Induced Formation of Primordial Low-Mass Stars

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Abstract

We show that the explosion of the first supernovae can trigger low-mass star formation via gravitational fragmentation of the supernova-driven gas shell. If the shell mass does not exceed the host galaxy gas mass, all explosions with energies $E_{SN} \geq 10^{51}$ erg can lead to shell fragmentation. However, the minimum ambient density required to induce such fragmentation is much larger, $n_0 > 300$ cm$^{-3}$, for Type II supernovae than for pair-instability ones, which can induce star formation even at lower ambient densities. The typical mass of the unstable fragments is $\sim 10^{4-7} M_\odot$; their density is in the range $110 - 6 \times 10^7$ cm$^{-3}$. Fragments have a metallicity strictly lower than $10^{-2.6} Z_\odot$ and large values of the gravitational-to-pressure force ratio $f \approx 8$. Based on these findings, we conclude that the second generation of stars produced by such self-propagating star formation is predominantly constituted by low-mass, long-living, extremely metal-poor (or even metal-free, if mixing is suppressed) stars. We discuss the implications of such results for Pop III star formation scenarios and for the most iron-poor halo star HE0107-5240.
1 Introduction

As many recent numerical (Bromm, Coppi & Larson 1999, 2002; Abel, Bryan & Norman 2000) and semi-analytical (Schneider et al. 2002, Omukai & Inutsuka 2002, Omukai & Palla 2003) studies have shown, the first luminous objects, the so-called Population III (Pop III) stars, are likely to be very massive. According to these studies, stars with a characteristic mass of 100-600 $M_\odot$ originate in the primordial gas, whereas low-mass objects should not have formed due to the lack of heavy elements. High-mass stars are indeed required to account for the unexplained Near Infrared Background (Salvaterra & Ferrara 2003; Magliocchetti, Salvaterra & Ferrara 2003). Bromm et al. (2001) and Schneider et al. (2002) have shown that there exists a critical metallicity ($Z_{cr} = 10^{-5.1} Z_\odot$) setting the transition from a high-mass to a low-mass fragmentation mode of star formation. The exact value of $Z_{cr}$ depends on the fraction of heavy elements that are depleted onto dust grains (Schneider et al. 2003). In this scenario, a gas cloud with a metallicity $Z \sim 10^{-5.1} Z_\odot$ can lead to the formation of low-mass stars if $\sim 20\%$ of the heavy elements is in dust grains (Schneider et al. 2003). The recent discovery of the most iron-poor star ([Fe/H] = $-5.3 \pm 0.2$) ever seen in our Galaxy (Christlieb et al. 2002) could be an example of such low-mass metal-poor stars originated from a gas with mean metallicity of $10^{-5.1} Z_\odot$ (Schneider et al. 2003; but see Umeda & Nomoto (2003), who have pointed out that this star could have instead formed from a carbon-rich, iron-poor gas, with a corresponding mean metallicity of $10^{-2} Z_\odot$).

An alternative potentially viable mechanism to form low-mass, metal-poor stars does exist. Indeed, Nakamura & Umemura (2001, 2002, hereafter NU01 and NU02) have studied the collapse and fragmentation of filamentary primordial gas clouds using one- and two-dimensional hydrodynamical simulations coupled with the nonequilibrium processes of molecular hydrogen formation. They have shown that filaments with relatively low initial density ($n \lesssim \text{few} \times 10^4$ cm$^{-3}$) tend to fragment into dense clumps before the central density reaches $10^8 - 10^9$ cm$^{-3}$; the fragment mass is around $100 M_\odot$. In contrast, if a filament has initially a larger density, fragmentation continues until the clumps become optically thick to H$_2$ lines, leading to a typical fragment mass of $\sim 1 M_\odot$. So the resulting IMF of first stars would be bimodal, with a low-mass peak around $\sim 1 - 2 M_\odot$ and a high-mass peak at a few hundred $M_\odot$. Mackey et al. (2003) have suggested that these low-mass peak stars could form in the gas shocked by the explosion of the first generation of very massive
supernovae (SNe).

In this paper, we put this hypothesis on a more quantitative basis. We will show that the shell is gravitationally unstable only for large explosion energies and that gravitationally unstable clumps are likely to form long-living, low-mass, metal-poor stars, that could be detected through dedicated surveys as the Hamburg/ESO objective prism survey (Christlieb et al. 2001).

The paper is organized as follows. In Section 2 we calculate the SN-driven shell evolution and derive the conditions for gravitational instability. In Section 3 we examine the instability in the expanding shell for different explosion energies and interstellar medium (ISM) densities, whereas in Section 4 we calculated the properties of unstable fragments. In Section 5 we constrain the fragment metallicity; Section 6 discusses the consequences for Pop III star formation scenarios.

2 Evolution of the shell

One can show that as far as the ambient gas pressure and cooling can be neglected, the shell evolution is described by the analytic expression derived by Sedov (1959):

\[ R_{sh} \propto \left( \frac{E_{SN}}{\rho_0} \right)^{1/5} t^{2/5}, \tag{1} \]

where \( t \) is the time elapsed from the explosion, \( E_{SN} \) is the total explosion energy, and \( \rho_0 = \mu m_H n_0 \) is the density of the ISM (\( n_0 \) is the gas number density and \( \mu = 0.59 \) is the mean molecular weight of a primordial ionized H/He mixture).

The further evolution of a SN-driven shell in the interstellar medium can be studied using the thin shell approximation (Ostriker & McKee 1988; Madau, Ferrara & Rees 2001). The momentum and energy conservation yield the following relevant equations:

\[ \frac{d}{dt}(V_{sh}\rho_0 \dot{R}_{sh}) = 4\pi R_{sh}^2 (P_b - P), \tag{2} \]

\[ \frac{dE_b}{dt} = -4\pi R_{sh}^2 P_b \dot{R}_{sh} - V_{sh} \dot{n}_{H,H}^2 \Lambda(\dot{T}_b), \tag{3} \]

where the subscripts ‘\( sh \)’ and ‘\( b \)’ indicate shell and bubble quantities, respectively. Here, \( R_{sh} \) is the shell radius, \( V_{sh} = (4\pi/3) R_{sh}^3 \) is the volume enclosed by
the shell; the overdots represent time derivatives. $P$ is the ISM pressure. The shell expansion is driven by the internal energy $E_b$ of the hot bubble gas, whose pressure is $P_b = E_b/2\pi R_{sh}^3$ (for a gas with adiabatic index $\gamma = 5/3$). Finally, $\bar{n}_{H,b}\Lambda(T_b)$ is the cooling rate per unit volume of the hot bubble gas, whose average hydrogen density and temperature are $\bar{n}_{H,b}$ and $T_b$, respectively. The right-hand side of eq. (2) represents the momentum gained by the shell from the SN-shocked wind, while the right-hand side of eq. (3) describes the mechanical energy input, the work done against the shell, and the energy losses due to radiation.

As cooling becomes important for the swept up gas, the shock is no longer driven by the heated gas and the evolution enters the momentum conserving phase, satisfying the familiar ‘Oort snowplow’ solution, $R_{sh} \propto t^{1/4}$.

2.1 Cooling time

The cooling time is given by

$$t_{cool} = \frac{3}{2} \frac{kT_{ps}}{\bar{n}_{ps}\Lambda(T_{ps})},$$  \hspace{1cm} (4)

where $\bar{n}_{ps} = n_0(\gamma + 1)/(\gamma - 1)$ is the post-shock density and $T_{ps}$ the post-shock temperature for an adiabatic shock, and $\Lambda(T_{ps})$ is the cooling function for a primordial gas. The evolution of the bubble gas temperature $T_b$ is given by (Madau, Ferrara, Rees 2001)

$$\frac{dT_b}{dt} = 3 \frac{T_b}{R_{sh}} \dot{R}_{sh} + \frac{T_b}{P_{sh}} \dot{P}_{sh} - \frac{23}{10} \frac{C_1}{C_2} \frac{kT_{b}^{9/2}}{R_{sh}^2 P_{sh}}.$$  \hspace{1cm} (5)

where $C_1 = 16\pi \mu m_p \eta / 25k$ and $C_2 = (125/39)\pi \mu m_p$ and $\eta = 6 \times 10^{-7}$ (c.g.s. units) is the classical Spitzer thermal conduction coefficient (we have assumed a Coulomb logarithm equal to 30). This relation closes the system of equations (2)-(3).

If the shell lives for sufficiently long time (i.e. $t_{cool} \ll t$), the gas cools down to a final temperature $T_f \sim 300$ K. This temperature is the minimum temperature provided by cooling from H$_2$ molecules forming under nonequilibrium conditions in the post-shock gas (Ferrara 1998).
2.2 Perturbations in the shell

The problem of the fragmentation of expanding shell has been addressed by several authors (Ostriker & Cowie 1981; Elmegreen 1994; Wünsch & Palous 2001; Ehlerova & Palous 2002). Here we apply these studies to the case of first SNe exploding in a medium of primordial composition.

The linear growth of perturbations in an expanding shell was derived by Elmegreen (1994). Expansion tends to suppress (stabilize) the growth of density perturbations owing to stretching, hence counteracting the self-gravity pull. The instantaneous maximum growth rate is

$$\omega = -\frac{3\dot{R}_{sh}}{R_{sh}} + \left[ \left( \frac{\dot{R}_{sh}}{R_{sh}} \right)^2 + \left( \frac{\pi G\rho_0 R_{sh}}{3c_{s,sh}} \right)^2 \right]^{1/2},$$

(6)

where $c_{s,sh} = (kT_f / \mu m_H)^{1/2}$ is the sound speed in the shell. Instability occurs only if $\omega > 0$, or

$$\frac{\dot{R}_{sh}}{R_{sh}} < \frac{1}{8^{1/2}} \frac{\pi G\rho_0 R_{sh}}{3c_{s,sh}} \propto \frac{t_{cross}}{t_{ff}^2},$$

(7)

where $t_{cross} \sim R_{sh}/c_{s,sh}$ is the crossing time in the shell and $t_{ff}$ is the free-fall time. Furthermore, if the fragment mass is close to (but slightly above) the Jeans mass, the $\omega > 0$ condition translates into $\dot{R}_{sh}/R_{sh} < 1/t_{ff}$. So, large shell velocity-to-radius ratios inhibit the formation of gravitationally unstable fragments. These relations are derived under the assumption of supersonic motion, i.e. $\dot{R}_{sh}(t) > c_{s,0}$, where $c_{s,0}$ is the sound speed in the ISM. If the shock decays into a pressure wave before the onset of the instability (i.e. before $\omega > 0$), no fragmentation will take place and the shell will be dispersed by random gas motions.

The most rapidly growing mode has wavelength

$$\lambda_f = \frac{6c_{s,sh}^2}{G\rho_0 R_{sh}} \left[ 1 + (1 - \xi^2)^{1/2} \right]^{-1},$$

(8)

where the dimensionless parameter $\xi$ is given by

$$\xi = \left( \frac{8^{1/2} \dot{R}_{sh}}{R_{sh}} \right) \left( \frac{\pi G\rho_0 R_{sh}}{3c_{s,sh}} \right).$$
We will show later that the typical fragment size \((R_f = \lambda_f/2)\) is greater than the thickness of the shell. In the radiative phase the thickness is determined by the so-called cooling length, i.e. the distance travelled by the gas accelerated at the postshock velocity in a cooling time: \(\Delta R_{sh} \approx \dot{R}_{sh} t_{\text{cool}}\). In this case it is likely that disk-like fragments form with mass

\[
M_f = \pi \rho_{sh} \Delta R_{sh} R_f^2,
\]  

(9)

where \(\rho_{sh}\) is the mean density in the thin shell, given by the ratio between its mass \(M_{sh}\) (equal to the shell swept up mass) and its volume \(V_{sh}\)

\[
\rho_{sh} = \frac{M_{sh}}{V_{sh}} = \frac{4}{3} \rho_0 \frac{R_{sh}}{\Delta R_{sh}}.
\]

(10)

For subsequent purposes we define the ratio of gravitational-to-pressure force evaluated in the direction along the fragment radius, \(R_f\):

\[
f = \frac{\pi G \mu m_H \rho_{sh} R_f \Delta R_{sh}}{(3/2) kT_f}.
\]

(11)

3 Instability in the expanding shell

We solve numerically Eq. (2)-(3) and Eq. (5) for different values of the unperturbed ISM density \(n_0\), and of the explosion energy, \(E_{SN}\), following the time evolution of the shell radius \((R_{sh})\) and velocity \(\dot{R}_{sh}\).

The unperturbed medium is assumed to be metal free and homogeneous. The SN progenitor medium within its Strömgren radius, \(R_s = (3Q_H/4\pi n_0^2 \alpha^2)^{1/3}\), where \(Q_H\) is the mass-dependent stellar ionizing photon rate and \(\alpha\) is the hydrogen recombination rate to levels \(\geq 2\). The radius of the ionized bubble reaches \(R_s\) is a recombination time \(t_{\text{rec}} = (\alpha n_0)^{-1}\); however, the heated gas will start to freely expand at roughly its sound speed \((c_s \approx 10\ \text{km/s for an ionized gas})\) if the dynamical time \(R_s/c_s < t_s\), the lifetime of the star. In this case, by the time of the SN explosion the ionized region has grown to several tens of pc essentially independent of the initial value of \(R_s\); inside this region the density and pressure are almost constant, thus motivating our constant density approximation.

After the SN explosion, in the absence of ionizing photons, the gas would recombine on a timescale, \(t_{\text{rec}}\). In practice, the gas is kept ionized by the radiation from the shock radiative precursor and its temperature remains \(\approx 10^4\ \text{K}\) until ionizing photons continue to be produced. This condition is fulfilled as long as the shock velocity is larger than 80 km/s (Draine & McKee 1993). It is
only a recombination time after such event that the gas can finally recombine and cool to 300 K.

At each time step we check the supersonic motion ($\dot{R}_{sh} > c_{s,0}$) and instability ($\omega > 0$) conditions. If both conditions are satisfied we further check that the cooling time is shorter than the age of the shell, so that the temperature has decreased to $T_f \approx 300$ K. At this point we calculate the fragment density (Eq. 10), mass (Eq. 9), and the ratio $f$ (Eq. 11).

We consider here SN energies in the range $10^{51} - 10^{53}$ erg, the lower limit being typical of core-collapse Type II SNe (SNII) explosions and the upper limit corresponding to the energy released by the most massive pair-instability SN (SN$_{\gamma\gamma}$) explosions (Heger & Woosley 2002). We explore the range of ISM densities $n_0 = 10^{-2} - 10^4$ cm$^{-3}$. Fig. 1 shows the time-evolution of the shell radius and velocity for $n_0 = 5$ cm$^{-3}$ and three explosion energies. The bottom panel shows the corresponding evolution of the instability growth rate $\omega$. Only the explosions of SN$_{\gamma\gamma}$ induce shell instability and fragmentation.

Fig. 2 shows the region of the parameter space $E_{SN} - n_0$ where both the conditions $\omega > 0$ and $\dot{R}_{sh} > c_{s,0}$ are verified and therefore the shell is gravitationally unstable. In addition, we also require that the shell mass at the time of instability does not exceed the total gas mass of the host galaxy. To exemplify, in the Figure we assume that the first stars form in halos with mass $M_{gal}$ corresponding to virial temperature $T_{vir} = 10^4$ K. Under these conditions, we see from Fig. 2 that, if the shell mass does not exceed the baryonic in the galaxy, all explosions with energies $E_{SN} \geq 10^{51}$ erg can lead to shell fragmentation. However, the minimum ambient density required to induce such fragmentation is much larger, $n_0 > 300$ cm$^{-3}$, for SNII (explosion energy $10^{51}$ erg) than for SN$_{\gamma\gamma}$, for which the instability can occur even at lower ambient densities. Hence, pair-instability SNe are more suitable triggers of induced star formation.

We conclude that the first pair-instability SNe are able to trigger self-propagating star formation under a wide range of ambient conditions, whereas expanding shells created by less energetic ‘classical’ or subluminous (as those proposed by Shigeyama & Tsujimoto 1998) SNII cannot fragment unless the density is very high.

4 Properties of the fragments

Let us now explore in more details the properties of the gravitationally unstable fragments. As it is clear from Eqs. (8)-(9) the fragment mass is a function of the explosion energy (through $R_{sh}$ and $\dot{R}_{sh}$), of the initial density of the
Fig. 1. Top panel: shell radius (increasing curves) and velocity as a function of time for three SN energies (solid line: $E_{SN} = 10^{53}$ erg; dotted line: $E_{SN} = 10^{52}$ erg; dashed line: $E_{SN} = 10^{51}$ erg). The ISM density is $n_0 = 5$ cm$^{-3}$. Bottom panel: instability growth rate evolution for the three SN energies. The curves are plotted until the shock decays into a pressure wave.

medium, $n_0$, and of the density of the thin shell, $\rho_{sh}$ (proportional to the shell swept up mass, and thus function of $R_{sh}$). The growth time of the unstable fragments is $\sim \omega^{-1}$.

In all unstable cases, the age of the shell is larger than the cooling time and the thin shell approximation is valid ($\Delta R_{sh}/R_{sh} < 10^{-3}$). The instability sets in at 0.2-50 Myr after the explosion and the typical fragment radius and mass is in the range $2 - 1000$ pc and $10^{4-7} M_\odot$, respectively (the upper limits refer to the lowest ambient density). The density of the fragments varies between $110$ cm$^{-3}$ and $6 \times 10^7$ cm$^{-3}$; as we discuss below, this spread has important implications for the mass of the second generation of stars formed. Large values of the gravitational-to-pressure force ratio ($f \simeq 8$) are found in all unstable cases. This is because high shell velocities stretch the perturbations, stabilizing the shell (see Eq. 7) and so the instability conditions are satisfied only when the fragments have collected a sufficiently large mass, yielding large values of $f$. 
Fig. 2. Region of the parameter space \((E_{SN} - n_0)\) where fragmentation occurs. See text for details.

NU01 (see their Fig. 6) have shown that primordial filaments fragment into dense clumps whose masses depend on \(n_{sh}\) and \(f\). For a quasi-equilibrium clump (i.e. \(f \gtrsim 1\)), fragmentation proceeds until the fragment is close to the Bonnor-Ebert mass value corresponding to the initial density of the clump\(^1\) (Palla 2002, Mackey et al. 2003). If \(f\) is increased to 3, a bifurcation takes place at \(n_{sh} \sim 10^5 \text{ cm}^{-3}\). For models with \(n_{sh} \gtrsim 10^5 \text{ cm}^{-3}\) the minimum fragment mass is \(1-2 M_\odot\), while for \(n_{sh} \lesssim 10^5 \text{ cm}^{-3}\) it is larger than \(\sim 100 M_\odot\). Further increase of \(f\) causes the low mass regime to extend down to \(n_{sh} \sim 10^4 \text{ cm}^{-3}\).

In the low mass regime, the fragmentation proceeds down to smaller subclumps searching for an equilibrium between gravitational and pressure forces (thus decreasing \(f\)); at the same time the density of the subclumps tends to increase. For \(f\) values around 8, this equilibrium cannot be reached before the subclump becomes optically thick to H\(_2\) lines. At this stage, the initial clump has already fragmented into protostellar cores with typical masses \(\sim 10^{-2} M_\odot\)\(^2\). Although

\[^1\] This is strictly true only for \(n_{sh} \geq n_{cr} = 10^4 \text{ cm}^{-3}\) where \(n_{cr}\) is the critical density which marks the transition from NLTE to LTE regime for H\(_2\) cooling (see discussion in Schneider et al. 2002).

\[^2\] In the case of a strictly metal-free gas the minimum mass essentially coincides
the exact value of the resulting stellar mass depends on the details of subsequent gas accretion and, possibly, on the merging of protostellar cores, it is unlikely that these are so efficient to form a massive star. In fact, the relaxation time corresponding to the ensemble of $m \sim 10^{-2} M_{\odot}$ protostellar cores resulting from the fragmentation of a $M_f = 10^5 M_{\odot}$ clump is $\sim 36$ Gyr.

As mentioned above, we find $f \approx 8$ for all the unstable case. According to NU02 (see their Fig. 5a), this $f$ value leads to the preferential formation of low-mass stars provided the density of the fragment is larger than $\sim 2 \times 10^3$ cm$^{-3}$. Such condition is verified for all values of the ambient density $n_0$ and explosion energy $E_{SN}$ except for the small area depicted in Fig. 2, where instead high mass ($M \approx 100 M_{\odot}$) stars can form as a result of the fragment collapse. The formation of high mass stars can only be induced by SN$_{\gamma\gamma}$, but the range of suitable ambient densities is small enough that such event can be regarded as unlikely.

5 Mixing efficiency and metallicity of the fragments

In order to derive the mean metallicity of the thin shell (and of the fragments), one should be able to follow the mixing of SN ejecta with the shell gas. The standard hydrodynamical response to a sudden release of energy implies that the two gases (the swept up matter and the ejecta), after crossing their respective shocks find themselves well separated by a contact discontinuity. However, many mechanisms (e.g. cloud crushing, thermal evaporation, hydrodynamical instabilities, effects caused by explosion inside wind-driven shells and by fragmented ejecta) can disrupt the contact discontinuity leading to a mixing of the heavy elements into the swept-up matter in the thin shell (Tenorio-Tagle 1996). A precise description of such physical processes is extremely difficult as it requires ultra-high resolution simulations (de Avillez & Mac Low 2002; Kifonidis et al. 2003).

The mean metallicity of the shell (or fragment) is

$$Z_f = f_{mix} \frac{M_{ej}}{M_{sh}}$$

where $f_{mix}$ is the (unknown) mixing factor of ejected matter in the thin shell and $M_{ej}$ is the ejected mass in heavy elements. For SN$_{\gamma\gamma}$, $M_{ej} \simeq 0.4M_*$ (Heger & Woosley 2002). Even requiring that mixing is very efficient (i.e. $f_{mix} = 1$), we always find that the mean metallicity of the fragments is $10^{-3.5} Z_{\odot} < Z < 10^{-2.6} Z_{\odot}$. In more realistic cases, however, mixing is likely to be much more

with the Chandrasekhar mass, i.e. $\sim 1 - 2M_{\odot}$ (Uehara et al. 1996)
inefficient \( (f_{\text{mix}} \ll 1) \), so the above value, \( 10^{-2.6} Z_\odot \) is a strict upper limit. At face value, if the most iron poor star observed in our Galaxy ([Fe/H] = −5.3, Christlieb et al. 2002) formed through this mechanism, it would imply that \( f_{\text{mix}} \sim 0.03 \). Note that in principle zero-metallicity low-mass stars can form via the proposed mechanism if \( f_{\text{mix}} = 0 \).

6 Discussion

We have shown that the explosion of the first SNe are able to trigger further star formation. If the shell mass does not exceed the baryonic in the galaxy, all explosions with energies \( E_{\text{SN}} \geq 10^{51} \) erg can lead to shell fragmentation. However, the minimum ambient density required to induce such fragmentation is much larger, \( n_0 > 300 \) \( \text{cm}^{-3} \), for SNII (or subluminous supernovae) than for pair-instability ones, which can induce star formation even at lower ambient densities. Fragmenting shells become gravitationally unstable 0.2-50 Myr after the explosion, depending on the explosion energy and density of the unperturbed medium. We have identified the fastest growing mode in the unstable shells and derived the mass, density and gravitational-to-pressure force ratio, \( f \), of the corresponding fragments. Their typical mass is in the range \( 10^{4-7} M_\odot \) and density in the range \( 110 - 6 \times 10^7 \) \( \text{cm}^{-3} \). In all cases, we find very large values of the gravitational-to-pressure force ratio \( (f \simeq 8) \), indicating that the formation of low-mass, long-living stars is the most likely outcome. A narrow region of the \( n_0 - E_{\text{SN}} \) parameter space allows the formation of massive stars from fragments originating from SN\( \gamma \gamma \) shells. However, the density range is small enough to consider this possibility as unlikely.

The mean metallicity of the stars formed through this mechanism depends on the mixing history of the shell which is largely unknown, as discussed in the previous Section. Depending on the efficiency of this process and on the combined properties of the explosion energy and ambient density, the metallicity of this second generation, low-mass stars can be anywhere in the range \( 0 \leq Z \leq 10^{-2.6} Z_\odot \).

The mechanism here proposed is thus able to produce long-living, low-mass extremely metal-poor (or even metal-free, if \( f_{\text{mix}} = 0 \)) stars that can be found in the Milky Way halo. These stars can populate the low-mass peak of the bimodal IMF proposed by NU01 and NU02 or can be the typical members of the so-called II.5 population (Mackey et al. 2003). The formation of these second generation stars requires the presence of a first generation of massive stars exploding as pair-instability SNe.

So far, only one extremely iron-poor star with [Fe/H] < −5 has been identified (HE0107-5240, Christlieb et al. 2002). If this result were to be confirmed by the
analysis of the complete volume sampled by the Hamburg/ESO survey, several implications for the self-propagating star formation mode can be drawn: the observed lack of \([\text{Fe/H}] < -5\) halo stars would imply that mixing of metals in the unstable shell must occur with moderately high efficiencies \((f_{\text{mix}} \gtrsim 10\%)\). Alternatively, the mechanism here proposed might not lead to a large number of observed iron-poor halo stars because: (i) the typical mass of this second-generation stars is \(\gtrsim 1 - 2 M_\odot\) so that their lifetimes are not long enough to be observable as main sequence stars in our Galaxy halo; (ii) pair-instability SNe are rare because the IMF of the first stars is shaped so that only a small fraction of zero-metallicity massive stars form in the mass range of pair-instability SNe, \(140 M_\odot \lesssim M_{\gamma\gamma} \lesssim 260 M_\odot\).

Conversely, if more very iron-deficient \((\text{[Fe/H]} < -5)\) stars were to be identified, the statistics and properties of these old stellar relics might lead to important constraints on the dominant processes which enable low-mass star formation in primordial environments. In particular, three viable mechanisms have been proposed for the origin of HE0107-5240 (Christlieb et al. 2002). Their main difference relies in the interpretation of the observed surface abundance of C, N (and O; Christlieb et al. 2004). In particular, if one assumes that the observed Fe is not a good indicator of the metallicity of the gas cloud out of which the star formed and that C and N were already present in the star forming gas (C, N pre-formation scenario), then HE0107-5240 formed with an initial metallicity of \(Z \sim 10^{-2} Z_\odot\). Indeed, Umeda & Nomoto (2003) have shown that the abundance pattern of HE0107-5240 is in good agreement with nucleosynthesis yields of a faint SN explosion of a \(\sim 25 M_\odot\) zero-metallicity star releasing a kinetic energy of \(0.3 \times 10^{51}\) erg. If so, due to the small explosion energy, self-propagating star formation could not have occurred and the star must have formed on a longer timescale from the gas enriched by the SN. Alternatively, if one assumes that the observed Fe is a good indicator of the parent cloud metallicity and that C and N were synthetized in the stellar interior (C, N post-formation scenario), then HE0107-5240 formed with an initial metallicity of \(Z \sim 10^{-5.1} Z_\odot\). Indeed, the observed abundance pattern for elements heavier than Mg (that cannot be formed in the interior of a 0.8\(M_\odot\) star such as HE0107-5240 and thus retain memory of the nucleosynthesis yields of the pre-enriching star) are well reproduced by the predicted yields of a 200 \(M_\odot\) SN_{\gamma\gamma}. In this case, HE0107-5240 could have formed on a short timescale through the self-propagating star formation mechanism or, on a longer timescale, from the gas enriched by the SN if 20\% of the metals were depleted onto dust grains (Schneider et al. 2003; Schneider, Ferrara & Salvaterra 2003).

3 These “post-formation” scenarios require a sensible explanation for the large observed C and N abundances. So far, it is still unclear whether efficient mixing during the He-flash can fully account for the observed abundances or if it had enough time to operate in HE0107-5240 (Schlattl et al. 2001, 2002; Siess et al. 2002).
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