"Gas always goes down."

F.H. Shu in Discussion II.2

HOT GAS IN THE GALAXY: HOW EXTENSIVE IS IT?

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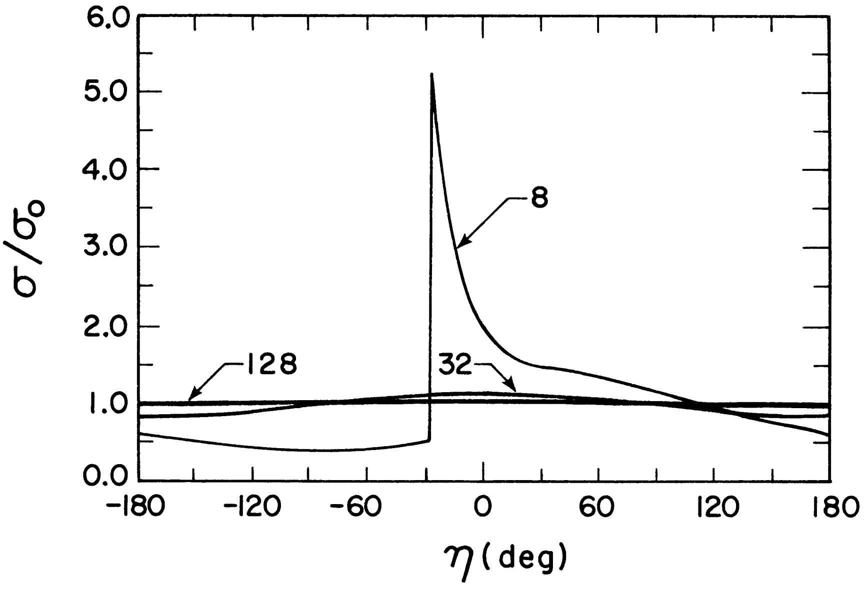
1. INTRODUCTION

Recent satellite detections of O VI absorption and soft X-ray emission leave little doubt that, locally, a substantial fraction of the volume of space between interstellar clouds must be filled with rarified and highly ionized gas at temperatures ranging from 2×10^5 to $> 10^6$ K. (See the reviews of Spitzer and Jenkins 1975, and Kraushaar 1977.) The physical state of this gas contrasts sharply with the theoretical picture of a largely neutral, warm, intercloud medium at $\sim 10^4$ K developed by Pikel'ner (1967), Field, Goldsmith, and Habing (1969), and Spitzer and Scott (1969). My purpose here is to review the evidence, observational and theoretical, concerning how extensive hot gas at $\sim 10^6$ K might be.

2. IMPLICATIONS FOR GALACTIC SHOCKS

Hot gas which fills a large fraction of interstellar space would have important consequences for galactic shocks. The response of any component of a galaxy to forcing by a spiral gravitational field supported by the disk stars depends very sensitively on the effective dispersive velocity of that component. Shown in Figure 1 are the theoretical variations in surface density of matter with velocity dispersions of 8, 32, and 128 km/s when this material is exposed to the spiral field believed to be present at the solar circle. (See Roberts 1969; Shu, Milione, and Roberts 1973.) To fix ideas, we may think of the curves labelled 8 and 128 as the responses, respectively, of hypothetical intercloud media at 10^4 and 10^6 K to the forcing of the spiral density wave supported by the disk stars — curve 32. The response of the warm neutral medium is very strong and involves the production of galactic shocks. The response of the hot ionized medium is not detectable on the scale of this graph. If a distribution of interstellar clouds were embedded in the former, the sharp increase of pressure inside spiral arms can be expected to induce the more massive clouds in the distribution to collapse to form clusters of stars (Shu et al. 1972).

E. M. Berkhuijsen and R. Wielebinski (eds.), Structure and Properties of Nearby Galaxies, 139-145.



In contrast, if interstellar clouds were embedded in an intercloud medium at 10^6 K, no significant increase of their surface pressure can be expected. Does the observed predominance of massive stars in spiral arms then prove that 10^6 K gas cannot be pervasive in most spiral galaxies?

Unfortunately, the answer to this question is more complex than appears at first sight. The observed velocity dispersion of interstellar clouds is also about 8 km/s; hence, if their collision mean-free-path is short enough to treat the ensemble of clouds as a dissipative continuum, the curve labelled 8 in Figure 1 should also approximate the variation of the number of clouds per unit area. The large increase of the number of clouds per unit area inside spiral arms would then give rise not only to the dust lanes, but also to an increase in the frequency of cloud-cloud collisions. The latter process may enhance the fraction of massive clouds susceptible to gravitational collapse at a fixed external pressure. Observationally, only $\sim 10^7$ yr elapse between the time of the formation of the dust lane ("shock") and the appearance of massive OB stars (Mathewson, van der Kruit, and Brouw 1972). Such a timescale may seem too short to trigger star formation by the process of building up big clouds from little ones, but our knowledge of such processes is too insecure to claim that the timescale is prohibitive.

Another serious obstacle facing proponents of an extensive hot intercloud medium is the observational evidence from radio continuum and gamma-ray studies that the entire interstellar medium -- and not just the collection of cloud centers -- suffers an overall compression in spiral arms (van der Kruit and Allen 1976; Kniffen, Fichtel, and Thompson

1977). The compression of magnetic field and cosmic rays is most easily accomplished by directly compressing the intercloud gas, but it may also be possible to accomplish this task indirectly by only bringing cloud centers closer together if most of the interstellar magnetic flux threads clouds. We conclude that a 10^6 K intercloud medium is difficult but perhaps not impossible to reconcile with the observed compression of the interstellar medium by spiral density waves. Thus, to address definitively the question of how pervasive such hot gas might really be, we must turn to the observations.

3. REVIEW OF THE OBSERVATIONS AND INTERPRETATIONS

3.1 H I observations

The strongest evidence for the intercloud medium being warm and neutral comes from the H I radio observations of 21-cm line emission and absorption (Clark 1965; Hughes, Thompson, and Colvin 1971; Radhakrishnan et al. 1972). Emission line profiles show broad wings which are absent in the absorption lines produced in the directions toward discrete radio continuum sources. This fact has been widely interpreted to indicate the presence of two components of H I: a cold cloud component with temperatures $\sim$ 70 K which is seen both in emission and absorption, and a warm intercloud component with temperatures in excess of 1000 K which is seen only in emission.

3.2 O VI observations

Ultraviolet line observations have revealed substantial column densities of O VI in the absorption spectra of bright OB stars (Jenkins and Meloy 1974). Interpreted as thermal broadening, the line widths suggest interstellar gas at temperatures in excess of 2×10^5 K. Ionization equilibria considerations suggest that $10^{5.5}$ K probably represents a good estimate for the state of most of the observed O VI gas. This temperature is lower than the best estimates of the temperature of the soft X-ray emitting regions; hence, it is likely that the O VI gas and soft X-ray observations refer to different gas (cf. Shapiro and Field 1976).

Gas at a few hundred thousand degrees is near the peak of the theoretical cooling function of a collisionally ionized gas (Cox and Tucker 1969). Thermal stability and energy requirements then suggest that the filling factor of O VI gas cannot be very large. The two main theories which attempt to explain the O VI observations place the O VI gas in special locations -- namely, at the conductive interfaces between cool or warm gas and hot gas. In the model of interstellar bubbles driven by stellar winds (Castor, McCray, and Weaver 1975; Weaver et al. 1977), this conductive interface occurs between shocked stellar wind ($T \sim 10^6$ K) and the swept-up outer shell of interstellar H II gas ($T \sim 10^4$ K). In McKee and Ostriker's (1977) elaboration of a model proposed by Cox and Smith (1974), the conductive interface occurs between H I clouds and a 10^6 K intercloud medium generated by overlapping supernova remnants (SNR).

3.3 Soft X-ray observations

The diffuse X-ray background above 2 keV in energy is almost certainly extragalactic (see Silk 1973); however, the excess emission below 1 keV is predominantly Galactic. Indirect evidence for this contention exists in the correlation of the soft X-ray emission with known Galactic objects -- e.g., with the radio continuum emission from Loop I or the North Polar Spur (Bunner et al. 1972). Direct evidence exists in the failure to detect measurable soft X-ray absorption by M 31 (Margon et al. 1974) and by the Large and Small Magellanic Clouds (Rappaport et al. 1975; Long, Agrawal, and Garmire 1976; McCammon et al. 1976).

The accepted explanation for the diffuse soft X-ray flux is that it arises by thermal emission, mostly in unresolved X-ray lines, from a hot rarified gas ($T \sim 10^6$ K, $n \sim 0.003$ cm^{-3}). The strong differential absorption by interstellar gas implies that most of the observed soft X-ray flux originates from a local region whose column density is $\lesssim 10^{20}$ cm^{-2} (Kraushaar 1977). Thus, the observations suggest that we are locally inside a region containing million degree gas, but they do not tell how common such regions are in a typical spiral galaxy.

3.4 Theoretical estimates

Theoretical estimates of the filling fraction f of 10^6 K gas have been made on the basis of the model of overlapping SNR (Cox and Smith 1974, McKee and Ostriker 1977). The fundamental idea is straightforward. Let f(t) represent the filling fraction of SNR at time t in a statistically homogeneous medium. Moreover, let τ = the average lifetime of a SNR, V = the average volume occupied by a SNR, and r = the rate per unit volume of supernova explosions. The probability f(t+dt) that a point is inside a SNR at time t+dt is equal to the probability f(t) that it was inside one at time t, multiplied by the probability $(1-dt/\tau)$ that this SNR has not died; plus the probability [1-f(t)] that the point was not inside a SNR at time t, multiplied by the probability rVdt that a SNR has since been created at its location:

$$f(t+dt) = f(t)(1-dt/\tau) + [1-f(t)]rVdt. \qquad (1)$$

In a steady state, $f(t+dt) = f(t) \equiv f$. Solving for f, we obtain

$$f = Q/(1+Q) \quad \text{where} \quad Q \equiv rV\tau. \qquad (2)$$

In our definition of the dimensionless parameter Q, the volume V and lifetime τ represent averages after taking into account the possibility that a significant fraction of interstellar space might already be filled with SNR (cf. Cox and Smith, McKee and Ostriker 1977). Complications enter in making reliable estimates for f because Q in equation (2) is itself a function of f. In particular, Q(f) clearly increases for increasing f because larger and longer lasting SNR can be blasted if a bigger fraction of the interstellar medium is filled with rarified gas. Cox and Smith rely on basically this "bootstrapping" mechanism to form a networkof supernova "tunnels" with $f \simeq 0.5$ even though the unperturbed "porosity" $q = Q(f = 0)$ may be fairly modest. Smith (1977) has revised this estimate to $f > 0.3$ inside spiral arms. McKee and Ostriker, using a different set of assumptions, obtain a filling factor $f \simeq 0.8$; thus, their overlapping SNR constitute the entire intercloud medium.

Simple but generous estimates for the important parameters (e.g., $r = 10^{-13}$ pc^{-3} yr^{-1}, $V = 10^{6}$ pc^{3}, $\tau = 10^{7}$ yr) yield marginal values for Q -- i.e., values on the order of unity. Hence, it is clear that more sophisticated analyses can give almost any value of f, large or small, that one wants. As an example, if one's prejudices lie in a small general value of f, one might follow Scott, Jensen, and Roberts (1977) and suppose that supernova explosions are highly correlated in space and time since massive stars tend to be found in OB associations, which in turn concentrate in gas-rich spiral arms. Repeated explosions at the same isolated places would shred neighboring big clouds into many small ones (see, e.g., Woodward 1975). The subsequent conduction of heat from the hot gas of the blast wave into the small fragments may evaporate the latter, and may lead to large but isolated "holes" of HI. Such holes have in fact already been seen in the high resolution studies of M101 (Allen 1974). These holes would be important and interesting for theories of the interstellar medium -- especially if we happen to sit in a hole (see Weaver 1977) -- but they may be too few in number to influence appreciably the large-scale galactic dynamics.

4. CONCLUSIONS

Definitive determinations of the filling factor of 10^{6} K gas in spiral galaxies await future observations, particularly in the radio and soft X-ray portions of the electromagnetic spectrum. High resolution 21-cm line investigations should reanalyze the question of whether the properties of individual clouds change systematically inside and outside spiral arms (see Weaver 1970). Especially important would be indications of whether the surface pressure of interstellar clouds increase or not inside spiral arms. A detailed investigation of the large holes of H I seen occasionally in the spiral arms of external galaxies would also be informative.

If hot gas fills almost the entire volume of interstellar space, high resolution studies should detect enhanced soft X-ray emission in the directions toward external spiral galaxies. Relevant observations already exist for the Large Magellanic Cloud (LMC). Rappaport et al. (1975) and Long et al. (1976) differ on the interpretation of the data at energies between 0.4 and 1.5 keV, but neither group finds excess emission from the LMC at energies $\sim$ 1/4 keV -- energies which characterize the observed radiation of the hot gas in the solar neighborhood. It would be important to see if enhanced X-ray flux at 1/4 keV is also absent from normal spiral galaxies. Experiments with sufficient angular resolution probably await the launch of the HEAO-B satellite.

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DISCUSSION FOLLOWING PAPER II.6 GIVEN BY F.H. SHU

GALLAGHER: Do you consider the North Galactic Spur local, and is it not evidence for a hot tunnel type of model?

SHU: Yes, I think that it is local, and that the evidence of hot tunnels is an indication for this.

VAN DER LAAN: In your simple derivation of the hot gas filling factor the product $rV\tau$ occurs, where τ is the SNR duration. It seems to me that τ is ill defined in the case of overlapping SNRs. After all, τ does not then have the old meaning of age till the SNR loses its identity among interstellar clouds, but rather the duration of the hot (Sedov) gas' persistence. This may be much longer than 10^7 years, in which case f goes to 1 and the hot gas will escape as a galactic wind in the z-directions. The HEAO-B imaging X-ray telescope will hopefully map such situations in nearby spirals in a year or so, or it will dismiss the whole scenario.

SANCISI: Are you aware of the Perseus-Taurus "hole" and that we may be inside it?

SHU: Weaver favours the idea that we are inside a big hole, and I think there is no question that we must be quite close to gas of a million degrees. Whether the rest of the interstellar medium looks like that I don't know. Neither do I know of observations bearing on that question.

BURBIDGE: If we live in a large hole you are putting us in a special position. Apart from the philosophical problems this might mean that hot gas is rare in our Galaxy and other galaxies.

GIOVANELLI: I would like to point out that high velocity clouds may cause the production of soft X-rays, especially in the northern hemisphere. If HVCs are infalling material interacting with the galactic disk, post-shock temperatures on the order of 10^6 K would be achieved. According to Chow and Savedoff (1972, Nuovo Cimento 88) the emission measure could be high enough to contribute a significant fraction of the soft X-ray background.

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