The formation of the extremely primitive star SDSS J102915+172927 relies on dust

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ABSTRACT
The relative importance of metals and dust grains in the formation of the first low-mass stars has been a subject of debate. The recently discovered Galactic halo star SDSS J102915+172927 has a mass less than 0.8 M⊙ and a metallicity of Z = 4.5 × 10^{-5} Z⊙. We investigate the origin and properties of this star by reconstructing the physical conditions in its birth cloud. We show that the observed elemental abundance trend of SDSS J102915+172927 can be well fitted by the yields of core-collapse supernovae (SNe) with metal-free progenitors of 20 and 35 M⊙. Using these selected SN explosion models, we compute the corresponding dust yields and the resulting dust depletion factor taking into account the partial destruction by the SN reverse shock. We then follow the collapse and fragmentation of a star-forming cloud enriched by the products of these SN explosions at the observed metallicity of SDSS J102915+172927. We find that 0.05–0.1 M⊙ mass fragments, which then lead to the formation of low-mass stars, can occur provided that the mass fraction of dust grains in the birth cloud exceeds 0.01 of the total mass of metals and dust. This, in turn, requires that at least 0.4 M⊙ of dust condense in the first SNe, allowing for moderate destruction by the reverse shock. If dust formation in the first SNe is less efficient or strong dust destruction does occur, the thermal evolution of the SDSS J102915+172927 birth cloud is dominated by molecular cooling, and only ≥8 M⊙ fragments can form. We conclude that the observed properties of SDSS J102915+172927 support the suggestion that dust must have condensed in the ejecta of the first SNe and played a fundamental role in the formation of the first low-mass stars.

Key words: stars: low-mass – supernovae: general – ISM: clouds – dust, extinction – Galaxy: halo – galaxies: evolution.

1 INTRODUCTION
The observed elemental abundances of metal-poor stars in the halo of the Milky Way or in its dwarf satellites record the physical conditions prevailing in star-forming regions at high redshift. The mass fraction of Fe relative to H, {\([\text{Fe}/\text{H}] = \log (M_{\text{Fe}}/M_{\text{H}}) - \log (M_{\text{Fe}}/M_{\text{H}})_{\odot}\)} normalized to the abundance in the Sun, is generally used as a metallicity tracer. Galactic halo stars show a remarkably uniform trend of elemental abundance ratios (Cayrel et al. 2004) at {\([\text{Fe}/\text{H}] < -2.5\)}. An exception are the so-called carbon-enhanced extremely metal poor stars (CEMPs; Beers & Christlieb 2005) which show a large C overabundance, [C/Fe] > 1. Interestingly, the fraction of carbon-enhanced stars increases with decreasing metallicity and three out of the four known halo stars with [Fe/H] < −4 are CEMP stars (Christlieb et al. 2002; Frebel et al. 2005; Norris et al. 2008). Since C I and O I fine-structure lines are amongst the most efficient gas coolants (Bromm & Loeb 2003), the observed CNO enhancement has been interpreted as the key environmental condition for the formation of low-mass stars (Frebel, Johnson & Bromm 2007). This hypothesis has been recently challenged by the discovery of SDSS J102915+172927 (Caffau et al. 2011), which has [Fe/H] = −4.99 and a chemical pattern typical of classical EMPs, i.e. no CNO

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enhancement; its inferred metallicity falls in the critical range, $Z_{\odot} = 10^{-5} \pm 1 Z_{\odot}$, in which low-mass star formation is possible provided that a fraction of the metals is in the form of dust grains (Schneider et al. 2002, 2003, 2006, 2011; Omukai et al. 2005).

In this work, we investigate the origin of SDSS J102915+172927 by reconstructing the physical conditions in its birth environment. We use detailed pre-supernova (pre-SN) and supernova (SN) explosion models to fit the observed elemental abundances of SDSS J102915+172927 and identify plausible SN progenitors responsible for its birth cloud (Section 2). We use these SN explosion models to calculate the amount of dust produced in their ejecta and its partial destruction by the associated reverse shock (Section 3). We then study the collapse and fragmentation properties of a star-forming cloud enriched by the products of these explosions and identify the conditions that enable the formation of subsolar mass stars (Section 4). Finally, in Section 5 we draw our conclusions.

2 SDSS J102915+172927 ELEMENTAL ABUNDANCE FIT

The observed elemental abundances of EMPs (with $[\text{Fe/H}] \leq -3$) and ultra-metal-poor stars (UMPs, with $[\text{Fe/H}] \leq -4$) have been interpreted in terms of individual metal-free SN explosion models (Umeda & Nomoto 2003; Iwamoto et al. 2005; Tominaga, Umeda & Nomoto 2007) or involving a combination of metal-free SN models with different progenitor masses, explosion energies and mixing (Limongi, Chieffi & Bonifacio 2003; Heger & Woosley 2010). Samples of EMPs with typical halo signatures (Cayrel et al. 2004) can be well reproduced by the yields of Population III (Pop III) massive (30–50 M$_{\odot}$) energetic hypernovae (Tominaga et al. 2007) or by the integrated yields of ordinary Pop III SN with reduced mixing and explosion energy (Heger & Woosley 2010). The peculiar abundance pattern of extreme CEMP s such as HE 0107–5240 with $[\text{Fe/H}] = -5.2$ (Christlieb et al. 2002) and HE 1327–2326 with $[\text{Fe/H}] = -5.4$ (Frebel et al. 2005) has been interpreted with the yields of a Pop III 25 M$_{\odot}$ faint SN that underwent strong mixing and fall back (Umeda & Nomoto 2003; Iwamoto et al. 2005), with the pollution of the birth cloud by two core-collapse Pop III SNe (Limongi et al. 2003) or with the yields of Pop III SN with progenitor mass 12–30 M$_{\odot}$ with reduced mixing and explosion energy (Heger & Woosley 2010). Additional hypothesis involve mass transfer of CNO elements from a postulated binary companion (Suda et al. 2004) or mass loss by massive (60 M$_{\odot}$) near metal-free stars (Meynet, Ekström & Maeder 2006). It is clear from the above that a solid picture for the origin of EMPs, and in particular for CEMP s, is still lacking.

Despite its very low iron content, the recently discovered halo star SDSS J102915+172927 shows an abundance pattern consistent with typical Galactic halo signatures. Our aim here is to identify a set of plausible Pop III SN models which may have polluted its birth cloud. The procedure that we follow is to fit the elemental abundance pattern of SDSS 102915+172927 with the chemical yields produced by a new set of Pop III core-collapse SN models. We refer the interested reader to Limongi & Chieffi (2012) for a thorough presentation of the models. Here we simply recall the basic properties that are relevant for the present investigation.

The set of models extends in mass between 13 and 80 M$_{\odot}$ and has been followed from the pre-main-sequence phase up to the onset of the iron core collapse by means of the FRANEC stellar evolutionary code. The initial composition is set to the pristine big bang nucleosynthesis one ($Y = 0.23$) and mass loss is switched off during all the evolutionary stages. Calculations based on the radiatively driven wind theory show that the mass loss scales with the metallicity of the surface of the star as $(Z/Z_{\odot})^\alpha$, with $\alpha$ between 0.5 and 0.8 (Kudritzki et al. 1987; Vink et al. 2001). Such a dependence would become much stronger at lower Z (Kudritzki 2002). Hence we expect mass loss to be strongly inhibited in zero metallicity stars (but see also Meynet et al. 2006).

The explosive nucleosynthesis has been computed in the framework of the induced explosion (Limongi & Chieffi 2006) approximation. More specifically, the explosion of the mantle of the star is started by imparting instantaneously an initial velocity $v_0$ to a mass coordinate of $\sim 1$ M$_{\odot}$ of the pre-SN model, i.e. well within the iron core. The propagation of the shock wave that forms consequently is followed by means of a hydro code that solves the fully compressible reactive hydrodynamic equations using the piecewise parabolic method in the Lagrangian form (see Chieffi & Limongi 2002; Limongi & Chieffi 2003).

Since the energy of the shock wave that drives the ejection of part of the collapsing star cannot yet be determined on the basis of first principles, some kind of arbitrary choice is necessary. The standard procedure followed by most of the leading groups working in this field (see e.g. Umeda & Nomoto 2003, 2005; Tominaga et al. 2007; Heger & Woosley 2010) is to calibrate the explosion by requiring the final kinetic energy of the ejecta to have a specific value, the ejection of a given amount of $^{56}$Ni, or by choosing the mass of the remnant in order to fit a specific elemental ratio. Here we follow a slightly different approach: we do not impose the fit to just one elemental ratio, but we choose the mass cut that provides the best fit to the elemental ratios measured on the surface of SDSS J102915+172927. From a technical point of view, since we inject energy in the star by imparting an arbitrary velocity $v_0$ to an internal mass layer, the final size of the mass of the remnant will be controlled by this (artificial) parameter (the larger $v_0$, the smaller the mass of the remnant).

Following this procedure, we find that the best overall fit to the observations is achieved for progenitor masses of 20 and 35 M$_{\odot}$ with mass cuts, explosion energies and ejected $^{56}$Ni mass equal to 1.73 M$_{\odot}$, $10^{51}$ erg, $M(^{56}\text{Ni}) = 0.06$ M$_{\odot}$ and 1.73 M$_{\odot}$, 2.4 x $10^{51}$ erg, $M(^{56}\text{Ni}) = 0.16$ M$_{\odot}$, respectively. These results represent standard values for ordinary core-collapse SN, in agreement with what has been recently found by Heger & Woosley (2010) to interpret the observed abundances of EMPs with typical Galactic halo signatures. Fig. 1 shows the comparison between SDSS J102915+172927 elemental ratios relative to iron and the chemical yields of Pop III SN with 20, 35 and 50 M$_{\odot}$ progenitor masses. Except for the [Ti/Fe] and [Ni/Fe] ratios, the chemical yields of the 20 and 35 M$_{\odot}$ SN models provide a good fit to the observations. It is well known that the fit to the [Ti/Fe] and [Ni/Fe] abundance ratios can be improved by assuming some kind of unconventional behaviour of the deep interior of the star, like the mixing and fall back mechanism proposed by Umeda & Nomoto (2005). We stress, however, that these uncertainties do not affect the computation of dust production in the SN ejecta, which is the main purpose of the present investigation.
If the SN explodes in a denser circumstellar medium, the reverse shock travels faster inside the ejecta and encounters a gas at higher density. This increases the effect of sputtering. When the number of monomers in each grain becomes less than two, the grain is evaporated, returning the metals into the gas phase. Depending on the average density of the circumstellar medium, of the original ∼0.4 M⊙ of dust formed in the ejecta of the two SN models, between 1 and 20 per cent are able to survive the passage of the reverse shock. A large fraction of newly formed dust mass is returned to the gas phase on a time-scale of ∼(3−20) × 10⁵ yr after the explosion, thus fixing the final depletion factor fdep. The dust mass is dominated by MgSiO₃ and Fe₂O₄ grains for the 20 and 35 M⊙ SN models, respectively. These remain the dominant dust species after the partial destruction in the reverse shock (see Fig. 2).

4 BIRTH CONDITIONS OF SDSS J102915+172927

According to the recent analysis by Schneider et al. (2011), in the EMP environments, such as the birthplace of SDSS J102915+172927, subsolar mass stars can form only if

\[ D > 1.4 \times 10^{-8} \left[ \frac{S}{10^{18} \text{cm}^{-2}} \right]^{-1} \left[ \frac{T}{10^4 \text{K}} \right]^{-1/2} \left[ \frac{n_H}{10^{12} \text{cm}^{-3}} \right]^{-1/2}, \]

where \( D = Z f_{\text{dep}} \) is the dust-to-gas ratio, \( S \) is the grain geometric cross-section per unit dust mass and \( n_H = 10^{12} \text{cm}^{-3} \) and \( T = 10^4 \text{K} \) are the characteristic density and temperature at which dust cooling becomes efficient. At the observed metallicity of SDSS J102915+172927, this yields \( f_{\text{dep}} > 0.01 \), when the values \( S \sim (1.5−2.5) \times 10^6 \text{ cm}^2 \text{ g}^{-1} \), appropriate for shock-processed SN grains, have been adopted. According to the results shown in Fig. 2, if the parent gas cloud has been enriched by a metal-free 20 M⊙ SN, the criterion is satisfied for three out of the four shock models explored, i.e. if the SN explodes in a medium with density \( \leq 10^{-24} \text{ g cm}^{-3} \). If the enrichment has been caused by the explosion of a 35 M⊙...
When the density $\rho < \sim 10^{-3} \text{cm}^{-3}$, the minimum fragment mass corresponds to the Jeans mass at the inflection point of the equation of state (Larson 2003). Depending on the metallicity, the first phase of fragmentation is due to molecular or metal line cooling. For all the models presented in Fig. 3, we find that at $n_{\text{H}} \sim 10^5$–$10^6 \text{cm}^{-3}$, cooling is dominated by OH molecules. The smallest fragment that forms has a mass $\sim 8 M_\odot$. When the density increases to $n_{\text{H}} \geq 10^9 \text{cm}^{-3}$, dust continuum emission starts to be efficient and the gas enters a new phase of cooling; where the fragmentation conditions are met (Schneider & Omukai 2010), the typical masses that form are $\sim (0.05–0.1) M_\odot$. Although these numbers cannot be directly associated with the final stellar masses, theoretical arguments, observational data and numerical simulations confirm that the thermal properties of star-forming clouds play an important role in determining the stellar initial mass function, and support the hypothesis that the Jeans mass at the point of minimum temperature is important in determining the stellar characteristic mass (Larson 2003; Clark, Glover & Klessen 2008; Dopcke et al. 2011).

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**DISCUSSION AND CONCLUSIONS**

The formation of the first low-mass stars requires the presence in the star-forming gas of metals, mostly C and O, which contribute to gas cooling. In the ejecta of core-collapse SNe, a fraction of these metals can condense into dust grains that provide an additional cooling channel to the star-forming gas. The relative importance of metals and dust grains in the formation of the first low-mass stars is still a subject of debate.

Observations show that the fraction of CEMP in the Galactic halo increases with decreasing metallicity and that three out of the four halo stars with [Fe/H] $< -4$ are carbon enhanced. This has given support to a metal (mostly O and C) driven transition in the fragmentation scales that allows the formation of low-mass stars when [C/H] and [O/H] (or a combination of the two) exceed a critical threshold (Bromm & Loeb 2003; Frebel et al. 2007). Despite the fact that the origin of the large CNO enhancement in CEMPs is still unclear (see Section 2), if these elements were already present in the parent birth clouds, the formation of low-mass CEMPs does not appear to be problematic, even at the lowest observed [Fe/H] (Schneider et al. 2003).

The recent discovery of SDSS J102915+172927 challenges this scenario because the observed [C/H] and [O/H] places this star in a ‘forbidden zone’ for low-mass star formation via metal-fine-structure line cooling. Our analysis shows that the formation of subsolar mass stars at very low metallicities, such as the one inferred for SDSS J102915, relies on dust. The observed properties of this primeval star constrain the SN progenitors to have masses $\sim (20–40) M_\odot$ and to release $\sim (0.01–0.4) M_\odot$ of dust in the surrounding medium. If these values are representative of the properties of the first SNe, then rapid dust enrichment must have followed the formation of the first stars. As a consequence, the transition from a star formation epoch dominated by massive Pop III stars to an epoch where Pop II and Pop I stars form with an ordinary stellar initial mass function may be driven by dust and proceed more rapidly than previously thought (Tornatore et al. 2007; Maio et al. 2010). This has important implications for the nature of the first galaxies and their contribution to the process of cosmic reionization.
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