GLOBAL PHYSICAL CHARACTERISTICS OF THE HI GAS.

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The interstellar HI is best discussed in temperature categories because the requirement of pressure equilibrium leads to gross differences between hot and cold gas. The temperature of the hot (6000K) neutral gas has been measured by five techniques while the cold (60K) gas is visible mainly in 21cm absorbtion. There is evidence for warm (200K to 1000K) gas. Because of emission line blending, the small scale structural morphology is undetermined; however, there is evidence it is filamentary. With few exceptions, spatial sizes observe a lower limit of about 5 pc. On a larger scale, the gas is organized into sheets which reflect the recent history of cloud formation.

I. THE CLASSIFICATION OF NEUTRAL HYDROGEN.

The study of HI gas is an interesting field of Astronomy because the amount of data which can be obtained is so large that the observations tend to demolish the assumptions used to interpret them. As a result, 21cm studies force us to face the hermeneutical question: where does one begin with the derivation of physical characteristics from the emission of a single spectral line? The first interpretations were based on models of randomly-placed independently-moving spherical clouds of gas. This historical assumption was critically reviewed by Heiles in the previous symposium in this series (Heiles 1974). The situation in brief is that the gas elements do not move independently, nor are they spherical.

To formulate a correct interpretation of the data, it may be fruitful to make an initial generalization from observations. It appears that the gas is approximately in pressure equilibrium, a circumstance which is also theoretically comfortable. If this is the case, the physical characteristic of temperature should assign the gas to remarkably distinct thermal classes or phases. Decreasing temperature will correlate with increasing gas density; so that cold gas, no matter how abundant, can occupy only a tiny fraction of the interstellar volume. Most of the volume must be filled with hot tenuous material. The hot gas is therefore exposed to mechanical disturbances and radiation which main-

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tain its elevated temperature, while the cold material tends to shield itself and present a low interaction cross section. These differences of density, volume filling factor and exposure mean that the dominent physical processes change with temperature. Moreover, gas elements with different temperatures have certainly experienced separate histories.

It is useful to retain the term cloud in a temperature classification as a name for formations in the cold gas. Such formations are distinct because the small volumes containing cold material are clearly defined by a temperature-density contrast. The objection that observers have made to theoretical cloud models in the past concerns not the existence of cloud material but the inference that the cloud material forms quasipermanent and isolated entities that move randomly. Later, I will try to justify the view that this seemingly pedantic difference in interpretation is connected with a rather gross difference in the physical state of the interstellar gas. First however, let us review some measurements of the gas temperature.

II. NEUTRAL HYDROGEN TEMPERATURES

The coldest HI gas has a temperature of about 10K, but since it occurs in clouds that are primarily molecular (Burton et al. 1978 and references therein), it will not be discussed here. The cold atomic hydrogen clouds have higher temperatures on the order of 60K. One may set upper limits on the temperature of this cloud material from the width of its emission line, but an accurate average temperature can be determined from absorption measurements against background continuum sources (Shuter and Verschuur 1964, Hughes et al. 1971, Radhakrishnan et al. 1972). Only an average temperature is available because a statistical correction must be made for foreground emission from the hotter gas. The most recent high-sensitivity absorbtion experiments confirm the older work for high opacity features but have also detected a type of low-opacity HI which one might call warm gas (Davies and Cummings 1975, Lazareff 1975, Dickey et al. 1977, 1978). The individual temperature measurements for this gas range from a few hundred to a thousand Kelvin, without correction for foreground emission. One would be tempted to ascribe the unusual temperatures simply to the absence of an emission correction were it not for the common occurrence of the same velocity structure in both emission and absorbtion. The similarity of opacity and emission profiles could arise either from gas at the indicated intermediate temperature or from spatial volumes containing a heterogeneous mixture of hot and cold gas. A few instances of warm gas have also been located by independent techniques such as the 590K HI measured by Baker (1973a) and the 570K gas measured in NaI by Hobbs (1976). These detections would argue against the heterogeneous mixture explanation. At the moment, observations are insufficient to quantify the amount of warm gas in the Galaxy, or to prove or exclude a connection with the cold gas.

The highest measured HI temperatures are those associated with the diffuse, neutral, intercloud medium. For this gas, we are fortunate to have five independent temperature sensitive techniques. To indicate the degree of consistency of the results, the measurements are summarized in Figure 1. Hobbs (1976) used NaI optical lines to obtain measurements or lower limits whose average is displayed as the lower end of the NaI range in Figure 1. The upper end is an average of Hobbs's upper limits established by line widths. Figure 1 also displays the HI absorbtion temperatures obtained by Mebold and Hills (1975). In this case, the range shows the spread of temperatures for distinct spectral components. Apparently, the intercloud temperature is not a constant (Davies and Cummings 1975). These published values are systematically high due to stray radiation; however, the open circle in Figure 1 shows the average temperature of the components after correction for this effect (Kalberla 1978). On the whole, the stray radiation effect is not serious in this case. For a few samples of gas, there are temperature measurements from emission data that were analysed by one of two methods. In principle, both methods seek to establish the thermal broadening pertinent to the smallest discernable spatial structure. The presumption is that no significant nonthermal broadening occurs on this small spatial scale because turbulence would dissipate too quickly. The analysis is complicated by the fact that if one has N structures spread over a velocity range V and each emits with a linewidth of v, blending of the spectral lines from these structures becomes serious when N exceeds V/v. For small structures in the intercloud medium with a large thermal broadening v, blending will always occur. Consequently, the analysis must

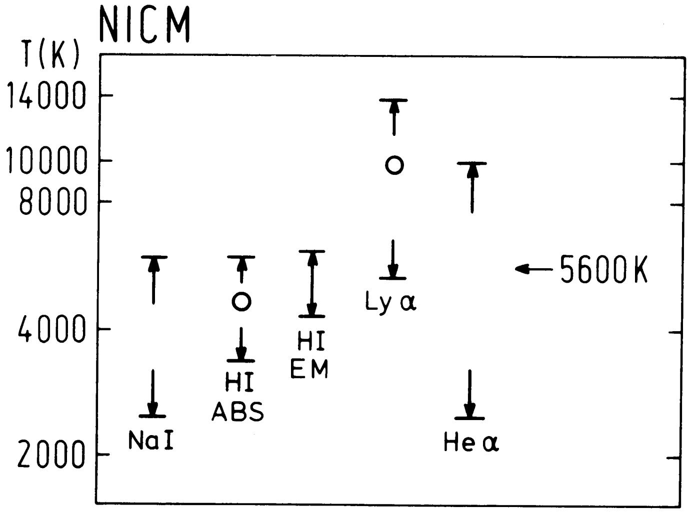

Figure 1. A comparison of temperature measurements of neutral intercloud gas obtained by 5 techniques. A temperature of 5600K is compatible with all of the available data (references are given in the text); however, the range for HI absorption is clearly due to point to point temperature variations.

exploit the spatial fluctuations of blended emission profiles. Baker (1973a) analysed primarily the velocity autocorrelation function of the fluctuations to derive the thermal line width, while Mebold, Hachenberg, and Laury-Micoulaut (1974) relied on a Gaussian model of turbulence that allowed a temperature estimate based on the variance profile. It should be noted that if the assumptions of the 21cm methods fail, the absorbtion measurements of the spin temperature of the hot medium yield estimates of the kinetic temperature that are too low (1) because some of the opacity may be due to cooler material and (2) because the collision rate may be insufficient to thermalize the spin temperature (Field 1958, Davies and Cummings 1975). On the other hand, the emission measurements may be too high if there exists a form of subparsec scale turbulence that mimics thermal broadening. The agreement of the two 21cm techniques is therefore especially satisfying.

While the preceding measurements refer to the gas within a few hundred to several kiloparsecs from the sun, the backscatter of solar Lyman alpha photons yields a measurement of temperature for just those neutral hydrogen atoms entering the solar wind cavity. To indicate the uncertainty in the individual experiments, Figure 1 contrasts the average of the lowest temperatures compatible with the data of three independent observing groups with the average of the highest compatible temperatures (Fahr 1974, Bertaux et al. 1976, Adams and Frisch 1977). The open circle shows the average of all the values. A similar experiment can be performed using the backscatter of 584 Å photons from interstellar helium. The helium result in Figure 1 (Weller and Meier 1974) serves as a check on the backscatter analysis because hydrogen and helium atoms follow different trajectories through the solar cavity.

There is a range of overlap for the temperature determinations which lies at about 5600 K. This result is somewhat lower than theorists had expected for the neutral ICM. In addition, the existence of temperature variation is also not well understood.

III. THE SPATIAL DISTRIBUTION OF HI GAS

Because the volume filling factor of cloud material is small, it was expected that the sun would lie in an intercloud region as proven by the backscatter measurements. However, the fact that the interstellar gas entering the solar system is neutral could not have been predicted so readily. The large exposure of the hot medium hints that a significant fraction of its volume may be ionized by stars (Grewing and Walmsley 1971, Torres-Peimbert 1974). Indeed, large ionized regions must exist near the sun because of the small Lyman alpha opacity in the direction of certain nearby stars (Bohlin 1975) and the detection of stellar EUV radiation (Lampton et al. 1976). The spatial distribution of the remaining neutral intercloud material should be obtainable from 21cm observations. However, reliable information is nearly nonexistent because one needs the brightness temperature to derive the column density. Most observers process 21cm antenna temperatures in a manner recommended by the IAU (van Woerden 1971) in answer to a demand for standardization (van Woerden 1964), and frequently denote the result as brightness temperature. However, the standard procedure is simply a scale change, not a correction for antenna response. The method given by Westerhout et al. (1973) is correct for their special case; but in general, the antenna response far from the main beam must be known and the differential doppler shift of the Earth's motion in these directions must be taken into account. The feasibility of exactly measuring the response of a given antenna by including it in an interferometer was demonstrated by Hartsuijker et al. (1972). Recently, Kalberla derived the response of the Effelsberg telescope without an interferometer and demonstrated a reproducible brightness temperature calibration (Kalberla 1978). The aspect of this problem that is relevant here is that the derivation of the brightness temperature of emission from a low intensity, intercloud field requires the removal of the stray radiation received from other, usually more intense areas on emission. We observe the dim intercloud regions only through a haze of scattered emission and we cannot readily measure the actual column density or its variations. This technical problem also prevents us from defining the boundaries of galactic gas (Baker 1976) and confuses the comparison of 21cm column density against interstellar reddening (Kalberla 1978) and stellar spectra (Giovanelli et al. 1978).

The 21cm lines from the cold and warm gas are bright and relatively narrow in velocity; consequently, they are not seriously confused with contributions from stray radiation or from the neutral ICM. Nevertheless, confusion due to emission line blending complicates the study of small common structures. While it is straight forward to construct a map of blended emission or to assign its fluctuations to putative spatial entities by Gaussian fitting, the result is without significance unless there is a one-to-one and not a one-to-many correspondence between emission structure and spatial structure. One can minimize the blending problem by examining high galactic latitudes where the line of sight leaves the galactic disc after a short distance. Small scale structure seen here is largely filamentary (Heiles and Jenkins 1976). Blending is also avoided if one picks out rare features that are exceptional in velocity or intensity. These structures again appear to be filamentary (Baker 1973b). These results cannot conclusively establish the small scale morphological structure of the gas, but they suggest that filamentary structure is very common (Heiles 1974).

The typical length scale of spatial structure can be measured with some confidence even in the presence of blending because the emission scale size should reflect the underlying spatial scale through the decorrelation length of the chance arrangements in space that - when blended in emission - produce the observed line. Observations relating to the length scale seem to show that structure grows more common with decreasing size until a lower limit is reached. It is rare to find smaller features than this limit. There has been no systematic attempt to determine whether the size cutoff is just what it seems, namely a limit to or turnover in the size spectrum, or whether it results from some interaction between the spectrum of sizes and the sensitivity of the observations. Nevertheless, it is striking that improvements in angular resolution and receiver sensitivity have left the observational situation little changed. The minimum size seen in emission appears to be 5 pc according to a number of surveys tabulated by Verschuur (1974). The main uncertainty seems to be the distance of the observed gas. A similar size is required by emission observations pertaining selectively to the cold cloud material (Baker and Burton 1975); however, absorption measurements of the same material indicate a smaller cutoff at 1 pc (Griesen 1976). These results are not necessarly contradictory because Baker and Burton tested the size of gas patches showing significant opacity at one velocity. Their definition allows smaller size enhancements in opacity at the same velocity; furthermore, it does not exclude a spatial extension of the gas patch at a different velocity.

It has become increasingly common for observers to interpret the intermediate size scale morphology of HI gas - that between 20pc and 100pc - in terms of sheet distributions. This term was invoked by Heiles (1967) to describe the distribution of gas in one large area where the emission showed rifts. Without an unlikely preferential alignment, rifts cannot be seen if the gas is more extended in the line of sight than the width of the rift. The sheet geometry also appears to describe a large area of saturated 21cm emission in the galactic anticenter region (Baker 1974a). For this region, the measured spin temperature implies a number density necessary for pressure equilibrium. This density together with the column density yields a depth of a few parsecs for gas covering tens of parsecs on the sky i.e. the gas occurs in a thin layer. The 21cm opacity of this sheet has also been measured at the location of 5 continuum sources by means of the NRAO 3-element interferometer (Baker 1974b). While the absorption was present at the expected velocity at every point, the opacity varied greatly. This variation confirms the existence of substructure in the sheet.

If one speaks of cloud-like morphologies for HI, one should have in mind the terrestrial cirrocumulus or altocumulus clouds which consist of small filaments or cloudlets organized into a much larger coherent layer. Because both terrestrial and interstellar clouds move, one might think of the sheets as a coherent pattern of motion common to the gas fragments composing the sheet. In this respect, cloud gas imitates star streams - those groups of young stars that move through the solar neighborhood with a coherent velocity determined by their common point of origin. These three velocity groupings - terrestrial clouds, star streams, and HI sheets - must all consist of relatively young objects. For example, if terrestrial clouds were old, the atmosphere would mix them and every day would bring a new arrangement of standard clouds, but a statistically homogeneous one. Because the velocity groups show little mixing, the objects cannot have travelled far. The conclusion must be that HI clouds are continually formed and destroyed and that the temperature-density contrast which distiguishes clouds observationally is transient.

The impermanence of structure in the cloud medium may derive from the weakness of the selfgravitation. Cloud material cannot resist turbulent motion in the interstellar medium and it will be advected into a large volume by turbulent diffusion. The requirement of pressure equilibrium maintains the density contrast but the difference in exposure between hot and cold material is quickly lost. As the cloud material is drawn into ever more extended shapes, its surface to volume ratio increases dramatically and the energy fluxes that maintain the hot medium can then reheat the cloud material.

The cloud hypothesis concerning HI has one correct implication, we are studying a kind of interstellar weather; namely, organized, time-dependent changes of phase and form in the atmosphere of the Galaxy. Most of the results discussed here were won from observations near the sun; and given the nature of the phenomenon, changes in position in the Galaxy should be expected. The global characteristics that can be abstracted from our experience with the local gas are the coexistence of temperature-density phases and the continual reprocessing of material between the phases. In the future, it should be possible to extend measurements to greater distances using high-sensitivity, high-angular resolution instruments. It may then be possible to speak of climatic conditions in the HI and not just of todays weather in the local HI swimming hole.

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