HEATING OF THE INTERSTELLAR MEDIUM BY SUPERNOVA REMNANTS

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We observe the heating of interstellar material in young supernova remnants (SNR). In addition, when analyzing the soft X-ray background we find evidence for large isolated regions of apparently hot, low density material. These, we infer, may have been heated by supernovae. One such region seems to surround the Sun. This has been modeled as a supernova remnant viewed from within. The most reasonable parameters are ambient density $n_0 \sim 0.004$ cm^{-3}, radius of about 100 pc, age just over 10^5 years (Cox and Anderson 1982).

Besides what is and what may be heated by SNR, there is also that category of what ought to be so heated. The story is by now familiar and not particularly sensitive to who is telling it. The underlying assumptions seem to be few: If supernovae as energetic as several times 10^{50} ergs occur in the Galaxy more frequently than one per 100 years, if the spatial and temporal positioning of the explosions (or a significant subset of them) is fairly random, and if most of the interstellar hydrogen is in clouds, then the picture should be appropriate.

The interstellar volume should be dominated by a low density high temperature matrix. The hot gas should not be gravitationally bound to the disk so should rush outward to form a fountain, a quiescent corona, or a wind (or some combination of the three). Pressure variations in the hot component beat on cloud boundaries and contribute significantly to the heating of low density HI regions. This heating alone is sufficient to sustain a neutral "intercloud" phase with $T \sim 10^4$ K. Finally, the far-reaching SN shockwaves in the hot matrix can potentially accelerate the cosmic rays by mechanisms which seem able to provide both the required power and the spectrum.

The basic idea of this model is that supernovae mechanically heat not only their surrounding matrix material, but also some material which was not previously part of the hot phase. One does not at the outset assume just how much material is heated in this way but there are limits. For example, with an average density of 1 cm^{-3}, there are 1000 $M_\odot$ in a sphere of radius 20 pc. But calculations for SNR evolving

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in a homogeneous medium (so that all mass enclosed is heated) reveal that remnants radiatively cool by the time they heat about 1000 $M_\odot$ $(1\ \mathrm{cm}^{-3}/n_0)^{2/7}$. The insensitivity to density implies that this result will be approximately valid for the inhomogeneous case as well. In order for remnants to reach immense sizes (R > 100 pc) the fraction of enclosed mass which is heated and transferred to the hot phase (the mass acquisition) must be quite small.

Fountain or wind models rely on three basic equations and are inherently two parameter models. One parameter is the supernova power, E_0/τ_{SN}, the other is the mass acquisition rate, $\dot{M}$. The three equations are

$$\frac{5kT}{m} \sim \frac{E_0/\tau_{SN}}{\dot{M}} \qquad (1)$$

(the temperature of the hot phase is just the ratio of energy to mass inputs),

$$\left(\frac{3}{2}\ p\right)\left(2\pi R_g^2\right) c \sim E_0/\tau_{SN} \qquad (2)$$

(the thermal energy is convected out of the plane at its sound speed, $c = (10\ kT/3m)^{1/2}$ where $p = 2nkT$, and finally

$$L(T)n^2(2\pi R_g^2\ H_0) = F\ E_0/\tau_{SN} \qquad (3)$$

where F is the fraction of the energy which is radiated by matrix material while still in the plane. In the equations above, E_0 is the explosion energy, τ_{SN}^{-1} the supernova rate, R_g is the galactic radius, H_0 the plane thickness, p, T, n are the hot matrix pressure, temperature, and number density, respectively, m is the mean nuclear mass, and L(T) is the cooling coefficient which I take to be the usual $L(T) \sim 1.3\times10^{-22}$ $(T/10^6\ \mathrm{K})^{-1/2}$ erg cm^3 s^{-1} approximation (for coronal temperatures) to the collisional equilibrium calculations of Raymond, Cox, and Smith (1976).

In preparation for this presentation I calculated the detailed structure of a one dimensional gas flow approximation for the behavior of this material. I wanted to see just how sensitive the above equations were to detailed choices. The results for the model which I made were that if the equations were to be used to represent conditions in the plane, the right-hand side of equation (1) should be multiplied by 6/5, while the right-hand side of equation (2) should be multiplied by 0.97. In short, the equations are very insensitive to model details.

The flow away from the plane had a sonic point just above the region of SN input. The temperature there was 3/4 of the central plane value, while the pressure was down by a factor of 3. The magnitude of the pressure drop is an interesting find; it is clearly required to accelerate the material to supersonic velocities.

It is useful now to substitute some numbers into the two parameter model to see just how many things fall out. Any two parameters will do and I will use the supernova power E_0/τ_{SN} = 5×10^{50} ergs/50 years and the midplane temperature $T = 10^6$ K. (I also assumed R_g = 15 kpc and H_0 = 100 pc.) The derived properties of the system are then c = 152 km s^{-1}, $\dot{M}$ = 17 $M_\odot$ yr^{-1} (corresponding to 850 $M_\odot$ per SN), $p = 1.0\times10^{-12}$ dyn cm^{-2} (p/k = 7250 cm^{-3} K), $n = 3.6\times10^{-3}$ cm^{-3}, and F = 0.02. That is, the choice of supernova power and any one of the other parameters provides all of the other familiar sounding results above.

Two of the best known models (McKee and Ostriker 1977, hereafter MO, and Cox 1981, hereafter paper II) attempt to provide an understanding of mass acquisition which will reduce the above model to one parameter. The model is then the system response to the supernova rate. In fact, paper II goes on to look for ways in which the system decides its own supernova rate, removing even the last free parameter.

MO use thermal evaporation of clouds as their mass acquisition process. This is extremely temperature sensitive, and operating on the interstellar clouds it offers an additional relationship between T and $\dot{M}$. They went beyond that, however, arguing that in effect, $F \simeq 1$. By making this choice, they already eliminate the second parameter, fixing T, p, n, $\dot{M}$, etc. for a given supernova rate. Their use of thermal evaporation then serves to determine the parameters of clouds required to provide $\dot{M}$ in equilibrium. It also gives a concrete mechanism for maintaining that equilibrium. (Insufficient evaporation raises T which very much raises the evaporation rate.)

One could generalize the MO model by abandoning $F \simeq 1$ in favor of $F \lesssim 1$ in which case it would no longer be overdetermined. It would allow fountains and winds for sufficiently high supernova rates or when there were too few clouds available for evaporation.

It is well-known (to those who know me well) that I have long been suspicious of thermal evaporation. I could visualize far too many processes which would provide tangential magnetic fields along cloud boundaries, among them the prior evaporation of those clouds which did not have such fields. Nevertheless, I came to realize that mass acquisition in some form was necessary for fountain models, because the cooling of material in the fountain removes material from the hot phase at a terrific rate.

In the model in paper II I reasoned that suitable mass acquisition could be achieved mechanically if there were, in addition to the hot matrix, also a warm neutral intercloud medium (something like MO's WNM but heated differently and not necessarily bounding denser cores) which occupied something like half the volume. This intercloud component was fed both by returning fountain material and by mass loss from stars, and it needed to be close to the point of instability for condensing into clouds, so that it could occasionally rid itself of excess material.

This is all the more important if there is a substantial infall of new material into the Galaxy. The mechanical heating rate per unit volume of this material was estimated to equal the supernova power per unit volume. A study of the phase diagram indicated that this material needed to have $T \sim 10^4$ K and that on average the heating had to balance a cooling coefficient $L_d \sim 5\times10^{-25}$ erg cm^3 s^{-1}. (The subscript d refers to destabilization.) Owing to partial magnetic support, the thermal pressure was taken as half the matrix pressure, p. This combination of results implies

$$h \sim E_o/(2\pi R_g^2\ H_o \tau_{SN}) \sim L_d \left(\frac{p/2}{k\cdot10^4 K}\right)^2 . \qquad (4)$$

Also, because it assumes that half the supernova power goes into maintaining intercloud material, and only half the plane volume is in matrix form, there are factor of two changes in parts of each of the first three equations.

Since equation (4) provides one more relationship, the model is reduced to one parameter. Oddly enough, the result is an $\dot{M}$ which is independent of the supernova rate. The matrix temperature is then proportional to the supernova power, while the pressure increases only as the square root, and the density inversely to the square root of supernova power. In any case, a one parameter system is achieved, different from the $F \simeq 1$ model of MO or even the $F \lesssim 1$ generalization of their model.

One or the other of these models would have been dismissed if they weren't each providing about the same results for the supernova rate the Galaxy has. Since they do, it falls to a good hearted squabble among us modelers to resolve the issue.

Meanwhile the Galaxy is telling us some things we should be listening to. One way to picture one of these is to go back to the two parameter model (skirting the issue of how to determine $\dot{M}$) and simply write the general expression for F (the fraction of the SN power radiated in the plane) in terms of combinations of two of the other parameters. The result is

$$\begin{aligned} F &\sim 0.02\ (10^6\ K/T)^3\ (p/10^{-12}\ \text{dyn cm}^{-2}) \\ &\propto (E_o/\tau_{SN})/T^{7/2} \qquad \propto (\dot{M})^{7/2}/(E_o/\tau_{SN})^{5/2} . \end{aligned} \qquad (5)$$

What we have is a parameter which is extremely sensitive, and which also has strong observational restrictions. From the soft X-ray background, we know that the entire background would derive from material with $p = 10^{-12}$ dyn cm^{-2}, $T = 10^6$ K, and path length ~ 100 pc, that is, from material in the plane, while something like 50 times as much emission (for F = 1/50) will derive from the fountain. This factor of 50 is the ratio of what we believe to be the supernova power to the fraction of that power which the soft X-ray background implies is being radiated at 10^6 K.

In short, the bulk of the supernova power is not being radiated by a plasma at 10^6 k, not in a fountain, not in a corona, not in the plane, nowhere. We could see it and we don't. There are only two ways around this within the context of this model. The first, espoused both in MO and in paper II, is that the energy is being radiated at a lower temperature, perhaps 3×10^5 K where it could hide from the X-ray telescopes. From equation (5) it is clear that this option implies large F and both papers essentially espouse $F \sim 1$ with most of the radiation coming from material in or near the plane. The second option is that the energy is not radiated at all. It is instead used to drive material out of the galactic plane. The required value of T is at least 2×10^6 K to get the material out. A higher temperature yet, perhaps 4×10^6 K, is required to prevent greater than observed X-ray emission. This higher temperature is also desirable because it lowers the mass outflow in the wind ($\sim 17\times10^6/T\ M_\odot\ yr^{-1}$) toward more acceptable values.

I personally do not accept the possibility of such a hot wind bearing most of the supernova power. It is certainly not allowed if thermal evaporation is taking place at close to the MO value. It is not allowed if $\dot{M}$ is at the paper II value (although the need for destabilization is also not so pressing in this case). What troubles me more is universality.

Let me restate the situation. If the average supernova heats less than $\sim 100\ M_\odot$, there will be a strong hot wind, probably not too bright in X-rays. If it heats $\gtrsim 1000\ M_\odot$, the energy will be radiated in or near the plane as hard UV and will also not appear too bright in soft X-rays. The intermediate regime is forbidden by observations. It is forbidden for our Galaxy on average, or even as a significant fluctuation. It is forbidden in other galaxies as well, as more and more are found not to show strong X-ray emitting coronae.

That wouldn't be so bad, if we knew that supernovae managed never to heat even $100\ M_\odot$. But they seem to. The Cygnus Loop already has. So we require some mechanism that shuts off acquisition after $100\ M_\odot$, to assure a sufficiently hot wind. Or we need one which assures that it continues beyond $1000\ M_\odot$ to assure dissipation as UV. My lack of acceptance of the hot wind possibility thus derives from my inability to visualize a mechanism which restricts the energy to $100\ M_\odot$ and then liberates that heated gas intact. Despite my prejudice, I would urge caution on this point, however, because the remnants in the LMC seem to show a disturbing tendency to disappear after heating about $100\ M_\odot$. This disappearing act evidences itself as an apparent constant velocity expansion law, since the oldest and most common remnants have about the same expansion rate after interacting with the same mass.

The high mass acquisition end is, however, self-regulatory, particularly in the MO model. Mass acquisition simply remains high until the temperature gets too low. Their model is even stable as regards fluctuations in the supernova rate. Consider equation (5) with $F = 1$. We find that $T^{7/2} \propto (E_0/\tau_{SN})$. But in the MO model, $\dot{M} \propto T^{5/2}$ so $\dot{M}T$ is proportional to the supernova power as in equation (1), with no change required in the required cloud population. The temperature of the hot component is a weak function of supernova power, and hot emissive coronae do not have access to a major part of the SN energy.

This kind of rigidity is not as clear in the paper II model for which $\dot{M}$ is constant, and therefore depends on the additional regulation of the massive star formation and supernova rates.

Returning finally to my original point, for the supernova rate which the Galaxy is thought to have, the hot gas parameters, system pressure, and mass exchange rate are all essentially the same for either the MO model (as herein simplified) or the paper II model, because that information all follows from equations (1) through (3), subject to $F \sim 1$ in the MO case, or equation (4) in the paper II case. Both satisfy the soft X-ray background constraint. The difference between the two (at the given SN rate) is the manner in which $\dot{M}$ is achieved. The MO picture requires remnants to show strong evaporative effects. The paper II picture requires the presence of a considerable amount of warm intercloud material ($n \sim 0.3$ cm^{-3}).

Before closing, there are three other points to which I would like to call attention:

(1) A blast wave model now exists which includes shock heating of electrons and thermal conduction (Edgar and Cox 1983) and will soon be available for nonequilibrium ionization modeling of SNRs.

(2) If cosmic ray acceleration takes place efficiently in shock waves in time scales of 10^5 years, and if the soft X-ray background truly derives from our being inside an explosion remnant with that age, then the locally measured cosmic rays could contain a substantial component of essentially zero age.

(3) If the cosmic ray pressure tracks the variations expected in the thermal pressure in the matrix, either because of efficient acceleration plus localization by scattering, or perhaps even because of localization alone, the expected variations in cosmic ray pressure will be markedly at odds with the apparent near constancy of the cosmic ray flux at Earth over the last few million years (Szentgyorgyi and Cox 1983).

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DISCUSSION

MCKEE: In your model of the ISM you find a mass exchange rate from clouds to the hot matrix of 17 $M_\odot$ yr^{-1} or 850 $M_\odot$ per SNR, which is comparable to the value Ostriker and I obtained. A key question is how this mass exchange affects the evolution of individual remnants; Ostriker and I found rather dramatic effects. What effects do you think the mass exchange has on SNR evolution?

COX: Ach! You're a good man, McKee. You know I'm reluctant to answer that question but maybe you don't know why. I think of the ISM as a very chaotic place about which it is dangerous to be too specific. I think remnants interact with a variety of environments and that getting mass into the low density phase may well be a two step or collective process. I am reasonably certain that we are seeing acquisition taking place as the Cygnus Loop shocks material with ambient density around 0.2 cm^{-3} to something like 3×10^6 K. We see roughly 200 $M_\odot$ which has been so acquired. In the case of the Cygnus Loop, the problem is how to stop acquisition before it goes too far. And for that we need for it to find the matrix phase and to begin propagating in that lower density environment. I'm not sure it has, as yet, and that troubles me.

Roughly speaking, however, my point of view is that when a remnant evolves in the hot phase, it engulfs, pressurizes, and therefore heats intercloud material substantially, as long as $R \lesssim 25$ pc. You have made a calculation of the radiative lifetime of this material and concluded that, if I remember correctly, not enough of it would stay hot until another blast wave happened by. I haven't yet checked that calculation but, given that it is correct, I still am not convinced that acquisition has failed. What is needed is not to keep the material hot (which reverberations might anyway) but to keep it diffuse. It competes for the available volume only with the previous generation of matrix material, which has by then gotten so diffuse that I think we have to rethink the notion that it can be treated as a fluid.

DOPITA: Have your Galactic fountain/corona/wind models taken into account the resultant radial zone mixing that will occur? In view of the relatively large mass transfer occurring now (which may have been still larger in the past) such an effect could be very important in determining the present Galactic abundance gradient.

COX: No. Joel Bregman may have done some work in this area, but I think that by and large one should at present keep this mixing as a free parameter in the chemical evolution models with an eye on the fountain as a possible mechanism. Because of the extreme sensitivity of F to the parameters, the mass flux above the plane could be anything from zero to perhaps 20 $M_\odot$ per year.

FEDORENKO: You have argued that the Sun is situated within a SNR of radius 100 pc. But there are Soviet observations of Lyα from the environment of the Sun of order 20 a.u. They indicate that we are placed in a much denser medium with $n \sim 0.1$ cm^{-3}. How can you resolve this contradiction?

COX: There are a number of observations bearing on this question and the picture which emerges is that the Sun is in a small piece of intercloud material, probably partly ionized, with a temperature $\sim 10^4$ K, density ~ 0.1 cm^{-3}, and radial extent of at most 10^{19} cm. Beyond that, the average neutral hydrogen density is extremely low for a long way. I know that sounds implausible, but one supposes that our little cloud is but one of many. If so, however, their total volume occupation must be quite low, much less than the 1/2 that I have suggested for this component.

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