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Elemental Compositions of Hyper-Metal-Poor Stars Formed in Dust-Enriched Dense Shells of Population III Supernova Remnants

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Abstract. We describe the evolution of dust within Population III supernova remnants (SNRs) and investigate the chemical compositions of the dust piled up in their dense shells. We show that the resulting abundance patterns of the major elements in the dense shells are in good agreement with that observed for a Galactic halo star, SDSS J102915+172927. This allows us to propose that SDSS J102915+172927 might be the second-generation star formed in the dust-enriched dense shell of a Population III SNR. We conclude that the segregation of dust from the metal-rich ejecta gas can be an important process in determining the abundance patterns of primitive low-mass stars.

Keywords: dust, extinction – ISM: supernova remnants – supernovae: general – stars: abundances, stars; chemically peculiar – stars: low-mass
PACS: 97.10.Bt, 97.10.Tk, 97.20.Tr, 97.60.Bw, 98.38.Cp, 98.38.Mz

INTRODUCTION

Hyper-metal-poor stars with [Fe/H] ≤ -5 are considered to be vestiges of stellar populations in the early universe [1]. Since they must have been formed in very little enriched gas clouds, their chemical compositions are expected to reflect the nucleosynthesis in the very early generations of stars [2–6]. Such old metal-poor stars also provide deep insight into the formation mechanism of low-mass ($\leq 1\ M_\odot$) stars in low-metallicity environments. The most primitive Galactic star discovered so far, SDSS J102915+172927 shows an extremely low metal content ($Z \leq 4.5 \times 10^{-5}\ Z_\odot$) [7], suggesting that the formation of this star must have been induced through the cooling by dust grains [8, 9].

Here we propose one possible scenario for the origin of SDSS J102915+172927; this star might be the second-generation star that was formed in the dust-enriched dense shell of a Population III supernova remnant (SNR). This scenario can naturally explain (1) the presence of dust grains necessary for the formation of sub-solar mass stars and (2) the abundance pattern of the major elements observed for SDSS J102915+172927. In the followings, we briefly describe the evolution of newly formed dust in SNRs and analyze the elemental compositions of the dust grains accumulated in the dense SN shells.

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EVOLUTION OF DUST IN POP III SNRS

The evolution of dust inside SNRs is described in detail in [10], where we calculated the dynamics of dust and its destruction by sputtering, based on the size distribution and spatial distribution of dust formed in the unmixed ejecta of Population III core-collapse supernovae (SNe) [11]. The time evolution of the gas temperature and density in SNRs are also computed for the uniform interstellar medium (ISM) with the hydrogen number density of $n_{\rm H,0} = 0.1$, 1.0, and 10 cm^{-3}. As the initial condition of the gas in the ejecta, we adopted the hydrodynamic models of Population III SNe with the progenitor masses of $M_{\rm ZAMS} = 13$, 20, 25, and 30 $M_\odot$, all of which have explosion energy of 10^{51} erg [12].

The results of the calculations show that the evolution of dust in SNRs heavily depend on their initial radii $a_{\rm ini}$. For $n_{\rm H,0} = 1.0$ cm^{-3}, small grains with $a_{\rm ini} <\simeq 0.05$ μm are trapped in the shocked hot gas and are completely destroyed through thermal sputtering. Grains with $a_{\rm ini} \simeq 0.05$–0.2 μm reduce their radii by $\sim$50% but are eventually piled up in the dense shell behind the forward shocks. Large grains of $a_{\rm ini} >\simeq 0.2$ μm are injected into the ISM without being decelerated and eroded significantly, Note that the transport and destruction of dust in SNRs also depend on the density of gas in the ISM; for a higher ISM density, dust grains undergo more efficient deceleration and erosion, and thus the majority of newly formed grains are destroyed for $n_{\rm H,0} = 10$ cm^{-3}.

ELEMENTAL COMPOSITIONS IN DENSE SN SHELLS

The calculations of dust evolution within SNRs indicate that a part of the dust grains surviving the destruction are finally incorporated into the dense SN shells. These piled-up grains can drive the formation of sub-solar mass stars in the shells [13] and affect significantly the elemental abundances of the newly formed stars. Therefore, assuming that the composition of the piled-up grains determines the elemental composition of those low-mass stars, we derive the metal abundances in the dense shells of Population III SNRs and compare to those observed for SDSS J102915+172927.

Figure 1 shows the calculated abundances of C, O, Mg, and Si relative to Fe in the shells. For $n_{\rm H,0} = 0.1$ and 1.0 cm^{-3}, the metallicity in the shells is less than 4.5×10^{-5} $Z_\odot$, and the iron abundances are in the range of [Fe/H] $\simeq -6$ to -5, both of which are in good agreement with those for SDSS J102915+172927 (see [10, 14] for the tabulated values of the elemental abundances and metallicity in the dense SN shells). It can be seen that most of the models show the modest overabundances of C and Si ($0.1 \leq$ [C/Fe] ≤ 1.1 and $0.4 \leq$ [Si/Fe] ≤ 1.3) and the nearly solar abundances of O and Mg ($-0.7 \leq$ [O/Fe] ≤ 0.6 and $-0.5 \leq$ [Mg/Fe] ≤ 0.7), except for one or two extreme cases. These tendencies are entirely consistent with the abundance pattern of SDSS J102915+172927. In particular, the results for $M_{\rm ZAMS}$ = 30 $M_\odot$ and $n_{\rm H,0} = 0.1$ cm^{-3} (open triangles) and $M_{\rm ZAMS}$ = 25 $M_\odot$ and $n_{\rm H,0} = 1.0$ cm^{-3} (open circles) well match the observed abundances of the major elements. Thus, these results suggest that SDSS J102915+172927 could be the second-generation star that was formed in the dust-enriched dense shell of a Population III SNR. We conclude that the formation of dust in the SN ejecta and the subsequent decoupling of the dust from metal-rich ejecta can be critical processes to form the primitive low-mass stars such as SDSS J102915+172927.

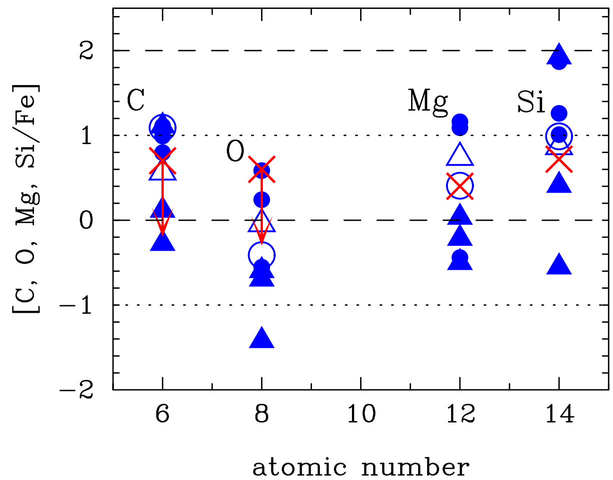

FIGURE 1. Abundances of C, O, Mg, and Si relative to Fe derived from the chemical compositions of dust grains piled up in the dense shells of Population III SNRs that expand into the uniform ISM with $n_{H,0} = 0.1$ cm^{-3} (triangles) and $n_{H,0} = 1.0$ cm^{-3} (circles). Models of core-collapse SNe with M_{ZAMS} = 13, 20, 25, and 30 $M_\odot$ are taken from [12]. The observed elemental abundances (and upper limits) of a Galactic halo star SDSS J102915+172927 are plotted by the red crosses (with the arrows) [7]. The open triangles and circles are, respectively, the results for the models with M_{ZAMS} = 30 $M_\odot$ and $n_{H,0} = 0.1$ cm^{-3}, and M_{ZAMS} = 25 $M_\odot$ and $n_{H,0} = 1.0$ cm^{-3}. which show the best agreement with the observed elemental composition of SDSS J102915+172927 among the models considered here.

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