Metal Pollution of Low-Mass Population III Stars through Accretion of Interstellar Objects like ‘Oumuamua

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Abstract
We calculate accretion mass of interstellar objects (ISOs) like ‘Oumuamua onto low-mass population III stars (Pop. III survivors), and estimate surface pollution of Pop. III survivors. An ISO number density estimated from the discovery of ‘Oumuamua is so high (\(\sim 0.2\ \text{au}^{-3}\)) that Pop. III survivors have chances at colliding with ISOs > \(\sim 10^5\) times per \(1\ \text{Gyr}\). ‘Oumuamua itself would be sublimated near Pop. III survivors, since it has small size, \(\sim 100\ \text{m}\). However, ISOs with size > \(\sim 3\ \text{km}\) would reach the Pop. III survivor surfaces. Supposing an ISO cumulative number density with size larger than \(D\) is \(n \propto D^{-\alpha}\), Pop. III survivors can accrete ISO mass \(\gtrsim 10^{-16}\ M_\odot\), or ISO iron mass \(\gtrsim 10^{-17}\ M_\odot\), if \(\alpha < 4\). This iron mass is larger than the accretion mass of interstellar medium (ISM) by several orders of magnitude. Taking into account material mixing in a convection zone of Pop. III survivors, we obtain their surface pollution is typically \([\text{Fe}/\text{H}] < \sim -8\) in most cases, however the surface pollution of Pop. III survivors with 0.8\(M_\odot\) can be \([\text{Fe}/\text{H}] > -6\) because of the very shallow convective layer. If we apply to Pop. III survivors located at the Galactocentric distance of 8 kpc, the dependence of the metal pollution is as follows. If \(\alpha > 4\), Pop. III survivors have no chance at colliding with ISOs with \(D > 3\ \text{km}\), and keep metal-free. If \(3 < \alpha < 4\), Pop. III survivors would be most polluted by ISOs up to \([\text{Fe}/\text{H}] \sim -7\). If \(\alpha < 3\) up to \(D \sim 10\ \text{km}\), Pop. III survivors could hide in metal-poor stars so far discovered. Pop. III survivors would be more polluted with decreasing the Galactocentric distance. Although the metal pollution depends on \(\alpha\) and the Galactocentric distance, we first show the importance of ISOs for the metal pollution of Pop. III survivors.

Key words: minor planets, asteroids: general — stars: low-mass — stars: Population III

1 Introduction
Population III (Pop. III) stars, metal-free stars, or first stars are epoch-making objects in the universe history. They bring an end to the universe’s dark ages, and mark the opening of metal enrichment in the universe. It is also interesting that their formation mode is completely different from those of Pop. I and II stars. Their typical mass is theoretically predicted to be 10 – 1000\(M_\odot\) (Omukai & Nishi 1998; Abel et al. 2002; Bromm & Larson 2004; Yoshida et al. 2008; Hosokawa et al. 2011; Stacy et al. 2011, 2012; Bromm 2013; Susa 2013; Susa et al. 2014; Hirano et al. 2015). Direct observations of Pop. III stars are essential to investigate the Pop. III star era and Pop. III stars themselves. Since massive stars with > 10\(M_\odot\) have short lifetimes \(\sim 10\ \text{Myr}\), Pop. III stars should be explored in the high-redshift...
universe. So, the direct observation is quite difficult, and consequently they have not yet been detected so far. Bowman et al. (2018) have reported an observation for a relic of Pop. III stars, although further confirmation is required, since the signal is much stronger than predicted by existing cosmological models (Barkana 2018).

Alternatively, Pop. III stars can be explored in the Galaxy. If they are born as low-mass stars, they have longer lifetimes than the Hubble time. Low-mass Pop. III stars are thought to be formed in the circumstellar disk around massive Pop. III stars (Machida et al. 2008; Clark et al. 2011a, 2011b; Greif et al. 2011, 2012; Machida & Doi 2013; Susa et al. 2014; Chiaki et al. 2016). We call such low-mass Pop. III stars “Pop. III survivors”. However, Pop. III survivors have not been found, although great efforts have been taken to (e.g. Aoki et al. 2006; Frebel & Norris 2015).

One possibility of the absence of Pop. III survivors is that Pop. III survivors suffer from metal pollution through accretion of interstellar medium (ISM) (Yoshii 1981; Komiya et al. 2015; Shen et al. 2017). Komiya et al. (2015) have considered Bondi-Hoyle-Lyttleton accretion of ISM, and have asserted some metal-poor stars can be Pop. III survivors polluted by ISM. However, Johnson (2015) have shown radiation pressure prevents accretion of dust in ISM, and Tanaka et al. (2017) have shown stellar wind prevents accretion of gas in ISM. Although stellar wind in their model is Pop. I stellar wind, Suzuki (2018) have made clear that stellar wind of metal-poor stars (Pop. II and III stars) prevents the ISM accretion more strongly than that of Pop. I stars. Eventually, Pop. III survivors have iron abundance [Fe/H] only up to −14 (Tanaka et al. 2017). This metallicity is much smaller than currently discovered very metal deficient stars (e.g. Keller et al. 2014).

Recently, Meech et al. (2017) have discovered the first interstellar object (ISO) or interstellar asteroid, called ‘Oumuamua. They have estimated the ISO number density is ∼ 0.1 au−3. Do et al. (2018) have also inferred the ISO number density ∼ 0.2 au−3 from an estimate of the Pan-STARRS survey volume. This number density is so high that ISOs can plunge into and pollute Pop. III survivors many times in lifetimes of Pop. III survivors. In this paper, we calculate an ISO accretion rate onto Pop. III survivors, and their metal pollution.

This paper is structured as follows. In section 2, we calculate an ISO accretion rate onto Pop. III survivors. In section 3, we estimate metallicity of polluted Pop. III survivors, taking into account surface convection zones of Pop. III survivors. In section 4, we summarize this paper.

## 2 Accretion Rate

We can express an ISO accretion rate onto Pop. III survivors in number as

\[ \hat{N}_{\text{acc}} = fn\sigma v, \]  \hspace{1cm} (1)

where \( n \) is an ISO cumulative number density with ISOs’ radii larger than \( D \), \( \sigma \) is cross section of collision between ISOs and Pop. III survivors, and \( v \) is a relative speed between ISOs and Pop. III survivors. The value \( f \) is a fraction of an ISO-rich region in an orbit of a Pop. III survivor. Next, we write an ISO accretion rate in mass as

\[ M_{\text{acc}} = \int_{D_{\text{min}}}^{D_{\text{max}}} \left\{ f \frac{dn}{dD} \sigma v \left[ m_0 \left( \frac{D}{D_0} \right)^3 \right] \right\} dD, \]  \hspace{1cm} (2)

where \( m_0 \) is the mass of an ISO with its radius \( D_0 \), \( D_{\text{min}} \) is the minimum radius of an ISO reaching a Pop. III survivor surface without sublimation, and \( D_{\text{max}} \) is the maximum radius of an ISO colliding with a Pop. III survivor once at least. We assume the ISO cumulative number density can be written as a single power-law function. Then, we give the cumulative number density as

\[ n = n_0 \left( \frac{D}{D_0} \right)^{-\alpha}, \]  \hspace{1cm} (3)

where \( n_0 \) is the ISO cumulative number density with its radius larger than \( D_0 \). From the observation of ‘Oumuamua, we adopt \( n_0 \sim 0.2 \text{ au}^{-3} \), and \( D_0 \sim 100 \text{ m} \) in this paper (Do et al. 2018).

Since the power \( \alpha \) has not yet been constrained strictly even from an estimate of the Pan-STARRS survey volume (Do et al. 2018), we consider a wide range of the power \( \alpha \). Rewriting Equation (2), we finally obtain the following equation:

\[
\hat{M}_{\text{acc}} = \hat{M}_{\text{acc,0}} \times \left\{ \frac{\alpha}{\alpha - 3} \left( \frac{D_{\text{min}}}{D_0} \right)^{-\alpha + 3} - \left( \frac{D_{\text{max}}}{D_0} \right)^{-\alpha + 3} \right\} \quad (\alpha > 3),
\]

\[
\times \left\{ \frac{\alpha}{3 - \alpha} \left[ \log(D_{\text{max}}) - \log(D_{\text{min}}) \right] \right\} \quad (\alpha = 3),
\]

\[
\times \left\{ \frac{\alpha}{3 - \alpha} \left( \frac{D_{\text{max}}}{D_0} \right)^{3-\alpha} - \left( \frac{D_{\text{min}}}{D_0} \right)^{3-\alpha} \right\} \quad (\alpha < 3),
\]

where

\[ \hat{M}_{\text{acc,0}} = m_0 \hat{N}_{\text{acc,0}}, \]  \hspace{1cm} (5)

\[ \hat{N}_{\text{acc,0}} = fn_0\sigma v. \]  \hspace{1cm} (6)

The right sides of Equation (4) are the same in the cases of \( \alpha > 3 \) and \( < 3 \). We divide these cases for visibility. The total mass of ISOs can be written as

\[ M_{\text{iso}} = \int \frac{dn}{dD} \left[ m_0 \left( \frac{D}{D_0} \right)^3 \right] dD \]  \hspace{1cm} (7)

\[ = - \frac{\alpha m_0 n_0}{D_0} \int \left( \frac{D}{D_0} \right)^{-\alpha + 2} dD. \]  \hspace{1cm} (8)

Note that the total mass of ISOs diverges for \( \alpha \leq 3 \) if the power \( \alpha \) keeps constant at \( D \to \infty \). When we adopt \( \alpha \leq 3 \), we suppose there are a knee or cutoff at some size \( D \).

Now, we calculate the accretion rate in number, \( \hat{N}_{\text{acc,0}} \). The distribution of ISOs is concentrated in the Galactic disk region that consists of more metal-rich Pop. I stars, because ISOs are themselves made from heavy elements. Therefore, we
can safely assume that ISOs orbit around the Galaxy with the Galactic disk at a circular velocity of the Galaxy, $\sim 220 \text{ km s}^{-1}$. On the other hand, Pop. III survivors must have been formed before the formation of the Galactic disk. They would wander in the Galactic halo (e.g. Ishiyama et al. 2016), and are distributed in an isotropic manner with the average circular velocity, $\sim 220 \text{ km s}^{-1}$. Eventually, a typical relative speed between ISOs and Pop. III survivors would be $\sqrt{2}$ times the circular velocity, i.e. $v \sim 310 \text{ km s}^{-1}$. Pop. III survivors would accrete ISOs only when they traverse the Galactic disk twice an orbit. Let us consider, as a typical example, a Pop. III survivor that orbits at a distance from the Galactic center with the inclination angle of 30 degree with respect to the Galactic plane. This inclination angle is the average value in isotropic velocity distribution. If we take 400 pc for the thickness of the Galactic disk, we obtain $f$ in equation (1) is $\sim 0.032$. We may underestimate $f$. Pop. III survivors spend longer time orbiting in an ISO-rich region with decreasing the Galactocentric distance, since the Galactic disk becomes thicker, and the Galactic bulge is present at the Galactic center. Note that Pop. III survivors could be preferentially concentrated at the Galactic center, such as the Galactic bulge (Scannapieco et al. 2006; Salvadori et al. 2010; Tumlinson 2010). Considering gravitational focusing, we obtain the cross section $\sigma$ as

$$\sigma = \pi r^2 \left( 1 + \frac{2GM_*}{r_* v^2} \right),$$

where $r_*$ and $M_*$ are respectively the radius and mass of a Pop. III survivor, and $G$ is the gravitational constant. We adopt the solar radius and mass for $r_*$ and $M_*$, respectively. This is because Pop. III survivors have $\lesssim 0.8M_\odot$ and similar $M_*/r_*$ to that of the Sun (Richard et al. 2002). Then, we obtain $\sigma \sim 7.6 \cdot 10^{22} \text{ cm}^2$. Using the above $f$, $\sigma$, and $v$, we get $\dot{N}_{\text{acc},0}$ as

$$\dot{N}_{\text{acc},0} \sim 1.4 \cdot 10^{-4} \left( \frac{n_0}{0.2 \text{ au}^{-3}} \right) \text{ yr}^{-1} [\text{yr}^{-1}].$$

As is clear from the above equation, Pop. III survivors have chances at accreting a large number of ISOs in their lives, $1.4 \cdot 10^5$ times per 1 Gyr.

Before proceeding to this calculation, we show accretion rates (or collision rates) of larger objects such as stars and planets are extremely small. In the solar neighborhood, stellar number density is $\sim 0.1 \text{ pc}^{-3}$. Then, $\dot{N}_{\text{acc},0} \sim 8.8 \cdot 10^{-21} \text{ yr}^{-1}$ for stars. The number density of free floating planets (Sumi et al. 2011) could be 2000 times higher than the stellar number density (Dai & Guerras 2018). Nevertheless, the collision rate is $\sim 1.8 \cdot 10^{-17} \text{ yr}^{-1}$ for free floating planets. It is clear that Pop. III survivors have no chance to collide with other stars and free floating planets.

We can obtain the accretion rate in mass, $\dot{M}_{\text{acc},0}$, as

$$\dot{M}_{\text{acc},0} \sim 9.9 \cdot 10^{-25} \left( \frac{m_0}{1.4 \cdot 10^{13} \text{ g}} \right) \left( \frac{n_0}{0.2 \text{ au}^{-3}} \right) [M_\odot \text{ yr}^{-1}],$$

where we assume the mass density of a spherical ISO is 3 g cm$^{-3}$, when we derive $m_0$ for $D_0 = 100 \text{ m}$, which is a typical value of asteroids (Suzuki 2010; Tumlinson 2010). Considering gravitational focusing, we could be preferentially concentrated at the Galactic center, such as is present at the Galactic center. Note that Pop. III survivors avoid the cross section $\sigma \sim \kappa$ because Pop. III survivors have $\kappa$ due to $\kappa < \kappa$ since the Galactic disk becomes thicker, and the Galactic bulge is ISO-rich region with decreasing the Galactocentric distance, $r_0$. Pop. III survivors have no chance to collide with other stars and free floating planets.

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2.5 \times 10^{17}$ g, where the mass density is assumed to be 3 g cm$^{-3}$. On the other hand, comets with size of $\sim 10^{13}$ g can reach the solar photosphere (Brown et al. 2015). Our $D_{\text{min}}$ could be consistent with the minimum size of comets plunging into the Sun, since comets are volatile whereas asteroids are not.

We derive $D_{\text{max}}$, the maximum radius of ISOs colliding with Pop. III survivors once at least. The number density of ISOs increases with time via metal enrichment in the Galaxy. As a result, the ISO cumulative number density is expected to be comparable to the present value in the last few Gyr; we here define $\Delta t_{\text{iso}}$ for this duration. Then we can derive $D = D_{\text{max}}$ from $N_{\text{acc}} \Delta t_{\text{iso}} \sim 1$. Using Equation (1), (3), and (6), we can write $D_{\text{max}}$ as

$$D_{\text{max}} \sim D_0 \left( \frac{N_{\text{acc}} \Delta t_{\text{iso}}}{M_{\odot}} \right)^{\frac{1}{\alpha}}.$$

The actual value of $\Delta t_{\text{iso}}$ is unknown. So, we assume $\Delta t_{\text{iso}} \sim 5$ Gyr and 1 Gyr. The former ($\Delta t_{\text{iso}} \sim 5$ Gyr) is equivalent to the solar age, or to the age of the Galactic disk at the solar neighborhood (e.g. Grisoni et al. 2017). ISOs would be formed simultaneously with the Galactic disk formation, if they are ejected from the inner protoplanetary disk (Gaidos et al. 2017; Portegies Zwart et al. 2017). ISOs would be formed $< 1$ Gyr after the Galactic disk formation, if their progenitors are a sort of the Oort cloud around intermediate-mass stars with $2 - 8 M_{\odot}$, and are released when the intermediate-mass stars enter into asymptotic giant branch phases (Veras et al. 2011). Regardless of the formation scenarios of ISOs, ISOs could be in the Galactic disk for $\Delta t_{\text{iso}} \sim 5$ Gyr. We adopt the latter ($\Delta t_{\text{iso}} \sim 1$ Gyr) in order to take into account account timescale on which ISOs accumulate in the Galactic disk for more conservative constraints. Figure 1 shows $D_{\text{max}}$ as well as $D_{\text{min}}$ as a reference.

We calculate the total accretion mass of ISOs onto a Pop. III survivor, $M_{\text{acc}} \sim M_{\text{acc}} \Delta t_{\text{iso}}$, using Equation (4). We draw $M_{\text{acc}}$ as a function of $\alpha$ in Figure 2. Figure 2 shows steep decrease of $M_{\text{acc}}$ at $\alpha \sim 4$ for $\Delta t_{\text{iso}} = 5$ Gyr and at $\alpha \sim 3.5$ for $\Delta t_{\text{iso}} = 1$ Gyr due to $D_{\text{max}} < D_{\text{min}}$ (see Figure 1) for $n_0 = 0.2$ au$^{-3}$. We can see $M_{\text{acc}} \gtrsim 10^{-16} M_{\odot}$, unless $D_{\text{max}} < D_{\text{min}}$, or $\alpha$ is large. On the analogy of the cumulative number density of asteroids in the main belt, those in Edgeworth-Kuiper belt, and long period comets from sub-km to km (Gladman et al. 2009; Kenyon & Bromley 2004; Fernández & Sosa 2012, respectively), the power $\alpha$ could be close to, or shallower than 3.

Our $M_{\text{acc}}$ is even larger than ISM’s $M_{\text{acc}}$ by several orders of magnitude. ISOs would contain about 10% iron in mass, similarly to the solar compositions (Asplund et al. 2009). Thus, Pop. III survivors accrete iron mass of $\gtrsim 10^{-17} M_{\odot}$ through collision with ISOs. On the other hand, Tanaka et al. (2017) have shown the total accreted iron mass from the gas component of ISM is $\lesssim 10^{-19} M_{\odot}$ from ISM accretion.

The estimated value of $n_0$ can contain large uncertainties, since ‘Oumuamua is only one ISO so far discovered. We pessimistically decrease $n_0$ from 0.2 au$^{-3}$ to 0.02 au$^{-3}$ in order to examine an effect of $n_0$ on metallicity of polluted Pop. III survivors. Figure 2 also shows $M_{\text{acc}}$ of Pop. III survivors when $n_0 = 0.02$ au$^{-3}$. The $M_{\text{acc}}$ decreases by more than an order of magnitude. This is because $D_{\text{max}}$ as well as $N_{\text{acc},0}$ becomes smaller with $n_0$ decreasing. Moreover, $M_{\text{acc}}$ steeply decreases at smaller $\alpha$ than in the case of $n_0 = 0.2$ au$^{-3}$ due to smaller
\[ D_{\text{max}}. \] Nevertheless, \( M_{\text{acc}} \gtrsim 10^{-16} M_\odot \), if \( \alpha \lesssim 3 \). In conclusion, ISOs can be the most dominant polluters of Pop. III survivors.

### 3 Discussion

We estimate surface pollution of Pop. III survivors, considering the thickness of their convection zones under their surfaces. Accreting metals are mixed only within the surface convective zone and do not leak downward into the stable radiative zone. According to Richard et al. (2002), metal-poor stars with \( \lesssim 0.8 M_\odot \) have their lifetimes \( > 12 \) Gyr. So, we suppose Pop. III survivors that were born after \( < 1 \) Gyr of the Big Bang and have mass \( \lesssim 0.8 M_\odot \). In the cases of \( 0.75 M_\odot \) and \( 0.7 M_\odot \) stars, the mass fractions of convection zones are respectively \( 10^{-2.5} \) and \( 10^{-2} \) in the last 5 Gyr. On the other hand, in a \( 0.8 M_\odot \) star the mass fraction of a convection zone rapidly decreases with time from \( 10^{-3.5} \) at \( \approx 5 \) Gyr ago and \( 10^{-6} \) at \( \approx 1 \) Gyr ago.

We calculate metallicity of a Pop. III survivor as follow:

\[
[\text{Fe/H}] \sim \log_{10} \left( \frac{1}{f_{\text{conv}}} \frac{M_{\text{acc}} \Delta t_{\text{pol}}}{M Z_\odot} \right).
\]

We set the mass fraction of metals in the Sun, \( Z_\odot \), to 1.4 \% (Asplund et al. 2009). We set the mass fraction of a surface convection zone, \( f_{\text{conv}} \), in reference to Richard et al. (2002) as follows. For \( M_* = 0.7 \) and \( 0.75 M_\odot \), we adopt \( f_{\text{conv}} = 10^{-2} \) and \( 10^{-2.5} \), respectively, and \( \Delta t_{\text{pol}} = \Delta t_{\text{iso}} \). For \( M_* = 0.8 M_\odot \) with \( \Delta t_{\text{iso}} = 1 \) Gyr, we adopt \( f_{\text{conv}} = 10^{-6} \), and \( \Delta t_{\text{pol}} = \Delta t_{\text{iso}} \). For \( M_* = 0.8 M_\odot \) with \( \Delta t_{\text{iso}} = 5 \) Gyr, we calculate \([\text{Fe/H}]\), taking into account the time dependence of the mass fraction of a convection zone. If the Pop. III survivor is dominantly polluted in the last 1 Gyr, we adopt \([\text{Fe/H}]\) the same as that in the case of \( M_* = 0.8 M_\odot \) with \( \Delta t_{\text{iso}} = 1 \) Gyr. If not, we calculate \([\text{Fe/H}]\), adopting \( f_{\text{conv}} = 10^{-3.5} \) and \( \Delta t_{\text{pol}} = \Delta t_{\text{iso}} \).

We summarize the surface pollution of Pop. III survivors in Figure 3, where we set \( n_0 = 0.2 \) au\(^{-3} \). Since we suppose ISO compositions are the same as the metal compositions of the Sun, \([\text{Fe/H}]\) is the same as metallicity \([M/H]\). For Pop. III survivors with \( 0.8 M_\odot \), the metallicity in \( \Delta t_{\text{iso}} = 5 \) Gyr is the same as in \( \Delta t_{\text{iso}} = 1 \) Gyr when \( \alpha \lesssim 3.5 \), since the metal pollution in the last 1 Gyr is dominant. Pop. III survivors with \( 0.7 \) and \( 0.75 M_\odot \) get metallicity with \([\text{Fe/H}]\) \( \sim -8 \) at most even if \( \alpha > 2.5 \). On the other hand, Pop. III survivors with \( 0.8 M_\odot \) can get metallicity with \([\text{Fe/H}]\) \( \gtrsim -6 \), if \( \alpha \gtrsim 2.5 \). The metallicity \([\text{Fe/H}]\) steeply decreases at \( \alpha \sim 4 \) for \( \Delta t_{\text{iso}} = 5 \) Gyr and \( \alpha \sim 3.5 \) for \( \Delta t_{\text{iso}} = 1 \) Gyr, since \( D_{\text{max}} < D_{\text{min}} \).

We use SAGA database (e.g. Suda et al. 2008), and search for metal-poor stars with \([\text{Fe/H}] < -5 \). Additionally, we investigate their effective temperature in order to conjecture their mass. According to Richard et al. (2002), mass of a Pop. III survivor is \( \sim 0.8 M_\odot \) if its effective temperature is \( > 6000 \) K, and is \( \lesssim 0.75 M_\odot \) if not. Then, we find three stars with \([\text{Fe/H}] < -5 \): SMSS J031300.36-670839.3 with \([\text{Fe/H}] < -7.3 \) and \( \sim 5100 \) K (Keller et al. 2014), SDSS J1035+0641 with \([\text{Fe/H}] < -5.07 \) and \( \sim 6300 \) K (Bonifacio et al. 2015), and SDSS J131326.89-001941.4 with \([\text{Fe/H}] \sim -5.00 \) and \( \sim 5200 \) K (Frebel et al. 2015). SMSS J031303.36-670839.3 and SDSS J131326.89-001941.4 could be Pop. III survivors with \( \sim 0.75 M_\odot \), if \( \alpha < 2 \) for \( D_{\text{max}} > 1 \) km. SDSS J1035+0641 could be a Pop. III survivors with \( \sim 0.8 M_\odot \), if \( \alpha > 2.5 \) up to \( D > 10 \) km. Therefore, SDSS J1035+0641 has the most loose conditions of ISOs among the three metal-poor stars to be a Pop. III survivor.

### 4 Summary

We calculated the total accretion mass of ISOs onto Pop. III survivors. The mass is \( \gtrsim 10^{-16} M_\odot \), if the power of the ISO cumulative number density \( \alpha \) is \( \gtrsim 4 \). We can convert the accretion mass to iron mass \( \gtrsim 10^{-17} M_\odot \). This accretion mass is even larger than ISM accretion mass by several orders of magnitude. Therefore, ISOs can be the most dominant polluters of Pop. III survivors.

We estimated the surface metallicity of Pop. III survivors polluted by ISOs, considering convection zones of Pop. III survivors. If Pop. III survivors have \( 0.7 M_\odot \) and \( 0.75 M_\odot \), their metallicity can be \([\text{Fe/H}] \lesssim -8 \). On the other hand, if Pop. III survivors have \( 0.8 M_\odot \), their metallicity can be enhanced to \([\text{Fe/H}] \gtrsim -6 \). This is because the mass fraction of a convection zone is down to \( 10^{-6} \) when their ages are \( > 10 \) Gyr.

The star SDSS J1035+0641 has metallicity of \([\text{Fe/H}] \sim -5 \), and effective temperature of \( 6300 \) K. It can have a thin convection zone, and could be a Pop. III survivors, if the ISO cumula-
tive number density has shallow power law with $\alpha \gtrsim 2.5$ up to $D \sim 10$ km. In order to conclude whether SDSS J1035+0641 and other metal-poor stars are Pop. III survivors or not, we need ISO cumulative number density up to $D \sim 10$ km.

We note that the ISO accretion mass strongly depends on the power of the ISO cumulative number density, $\alpha$. If we apply to Pop. III survivors located at the Galactocentric distance of 8 kpc, the dependence of the metal pollution is as follows. If $\alpha > 4$, Pop. III survivors are never polluted by ISOs. If $3 < \alpha < 4$, Pop. III survivors can be polluted up to $[\text{Fe/H}] \sim -7$. If $\alpha < 3$ up to $D \sim 10$ km, Pop. III survivors could hide in metal-poor stars so far discovered. We expect the ISO cumulative number density will be determined in near future.

Since Pop. III survivors could be preferentially concentrated at the Galactic center (Scannapieco et al. 2006; Salvadori et al. 2010; Tumlinson 2010), we may underestimate the metal pollution of Pop. III survivors. This is because Pop. III survivors spend longer time orbiting in an ISO-rich region with the Galactocentric distance decreasing. Note that the Galactic disk becomes thicker with the Galactocentric distance, and the Galactic bulge is present at the Galactic center. In other words, $f$ becomes larger as the Galactocentric distance becomes smaller.

We should derive chemical abundance of Pop. III survivors in order to observationally confirm that Pop. III survivors are most polluted by ISOs, although we discuss only about $[\text{Fe/H}]$ in this paper. The chemical abundance would be determined by a combination of ISO composition and volatility. In future work, we will obtain the chemical abundance of Pop. III survivors polluted by ISOs.

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