Critical Metallicities for Second-Generation Stars

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Abstract. The first massive stars may influence the formation of second-generation stars, in part by their metal enrichment of the surrounding gas. We investigate the "critical metallicity", defined as the the value, \(Z_{crit}\), at which primordial gas cools more efficiently by fine-structure lines of O I (63.18 \(\mu\)m), Si II (34.8 \(\mu\)m), Fe II (25.99 and 35.35 \(\mu\)m), and C II (157.74 \(\mu\)m) than by either H\(^+\) or H\(_2\) line emission. We explore the time-dependent thermodynamics and fragmentation of cooling gas at redshifts \(z = 10 - 30\), seeded by trace heavy elements expelled from early supernovae. Because different modes of nucleosynthesis (\(\alpha\)-process, Fe-group) produce abundance ratios far from solar values, these early stellar populations are likely to be influenced by O, Si, and Fe cooling. Our models also include radiative coupling of the fine-structure lines and H\(_2\) to the cosmic microwave background (CMB), which sets a temperature floor (70–80 K at \(z = 25–30\)) that may increase the Jeans mass. The H\(_2\) forms from catalytic effects of electrons left over from the recombination epoch or produced during virialization. These electrons form the H\(^-\) ion (H\(^+\) + e\(^-\) \(\rightarrow\) H\(^-\) + \(\gamma\)), which in turn forms H\(_2\) through associative detachment (H\(^-\) + H\(^+\) \(\rightarrow\) H\(_2\) + e\(^-\)). In virialized halos at \(z = 10 - 30\), the gas densities \((n = 1 - 100 \text{ cm}^{-3})\) are well below the critical densities, \(n_{crit} = 10^{3-6} \text{ cm}^{-3}\), at which (O, Si, Fe) fine-structure lines reach LTE populations and produce their most efficient cooling. Thus, \(Z_{crit}\) may initially exceed 0.01Z\(_{\odot}\) at \(n \approx 1-100 \text{ cm}^{-3}\), and then drop to \(10^{-3-5} Z_{\odot}\) at \(n \approx 10^6 \text{ cm}^{-3}\), where the Jeans mass may be imprinted on the stellar mass function. Primordial clouds of \(10^8 M_{\odot}\) at 0.01Z\(_{\odot}\) and 200 K will produce redshifted fine-structure lines, with fluxes between \(10^{-22}\) and \(10^{-21} \text{ W m}^{-2}\) at \(z \approx 4\).

Keywords: Metal abundances, Intergalactic Medium

INTRODUCTION

What is meant by the term Critical Metallicity in the context of first- and second-generation stars? We define \(Z_{crit}\) as the heavy-element abundance at which metal-line cooling of the gas begins to dominate over cooling by H and He (and molecules H\(_2\) and HD). In order for the gas to collapse gravitationally and continue to radiate away the heat produced by adiabatic compression, the radiative cooling time, \(t_{cool} \approx (3n_T/2 \mathcal{L})\), must be less than the gravitational collapse time, \(t_{coll} \approx (3\pi/32G\rho)^{1/2}\), where \(\mathcal{L}\) is the cooling rate per volume and \(\rho\) is the gas mass density. Recent studies, based on Jeans-mass arguments and thermodynamic histories of cloud collapse, suggest that the mode of star formation may change, shifting from higher-mass stars at low-Z (Pop III) to a more normal (Pop II) initial mass function (IMF) at \(Z > Z_{crit}\).

At zero metallicity, because of the lack of CNO-burning and the inefficiency of the p-p chain, the first stars are smaller, hotter, and shorter-lived than their current counterparts (e.g., Tumlinson & Shull 2000). Their efficient production rates of ionizing radiation give them special importance for IGM reionization (Venkatesan, Tumlinson, & Shull 2003; Wyithe & Loeb 2003; Shull & Venkatesan 2007). The most massive stars have large yields of heavy elements (Heger & Woosley 2002), particularly \(\alpha\)-process elements (O, Si) and the iron-group. Thus, it is astrophysiologically important to understand the transition from first to second-generation stars when \(Z > Z_{crit}\). However, this transition probably varies spatially and temporally, owing to the inhomogenous nature of metal production and transport into the IGM.

In cold dark matter (CDM) cosmologies, the first galaxies in the universe are predicted (Ricotti, Gnedin, & Shull 2002, 2007) to be \(10^6\) times smaller than the Milky Way, with characteristic masses comparable to mass estimates for the smaller dwarf spheroidal galaxies (dSph) observed around our Galaxy and Andromeda (Mateo 1998; Belokurov et al. 2006). The gravitational potentials of these \(10^6-8 M_{\odot}\) objects are so weak that warm and hot ionized phases of their interstellar medium are weakly bound. As a result, each episode of star formation may produce powerful outflows that could temporarily inhibit further star formation.

The first subgalactic structures form from the collapse of rare dark matter density perturbations, with masses \(10^{5-6} M_{\odot}\) at \(z \approx 30 - 40\). The initial gas cooling is from collisionally excited H\(_2\) rotational and vibrational transitions (Lepp & Shull 1984). A minimum H\(_2\) abundance \(x_{H_2} \approx 10^{-4}\) is required to trigger star formation in a dark halo in less than a Hubble time. In dust-free gas, H\(_2\) formation is catalyzed by the H\(^-\) ion, that forms as a consequence of the shocks that partially ionize and heat the gas during the virialization process. At a given redshift, the mass of the smaller halo that can form stars is determined by its virial temperature and therefore by its mass. This analytical result has been confirmed by hydrodynamical cosmological simulations.
Abel, Bryan, & Norman (2002) carried out such numerical simulations for a selected $10^9$ $M_\odot$ halo, using adaptive-mesh refinement that resolves the collapse over a large range of scales. In this selected halo, they find that only one star forms, with mass $10$–$100$ $M_\odot$. Bromm, Coppi, & Larsen (1999) found similar results with a variety of initial conditions for the protogalaxies. These numerical results confirm longstanding theoretical suggestions that the first stars should be massive: their characteristic mass reflects the larger Jeans mass in the inefficiently cooling metal-free gas. However, the cooling by trace-metal fine-structure lines depends on the gas density (Santoro & Shull 2006, 2008) and radiative coupling to the CMB. Thus, the Jeans mass and critical metallicity are sensitive to local gas density.

PREVIOUS CALCULATIONS OF $Z_{\text{crit}}$

The first static models of $Z_{\text{crit}}$ (Bromm & Loeb 2003) found $Z_{\text{crit}} \approx 10^{-3} Z_\odot$ for fine-structure cooling by [C II] 158 $\mu$m and [O I] 63 $\mu$m. Santoro & Shull (2006) confirmed these results for C II and O I, but suggested that fine-structure lines of [Si II] and [Fe II] might also contribute, since IGM “metal pollution” from massive-star nucleosynthesis is weighted toward heavier elements. They further noted that $Z_{\text{crit}}$ depends on the gas density, $n$, owing to the change in cooling rate, from $\mathcal{L} \propto n^2$ (at low-density) to $\mathcal{L} \propto n$ (high-density), as the fine-structure levels reach Boltzmann (LTE) populations at “critical density” ($n_{\text{cr}}$). For $H^0$ excitation at 200 K, $n_{\text{cr}}$ ranges from $3000$ cm$^{-3}$ ([C II]) to $(1 - 2) \times 10^6$ cm$^{-3}$ ([O I] and [Fe II]). Santoro & Shull (2006) found that $Z_{\text{crit}}$ exceeds 0.01$Z_\odot$ at the low gas densities, $n \approx 1$–$100$ cm$^{-3}$, present in virialized halos at $z > 20$.

Figure 1 shows values of $Z_{\text{crit}}$ for C, O, Si, and Fe, where metallicity is labelled by a single parameter $Z$. In fact, there is no single “metallicity”, since the primary coolants (C, O, Si, Fe) are rarely produced in solar abundance ratios. Because of the density dependence of the cooling, Santoro & Shull (2008) examined the thermodynamic history of cloud collapse and refined the definition of $Z_{\text{crit}}$. In the new models they included collisional coupling of the gas and level populations ($H_2$, HD, fine-structure lines) and radiative coupling to the cosmic microwave background (CMB). The latter effect can be especially important at high redshifts, $z = 25$ – 30, where the CMB temperature, $T_{\text{CMB}} = (82 K) (1 + z)/30$, sets a floor on gas temperature sufficient to increase the Jeans mass. This, in turn, may produce more massive stars at high redshift (Tumlinson 2007).

RESULTS

The results of our time-dependent models are shown in Figures 2 and 3, with the astrophysical importance summarized in the captions. Figure 2 shows the thermodynamic ($T, n$) collapse history at $z = 30$. After an initial rise due to adiabatic heating, the temperature turns downward (injection point at [Fe/H] $\leq -2.0$). Once the density exceeds $n \geq 10^6$ cm$^{-3}$ at $z > 10^{-3.5} Z_\odot$, $T$ is driven toward $T_{\text{CMB}}$. Figure 3 illustrates the dependence of $Z_{\text{crit}}$ on the time allowed to cool, expressed as a fraction of the local Hubble time. Most of the cooling time is spent at low densities. In order to cool in 10–15% of $t_H$, the gas must reach $Z_{\text{crit}} \approx 0.01 Z_\odot$, until the density reaches the point ($\sim 10^6$ cm$^{-3}$) of most efficient cooling.

These far-infrared fine-structure lines dominate the $H_2$ cooling once $Z > Z_{\text{crit}}$, and their detection represents a challenge for FIR and sub-mm astronomy. As shown by Santoro & Shull (2006), the strongest lines are [O I] 63 $\mu$m, [Si II] 34.8 $\mu$m, and [Fe II] 25.99 $\mu$m, which at $z = 4$ redshift to 316 $\mu$m, 174 $\mu$m, and 130 $\mu$m. For $(10^8 M_\odot)M_8$ of high-density (LTE) gas at 200 K and $Z = (0.01 Z_\odot)Z_{0.01}$, the line luminosities are predicted to be $L_{\text{line}} \approx (0.8 - 2.0) \times 10^{41}$ erg s$^{-1}$ $M_8 Z_{0.01}$. The luminosity distance at $z \approx 4$ is $d_L \approx 10^{29}$ cm, and the expected line fluxes are $\sim 10^{-21}$ W m$^{-2}$, within reach of facilities such as ALMA, SPIRA, or SAFIR. At higher redshifts, these lines shift into the 350 $\mu$m (sub-mm) window. The fluxes will probably be lower, owing to the larger $d_L$, lower $Z$, and smaller masses of cooling gas.

OBSERVATIONS & DISCUSSION

The “fossil record” of the first stars may be observed in gas-phase (IGM), as well as in metal-poor halo stars. Metallicities $Z \sim 10^{-3}$ $Z_\odot$ are measured from absorption lines in the Ly$\alpha$ forest at $z \sim 2$ – 5 (Songaila 2001; Schaye et al. 2003; Pettini et al. 2003; Simcoe et al. 2004). This mean metallicity, typically inferred from abundances of C IV and Si IV, shows little evolution from $z = 5$ to $z = 2$. However, a possible redshift-dependent ionization correction may conspire to mask any real metallicity evolution.

The origin of the metals observed in the low-density Ly$\alpha$ forest at redshifts $z \sim 2$ – 5 is still under some debate. One view invokes a nearly uniform pre-enrichment of the intergalactic medium (IGM) produced by the first stars at high-redshift (Madau et al. 2001). The other view attributes the origin of the observed metal lines to hot, metal-enriched superbubbles located around Lyman-break galaxies (Adelberger et al. 2003). Given the difficulties associated with both scenarios, it is important to know the amount and volume filling factor of metal-enriched IGM produced by primordial stars and galaxies.
FIGURE 1. Minimum critical metallicities, $Z_{\text{crit}}$, vs. total gas density $n$ (Santoro & Shull 2006) for static cooling at $T = 200$ K by individual heavy elements. Curves correspond to gas enriched by C II, Si II, O I, and Fe II (see labels). Bottom envelope shows all four species together in solar abundance ratios. Minimum values occur at high densities (near $n_{\text{cr}}$ for each coolant) at $\log (Z_{\text{crit}}/Z_{\odot}) = -3.48$ (C II), $-3.54$ (Si II), $-3.78$ (O I), $-3.52$ (Fe II), and $-4.08$ (all elements).

As modeled by many groups (e.g., Ricotti, Gnedin, & Shull 2002, 2007), the first sources of metals may come from "dwarf primordial" (dPri) galaxies, with virial temperatures $T_{\text{vir}} \leq 20,000$ K and circular velocities $v_c \leq 20$ km s$^{-1}$. In contrast to more massive galaxies, the dark matter (DM) halos of dPri galaxies are too shallow to contain much photoionized gas, with temperatures $10,000$–$20,000$ K. During their formation, the gas is only heated to temperatures below $10^4$ K, where it is unable to cool by atomic hydrogen (Ly$\alpha$) line emission. The mass of these halos is $M_{\text{dm}} \leq 2 \times 10^8$ M$_{\odot}$ at their typical redshifts of formation ($z \geq 10$). These galaxies rely primarily on the formation of H$_2$ to cool and form stars, because metal cooling is negligible as long as the gas has almost primordial composition. This situation changes, after the metallicity rises above $Z_{\text{crit}}$, which could be as large as $0.01Z_{\odot}$ at halo gas densities $n \approx 10$–$100$ cm$^{-3}$. As the first stars form, these requirements no longer hold, since some gas is heated above $10,000$ K and is polluted with heavy elements.

At low redshifts ($z < 0.4$), ultraviolet spectrographs aboard Hubble and FUSE have made similar measurements of the gas-phase baryon content and metallicity of the IGM, using Ly$\alpha$, Ly$\beta$, and trace metal lines of O VI, C III, C IV, etc. (Danforth & Shull 2005, 2007). The current observational sensitivity to metallicity is $\sim 10^{-1.5}Z_{\odot}$ at high redshift (Songaila 2001; Simcoe et al. 2004) and $10^{-2}Z_{\odot}$ at low redshift (Danforth & Shull 2007; Stocke et al. 2007). Figure 4 shows how these lines can be used to derive the statistical metallicity ($\sim 0.1Z_{\odot}$) from ratios of O VI to H I. However, the IGM appears to have widely varying metal abundances, with differences between "filaments" and "voids" in the "Cosmic Web" of absorbers. If underdense regions of IGM contain some metals, then star formation in high redshift galaxies may have pre-enriched it (Madau et al. 2001). If, instead, the metals detected along a line of sight are associated with nearby bright galaxies at $z \sim 2$–$5$, the metal distribution is probably quite inhomogeneous. In this second case, observations are not probing a minimum floor of metal enrichment produced by the first galaxies.

The degree of inhomogeneity in the IGM metal distribution IGM is not well characterized, although this should change with the installation of the powerful Cosmic Origins Spectrograph (COS) on the Hubble Space Telescope in August 2008. The spectroscopic throughput of COS should be over $20 \times$ that of STIS, and the resulting ultraviolet spectra will be used for a wide range of
FIGURE 2. Temperature–density ($\log T, \log n$) evolution of a collapsing gas cloud (Santoro & Shull 2008) starting with virial conditions of mass, density, and temperature at $z = 30$. Curves are labelled by metallicity $\log(Z/Z_\odot)$ or [Fe/H]. The initial rise in temperature comes from adiabatic heating, while the subsequent decreases in $T$ are driven by cooling from $H^\circ$-excited $H_2$ rotational lines and fine-structure lines of [O I], [Si II], [Fe II], [C II]. The broad temperature minima occur at $n \approx 10^{5.5}$ to $10^{6.5}$ cm$^{-3}$, near the critical densities for $H^\circ$ de-excitation of [O I], [Si II], and [Fe II] fine-structure levels. When level populations reach LTE, the volume cooling rate $\dot{E} \propto n$ rather than $n^2$, and $T$ begins to rise at $n > n_{cr}$. Radiation and collisions couple the gas and fine-structure levels to the CMB ($T_{CMB} \approx 80$ K at $z = 25–30$). The stellar IMF may be imprinted when $T \leq 200$ K and $n \approx 10^6$ cm$^{-3}$. 
FIGURE 3. Critical metallicity (Santoro & Shull 2008) for collapsing clouds, allowed to cool for various fractions (5%, 10%, 15%) of the local Hubble time at $z = 20–30$. As shown by the lower two curves, the gas within virialized halos may need to reach metallicities as large as $\sim 1–2\% Z_\odot$ in order to cool in 10–15% of the local Hubble time, $t_H$.

observations of the IGM and surrounding galaxies: (1) surveys of the baryon content and metallicity of the low-$z$ IGM; (2) searches for nucleosynthetic patterns among heavy elements; (3) absorber-galaxy correlation studies, seeking connections between the IGM and the galaxies responsible for metal enrichment; (4) Surveys of baryons and metals residing in absorbers within voids. Preliminary studies of several of these issues with HST and FUSE spectrographs is now underway (Danforth & Shull 2005, 2007; Stocke et al. 2006; Stocke et al. 2007).

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FIGURE 4. The “fossil record” of the first stars may be studied in the gas phase at $z < 0.4$, through quasar absorption lines. This plot shows the “multiphase ratio” of O VI and H I absorbers, measured by Hubble Space Telescope and the Far Ultraviolet Spectroscopic Explorer (Danforth & Shull 2005, 2007). The ratio, $N$(H I)/$N$(O VI) varies from high column density filaments in the Cosmic Web to low-column gas in voids, with $N_{\text{HI}} < 10^{14}$ cm$^{-2}$. Our surveys and abundance analyses show that low-$z$ filaments have mean metallicities $\sim 0.1Z_{\odot}$, whereas no metals have been detected in voids, down to limits of $0.02Z_{\odot}$ (Stocke et al. 2007). The major conclusions of this study are: (1) the filaments have increased their metallicity by factors of 30-100 from $z \geq 3$ to the present; and (2) the IGM in voids may contain low-metallicity pockets at $Z < 0.01Z_{\odot}$. 