The Role of H$_2$ Molecules in Cosmological Structure Formation

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We review the relevance of H$_2$ molecules for structure formation in cosmology. Molecules are important at high–redshifts, when the first collapsed structures appear with typical temperatures of a few hundred Kelvin. In these chemically pristine clouds, radiative cooling is dominated by H$_2$ molecules. As a result, H$_2$ “astro–chemistry” is likely to determine the epoch when the first astrophysical objects appear. We summarize results of recent three–dimensional simulations. A discussion of the effects of feedback, and implications for the reionization of the universe is also given.

1. Introduction

In current “best–fit” cosmological models, cold dark matter (CDM) dominates the dynamics of structure formation, and processes the initial density fluctuation power spectrum $P(K) \propto k^n$ with $n = 1$ to predict $n = 1$ on large scales and $n \approx -3$ on small scales (Peebles 1982). The r.m.s. density fluctuation $\sigma_M$ then varies inversely with the mass–scale ($\sigma_M \propto M^{-2/3}$ for $M \geq 10^{12} M_\odot$), while the dependence is only logarithmic for $M \ll 10^{12} M_\odot$). The more overdense a region, the earlier it collapses, implying that the present structure was built from the bottom up, with smaller objects appearing first, and subsequently merging and/or clustering together to assemble the larger objects (Peebles 1980). The predicted formation epochs of “objects” (i.e. collapsed dark matter halos) with various masses in the so–called standard CDM cosmology (Bardeen et al. 1986) are shown in Figure 1. Galaxies, which have masses around $10^{11} - 12 M_\odot$, are expected to have formed when the universe had approximately 10% of its present age (redshift $z \sim 3$), just around the limit of the deepest present–day observations (i.e. the Hubble Deep Field, HDF, Williams et al. 1996; or Ly$\alpha$ emission line detections, Weymann et al. 1998). Clusters of galaxies with masses around $10^{14} - 15 M_\odot$ are predicted to have formed as recently as 80% of the current age, with the more massive clusters still assembling at the present time.

Objects with the masses of globular clusters, $10^5 - 6 M_\odot$, are predicted to have condensed as early as $\sim 1\%$ of the current age, or $z \sim 20$. It is natural to identify these condensations as the sites where the first “astrophysical” objects (stars, or quasars) might be born. Although the CDM model in Figure 1 predicts still smaller condensations at even earlier times, the cosmological Jeans mass in the smooth gas after recombination is $\sim 10^{4} M_\odot$ (Peebles 1965), implying that gas pressure inhibits the collapse of gas below this scale (see Haiman, Thoul & Loeb 1996 on collapse on somewhat smaller scales due to gas/DM shell–crossing, hereafter HTL96). What happens in a newly collapsed halo? Formally, in the absence of non–gravitational forces, a perfectly spherical top–hat perturbation simply collapses to a point (Peebles 1980). According to more accurate treatments describing self–similar solutions of spherical, but inhomogeneous secondary infall for a mixture of cold dark matter and baryons (Gunn & Gott 1972, Fillmore & Goldreich 1984, Bertschinger 1985), the evolution is...
Figure 1. The formation epoch of objects with various masses in a standard CDM model ($\Omega = n = \sigma_{\text{th}}^{-1} = 1$), shown as a fraction of the current age of the universe. The upper labels indicate redshifts. The first objects form at redshift $z \sim 20$, at a “lookback” fraction of $\sim 99\%$.

as follows. In the initial stages, while the bulk of the cloud is still turning around or expanding, the central, densest region of the cloud collapses and forms a dense virialized clump. The dark matter component virializes through violent relaxation (Lynden–Bell 1967), while the kinetic energy of the gas is converted into thermal energy through a hydrodynamic shock that raises the gas temperature to its virial value. As subsequent gas shells fall towards the center, they encounter an outward–propagating shock, and are brought to a sudden a halt. Continuous accretion onto the center then establishes a stationary, virialized object with $\rho \propto r^{-2.25}$ density profile.

Early discussions of the formation of galaxies and clusters have argued that the subsequent behavior of the gas in such a virialized object is determined by its ability to cool radiatively on a dynamical time (Rees & Ostriker 1977; Dekel & Silk 1986). The same ideas apply on the smaller scales expected for the first collapsed clouds (Silk 1977; Kashlinsky & Rees 1983). Objects that are unable to cool and radiate away their thermal energy maintain their pressure support and identity, until they become part of a larger object via accretion or mergers. On the other hand, objects that can radiate efficiently will cool and continue collapsing.

The cooling time is determined by the virial temperature, $T_{\text{vir}} \sim 10^4 \text{K} (M/10^8 \text{M}_\odot)^{2/3} [(1 + z)/11]$. For the largest halos, above $T_{\text{vir}} \gtrsim 10^6 \text{K}$, the most important cooling mechanism is Bremsstrahlung; for galaxy–sized halos ($10^4 \text{K} \lesssim T_{\text{vir}} \lesssim 10^6 \text{K}$), cooling is possible via collisional excitation of neutral H and He. As first pointed out by Saslaw & Zipoy (1967) and Peebles and Dicke (1968), the virial temperatures of the first clouds are below $10^4 \text{K}$. In the primordial gas, the only molecule that could have a sufficient
abundance is \( \text{H}_2 \), allowing cooling between \( 10^2 \text{K} \lesssim T \lesssim 10^4 \text{K} \) (see Dalgarno & Lepp 1987 for a review of astrochemistry in the early universe, and Stancil, Lepp and Dalgarno 1996 on the possible importance of other molecules, such as HD and LiH). Below \( T \lesssim 10^2 \text{K} \), the collapsed clouds are unable to cool, and remain pressure–supported for longer than a Hubble time.

Although \( \text{H}_2 \) molecules are unimportant in the formation of structures on galactic scales, they likely play a key role in the formation of the first, smaller structures. In particular, the abundance of \( \text{H}_2 \) controls the minimum sizes and formation times of the very first systems (HTL96, Tegmark et al. 1997).

The main issues regarding \( \text{H}_2 \) molecules in structure formation, addressed in this review, are:

- What is the \( \text{H}_2 \) abundance in the first collapsed objects?
- What is the parameter space (in mass, redshift and metallicity) when \( \text{H}_2 \) cooling dominates over all other cooling mechanisms?
- What is the parameter space when the \( \text{H}_2 \) cooling time is shorter than the dynamical time, so that \( \text{H}_2 \) can effect the dynamics of a system?
- What feedback mechanisms effect the \( \text{H}_2 \) abundance once the first stars or quasars light up?

2. \( \text{H}_2 \) Chemistry and Cooling

Because the cosmological background density of baryons \( \sim (\Omega_B h^2/0.01)(1+z)^3 10^{-7} \text{cm}^{-3} \) is very small, chemical reactions in the smooth background gas occur on long timescales. As a consequence, for dynamical situations of structure formation chemical equilibrium is rarely an appropriate assumption. The dominant \( \text{H}_2 \) formation process in the gas phase,

\[
\text{H} + e^- \rightarrow \text{H}^- + h\nu,
\]

\[
\text{H}^- + \text{H} \rightarrow \text{H}_2 + e^-,
\]

relies on the abundance of free electrons to act as catalysts. At temperatures low enough to inhibit collisional dissociations by collisions with neutral hydrogen such electrons can only exist due to non-equilibrium effects. Electrons are also produced by photoionization of neutral hydrogen from an external UV radiation field. It is required to solve the time dependent chemical reaction network including the dominant chemical reactions. A very fast numerical method to solve this set of stiff ordinary differential equations has been developed by Anninos et al. (1997). The number of possible chemical reactions involving \( \text{H}_2 \) is large, even in the simple case of metal free primordial gas. The tedious work of selecting the dominant reactions and their reaction rates has been done by many authors, some recent examples being HTL96, Abel et al. (1997) and Galli & Palla (1998, see also Galli and Palla in this volume).

Cooling (defined here as the radiative loss of internal energy of the gas) is either due to reaction enthalpy released by a photon, or due to the radiative decay of collisionally excited atomic or molecular levels. For typical densities and proto-galactic scales it is accurate to assume the gas to be optically thin and only consider excitations from atomic and molecular ground states. The latter fact is due to the low densities resulting in collisional excitation time scales much longer than the corresponding radiative decay times (sometimes referred to as the coronal limit). For \( \text{H}_2 \) molecules this assumption breaks down for neutral hydrogen number densities in excess of \( \sim 10^{2-3} \text{cm}^{-3} \). In comparison, for hydrogen atoms the coronal limit is reached only at electron densities of \( \sim 10^{17} \text{cm}^{-3} \) (Abel et al. 1997, and references therein). The calculations of the appropriate cooling
function for molecular hydrogen seem to be converging. See Flower (2000, this volume) for a discussion and further references.

3. \( H_2 \) and the First Structures

Studies that incorporate \( H_2 \) chemistry into cosmological models and address issues such as non–equilibrium chemistry, dynamics, or radiative transfer, have appeared only in the past few years. However, pioneering works on the effect of \( H_2 \) molecules during the formation of ultra–high redshift structures go back to the 1960’s. Saslaw & Zipoy (1967) first mentioned the importance of \( H_2 \) in cosmology. Peebles & Dicke (1968) speculated that globular clusters formed via \( H_2 \) cooling constitute the first building blocks of subsequent larger structures. Several papers soon constructed complete gas–phase reaction networks, and identified the two possible ways of gas–phase formation of \( H_2 \) via the \( H_2^+ \) or \( H^- \) channels. These were applied to derive the \( H_2 \) abundance in the smooth gas in the post–recombination universe (Lepp & Shull 1984; Shapiro, Giroux & Babul 1994), and under densities and temperatures expected in collapsing high–redshift objects (Hirasawa 1969; Matsuda et al 1969; Ruzmaikina 1973). Pallà et al. (1983) combined the molecular chemistry with simplified dynamics, assuming a uniform sphere in free–fall, finding that three–body reactions significantly increase the \( H_2 \) abundance at the later (dense) stages of the collapse. The significance of non–equilibrium \( H_2 \) chemistry was realized by Shapiro & Kang (1987), who studied \( H_2 \) formation in a shock–heated gas, and found that the high electron fraction in the post–shock region leads to a significantly enhanced \( H_2 \) abundance. Based on a self–consistent treatment of radiative transfer of the diffuse radiation field (Kang and Shapiro 1992), this \( H_2 \) enhancement, regulated by photodissociation inside proto–galaxies, was suggested to lead to the formation of globular clusters (Kang et al. 1990).

The basic picture that emerged from this papers is as follows. The \( H_2 \) fraction after recombination in the smooth ‘intergalactic’ gas is small \((x_{H_2} = n_{H_2}/n_H \sim 10^{-6})\). At high redshifts \((z \gtrsim 100)\), \( H_2 \) formation is inhibited even in overdense regions because the required intermediaries \( H_2^+ \) and \( H^- \) are dissociated by cosmic microwave background (CMB) photons. However, at lower redshifts, when the CMB energy density drops, a sufficiently large \( H_2 \) abundance builds up inside collapsed clouds \((x_{H_2} \sim 10^{-3})\) at redshifts \( z \lesssim 100 \) to cause cooling on a timescales shorter than the dynamical time. This last conclusion was found to hold when the rotation of a collapsing sphere was also included (Hutchins 1976). Using a different approach, Silk (1983) explicitly demonstrated that a thermal instability exists for a collapsing gas–cloud forming \( H_2 \) molecules, leading to fragmentation. In summary, these early papers identified the most important reactions for \( H_2 \) chemistry, and established the key role of \( H_2 \) molecules in cooling the first, relatively metal–free clouds, and thus in the formation of population III stars.

The minimum mass of an object that can collapse and cool as a function of redshift has been studied by Tegmark et al. (1997) assuming constant density objects, and by HTL96 (see also Bodenheimer and Villere 1986), using spherically symmetric one–dimensional Lagrangian hydrodynamical models (see also Bodenheimer and Villere 1986). Sufficient \( H_2 \) formation and cooling requires the gas to reach temperatures in excess of a few hundred Kelvin; or masses of few \( 10^5 \ M_\odot \) \([(1 + z)/11]^{-3/2} \). Initially linear density perturbations are followed as they turn around and grow in mass. When the DM dynamics are included, the center of the collapsing object contracts adiabatically into the growing DM potential well. As the object grows in mass, a weak accretion shock is formed. One might imagine a case where the adiabatic central core forms molecules early and allows rapid collapse before the accretion shock is formed; however this is not
seen in the simulations. These temperatures are much larger than the temperature of the intergalactic medium \( T_{IGM} \sim 0.014(1+z)^2 \) at the redshifts of interest. In other words, CDM models predicts the existence of numerous virialized objects with temperatures \( \lesssim 500 \text{K} \) that cannot cool. The object that contained the first star in the universe grows by the infall of both intergalactic DM and of gas, heated in an accretion shock. The residual fraction of free electrons catalyze the formation of \( \text{H}_2 \) molecules in its central region.

4. Three-dimensional Numerical Simulations

Cosmological hydrodynamical simulations of hierarchical models of structure formation have proven very successful in explaining cosmic structure on sub-galactic scales (Cen et al. 1994, Zhang et al. 1995, Hernquist et al. 1996, Davé et al. 1999), galactic scales (e.g. Kauffmann et al. 1999, Katz et al. 1999) and galaxy clusters (e.g. Frenk et al. 1999, Bryan and Norman 1998). With a realistic primordial chemistry model (e.g. Abel et al. 1997) and efficient numerical methods (e.g. Anninos et al. 1997) it is possible to also simulate the formation of the first cosmological objects. The first two–dimensional simulations of structure formation studied the collapse and fragmentation of cosmological sheets (Anninos and Norman 1996). In these simulations, the collapsing gas is heated in the accretion shock, and subsequently found to cool isobarically. The non–equilibrium abundance of electrons behind the strong accretion shock with \( T \gg 10^4 \text{K} \) reaches its maximum value, and fast \( \text{H}_2 \) formation up to an abundance of a few \( 10^{-3} \) (number fraction) is observed, in agreement with the study of \( \text{H}_2 \) formation in shock–heated gas by Shapiro & Kang (1987). A similar calculation has been carried out by Abel et al. (1998b) for the study of the two dimensional collapse of long cosmic string induced sheets. In this cosmic string scenario, the dominant mass component was assumed to be hot dark matter (HDM, e.g. massive neutrinos). One then envisions long, fast moving cosmic strings to induce velocity perturbations, causing sheets to collapse, cool and fragment (Rees 1986). The feedback from the newly formed stars might have then induced further structure formation as in Ikeuchi and Ostriker (1986). It turns out, however, that \( \text{H}_2 \) formation is inefficient at high redshift where the CMBR dissociates the intermediaries \( \text{H}^- \) and \( \text{H}_2^+ \). Furthermore, the shocks caused by the string–induced velocity perturbations are too weak to enhance \( \text{H}_2 \) formation. Consequently Abel et al. (1998b) concluded that the cosmic string plus HDM model cannot develop luminous objects before the HDM component becomes gravitationally unstable.

Numerical calculations of more “mainstream” structure formation scenarios have been presented by Abel (1995), Gnedin and Ostriker (1997, GO97 hereafter), Abel et al. (1998a, AANZ98), and Abel, Bryan, and Norman (2000, ABN00). The simulations presented in GO97 focused on simulating the thermal history of the intergalactic medium and included star formation and feedback mechanisms. Their simulations were designed to accurately compute the number of the first objects able to cool and collapse and hence had to sacrifice numerical resolution within the collapsed objects. Results such as the typical fragment masses, typical temperatures, etc. are also found in multi–dimensional simulations that start from more idealized initial conditions (e.g. Bromm, Coppi, and Larson 1999).

In general cosmological hydrodynamical simulations treat the dynamics of the assumed collisionless cold dark matter using N–body techniques. This is typically coupled to a hydrodynamic grid code, solving the fluid equations for a gas of primordial composition. The simulations are initialized at a high redshift ( \( \gtrsim 100 \) ) where density and velocity perturbations are small and in the linear regime. The simulation volume typically needs
to be chosen rather small (\(\lesssim 1\) comoving Mpc) to make sure that the simulation is at least capable of resolving the baryonic Jeans Mass prior to reionization,

\[
M_{J, IGM} \approx 1.0 \times 10^4 M_\odot \left(\frac{1 + z}{10}\right)^{3/2} \left(\frac{\Omega_B h^2}{0.02}\right)^{-1/2}.
\] (4.3)

The use of periodic boundary conditions for such small box sizes is only accurate at relatively high redshifts where they do model a representative piece of the model universe. Even in the lowest resolution simulations it becomes clear that an intricate network of sheets, and dense knots at the intersection of filaments is found. To the eye this structure is very similar to the simulation results on much larger scales.

Sufficient \(H_2\) molecules, enabling the gas to cool, form only in the dense spherical knots at the intersection of filaments (AANZ98). These knots consist of virializing dark matter halos that accrete gas mostly from the nearby filaments but also from the neighboring voids. An accretion shock transforms the kinetic energy of the incoming gas into internal thermal energy. This shock tends to be spherical towards the directions of the voids but is often disturbed and more complex in morphology at the interface to the filaments. For the first objects that show any molecular hydrogen cooling the accretion shock is too weak to raise the ionization level of the gas over its residual primordial fraction of \(n_{H^+}/n_H \approx 2.4 \times 10^{-4} \Omega_0^{1/2} h_{10}^{0.05}/(h \Omega_B)\) Peebles (1993). However, the associated raise in temperature of the post-shock gas allows molecule formation to proceed at time scales smaller than the Hubble time.

For the very first (i.e. least massive) objects with virial temperatures \(\lesssim 1000\) K molecule formation is relatively slow, and the cooling time remains longer than the free fall time. As the objects merge and accrete, the higher virial temperature allows the chemistry and cooling to operate on faster than dynamical time scales. This further merging induces a rather complex velocity and density field in the gas, as well as the dark matter. Typical cosmological hydrodynamic methods can not follow the further evolution of the fragmentation of the gas clouds due to lack of numerical resolution and it was not possible to assess the nature of the first luminous objects by direct simulation. This drawback was recently overcome by the simulations presented in Abel, Bryan and Norman (2000, ABN00) by exploiting adaptive mesh refinement techniques (Berger and Collela, 1989, Bryan & Norman 1997, 1999). This numerical scheme allows to follow the gas dynamics to smaller and smaller scales by introducing new finer grids as they are needed. Since this is done at a scale much below the local Jeans length one is confident to capture the essential scale of the fragmentation due to gravitational instability.

These simulations clearly show how a region at the center of the virialized halo, containing approximately \(200 M_\odot\) in baryons, collapses rapidly. This “core” is formed via the classical Bonnor–Ebert instability of isothermal spheres. It contracts faster than the dynamical time scales in its parent halo. Hence these simulations indicate that the first luminous object(s) (perhaps a massive star) will form before most of the gas in the halo can fragment (ABN00). This core might still fragment further when it turns fully molecular via the three body formation process (Palla et al. 1983, Silk 1983\footnote{Abel, Bryan, and Norman (unpublished) have carried out a simulation which includes the three–body \(H_2\) formation covering a dynamic range of \(3 \times 10^7\). A preliminary analysis suggests that the core does not fragment further when it turns full molecular. This suggests that most likely a massive star will form in the collapsing core.}). If the core forms stars at 100% efficiency an the ratio of produced UV photons per solar mass is the same as in present day star clusters than about \(6 \times 10^{63}\) UV photons would be liberated during the average life time of massive star (\(\sim 5 \times 10^7\) yrs). This is a few million times...
more than the $\sim 10^{57}$ hydrogen molecules within the virial radius, further suppressing $\mathrm{H}_2$ cooling and fragmentation. Hence, the first star(s) may halt star formation until the massive star(s) die(s). Only a small fraction of primordial gas might be able to condense into PopIII stars of pristine primordial composition.

5. Feedback Issues

The first stars formed via $\mathrm{H}_2$ cooling are expected to produce UV radiation, and explode as supernovae (if they are more massive than $\sim 8\, M_\odot$), producing significant prompt feedback on the $\mathrm{H}_2$ abundance in their own parent cloud. In addition, any soft UV radiation produced below 13.6eV and/or X–rays above $\gtrsim 1\,$keV from the first sources can propagate across the smooth H background gas, possibly influencing the chemistry of distant regions. Soft UV radiation is expected either from either a star or an accreting black hole, with a black hole possibly contributing X–rays, as well. (Although recent studies find that metal–free stars have unusually hard spectra, these do not extend to $\gtrsim 1\,$keV. See, e.g. Tumlinson & Shull 1999). The most important (and uncertain) quantity for assessing a stellar feedback is the IMF of the first stars. Several authors have argued that the IMF might be (see, e.g. Larson 1999 and references therein) biased towards massive stars. The lack of zero–metallicity stars, the so–called G–dwarf problem is resolved if the first generation of stars were short–lived; while the relatively inefficient cooling of metal–free gas could impose a minimum mass. A similar conclusion was reached by a recent 3D simulation (Bromm, Coppi, and Larson 1999).

The key question is whether the $\mathrm{H}_2$ abundance in a collapsed region is effected shortly after the first few sources turn on (either in the same collapsed region, or elsewhere in the universe), i.e. before the $\mathrm{H}_2$ abundance becomes irrelevant either because objects with $T_{\text{vir}} \lesssim 10^4\,$K are already collapsing, or because metal enrichment has reached sufficiently high levels that $\mathrm{H}_2$–cooling no longer dominates ($\sim 1\%$ solar, Bühringer & Hensler 1989). Ferrara (1998) considered the internal feedback from supernova explosions, and found that the non–equilibrium chemistry in the shocked gas can increase the $\mathrm{H}_2$ abundance. However, Omukai & Nishi (1999) argued that a single OB star can photodissociate the $\mathrm{H}_2$ molecules inside the whole $M \sim 10^6\, M_\odot$ cloud. Even if molecules re-form after SN explosions, they found a net negative feedback.

External feedback from an early soft UV background were considered by Haiman, Rees & Loeb (1997). It was found that $\mathrm{H}_2$ molecules are fragile, and easily photo–dissociated even inside large collapsed clumps via the two–body Solomon process (cf. Field et al. 1966)† – even when the background flux is several orders of magnitude smaller than the level $\sim 10^{-21}\,$erg cm$^{-2}$s$^{-1}$ Hz$^{-1}$ sr$^{-1}$ inferred from the proximity effect at $z \sim 3$ (Bajtlik et al. 1988), and needed for cosmological reionization at $z > 5$. These results were confirmed by a more detailed, self–consistent calculation of the build–up of the background and its effect on the contributing sources (Haiman, Abel & Rees 1999). The implication is a pause in the cosmic star–formation history: the buildup of the UVB and the epoch of reionization are delayed until larger halos ($T_{\text{vir}} \gtrsim 10^4\,$K) collapse. (This is somewhat similar to the pause caused later on at the 'H-reionization' epoch, when the Jeans mass is abruptly raised from $\sim 10^4\, M_\odot$ to $\sim 10^{8-9}\, M_\odot$.) An early background extending to the X–ray regime would change this conclusion, because it catalyzes the formation of $\mathrm{H}_2$ molecules in dense regions (Haiman, Rees & Loeb 1996, Haiman, Abel & Rees 2000). If quasars with hard spectra ($\nu F_\nu \approx \text{const}$) contributed significantly to

† Note that these objects might also explain the large number of Lyman Limit Systems observed in high redshift quasar spectra (Abel & Mo 1998).
the early cosmic background radiation then the feedback might even be positive, and reionization can be caused early on by the small halos.

6. Conclusions

In popular CDM models, the first stars or quasars likely appeared inside condensed clumps with virial temperatures \( T_{\text{vir}} \lesssim 10^4 K \) at redshifts \( z \sim 20 \). Because of the low virial temperatures, \( H_2 \) cooling (or lack thereof) played a dominant role in the gas dynamics inside these condensations. State–of–the–art numerical simulations identify the sites for the first star–formation with the intersection of dense filaments (Abel et al. 1998, 2000). Although not directly visible in \( H_2 \) emission, these star–formation sites could be detected out to \( z \sim 15 \) with the Next Generation Space Telescope, provided they have a star formation efficiency of \( \gtrsim \) one percent (Haiman & Loeb 1998), or they form quasar black holes with an efficiency of \( \sim 10^{-3} \) and shine at the Eddington luminosity (Haiman & Loeb 1998). In the latter case, early mini–quasars from \( H_2 \) cooling would reionize intergalactic hydrogen by \( z \sim 10 \). The average star–formation efficiency in collapsed halos before \( z \sim 3 \) can be estimated by matching the average metal enrichment of the Ly \( \alpha \) forest. If the latter is \( \sim 10^{-3} \) solar, this implies that \( \sim 2\% \) of the gas mass in collapsed regions are processed through stars (assuming a ratio in the number of high–mass to intermediate–mass stars as in a Salpeter IMF, see Haiman & Loeb 1997). This value is not far from the efficiency of \( \sim 1\% \) suggested by 3D simulations that resolve sub–parsec scales (ABN00); however it is unlikely that the early IMF was similar to the one observed in the local universe (e.g. Larson 1999). Arguably, further progress towards answering this question will have to come from a combination of more accurate simulations of star–formation in a metal–free plasma; including realistic radiative transfer.

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