FORMATION OF FILAMENTS IN FOSSIL H II REGIONS

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ABSTRACT

Ionized filaments of temperature $\sim 10^{4.5}$ K and density contrast $\sim 10:1$ are formed by thermal instability in a low-density optically thin medium which cools radiatively from an initial temperature $\sim 10^{5.5}$ K. Typical scale lengths are $\sim 0.1/n_0$ pc. The outlying filaments of the Gum Nebula may result from this mechanism.

Field (1965) pointed out that low-density, optically thin gas which is radiatively cooling is unstable to the development of thermal condensations provided that the logarithmic derivative of the cooling rate $s \equiv d \log \Lambda(T)/d \log T < 2$, where $n_0 \Lambda(T)$ is the rate of radiative energy loss per particle (ergs s$^{-1}$). This condition is satisfied for a gas of cosmic abundance in two temperature ranges, $30^\circ$ K $< T < 8200^\circ$ K, and $T \gtrsim 15,000^\circ$ K. McCray and Schwarz (1971) suggested that the thermal instability could be responsible for the formation of H I clouds and of H II filaments subsequent to a sudden heating of the interstellar medium, perhaps as a result of a supernova explosion. Schwarz, McCray, and Stein (1972) performed detailed calculations of development of H I condensations in a gas cooling from $8200^\circ$ K to $\sim 30^\circ$ K. In this Letter we discuss the development of H II condensations subsequent to a supernova explosion which ionizes and heats the neighboring interstellar medium to a very high temperature ($T > 10^{5.5}$ K), and we apply our results to the Gum Nebula.

Thermal instabilities grow on a timescale of order of the radiative cooling timescale $\tau_c \equiv T |dT/dt|^{-1} = (3/2)kt/n_0 \Lambda(t)$, provided that the wavelength $\lambda_i$ of the initial perturbation obeys the relation $\lambda_{\text{min}} < \lambda_i < \lambda_{\text{max}}$. The limit $\lambda_{\text{max}}$ is set by the requirement that the time for a sound wave to propagate across the condensation be less than the cooling timescale: $\lambda_{\text{max}} \approx c\tau_c$, where $c$ is the sound speed. Thermal conduction suppresses the development of condensations of sufficiently short wavelength, $\lambda_i < \lambda_{\text{min}}$, that thermal conduction heating can replenish the radiative cooling: $\lambda_{\text{min}} \approx (K\tau_c/kn_0)^{1/2}$, where $K$ is the thermal conductivity (Field 1965). In a sheet-like condensation, the maximum density enhancement is $n_{\text{max}}/n_0 \approx T_i/T_{\text{min}}$, where $n_0$ and $T_i$ are the initial ambient density and temperature, $n_{\text{max}}$ is the maximum density of the condensation, and $T_{\text{min}}$ is the temperature at which the thermal instability shuts off ($s = 2$). The final thickness of the condensation is $d_f = (n_0/2n_{\text{max}})\lambda_i$.

A supernova may ionize and heat a region of the interstellar medium large compared to its remnant by a burst of ultraviolet radiation (Morrison and Sartori 1969; Kafatos and Morrison 1971), X-rays (Werner, Silk, and Rees 1970; McCray and Schwarz 1971; Schwarz 1972) or low-energy cosmic rays (Ramaty et al. 1971), or by radiation from the shock in a rapidly expanding supernova shell (Tucker 1971). Such radiation can heat the gas to high temperatures ($T \gtrsim 10^{5.5}$ K). For example,
Schwarz (1972) has calculated the initial radial distribution of temperature and ionization resulting from a burst of monochromatic X-rays. According to his calculations, an X-ray outburst of \( \sim 5 \times 10^{52} \) ergs in an initially neutral medium of hydrogen density \( n_o = 0.3 \) cm\(^{-3}\) would yield a fully ionized region extending to a radial distance of \( \sim 150 \) pc which has \( T \approx 3 \times 10^{5^0} \) K for 100-eV X-rays. In a gas which cools from such high initial temperatures, small initial perturbations must condense into ionized filaments.

The conjecture that supernova events may be accompanied by an energetic \(( \geq 10^{51} \) ergs) burst of ultraviolet, X-rays, or cosmic rays is supported by observations of a giant H II region surrounding the Vela pulsar PSR 0833-45 (Brandt et al. 1971), and especially by the low-frequency radio observations which suggest a temperature \( \geq 5 \times 10^{4^0} \) K in the surrounding region (Alexander et al. 1971). The Gum Nebula, which is a system of filaments at a distance up to 200 pc from the Vela supernova remnant and pulsar, is centered approximately on the pulsar and is apparently causally related to the supernova event which probably occurred about \( 10^4 \) years ago. No blast wave of reasonable energy could have propagated such a great distance in that time.

We suggest that the filaments comprising the Gum Nebula were produced by time-dependent thermal instability as the gas cooled after sudden heating and ionization by the supernova outburst. Table 1 gives values for the cooling timescale \( \tau_c \), the minimum and maximum wavelengths, \( \lambda_{\text{min}} \) and \( \lambda_{\text{max}} \), of perturbations which can grow rapidly, and the density enhancement, \( n_f/n_i \), for various initial temperatures \( T_i \), assuming \( n_o = 0.3 \) cm\(^{-3}\). The cooling timescales, \( \tau_c \), were derived from time-dependent cooling rates calculated by Kafatos (1972). The thermal conductivity for a fully ionized gas is \( K = 1.2 \times 10^{-6} T^{5/2} \) (Spitzer 1962).

Brandt et al. (1971) have estimated a filling factor \( \langle n_e^2 \rangle / \langle n_e \rangle^2 \approx 65 \) by comparing the H\( \alpha \) emission measure with the pulsar dispersion measure. This value is roughly in accord with the density contrast expected from thermal instability.

A magnetic field will affect the shape of thermal condensations. In the case of condensations in a low-temperature \(( T < 8000^0 \) K) gas, the magnetic pressure is comparable to the interstellar gas pressure. Because the magnetic field is frozen into the partially ionized gas for a time greater than the cooling time, condensations perpendicular to field lines are suppressed (Goldsmith 1970; Defouw 1970). The resulting condensations therefore tend to be in the form of sheets perpendicular to the field. In contrast, the high-temperature gas considered here probably has a pressure greater than the magnetic pressure—e.g., for \( B = 3 \times 10^{-6} \) gauss, \( n_o = 0.3 \) cm\(^{-3}\), \( T = 3 \times 10^{5^2} \) K, we have \( P_o/P_m \approx 30 \). Therefore, to a first approximation the dynamic effect of the magnetic field can be neglected.

<table>
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<th>TABLE 1</th>
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<td>GROWTH TIMES, UNSTABLE WAVELENGTHS, AND FINAL DENSITY CONTRASTS</td>
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<td>FOR FILAMENT FORMATION IN A MEDIUM OF DENSITY ( n_o = 0.3 ) cm(^{-3})</td>
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| PARAMETER | \( T_i(\circ K) \) |
| --- | --- | --- | --- |
| \( \tau_c \) (years) | \( 10^4 \) | \( 3 \times 10^6 \) | \( 6 \times 10^6 \) |
| \( \lambda_{\text{min}} \) (pc) | 0.1 | 0.5 | 3.6 |
| \( \lambda_{\text{max}} \) (pc) | 0.3 | 0.8 | 4.4 |
| \( n_f/n_i \) | 7 | 20 | 40 |
However, the magnetic field drastically reduces the thermal conductivity and hence $\lambda_{\min}$ perpendicular to the field. Using a formula from Field (1965), we find that $K_{\perp}/K_{\parallel} \approx 10^{-16}$ for typical interstellar parameters. According to table 1, a very limited range of wavelengths $\lambda_{\parallel}$ will condense parallel to the field, but all wavelengths $\lambda_{\perp}$ less than $\lambda_{\max}$ can condense perpendicular to the field. We conclude that large-scale condensations (initial wavelengths $\lambda = \lambda_{\max}$) have shapes affected only slightly by the magnetic field, but that fine-scale condensations (initial wavelengths $\lambda_{\perp} < \lambda_{\min}$) must be in the form of spaghetti aligned along the field. Observations of fine-scale structure in filaments may offer the possibility of determining the local magnetic-field orientation.

If in fact the filaments of the Gum Nebula are a result of the mechanism described here, we expect them to dissipate in a timescale comparable to their formation timescale, about $10^4$ years. As the gas between the filaments also cools to $10^{4.5}$ K, the filaments will expand to maintain pressure equilibrium. Then, on a much longer timescale ($\sim 10^9$ years), H I condensations may also form and dissipate again as a result of the supernova outburst (Schwarz et al. 1972).

REFERENCES
Kafatos, M. C. 1972, private communication.

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