Modelling the Local Interstellar Medium As A Supernova Remnant In A Multiphase Gas

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INTRODUCTION

Trying to understand the local interstellar gas in detail may be a hopeless task for a theorist. In the interstellar medium as a whole, we can at least address global properties and perhaps come to some reasonable "time averaged" conclusions such as those of Cox and his collaborators (e.g. Cox and Smith 1974, Cox 1979) or McKee and Ostriker (1977). Even this is quite uncertain of course, both because the ISM gas has structure on scales from at least 1 Pc (and probably much smaller) all the way up to the size of the galaxy, and because none of us are quite sure which physical processes (such as thermal evaporation or heating of cooler gas by magnetohydrodynamic processes) are really important. However, in the local ISM things are significantly worse in that we no longer have even the ergodic hypothesis available to us - rather we have to try and deal with individual events and structures. On the other hand, we do have more detailed observations and hence a laboratory to try to decide on the importance of the various physical processes.

More specifically, it now seems highly likely from the X-ray measurements that locally we live within a "middle aged" supernova remnant with a radius of about 100 Pc (e.g. Cox and Anderson 1982 and references therein) and that the local ISM was reheated about 10^5 years ago. The question I would like to answer here is whether we can construct a model of this remnant which is consistent in detail with the observations and what it tells us about the theory. It is clear at once that this is far too complex and I will indeed concentrate on certain of the observations. However, I shall argue that thermal evaporation and local inhomogeneity are crucial elements which are essential to any satisfactory description.

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Inhomogeneity

The optical and UV absorption line studies would seem to unequivocally demonstrate the presence of high column density cold gas in some regions within the local hot bubble. From Paresce's (1984) recent compilation one sees that eight of the stars (αOph, δ Cyg, σ Sgr, o And, o Per, κ Vel, η Cen and α Crucis) within 100 Pcs could have hydrogen column densities in excess of $10^{19.5}$. In the cases of α Oph, κ Vel and η Cen, such material is certainly present. The total sampled line of sight distance of all observed stars is 1300 Pc and the average line of sight distance to high column density cold gas is then between 150 Pc and 430 Pc compared to typical ISM values of around 100 Pc (e.g. Spitzer 1977). This may suggest a local deficiency of high column density cold gas by a factor of up to 4, but there is no doubt that such material does exist locally. It should be emphasized of course, that the number of objects expected (12 or so) is so small that the deficiency has little significance. Similar conclusions arise from the Na optical absorbtion line studies (see the discussions of Frisch and Ardeberg in the present colloquium).

All this of course says nothing about whether the material is in sheets or clouds but we can leave this for the moment because in modelling the hot gas in the supernova remnants this type of material is actually of minor importance. It has too high a space density and too high a column density to much affect (or be affected by) the hot gas. (A corollary is, of course, that it would have been surprising if it had been locally absent and it is just as well it isn't). The material which can provide a mass source and energy sink to the hot gas is the 10^4 $^{\circ}$K material (hereafter the WM) which, as MO pointed out, must form given the presence of the cold gas. Given a typical UV flux, standard interstellar pressures and the presence of the cold gas, ionized warm material will rapidly occupy a significant fraction of interstellar medium. While we have no good heating mechanisms available except perhaps magnetohydrodynamic waves (e.g. Spitzer 1982), presumably a substantial fraction of warm neutral material forms too.

EVAPORATIVE SUPERNOVA REMNANTS

The importance of the WM lies in its potential to contribute mass to the hot gas by thermal evaporation (MO, Cowie McKee and Ostriker, 1981 hereafter CMO). The importance of thermal evaporation is the major controversial question in describing the hot gas in the local supernova remnant (and indeed in supernova remnants in general). Supernova remnant evolution with thermal evaporation from embedded material (such as described by MO and CMO) has a radically different appearance from the classical Sedov solution. (The Sedov solution is an approximately valid description of the gas when evaporation is not present even if there is a population of embedded cold gas, provided only this gas does not occupy too large a fraction of the volume or cover too large a fraction of the surface area.)

Since many people may not be familiar with the evaporative remnant theory let me run at least briefly through the principal features. In figure 1, I have shown the density profiles for the hot component of the gas obtained by CMO for a 3×10^{50} ergs fully evaporative supernova remnant (their model 1). Before I even start describing it, I should say that the salient features of the WM in this numerical model is that it had a filling factor of 27%, an assumed cylindrical shape, and a size of 2.7 Pc. It would have made very little difference if the WM had initially been in sheets since, because of the low column densities in WM structures, dynamical effects would fragment them very rapidly anyway. The density distribution inside the remnant is very flat compared to Sedov solutions which are sharply peaked towards the outside edge. It should also be noted that once the WM properties are specified, the density of the hot gas is predicted.

Specifically, we can make an approximate calculation of the average density of the hot gas as follows. If,

n = average hot gas proton density, T = average hot gas temperature
R = remnant radius, E_{51} = supernova energy in units of 10^{51} ergs
(70% thermal, 30% kinetic)
c = isothermal sound speed at T, m = average mass per proton
$R = \alpha c$ (defines α), a_{pc} = cloud radius in parsecs
M = mass of hot gas in remnant, n_{clouds} = number density clouds/Pc^3
$\dot{m} = 2.8 \times 10^4\, T^{5/2}\, a_{pc}\, \Phi$ g/s (Φ = efficiency)
= thermal evaporation rate from single cloud,

then

$$T = \frac{0.7\, \bar{m}\, E}{3\, Mk} = 1.7 \times 10^9\, E_{51} \left\{\frac{M}{M_\odot}\right\}^{-1} {}^oK$$

and $$M = \frac{4\,\Pi}{3}\, R_{pc}^{\ 3}\, n_{clouds}\, \dot{m}$$

This can be integrated to give

$$M = 16\, R_{pc}^{\ 4/3}\, E_{51}^{\ 2/3} \left\{\frac{n_{clouds}\, \Phi\, a_{pc}}{\alpha}\right\}^{1/3} M_\odot$$

or $$n = 130\, R_{pc}^{\ -5/3}\, E_{51}^{\ 2/3} \left(\frac{\sigma}{\alpha}\right)^{1/3} cm^{-3}$$

where $\sigma = n_{clouds}\, \Phi\, a_{pc}$

α is an indeterminate parameter of order unity which is best determined by comparison with the numerical solutions. Setting standard parameters of $f_{wm} = 0.23$, $a_{pc} = 2.3$ and $\Phi = 1$ (or $n_{clouds} = 6 \times 10^{-3}$ Pc^3 to define standard $\sigma = 1.2 \times 10^{-2}$ gives:

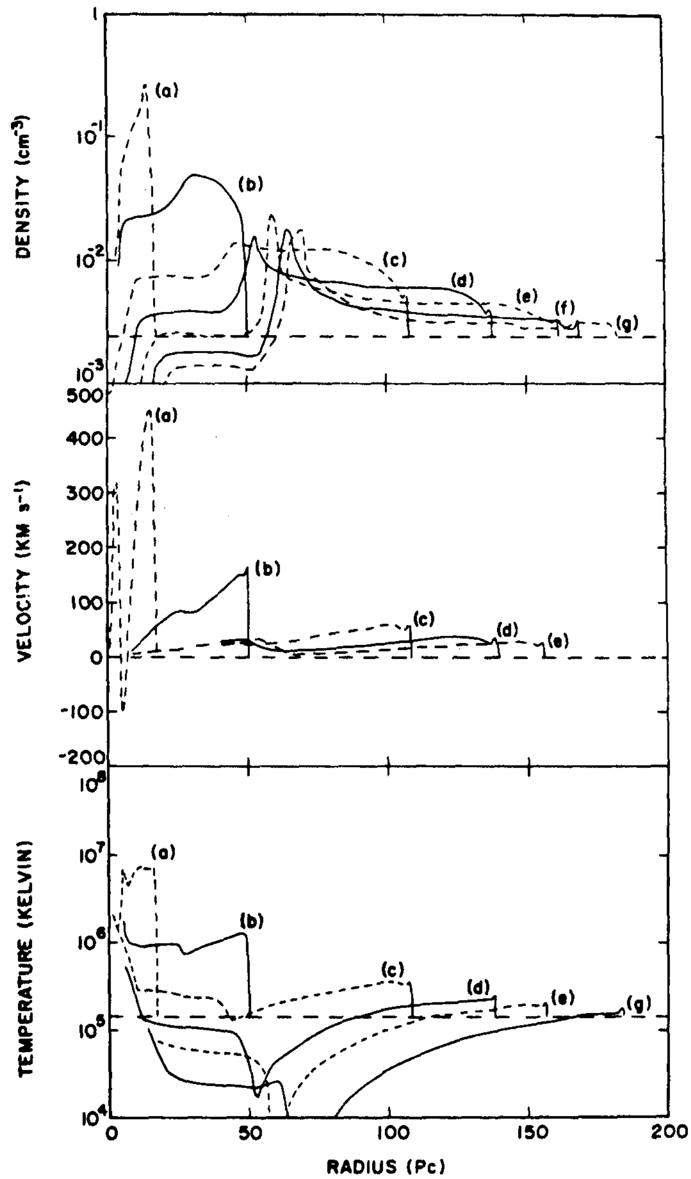

Figure 1 Density, velocity and temperature of hot gas within an evaporative supernova remnant at various timesteps. (From Cowie, McKee and Ostriker 1981). The parameters of the remnant (model 1 of CMO) are discussed in the text. Ages are a = 1.01×10^4 yrs., b = 9.9×10^4 yrs, c = 4.6×10^5 yrs, d = 7.7×10^5 yrs., e = 9.8×10^5 yrs., f = 1.21×10^6 yrs., g = 1.36×10^6 yrs. Stage (b) corresponds most closely to the radius, age and density of the local region, but for the assumed model parameters the density of the hot gas is too high.

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$$n = 40\ R_{pc}^{-5/3}\ E_{51}^{2/3} \left\{ \frac{\sigma}{\sigma\ \text{standard}} \right\}^{1/3}\ cm^{-3}$$

The rapid fall-off in interior density radius and age is another striking difference between evaporative and Sedov models. The final striking difference of the evaporative solutions (and the one I like best) is that they go radiative in the interiors rather than at the edge (c,f, Fig. 1). This is just a consequence of the constant density and temperature profiles, but it is extremely useful because cooling occurs at low velocities. As Ed Jenkins discussed in his presentation, observationally we cannot let cooling occur at high velocities (Cowie and York 1978) because low column density material in ionization stages such as Si III and N II is relatively scarce at velocities much greater than about 50 km S^{-1}. This means in turn that evaporative models can achieve radiation balance in the disk and non evaporative models cannot.

Looking out from the interior of the evaporative supernova remnant, one sees ony a slightly lower emission measure than one would see in a Sedov solution with an ambient density equal to the average interior density. This means that we can draw on the results of Cox and Anderson for example (at least to the degree of some uncertainty in the ionization balance) and that we should have temperatures of about $10^6\ {}^{o}K$, a radius of about 100 Pc, and an average interior density of about $5x10^{-3}\ cm^{-3}$. (We adopt a slightly higher value for the density than Cox and Anderson because the interior density is more uniform.)

This means in turn that we need a σ which is about 15% of my so- called standard value. This is probably mainly caused by inefficiency in the evaporative process (MO suggest = 1/3) but could also correspond in part to the possible local deficiency of material by factors of 2 or 3. The accuracy of the prediction is actually remarkably good however, (and it should be emphasized that it is a prediction).

THE DISTRIBUTION OF WARM MATERIAL

A substantial fraction of the interior of the remnant is cleaned of WM by the supernova remnant. There are three contributory processes:

$$\left.\begin{array}{l} \text{1) WM sweep out} \\ \text{2) WM evaporation} \end{array}\right\} \text{dominate in earlier stages}$$

3) WM compression later stages

The numerical solutions show that the last mechanism is probably dominant by radii of 100 Pc. The rise in pressure by about a factor of four or five reduces the volume of the WM by a corresponding amount given a fixed heating source. However, it does take a finite time to compress, and after entering the remnant, WM "clouds" will remain through a region of approximately

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$$R = \left\{ \frac{n_{WM}}{n_{Hot}} \right\}^{1/2} a \quad \approx 10 \text{ a or rougly 20-25 Pc}$$

The sun probably should lie in this region because the local heliospheric hydrogen and helium measurements suggest pressure of less than 2000 $^{\circ}K\ cm^{-3}$ which is almost an order of magnitude lower than the remnant pressure. (As Ed Jenkins pointed out during the conference, searching for surface motions of this very local WM driven by the remnant pressure might provide a very interesting test of this point. However, as Don Cox pointed out, magnetic field pressure might allow us to avoid it.)

I've illustrated this schematically in figure 2 and initially looking at this one might worry about isoptropy. However, in the Sedov, and to a lesser extent, the evaporative models the outer regions dominate and as long as one is interior to most of the emission, it will appear rougly isotropic.

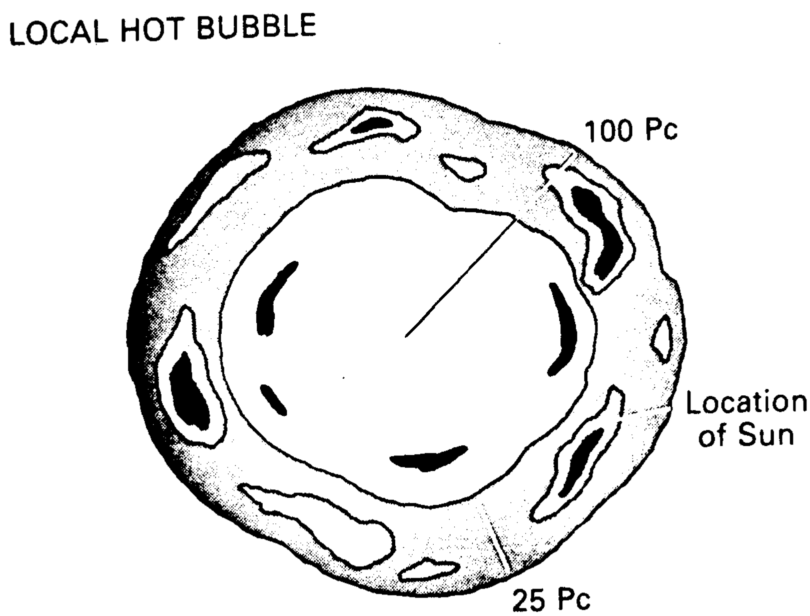

Figure 2 A schematic illustration of the local hot bubble. Cold dense material is shown by the darkest shading and is spread throughout the region. Regions of warm material only survive in the outer regions where they may not yet have come to pressure equilibrium with the hot gas. (The sun is shown as lying in such a region). The density of the hot gas is slightly lower to the center and higher towards the outside edge as illustrated by the uniform shading. The dimensions indicated are quite approximate.

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O VI AS A DIAGNOSTIC OF THERMAL EVAPORATION

Apart from the theoretical considerations about energy balance there is little to choose between the models to this point and to my mind the key diagnostic between evaporative and non evaporative models is the local O VI (Jenkins 1978). Of the eight stars observed by Jenkins, within 100 Pc and tabulated in Table I, three have been detected in O VI with column densities around 10^{13} cm^{-2}; the remaining stars are undetected. (In one or two cases at significantly lower levels.)

TABLE I

LOCAL OVI OBSERVATIONS OF STARS WITHIN 100 PC

	DISTANCE (Pc)	LOG N(OVI) (cm^{-2})	(l,b)
α LEO	25	$\leq$13.4	226,49
α GRU	25	$\leq$12.9	350,-52
η U Ma	30	$\leq$12.4	100,65
α ER3	40	13.1	291,-59
σ SGR	65	$\leq$12.9	10,-12
δ PER	80	$\leq$13.7	150,-6
α VIR	85	13.4	316,51
ζ CEN	100	13.1	314,14

The evaporative model finds it easy to interpret these results. With substantial WM destruction, the O VI arises on the evaporative surfaces of cold clouds or on residual WM clouds. From Cowie, Jenkins, Songaila and York (1980) (CJSY) each cloud has a column density (both surfaces included) of

$$N_{O\ VI} = 6 \times 10^{12} \left\{\frac{\beta}{3}\right\} T_6^{-3/2} \quad a_{pc} \quad n_{-2}\ cm^{-2}$$

where the β factor allows for time dependent ionization effects. For a_{pc} = 2.1 n_{-2} = 0.6, N_{OVI} = 7x 10^{-12} cm^{-2} and intersection of a single cloud can give the positive detections. Sheets with longer dimensions would give a somewhat larger value (Cowie and Songaila 1977) since the OVI column density depends roughly linear on the longest dimension. The measured mean free path to individual O VI regions is roughly 120 Pc, which again suggests some deficiency of cold local material. Apart from accounting for the discrete nature of the detections, this mechanism also nicely accounts for the velocity width and velocity structure of the O VI and its correlation with lower ionization stages (CJSY), as Ed Jenkins has emphasized in his talk. In the final figure (3), I've illustrated this with some examples including the nearby α Vir.

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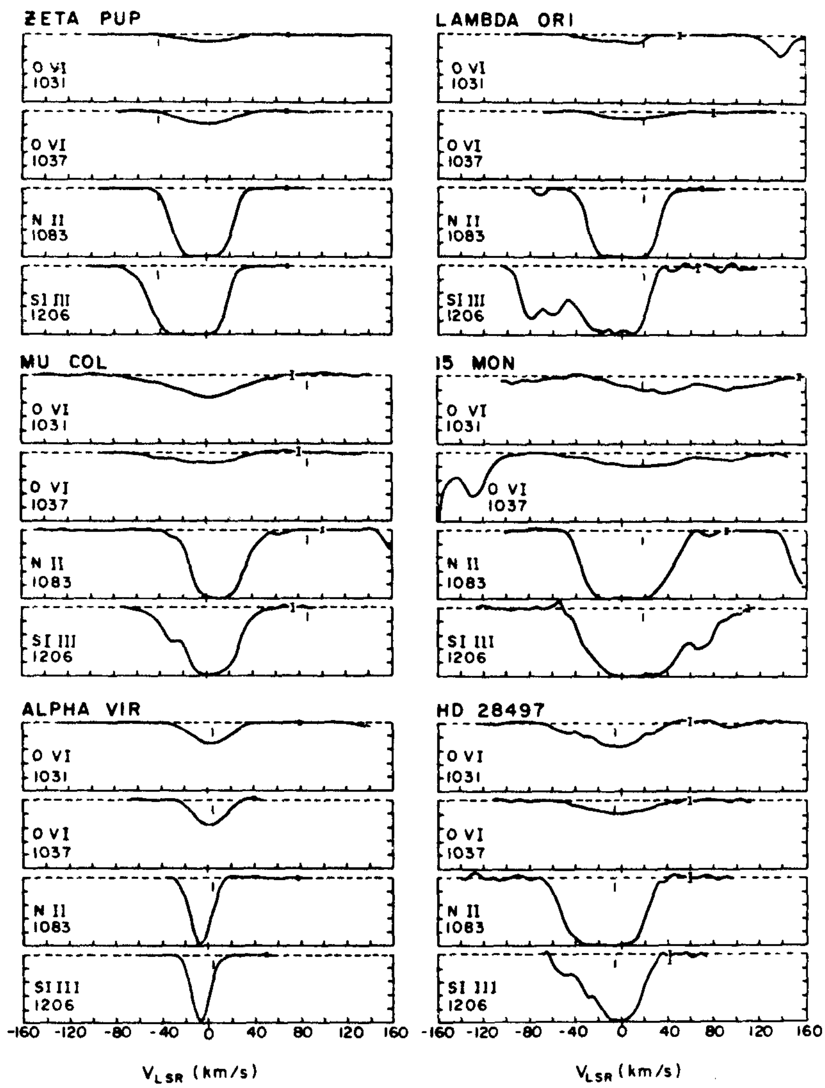

Figure 3 Profiles of OVI lines are shown in comparison with the lower ionization stages (from Cowie, Jenkins, Songaila and York (1980)). All the profiles have been normalized to second order polynomial continua and plotted against LSR velocity. (Wider OVI components could be hidden by this procedure) α VIR lying at 85 Pc has the simplest and narrowest profiles.

The Sedov models get into severe trouble with the OVI, however. There is little OVI production in the interior of the remnant which is too hot and too difuse. If the preshock material is in low ionization stages, one can get enormous amount of OVI in the shock front (C.F. Cox and Anderson 1982), but this would be at velocities of several hundred km s^{-1}. Therefore, stars with observed OVI must lie outside the blast wave and in the ambient material. Fortunately, all the stars with observed OVI do lie to one side so that this interpretation is at least possible, particularly since I have argued above that we may be close to the edge of the remnant. However, there still seems no way to account for the near zero velocity, narrow velocity character of the OVI nor for its correlation with lower ionization stages.

CONCLUSIONS

The conclusions from all of this would seem to be

1. A Multiphase SNR does seem to provide a plausible description of the local ISM.

2. The local region could quite likely have been deficient (by about a factor of 2-3) in cool gas prior to the supernova both on theoretical and observational grounds. However, there are no totally compelling arguments for this as yet.

3. The sun may lie in a region towards the outside of the supernova remnant which hasn't yet come into pressure equilibrium with the hot gas.

4. Evaporative models give a much more satisfactory description of the OVI observations than Sedov Solutions.

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