THE X-RAY APPEARANCE OF SUPERNOVA REMNANTS IN TENUOUS MEDIA

DENIS F. CIOFFI
Physics Department
North Carolina State University
Raleigh, NC 27695-8202 USA

ABSTRACT. By estimating the X-ray intensities of old supernova remnants in the disk-halo interface, deductions can be made about the ability of isolated supernovae to have created a coronal halo.

1. INTRODUCTION

The relative lack of obscuration to the halo permits some confidence that no high-z supernovae (SNe) have escaped detection in recent human history (500 - 1000 yr), but some halo massive stars (e.g., Tobin, this volume), or Type I's in binary systems, presumably have exploded in the past as SNe. The remnant of SN1006, with galactic latitude $b = 14.°6$, and the Lupus Loop ($b = 15.°0$) are the known supernova remnants (SNRs) with the greatest heights above the plane (Green 1988). Do the more ancient remnants still emit X-rays, and how important are these SNRs to the large-scale structure of the halo?

First consider how the environmental conditions peculiar to the halo affect, in general, the evolution of SNRs. Most importantly, the low density will result in a larger expansion than disk SNRs, with lower interior pressure and lower luminosity. The lower metallicity of the swept material also means a less-luminous remnant. A smaller amount of dust means that infrared radiation will have even less of an effect on the dynamics than it might have for disk SNRs (Dwek 1981). Finally, when compared to the two-dimensionality of the disk (Heiles 1987), the full three-dimensionality of the halo allows a straightforward porosity calculation (§4).

2. THE CALCULATION

In extremely tenuous media SNRs will never evolve beyond the Sedov-Taylor stage (Sedov 1959; Taylor 1950; Cioffi, McKee, Bertschinger 1988, hereafter CMB), but in the disk-halo interface (DHI) the investigation of dynamically old remnants generally refers to SNRs that have made the transition to the radiative stage and formed a cold shell (CMB; see Cioffi [1990] for a simple description of SNR evolution

H. Bloemen (ed.), The Interstellar Disk-Halo Connection in Galaxies, 355–358.
© 1991 *IAU. Printed in the Netherlands.*

Downloaded from https://www.cambridge.org/core. IP address: 3.229.120.26, on 12 Apr 2021 at 01:44:03, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms. https://doi.org/10.1017/S0074180900089294

throughout all stages). Here I sketch the basic physics behind the luminosity calculations, with details to be found in Cioffi and McKee (1988, 1991).

If one can approximate the cooling of a hot gas with a power law in temperature T such that the cooling rate ($\mathrm{ergs\,cm^3\,s^{-1}}$) is proportional to $T^{-1/2}$, then, at time t, the entropy of a parcel of gas that was shocked at time t_s depends only on its initial entropy (i.e., on the speed of the shock at t_s) and on the time interval $t - t_s$ (Kahn 1976). For a gas of cosmic abundances we can make this cooling approximation for $5 \lesssim \log T \lesssim 7.5$. The time t_s thus "flags" all gas elements that were originally at a distance $R_s(t_s)$ from the center of the spherical explosion.

If n_o is the hydrogen density of the ambient medium, and R_s and v_s are the radius and the velocity of the SNR shock, then the volume occupied by those gas elements that have been shocked prior to any chosen time $t_s \leq t$ is given by

$$\mathcal{V}(t, t_s) = \int_0^{t_s} \frac{n_o}{n(t, t'_s)} 4\pi R_s^2(t'_s)\, v_s(t'_s)\, dt'_s;$$

when $t_s = t$, the volume $\mathcal{V}$ equals the total volume of the SNR, $V = 4/3\pi R_s^3$. With a uniform pressure throughout the SNR (CMB), one can find the density $n(t, t_s)$ and then transform from the volume $\mathcal{V}$ to a radius r to produce the profiles $T(r)$ and $n(r)$. The product $n^2 T^{-1/2}$ is proportional to the emissivity, and we introduce a rough spectral dependence by multiplying by $\exp(-\epsilon/k_b T)$, where k_B is Boltzmann's constant and ϵ has been set to $0.1\,\mathrm{keV}$ in this work .

Non-equilibrium ionization will not be important at late times, but including magnetic fields and thermal conduction (see Cox, this volume) will result in a cooler interior, so the luminosities that I calculate here are upper limits.

2.1 Relevant Parameters

The scale heights of the thick disk of Population II stars (Gilmore, this volume), the neutral hydrogen layer (Lockman, this volume), and the ionized hydrogen layer (Reynolds, this volume) are all $\sim 1 - 2\,\mathrm{kpc}$, so in the DHI[1] a SN probably evolves into densities of the order $0.1 - 0.01\,\mathrm{cm^{-3}}$. The mean metallicity (from K giants) is ~ 0.25 solar (Gilmore *et al.* 1989). Burton (1991, this volume) has pointed out that conditions in the outer Galaxy duplicate those in the DHI.

3. X-RAYS FROM DHI SNRS

At densities $\log n_o = 0, -1, -2, -3$, Figure 1 shows the radius $r_{0.1}$ within which the temperature is above $1.16 \times 10^6\,\mathrm{K}$ (i.e., $0.1\,\mathrm{keV}$), as a function of time from the shell formation time, t_{sf} (CMB), to $10 t_{sf}$. Although the radius of the outer shell doubles in this time, $r_{0.1}$ increases by only $\approx 50\%$: the volume increase of the hot gas is less than half the total increase of volume enclosed by the SNR. Figure

[1] OB stars may exist at much greater heights, $z \sim 6\,\mathrm{kpc}$ (e.g., Keenan *et al.* 1986).

Downloaded from https://www.cambridge.org/core. IP address: 3.229.120.26, on 12 Apr 2021 at 01:44:03, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms. https://doi.org/10.1017/S0074180900089294

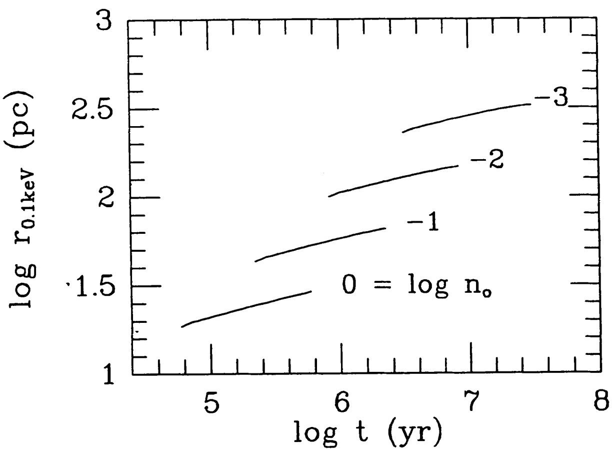

Figure 1. Log radius (pc) within which gas temperature is above 1.16×10^6 K. Merger with ISM probable before large radii shown at $n_o = -3$ dex (CMB).

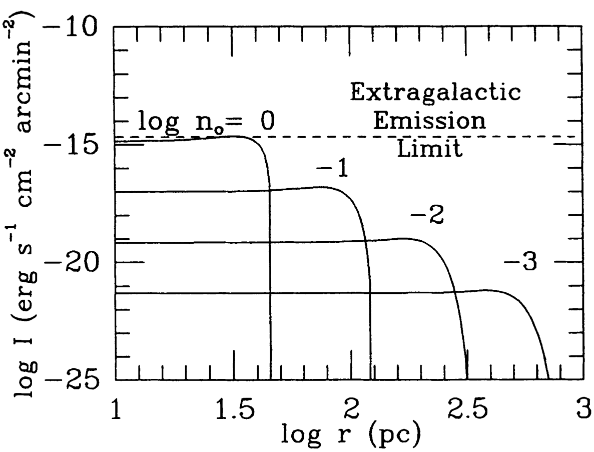

Figure 2. Intensity of old ($t = 10t_{sf}$) SNRs as a function of size. Most are below background. (At a distance of 3.44 kpc, 1 pc subtends 1 arcmin on the sky.)

2 shows the intensity (ergs s^{-1} cm^{-2} $arcmin^{-2}$) across the spherical surface. From Wu *et al.* (1991) the number for the extragalactic X-ray background is also noted.

4. CONSEQUENCES

X-ray luminosity peaks at $t \approx t_{sf}$. Figure 2 indicates that we will not detect older halo SNRs; even if X-ray emission is observed, the lack of substantial limb brightening may prevent recognizing the SNR as a distinct object.

Downloaded from https://www.cambridge.org/core. IP address: 3.229.120.26, on 12 Apr 2021 at 01:44:03, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms. https://doi.org/10.1017/S0074180900089294

A three-dimensional porosity calculation (e.g., Heiles 1987) should use the volume of the hot gas, not the entire SNR. The porosity parameter Q gives the volume fraction of hot gas through $Q/(Q+1)$. Obtaining $Q = 1$ in the DHI would require the volumetric SN rate to be $\sim$ 0.25 times the disk rate (van den Bergh *et al.* 1987), an unlikely number: individual SNRs in the halo will leave behind isolated hot volumes that will not create a global coronal medium.

ACKNOWLEDGEMENTS

"At-home," I thank Eric Sharpe for intensity integrations and Steve Reynolds for many discussions. "On the road," I thank Hans & the L.O.C. for a most pleasant, well-organized, and stimulating meeting, where discussing this particular topic with Mike Shull, Jeff Hester, and Paul Shapiro was both enlightening and enjoyable.

REFERENCES

Burton, W. B. (1991) this volume
Cioffi, D. F. (1990) in *Physical Processes in Hot Cosmic Plasmas*, eds. W. Brinkmann, A. C. Fabian, F. Giovannelli, Kluwer, Dordrecht, p. 1
Cioffi, D. F., McKee, C. F. (1988) in *Proc of IAU Coll. 101, Supernova Remnants and the Interstellar Medium*, eds. R. S. Roger, T. L. Landecker, C.U.P., Cambridge, p. 435
________________________ (1991), in preparation
Cioffi, D. F., McKee, C. F., Bertschinger, E. (1988) *Ap. J.* **334**, 252 (CMB)
Cox, D. P. (1991) this volume
Dwek, E. (1981) *Ap. J.* **247**, 614
Gilmore, G. (1991) this volume
Gilmore, G., Wyse, R. F. G., Kuijken, K. (1989) *Ann. Rev. Astr. Ap.* **27**, 555
Green, D. A. (1988) *Ap. & Sp. Sci.* **148**, 3
Heiles, C. (1987) *Ap. J.* **315**, 555
Kahn, F. D. (1976) *Astr. Ap.* **145**, 50
Keenan, F. P., Lennon, D. J., Brown, P. J. F., Dufton, P. L. (1986) *Ap.J.* **307**, 694
Lockman, F. J. (1991) this volume
Sedov, L. I. (1959) *Similarity & Dimensional Methods in Mechanics*, Academic Press, NY
Taylor, G. I. (1950) *Proc. Roy. Soc. London* **201A**, 159
Tobin, W. (1991) this volume
Wu, X., Hamilton, T., Helfand, D. J., Wang, Q. (1991), preprint
van den Bergh, S., McClure, R. D., Evans, R. (1987) *Ap. J.* **323**, 44

Downloaded from https://www.cambridge.org/core. IP address: 3.229.120.26, on 12 Apr 2021 at 01:44:03, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms. https://doi.org/10.1017/S0074180900089294