detected as much as 15 kpc out of the mid-plane. This high-$z$ gas rotates systematically more slowly with height from the plane by some 20 to 50 km $s^{-1}$. There is also a component of systematic radial inflow of 15 to 20 km $s^{-1}$ for this gas. In relatively face-on systems it has been possible to detect localized vertical outflows as large as 200 km $s^{-1}$. This last attribute in particular can be quite confidently associated with a "Galactic Fountain" or "chimney" phenomenon. It seems likely that other aspects of the halo gas are also associated with these phenomena.

However, other mechanisms which may well be important in fueling galaxy halos are (1) the tidal disruption of satellite galaxies and (2) accretion of both diffuse and discrete structures from the extended environment. A recent deep study of a 95×95 kpc field centered on M31 has been carried out with the Green Bank Telescope (GBT) by Thilker et al. (2004). This survey reaches an RMS sensitivity of $1.5\times10^{17}$cm$^{-2}$ over 18 km $s^{-1}$ and detects a multitude of peculiar velocity HI clouds and streams, extending over the entire surveyed region, as shown in Fig. 3. Several of the detected features, particularly the complex to the south of the M31 disk, are very likely tidal in origin since they partially overlap with clear stellar streams in position and velocity (eg. Ferguson et al. 2002). Other features in the M31 environment are less likely to have a tidal origin, since they have no stellar counterparts, are well-separated from the disk, yet have large internal velocity widths, which are rather suggestive of a significant dark matter content. As seen in the right-hand panel of Fig. 3, the mass/line-width distribution of discrete clouds in the M31 environment is suggestive of a typical dark (and/or ionized) to HI mass ratio of about 100:1.

On even larger scales, there is evidence for large-scale accretion of gas along "cosmic web" filaments providing continued fueling of both M31 and M33. Braun & Thilker (2004) have used the fourteen telescopes of the WSRT array to image an 1800 deg$^2$ region centered on M31 with auto-correlation spectra. This survey reaches an RMS column density sensitivity of $4\times10^{16}$cm$^{-2}$ over 17 km $s^{-1}$, making it the deepest HI look yet at the nearby extragalactic sky. In addition to detecting many of the discrete features noted above within about 50 kpc of M31, a diffuse filament is detected connecting the systemic velocities of M31 and M33 and extending beyond M31 in the anti-M33 direction, as seen in Fig. 4. The total extent of this feature is some 260 kpc. In the immediate vicinity of both M31 and M33 it terminates in what appear to be ongoing accretion features. The distribution function of HI column density in the M31 environment is also shown in Fig. 4, where it is compared with the statistics from QSO absorption lines. The good agreement illustrates that we are now making the first images of so-called Lyman Limit Systems, which had previously only been detected via Ly$\alpha$ absorption. As noted in the previous section, we expect that the HI at these low column densities is the trace neutral fraction (about 1%) in what is probably a highly ionized plasma. Indeed, there are already some indications that much of the filament shown in Fig. 4 has a kinetic temperature of $2\times10^5$ K (Braun & Thilker 2005).

## References

Binney J., 2004, MNRAS, 347, 421

Boosma R., Oosterloo T., Fraternali F., van der Hulst, J.M., Sancisi R., 2005, A&A, in press, astro-ph/0410055

Boosma R., Oosterloo T., Fraternali F., van der Hulst, J.M., Sancisi R., 2005, in "Extra-planar Gas", Ed. R. Braun, ASP Vol. 331, in press, astro-ph/0410022

Braun R., Walterbos R.A.M., 1992, ApJ, 386, 120

Braun R., 1995, A&AS, 114, 409

Braun R., 1997, ApJ, 484, 637

Braun R., 1999, in "Interstellar Turbulence", Eds. J. Franco and A. Carraminana, CUP, p.12

Braun R., Thilker D.A., 2004 A&A, 417, 421

Braun R., Thilker D.A., 2005, in "Extra-planar Gas", Ed. R. Braun, ASP Vol. 331, in press

Braun R., Thilker D.A., Corbelli E., Walterbos R.A.M., 2005, in prep.

Corbelli E., Salpeter E.E., 1994, ApJ, 419, 104

Corbelli E., Bandiera R., 2002, ApJ, 567, 712

Davé R., Hernquist L., Katz N., Weinberg D.H., 1999, ApJ, 511, 521

Davé R., Cen R., Ostriker J.P., et al., 2001, ApJ, 552, 473

de Avillez M.A., Breitschwerdt D., 2004, A&A, 425, 899

Dove J.B., Shull J.M., 1994, ApJ, 423, 196

Draine B.T., 1978, ApJS, 36, 595

Ferguson, A.M.N., Irwin M.J., Ibata R.A., Lewis G.F., Tanvir N.R., 2002, AJ, 124, 1452

Field G.B., 1965, ApJ, 142, 531

Fraternali F., van Moorsel G., Sancisi R., Oosterloo T., 2002, AJ, 123, 3124

Fraternali F., Oosterloo T., Sancisi R., Swaters, R., 2005, in "Extra-planar Gas", Ed. R. Braun, ASP Vol. 331, in press, astro-ph/0410375

Keres D., Katz N., Weinberg D.H., Davé R., 2004, MNRAS, astro-ph/0407095

Maloney P., 1993, ApJ, 414, 41

Norman C.A., Ikeuchi S., 1989, ApJ, 345, 372

Shaprio P.R., Field G.B., 1976, ApJ, 205, 762

Shull J.M., Woods D.T., 1985, ApJ, 288, 50

Thilker, D. A., Braun, R., Walterbos, R. A. M., et al., 2004 ApJ, 601, L39

Wolfire M.G., McKee C.F., Hollenbach D., Tielens A.G.G.M., 2003, ApJ, 587, 278