

STRUCTURE AND EVOLUTION OF FOSSIL H II REGIONS*

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Abstract

We consider the structure and evolution of a fossil H II region created by a burst of ionizing radiation from a supernova. If 10^{51} erg in UV and soft X-ray continuum radiation are released into a homogeneous gas of density $n_0 = 1 \text{ cm}^{-3}$, the resulting structure is a fully ionized zone of radius roughly 70 pc at temperature $\sim 2 \times 10^5 \text{ }^\circ\text{K}$ surrounded by a partially ionized shell at temperature $\sim 10^4 \text{ }^\circ\text{K}$ extending some 70 pc further. The whole region cools to $10^4 \text{ }^\circ\text{K}$ in about 10^4 years. The fully ionized zone further cools to $\sim 30 \text{ }^\circ\text{K}$ in about 10^5 years, while the partially ionized shell remains at $10^4 \text{ }^\circ\text{K}$. The cooling time scale for the shell is about 10^6 years. We suggest that superposition of million-year-old fossil H II regions may account for the temperature and ionization of the interstellar medium.

Fossil H II regions are unstable to growth of thermal condensations. Highly ionized filamentary structures (scale length ~ 0.1 pc, $T \sim 10^4 \text{ }^\circ\text{K}$) form and dissipate in about 10^4 years. Partially ionized clouds (scale length 1-10 pc, $T \sim 30 \text{ }^\circ\text{K}$) form and dissipate in about 10^6 years.

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I. Introduction

The suggestion that giant relict H II regions, or "fossil Strömngren spheres," are created by supernova outbursts has been put forward recently in several different contexts. Morrison and Sartori (1969) calculated from their He II fluorescence model that approximately 10^{62} ionizing (40 eV) photons would be produced during the visible outburst. Bottcher *et al.* (1970) proposed that the temperature and electron density in the interstellar gas are due to a superposition of fossil H II regions (most of which are about 10^6 years old) that are recombining and cooling; the interpretation requires approximately 10^{62} ionizations per supernova if the mean interval for supernova outbursts in the galaxy is 30 years. Brandt *et al.* (1971) suggested that the Gum Nebula is a fossil H II region created by the supernova outburst responsible for the Vela X supernova remnant and for the pulsar PSR 0833-45. If so, the outburst must have produced of order 10^{62} ionizations at the time that the event occurred, which according to the pulsar deceleration rate was some 1.1×10^4 years ago. Less than one percent of the interstellar matter would have recombined in the time elapsed since the ionization occurred, unless most of the matter is concentrated in dense filaments.

Several of us* at Harvard College Observatory have been working on topics closely related to the structure and evolution of fossil H II regions. Our work can be divided into three closely related problems: (1) the temperature and ionization structure of a region exposed to a "sudden" burst of ionizing radiation; (2) the subsequent time evolution of "fossil H II regions," and the role that such regions play in the ionization and thermal balance of the interstellar medium; and (3) the formation of condensations such as filaments and clouds in this context.

II. Supernovae as Ionization Sources

The mechanism whereby a supernova explosion might create a fossil H II region is a controversial subject. The ionization of the Gum Nebula region requires an energy of at least 3×10^{51} erg ($E_{51} = 3$), and more likely $E_{51} = 10$. In terms of the total energetics of supernovae, this is a reasonable value. If supernovae occur at a rate $(30 \text{ year})^{-1}$ in the galaxy, each one must release about 10^{51} erg in high energy ($\gtrsim 100$ MeV) cosmic rays in order to account for the origin of cosmic rays in the galaxy (assuming an escape time of 3×10^6 years). Also, an interpretation of several supernova remnants according to the spherical blast wave theory suggests that supernovae release between 10^{50} and 10^{51} erg in mechanical energy (Minkowski 1968; Shklovsky 1968).

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There is little evidence that supernovae release comparable energy in ionizing radiation. The observed optical (2-5 eV) output integrated over the light curve of the outburst is typically 3×10^{49} erg. If the spectrum extended out to 500 eV as a flat bremsstrahlung continuum from an optically-thin plasma at 5×10^6 °K, it would release 3×10^{51} erg in ionizing radiation. Color temperatures and bolometric corrections obtained from the optical spectrum are of little value in estimating the ionizing part of the supernova spectrum.

Morrison and Sartori (1969) have suggested, on the basis of a He II fluorescence model for the supernova light curve, that roughly 10^{52} erg in 40.8 eV UV radiation accompanies a type I supernova outburst.

Yet another way in which a supernova might create a fossil H II region is by radiation from the blast wave associated with the remnant (Tucker 1971a). The blast wave converts its mechanical energy ($E_{51} \approx 1$) into ionizing radiation with almost complete efficiency in a time scale of order 3×10^4 years. This process may be occurring now in the Gum Nebula (Tucker 1971b).

It may be that the Gum Nebula region is ionized by low energy cosmic rays instead of radiation (Ramaty et al. 1971). We doubt it, because low energy cosmic rays cannot propagate freely through an H II region (Cesarsky 1971). Their streaming velocity is limited to the Alfvén velocity, and they can propagate only a few parsecs from their source before dissipating their energy.

The physical nature of the supernova outburst is quite uncertain at present. Perhaps, as Ostriker and Gunn (1971) suggest, the outburst is driven electromagnetically by a newly-formed pulsar. At any rate, it seems premature to adopt a firm opinion as to the relative efficiencies of the supernova event in producing ionizing radiation, mechanical energy, and fast particles. Our approach has been to work out the consequences of various models for the ionizing source. We have worked mainly with photoionizing burst models because their consequences can be described with few parameters. However, most of the conclusions discussed in sections IV and V apply also to regions suddenly ionized by cosmic rays.

III. Structure of Photoionized Fossil H II Regions

An ultraviolet or soft X-ray burst that releases an energy $E_{51} \times 10^{51}$ erg of ionizing radiation into an initially cold H I region of hydrogen density n_0 cm⁻³ will create a fully ionized zone of radius roughly

$$R_1 \approx 70 \left(\frac{E_{51}}{n_0} \right)^{1/3} \text{ pc}, \quad (1)$$

containing a mass of roughly $3 \times 10^4 E_{51}$ solar masses. This radius is much larger than the maximum radius (~ 10 pc) of the supernova remnant.

If the duration of the ionizing flux is less than 10^5 years, the zone can be described as "fossil," but it is not a "Strömgren sphere," for two reasons. First, the spectrum of ionizing radiation is not at all like a blackbody spectrum. It may be quite hard, with the consequence that the transition from H II to H I is not a sharp boundary at all, in contrast to the Strömgren case. Also the ionization occurs in a time short compared to the recombination time scale, so that recombinations play no role in determining the structure of the zone. The radius of the zone is set by the total number of ionizing photons emitted during the outburst rather than by the recombination rate.

In order to find the structure of the zone, it is necessary to calculate the ionization (including secondary ionization) and associated heating for each radial distance r . The problem is complicated by the fact that, as the inner zone becomes more ionized, the optical depth $\tau_\nu(r,t)$ decreases with time. If the source spectrum is not monochromatic, the only photons that reach a given radius initially are the hard ones, for which the optical depth is small ($\tau_\nu \propto \nu^{-3}$). Later, the same radius may be exposed to soft photons. The number of secondary ionizations per primary ionization and the heating per ion pair are functions of the primary photon spectrum and of the ionized fraction $x = n_e/n_o$, where $n_o = n_{\text{H I}} + n_{\text{H II}}$ (cm^{-3}). These functions have been calculated in detail by Jura (1971).

We have solved the coupled equations for heating and ionization by a sudden burst for the idealized model of a pure hydrogen gas exposed to various simple source spectra, such as a monochromatic spectrum, power law spectra, and a bremsstrahlung spectrum. The results for the last case provide an interesting example. We find that for R less than R_1 of equation (1), $x \approx 1$ and $T \approx 2 \times 10^5$ °K. The ionized fraction begins to decrease slowly for $R > R_1$, but it is still significant at $R = 2R_1$ where $x \approx 0.05$ and $T \approx 10^4$ °K. The partially ionized region is generally thinner for monochromatic UV spectra or decreasing power law spectra, but the results are otherwise similar. A photoionized fossil H II region consists of a fully-ionized zone at a temperature roughly 2×10^5 °K, surrounded by a thick, partially ionized shell, the temperature of which is above 10^4 °K if $x > 0.05$.

The inclusion of processes involving helium modifies the temperature and ionization structure of the region quantitatively but not qualitatively. Photoionization of trace elements such as oxygen does not significantly change the initial structure of the region, but it does have important effects on the subsequent evolution of the region, as we shall presently see.

IV. Evolution of Fossil H II Regions; Relation to Structure of the Interstellar Medium

To make the calculations described in the last section we assumed that heating and ionization occurred in a time short compared to the cooling and recombination time scales of the gas. Then the structure of the zone after the ionizing burst may be adopted as the initial condition for the subsequent evolution of the fossil H II region.

The power radiated per unit mass by a low density plasma can be written $P = (n_o/m_H)\Lambda(x, T)$. The function $\Lambda(\text{erg cm}^3\text{sec}^{-1})$ for a gas of normal cosmic abundance has been calculated by Cox and Tucker (1969) for $T_4 = T/10^4 \text{ }^\circ\text{K} > 1$, and by Jura (1971) for $T_4 < 1$. It is displayed in Figure 1.

Cooling in the high temperature range ($1 < T_4 < 30$) is dominated by electron impact excitation of atomic lines of H I, He I, He II, multiply-ionized oxygen, and other trace elements. In this temperature range hydrogen is ionized by thermal collisions, so that the free electron concentration is a function of temperature. We may represent this cooling by defining a cooling time scale $\tau_c \equiv T/(dT/dt)$. Very roughly,

$$\tau_c \approx \frac{2000}{n_o} \text{ years}; \quad 1 < T_4 < 30. \quad (2)$$

Kafatos (1971) has shown that the Cox and Tucker results approximate the actual time-dependent cooling fairly well.

Cooling in the low temperature range ($T_4 < 1$) is dominated by electron impact excitation of infrared fine structure transitions in trace constituents such as C^+ , O, and Fe^+ . In this temperature range hydrogen is not thermally ionized. Hence, the ionized fraction of interstellar gas is not necessarily a function of temperature alone. In Figure 1, the cooling rate is plotted for three different values of the ionized fraction x . The cooling at a given temperature is linear with x for $x > 10^{-2}$ because electron impact excitation dominates. In this case, the cooling time scale can be written

$$\tau_c \approx \frac{2 \times 10^4 T_4}{n_o x} \text{ years} \quad 10^{-2} < T_4 < 1. \quad (3)$$

For temperatures below 100°K , the cooling time scale becomes long again. For very low fractional ionizations ($x < 10^{-3}$), the cooling becomes independent of x because impact excitation by neutral hydrogen becomes dominant.

Jura (1971) has pointed out an important effect that has not been fully appreciated. Ultraviolet or soft X-rays may photoionize trace constituents such as C^+ , O , Fe^+ to more highly ionized states which may take a long time to recombine. The usual result of photoionizing the cooling agents is an increase of the cooling time scale, perhaps by as much as a factor 5 above that given by equation (3). This may have a significant effect on the evolution of fossil H II regions.

We may apply these results to the evolution of the fossil H II region described in section III. Consider a medium that has been suddenly heated and partially ionized. The hydrogen recombination time scale $\tau_R \equiv x/(dx/dt)$ is longer than the cooling time scale for all $T < 30^\circ K$:

$$\tau_R \approx \frac{10^5 T_4^{1/2}}{n_0 x} \text{ years.} \quad (4)$$

Therefore, it is a fairly good approximation to assume that the medium will maintain its initial ionized fraction until its temperature drops below $100^\circ K$.

On a time scale that we might call "recent prehistory" ($t < 10^4$ years), only the high temperature material ($T_4 > 1$) has time to cool. In a few times τ_C (equation 2), all matter that was initially hotter than $10^4^\circ K$ will cool to roughly $10^4^\circ K$, with no significant recombination. This would be the case for the Gum Nebula, for which $t = 1.1 \times 10^4$ years (Reichley, Downs, and Morris 1970).

Cooling of the fossil H II region below $T_4 = 1$ (equation 3) occurs on a longer time scale which varies according to the initial ionized fraction x . Jura (1971) has calculated time-dependent cooling and recombination curves for initial temperature $T_4 \approx 1$ and various initial ionized fractions x , including the effect of ionizing trace elements, which lengthens the cooling time scale. With a density $n_0 = 1 \text{ cm}^{-3}$, the inner, fully ionized zone will cool to roughly $30^\circ K$ and begin to recombine within 10^5 years, while the outer, partially ionized zone remains at $T_4 \approx 1$. On a still longer time scale, which we might call "Pleistocene" ($t \approx 10^6 - 10^7$ years), the outer shell will also cool to $30^\circ K$.

Bottcher *et al.* (1970) suggested that these "Pleistocene" fossil H II regions play a major role in keeping the general interstellar medium heated and partially ionized. The argument is simple: every time an ionizing burst occurs, it sets up approximately $3 \times 10^5 E_{51}$ solar masses of interstellar matter in a hot ionized condition. This matter then begins to cool and recombine. The frequency of supernova outbursts in the galaxy (Shklovsky 1968) is roughly $(30 \text{ years})^{-1}$. If we assume the same frequency for ionizing bursts, each with $E_{51} = 1$, we have $10^3 M_\odot/\text{year}$ interstellar matter returned to the initial condition. The total

galactic content of interstellar matter is roughly $2 \times 10^9 M_{\odot}$, which means that any given region of the galaxy is likely to be cycled back to the initial condition after a time scale of order 2×10^6 years. Accordingly, most of the interstellar medium at present would be composed of Pleistocene fossil H II regions.

A model for the interstellar medium composed of a superposition of these regions would have a distribution of temperature and ionization that agrees reasonably well with observations. The central regions would have $x \approx 10^{-2}$, $T \approx 30^{\circ}\text{K}$, and the outer shells would have $x \approx 10^{-1}$, $T \approx 10^4$ °K. Very little matter would be expected with 10^2 °K $< T < 10^3$ °K, because the time to cool through that temperature range is short, according to equation (3). The resulting sharp division of temperature that occurs in a fossil H II region model for the interstellar medium will resemble that in hydrostatic models in which clouds and intercloud medium are maintained in thermodynamic balance by a hypothetical flux of low energy (~ 2 MeV) cosmic rays (Field, Goldsmith and Habing 1969; Hjellming, Gordon and Gordon 1969; Jura 1971) or ionizing photons (Habing and Goldsmith 1971; Bergeron and Souffrin 1971; Jura 1971).

The earlier time-dependent model of Bottcher et al. (1970) for the interstellar medium did not agree very well with observations because the authors assumed that ultraviolet bursts created fully ionized zones, which cool too fast. For that reason, Jura (1971) proposed cosmic rays as an additional source of heating. The model described here, in which a substantial part of the H II region is partially ionized by soft X-rays, fits the observations better than that of Bottcher et al. Such a soft X-ray burst model was first suggested by Werner, Silk and Rees (1970).

All models for heating and ionizing the interstellar medium have difficulties. It is doubtful that a spatially homogeneous flux of low energy cosmic rays can exist (Bottcher et al. 1970). The observed soft X-ray background fails by at least one order of magnitude to provide the necessary flux (Silk and Werner 1969). Discrete X-ray sources also seem inadequate. If the galaxy contained X-ray stars in sufficient quantity to heat the medium, we should see roughly 50 sources brighter than Sco X-1. Given these circumstances, it is gratifying to see in the Gum Nebula fossil H II region at least one observed member of a class of sources that is potentially capable of ionizing and heating the interstellar medium to the necessary degree. Indeed, a Gum Nebula ($E_{51} = 10$) type event every 30 years would provide too much heating and ionization.

We have not considered possible fluid motions, despite the fact that the fossil H II regions will have pressures that are two or three orders of magnitude greater than their surroundings. The associated pressure gradients can move matter at velocities comparable to the sound velocity c . Substantial changes in

density over a scale length λ can occur in a time $t_3 \sim \lambda/c$. For scale lengths typical of the model fossil H II regions described here ($\lambda \sim 20$ pc), $t_3 \simeq 2 \times 10^6 T_4^{-1/2}$ years. This time scale is long compared to most cooling time scales associated with fossil H II regions. As a result, large scale fluid motions that occur during the cooling time scale of the medium have little effect. We may therefore assume that, on a large scale, the region cools at constant density (isochorically). The partially ionized shell may be an exception; the shell may expand (both inward and outward) substantially as it cools.

V. Thermal Condensations in Fossil H II Regions; Formation of Filaments and Clouds

Perhaps the most interesting type of fluid motion that occurs in fossil H II regions involves density perturbations of scale length smaller than that of the region. Matter that is set up in an initially hot condition and subsequently cools by radiation almost always favors the growth of thermal condensations. Regions of enhanced density cool faster than their surroundings, and condense further as the medium attempts to maintain pressure equilibrium. Gravity plays no role in the initial development of these condensations – only thermal pressure is effective. This process provides a natural mechanism whereby fossil H II regions can spawn filaments and clouds.

In order to study the growth of the condensations, we have modified the linearized theory of thermal instability (Field 1965) to take account of the fact that the fluctuations are departures from a nonequilibrium initial state (the isochorically cooling region). In this case, density fluctuations can grow in a time comparable to the cooling time scale whenever the slope of the cooling curve $s \equiv d \ln \Lambda / d \ln T$ is less than 2. (By contrast, Field's analysis of development of perturbations from an initial state of heating balanced by cooling requires $s < 1$ for instability.) Figure 1 shows that, except for narrow temperature bands near $T = 10^4$ °K, and below about 30°K, our model region favors the growth of thermal condensations.

Condensations that result from high-temperature cooling (equation 2) and those that result from low-temperature cooling (equation 3) will grow in two different time scales, and will be characterized by different length scales. The linearized theory shows that isobaric perturbations of all wavelengths λ less than $\tau_c c$ grow at nearly the same rate. Perturbations of longer wavelength grow more slowly. Physically, we can see that the condition $\lambda < \tau_c c$ is necessary for the condensation to develop isobarically, since pressure equilibrium is re-established in the sound travel time across the condensation. This time must be small compared to the cooling time. We may apply these general considerations

to formation of condensations in fossil H II regions in (a) the inner, fully ionized central region: $x = 1$, $T_0 \approx 2 \times 10^5$ °K, $n = n_0$; and (b) the outer, partially ionized shell: $x < 1$, $T_0 \approx 10^4$ °K, $n = n_0$.

In case (a), condensations with a scale length roughly $0.1/n_0$ pc will grow in the cooling time scale $2000/n_0$ years. The growth of smaller condensations is suppressed by thermal conduction. The condensations can reach a maximum density enhancement of order 10, and they remain highly ionized at a temperature 10^4 °K. We expect these condensations to dissipate in a time scale comparable to their formation time scale. A condensation that cools to 10^4 °K before its surroundings will remain at that temperature while the surrounding medium also cools to 10^4 °K, because of the abrupt increase in cooling time scale. The condensation will then expand in order to re-establish pressure equilibrium.

Some of the filamentary structures in the Gum Nebula may be a manifestation of this process (but not the filaments associated with the Vela supernova remnant, which must be related to mechanical shock waves). If there is a fossil H II region surrounding the Tycho supernova remnant, as Kafatos and Morrison (1971) suggest, we do not expect to see filamentary structures in it, because the filaments have not had enough time to form.

On the longer time scale associated with cooling below 10^4 °K (case b) the gas is again unstable to growth of condensations, but the scale length is considerably larger than for case (a). The maximum scale length of a condensation is roughly $\lambda_m \approx 0.5/n_0 x$ pc, typical of interstellar clouds. The larger clouds will be formed in the outer shell of the fossil H II region, where the initial ionized fraction x is less than one. The clouds cool to about 30°K and reach a maximum density enhancement of order 100. At that point the instability shuts off ($s > 2$), and the clouds begin to dissipate again.

The formation of interstellar clouds is a natural consequence of the fossil H II regions. Clouds will be transient phenomena that are formed and then dissipated in time scales of the order of millions of years.

A number of important questions remain concerning the morphology of thermal condensations. For example, in case (b) the growth rate is approximately constant for a range of wavelengths from $10^{-2} \lambda_m$ to λ_m . We are not sure to what extent a condensation that starts with a wavelength λ_m will fragment into subcondensations as it forms. Two-dimensional instabilities might also cause fragmentation when the condensation becomes nonlinear. We do not know to what extent condensations will tend to be one-, two-, or three-dimensional. A preferred axis provided by, say, a magnetic field or an initial temperature gradient may cause the condensations to form in sheets. These questions can be

answered properly only by nonlinear hydrodynamic calculations, which have yet to be performed.

Fragmentation does not prevent the condensation process from running its course and forming clouds at 30°K. However, our discussion suggests that the structure of such clouds will be complicated.

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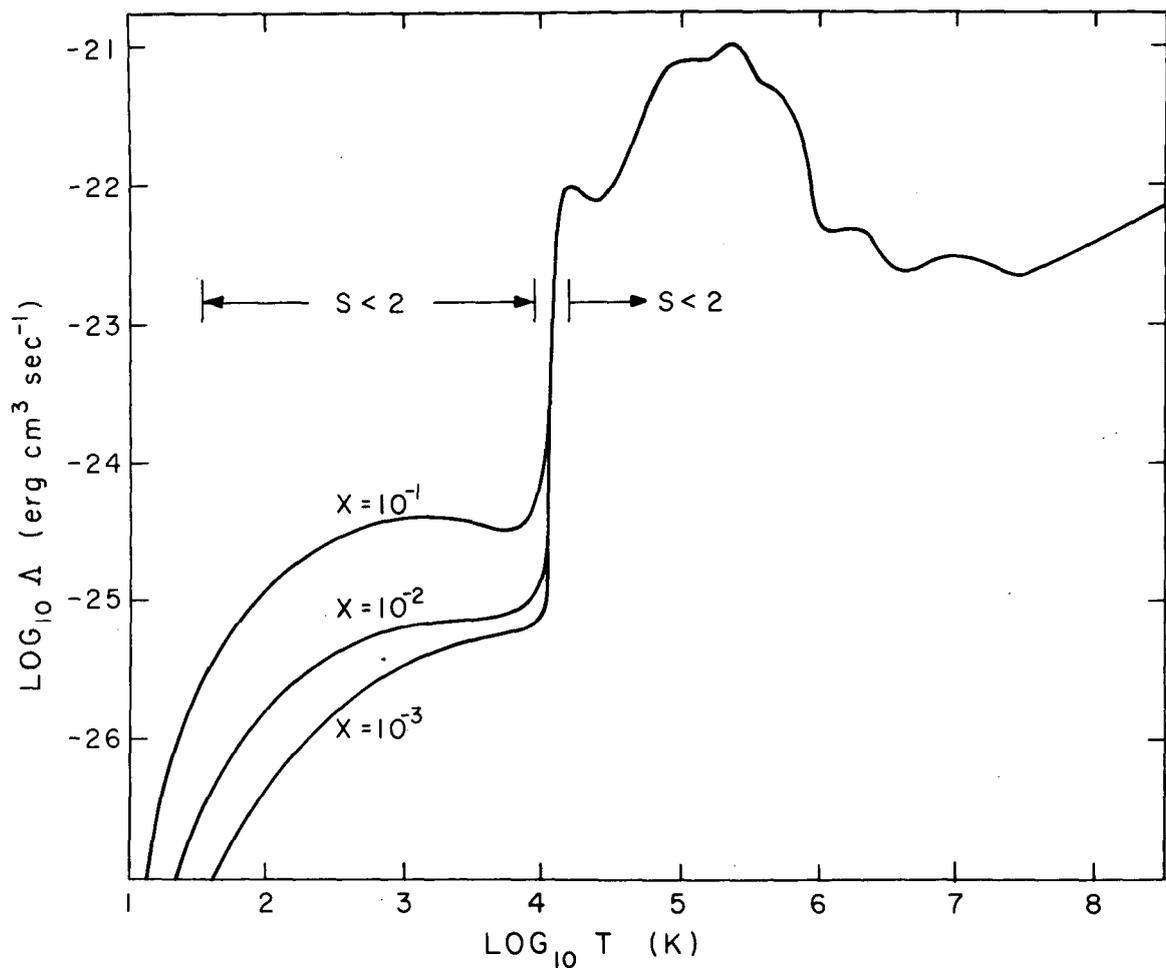


Figure 1. Cooling of a low density plasma with cosmic abundances. The power radiated per unit mass is given by $p = \frac{n_o \Lambda}{m_H}$. For $\log T < 4$, Λ is given for three values of the ionized fraction $x = n_e/n_o$. Temperature ranges favoring thermal condensation (logarithmic slope $s < 2$) are indicated.

DISCUSSION

T. L. Page: On this model, the center of the Gum Nebula would not yet be cooler than the outer region?

R. McCray: No, on the 10,000-year time scale it is still in the high-temperature cooling regime. The interior would probably still be somewhat hotter.