THE INTERCLOUD GASES OF THE INTERSTELLAR MEDIUM

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ABSTRACT. This paper summarizes the physical conditions in interstellar gas occurring outside classical atomic or molecular clouds, from a view-point which is purely observational.

1. Historical Perspective

When the term "intercloud" came into widespread use, the interstellar medium (ISM) was viewed in simple terms. There were two widely distributed components of the local ISM, in the form of clouds--atomic/diffuse/HI and, more rarely, dark--and an intercloud component. Roughly put, and viewed with highly selective acumen, the physical and morphological properties of these constituents might now be summarized as follows:

TABLE 1. Classical Properties of the Cloud and Intercloud Gas

Property	Component	
	Cloud	Intercloud
Temperature	10 K (dark), 80 K (HI)	10^4 K
Total Density	1 H cm^{-3} at z = 0pc	0.2 cm^{-3}
z-Extent	50-100 pc	150 pc
Volume Fraction	few % ($\langle n\rangle/n$ = 1/20 or 1/300)	near 1
Mean Free Path	0.15 (HI)--few (dark) kpc	0
Size	few--few 10's of pc	

The evidence for the existence of clouds consisted of several independent lines of argument. Cloud features often appear multiple in absorption spectra, and are well separated in velocity; if a certain velocity range is expected from galactic rotation, only a small fraction is occupied. From estimates of the internal physical properties of the clouds, which lead to densities greater than the overall mean by factors of 20 to 300,

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it was clear that a small fraction in the velocity space of a line profile mapped, somehow, into a small part of the galactic volume. In addition, there were observations like those of Heeschen (1954) in HI (showing clear temperature inhomogeneities in the gas) and in a relatively few direct cases, but only for the darker material, it was possible to trace the boundaries in optical light.

For the intercloud gas, there were also several indications. Spurred by the presence of clouds quite far from the galactic plane, Spitzer (1956) advanced the notion of a very hot gas (10^6 K) which would keep them from dispersing and would have sufficient internal turbulence to support itself even at a great remove from the galactic plane. The dispersion of pulsar emission in the general ISM implied a widespread component of electrons which could be accommodated by having a small ionization fraction within the HI intercloud. Most clearly of all there was (is) a broad, undifferentiated component of HI emission at radio wavelengths from which absorption could not be detected (and still typically cannot be), implying a high-temperature, optically thin gas. The disparities between HI emission absorption and emission line profiles are shown beautifully in Figure 2 of Dickey and Lockman (1990). They show that emission spectra taken with beam sizes varying by two orders of magnitude retain far more resemblance to each other than to ANY absorption profile.

From HI observations, the intercloud could easily be believed to be a volume-filling component of the Galaxy at large. To this day, no line of sight has yet been found for which the HI emission column density is less than 4×10^{19} H cm^{-2}, even after the most stringent correction for confusion (stray radiation) has been performed (Lockman, Jahoda, and McCammon (1986))!

1.1 PROBLEMS WITH THE SIMPLEST CLOUD-INTERCLOUD PICTURE

This cloud-intercloud picture--the raisin pudding model of Clark (1965) buttressed by the two-phase model of Goldsmith et al. (1969) incorporating thermal and pressure equilibrium--led to many successes, as for instance, the HI emission simulations of Baker and Burton (1975). But it also seems to be very clearly wrong in many particulars. Vis-a-vis the clouds it led to an oversimplified and overly disorganized view of little round (identical, uniform) pills meandering aimlessly--hardly surprising given the difficulty involved in tracing features in HI--whereas in fact there is considerably more organization, with the material actually pushed into sheets, filaments, or what have you, under the influence of local events like supernovae. This view also does not admit the possibility that a large fraction of the cloud mass is in denser molecular gas.

With regard to the intercloud gas, the failings were several. One is the inability to accommodate more than one kind of gas in the intercloud ISM, the necessity for which will be demonstrated at some length here; clearly the filling of ANY substantial fraction of the galactic layer by an unaccounted component will force reconsideration of the entire concept of this model. Another failing is a confusion between the ubiquity of intercloud emission in HI profiles and the prevalence of such gas in space. Although cloud material can be believed to be relatively rare both kinematically--in profiles--and in space, it does NOT follow that the intercloud HI emission which is so unavoidable at the telescope actually arises from a gas component which fills all or even most of the galactic layer.

1.2 COVERING AND VOLUME FILLING FACTORS--SCARCITY AND UBIQUITY

The fraction of space filled by clouds must be fairly small. We have from Munch's study of extinction and a canonical gas/dust ratio the basic result that, locally, the mean density of neutral material is about 1 H-atom per cc (actually 1.2; see Spitzer (1978)). Any component of the interstellar medium which is denser than this can occupy only a portion of the galactic disk. Given that our probes of clouds in the atomic medium yield nT = 3000 cm^{-3} K (Jenkins and Shaya (1979)), that 100 K is a typical brightness for optically thick HI or for the rotational equilibrium of H_2 molecules seen optically in thin clouds, and that some fraction of the local mean density is in denser molecular gas, we conclude that diffuse or atomic clouds occupy at most a few percent (1/30 in this example) of the disk.

Before proceeding, it is useful to define some quantities relating to the overall spatial distribution. First is the mean free path λ_i whose inverse υ_i is the frequency with which some class i of interstellar object is encountered in a random line of sight at z = 0. For interstellar clouds studied optically, $\upsilon = 1/\lambda = 6$/kpc. This is the usual definition in which $\lambda_i = 1/n_i\sigma_i$, where n_i is the spatial number density and σ_i is the cross-section. The fraction of the volume occupied by the class i is $f3 = d_i/\lambda_i$, within a factor of order unity (if i represents spheres, d_i is the diameter and the factor is 2/3). The volume filling factor appears to be defined as the ratio of two one-dimensional quantities and, when λ_i is fixed by observation, as is often the case, it varies only with the assumed size of the members of class i.

Another quantity of note is the covering (area filling) factor, which we define as related to the probability that a line of sight will cross the Galaxy perpendicular to the galactic plane and not encounter an instance of class i. This probability is $1-\exp(-H/\lambda_i)$ where H is the effective thickness of the galactic layer. We define the covering factor, which can exceed unity, as $f2_i = H/\lambda_i = (H/d_i)f3_i$. Typically $H/d_i >> 1$ because we are considering objects which fit comfortably within the Milky Way. Thus we see that even objects with fairly small volume filling factors can cover the Galaxy such that they occur with very high probability along every line of sight.

This last point is important. The ubiquity of HI emission or any other tracer does not prove that a large fraction of the volume is occupied, only that the overall mean free path is short compared to the vertical size of the galactic system. For HI, it is possible that a new generation of very clean HI data may measure fluctuations in the intercloud HI emission so clearly that the volume filling factor of the HI intercloud gas will be ascertained, but this is impossible at the present time.

In closing, note that hard spheres have f3 = $\pi/6$ when packed at maximum density and infinite cylinders have f3 = $\pi/4$. If any phase of the ISM is imagined as having components distributed with such volume filling factors on the order of one-half, it must be reckoned that the constituents are actually in close communication with their neighbors at all times.

2. Constituent Properties of the Intercloud Gases

The existence of pulsars enabled astronomers to discover a widely distributed, ionized component of the ISM which in the two-phase model had to arise throughout the intercloud medium, and this in turn had to be weakly ionized. In fact the need to heat and ionize the interstellar gas with the same agent was something of a problem (which we avoid now at the expense of other complications); the flux of ionizing cosmic rays in the two phase model was much too large to be reconciled with current astro-chemistry and the electron density is now known to be much larger anyway.

The ionized gas sampled by pulsars was only the first of several additions to the roster of physically distinct phases, not sampled in HI, which could not be accommodated handily within the framework of the original two-phase model. We now describe briefly exactly what these were or have become. The order is descending in temperature.

2.1 CORONAL GAS

The Copernicus satellite detected OVI absorption and emission lines whose ensemble properties were derived statistically by Jenkins (1978). He found that 90 percent of the OVI gas was contained in a component having spatial frequency 6/kpc, macroscopic (clump-to-clump) 1-d velocity dispersion 26 km/s, with the remainder of the OVI in a population of larger and less common regions. The spatial frequency of the majority component is remarkably similar to that of classical diffuse clouds, but the cloud-cloud velocity dispersion of the latter is only 6-7 km/s. An exponential scale height 300(+200,-150) pc was derived, which is somewhat larger than is applicable to diffuse clouds except at the lowest end of the range but accords well with other components (see below) of the ISM.

Jenkins advanced several arguments concerning the volume filling factor of the OVI-bearing gas. If it displaces cold neutral clouds, the absence of anticorrelation with reddening places a limit f3 < 20 percent and the typical size follows as d < 30 pc. Alternatively, consideration of the detailed physical state of the gas--OVI traces gas in the range 0.5-20 x 10^5 K--led Jenkins to entertain the possibility that f3 was in fact much closer to 1. Unfortunately, this important quantity is no more certain now. According to the recent review by Spitzer (1990) there are arguments in favor of values in the range $0.2 \le$ f3 ≤ 0.7, and no means of deciding which is correct. Our continuing inability to re-observe this constituent of the interstellar medium--at wavelengths below 1050A--represents a most regrettable gap in our observational arsenal!

Another view of the hot gas in the immediate Solar vicinity is afforded by maps of the soft X-ray background. Such data is reviewed by McCammon and Sanders (1990).

2.2 WARM, IONIZED GAS.

Pulsar studies measuring DM = $\int n_e\, dl$ (Backer (1988) and Lyne et al. (1985)) and H-alpha profiles measuring EM = $\int n_e{*}n_e\, dl$ (Reynolds (1991a,b)) show there is a widely-distributed warm (10000 K) component of the ISM having a high ionization fraction. This component is now viewed as being distinct from the traditional HI intercloud gas at about the same temperature because the latter has a much smaller extent perpendicular to the galactic plane.

The warm ionized gas has several remarkable properties, among them its scale height, ≥ 1000 pc for the DM studies tracking $\langle n_e \rangle$, and the sheer quantity (or rate) of recombinations represented. The spectrum of this gas is well reproduced by a model in which stars earlier than B4 provide photo-ionization (Mathis 1986) but there are serious difficulties in imagining how so many ionizing photons leave the vicinity of their progenitor stars (near the galactic plane) to permeate the ISM (at large z, as well). Although shocks from SNR can propagate more readily, they do not represent sufficient energy input. Observed line ratios demand certain consistencies which random shock velocities cannot provide.

If we set $f3(z) = \langle n_e \rangle(z)/n_e = \langle n_e{*}n_e \rangle(z)/(n_e{*}n_e)$ for this component, we have $f3(0) = \langle n_e{*}n_e \rangle/\langle n_e \rangle = 0.007$ cm-3/$(0.025\ cm^{-3})^2 = 0.1$ (see Reynolds (1991a,b) and Lyne et al. (1985)). If the mean electron density $\langle n_e \rangle$ varies as $\exp(-|z|/h1)$ and $\langle n_e{*}n_e \rangle$ as $\exp(-|z|/h2)$, it follows that the actual electron density has a scale height $hn = h1{*}h2/(h1-h2)$ and the volume filling factor has scale height $hf3 = -h1{*}h2/(h1-2{*}h2)$. Kulkarni and Heiles (1988) took h1 = 1000 pc and referenced h2 = 300 pc, leading to hn = 429 pc, hf3 = -750 pc (the filling factor increases at larger $|z|$). More recently, Reynolds has taken h2 as large as 600-800 pc. If we follow him and use h1 = 1500 pc, it happens that $|hf3|$ is several (or many) kpc and hn = 1-2 kpc, i.e., things vary only very slowly with z-height. Physically, of course, the component with the largest scale height would be expected to occupy the entire volume at the furthest remove from the galactic plane.

2.3 WARM, NEUTRAL GAS

The traditional intercloud HI gas has a volume filling factor which in principle is as uncertain as that of the OVI-bearing gas, but cannot, given the previous discussion, exceed 0.7. Early on, the obvious ubiquity of this component in somewhat broad radio telescope beams was taken as a

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demonstration of high f3 but, as we noted above, all we can demand of the HI intercloud is sufficiently high spatial frequency. While it is possible that sensitive statistical observations of the HI intercloud gas might be made with a new and cleaner generation of telescopes and surveys, past arguments concerning the f3 for this phase have been somewhat impressionistic.

As noted by Dickey and Lockman (1990), there may be more than two distinct components to the atomic ISM. These authors find gaussian components with FWHM 212 and 530 pc (midplane densities 0.395 and 0.107 cm^{-3}) as well as an exponential with scale-height 403 pc and midplane density 0.064 cm^{-3}. Only the thinnest of these is identified with the cloud component.

There has been only one attempt to fit the HI cloud and intercloud gas into a small fraction of the interstellar volume, by Liszt (1983), who modeled the Arecibo emission/absorption results numerically. In that work, it was shown that one can fake the traditional intercloud medium by adopting cloud models with distinct, warm halos, but that such models do a poor job of reproducing the rather basic property that HI emission lines are broader than HI absorption on a line-by-line basis. A more satisfying model has continuous variation of temperature within a single cloud, from perhaps several tens to several thousands of Kelvins. In such a picture, the known higher scale height of intercloud gas requires the balance between cold and warm gas to change with distance from the galactic plane. Lower-z HI clouds would have cold cores which are at most barely present at high z.

3. Summary and Statement of Prospects for the Future

We do not have a clear and sufficient idea of the nature of the gases in the interstellar medium. There are enormous uncertainties in the simple quantities we presently discuss but even these cannot be merged to yield a comprehensive framework. Beyond the question of volume filling factors there is the overriding question of topology; beyond the art of describing there is the matter of providing physical explanation for the temperatures, densities, ionization state, scale height, etc. of the various constituents of the ISM. Beyond consideration of each phase we must explain why and how so many of them coexist with each other, and how they exist in the Galaxy at large (what are the sources of pressure in the ISM?). It's a big job. But what fun!

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