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# EVOLUTION OF PRIMORIDAL GAS CLOUDS

FINAL TECHNICAL REPORT

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## ABSTRACT

The dynamical, chemical, and thermal evolution of zero-metal gas clouds has been modeled to study conditions of star formation in the early universe. Numerical results are given for the collapse of spherical clouds of mass $10^4$ and $5 \times 10^5$ $M_\odot$. Cooling by $H_2$ lines and by photons emitted in $H + e^- \rightarrow H^- + h\nu$ maintains collapse until formation of an equilibrium protostellar core of mass 0.02 $M_\odot$. The cooling by photons produced with H  is essential for low-mass star formation. If the cloud is fragmented, the evolution of the pieces is similar to that of the parent cloud, but the equilibrium core has larger density and mass.

## I. BACKGROUND

The objective of the work performed under this NASA/Ames-UCSC Cooperative Agreement has been to numerically model the collapse and cooling of gas clouds containing hydrogen and helium but no heavier elements. This composition is chosen to represent the early universe following Big Bang nucleosynthesis, for which theoretical chemistry calculations predict a composition of 75 percent hydrogen and 25 percent helium with only a small fraction ($\sim 10^{-9}$) of heavy elements, i.e. "metals" (Wagoner 1973). The basic questions addressed by our work are whether stars can form as gravitational condensations within this gas and whether their masses and evolutionary histories differ from those of objects with the higher metal abundance characteristic of our galaxy today. A fundamental problem has been that stars completely devoid of the heavier elements are not seen: the smallest metal abundance observed in our Galaxy and its globular clusters is about $10^{-5}$. This has led to speculation that the first generation stars were all sufficiently massive (>1 $M_{\odot}$) to have completed their evolution by the present epoch, and therefore it is of interest to inquire whether there are theoretical arguments favoring the formation of massive stars.

A lower limit to the mass of gravitationally unstable perturbations in a homogeneous, static medium is the Jeans mass $M_J$, which varies with density and temperature as $M_J \sim T^{3/2}/n^{1/2}$ (Jeans 1928). A commonly employed model for the formation of galaxies and stars is the process of hierarchical fragmentation in which the background medium forms unstable condensations of progressively smaller size (see, e.g., Hoyle 1953). The gravitational energy of a collapsing condensation is converted ultimately to thermal energy, and if there is no means for cooling the gas, the temperature will increase as $n^{2/3}$, and the Jeans mass will increase as $n^{1/2}$. Thus for continued fragmentation the gas must radiate sufficient energy that the temperature increases more slowly than $n^{1/3}$. This may occur through collisional excitation of atoms or molecules followed by photon emission, but the excitation energies of atomic hydrogen and helium are so large that these species cannot cool the gas until the temperature approaches $10^4$ K. If, however, a sufficient fraction of the hydrogen exists as $H_2$, the gas can radiate at and therefore maintain a much lower temperature through the excitation of low-lying rotational and vibrational states.

It is widely assumed that molecular hydrogen is formed on dust grains within the dark clouds of our Galaxy, but it is difficult to envision grains in a gas without heavy elements. Mechanisms for forming $H_2$ in the primordial gas must be quite different from those acting today. The direct radiative association

$$H + H \rightarrow H_2 + h\nu \qquad (1)$$

is too slow for significant $H_2$ production within the present age of the universe (Gould and Salpeter 1963), but residual ionization from the Big Bang may have allowed production by ion-neutral reactions. Peebles and Dicke (1968), Takeda, Sato, and Matsuda (1969), and Hirasawa, Aizu, and Taketani (1969) showed that the reactions

$$H + e^- \rightarrow H^- + h\nu \qquad (2)$$
$$H^- + H \rightarrow H_2 + e^- \qquad (3)$$

yield an $H_2$ fraction of $10^{-3}$ during collapse to density $10^8\ cm^{-3}$. At higher densities Palla, Salpeter, and Stahler (1983) find that the three-body reactions

$$H + H + H \rightarrow H_2 + H \quad (4)$$
and
$$H + H + H_2 \rightarrow H_2 + H_2 \quad (5)$$

eventually convert almost all of the hydrogen to molecular form.

Prior to recombination, density fluctuations in the expanding universe are dissipated by radiation pressure, but following the decoupling of matter and radiation at $T \sim 4000$ K, $n \sim 10^4$ cm$^{-3}$, bound clouds can form and contract to high density (Peebles and Dicke 1968). Hutchins (1976) has modeled density perturbations which expand with but more slowly than the background universe for a time $t_m$ and then collapse. Both the perturbation and the background are assumed to evolve as Friedman models, characterized by a parameter $\Omega$ which determines whether the model is open, flat, or closed. Standard cosmological equations are solved for the background density and temperature and the density of the perturbation as functions of time. The temperature of the perturbation is derived from the rate of heating due to Thomson scattering of background radiation. Hutchins gives expressions for density, temperature, and electron concentration within the perturbation as functions of $t_m$ and $\Omega$. Comparable calculations have been performed by Matsuda, Sato, and Takeda (1969) and by Lepp and Shull (1983). Results from these calculations may be used as initial conditions for studies of the later phases of cloud collapse.

The collapse of gravitationally bound clouds in the post-recombination epoch has been studied by several investigators, all employing quite similar physical assumptions. In general the cloud has been taken as spherical and uniform with its evolution governed by (1) pressure-free Newtonian collapse; (2) $H_2$ formation by one or both of the reaction sets given above; (3) LTE excitation and optically thin emission from $H_2$ and $H^+$; and (4) energy balance employing spatially averaged temperature and density. Semiquantative descriptions of collapse based on comparison of free-fall, $H_2$-formation, and cooling times are given by Yoneyama (1972) and Silk (1977). Numerical integration of equations describing processes 1-4 has been performed by Saslaw and Zipoy (1967), Matsuda, et al. (1969), Hirasawa (1969), Hutchins (1976), Carlberg (1981), Palla et al (1983), and Lepp and Shull (1983). Some modifications to the general method have been the inclusion of a pressure gradient (Matsuda et al.) and the use of an escape probability (Carlberg) or Planck function (Palla et al.) for optically thick emission.

These various studies have yielded qualatatively similar descriptions of cloud evolution, but considerably different predictions for the minimum Jeans mass reached during collapse. In clouds with initial temperature $10^2$ - $10^3$ K and initial density $1-10^4$ cm , $H_2$ cooling keeps the temperature below 1500K until the density has increased to $10^{12}$ cm$^{-3}$ and the molecules are dissociated. During this evolution the Jeans mass falls by several orders of magnitude from $10^5$ M to 1-200 $M_\odot$ , the minimum value depending on the detailed treatment of physical processes - especially $H_2$ cooling. After $H_2$ dissociation is completed, the temperature rises nearly adiabatically and the Jeans mass increases until H is ionized at $T \sim 10^4$, $n \sim 10^{19}$ cm$^{-3}$. Absorption of ionization energy, together with free-free and bound-free emission, again slows the temperature increase, but as the cloud becomes optically thick the temperature resumes an almost adiabatic climb. The Jeans mass may have a second and smaller minimum during H ionization, but from the calculations performed to date there is no consensus as to whether the limiting mass for the first generation of stars is near that of the sun or 1-2 orders of magnitude larger.

The present research was undertaken to extend and improve these studies of zero-metal clouds by treating in more detail the spatial variation of physical variables and the transfer of radiation in lines and continuum. With such a treatment it is possible to model the formation of a hydrostatic protostellar core and thus derive more directly a lower limit to stellar masses. In addition we investigate effects of fragmentaton on cloud evolution and protostellar mass.

## II. METHOD

### a) Hydrodynamics

The hydrodynamic collapse of spherical gas clouds was simulated with a hydrodynamic computer code adapted from the work of Bodenheimer (1968b). The differential equations of motion, mass continuity, and energy balance:

$$\frac{\partial^2 r}{\partial t^2} + \frac{1}{\rho}\frac{\partial P}{\partial r} + \frac{GM}{r^2} = 0$$

$$\frac{\partial M}{\partial r} - 4\pi r^2 \rho = 0$$

$$P\frac{\partial}{\partial t}\left(\frac{1}{\rho}\right) + \frac{\partial E}{\partial t} + \Lambda = 0$$

are solved as implicit difference equations. The pressure P is that of an ideal gas, and the internal energy E includes terms for excitation of $H_2$ rotational and vibrational states, dissociation of $H_2$ and $H^-$, and H ionization. The form of the cooling function $\Lambda$ is discussed in Section IIc.

Evolutionary model sequences have been constructed for clouds of mass $10^4$ and $5 \times 10^5\ M_\odot$, starting from a homogeneous, quiescent configuration of of density $4.8 \times 10^{-24}$gm/cm$^3$ and temperature 100 K. The chemical composition is taken to be 75 percent hydrogen and 25 percent helium by mass, with all of the hydrogen initially in atomic form. The pressure at the cloud surface is assumed to remain at its initial value. Spatial variation of the physical variables is represented with 100 spherical zones, and time steps are chosen so that changes in the quantity $\rho^{1/3}$ do not exceed 6 percent in a single step.

### b) Chemistry

The numerical code includes formation of molecular hydrogen by the reactions (1) to (5) and also by three body combination involving helium:

$$H + H + He \longrightarrow H_2 + He. \qquad (6)$$

Molecular hydrogen is dissociated by the inverse reactions to (3) - (6), that is, by collision of H molecules with $H_2$ , H, and He. H atoms are ionized by collision with $e^-$, H, $H_2$, and He:

$$H + e^- \longrightarrow H^+ + e^- + e^- \qquad (7)$$
$$H + H \longrightarrow H^+ + e^- + H \qquad (8)$$
$$H + H_2 \longrightarrow H^+ + e^- + H_2 \qquad (9)$$
$$H + He \longrightarrow H^+ + e^- + He, \qquad (10)$$

and H+ recombines to H by the inverse reactions to (7)-(10) (3-body recombination) and by radiative recombination:

$$H^+ + e^- \longrightarrow H + h\nu. \qquad (11)$$

Photoionizaion (the inverse of 11) is not considered because for most of their histories the clouds are optically thin to photons released in (11), and there is no external radiation field. Likewise, photodissociation is negligible.

The reaction rates are identical to those used by Palla, et al., except that for reactions not considered by these authors (reactions 6 and its inverse; the inverses of 7 and 8; 9 and 10 and their inverses) rates were supplied by Prasad (private communication).

### c) Cooling

At densities less than $10^{-10}$ gm/cm$^3$, the radiative luminosity is primarily from rotational and vibrational transitions of collisionally excited $H_2$. The tables given by Hollenbach and McKee (1979) are used for the local cooling rate $\Lambda$ as a function of the temperature and the H, $H_2$, and He abundances. These calculations do not include excitation by He, but as the collisional cross-section of He is similar to that of $H_2$ (Green, et al. 1978), we use the combined abundance $n(H_2) + n(He)$ in place of $n(H_2)$. As the $H_2$ lines become optically thick, the cooling rate must be modified for trapping of photons within the cloud. We take

$$\Lambda = \sum\sum n_j A_{ji} \Delta E_{ij} \beta_{ij} \text{ (per unit volume),}$$

where $n_j$ is the population of the upper level, $A_{ji}$ is the probability of a spontaneous transition from level j to i, $\Delta E_{ij}$ is the photon energy, and $\beta_{ij}$ is the photon escape probability. The sum is over the rotational transitions within the v=0 vibrational state and over vibrational transitions between v = 0, 1, and 2 for which the molecular parameters and escape probabilities are averaged over the rotational substates. For the optically thick transitions, the calculation of the $n_j$ is simplified by the fact that the density is large and the populations are in LTE. Also, calculation of the escape probability is simplified because the collapse velocity is much larger than the thermal velocity and $\beta_{ij}$ may be determined from local physical parmeters by the method of Sobolev (1960). We take

$$\beta_{ij} = \frac{1}{2}\int_{-1}^{1} \frac{1-e^{-\tau_{ij}}}{\tau_{ij}}\, d\mu$$

$$\tau_{ij} = \frac{\kappa_{ij}\, c}{\nu_{ij} \frac{dv_s}{ds}}$$

$$\kappa_{ij} = h\nu_{ij}\left[n_i B_{ij} - n_j B_{ji}\right]$$

where $\mu$ is the cosine of the direction angle $\theta$, $V_s$ is the fluid velocity in direction $\theta$, and $h\nu_{ij} = \Delta E_{ij}$.

At densities exceeding $10^{-10}$ gm/cm$^3$, energy carried by the 0.75 ev photons produced in the reaction

$$H + e^- \longrightarrow H^- + h\nu$$

becomes the principal coolant. The numerical code treats emission and absorption of this radiation to determine the net local cooling $\Lambda$. The emission coefficient is

$$\epsilon = h\nu \; dn_{H^-}/dt = h\nu\,(n_H\, n_e\, R_{H,e})\,.$$

The opacity for the $H^-$ photons is mainly from free-free transitions of $H^-$ (Chandrasekhar 1946; Ohmura and Ohmura 1960, 1961), $H_2^-$ (Somerville 1964), and $He^-$ (Somerville 1965). We use

$$\kappa = (8.69 \times 10^{-44} n_H + 8.28 \times 10^{-50} n_{H_2} + 2.43 \times 10^{-46} n_{He}) n_e \quad cm^{-1}.$$

If the cloud is optically thin to the H radiation, the transfer equation

$$\frac{dI}{d\tau} = S - I$$

in which I is the specific intensity, $S = \epsilon/\kappa$ is the source function, and $d\tau = \kappa ds$ is integrated along the outward and inward radial directions to obtain two intensities $I^+$ and $I^-$ at each grid point. The mean intensity is obtained as a weighted mean

$$J = \omega I^+ + (1-\omega) I^-,$$

where $\omega$ is the angular size of the small, high-density core in which the $H^-$ photons are produced. The cooling rate is then obtained as

$$\Lambda = 4\pi\kappa(S - J).$$

If the cloud is optically thick, the radiative flux is determined from the diffusion approximation

$$F = -\frac{4\pi}{3}\frac{dS}{d\tau}$$

and the cooling rate from

$$\Lambda = \frac{4\pi}{\rho}\frac{d}{dr}(r^2 F).$$

## III. RESULTS

### a) Evolution of a $5 \times 10^5 M_\odot$ cloud

Characteristic features of the evolution are illustrated in Figures 1 and 2, which show the variation of temperature and $H_2$ mass fraction with density at the cloud center. Initially, the cloud mass exceeds the Jeans massby a factor of 25 and the collapse is nearly free-fall. During the evolution from points A to B the gas temperature increases almost adiabatically because there is insufficient $H_2$ for radiative cooling to balance compressional heating. (The quantity $\gamma = d(\ln T)/d(\ln\rho)$ is actually slightly larger than 2/3 because of energy gained from the association of H atoms.) However when the $H_2$ fraction has grown to $1.5 \times 10^{-4}$ at point B, most of the compressional energy is radiated, and from B to C the temperature decreases. Eventually an equilibrium is reached with nearly equal timescales for heating, $H_2$ formation, and cooling, and between C and D $\Lambda \gtrsim P\, d(1/\rho)/dt$. At D the 3-body reactions become highly effective, and there is increased heating from $H_2$ formation. Simultaneously, the cooling efficiency drops as the $H_2$ lines become optically thick. These effects cause the temperature to rise more steeply between D and E. At E the temperature has reached 2000 K and $H_2$ begins to dissociate. The temperature increases less steeply from E to F as the compressional energy is used in dissociation. With the destruction of $H_2$ the gas can no longer radiate and from F to G there is again an adiabatic temperature rise. At point G hydrogen begins to ionize, and there is an abrupt increase in the rate at which free electrons react with hydrogen to form $H^-$. The escape of photons produced in this reaction keeps the temperature nearly constant from G to H as the density increases by 5 orders of magnitude, and because the increase in density favors $H_2$ formation over dissociation, the $H_2$ abundance attains a second and slighly higher maximum of

$X(H_2) = 0.2$. At point H the temperature again increases sharply as the gas becomes optically thick to the $H^-$ radiation. The temperature gradient is nearly adiabatic from this point until the calculation was ended at K, with only a slight moderation between I and J as H is ionized.

Between points I and J the collapse decelerates near the cloud center and a small, nearly hydrostatic core is formed. This condensation grows by accretion of infalling material and should eventually become a star (see, e.g. Stahler, et. al 1985). Its mass thus represents the minimum mass of a star formed at the center of the cloud. Because there are no physical damping mechanisms, the core slightly overshoots its equilibrium configuration and begins a series of oscillations just before the calculation is terminated at K. At this point the core mass is 0.02 $M_\odot$ and the accretion rate ($4\pi r^2$ v just outside the core) is 0.6 $M_\odot$/yr.

If cooling by the photons produced with $H^-$ is neglected, the temperature rise would continue at point G in Figure 1, following the dotted curve. In this case the protostellar core has a mass of 0.5 $M_\odot$, suggesting that only a massive star could be formed.

The dashed curve in Figure 1 illustrates a collapse calculation by Palla, et al. (1983) that differs from ours in several important respects: (1) the density, temperature, and other physical parameters remain uniform; (2) the collapse is always free-fall; (3) the rate of optically-thick $H_2$ cooling is estimated from a Planck function; and (4) cooling by $H^-$ photons is not considered. Although their numerical results resemble ours, the agreement beyond point D is only a fortuitous result of their more efficient $H_2$ cooling compensating the absence of $H^-$ cooling. Pala, et al. find that the Jeans mass decreases during the collapse to a minimum of 0.1 $M_\odot$, but without spatial resolution they cannot identify the time at which a protostellar condensation forms. Our more detailed calculation provides a stricter lower limit for the stellar mass.

The spatial variation of physical quantities within several cloud models is illustrated in Figure 3, which gives the variation of density, temperature, $H_2$ abundance, and velocity with distance from the cloud center. The density is seen to be uniform near the cloud center and to decrease as $r^{-2}$ in the outer layers. This distribution is well known from previous studies of spherical collapse (e.g., Bodenheimer 1968a). The cloud collapses in free-fall until it is decelerated by a pressure wave moving inward from the surface. The uniform core is material not yet affected by the pressure gradient. The collapse velocity has a maximum between the edge of the core and the surface of the cloud. This maximum moves inward in radius and eventually steepens into a shock wave at the core boundary. The variation of temperature with radius is seen to resemble the variation of temperaure with density at the cloud center (Figure 1). This may be understood by noting that in the free-fall region the temperature is a function of density, and that in the more slowly evolving envelope the temperature at each point remains fixed at value related to the density of this point when it was at the core boundary. Likewise, the $H_2$ abundance varies with radius in Figure 3 much as it does with central density in Figure 2.

### b) Evolution of a $10^4$ M cloud

The variation of central temperature and $H_2$ abundance with density in a $10^4$ $M_\odot$ cloud is shown in Figures 4 and 5. The mass of this cloud is near the minimum for instability to collapse. (In the initial configuration the mass is equal to half of the Jeans mass). The evolution starts as a series of adibatic oscillations between point A and A′ until there is sufficient $H_2$ and radiative cooling for sustained collapse. Even during the collapse phase (until point D) the low-mass configuration is close to hydrostatic equilibrium. (Points in Figures 4 and 5 are labeled according to analagous points in Figures 1 and 2.) Again a balance is attained between the rates of compressional heating and radiative cooling, but these rates are smaller than in the case of free-fall collapse. The smaller cooling rate is reflected in the lower temperature between points B and D. However, the tracks of the low and high mass clouds converge when the 3-body reactions accelerate H formation and the cooling rate becomes more sensitive to density than temperature.

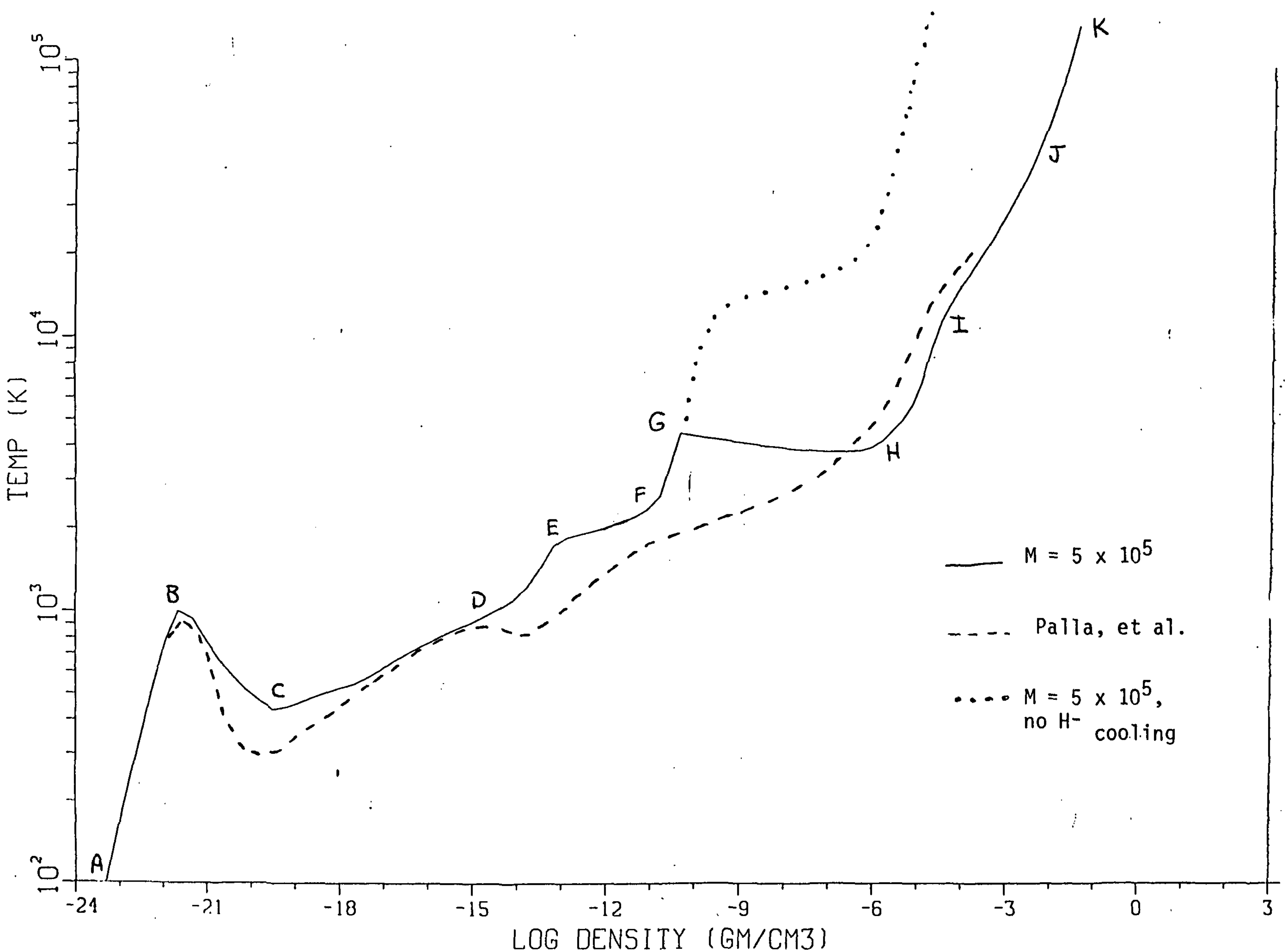
### c) Fragmentation sequences

Two additional sequences of models were constructed to simulate the sepapration of a collapsing cloud into successive fragments of increasingly smaller mass. The times of fragmentation and fragment properties have been chosen in analogy with the numerical calculations of Bodenheimer (1978). At selected intervals the collapse is restarted from a uniform configuration at rest. It is assumed that fragmentation occurs when the ratio of the central density to the initial density corresponds to values given as Bodenheimer's Table 1, Squence III; that the fragment mass is one eighth of the parent cloud mass; and that the fragment's density, temperature, and chemical composition have the values at the center of the parent cloud.

The evolution of fragments of the $5 \times 10^5\ M_\odot$ cloud is illustrated in Figure 6. The solid line shows the variation of central temperature with density in the parent cloud without fragmentation (Figure 1). The first fragment forms at point A, and its evolution follows the dotted line from A to B. Likewise, the evolutionary track of the second fragment begins at point B, and the third fragment at C. It is evident that the tracks of the first two fragments quickly approach and then closely follow the path of the parent cloud. This is because the compressional heating and radiative cooling are the same local functions of density and temperature in each case. The track of fragment C, however, differs from that of the parent cloud in that the temperature begins a nearly adiabatic rise at a lower density. This is a result of the density homogenization at the time of fragmentation, which gives the fragment more high density material and a larger optical depth to H- photons, the principal coolant at this time. But as a more significance difference in the evolution with fragmentation, we note that fragment C is still in nearly free-fall collapse at the density where the parent cloud forms an equilibrium core. This lengthing of the time to reach equilibrium occurs because the size of the dense, collapsing core is increased with each fragmentation, and it takes longer for the core mass to shrink to the Jeans mass. We thus have not determined a minimum stellar mass in the case of fragmentation, but we note that as the Jeans mass is increasing at the point where the calculation was terminated, the initial mass of the protostellar core should be larger than in the case without fragmentation.

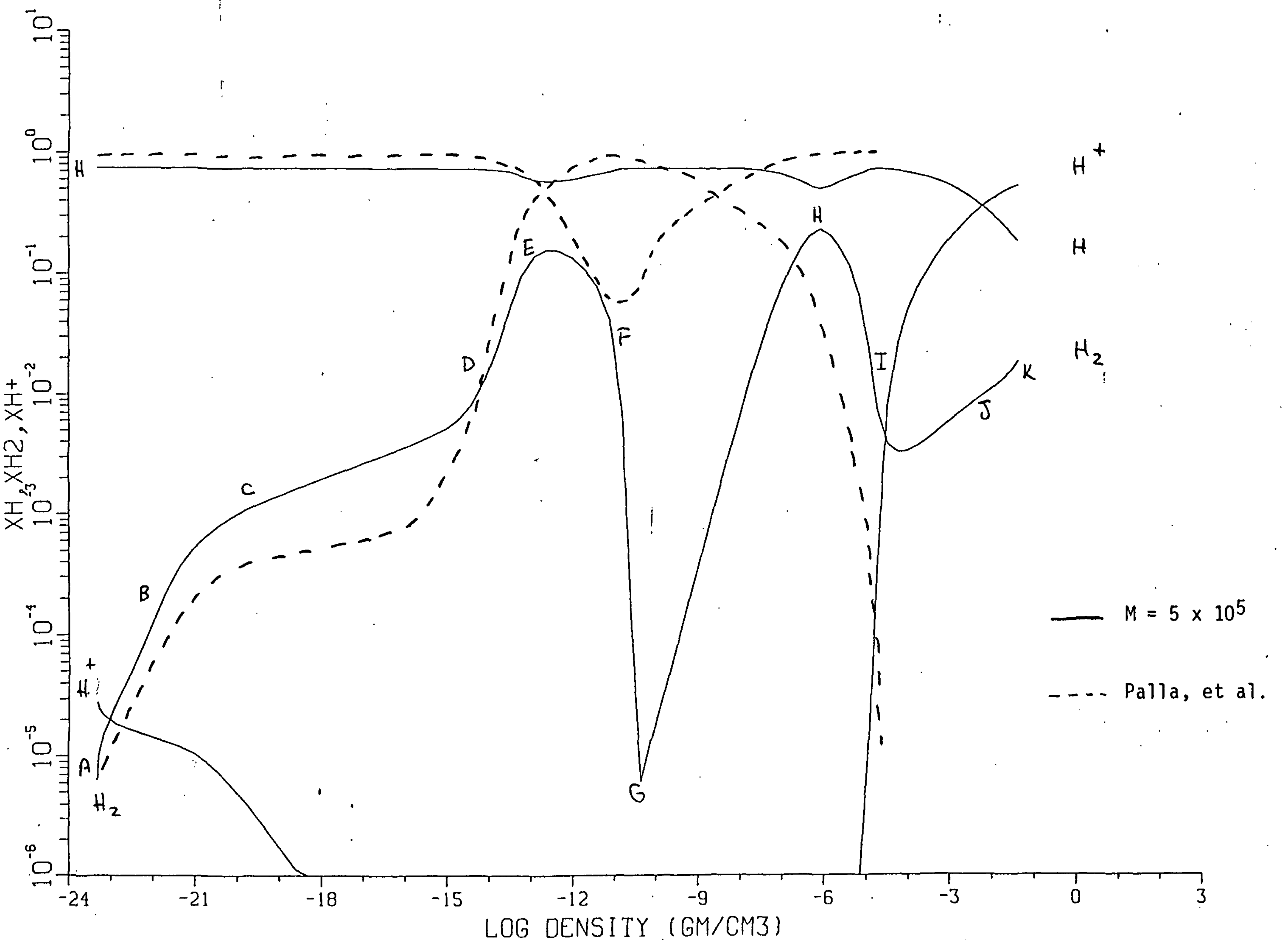
Similar evolutionary tracks are obtained for fragments of the $10^4\ M_\odot$ cloud (Figure 7), although in this case the first fragment maintains a temperature higher than that of the parent cloud. The tracks differ because the fragment is collapsing more rapidly than the parent cloud, which is close to equilibrium, and the higher temperature increases cooling to balance the extra compressional heating. The tracks for the second and third fragments are almost identical to tracks for corresponding fragments in the $5 \times 10^5\ M_\odot$ cloud.

Figure 1



$10^5$
$10^4$
$10^3$
$10^2$
TEMP (K)
-24
-21
-18
-15
-12
-9
-6
-3
0
3
LOG DENSITY (GM/CM3)
A
B
C
D
E
F
G
H
I
J
K
M = 5 x $10^5$
Palla, et al.
M = 5 x $10^5$, no H- cooling

Figure 2



$10^{1}$
$10^{0}$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
XH, XH2, XH+
-24
-21
-18
-15
-12
-9
-6
-3
0
3
LOG DENSITY (GM/CM3)
H
$H^+$
$H_2$
A
B
C
D
E
F
G
H
I
J
K
$H^+$
H
$H_2$
$M = 5 \times 10^5$
Palla, et al.

Figure 3 a

M = 5 x $10^5$ : epochs 100, 200, 300, 400, 450

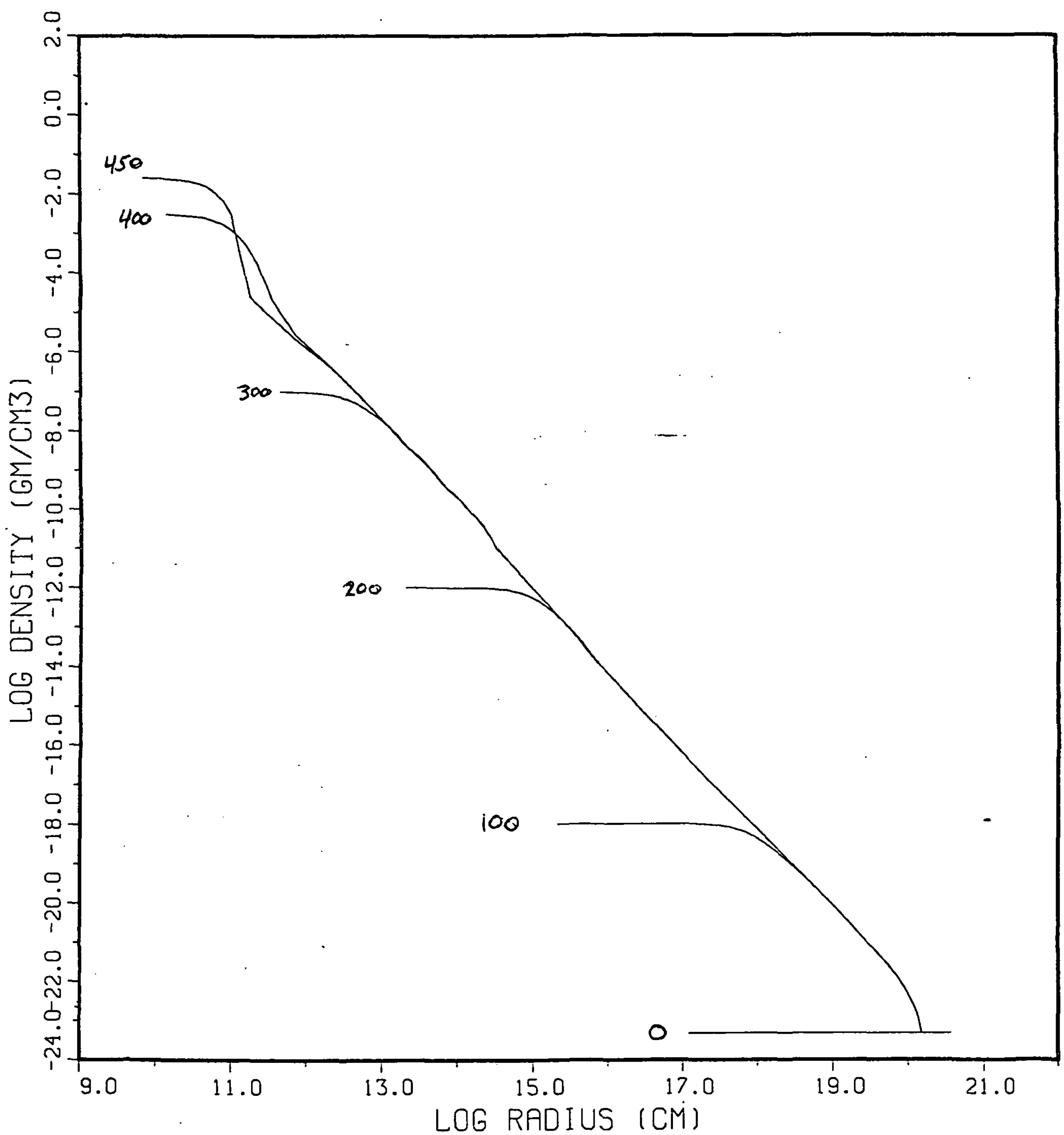


Figure 3 b

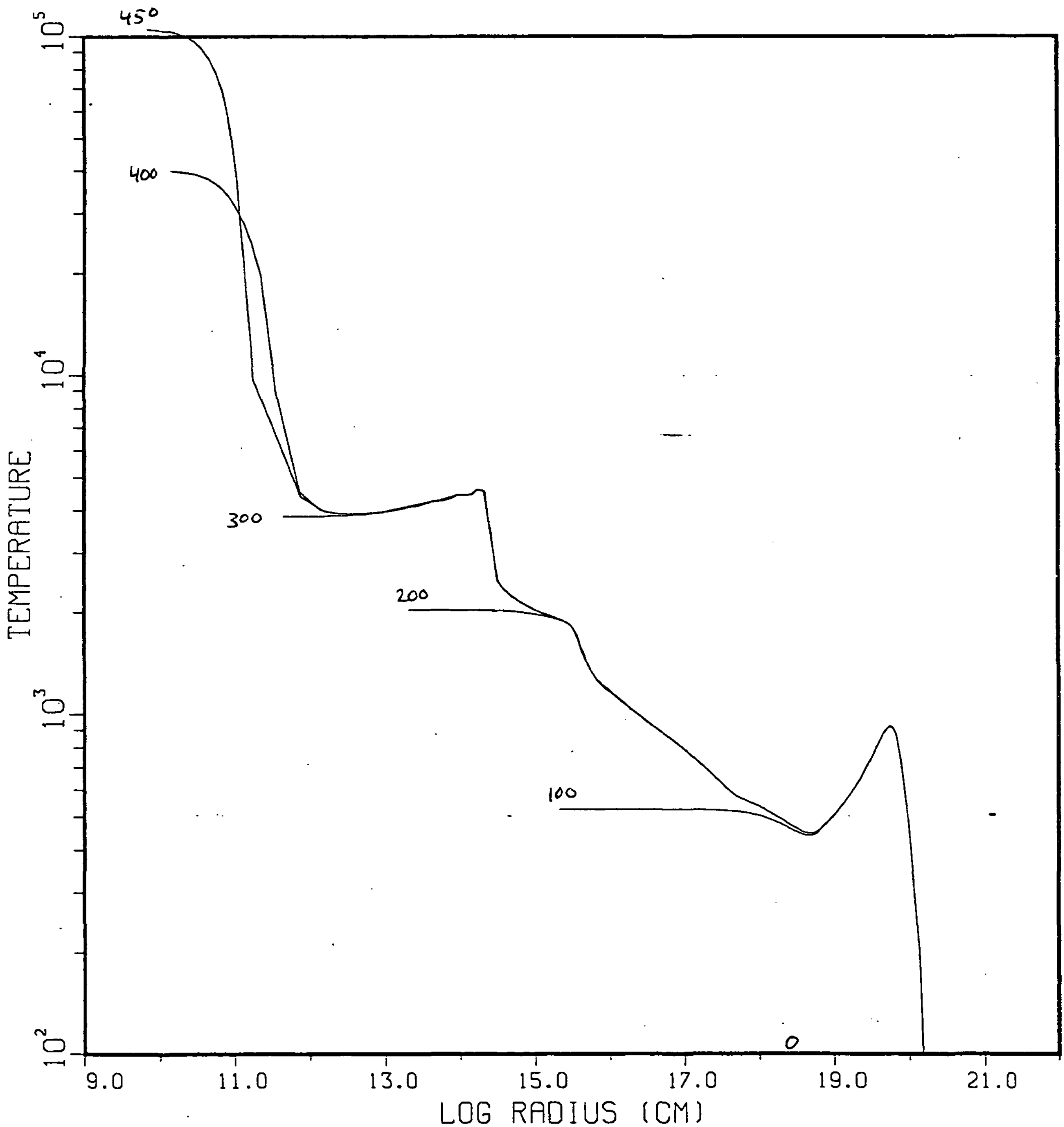

450
400
300
200
100
0
10^5
10^4
10^3
10^2
TEMPERATURE
9.0
11.0
13.0
15.0
17.0
19.0
21.0
LOG RADIUS (CM)

Figure 3 c

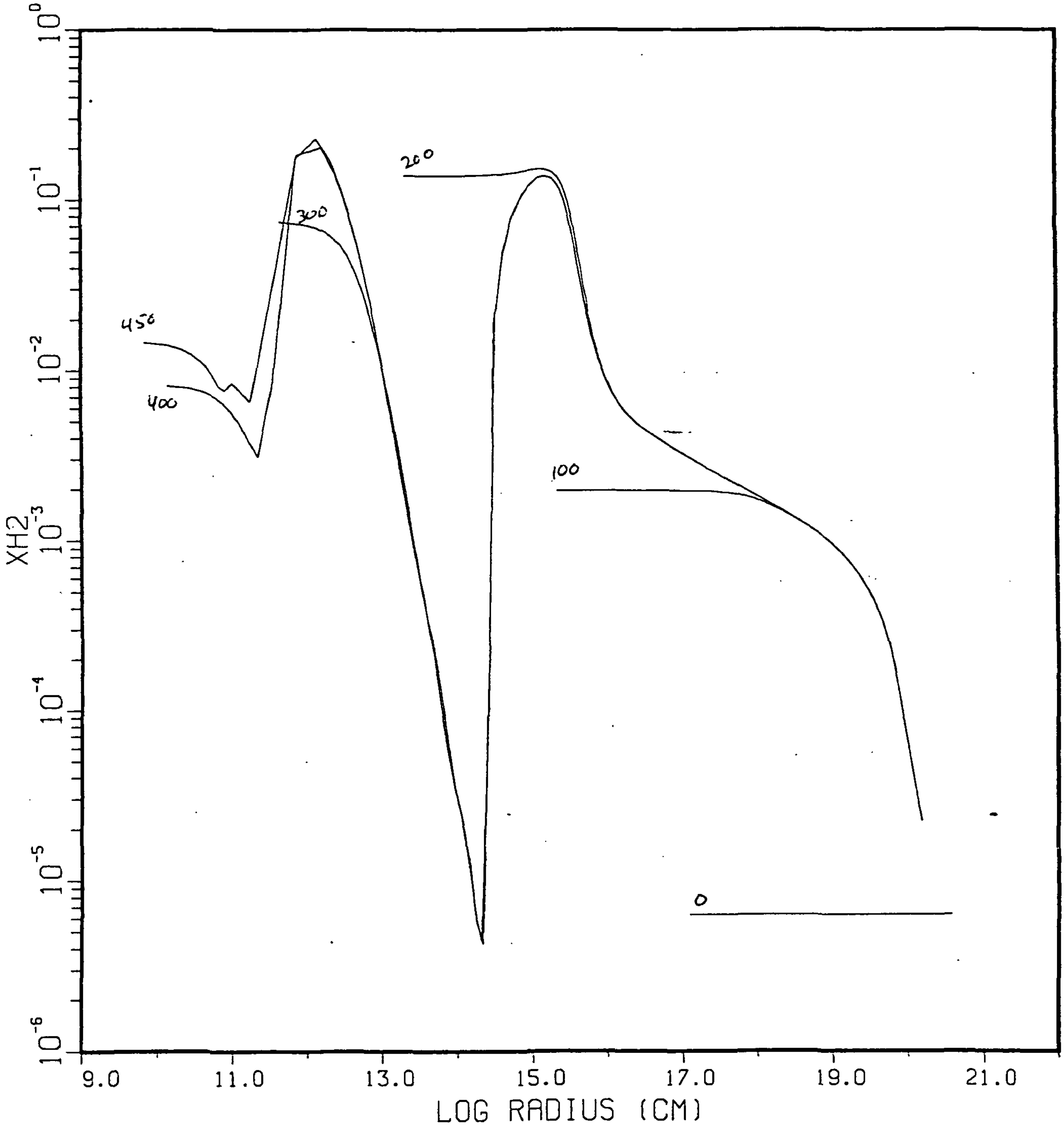
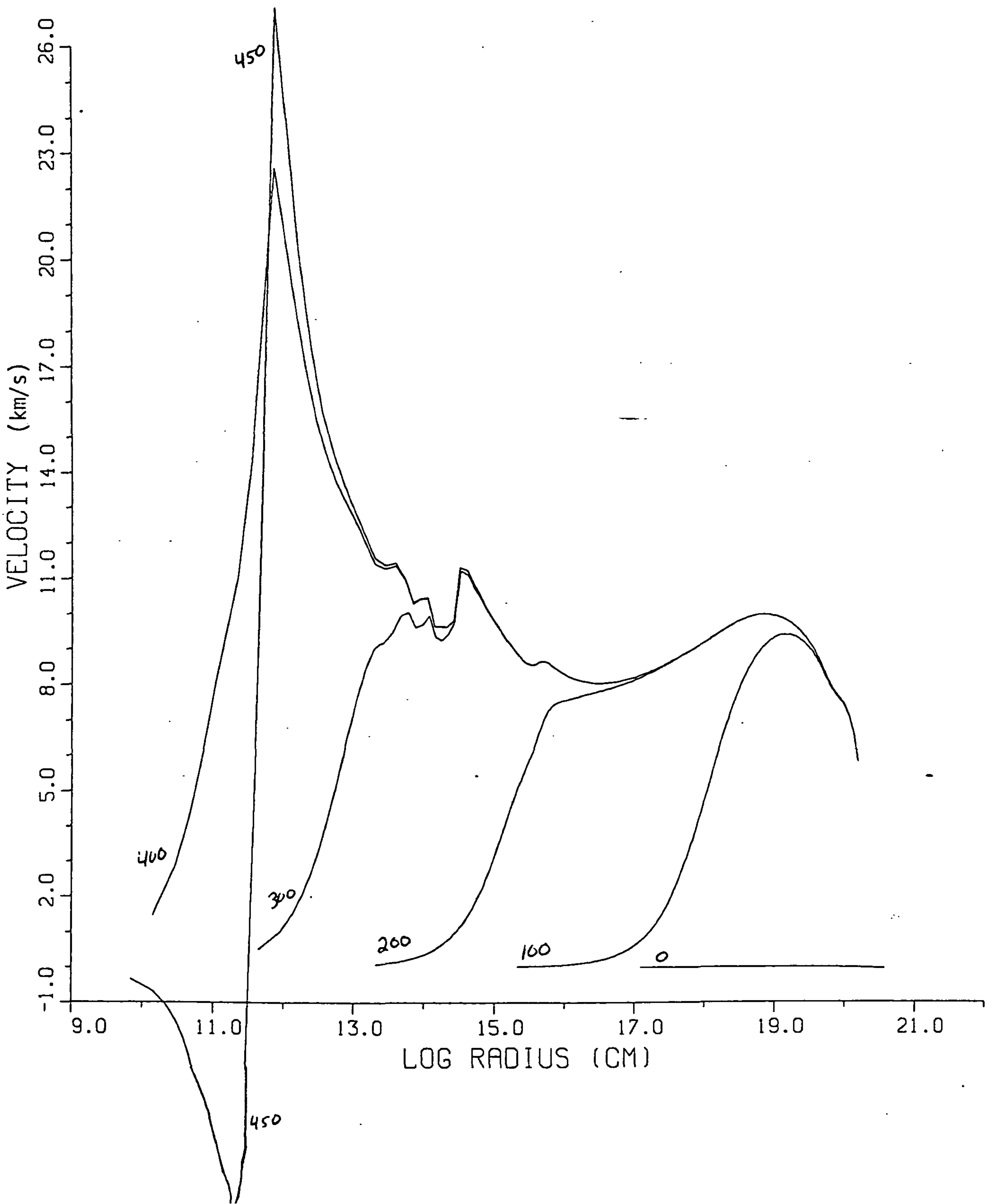
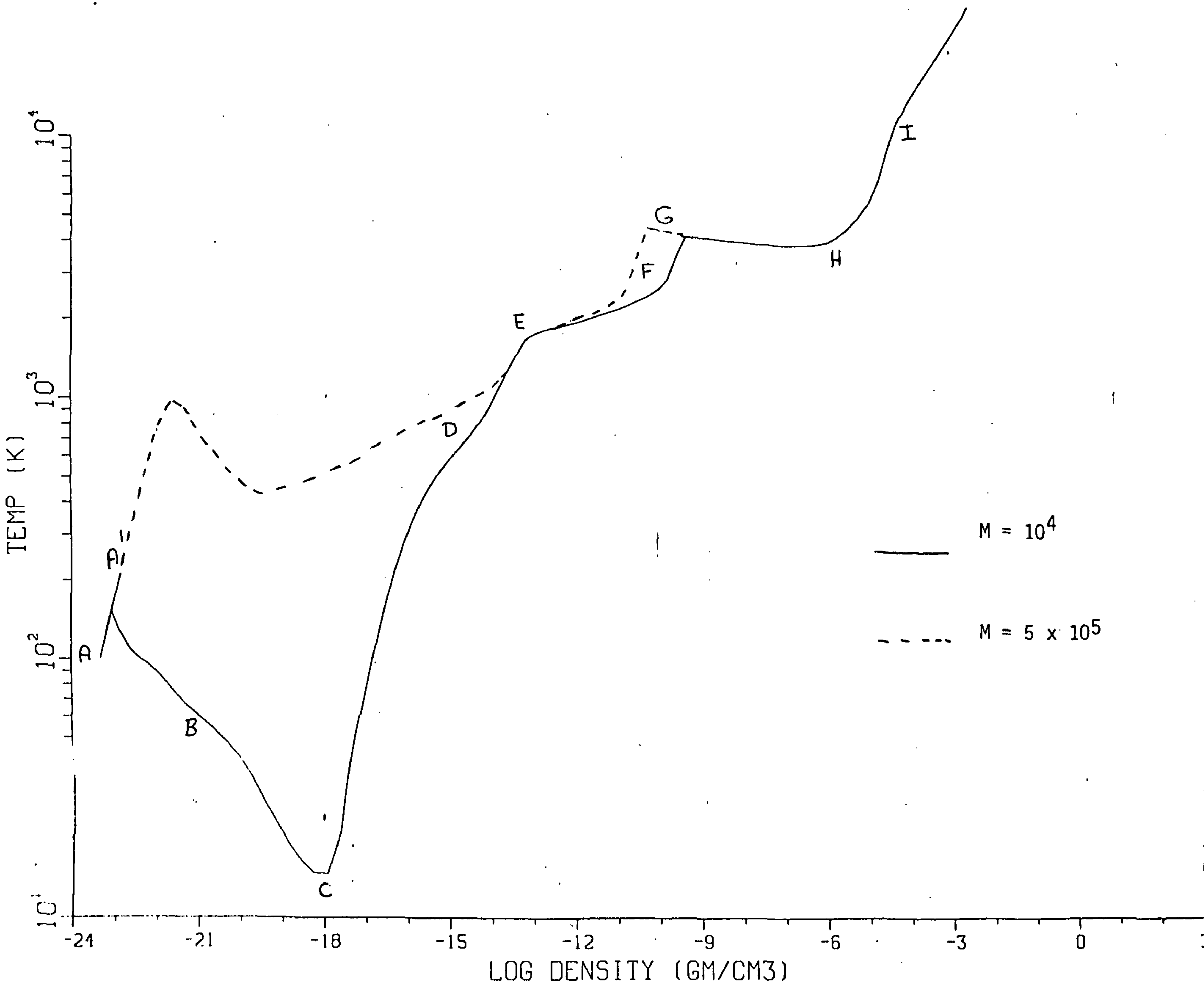

XH2
LOG RADIUS (CM)
$10^{0}$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
9.0
11.0
13.0
15.0
17.0
19.0
21.0
450
400
300
200
100
0

Figure 3 d



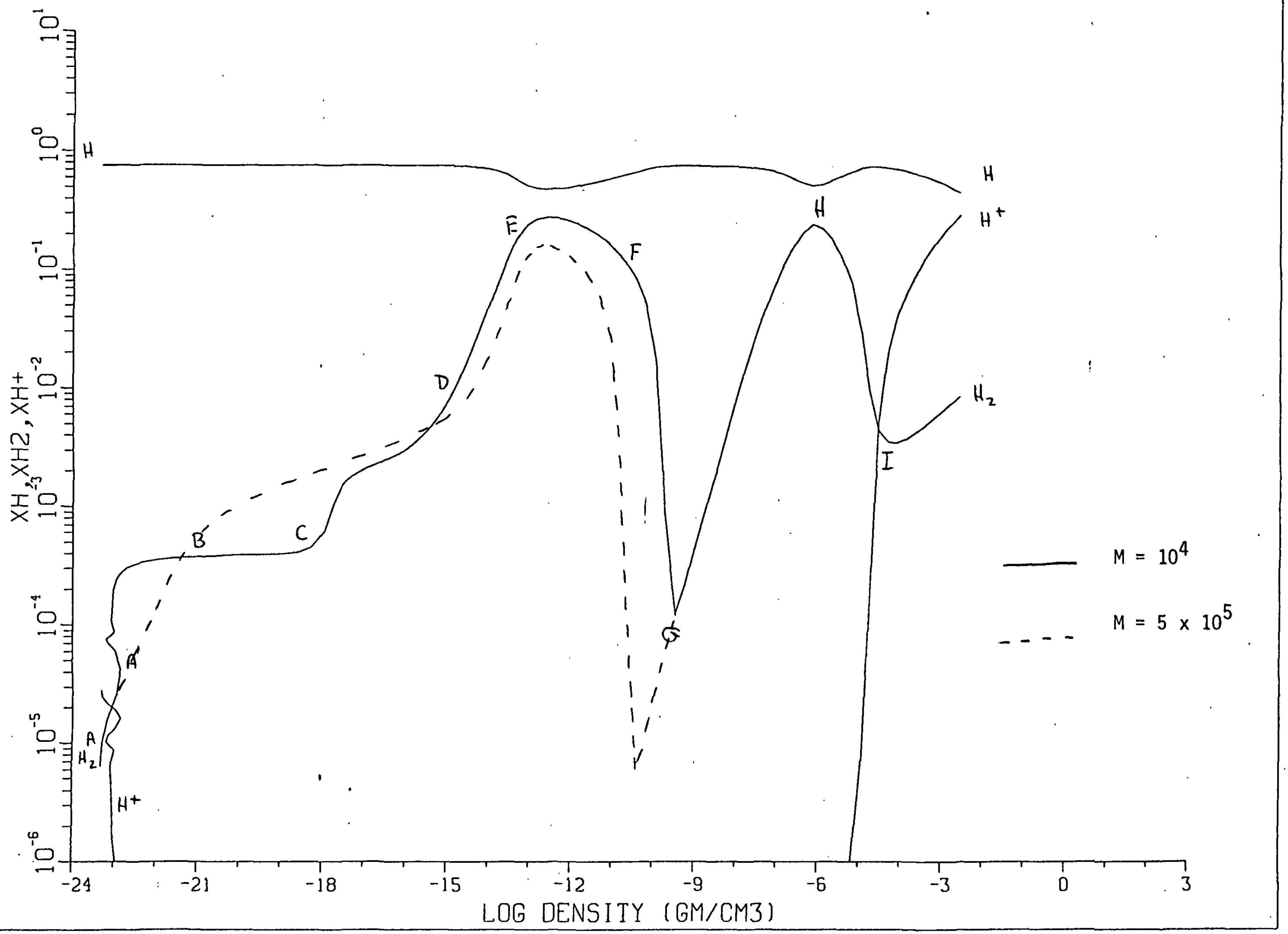
VELOCITY (km/s)
LOG RADIUS (CM)
-1.0
2.0
5.0
8.0
11.0
14.0
17.0
20.0
23.0
26.0
9.0
11.0
13.0
15.0
17.0
19.0
21.0
450
400
300
200
100
0
450

Figure 4



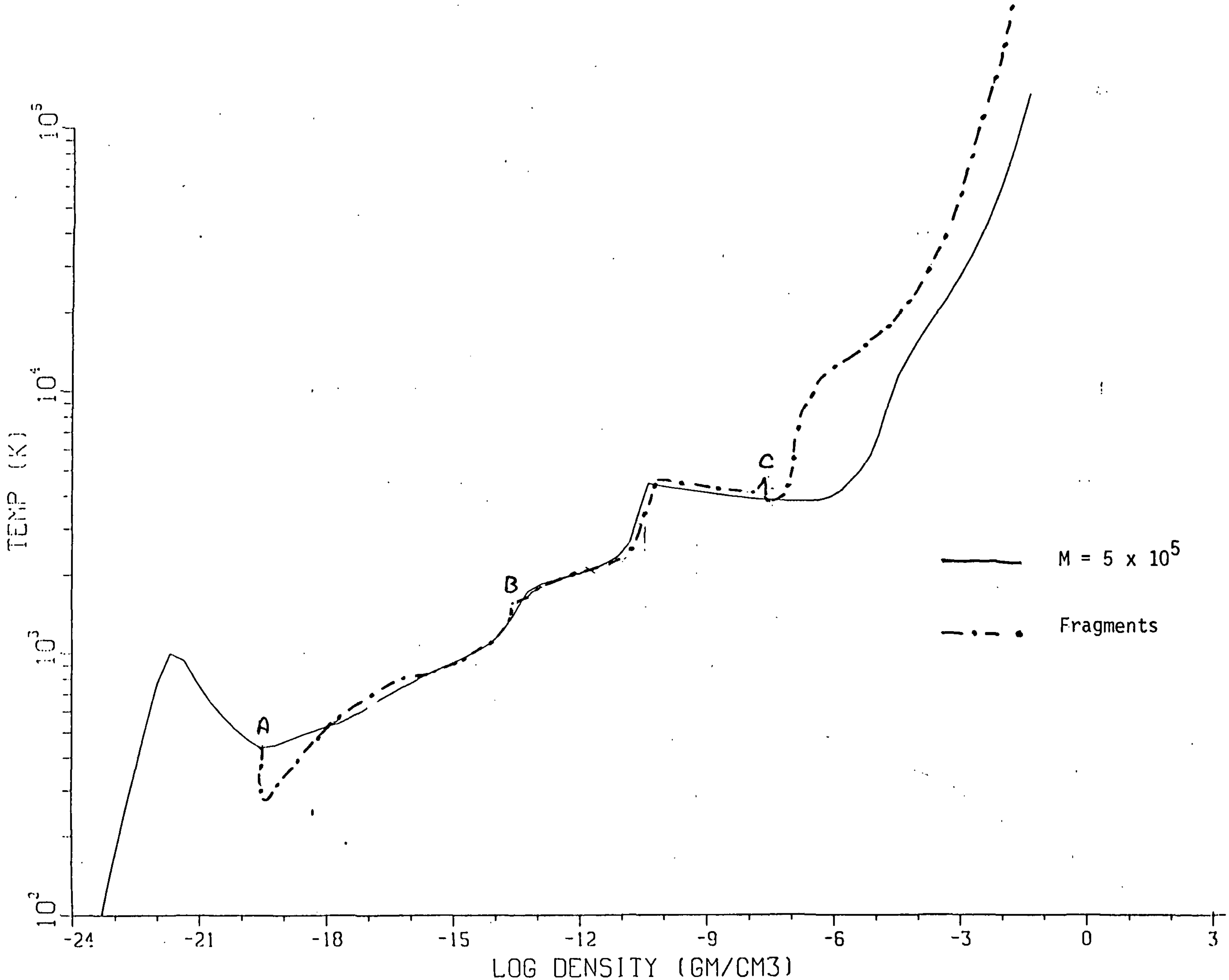
TEMP (K)
$10^4$
$10^3$
$10^2$
$10^1$
A
A
B
C
D
E
F
G
H
I
$M = 10^4$
$M = 5 \times 10^5$
-24
-21
-18
-15
-12
-9
-6
-3
0
3
LOG DENSITY (GM/CM3)

Figure 5



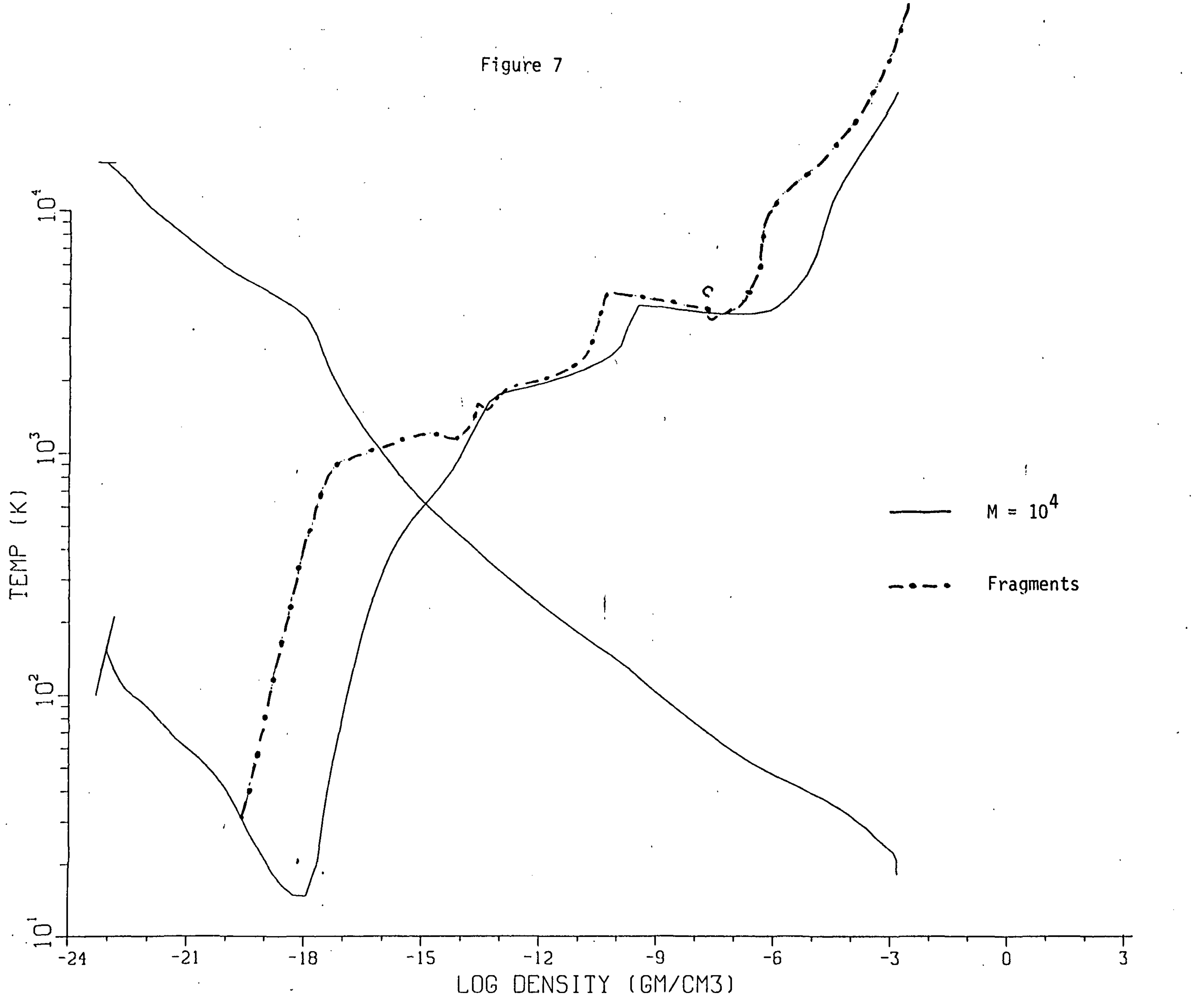
XH, XH2, XH+
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
-24
-21
-18
-15
-12
-9
-6
-3
0
3
LOG DENSITY (GM/CM3)
H
H
H
H+
H2
H+
A
A
B
C
D
E
F
G
I
M = 10^4
M = 5 x 10^5

Figure 6



$10^5$
$10^4$
$10^3$
$10^2$
TEMP (K)
-24
-21
-18
-15
-12
-9
-6
-3
0
3
LOG DENSITY (GM/CM3)
A
B
C
M = 5 x $10^5$
Fragments

Figure 7



TEMP (K)
$10^4$
$10^3$
$10^2$
$10^1$
-24
-21
-18
-15
-12
-9
-6
-3
0
3
LOG DENSITY (GM/CM3)
M = $10^4$
Fragments

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# EVOLUTION OF ZERO-METAL CLOUDS

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ABSTRACT. Dynamical, chemical and thermal evolution of zero-metal gas clouds has been modeled to study conditions of star formation in the early universe. Numerical results are shown for collapse of a spherical cloud of mass $5 \times 10^5\ M_\odot$. Cooling by $H_2$ lines and by photons emitted in $H + e^- \rightarrow H^- + h\nu$ maintains collapse until formation of an equilibrium protostellar core with mass $0.03\ M_\odot$. The cooling by photons produced with $H^-$ is essential for low-mass star formation. If the cloud is fragmented, the evolution of each piece resembles that of the parent cloud.

## 1. METHOD

Models for collapse of zero-metal clouds have been constructed with a numerical code based on the work of Bodenheimer 1968. The calculations include self-gravity, internal pressure, $H_2$ chemistry and radiative cooling with treatment of the spatial and time variation of all physical quantities. Molecular hydrogen is formed by associative attachment of H with $H^-$ and by three-body combination. The gas is cooled by rotational and vibrational emission from $H_2$, with a photon escape probability consistent with the supersonic collapse velocity, and by emission of 0.75 ev photons produced in $H + e^- \rightarrow H^- + h\nu$. The cooling associated with $H^-$ formation has not been considered in previous collapse studies.

## 2. RESULTS AND CONCLUSIONS

Figure 1 shows the evolution of central temperature with density in a $5 \times 10^5\ M_\odot$ cloud of 75 percent hydrogen and 25 percent helium which begins collapse from density $5 \times 10^{24}$ gm/cm$^3$ and temperature 100 K. The temperature first increases sharply, reaching a maximum (point A) when sufficient $H_2$ is formed that the cooling time equals the compressional heating time. The temperature rise steepens again at B as the $H_2$ emission becomes optically thick and at C following $H_2$ dissociation. The onset of cooling by $H^-$ photons is abrupt at point D, and subsequent evolution is nearly isothermal until the cloud is opaque to this radiation at E. Without $H^-$ cooling the temperature rise would continue along the dotted curve. Point F marks hydrogen ionization and G the cessation of collapse in a small core. The core mass is 0.03 $M_\odot$ with the H- cooling and 0.05 $M_\odot$ without. Numerical accretion studies (e.g., Stahler et al. 1985) suggest that the core mass will grow by a factor of at least $10^3$ before the formation of a main sequence star. Thus only the models with H- cooling could yield stars of low mass.

The dashed curve in Figure 1 illustrates a calculation by Palla et al. for collapse and cooling of a pure H cloud. Although their numerical results resemble ours, the agreement is likely fortuitous as the physical basis of cooling differs in the two calculations. The Palla et al. model does not include H- cooling, but it has more efficient cooling in the optically thick $H_2$ lines.

If our cloud model is assumed to fragment during collapse, the evolutionary tracks of the fragments quickly converge to that of the parent cloud. Fragmentation may thus provide multiple centers for collapse, but it should not affect the stellar mass function.

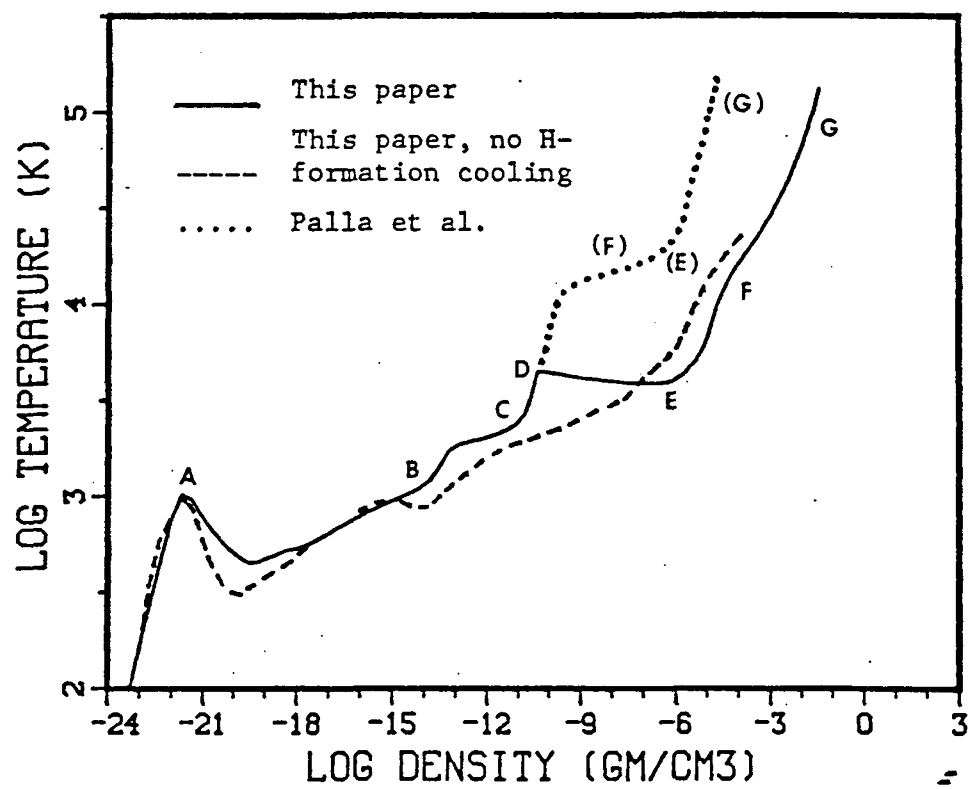


Figure 1. Temperature and density evolution in zero-metal clouds.

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