FIRST STARS, VERY MASSIVE BLACK HOLES, AND METALS
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ABSTRACT
Recent studies suggest that the initial mass function (IMF) of the first stars (Population III) is likely to have been extremely top-heavy, unlike what is observed at present. We propose a scenario to generate fragmentation to lower masses once the first massive stars have formed and derive constraints on the primordial IMF. These studies have shown that gravitational collapse induces fragmentation of the first heavy elements. These metals enrich the surrounding gas up to \( \approx 10^{-4} Z_{0.1} \) when a transition to efficient cooling-driven fragmentation producing \( \lesssim 1 M_\odot \) clumps occurs. We argue that the remaining fraction of the first stars ends up in \( \approx 100 M_\odot \) VMBHs (very massive black holes). If we further assume that all these VMBHs are likely to end up in the centers of galactic nuclei constituting the observed supermassive black holes (SMBHs), then \( \approx 6\% \) of the first stars contributed to the initial metal enrichment and the IMF remained top-heavy down to a redshift \( z \approx 18.5\% \). Interestingly, this is the epoch at which the cool metals detected in the Ly\( \alpha \) forest at \( z \approx 3 \) must have been ejected from galaxies. At the other extreme, if none of these VMBHs has as yet ended up in SMBHs, we expect them to be either (1) en route toward galactic nuclei, thereby accounting for the X-ray–bright off-center sources detected locally by ROSAT, or (2) the dark matter candidate composed of the entire baryonic halos of galaxies. For case 1 we expect all but a negligible fraction of the primordial stars to produce metals, causing the transition at the maximum possible redshift of \( \gtrsim 22.1 \) and for case 2, \( \sim 3 \times 10^3 \), a very negligible fraction of the initial stars produce the metals and the transition redshift occurs at \( z_f \gtrsim 5.4 \). In this paper, we present a framework (albeit one that is not stringently constrained at present) that relates the first episode of star formation to the fate of their remnants at late times. Clearly, further progress in understanding the formation and fragmentation of Population III stars within the cosmological context will provide tighter constraints in the future. We conclude with a discussion of several hitherto unexplored implications of a high-mass–dominated star formation mode in the early universe.

Subject headings: black hole physics — cosmology: theory — galaxies: formation — intergalactic medium

On-line material: color figures

1. INTRODUCTION
Recent studies have started to tackle the formation and collapse of the first cosmic structures (often referred to as Population III objects) through numerical simulations (Abel et al. 1998; Bromm, Coppi, & Larson 1999; Bromm et al. 2001; Abel, Bryan, & Norman 2000) based on hierarchical scenarios of structure formation. These studies have shown that gravitational collapse induces fragmentation of pregalactic units with an initial baryonic mass \( \approx 10^5 M_\odot \) into smaller clumps with a typical mass of \( 10^3 M_\odot \), which corresponds to the Jeans mass set by molecular hydrogen cooling. However, a considerable mass range \( (10^2-10^4 M_\odot) \) for the clumps seems plausible.

Tracking the subsequent gravitational collapse of these metal-free clumps is a very challenging problem, as it requires the simultaneous solution of hydrodynamics and of (cooling lines) radiative transfer (Omukai & Nishi 1998; Nakamura & Umemura 1999; Ripamonti et al. 2001). Preliminary attempts and several physical arguments indicate that these clumps do not fragment into smaller units as the evolution progresses to higher densities. Independent studies (Hernandez & Ferrara 2001) comparing the observed number of metal-poor stars with that predicted by cosmological models also imply that the characteristic stellar mass sharply increases with redshift. Hence, there are grounds to believe that the first stars were very massive.

The evolution of massive, metal-free stars is currently subject to a rapidly growing number of studies (Fryer 1999; Fryer, Woosley, & Heger 2001; Heger & Woosley 2001) that rejuvenate earlier activity (Fowler & Hoyle 1964; Carr, Bond, & Arnett 1984; El Eid et al. 1983; Fricke 1973; Fuller et al. 1986). As we discuss in detail later in this paper, stars more massive than about 260 \( M_\odot \) collapse completely to black holes, therefore not contributing to the metal enrichment of the surrounding gas. Similar arguments apply to stars in a lower mass window (30–140 \( M_\odot \)), which are also expected to end their evolution as black holes. Hence, if supernovae from more standard progenitors (stellar masses in the range 8–40 \( M_\odot \)) are neither formed efficiently nor occur in negligible numbers, it appears that the initial cosmic metal enrichment had to rely on the heavy-element yield from the so-called pair-unstable supernovae (SN\( \gamma \)), whose explosion leaves no remnant. This conclusion can potentially be tested by studying peculiar elemental abundances, for example, of heavy \( r \)-process elements (Oh et al. 2001).

Metallicity is thought to noticeably affect the fragmentation properties of a gravitationally unstable gas. For example, Bromm et al. (2001) have shown that the evolution of a collapsing protogalaxy depends strongly on the level of gas preenrichment. These authors argue that a critical metallic-
ity $\approx 10^{-4} Z_{\odot}$ exists such that above that value vigorous fragmentation into relatively low mass ($\approx 10 M_{\odot}$) clumps takes place, differently from what is discussed above under metal-free conditions.

The key question, then, concerns the interplay between the properties of the initial mass function (IMF) and the metal enrichment of the gas. To better illustrate this, let us ideally suppose that the first stars are all formed—as suggested by numerical simulations—with masses above the SN$_{\gamma}$ mass threshold, thus leading to the formation of black holes. Then, because metals are completely swallowed by the latter, the gas retains its primordial composition and star formation continues in the high-mass–biased mode. A solution to this “star formation conundrum” must evidently exist, as at present stars form with a much lower characteristic mass ($\approx 1 M_{\odot}$).

In this paper, we describe in detail a possible solution to this conundrum utilizing various constraints: metal abundance patterns in clusters, the mass density of supermassive black holes, off-nuclear galactic X-ray sources, and to a more speculative extent, the nature of a particular class (optically hidden) of gamma-ray bursts; we attempt to infer the main properties of the early stages of cosmic star formation.

2. FRAGMENTATION MODES

In this section, we focus on the first episode of star formation and discuss the relevant cooling criteria and timescales in detail. We work within the paradigm of hierarchical cold dark matter (CDM) models for structure formation, wherein dark matter halos collapse and the baryons in them condense, cool, and eventually form stars. Once a halo of mass $M$ collapses at redshift of $z_c$, the baryons are shock-heated to the virial temperature given by

$$T_{\text{vir}} = 10^4 \frac{\mu M_8^{2/3}}{(1 + z_c/10)} \text{K},$$

where $M_8 = M/10^8 h^{-1} M_{\odot}$ and $\mu$ is the molecular weight. If $T_{\text{vir}} \gtrsim 10^4 \text{K}$ [or equivalently $M \gtrsim 10^4 (1 + z_c/100)^{3/2} h^{-1} M_{\odot}$], the baryonic gas cools because of the excitation of the hydrogen Ly-$\alpha$ line. In the absence of metals, as expected for the very first episode of star formation, objects with $T_{\text{vir}} \lesssim 10^4 \text{K}$ can cool only through the collisional excitation of molecular hydrogen. Hereafter in this work, we refer to the former objects as Ly-$\alpha$-cooling halos and to the latter as Population III objects.

The first stars form once the gas cools. The typical IMF of this first generation of stars is still highly uncertain. Several authors have tackled this crucial issue through theoretical (Rees 1976; Rees & Ostriker 1977; Silk 1977, 1983; Haiman, Thoul, & Loeb 1996; Uehara et al. 1996) and numerical approaches (Omukai & Nishi 1998; Nakamura & Umemura 1999, 2001; Abel et al. 2000; Bromm et al. 1999; Omukai 2000, 2001; Ripamonti et al. 2001). Recent multidimensional simulations of the collapse and fragmentation of primordial gas within Population III objects show preliminary indications that the IMF could be either top-heavy with typical masses of the order of $\approx 10^2 M_{\odot}$ (Abel et al. 2000; Bromm et al. 2001) or bimodal with peaks at $\approx 10^2$ and $\approx 1 M_{\odot}$ (Nakamura & Umemura 2001). Note that these numerical treatments cannot address the issue of the mass spectrum. Therefore, it is important to understand what physical processes set the scales of fragment masses and hence the stellar mass spectrum.

It is obvious that much hinges on the physics of cooling, primarily the number of channels available for the gas to cool and the efficiency of the process (Rees & Ostriker 1977). In general, cooling is efficient when the cooling time $t_{\text{cool}} = 3n_b T/2\Lambda(n, T)$ is much shorter than the free-fall time $t_{\text{ff}} = (3\pi/32G\rho)^{1/2}$, i.e., $t_{\text{cool}} \ll t_{\text{ff}}$, where $n\rho$ is the gas number (mass) density and $\Lambda(n, T)$ is the net radiative cooling rate (ergs cm$^{-3}$ s$^{-1}$). This efficiency condition implies that the energy deposited by gravitational contraction cannot balance the radiative losses; as a consequence, temperature decreases with increasing density. Under such circumstances, the cloud cools and then fragments. At any given time, fragments form on a scale that is small enough to ensure pressure equilibrium at the corresponding temperature, i.e., the Jeans length scale,

$$R_F \approx \lambda_{\odot} \times c_s t_{\text{ff}} \propto n^{7/2-1},$$

where the sound speed $c_s = (RT/\mu)^{1/2}, T \propto n^{-1}$, where $\gamma$ is the adiabatic index. Since $c_s$ varies on the cooling timescale, the corresponding $R_F$ becomes smaller as $T$ decreases. Similarly, the corresponding fragment mass is the Jeans mass,

$$M_F \propto n R_F^3 \propto n^{\gamma/2 + (1-\eta)},$$

with $\eta = 2$ for filaments and $\eta = 3$ for spherical fragments (Spitzer 1978). This hierarchical fragmentation process comes to an end when cooling becomes inefficient because (1) the critical density for LTE is reached or (2) the gas becomes optically thick to cooling radiation; in both cases, at that juncture $t_{\text{cool}} \approx t_{\text{ff}}$. At this stage, the temperature cannot decrease any further, and it either remains constant (if energy deposition by gravitational contraction is exactly balanced by radiative losses) or increases. The necessary condition to stop fragmentation and start gravitational contraction within each fragment is that the Jeans mass does not decrease any further, thus favoring fragmentation into subclumps. From equation (3), this implies the condition

$$\gamma \geq 2 \frac{\eta - 1}{\eta},$$

which translates into $\gamma \gtrsim 4/3$ for a spherical fragment and $\gamma \gtrsim 1$ for a filament. Thus, a filament is marginally stable and contracts quasi-statically when $t_{\text{cool}} \approx t_{\text{ff}}$ and the gas becomes isothermal. Finally, when $t_{\text{cool}} \gg t_{\text{ff}}$ or the fragments become optically thick to cooling radiation, the temperature increases as the contraction proceeds adiabatically.

2.1. Fragmentation of Metal-free Clouds

In this subsection, we follow the evolution of metal-free primordial clumps during the fragmentation process. These results are based on the model of Omukai (2001). The gas within the dark matter halo is given an initial temperature of $100$ K, and the subsequent thermal and chemical evolution of the gravitationally collapsing cloud is followed numerically until a central protostellar core forms.

The gas within the dark matter halo gets shock-heated to the virial temperature $T_{\text{vir}}$, which is typically $\gg 100$ K. However, after a short transient phase (irrelevant for the present analysis), the evolutionary track in the $(n, T)$ plane shown in Figure 1 (top curve, top panel) provides a good description
of the thermal evolution of the gas. The metal-free gas is able to cool down to temperatures of a few hundred kelvin regardless of the initial virial temperature. This is the minimum temperature at which molecular line cooling becomes effective.

In this analysis, external sources of heating are not included (i.e., external UV background or cosmic microwave background [CMB] radiation). This is because at redshifts prior to reionization, the UV background field is relatively weak and inhomogeneous (Ciardi, Ferrara, & Abel 2000), and hence we do not expect it to be important. Also, the CMB energy input is negligible for clouds with $T > 10^4$ K (or $Z < 10^{-4} Z_\odot$), where the first stars presumably formed at redshifts $z < 30$. It might affect the temperature evolution of more metal-rich systems shown in Figure 1, but it does not modify the conclusions drawn here.

The gas within halos with $T_{\text{vir}} > 10^4$ K starts to cool through the hydrogen Ly$\alpha$ line. It quickly reaches a temperature of $\approx 8000$ K, and at this stage, the fraction of molecular hydrogen formed is sufficient to activate H$_2$ rovibrational line cooling. Thereafter, the gas within a Ly$\alpha$-cooling halo follows the same thermal evolution as the gas within Population III objects. Independent of the virial temperature, the thermal evolution of the gas rapidly converges to the $(n, T)$ track corresponding to $Z = 0$ (the zero-metallicity track) shown in Figure 1. The temperature of the gas decreases with increasing density, thus favoring fragmentation into subclumps.

As the number density increases, it reaches the critical value $n_\text{cr} \approx 10^3$ cm$^{-3}$, and the corresponding Jeans mass is $\approx 10^4 M_\odot$ (open circle in the top panel of Fig. 1). The cooling time at this critical point becomes comparable to the free-fall time as a consequence of the H$_2$ levels being populated according to LTE [regime in which the cooling rate $\Lambda(n, T) \propto n$] and no longer according to non-LTE (NLTE) [regime in which $\Lambda(n, T) \propto n^2$]. The temperature then starts to rise slowly.

At this stage, the stability of the fragments toward further increase in the density needs to be investigated according to equation (4) above. The bottom panel of Figure 1 shows the density dependence of $\gamma$ (see eq. [2]) for each metallicity track. For a metal-free gas, $\gamma$ lies in the range $0 < \gamma < 30$, implying that further fragmentation is unlikely to occur unless the fragments are spherical. Although the gravitational evolution will probably favor a tendency toward spherical symmetry, this is not likely to occur until the central density has reached high ($\approx 10^8$ cm$^{-3}$) values as seen from simulations (e.g., Abel et al. 2000).

The only two deviations from the above range occur (see Fig. 1, bottom panel) around $n = 10^{10}$ and $10^{16}$ cm$^{-3}$. The former is a result of the thermal instability due to three-body H$_2$ formation (Silk 1983; Haiman et al. 1996). However, this instability is quite weak and does not lead to fragmentation (Abel et al. 2000). The latter (at $n = 10^{16}$ cm$^{-3}$) is caused by H$_2$ collision-induced emission. This instability is also weak and probably unimportant.

It is important to stress that, even if the fragments are nearly spherical, fragmentation will be modest and is likely to result only in a low-multiplicity stellar system. As the density increases, quasi-static contraction takes place ($n = 10^{20}$ cm$^{-3}$) until the fragments become optically thick to H$_2$ lines, $t_{\text{cool}} \gg t_{\text{ff}}$, and adiabatically collapse to increasingly higher central densities and temperatures. At this stage, $\gamma > 4/3$ and a central hydrostatic core (stellar core; filled circle in Fig. 1, top panel) is formed, with mass $\approx 10^{-3} M_\odot$ (Omukai & Nishi 1998).

We stress again that as long as the gas is metal free, this sequence of events and conclusions hold independent of the halo virial temperature, i.e., for Population III objects as well as for Ly$\alpha$-cooling halos. In Figure 2, we show the evolution with temperature of the ionization fraction and of the fraction of molecular hydrogen for typical Ly$\alpha$-cooling halos of mass $M = 10^8 M_\odot$ at three different redshifts, $z = 15, 20,$ and 25. We find that the evolution of these fractions is independent of the mass (or, equivalently, $T_{\text{vir}}$) and virialization redshift. Molecular formation in the postshock flow that follows the virialization of the gas within a dark matter halo has been recently investigated by Uehara & Inutsuka (2000). If the gas is fully ionized, molecules form through nonequilibrium recombination, leading to overall fractions that are much higher than in the expanding homogeneous universe. As a consequence of enhanced H$_2$ and HD fractions, the gas rapidly cools to well below $10^4$ K and fragments. Molecular chemistry is important also for star formation in halos with $T_{\text{vir}} > 10^4$ K as assessed by Susa et al. (1998) and Oh & Haiman (2002). They find that initial atomic line cooling leaves a large residual free electron density that allows molecule formation up to a universal fraction of $x_{\text{H}_2} = 10^{-3}$. The newly formed molecules cool the gas further to $\approx 100$ K, and the gas fragments on mass scales of a few $10^8 M_\odot$.

Once the critical density for H$_2$ ($n_\text{vir} \approx 10^5$ or $10^6$ cm$^{-3}$ for HD, if this is assumed to be the main coolant) has been reached, LTE conditions for the level populations disfavor freezeout of molecules.

![Figure 1](image.png)

**Fig. 1.** Top: Evolution of the temperature as a function of the hydrogen number density of protostellar clouds with the same initial gas temperature but varying metallicities $Z = (0, 10^{-6}, 10^{-4}, 10^{-2}, 1) Z_\odot$ ($Z$ increasing from top to bottom curves). The dashed lines correspond to the constant Jeans mass for spherical clumps; open circles indicate the points where fragmentation stops; filled circles mark the formation of hydrostatic cores. This figure is reproduced from Fig. 1 of Omukai (2000) for illustration after some modifications. Bottom: The adiabatic index $\gamma$ as a function of the hydrogen number density for the curves shown in the top panel. Dotted (dashed) lines correspond to $\gamma = 1$ ($\gamma = 4/3$); open and filled circles as above.
Further cooling and fragmentation. At this stage, fragments have masses comparable to the Jeans mass corresponding to the point \((n_{\text{cr}}, T_{\text{vir}})\) and virialize, following the evolution described above. Therefore, independent of the initial virial temperature, fragments are formed with typical masses \(\approx 10^3 - 10^4 M_\odot\).

Each fragment is characterized by a central core of \(10^{-3} M_\odot\) surrounded by a large envelope of gravitationally unstable gas. The core grows in mass because of gas accretion from the envelope. The mass of the formed stars depends on the accretion rate as well as on the fragment mass (Larson 1999). In the absence of metals, radiation pressure cannot counterbalance mass accretion onto the core (Ripamonti et al. 2001; Omukai & Inutsuka 2001), and the mass of the resulting star is comparable to that of the original fragment, i.e., \(m \lesssim 10^3 M_\odot\). We will return to this crucial issue in §2.3. Of course, if the parent cloud is rotating, angular momentum, if not dissipated, might prevent the collapse of the entire cloud. However, for the arguments relevant to this paper, it is sufficient that the overall efficiency is a few percent, thus yielding a few hundred solar mass stars out of the \(\approx 10^4 M_\odot\) fragments predicted by Figure 1. The question that needs to be addressed now is what mechanism can finally lead to the transition to a conventional mode of star formation, i.e., to a standard IMF, and what are the necessary conditions for this to occur.

2.2. Fragmentation of Metal-enriched Clouds

We now consider the effects of the presence of heavy elements on the fragmentation process. The discussion presented in this section is based on the analysis by Omukai (2000) (see the original paper for details). Figure 1, reproduced from Omukai (2000), shows the effects of metal enrichment on the \((n, T)\) tracks for the same initial conditions and different values of the mean metallicity.

In general, clouds with lower metallicity tend to be warmer because of their lower radiative cooling ability. As long as the clouds are transparent, cooling and fragmentation occur. Clouds with a mean metallicity \(Z \approx 10^{-6} Z_\odot\) follow the same evolution as that of the gas with primordial composition in the \((n, T)\) plane. However, at \(Z \gtrsim 10^{-4} Z_\odot\), \(H_2\) formation on grain surfaces enhances cooling at low density. Dust grains are well known to condense out the ejecta of SNe (see Todini & Ferrara 2001 and references therein). When the LTE-NLTE transition occurs for \(H_2\), the cloud can still cool (although less efficiently) because of \(O\) line cooling. At densities greater than \(10^6\) cm\(^{-3}\), heating due to \(H_2\) formation becomes larger than compressional work, i.e., \(\gamma > 1\), and the temperature starts to increase until thermal emission from grains due to energy transfer between gas and dust dominates the cooling. This occurs at a density \(n \approx 10^{10}\) cm\(^{-3}\), where the temperature drops to \(\approx 100\) K and a new fragmentation phase occurs. This shows up in the bottom panel of Figure 1 as the large dip in the \(\gamma\) evolution. The minimum fragment mass is reached at the point indicated by the open circle, when the density is \(\approx 10^{13}\) cm\(^{-3}\) and the corresponding Jeans mass is of the order \(10^{-2} M_\odot\). Finally, as the density increases, the gas becomes opaque to dust thermal emission, fragmentation stops, and compressional heating causes the fragments to contract adiabatically (\(\gamma > 4/3\)). Therefore, a critical metallicity of \(Z_{\text{cr}} \approx 10^{-4} Z_\odot\) can be identified, which marks the transition point between metal-free and metal-rich gas evolution.

When the metallicity is \(Z > 10^{-4} Z_\odot\), at density \(\lesssim 10^4\) cm\(^{-3}\) cooling is driven by \(O\) line and CO line emission. When the NLTE-LTE transition for the level populations of CO occurs, fragmentation stops and the temperature increases because of \(H_2\) formation. The larger concentration of dust grains (assumed here to be proportional to the mean metallicity) leads to a significant thermal emission that is responsible for cooling the gas and starting a new phase of fragmentation. This stops when \(T_{\text{grain}} \approx T\), and thereafter the fragments contract quasi-statically until they become optically opaque to dust emission and adiabatic contraction occurs. Because of the enhanced ability to cool, fragmentation stops at lower temperatures and densities for higher metallicity clouds (see open circles in the bottom panel of Fig. 1). However, the Jeans mass corresponding to the minimum fragmentation scale is always \(10^{-2} M_\odot \lesssim M_F \lesssim 1\) \(M_\odot\) for the metallicity range \(10^{-4} \lesssim Z/Z_\odot \lesssim 1\), several orders of magnitude smaller than for a cloud with no metals.

At the onset of adiabatic contraction, when \(\gamma\) becomes larger than \(4/3\), an initial hydrostatic core (transient core) forms with a mass \(\approx 10^{-2} M_\odot\), regardless of the metallicity of the gas. This transient core is fully molecular and is absent when the gas is metal free. The temperature of the transient core increases as its mass increases because of accretion of surrounding gas. Eventually, the temperature reaches about 2000 K, where \(H_2\) dissociation begins. This softens the equation of state until the dissociation is almost complete. Then, \(\gamma\) falls below \(4/3\) in the density range \(10^{16} - 10^{20}\) cm\(^{-3}\). Note that the thermal evolution after \(H_2\) dissociation (i.e., \(n > 10^{16}\) cm\(^{-3}\)) is the same independent of the initial composition of the gas. After \(\gamma\) once again exceeds \(4/3\), a hydrostatic core (so-called stellar core) forms. Its
physical characteristics are independent of metallicity \( (n \approx 10^{22} \, \text{cm}^{-3}, M \approx 10^{-3} \, M_\odot; \text{Omukai} \, 2000) \).

2.3. Formation of Protostars

Protostars, whose mass is initially very low (about \( 10^{-3} \, M_\odot \)), grow in mass by accretion of the envelope material. The final mass of stars is then determined not only by the mass of the fragments, but also by when accretion stops. The accretion rate onto the protostar is related to the sound speed (and therefore, temperature) of the protostellar cloud by the relation \( M \approx c_s^3/G \) (Stahler, Shu, & Taam 1980).

As seen in Figure 1, the temperature of protostellar clouds decreases with metallicity. Therefore, the mass accretion rate is higher for protostars formed from lower metallicity gas. If dust is present in the accretion flow, accretion onto the massive protostar becomes increasingly difficult owing to the radiation pressure onto the dust. In present-day interstellar gas, accretion onto stars more massive than \( 30 \, M_\odot \) is inhibited by this mechanism (Wolfire & Cassinelli 1987). In gas with lower metallicity, the mass bound is expected to be higher because of the higher accretion rate and lower radiation force. In particular for metal-free gas this mechanism does not work. Therefore, without dust, accretion is likely to continue until the ambient gas supply is exhausted (Ripamonti et al. 2001; Omukai & Inutsuka 2001).

In conclusion, the presence of metals not only enables fragmentation down to smaller mass scales \( 10^{-2} \, M_\odot \), but also breaks the one-to-one correspondence between the mass of the formed star and that of the parent fragment by halting the accretion through radiation force onto the dust.

3. THE STAR FORMATION CONUNDRUM

According to the scenario proposed above, the first stars that form within Population III and Ly\( \alpha \)-cooling halos out of gas of primordial composition tend to be very massive, with masses \( \approx 10^2-10^3 \, M_\odot \). It is only when metals change the composition of the gas that further fragmentation occurs, producing stars with significantly lower masses. It is at this stage that we expect a transition to occur from a top-heavy IMF toward a more conventional IMF with a wide range of masses, such as the one observed locally (Scalo 1998; Kroupa 2001).

A growing body of observational evidence points to an early top-heavy IMF (see Hernandez & Ferrara 2001 and references therein). Compelling arguments for an early top-heavy IMF can also be made from observations on various scales: (1) the early enrichment of our Galaxy required to solve the so-called G dwarf problem, (2) the abundance patterns of metals in the intracluster medium (ICM), (3) the energetics of the ICM, (4) the nondetection of metal-free stars, and (5) the overproduction of low-mass stars at the present epoch and metals at \( z \approx 2-5 \) for the submillimeter-derived star formation histories using Submillimeter Common-User Bolometric Array (SCUBA) detections for a standard IMF can be resolved with an early top-heavy IMF.

For instance, the ICM metal abundances measured from \textit{Chandra} and \textit{XMM} spectral data are higher than expected from the enrichment by standard IMF SN yields in cluster galaxy members, which can be explained by a top-heavy early IMF. Furthermore, the observed abundance anomalies (e.g., oxygen) in the ICM can be explained by an early generation of Population III SNe (Loewenstein 2001). There is observational evidence from the abundance ratio patterns of [Si/Fe], [Mg/Fe], [Ca/Fe], and [Ti/Fe] in the extremely metal poor double-lined spectroscopic binary CS 22876-032 in the halo of our Galaxy (Norris, Beers, & Ryan 2000) for enrichment by a massive, zero-metallicity supernova in comparison with the theoretical models of Woosley & Weaver (1995). These issues, highly suggestive of top-heavy early star formation, have recently motivated a series of numerical investigations of the nucleosynthesis and final fate of metal-free massive stars (Heger & Woosley 2001; Fryer et al. 2001; Umeda & Nomoto 2002). In their recent paper, Heger & Woosley (2001) delineate three mass ranges characterized by distinct evolutionary paths:

1. \( M_\star \gtrsim 260 \, M_\odot \). The nuclear energy release from the collapse of stars in this mass range is insufficient to reverse the implosion. The final result is a very massive black hole (VMBH) locking up all heavy elements produced.

2. \( 140 \, M_\odot \lesssim M_\star \lesssim 260 \, M_\odot \). The mass regime of the pair-unstable supernovae (SN\( u_e \)). Precollapse winds and pulsations result in little mass loss; the star implodes to a maximum temperature that depends on its mass and then explodes, leaving no remnant. The explosion expels metals into the surrounding ambient ISM.

3. \( 30 \, M_\odot \lesssim M_\star \lesssim 140 \, M_\odot \). Black hole formation is the most likely outcome, because either a successful outgoing shock fails to occur or the shock is so weak that the fallback converts the neutron star remnant into a black hole (Fryer 1999).

Stars that form in the mass ranges 1 and 3 above fail to eject most of their heavy elements. If the first stars have masses in excess of \( 260 \, M_\odot \) (in agreement with numerical findings), they invariably end their lives as VMBHs (in the following we will refer to VMBHs as black holes of a hundred solar mass or so) and do not release any of their synthesized heavy elements. However, as we have shown, as long as the gas remains metal free, the subsequent generations of stars will continue to be top-heavy. This “star formation conundrum” can be solved only if a fraction of the first generation of massive stars have masses \( \lesssim 260 \, M_\odot \). Under such circumstances, these will explode as SN\( e \) and enrich the gas with heavy elements up to a mean metallicity of \( Z \gtrsim 10^{-4} \, Z_\odot \), and as per arguments outlined in § 2 (see Fig. 1), thereafter causing a shift over to an IMF that is similar to the local one. In what follows, we further explore the implications of the above scenario and derive the conditions for the solution of the conundrum.

3.1. Abundance of VMBHs and Metals

As a consequence of the picture proposed above, VMBHs are an inevitable outcome. We now compute the expected mass density of metals and the mass density of remnant VMBHs produced in such a first episode of star formation. For a collapsed dark matter halo of total mass \( M \), the associated baryonic mass is assumed to be \( M(\Omega_B/\Omega_M) \) (where \( \Omega_B/\Omega_M \) is simply the baryon fraction). Following the results of numerical simulations at different resolutions (Bromm et al. 2001; Abel et al. 2000), we assume that \( \approx \frac{1}{3} \) of the total available gas is utilized in star formation, the rest remaining in diffuse form.
The relative mass fractions of SN\textsubscript{\gamma} and VMBH progenitors are parameterized as

\[ M_{\gamma} = f_{\gamma} \frac{M}{2} \left( \frac{\Omega_B}{\Omega_M} \right) = f_{\gamma} M_* , \tag{5} \]

\[ M_{\text{BH}} = (1 - f_{\gamma}) \frac{M}{2} \left( \frac{\Omega_B}{\Omega_M} \right) = (1 - f_{\gamma}) M_* , \]

where \( M_{\gamma} \) (\( M_{\text{BH}} \)) is the total mass that ends up in SN\textsubscript{\gamma} (VMBHs) and \( M_* \) is the mass processed into stars. Thus, only a fraction \( f_{\gamma} \) of the formed stars can contribute to gas metal enrichment. The metal yields for the dominant elements have been computed using the results of Heger & Woosley (2001) and are plotted in Figure 3 as a function of the mass of the progenitor star. The bulk of the yield is contributed by O\textsuperscript{16}, and the mass of metals ejected can be written as

\[ M_Z \approx \frac{M_{\gamma}}{2} - 10 \frac{M_*}{200 M_*} , \tag{6} \]

where we have taken \( \approx 200 M_* \) as a fiducial mass for SN\textsubscript{\gamma} progenitors. Next, the further assumption is made that metals are ejected from the parent galaxy into the IGM and that their cosmic volume filling factor is close to unity, therefore uniformly polluting the IGM. This comes from the results of Madau, Ferrara, & Rees (2001, hereafter MFR01) and Mori, Ferrara, & Madau (2002), in which it is shown that for reasonable values of the star formation efficiency, metal bubbles produced by (standard SNe II in) protogalaxies that result from 2 \( \sigma \) peaks of the density power spectrum at redshift 10 do overlap. Indeed, the kinetic energy released by SN\textsubscript{\gamma}, is much higher than for ordinary SNe II (see Fig. 2), hence making our assumption even more solid. The temperature of the hot gas is expected to be somewhat higher than estimated by MFR01; however, because of the higher redshifts and consequent stronger inverse Compton cooling, ejected metals have enough time to cool by \( z \approx 3 \).

As long as the average metallicity is below the critical value, i.e., \( Z_{cr} = 10^{-4} Z_{\odot} \), we argue that the IMF remains top-heavy and the redshift-dependent critical density of metals contributed by all SN\textsubscript{\gamma} at redshifts greater than \( z \) can be computed as

\[ \Omega_Z(z) = \frac{1}{ \rho_{cr} } \int_0^\infty \int_{f_{\gamma}(z)}^{f_{\gamma}(z)} dM n(M, z) M_Z , \tag{7} \]

where \( n(M, z) \) is the number density of halos per unit mass predicted by the Press-Schechter formalism, and the integration is performed from \( M_{\text{min}}(z) \), which is the minimum mass that can cool within a Hubble time at the specified formation redshift \( z \), i.e., \( t_{cool}(M, z) \leq t_{H}(z) \) (see Ciardi et al. 2000). We adopt a cosmological model with the following parameters to compute the abundance of halos: \( \Omega_M = 0.3, \Omega_L = 0.7, h = 0.65, \) and \( \Omega_B = 0.047 \) (latest predictions from big bang nucleosynthesis; see Burles, Nollett, & Turner 2001), and use the COBE-normalized power spectrum for fluctuations as described in Efstathiou, Bond, & White (1992).

From equation (7), we can estimate the transition redshift \( z_f \) at which the mean metallicity is \( 10^{-4} Z_{\odot} \),

\[ \langle Z(z_f) \rangle = \frac{\Omega_Z(z_f)}{\Omega_B} \approx 10^{-4} Z_{\odot} , \tag{8} \]

for various values of the fraction \( f_{\gamma} \). The results are plotted in Figure 4 along with the corresponding critical density \( \Omega_{\text{VMBH}} \) contributed by the VMBHs formed, which is given by the \( z_f \) curve. [See the electronic edition of the Journal for a color version of this figure.]

**Fig. 3.**—Metal yields of the main elements synthesized in metal-free SN\textsubscript{\gamma}, according to Heger & Woosley (2001). The upper solid line corresponds to the total yield ejected, and the dashed line indicates the kinetic energy of the explosion. [See the electronic edition of the Journal for a color version of this figure.]

**Fig. 4.**—Top-heavy to normal IMF transition redshift, \( z_f \), as a function of SN\textsubscript{\gamma} progenitor mass fraction and the mass density contributed by VMBHs \( \Omega_{\text{VMBH}} \). Top: The computed critical density of VMBH remnants is compared to the observed value for SMBHs (upper dashed line). Bottom: The computed critical density of VMBH remnants is compared to the contribution to \( \Omega \) from the X-ray–bright, off-center ROSAT sources (lower dashed line) and to the abundance predicted assuming that the baryonic dark matter in galaxy halos is entirely contributed by VMBHs (upper dashed line). The observations on \( \Omega_{\text{VMBH}} \) constrain the value for \( f_{\gamma} \). For a given \( f_{\gamma} \), the corresponding value for the transition redshift can be inferred by the \( z_f \) curve. [See the electronic edition of the Journal for a color version of this figure.]
Unavane (1998) have convincingly argued that low-mass stars (in fact, hydrogen-burning stars of any mass) do not provide a substantial portion of the dark matter inferred in the halos of galaxies. In combination with the mass limits obtained on potential dark matter candidates from the MACHO (Alcock et al. 2001) and EROS (Lasserre et al. 2000) experiments (microlensing studies) in our Galaxy, low-mass objects with masses under 10 M⊙ are ruled out, thereby making VMBHs (∼100 M⊙ BHs) in halos (case B) plausible dark matter candidates.

For case A, we can simply equate f_0 to the measured mass density in SMBHs found from the demography of nuclei of nearby galaxies (Magorrian et al. 1998; Gebhardt et al. 2001) indicated by the horizontal line in Fig. 4 (top panel). The most recent value reported by Merritt & Ferrarese (2001) is Ω_{SMBH}^0 = 10^{-4} h Ω_b, which for h = 0.65 and Ω_b = 0.047 yields f_0 = 3.05 × 10^{-6}. From the top panel of Figure 4, we see that this gives f_0 ≈ 0.06. The corresponding value for the transition redshift can be found on the z_f curve on the same plot, yielding a value z_f ≈ 18.5. This constraint implies that all but a small fraction of the mass involved in the first episode of star formation—approximately 60%—went into objects outside the mass range 140 M⊙ < M_s < 260 M⊙, yielding remnant black holes with mass 10–500 M⊙. The scenario corresponding to case A therefore implies that z_f, the transition redshift from top-heavy to normal IMF, occurred at ≈10. This value for z_f is consistent with the estimate from MFR01 for the redshift at which the metals in the Lyman forest need to have been released to explain their absorption line widths measured at z ≈ 3 (their cool temperature requires ejection at much higher redshift).

Let us now look at the other extreme case, B, wherein the assembled SMBHs in galactic centers have formed primarily via accretion and are unrelated to VMBHs. This leads us to two further possibilities: (1) VMBHs would still be in the process of spiraling into the centers of galaxies because of dynamical friction but are unlikely to have reached the centers within a Hubble time because of the dynamical friction timescale being long (Madau & Rees 2001), or (2) VMBHs contribute the entire baryonic dark matter in galactic halos.

Pursuing scenario 1, at best some fraction of these VMBHs (for instance, those in gas-rich regions of gas-rich systems) might appear as off-center accreting sources that show up in the hard X-ray wave band. Such sources have indeed been detected both by ROSAT (Roberts & Warwick 2000) and more recently by Chandra in nearby galaxies (M84: Jones 2001; NGC 720: Buote 2001).

In a survey of archival ROSAT HRI data to study the X-ray properties of the nuclei of 486 optically selected bright nearby galaxies (Ho, Filippenko, & Sargent 1995), Roberts & Warwick (2000) found a large number of off-center X-ray sources. The X-ray sources detected within the optical extent of these galaxies were classified either as nuclear or nonnuclear (and therefore off-center) depending on whether the source was positioned within 25″ of the optical nucleus. They detect a nuclear source in over 70% of the galaxy sample and a total of 142 off-center sources. Roberts & Warwick (2000) find that the nonnuclear sources follow a steep, near power-law X-ray luminosity distribution in the 10^{36}–10^{40} ergs s^{-1}, which leads to an L_X/L_B ratio of

\[
\frac{L_X}{L_B} = 1.1 \times 10^{39} \text{ergs s}^{-1}(10^{10} L_\odot)^{-1}.
\]
The median luminosity of the nonnuclear sources is found to be a factor of ~10 lower than that of the nuclear sources. However, they estimate the incidence rate of off-center sources with $L_X \geq 10^{38.3} \text{ergs s}^{-1}$ (which corresponds to the Eddington luminosity for a 1.4 $M_\odot$ neutron star) to be $\approx 0.7$ per $10^{10} L_\odot$ galaxy. The existence of accreting VMBHs might also help explain the following observation. The far-IR (FIR) excess detected with DIRBE at 60 and 100 $\mu$m has been tentatively interpreted as an extragalactic background with integrated intensity of $44 \pm 9 \text{nW m}^{-2} \text{sr}^{-1}$ in the range 60–100 $\mu$m (Finkbeiner, Davis, & Schlegel 2000). The energy required to produce such a FIR background could derive from a highly obscured population of accreting VMBHs at moderate redshifts (for an alternative to this, see explanation of scenario 2 below).

In order to estimate the mass density contributed by these VMBHs, we can compare the mass in VMBHs to that of the SMBH in a typical galaxy of luminosity, say $10^{10} L_\odot$ for case B. Most of the VMBHs are likely to be en route to galactic centers. Note, however, that not all the inspiraling VMBHs will be accreting and X-ray bright; many of these could, in fact, be low radiative efficiency advection-dominated accretion flows (ADAFs), and therefore be too faint to be detected by ROSAT or Chandra, or not accreting at all if they do not happen to be in gas-rich regions of the galaxy. Thus, using the following argument we can obtain a lower limit on the abundance of VMBHs.

The mass of the central SMBH hosted by a galaxy with a luminosity $L_{\text{galaxy}} = 10^{10} L_\odot$ (assumed to be the fiducial galaxy for these purposes) in the B band is given by (Merritt & Ferrarese 2001)

$$M_{\text{SMBH}} = 10^{-3} M_{\text{bulge}} = 10^{-3} L_{\text{galaxy}}.$$ 

where the mass-to-light ratio in the B band is taken to be $1 M_\odot/L_\odot$, and the galaxy luminosity is essentially dominated by the bulge luminosity. Hence, the mass of the central SMBH is $M_{\text{SMBH}} \approx 10^7 M_\odot$. Now, we use the luminosity of the ROSAT off-center sources (Roberts & Warwick 2000) and use the fact that they find $\approx 0.7$ off-center sources with luminosity $\geq 10^{38.3} \text{ergs s}^{-1}$ per $10^{10} L_\odot$ galaxy to estimate the mass of VMBHs in the fiducial galaxy. If we assume that these VMBHs have a typical mass of $\approx 300 M_\odot$, their Eddington luminosity is

$$L_{\text{Edd}} = 4.3 \times 10^{40} \left( \frac{M_{\text{VMBH}}}{300 M_\odot} \right) \text{ergs s}^{-1}.$$ 

Thus, VMBHs appear to be radiating at sub-Eddington luminosities, the average rate (given by eq. [10]) being $\approx 3\%$ of the Eddington value. This is consistent with the observed luminosities of the nuclear sources in the sample, which Roberts & Warwick (2000) find to be radiating at severely sub-Eddington rates.

Therefore, we expect the typical accreting VMBH mass in a $10^{10} L_\odot$ galaxy to be about $210 M_\odot$. Little is known about the spatial distribution of such objects. How can we take into account the fact that only a fraction of the sources are likely to be accreting? Since the detected ROSAT off-center sources are within the optical radius of the galaxies, the number of nonaccreting VMBHs in the halos of these galaxies can be large. One can obtain a simple estimate of this number by pursuing the following argument. Assume that VMBHs, being collisionless particles, closely trace the dark matter (which we take to obey a NFW profile; Navarro, Frenk, & White 1997) and that the ratio of virial to optical radius is $\approx 15$ for a $10^6 L_\odot$ disk galaxy (Persic, Salucci, & Stel 1996). These hypotheses require that we scale up the total mass in VMBHs by a factor of $\approx 10$, which gives $M_{\text{VMBH}} = 2.1 \times 10^5 M_\odot$. Now, the ratio $M_{\text{VMBH}}/M_{\text{SMBH}}$ is $\approx 2.1 \times 10^{-4}$, implying that $\Omega_{\text{VMBH}} = 2.1 \times 10^{-4} \Omega_{\text{SMBH}} = 6.4 \times 10^{-10}$, which in turn gives $f_{\gamma} \approx 1$ (see dashed line in bottom panel of Fig. 4) and $z_f \gtrsim 22.1$.

Now we explore scenario 2 of case B, the instance when VMBHs constitute the entire baryonic dark matter content of galaxy halos (but do not contribute to the disk dark matter). It is important to point out here that cosmological nucleosynthesis arguments require both baryonic and nonbaryonic dark matter (Pagel 1990). Essentially, this is due to the fact that the mass density contributed by baryons, $\Omega_B$, is well in excess of $\Omega_\gamma$, the contribution to the mass density by visible baryons.

Using the luminosity-dependent relation of visible to dark matter for spirals (Persic et al. 1996) for a fiducial galaxy of $10^{10} L_\odot$, we find

$$\frac{M_{\text{vis}}}{M_{\text{DM}}} \approx 0.05,$$ 

where $M_{\text{vis}}$ is the visible mass and $M_{\text{DM}} = M_{\text{DM}}^b + M_{\text{DM}}^n$ is the total dark matter mass, given as a sum of a baryonic and a nonbaryonic component. The total baryonic mass is a fraction $\Omega_B/\Omega_M$ of the total mass of the system, e.g.,

$$M_{\text{vis}} + M_{\text{DM}}^b = \frac{\Omega_B}{\Omega_M} (M_{\text{vis}} + M_{\text{DM}}).$$ 

From these two equations and assuming an NFW density profile, we estimate the total baryonic dark matter content as

$$M_{\text{DM}}^b \approx (\Omega_M^{-1} - 1) M_{\text{vis}} = 2.33 M_{\text{vis}};$$

moreover, 90% of this mass resides outside the optical radius and can be contributed by VMBHs,

$$\frac{M_{\text{VMBH}}}{M_{\text{SMBH}}} = \left( \frac{2.1 \times 10^3}{10^{-3} \times M_{\text{vis}}} \right) = 2.1 \times 10^3,$$  

implying

$$\Omega_{\text{VMBH}} = 2.1 \times 10^3 \times \Omega_{\text{SMBH}} = 6.4 \times 10^{-3}.$$ 

Incorporating this constraint into Figure 4 (bottom panel), we find $f_{\gamma} \approx 3.15 \times 10^{-3}$ and $z_f \gtrsim 5.4$. Note that this scenario does not violate the constraint on the overproduction of background light (see Carr 1998; Bond, Carr, & Hogan 1991; Wright et al. 1994). In fact, some fraction of the observed near-IR DIRBE excess could be produced by VMBHs. In a recent estimate of the cosmic background at 1.25 and 2.2 $\mu$m (corresponding to the J and K bands, respectively) using the Two Micron All Sky Survey (2MASS) and the DIRBE results, Cambresy et al. (2001) also find an excess (significantly higher than the integrated galaxy counts in the J and K bands), suggesting the contribution of other sources. Population III stars and their VMBH remnants (accreting at very high redshifts) postulated here are likely candidates.

According to case B, the average metal abundance at redshift $\sim 5.4$ should be $Z_{\text{av}} = 10^{-4} Z_\odot$, marking the transition
from a top-heavy IMF to a standard power-law IMF. This does not necessarily violate the observed metal abundances in damped Ly\={\alpha} systems, $Z \approx 10^{-3}$, as it is not yet clear to what extent the IGM metallicity is spatially uniform at these intermediate redshifts.

Therefore, case B is poorly constrained by the data, as scenarios 1 and 2 give large ranges for $f_{\gamma \gamma}$ and $z_f$: $3.15 \times 10^{-5} < f_{\gamma \gamma} < 1$ and $5.4 < z_f < 22.1$. Consistently, case A gives a limit on $f_{\gamma \gamma}$ and $z_f$ of $f_{\gamma \gamma} = 0.06$ and $z_f = 18.5$.

The actual data do not allow us at present to strongly constrain the two quantities above, but they provide interesting bounds on the proposed scenario. These ranges also have implications for the expected detection rate of SNe beyond $z_f$ with future instruments like the Next Generation Space Telescope (NGST) (Marri & Ferrara 1998; Marri, Ferrara, & Pozzetti 2000).

5. DISCUSSION

We have proposed a scenario to solve a puzzling star formation conundrum: the first stars are now thought to be very massive and hence to lock their nucleosynthesis products into a remnant (very massive) black hole. This high-mass–biased star formation mode continues as long as the gas remains metal free. During this phase, metal enrichment can occur only if a fraction $f_{\gamma \gamma}$ of the stars have mass in the window leading to pair-unstable SNe (140 $M_\odot < M_* < 260 M_\odot$), which disperse their heavy elements into the surrounding gas. Such metals enrich the gas up to $Z_{\text{cr}} \approx 10^{-4} Z_\odot$, when a transition to efficient cooling-driven fragmentation producing $\lesssim 1 M_\odot$ clumps occurs at redshift $z_f$. We argue that the remaining fraction of the first stars end up in $\approx 100 M_\odot$ VMBHs. By analyzing the evolutionary fate of such objects, we argue that in case A they could end up in the SMBHs in the centers of galactic nuclei; in case B, (1) they could be en route to the center and hence identified with the X-ray–bright, off-center ROSAT sources, or (2) they could constitute the entire baryonic dark matter content of galaxy halos. These possibilities are used to obtain constraints on the two quantities: $f_{\gamma \gamma} \sim 0.06$ and $z_f \sim 18.5$ for case A, and $f_{\gamma \gamma} \approx (10^{-2} \text{ to } 1)$ and $z_f \approx (5.4 \text{ to } 22.1)$ for case B. The value $Z_{\text{cr}} \approx 10^{-4} Z_\odot$ found here is admittedly somewhat uncertain. For this reason we have investigated how the above results might be affected by a different choice, e.g., assuming $Z_{\text{cr}} \approx 10^{-5} Z_\odot$. Indeed, lower values of $Z_{\text{cr}}$ imply that less efficient metal enrichment is required in order to change to a more conventional star formation mode. Thus, comparable values for $z_f$ are found, but the corresponding values for $f_{\gamma \gamma}$ tend to be systematically smaller, being $f_{\gamma \gamma} \approx 0.6\%$ for case A and in the range $3.15 \times 10^{-5} < z_f < 0.98$ for case B.

Several uncertainties remain in the comparison of the inferred density of VMBHs to local observations. For example, it is not obvious if SMBHs could at all form out of VMBHs. Dynamical friction can effectively drag VMBHs toward the center of the host system, at least within a distance of $\sim 100$ pc (Madau & Rees 2001). Unless most of the energy is radiated away in gravitational waves, it could be difficult for a VMBH cluster to coalesce into a single unit. Furthermore, accretion onto isolated VMBHs could be too inefficient to explain most of the off-center sources observed by ROSAT and Chandra. Higher accretion rates might be activated by the tidal capture/disruption of ordinary stars. The question remains if the frequency of such an event is in fact sufficiently high to explain the data.

In spite of the many difficulties and uncertainties discussed here, our study represents a first attempt to link the first episode of cosmic star formation activity to present-day observational evidence of their fossil remnants.

A top-heavy IMF for the early episodes of star formation in the universe might have other interesting observational consequences; we speculate further on them later. The kinetic energy released during the thermonuclear explosions powered by pair instability are $\approx 10^5$ larger than those of ordinary Type II SNe. This might cause the interaction with the circumstellar medium to be as strong as predicted for hypernovae (Woosley & Weaver 1982). However, these explosions do not lead to the ejection of strongly relativistic jets (Fryer et al. 2001) and therefore cannot power a gamma-ray burst (GRB).

In Population III progenitors of VMBHs, the estimated angular momentum is sufficient to delay black hole formation and the system might develop triaxial deformations (Fryer et al. 2001). If the instabilities have enough time to grow, the core might break into smaller fragments that would then collapse and merge to form the central VMBH. If not, the star might still develop a barlike configuration. Both these scenarios lead to a significant emission of gravitational waves (Schneider et al. 2000; Fryer, Holz, & Hughes 2002). Furthermore, significant emission of gravitational radiation can occur as a result of the inspiral and merger of VMBHs onto the SMBHs in the center of host systems (Madau & Rees 2001).

Once the VMBHs have formed, accretion continues through a disk at a rate that can be as large as $10 M_\odot \text{ s}^{-1}$ (Fryer et al. 2001). Magnetic fields might drive an energetic jet that can produce a strong GRB through the interaction with surrounding gas. The properties of these Population III GRBs would be considerably different from their more recent ($z < 5$) counterparts; depending on the uncertain interaction of the jet with the surrounding matter, the bursts would be probably longer [$10(1 + z)$ s], and the peak of emission, which in the rest frame is in $\gamma$-rays, would be shifted into X-rays. Indeed, BeppoSAX has revealed the existence of a new class of events, the so-called X-ray flashes or X-ray–rich GRBs, which emit the bulk of their energy in X-rays (L. Piro 2001, private communication). Furthermore, since Population III GRBs explode at very high redshifts, it is likely that their optical afterglow might be heavily absorbed by the intervening gas. These systems might be the natural candidates for the significant number (about 40\% of GRBs for which fast follow-up observations were carried out) of GRBs that do not show an optical counterpart, the so-called GHOST (GRB hiding optical source transient) or dark GRBs. Other explanations ascribe the failed optical detection to dust extinction within the host system, but the ultimate nature of GHOSTs is still highly debated (Lazzati, Covino, & Ghisellini 2002; Djorgovski et al. 2001).

Finally, the energetic jets generated by GRB engines produce, by photon-meson interaction, a burst of TeV neutrinos while propagating in the stellar envelope (Mészáros & Waxman 2001). We investigate this aspect in a companion paper (Schneider, Guetta, & Ferrara 2002) in which we use the constraints set by the AMANDA-B10 experiment on the total integrated flux of TeV neutrinos from Population III GRBs.
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