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LARGE-SCALE EFFECTS OF SUPERNOVA REMNANTS ON THE GALAXY: GENERATION AND MAINTENANCE OF A HOT NETWORK OF TUNNELS

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ABSTRACT

It is found that a supernova rate on the order of 1 per 50 years in the gaseous disk of our Galaxy is sufficient to generate and maintain throughout the interstellar medium a mesh of interconnected tunnels containing very low-density gas. This tunnel system would have $n \lesssim 10^{-2}$ cm^{-3}, $T \sim 10^6$ ° K, very low magnetic field strength, tunnel radii $\sim$ 10 pc, and would occupy roughly half the interstellar volume.

Such a tunnel network may already have been observed in soft X-ray emission, in ultraviolet absorption of O VI against background stars, in the seemingly chaotic distribution of local H I, and in the stringy appearance of velocity-correlated large-scale H I features.

Subject headings: Galaxy, The — interstellar matter — shock waves — supernova remnants — X-rays

In this *Letter* we follow the bulk kinetic energy released by supernovae, going beyond the formation of supernova remnants to its eventual dispersal in and disruption of the gaseous galactic disk.

I. EVOLUTION AND INTERACTIONS OF REMNANTS

First let us review the evolution of an isolated supernova remnant (SNR) with initial energy $\sim 4 \times 10^{50}$ ergs expanding into a homogeneous interstellar medium (ISM) with ambient density $n_0 \sim 1$ cm^{-3}. Studies by Cox (1972*a*, *b*), Chevalier (1973, 1974), Mansfield and Salpeter (1973), and Straka (1974) show that radiative cooling becomes rather suddenly important about 5×10^4 years after the outburst. During this epoch, approximately one-third of the blast energy is radiated in hard ultraviolet and X-ray photons over a period of 10^4 years, and the remnant divides into two distinct components. On the outer boundary there is a very thin, dense, cool ($T < 10^3$ ° K), expanding shell containing most of the swept-up interstellar matter and magnetic field. The radius R of the shell is about 20 pc at this time. Within the cavity bounded by this shell, there is very diffuse, hot material ($T \sim 10^6$ °–10^8 ° K) heated during the early high-velocity expansion of the remnant. The magnetic field strength in this hot interior is probably very low, but the thermal pressure is about 100 times the total pressure of the ambient ISM.

This configuration persists for a long time. The cooling time in the cavity is exceedingly long, and the velocity of the expanding shell is large enough that the hot interior material cannot expand through and ahead of it. The further evolution consists mainly of continued expansion of the shell and adiabatic cooling of the interior. After 10^6 years, the shell will have $R \gtrsim 40$ pc but a velocity of only 10–20 km s^{-1}. The interior pressure approaches $P_{\rm ISM}$, and further expansion is impeded. If this SNR structure does not interact with other remnants, it will eventually disappear by fragmentation of the shell and by replacement of the cooling low-density gas by expanding cooler material from the ISM. Since no process operating in the observed interstellar medium is likely to fill the cavity at a rate exceeding 10 km s^{-1}, it will probably persist for at least 4×10^6 years.

Occasionally the expanding shock front of a new SNR will encounter one of the "bubbles" left by an older remnant. The shock driven by the new remnant will then propagate preferentially into the old cavity, because the ratio of speeds of two strong shocks driven by the same pressure into regions of different mass density is $v_{s1}/v_{s2} \sim (\rho_2/\rho_1)^{1/2}$. The thermal energy remaining in the interior of the new remnant is quickly redistributed between the two; the pair of remnants then have a temperature and pressure comparable to that of an isolated remnant, and their interior will remain hot and diffuse for a comparable time. Significantly, the volume formed by this conjunction is larger than that of an isolated SNR and thus more likely to be struck by yet another supernova shock. Chains and clusters of connected remnants can grow by the extension of this process.

The importance of the growth of such chains can be estimated to first order from the dimensionless parameter

$$q = r\tau V_{\rm SNR} ,$$

where r is the average supernova rate per unit volume, τ is the lifetime of an isolated SNR (the age beyond which it cannot be efficiently reheated if encountered by another strong shock), and $V_{\rm SNR}$ is the average final volume of a remnant. In the limit of low supernova rate and thus low probability for overlapping remnants, the average fraction f of the interstellar volume which is occupied by cavities equals q. Hence in this limit q is analogous to porosity in soil percolation problems (cf. Baver 1948).

Before continuing, we estimate q for our Galaxy taken as a whole. With an assumed supernova rate of 1 per 80 years, and a mean lifetime of $\tau = 4 \times 10^6$ years, the collection of supernovae which should presently have remnants numbers 5×10^4. With remnants of mean radius $R \simeq 40$ pc distributed in a disk of density $n_0 \sim 1$ cm^{-3}, radius 15 kpc, and thickness 200 pc, the isolated cavities would occupy 10 percent of the interstellar volume; i.e., $q \sim 0.1$, with considerable uncertainty since $q \propto R^4$ and (Cox 1973*a*) $R^4 \propto n_0^{-1.7}$. However, even with this modest porosity the probability of overlap of remnants is rather high. A new supernova has probabilities 0.1 of occurring within an existing cavity, $1 - \exp(-8q) = 0.55$ of occurring within 40 pc of the boundary of an existing cavity and subsequently expanding to intersection, and so on.

II. THE TUNNEL NETWORK AND PERCOLATION

In order to investigate statistical and second-order effects in the interactions of remnants and in the growth of chains in our Galaxy, we have developed computer simulations for Monte-Carlo–injected supernovae in an initially homogeneous disk. We have included realistic SNR expansion and propagation of shocks in chains of cavities. The details of these simulations will be discussed in future papers; in general they support the qualitative description below.

When $q \ll 0.1$, overlap probabilities are small. SNRs generally remain isolated, although short chains occasionally grow as statistical accidents, disappearing soon after. At the opposite extreme, with $q \gtrsim 1.0$, overlapping SNRs occupy such a large fraction of the interstellar volume that there is insufficient cool, dense gas to absorb and then radiate away their energy. A galactic wind is formed which disperses the ISM (e.g., Mathews and Baker 1971). Between these extremes lies a range of q for which overlap probabilities and disruption of the gaseous disk are appreciable yet which allows the ISM to be present.

For $0.14 \lesssim q \lesssim 0.5$ (based on the present simulations), chains and clusters of remnants appear frequently and have high probabilities of growth to sizes above which they are so often rejuvenated that they persist indefinitely. These groups of remnants form a substantial network of tunnels through the normal ISM. If q is constant for several growth times (1 growth time $\sim \tau/q$), a steady state will be reached in which the time average of f is a constant. Three related effects moderate the rise of f, parts of the tunnel system being destroyed at a rate which balances the added volumes of new SNRs breaking into tunnels. First, the average of these new volumes decreases with increasing f, because the remnants expand far less than 40 pc before encountering a tunnel. This makes it geometrically difficult for a network of tunnels to occupy more than about half the interstellar volume. It also means that many remnants will not form dense shells by radiating ultraviolet and X-rays in a critical epoch, instead breaking into tunnels and dispersing their energies there. Second, the net conversion of normal interstellar material into hot tunnel gas is stopped when the tunnels are extensive enough that mechanical heating of the ISM is balanced on the average by radiative cooling. The losses by mechanical heating are further increased if the tunnels communicate with hot layers of gas in the expected galactic corona above and below the plane. The third important source of moderation is in the radiative cooling of the tunnel gas itself.

The geometry of the steady-state system of tunnels is affected by several factors. The tension in bent magnetic flux tubes in the walls of young parts of the tunnels will tend to relax the curvature (e.g., Rosenbluth and Longmire 1957), keeping the large-scale magnetic field lines straight and running through the lower-temperature ISM while the tunnels arrange themselves irregularly around the lines. Differential galactic rotation will shear a long-lived tunnel system; bouyancy may distort it in the Z-direction (Jones 1973). All these processes tend to lower the average cross-sectional dimensions of the tunnels while the volume of the system is unaffected. We then expect tunnels to have radii of about 10 pc rather than the 30–40 pc of the early configuration of intersecting SNRs.

The steady state is characterized by percolation of supernova energy through the tunnel system. When a new supernova occurs in this interstellar environment, it forms a remnant which expands, usually until a tunnel is reached. The interior SNR pressure then drives very fast, adiabatic shocks through the low-density tunnel gas to distances of 100–200 pc and much slower, radiating shocks into the tunnel walls, the normal ISM. The tunnels may also serve as channels in which cosmic rays rattle about freely in the low magnetic field, reflecting from and slowly diffusing into and out of the more highly magnetized walls.

We can easily narrow the range of temperatures likely for the tunnel gas. An upper limit is found by realizing that the temperature cannot exceed the averaged internal temperature of an expanding SNR which heats the gas in tunnels, i.e., $T \lesssim 10^6$ ° K. At this temperature, the density in pressure equilibrium with $P_{\rm ISM} \sim 10^{-12}$ dyn cm^{-2} would be about 3×10^{-3} cm^{-3}. Somewhat higher densities and pressures are expected in parts of the network which have recently been shocked. To find a lower limit for T, we equate the cooling time for gas at $P_{\rm ISM}$ to the mean time between reheatings. Using the cooling coefficient of Cox and Tucker (1969) which can be approximated by

$\Lambda \simeq 1.35 \times 10^{-16}$ T^{-1} erg cm^3 s^{-1} for $10^5 < T < 10^7$ ° K, we have

$$t_{\rm cool} \sim \frac{5kT}{\Lambda n_e} = \frac{10(kT)^2}{\Lambda P_{\rm ISM}}$$

$$= 4 \times 10^7 \text{ years} \left(\frac{T}{10^6 \,{}^\circ\,\mathrm{K}}\right)^3 \left(\frac{10^{-12} \text{ dyn cm}^{-2}}{P_{\rm ISM}}\right) .$$

Because $t_{\rm cool} \propto T^3$, there will be a well-defined temperature below which cooling is more rapid than reheating. If it is assumed that heating occurs suddenly and is required to replace all energy normally contained in the network, there is a characteristic volume over which the effects of one supernova can extend. If about three-quarters of the total supernova energy E_0 reaches the tunnels, the reheated volume is such that $\frac{3}{4}E_0 \sim (5/2)fP_{\rm ISM}V$. Thus $V \sim 2 \times 10^{62}$ cm^3 and the mean time between reheatings is $(rV)^{-1} = \tau(V_{\rm SNR}/qV)$, or roughly 10^6 years.

The tunnel system would apparently cool and collapse if $T \lesssim 3 \times 10^5$ ° K. For higher T, radiative cooling of the tunnel gas is effectively negligible.

III. OBSERVATIONS OF OUR GALAXY

Whether our Galaxy as a whole, or any particular region within it, happens to contain a mature tunnel system is purely an observational question. The question, in fact, is twofold: does something like a tunnel system exist; and can we observe the reheating of the system by known supernova remnants? We will address only the first part of the question here.

Establishing the existence of the tunnel system requires two kinds of observations: the tunnel gas at some million degrees must evidence itself in emission, absorption, or both; and the normal ISM (which in this case makes up the walls) must be arranged in chaotic but linear magnetized structures which appear to leave vacant a significant part of the interstellar volume. In addition, the walls must show the effects of occasional heating by shocks. One such effect—that the cooling rate of the observed gas approximately equals the total energy release rate by supernovae—is common to all theories of ISM heating mechanisms (e.g., low-energy cosmic rays or soft X-rays) which depend ultimately on supernovae for their power. This approximate equality is evidently observed; e.g., compare the heating rate predicted herein ($\sim 3 \times 10^{-26}$ ergs cm^{-3} s^{-1}) with the cooling rates in Dalgarno and McCray (1972).

The emission from the hot tunnel gas would appear in the very hard ultraviolet and soft X-rays. The model-independent requirements on distributed gas to produce the observed soft X-ray background in the plane have been calculated by Kraushaar (1973), who finds that $T \approx 10^6$ ° K and $\langle n_e^2 \rangle \sim 10^{-5}$ cm^{-6} are the necessary parameters to generate both the observed spectrum and intensity. Absorption measurements on this gas are only possible in two ultraviolet transitions of O VI (Rogerson *et al.* 1973). In collisional equilibrium at $T \sim 10^6$ ° K, one part in 300 of oxygen is O VI, most being O VII. In the dynamic environment of the tunnels, the gas may be even more highly ionized. In the three stars with measured O VI column densities, the average volume density inferred is $\langle n(\mathrm{O\ VI}) \rangle \sim 10^{-8}$ cm^{-3}. With oxygen and helium abundances relative to hydrogen of 9×10^{-4} and 0.1, respectively, and assuming collisional equilibrium, this implies $\langle n_e \rangle \sim 4 \times 10^{-3}$ cm^{-3}. Taken at face value, this implies a clumping factor $\langle n_e^2 \rangle / \langle n_e \rangle \sim 1$, in agreement with our suggestion that the tunnel phase would occupy a substantial fraction of the interstellar volume. On the other hand, both the generality of the O VI measurements and the ionization state predicted for the tunnels are presently uncertain.

Turning to observations of the normal ISM, a perusal of the pictorial data on H I brightness for high-latitude gas in the local spiral arm (Heiles 1973) suggests that the interstellar H I is grouped into rather large filamentary complexes somewhat like those we expect for tunnel walls. Similarly, van Woerden and Schwartz (1973) have made a study of velocity, dispersion, and brightness correlations of H I features on a closely spaced grid for part of the sky. Their results also show intertwined filamentary structures.

It is of course important to ask whether other tools used to probe the ISM can overlook half the volume being in the tunnel phase. It seems that this gas cannot be distinguished in background continuum emission or absorption (because of the low density and magnetic field in the tunnels) or in pulsar dispersion measures. However, features corresponding to tunnel walls might be visible in ideal cases by radio continuum studies of nonthermal emission, due to the somewhat compressed fields.

In short, the observations appear to permit, perhaps even encourage, but certainly not demand the presence of the tunnel network.

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