Classification of extremely metal-poor stars: absent region in \(A(C) - [\text{Fe/H}] \) plane and the role of dust cooling

Gen Chiaki,1* Nozomu Tominaga1 and Takaya Nozawa2

1Department of Physics, Konan University, 8-9-1 Okamoto, Kobe 658-8572, Japan
2Division of Theoretical Astronomy, National Astronomical Observatory of Japan, Mitaka, Tokyo 181-8588, Japan

Abstract

Extremely metal-poor (EMP) stars are the living fossils with records of chemical enrichment history at the early epoch of galaxy formation. By the recent large observation campaigns, statistical samples of EMP stars have been obtained. This motivates us to reconsider their classification and formation conditions. From the observed lower limits of carbon and iron abundances of \(A_{\text{cr}}(C) \sim 6\) and \([\text{Fe/H}]_{\text{cr}} \sim -5\) for C-enhanced EMP (CE-EMP) and C-normal EMP (CN-EMP) stars, we confirm that gas cooling by dust thermal emission is indispensable for the fragmentation of their parent clouds to form such low mass, i.e. long-lived stars, and that the dominant grain species are carbon and silicate, respectively. We constrain the grain radius \(r_c^{\text{cool}}\) of a species \(i\) and condensation efficiency \(f^{\text{cool}}_{ij}\) of a key element \(j\) as \(r_c^{\text{cool}}/f_{C,C} = 10\ \mu m\) and \(f_{\text{Sil}}/f_{\text{Sil,MP}} = 0.1\ \mu m\) to reproduce \(A_{\text{cr}}(C)\) and \([\text{Fe/H}]_{\text{cr}}\), which give a universal condition \(10^{[C/\text{H}]} - 2.30 + 10^{[\text{Fe}/\text{H}]} > 10^{-5.07}\) for the formation of every EMP star. Instead of the conventional boundary \([C/\text{Fe}] = 0.7\) between CE-EMP and CN-EMP stars, this condition suggests a physically meaningful boundary \([C/\text{Fe}]_b = 2.30\) above and below which carbon and silicate grains are dominant coolants, respectively.

Key words: stars: formation – stars: low-mass – stars: Population II – ISM: abundances – dust, extinction – galaxies: evolution.

1 Introduction

Long-lived stars with metallicities lower than our neighbourhood, so-called metal-poor (MP) stars, are discovered in our Galaxy and nearby dwarf galaxies. They are intensively studied as the clues to know the chemical evolution during the structure formation. This approach is called Galactic archaeology or near-field cosmology. MP stars are classified into carbon-enhanced MP (CEMP) and carbon-normal MP (CNMP) stars, divided at the boundary conventionally defined as \([C/\text{Fe}] = 0.7\) (Beers & Christlieb 2005; Aoki et al. 2007).

CEMP stars are apparently subdivided into three groups on the \((A(C) - [\text{Fe/H}])\) plane (Fig. 1). While CEMP Group I stars residing in \(-3.7 < [\text{Fe/H}] < -1.2\) and \(7.0 < A(C) < 9.0\) are dominantly CEMP-s stars, Group II (with \(-5.0 < [\text{Fe/H}] < -2.5\) and \(5.0 < A(C) < 7.0\)) and Group III (with \([\text{Fe/H}] < -3.5\) and \(6.0 < A(C) < 7.5\)) stars are mainly CEMP-no stars. Since almost all Group I stars show binary feature, they are considered to have acquired the gas rich with \(C\) and \(n\)-capture elements from their evolved companions (Suda et al. 2004). On the other hand, the physical explanation of distinction between Groups II and III stars has not been made so far.

MP stars with \([\text{Fe/H}] < -3\) including CEMP Groups II and III stars are particularly called extremely metal-poor (EMP) stars. The lower limits of their elemental abundances indicate the existence of the critical metallicity above which their parent clouds become unstable to fragment into small gas clumps through efficient gas cooling by heavy elements so that low-mass stars which survive until the present day are likely to be formed (Bromm & Loeb 2003; Frebel et al. 2005). Recent theoretical studies have shown that cooling by dust thermal emission is crucial to form low-mass fragments with \(\sim 0.1\) M\(_\odot\) (Omukai 2000; Schneider et al. 2003).

Marassi et al. (2014) and Chiaki et al. (2015) predict that dust grains are important commonly for the formation of C-enhanced EMP (CE-EMP) and C-normal EMP (CN-EMP) stars. They show that the dominant grain species are carbon and silicate, respectively.
and estimate the critical C and Si abundances. However, they resort to theoretical models of grain formation because the properties of grains such as radius and condensation efficiency can not be directly measured. Further, their analyses are based on the conventional classification of EMP stars, and do not explain the difference between Groups II and III stars.

In this Letter, we reconsider the classification and formation conditions of EMP stars. From Fig. 1, we point out three interesting features: (1) no EMP stars have so far been observed in the region of $A(C) < 6$ and $[\text{Fe/H}] < -5$, (2) Groups III and II stars are distributed in the regions with high ($[\text{C/Fe}] > 2$) and moderate ($[\text{C/Fe}] < 2$) C-enhancement, respectively and (3) the distribution of Group II stars appears continuously connected with CN-EMP stars.

We derive grain properties of carbon and silicate from the feature (1), and then present a formation condition applicable to every EMP star. Comparing the contributions of carbon and silicate grains to gas cooling, we propose the physically motivated boundary between EMP stars whose formation could be derived mainly by carbon and silicate. This boundary can simultaneously explain the features (2) and (3). Throughout this Letter, we use the solar abundance of Asplund et al. (2009) as $A_{\odot}(C) = 8.43, A_{\odot}(\text{Mg}) = 7.60$ and $A_{\odot}(\text{Fe}) = 7.50$.

## 2 CRITICAL ELEMENTAL ABUNDANCES

### 2.1 Critical Fe abundance and property of carbon grains

We first derive the effective radius $r_{\text{cool}}^{\text{C}}/f_{\text{C,C}}$ for carbon grains. For carbon grains, the key element is carbon, and $\mu_{\text{C,C}} = 12$ and $\xi_{\text{C}} = 2.23 \text{ g cm}^{-3}$. Then, from equation (1), we can obtain the critical carbon abundance above which gas cooling by carbon grains exceeds gas compressional heating as

$$A_{\odot}(C) = 5.67 + \log \left( \frac{r_{\text{cool}}^{\text{C}}/f_{\text{C,C}}}{10 \mu \text{m}} \right).$$

The horizontal red lines in the left-hand panel of Fig. 1 show the critical carbon abundances for $r_{\text{cool}}^{\text{C}}/f_{\text{C,C}} = 1, 10$ and $100 \mu \text{m}$ from bottom to top. CEMP Group III stars are distributed in a range of $A(C) > 6.0$ over a wide range of $[\text{Fe/H}]$ $(-7 \lesssim [\text{Fe/H}] \lesssim -4)$. Hence, $A_{\odot}(C) = 6$ can be taken as the lower limit of C abundances for CEMP Group III stars. Then, the effective grain radius is estimated to be $r_{\text{cool}}^{\text{C}}/f_{\text{C,C}} = 21.6 \mu \text{m}$. Taking the statistical uncertainties into consideration, we here adopt $r_{\text{cool}}^{\text{C}}/f_{\text{C,C}} = 10 \mu \text{m}$. Below the horizontal line corresponding to $r_{\text{cool}}^{\text{C}}/f_{\text{C,C}} = 10 \mu \text{m}$ (shaded region in Fig. 1), carbon dust cooling is inefficient to induce cloud fragmentation, and long-lived low-mass stars are unlikely to form. Some of CEMP Group II stars have lower carbon abundances than $A_{\odot}(C) = 6.0$, which is discussed in the subsequent sections.

### 2.2 Critical Fe abundance and property of silicate grains

Next, we constrain the property of the other major grain species, silicate. For silicates, we consider enstatite ($\text{MgSiO}_3$) with its key element being Mg, and $\mu_{\text{MgSiO}_3,\text{Mg}} = 100$ and $\xi_{\text{MgSiO}_3} = 3.21 \text{ g cm}^{-3}$, average of a physical quantity $x$ weighted by the size distribution $\varphi_{\text{i}}(r)$ of a grain species $i$. Equation (1) is given at the gas density $n_\text{g} = 10^{15} \text{ cm}^{-3}$ and temperature $T = 1000 \text{ K}$, where dust cooling is dominant over gas compressional heating in clouds with $[\text{Fe/H}] \sim -5$ (Schneider et al. 2012). $X_\text{H}$ is the mass fraction of hydrogen nuclei and $X_\text{H} = 0.75$ throughout this Letter.

\begin{equation}
\sum_i \frac{3\mu_{\text{i}}f_{\text{i}}X_{\text{H}}}{4\pi r_{\text{cool}}^{\text{C}}/f_{\text{C,C}}} \gamma(j) > 1.4 \times 10^{-3} \text{ cm}^2 \text{ g}^{-1},
\end{equation}

where $\mu_{\text{i}}$ denotes the molecular weight of a monomer and $\xi_{\text{i}}$ is the bulk density of a grain (Chiaki et al. 2015). This indicates that,
The result is unchanged for forsterite (Mg$_2$SiO$_4$), whose key element is Si. From equation (1), we can calculate the critical condition where gas cooling by silicate grains overcomes the compressional gas heating as

$$\frac{\text{Mg}}{\text{H}}|_{\text{cr}} = -4.70 + \log \left( \frac{r_{\text{Sil}}^{\text{cool}}}{f_{\text{Sil,Mg}}} \right)_{0.1 \mu \text{m}}. \quad (3)$$

We convert this critical Mg abundance to the critical Fe abundance, using the average abundance ratio $[\text{Mg}/\text{Fe}] = 0.368$ for stars with $[\text{Fe}/\text{H}] < -1$ (from SAGA data base), as

$$[\text{Fe}/\text{H}]|_{\text{cr}} = -5.07 + \log \left( \frac{r_{\text{Sil}}^{\text{cool}}}{f_{\text{Sil,Mg}}} \right)_{0.1 \mu \text{m}}. \quad (4)$$

The vertical blue lines in the right-hand panel of Fig. 1 indicate the critical Fe abundances for $r_{\text{Sil}}^{\text{cool}} / f_{\text{Sil,Mg}} = 0.01$, 0.1 and 1 $\mu$m from left to right. To realize the critical abundance $[\text{Fe}/\text{H}]|_{\text{cr}} = -5.0$ suggested by the distribution of CN-EMP stars, the effective grain radius $r_{\text{Sil}}^{\text{cool}} / f_{\text{Sil,Mg}} = 0.081 \mu$m is required. We set the fiducial value of the effective grain radius as $r_{\text{Sil}}^{\text{cool}} / f_{\text{Sil,Mg}} = 0.1 \mu$m, which is smaller than that of carbon grains by two orders of magnitude.

### 2.3 Combined criterion for CE-EMP and CN-EMP star formation

In the previous sections, we have considered separately the contributions of carbon and silicate grains to gas cooling, and derived their effective grain radii. In reality, both the grain species can contribute simultaneously to gas cooling in collapsing clouds. In this case, equation (1) is reduced to

$$\frac{10^{3.03}}{10^{17.5}} \frac{r_{\text{C}}^{\text{cool}}}{f_{\text{C},\text{C}}} y(\text{C}) + \frac{r_{\text{Sil}}^{\text{cool}}}{f_{\text{Sil,Mg}}} y(\text{Mg}) > 1.4 \times 10^{-3}. \quad (5)$$

Using $r_{\text{C}}^{\text{cool}} / f_{\text{C},\text{C}} = 10 \mu$m and $r_{\text{Sil}}^{\text{cool}} / f_{\text{Sil,Mg}} = 0.1 \mu$m derived in the previous sections gives

$$10^{[\text{C}/\text{H}]-2.30} + 10^{[\text{Fe}/\text{H}]} > 10^{-5.07}. \quad (6)$$

### 2.4 Boundary between CE-EMP and CN-EMP stars

Equating the first and second terms in the left-hand side of equation (5), we can define the transition line on which the contributions of carbon and silicate grains to gas cooling are equal as

$$[\text{C}/\text{Fe}]_b = 2.30. \quad (6)$$

This condition is indicated by the black line in Fig. 2 above which gas cooling by carbon grain is dominant over that by silicates. The boundary gives the physical explanation of the distinction between CEMP Group III and Group II stars.

### 3 MODEL CALCULATIONS OF GRAIN PROPERTIES IN POP III SN EJECTA

We have shown that the effective grain radius of carbon must be larger than that of silicate by two orders of magnitude to reproduce the observed distributions of EMP stars. In this section, we show this difference in grain radius with a dust formation model. In the early Universe, dust grains are mainly supplied by supernovae (SNe) arising from first-generation metal-free (Pop III) stars (Todini & Ferrara 2001; Nozawa et al. 2003). While the elemental abundances of CE-EMP stars are well reproduced by faint core-collapse SNe (FSNe) with C enhancement due to large fallback of Fe peak elements, those of CN-EMP stars are reproduced by energetic core-collapse SNe (CCSNe) or hypernovae (HNe) (Umeda & Nomoto 2003; Limongi & Chieffi 2012;

To estimate the properties of newly formed dust, we follow the temporal evolution of temperature $T$ and density $ρ$ of expanding SN ejecta with radiative transfer calculations including energy deposition from radioactive decay of $^{56}$Ni (Iwamoto et al. 2000). Applying the approximation formulae of Nozawa & Kozasa (2013), the average grain radius $r_{i}^{\text{max}}(M_{i})$ and condensation efficiency $f_{j}^{\text{cool}}(M_{j})$ are calculated at each mass coordinate $M_{i}$ from the concentration $c_{j}^{\text{cool}} = X_{j} ρ/m_{j}$ of a key element $j$ and the cooling time-scale $t_{j}^{\text{cool}}$ at the onset time $t_{j}^{\text{on}}$ of dust formation when $T$ declines down to the condensation temperature (2000 K and 1500 K for carbon and silicate grains, respectively). A dominant fraction of grains will be formed at the mass coordinate $M_{i}^{\text{ave}}$, where $r_{i}^{\text{max}}$ becomes largest because $c_{j}^{\text{cool}}$ marks maximum there. We thus take $r_{i}^{\text{max}} = r_{j}^{\text{max}}(M_{i}^{\text{ave}})$ as the fiducial value of the grain radius. At $M_{i}^{\text{max}}$, $f_{j}^{\text{cool}}$ turns to be $\approx 1$. We take a progenitor model of the SN which reproduces the chemical composition of HE0557 – 4840 with an intermediate C-enhancement [C/Fe] = 1.68 (Ishigaki et al. 2014). The mass cut is $M_{\text{cut}} = 5.65 M_{\odot}$ and progenitor mass is $M_{\text{SN}} = 25 M_{\odot}$. The masses of C and Mg atoms are $m_{c} = 12 m_{H}$ and $m_{\text{Mg}} = 24 m_{H}$, where $m_{H}$ is the mass of a hydrogen nucleus.

We first see the results for carbon grains. Since carbon grains are formed mainly in the layer rich with C, we set $X_{C} = 1.0$. Fig. 3 shows the temporal evolutions of gas temperature and density with a fixed $^{56}$Ni mass of $M_{i}^{\text{SN}}(^{56}$Ni) = $10^{-3} M_{\odot}$ and (b) with a fixed explosion energy of $E_{\text{SN}} = 1 \times 10^{51}$ erg at the mass coordinate where the largest carbon grains are formed. The circles are plotted at the onset time of carbon grain formation when $T$ becomes below the condensation temperature (2000 K) indicated by the black dashed line.

$r_{i}^{\text{max}}$ declines rapidly with $E_{\text{SN}} \gtrsim 1 \times 10^{51}$ erg because $t_{j}^{\text{on}}$ is coincident with the finishing time of the plateau phase when the ejecta becomes optically thin and the temperature decline suddenly. With shorter cooling time-scale, the larger number of grain seeds form, i.e., the radius of each grain becomes smaller.

With the same mass fraction $X_{C} = X_{\text{Mg}} = 1.0$, $r_{i}^{\text{max}}$ for carbon and silicate grains are similar for each $E_{\text{SN}}$ and $M_{i}^{\text{SN}}(^{56}$Ni). However, in the formation region of silicate grains, Mg is dominated by O, and we set the fiducial value as $X_{\text{Mg}} = 0.1$, following nucleosynthesis calculations (Tominaga et al. 2014). With $X_{\text{Mg}} = 0.1$, the $r_{i}^{\text{max}}$ decreases by an order of magnitude for each $E_{\text{SN}}$ and $M_{i}^{\text{SN}}(^{56}$Ni).

To reproduce the elemental abundance of the most iron-poor CE-EMP stars such as SDSS J0313 – 6708 (Keller et al. 2014), $E_{\text{SN}} \approx 10^{51}$ erg and $M_{i}^{\text{SN}}(^{56}$Ni) $\lesssim 10^{-3} M_{\odot}$ are favoured (Marassi et al. 2014; Ishigaki et al. 2014). In our calculations, we estimate $r_{i}^{\text{max}} = 34.3 \, \mu m$ with $E_{\text{SN}} = 1.0 \times 10^{51}$ erg and $M_{i}^{\text{SN}}(^{56}$Ni) = $1 \times 10^{-3} M_{\odot}$. The abundance ratio of the most metal-poor star SDSS J1029 + 1729 (Caffau et al. 2011) is reproduced by SN models with $E_{\text{SN}} \approx 5 \times 10^{52}$ erg and $M_{i}^{\text{SN}}(^{56}$Ni) $\approx 0.1 M_{\odot}$ (Tominaga et al. 2014). We predict $r_{\text{Sil}}^{\text{max}} = 0.188 \, \mu m$ with $E_{\text{SN}} = 1.0 \times 10^{52}$ erg, $M_{i}^{\text{SN}}(^{56}$Ni) = 0.1 $M_{\odot}$, and $X_{\text{Mg}} = 0.1$. These values are consistent with $r_{\text{C}}^{\text{cool}}/f_{\text{C,C}} = 10 \, \mu m$ and $r_{\text{Sil}}^{\text{cool}}/f_{\text{Sil,Mg}} = 0.1 \, \mu m$.

**4 DISCUSSION**

The observed lower limits of C and Fe abundances of CE-EMP and CN-EMP stars indicate that these stars form through the fragmentation of their parent clouds by gas cooling owing to thermal emission of two major grain species, carbon and silicate, respectively. We first derive the grain radius and condensation efficiency as $r_{i}^{\text{cool}}/f_{\text{C,C}} = 10 \, \mu m$ and $r_{\text{Sil}}^{\text{cool}}/f_{\text{Sil,Mg}} = 0.1 \, \mu m$ from the lower limits of C and Fe abundances, respectively. The tendency that carbon grains are larger than silicates is qualitatively explained by our simple analyses of dust formation. Carbon grains grow more efficiently than silicate because the gas density remains higher at the time when temperature declines to the condensation temperature with the smaller $E_{\text{SN}}$ and $M_{i}^{\text{SN}}(^{56}$Ni) favoured for CE-EMP stars, and because the mass fraction of C is higher than that of Mg in the dust formation region.

We can derive the critical condition for EMP star formation as equation (5), which can well reproduce the region where no stars have so far been observed as indicated by the shaded region in
Fig. 2. Then, we find that the dominant coolant switches from carbon to silicate from above to below the boundary [C/Fe]$_b = 2.30$, which gives the physically motivated classification of CE-EMP and CN-EMP stars. This simultaneously explain the discrimination of CEMP Group II and Group III stars (Yoon et al. 2016). Opposite to Group III stars, the dominant coolant for the formation of CEMP Group II stars is silicate grains as CN-EMP stars. Interestingly, the distribution of Group II stars is continuous with that of CN-EMP stars as indicated by Fig. 2.

Our estimation of the effective grain radii is based on the observed elemental abundances of EMP stars. Our model presented in Section 3 predicts the larger values $r_{\text{cool}}^{C}/f_{C,C} = 34.3$ µm and $r_{\text{Sil}}^{\text{max}}/f_{\text{Sil},\text{Mg}} = 0.188$ µm for the fiducial cases. Although we here take the maximum grain radius at the corresponding mass coordinate $M_{\text{max}}^{	ext{cool}}$, the mass fraction of smaller grains formed in other mass coordinates can non-negligible, and the average radius of grains will be smaller. Marassi et al. (2015) predict the smaller grain radii of $r_{\text{cool}}^{C}/f_{C,C} \lesssim 0.1$ µm by their grain formation models in FSN ejecta. It is still possible that stars with lower elemental abundances, which is permitted by smaller effective grain radii, are discovered by future observations. In the current state, although the number of samples in the Galactic halo is large ($\sim 10^6$ stars), statistics of EMP stars with [Fe/H] $< -3$ is still small (Hartwig et al. 2015). As the number of EMP stars increases by future observations, the accuracy of the estimation of grain property and the boundary between CE-EMP and CN-EMP stars presented in this Letter will get improved.

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