COOLING AND FRAGMENTATION OF PROTO-CLOBULAR CLUSTER CLOUDS

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Recently, Fall and Rees (1985) have proposed a theory for the origin of globular clusters forming from the largely primordial gas in the protogalaxy. These authors have explained the typical masses of proto-globular cluster clouds (~ 10^6 $M_\odot$) as gravitationally unstable condensations at temperature T ~ 10^4 in a hot protogalactic medium (T ~ 10^6 K) but they were not concerned with how these clouds would fragment into stellar masses (~ 1 $M_\odot$). In fact, their proto-globular cluster clouds are trapped at T ~ 10^4 K, and cannot cool to lower temperatures. However, substantial cooling must occur if these clouds are to form solar mass stars. It is known that under primordial conditions the only available cooling agent is molecular hydrogen, formed in the gas phase. Therefore, if sufficient molecular hydrogen is formed, it is possible to cool the gas well below T ~ 10^4 K. In the following we outline how non-equilibrium conditions lead to a larger H_2 abundance than derived by Fall and Rees, who assumed equilibrium conditions.

When the protocluster gas has cooled down from high temperatures (~ 10^6 K) to temperatures of the order of 15000 K, hydrogen recombination starts to occur, but it will be out of equilibrium, because the cooling time due to Ly-α photons is shorter than the recombination time. At T = 10^4 K the relation between the recombination and Ly-α cooling time scales is 10(1-x) where x is the fractional degree of ionization. This shows that ionization equilibrium (where x would be < 10^{-2} cannot be reached; therefore, a high ionization fraction (x < 0.9) is maintained at T ~ 10^4 K, and even below that temperature. Note that for high fractional ionization both time scales are much shorter than the free-fall time of the protocluster cloud (t_{ff} ~ 10^{65} years at cloud densities of ~ 10^2 cm^{-3}). The high fractional ionization promotes the efficient formation of H^- and H^+_2 which both contribute to H_2 formation. [$H + H^+ \rightarrow H^+_2 + \gamma$; $H^+_2 + H \rightarrow H_2 + H^+$; $H + e \rightarrow H^- + \gamma$; $H^- + H \rightarrow H_2 + e$]

Fall and Rees did not consider the H^+_2 channel, but this is the driving reaction at the highest temperatures (8000 K < T < 10000 K)

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since H^- is rapidly destroyed by collisions with H^+, rather than reacting with H atoms to form H_2. We note that the chemistry in this situation is more complicated (see Palla and Zinnecker 1986), but the net result can be approximated as above. Self-shielding of H_2 against photodissociation in the external radiation field also turns out to be non-negligible, since the H_2 column densities across the protocluster clouds exceed the critical value (Federman et al. 1979). As a result of the more efficient H_2 formation process, the final molecular abundance can be as high as 10^{-2} - 10^{-3} rather than 10^{-4} - 10^{-6} predicted in the equilibrium scheme. (Mac Low and Shull 1985, and Shapiro and Kang 1986 have studies the formation of H_2 in the context of pregalactic shocks and galaxy formation, reaching similar conclusions.)

With such a high fractional H_2 abundance the gas can cool almost instantaneously (in a time very short compared to the free-fall time) to temperatures as low as 100 K. At this temperature the protocluster density will be 10^4 cm^{-3}, in pressure equilibrium with the surrounding hot and diluted halo gas. The H_2 molecules will survive at these densities, because collisional dissociation will not be operative at such low temperatures, despite the strong density dependence of the dissociation rate (Lepp and Shull 1983). The same applies to HD molecules, which are a much better coolant than H_2 at $T < 150$ K (Dalgarno and Wright 1972) and may allow the gas to cool down to a few tens of degrees Kelvin so that the Jeans mass drops below 1 $M_\odot$.

In principle, isothermal contraction (at $T = 10^4$ K) implies lowering the Jeans mass, and when the density is sufficiently high (~ 10^9 cm^{-3}) H_2 formation via three-body reactions (Palla et al. 1983) may occur. The associated cooling can lower the temperatures to $T \sim 10^3$ K, but in order to get a Jeans mass of order 1 $M_\odot$ would require very high densities (~ 10^{12} cm^{-3}) and fragmentation at these densities would lead to a cluster far too compact to resemble a typical globular cluster. This suggests that cooling and fragmentation should occur at a much earlier stage in the evolution of the proto-globular cluster cloud. We thank Dr. R. Stanga at ESO for making this effort possible. We would also like to thank Professor M. Rees for a timely preprint.

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