The chemical signature of surviving Population III stars in the Milky Way

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ABSTRACT
Cosmological simulations of Population (Pop) III star formation suggest that the primordial initial mass function may have extended to sub-solar masses. If Pop III stars with masses \( \leq 0.8 \, M_\odot \) did form, then they should still be present in the Galaxy today as either main sequence or red giant stars. To date, however, despite searches for metal-poor stars in both the halo and the bulge of the Milky Way, no primordial stars have been identified. It has long been recognized that the initial metal-free nature of primordial stars could be masked due to accretion of metal-enriched material from the interstellar medium (ISM) over the course of their long lifetimes. Here we point out that while gas accretion from the ISM may readily occur, the accretion of dust from the ISM can be prevented due to the pressure of the radiation emitted from low-mass stars. This implies a possible unique chemical signature for stars polluted only via accretion, namely an enhancement in gas phase elements relative to those in the dust phase. Using Pop III stellar models, we outline the conditions in which this signature could be exhibited, and we derive the expected signature for the case of accretion from the local ISM. Intriguingly, due to the large fraction of iron depleted into dust relative to that of carbon and other elements, this signature is similar to that observed in many of the so-called carbon-enhanced metal-poor (CEMP) stars. We therefore suggest that some fraction of the observed CEMP stars may, in fact, be accretion-polluted Pop III stars. We find, more broadly, that this effect could also be at play in accretion flows onto protostars, implying that it may also impact the chemical signatures of second generation (Pop II) stars.

Key words: early universe — cosmology: theory — ISM: dust — stars: low-mass — abundances

1 INTRODUCTION
For decades it has been a critical open question what were the first stars, and what was their fate (e.g. Bond 1981). Increasingly broad and sensitive surveys have been carried out in the halo (e.g. Cayrel et al. 2004; Caffau et al. 2011; Keller et al. 2014) and bulge (e.g. Schlaufman & Casey 2014) of the Galaxy, as well as in nearby dwarf galaxies (e.g. Kirby et al. 2011; Frebel et al. 2014) in search of the most primitive stars (see e.g. Beers & Christlieb 2005; Frebel 2010 for reviews). While these surveys have uncovered a trove of extremely metal-poor stars that provide invaluable clues to the nature of the first stars, as of yet there have been found no stars with a truly primordial composition (i.e. no metals).

This null result in the hunt for Population (Pop) III stars is increasingly in tension with state-of-the-art cosmological simulations suggesting that low-mass Pop III stars may have formed in the early universe (e.g. Clark et al. 2011; Greif et al. 2011; Dopcke et al. 2013; Bromm 2013; Susa et al. 2014; Stacy & Bromm 2014; Greif 2014; Hirano et al. 2014) and that they may still reside in the Galaxy today (e.g. Madau et al. 2008; Gao et al. 2010; Tumlinson et al. 2010; Karlsson et al. 2013; Hartwig et al. 2014). One clear resolution to this tension between theory and observation emerges if low-mass Pop III stars accrete metals from the interstellar medium (ISM) during their long lives traversing the Galaxy (Yoshii 1981; Iben 1983; Frebel et al. 2009; Komiya et al. 2010; Johnson & Khochfar 2011). Such accretion events would result in the pollution of the stellar surface with heavy elements and mask the primordial nature of a Pop III star.

Here we consider the expected chemical signature produced by such accretion events. In particular, we show that a clear signature could be imprinted due to the fact that, owing to the force of the radiation emitted from low-mass stars, dust is often not accreted onto such stars even while...
gas is readily accreted. In Section 2, we estimate the impact of stellar radiation on the dynamics of dust grains. In Section 3, we describe the conditions under which dust and gas are segregated in accretion flows due to the influence of stellar radiation. In Section 4, we estimate the expected chemical signatures of first and second generation stars that are enriched via accretion of gas and dust from an ISM with heavy element abundance ratios and dust depletion properties similar to those of the local ISM. Finally, we give our conclusions and offer a brief discussion in Section 5.

2 THE EDDINGTON LIMIT FOR DUST

Here we consider the forces at play during the accretion of dust-enriched material from the ISM onto a star, as illustrated in Figure 1. In particular, we shall concern ourselves with accretion onto low-mass ($\leq 0.8\ M_\odot$) Pop III stars and low-mass Pop II protostars. While the radiation emitted from these objects couples weakly to gas, it can be readily absorbed by dust grains. In turn, this implies that the dynamics of dust grains can be quite different from that of the gas, as has been discussed previously in the context of asymptotic late-type stars (e.g. Ivezic & Elitzur 1995; 2010; Netzer 2007) and in pre-stellar cores (Whitworth & Bate 2002) and diffuse clouds (Weingartner & Draine 2001b) exposed to the radiation field in the diffuse ISM.

We shall define the Eddington limit for dust as the ratio of the outward radiative force on a grain to the inward gravitational pull on the grain. As shown in Figure 1, if a sufficient amount of radiation is absorbed by a grain, the Eddington ratio can exceed unity, which case the grain may be repelled from the star even as gas is accreted onto it.\(^1\) This is also provided that the inward drag force due to collisions with gas particles is sufficiently small, as we discuss in the next Section.

The Eddington ratio for a given dust grain depends on its size, density and the efficiency with which it absorbs radiation. Here we consider a range of dust grain densities between 0.3 and 3 g cm\(^{-3}\), appropriate for porous and compact dust grains, respectively (e.g. Ossenkopf 1993; Weingartner & Draine 2001a; Dullemond & Dominik 2005; Heng & Draine 2009), and we adopt the wavelength-dependent absorption efficiencies for both graphite and silicate grains presented in Draine & Lee (1984). These radiation absorption efficiencies are dependent on the wavelength of the radiation and so on the spectrum of the radiation emitted by the star. For the stellar radiation we adopt simple black body spectra. We use effective temperatures and luminosities appropriate for a 0.8 $M_\odot$ Pop III star, as presented in Siess et al. (2002). Specifically, we choose a temperature of 6500 K and a luminosity of 5 $L_\odot$ for the main sequence (MS) stage, and a temperature of 5500 K and a luminosity of 50 $L_\odot$ for the red giant (RG) stage.\(^2\) For Pop II protostellar radiation, we adopt values for the temperature and luminosity in the range of values derived from observations as presented in Dunham et al. (2014). We choose a temperature of 1000 K, near the upper end of the distribution of protostellar temperatures observed in the Galaxy, as we expect sub-solar metallicity protostars to be hotter, on average, than solar metallicity protostars in the Galaxy today, due to the lower opacity of metal-poor stellar envelopes (see e.g. Marigo et al. 2001; Schaerer 2002; Suda et al. 2007). Consistent with this temperature, we choose a luminosity of 100 $L_\odot$.\(^3\)

The Eddington ratios for dust grains, as functions of their radii (referred to as size in the Figures), are shown in Figures 2, 3 and 4, for Pop III MS stars, Pop III RGs and Pop II protostars, respectively. In each Figure, we present the Eddington ratios for compact and porous grains, for both graphite and silicates. In each Figure, it is clear that less dense (more porous) grains have higher Eddington ratios. This follows from the fact that, for a given size, denser grains are more massive and so experience a stronger gravitational pull toward the star; this is consistent with the Eddington ratio being inversely proportional to the density, for a given grain size, as shown in the Figures.

Comparing the Figures, it is also clear that the Eddington ratios are much higher for the more luminous Pop III RG and Pop II protostellar cases, than for the less luminous Pop III MS case. We note, in particular, that the Eddington ratio is $\sim$ 10 times higher in the Pop III RG case than in the Pop III MS case; this is expected, given that the luminosities we have adopted for these cases differ by just this factor and that the effective temperatures are similar in both cases.

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\(^1\) We note that here we assume the radiation is optically thin to dust absorption. Therefore, we restrict ourselves to cases with relatively low density accretion flows and/or relatively low dust abundances. These conditions are likely, however, to often be met in the cases of interest here, in the early Universe when the dust abundance is still low and during brief episodes of accretion from the ISM.

\(^2\) Other low-mass Pop III stellar models give similar values (Marigo et al. 2001; Picardi et al. 2004; Suda et al. 2007).

\(^3\) In principle, at these luminosities it is possible for dust grains to sublimate in the accretion flows that we consider, although in the Appendix we show that this is unlikely to occur.
The signature of Pop III stars

3 DUST SEGREGATION IN ACCRETION FLOWS

Here we consider the effect of gas drag on the dynamics of dust grains in accretion flows. We include this force in the overall force balance shown in Figure 1, and determine the conditions under which dust grains will be not be accreted along with the gas.

From the definition we have adopted for the Eddington ratio $f_{\text{Edd}}$ for dust, the net outward force $F_{\text{rad}}$ on a dust grain due to radiation from the star is given by

$$F_{\text{rad}} = (f_{\text{Edd}} - 1) \frac{GM_\star m_{\text{grain}}}{r^2},$$

where $m_{\text{grain}}$ is the mass of the grain, $M_\star$ is the mass of the star, and $r$ is the distance from the star; the last term on the right side is simply the definition of the gravitational force on the grain.

There is also an oppositely-directed force $F_{\text{col}}$ on the grain due to collisions with gas particles that are in the accretion flow onto the star. If the number density of these particles is $n_{\text{gas}}$, their mass is $m_{\text{gas}}$, and the velocity of the accretion flow (strictly speaking, relative to the dust grain) is $v_{\text{acc}}$, then

$$F_{\text{col}} = A_{\text{grain}} n_{\text{gas}} m_{\text{gas}} v_{\text{acc}}^2 \approx A_{\text{grain}} n_{\text{gas}} m_{\text{gas}} \frac{2GM_\star}{r},$$

where $A_{\text{grain}} = \pi r_{\text{grain}}^2$ is the cross-sectional area of the dust grain.
Figure 5. The ISM density above which gas drag entrains dust in an accretion flow, for the case of Bondi-Hoyle accretion with an ISM sound speed of $1 \text{ km s}^{-1}$, shown as a function of grain size (see equation 5). For a given grain size, less dense grains (dashed lines) experience a smaller gravitational force than more dense grains (solid lines), resulting in larger Eddington ratios and larger critical densities. Because graphite grains have a larger Eddington ratio, as shown in Figure 2, the critical density for these grains is higher.

4 In the second equality, we have assumed that the gas is freely-falling onto the star from a distance $r > r_{\text{Bondi}}$.

Now, equating the last two equations, and noting that the gas density is just $\rho_{\text{gas}} = m_{\text{gas}}/V_{\text{gas}}$, we find that the outward-directed radiative force will overcome the inward-directed force due to collisions (gas drag) if

$$\rho_{\text{gas}} < \frac{f_{\text{Edd}} - 1}{2r} \frac{4}{3} \rho_{\text{grain}} \rho_{\text{grain}} ,$$

where $\rho_{\text{grain}}$ is the grain density, and we have assumed that $m_{\text{grain}} = 4\pi r_{\text{grain}}^3 \rho_{\text{grain}}/3$. Normalizing to typical values, we have

$$\rho_{\text{gas}} < 2 \times 10^{-21} \text{ g cm}^{-3} \left( \frac{f_{\text{Edd}} - 1}{1} \right) \left( \frac{r}{1 \text{ pc}} \right)^{-1} \times \left( \frac{r_{\text{grain}}}{1 \mu\text{m}} \right) \left( \frac{\rho_{\text{grain}}}{1 \text{ g cm}^{-3}} \right) .$$

Under the assumption of Bondi-Hoyle accretion, we can obtain a lower limit for this critical gas density by evaluating this equation at the Bondi radius $r_{\text{Bondi}} = GM_*/c_s^2$ at which the accretion flow onto the star originates. As a function of the ISM sound speed $c_s$, we then have

$$\rho_{\text{gas}} < 4 \times 10^{-21} \text{ g cm}^{-3} \left( \frac{f_{\text{Edd}} - 1}{1} \right) \left( \frac{r_{\text{grain}}}{1 \mu\text{m}} \right) \times \left( \frac{\rho_{\text{grain}}}{1 \text{ g cm}^{-3}} \right) \left( \frac{c_s}{1 \text{ km s}^{-1}} \right)^{-1} \left( \frac{M_*}{M_\odot} \right)^{-1} .$$

4 Previous authors have also described similarly the effect of gas drag on radiation-driven gas and dust segregation (e.g. Baines et al. 1965; Draine & Salpeter 1979; Simpson et al. 1980).

5 We note that, following from the Bondi-Hoyle accretion equations, the critical densities would be higher if the star is moving with respect to the ISM from which it is accreting.
described in the last Section for the Eddington ratios, less dense grains are less susceptible to gas drag entraining them in accretion flows, due to their higher surface area-to-mass ratios. Also, the greater absorption efficiencies of graphite grains imply higher critical densities than silicates. Finally, due to the explicit linear dependence of the critical density on grain size (radius) in equation (5), there is a general trend of increasing critical density with radius, although the dependence is complicated by the grain size-dependence of the Eddington ratios.

The critical densities shown in the Figures are, in general, much larger than the densities of the gas clouds filling the vast majority of the Galaxy (see e.g. Talbot & Newman 1977; Rosolowsky 2010). Therefore, it is likely that accretion onto low-mass Pop III stars in the Galaxy would occur from regions of the ISM with densities lower than the critical values that we find in Figures 5 and 6. That said, for the case of Pop II protostars, accretion likely proceeds from within a molecular cloud which could have a density exceeding the critical values shown in Figure 7, especially for smaller grains (with lower critical densities). That said, for simplicity, in the next Section we shall estimate the chemical signatures of stars polluted via accretion under the assumption that the ISM density is lower than the critical values shown in the Figures; this will suffice to outline the qualitative trends that we expect dust segregation to imprint on the chemical signatures of accretion-polluted low-mass stars.

4 THE EXPECTED CHEMICAL SIGNATURES

To derive the expected chemical signatures of stars polluted with metals via accretion of gas and/or dust from the ISM, we must take into account the size distribution of dust grains and the depletion factors of the various elements onto dust grains. Here we consider grain sizes (for both graphite and silicates) defined by the commonly used, power law size distribution presented in Mathis, Rumpl & Nordsieck (1977; MRN), in which the number of grains $n$ with a given size $r_{\text{grain}}$ is given by $dn/dr_{\text{grain}} \propto r_{\text{grain}}^{-3.5}$. The minimum and maximum grain sizes are 5 nm and 250 nm, respectively. We use the element-dependent depletion factors derived for the local ISM, as presented in Jenkins (2009). For simplicity, and consistent with previous work (e.g. Field 1974; Draine 2003; Chiaki et al. 2014), we assume all depleted carbon to be in graphite and silicates to comprise all other depleted elements.

To obtain the chemical signatures, we sum up all of the elements that would be accreted in the form of gas and those that reside in dust grains which have Eddington ratios below unity. We do not include the elements residing in dust grains with Eddington ratios greater than unity, as these are assumed to not be accreted. Finally, for simplicity we assume that the chemical signature is due solely to the accretion of material from an ISM with solar abundance ratios of heavy elements (i.e. those heavier than hydrogen and helium) and dust depletion properties as observed in the solar neighborhood. While this allows for concrete predictions, since these are observed quantities, it is also likely that accretion onto low-mass Pop III stars and onto the earliest Pop II protostars could have occurred from an ISM with somewhat different heavy element abundance ratios and dust depletion properties (see e.g. Chiaki et al. 2014; Ritter et al. 2014).

We present the expected chemical signatures in Table

| [C/Fe] | [N/Fe] | [O/Fe] | [Mg/Fe] | [Si/Fe] | [Ti/Fe] | [Cr/Fe] | [Mn/Fe] | [Ni/Fe] | [Zn/Fe] |
|-------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| ρ_{grain} = 3 g cm^{-3} |
| Pop III MS | -0.03 | 0.15 | 0.12 | 0.01 | 0.009 | -0.001 | -0.0001 | 0.003 | -0.0005 | 0.06 |
| Pop III RG | 2.02 | 2.13 | 2.0 | 0.97 | 0.87 | -0.89 | -0.04 | 0.47 | -0.19 | 1.69 |
| Pop II protostar | 2.02 | 2.13 | 2.0 | 0.97 | 0.87 | -0.89 | -0.04 | 0.47 | -0.19 | 1.69 |
| ρ_{grain} = 0.3 g cm^{-3} |
| Pop III MS | 2.02 | 2.13 | 2.0 | 0.97 | 0.87 | -0.89 | -0.04 | 0.47 | -0.19 | 1.69 |
| Pop III RG | 2.02 | 2.13 | 2.0 | 0.97 | 0.87 | -0.89 | -0.04 | 0.47 | -0.19 | 1.69 |
| Pop II protostar | 2.02 | 2.13 | 2.0 | 0.97 | 0.87 | -0.89 | -0.04 | 0.47 | -0.19 | 1.69 |

Table 1. The expected chemical signatures of 0.8 M\(_{\odot}\) Pop III MS and RG stars, and for 0.8 M\(_{\odot}\) Pop II protostars, due to accretion of material from the ISM having a solar abundance pattern and dust depletion properties as observed in the solar neighborhood. The abundance ratios are given for dust densities of ρ_{grain} = 0.3 and 3 g cm^{-3}, in the bottom and top rows, respectively. The same distinct chemical signature, directly imprinted from the dust depletion properties of the local ISM, is predicted in nearly all cases. It is only the Pop III MS star in the case of compact (high density) grains, for which the Eddington ratio drops below unity (see Figure 2), that does not display this signature.

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1, for dust grain densities of 0.3 and $3\text{ g cm}^{-3}$. For each grain density, we present the results that we find for the cases of 0.8 $M_\odot$ MS Pop III stars, Pop III RGs, and Pop II protostars. For the Pop III cases, accretion is assumed to occur from the ISM, while for the Pop II protostar case it is assumed to take place during the growth of the protostar itself via accretion from a molecular cloud. We consider the abundances of ten elements relative to iron, as labeled in the Table.

For cases in which the Eddington ratios of all dust grains are below unity (as shown in Figures 2, 3 and 4), all dust and gas are accreted onto the star and the abundance ratios are solar (i.e. for an element X, $[X/\text{Fe}] = 0$). This is nearly the case for the Pop III MS star we consider, for dense grains (i.e. $\rho_{\text{grain}} \simeq 3\text{ g cm}^{-3}$), and hence the abundance ratios are all near solar values. The more luminous Pop III RGs and Pop II protostars, however, tend to have higher Eddington ratios, which result in a distinctive abundance pattern. In these cases, where the Eddington ratio is greater than unity for all grains, no dust is accreted onto the star and the abundance ratios follow directly from the dust depletion properties. This distinctive abundance pattern emerges for the cases of Pop II protostars and Pop III RGs, as well as for Pop III MS stars given sufficiently low grain densities. We note that this distinct signature predicted for Pop II protostars would likely be complicated by the fact that some amount of dust will have gone into the protostar at its initial collapse, before it begins radiating appreciably. Also, as noted in the last Section, such protostars may accrete from molecular clouds that may have densities higher than the critical densities shown in Figure 7.

We emphasize that the abundance ratios listed in Table 1 are for the specific case of an ISM with heavy element abundance ratios similar to those observed in the Sun and for dust depletion properties as observed in the local ISM. In reality, it is very likely that accretion onto low-mass Pop III stars could occur from an ISM that is different than this. Likewise, the earliest Pop II protostars likely accrete gas from an ISM that is different than this. That said, it is a robust conclusion that due to dust segregation in accretion flows elements that are heavily depleted onto dust grains are not as readily accreted as elements which are in the gas phase. In turn, this implies a robust chemical signature with elements largely in the gas phase being more abundant than elements that are largely depleted.

As mentioned above, the most clear signatures of dust-segregated accretion are present in cases in which the Eddington ratio exceeds unity for all grains, and no dust is accreted onto the star. In this case, since iron is almost completely depleted onto dust grains in the local ISM and carbon and oxygen are much less depleted (see e.g. Table 4 of Jenkins 2009), this implies large characteristic values of $[C/\text{Fe}] = 2.02$, $[N/\text{Fe}] = 2.13$, and $[O/\text{Fe}] = 2.0$. In turn, as magnesium and silicon are more depleted than carbon and oxygen, but still less depleted than iron, characteristic values for these elements are somewhat lower: $[\text{Mg}/\text{Fe}] = 0.97$ and $[\text{Si}/\text{Fe}] = 0.87$. Also, due to the high depletion factor of titanium, its expected abundance ratio is quite low, $[\text{Ti}/\text{Fe}] = -0.89$. Finally, the low depletion of zinc leads to a high expected abundance ratio of $[\text{Zn}/\text{Fe}] = 1.69$.

Many of these predicted abundance ratios are, in fact, similar to the abundance ratios that have been inferred for a large range of metal-poor stars. In particular, the carbon-enhanced metal-poor (CEMP) stars represent a large fraction of the most metal-poor stars known (e.g. Aoki et al. 2013; Lee et al. 2013; Yong et al. 2013; Carollo et al. 2014; Placco et al. 2014; Schlaufman & Casey 2014), and in many cases exhibit large carbon abundances relative to iron such as those shown in Table 1. There have been reported stars in the literature with abundances that are similar to those we find for other elements shown, as well.

In Figure 8, we compare our predicted chemical signature (for the case of no dust accretion, for the same ten elements shown in Table 1 (black points and lines), and the data for these elemental abundances for five CEMP stars reported in the literature, each color-coded separately as labeled. While the data cluster around the expected chemical abundances for most elements, in particular those with low atomic numbers, there are heavier elements which are outliers. The weak and strong depletion of zinc and titanium, respectively, lead to distinctive signatures which are not particularly well fit by the data.
5 CONCLUSIONS AND DISCUSSION

We have estimated the impact of the dynamics of dust grains in accretion flows on the chemical abundances of low-mass Pop III stars and Pop II protostars, and we have outlined the conditions in which distinct chemical signatures could be left due to the segregation of dust from the accreting gas. Based on these results, we have predicted the expected abundance patterns for low-mass Pop III stars and Pop II protostars that accrete gas from an ISM with heavy element abundance ratios similar to those of the Sun and with dust depletion properties similar to those observed in the local ISM. Our main conclusions are as follows:

- Due to the pressure of the radiation emitted from low-mass stars, dust grains can be segregated from the gas in accretion flows and therefore be prevented from accreting onto such objects.
- Dust segregation is more likely to occur for grains with lower densities (more porous grains) and in accretion flows onto relatively luminous low-mass stars, such as Pop III red giants and Pop II protostars in particular.
- Dust segregation is less likely to occur in dense accretion flows, however, due to the larger rate of collisions with accreting gas particles.
- As the distinct abundance ratios that we predict to result from dust-segregated accretion from the ISM are in broad agreement with those found for many observed CEMP stars, it appears possible that some fraction of observed CEMP stars may be Pop III stars that have been polluted by accretion from the ISM of the Galaxy.
- Two distinct chemical signatures that may particularly strongly indicate a Pop III origin for CEMP stars are a low titanium abundance relative to iron, and a large zinc abundance relative to iron, as shown in Figure 8.

We emphasize that there are other possible explanations for the origin of CEMP stars. Among these are fall-back in the first supernovae resulting in the preferential ejection of carbon over iron (e.g. Iwamoto 2005), mass transfer from companion stars (e.g. Lee et al. 2014), atomic line cooling by carbon and oxygen as the critical process leading to the first low-mass stars (Bromm & Loeb 2003), iron depletion in the formation of a circumstellar disk (e.g. Venn et al. 2014), and the preferential ejection of iron from the low-mass dark matter haloes in which the first stars formed (Cooke & Madau 2014). Conversely, we also note that low-mass Pop III stars may not exhibit the chemical signatures of accretion from the ISM at all, if they are able to repel interstellar material by launching solar-like winds (Johnson & Khochfar 2011); in this case, the primordial nature of such stars would be readily apparent.

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It is possible that dust grains could be sublimated in the accretion processes that we consider, in which case their constituent elements would enter the gas phase and could be accreted. In particular, sublimation is expected to occur for most grains at temperatures \( T > 10^3 \) K (e.g. Kobayashi et al. 2011). We can estimate the temperature of dust grains in an accretion flow, by assuming that they are in thermal equilibrium, i.e., that the grains radiate thermal energy at the same rate that they absorb radiative energy from the star. Taking it that all radiation incident on the grain is absorbed, which provides an upper limit to the heating rate of the grain, we find that the equilibrium dust temperature is

\[
T_{\text{dust}} \approx 3 \times 10^2 K \left( \frac{L_*}{L_\odot} \right)^{1/6} \left( \frac{r}{1\text{AU}} \right)^{-1/2},
\]

where \( L_* \) is the luminosity of the star and \( r \) is the distance from the star. While the low-mass Pop III stars and Pop II protostars of interest here may have luminosities up to \( \sim 100 \) times larger than that of the Sun, dust is likely to be sublimated only once it comes within \( \sim 1 \text{ AU} \) of the star. As this is orders of magnitude closer than the Bondi radius \( r_{\text{Bondi}} \) of the star, within which the dust would be segregated from the gas if the Eddington ratio for dust exceeds unity, it appears unlikely that dust grains that would not accrete onto the star could be destroyed due to sublimation.