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Metal production and dispersal from the first stars

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Abstract. The emergence of the first stars, the so-called Population III, marked the crucial transition in the early history of the universe from initial simplicity to ever-increasing complexity. A key aspect of this transformation is the seeding of the pristine, pure hydrogen-helium, pre-galactic medium with the first heavy chemical elements in the wake of Population III supernova explosions. The character of this initial metal enrichment sensitively depends on the properties of the first stars, specifically their initial mass function and rotation state. Recent highly-resolved numerical simulations of primordial star formation have resulted in an improved physical framework, positing that the first stars were typically massive, with masses of a few tens of solar masses, but with a broad distribution, and that they were rapidly rotating. The feedback from the first stars shapes the assembly history of the first galaxies, leading to the prediction that the faintest sources to be detected by the *James Webb Space Telescope* will already be metal-enriched, exhibiting long-lived Population II stellar systems.

Key words. cosmology: theory – galaxies: formation – galaxies: high-redshift – stars: formation – stars: Population II – hydrodynamics – galaxies: observations

1. Introduction

These are exciting times in the exploration of the high-redshift frontier. Advances in supercomputing technology have resulted in an increasingly realistic picture of how the cosmic dark ages ended (Loeb & Furlanetto 2013; Wiklind et al. 2013). At its foundation lies the prediction that the first stars, the so-called Population III (Pop III), were typically massive, with masses of $\sim 10 - 50 M_{\odot}$ (Bromm 2013). As a consequence, they are expected to exert rapid feedback on the pristine intergalactic medium (IGM). Specifically, the first stars initiated the reionization of the universe through their efficient output of ionizing photons (Barkana & Loeb 2007; Meiksin 2009; Robertson et al. 2010), and enriched the primordial, pure H/He, gas with the initial complement of heavy chemical elements upon their violent death (Karlsson et al. 2013). Once the first stars appeared on the scene, the universe made a rapid transition to an ever more complex state, eventually leading to the emergence of fully-developed, self-regulated galaxies, including the assembly of supermassive black holes in their centers (Bromm & Yoshida 2011).

This emerging theoretical picture will soon be tested with an upcoming array of next-generation observational facilities, such as the *James Webb Space Telescope (JWST)*, scheduled for launch in ~ 2018, and the planned giant 30-40 m telescopes on the ground. The former will provide unprecedented near-IR imaging sensitivity, ideally complemented by the adaptive optics (AO)-enabled spectroscopic capabilities of the latter. In-situ probes, aiming at detecting the signposts of the first stars and galaxies at high redshifts, stand next to the equally-promising near-field cosmological probes, often termed “Stellar Archaeology”. In this local approach, surveys of metal-poor stars in our Galaxy, and in other members of the Local Group, yield constraints on the properties of the first stars via their unique nucleosynthetic patterns that are preserved in the atmospheres of surviving, low-mass stars (Frebel & Norris 2013). Just ahead of those next-generation telescopes and greatly enlarged stellar-archaeological surveys, there is the exciting prospects for serendipitous “pre-views” into the very high-redshift frontier. An example are gamma-ray bursts (GRBs) that already probe the early IGM out to $z \gtrsim 9$ (Bromm 2012).

The plan for this brief review is as follows. We will first discuss our current understanding of Pop III star formation, based on numerical simulations, followed by a quick summary of what the first supernova (SN) explosions are expected to be like. We conclude with an equally quick survey of key empirical probes of pre-galactic metal-enrichment, both at high redshifts and locally. For further details, we refer the reader to the reviews cited above, and, regarding the focus of these proceedings, in particular to Karlsson et al. (2013).

2. Formation of the first stars

2.1. Cosmological initial conditions

Star formation in general is a highly complex process, involving non-linear and non-equilibrium physics (McKee & Ostriker 2007). One of the appealing features of primordial, Pop III, star formation is that we have a very good understanding of the initial conditions, provided by the successful ΛCDM model of cosmological structure formation, now calibrated with exquisite precision by *WMAP* and *Planck*. This is in difference from the present-day case, where initial conditions are given by the non-linear density distributions and velocity fields that result from the supersonic turbulence in giant molecular clouds (Mac Low & Klessen 2004). The basic result is that the first stars formed in so-called ‘mini-halos’, with total (dark matter plus gas) masses of $\sim 10^5 - 10^6 M_\odot$, at redshifts $z \simeq 20 - 30$ (Yoshida et al. 2003). This result is quite robust, and rather drastic deviations from standard ΛCDM are required to modify the properties of the primordial star formation site, such as warm dark matter (WDM) scenarios.

One significant recent development, which does impact when and where the first stars formed, is the discovery of a subsonic, relative streaming velocity between the dark matter and baryonic components (Tseliakhovich & Hirata 2010). This relative motion is imprinted at the epoch of recombination, when the baryonic sound speed experiences a precipitous drop from near-relativistic to few $\mathrm{km\,s^{-1}}$ values. Furthermore, the streaming motions are coherent on scales of a few comoving Mpc. The supersonic streaming velocity acts as an additional source of effective pressure, assisting the conventional thermal pressure in preventing gravitational instability. As a consequence, collapse of primordial gas into minihalos is delayed, and on average shifted to more massive systems (Stacy et al. 2011). However, at $z \lesssim 15$ the effect becomes increasingly negligible, as the streaming motions decay due to the Hubble flow.

2.2. Fragmentation and mass spectrum

The traditional paradigm of Pop III star formation, where only one massive star was thought to form per minihalo, has recently been revised in important ways (Bromm 2013). The new picture, based on very high-resolution simulations which, crucially, are able to follow the evolution for many free-fall times, posits that the first stars typically formed in small multiple groups (Turk et al. 2009; Stacy et al. 2010; Clark et al. 2011; Greif et al. 2011, 2012). This ubiquity of stellar multiplicity in Pop III is akin to what is typical for the present-day case where stars typically form in a clustered mode. It derives from the gravitational instability in the accretion disk that forms around a central protostar from the delayed infall of material with increasing levels of specific angular momentum. The gravitational torques acting to transport spin out, and mass in, are unable to drive sufficiently strong mass accretion rates to process the high infall rates, onto the disk, from the surrounding, hot envelope. Consequently, the Pop III disks are inevitably driven toward instability, and fragmentation into multiple protostellar systems ensues.

Recent debate has centered on whether the Pop III accretion disks could possibly be stabilized, thus suppressing any fragmentation and effectively restoring the one star per minihalo picture of the pre-2009 era. One idea invokes unresolved turbulence as a stabilizing agent (Turk et al. 2012; Latif et al. 2013). For brief periods after the initial, central protostar has formed, such stabilization is indeed seen, either in runs with extremely high resolution, or those that employ sub-grid models for the unresolved turbulence on small scales. However, these studies suffer from 'Courant myopia', where the simulations grind to a halt when the first parcel of gas, here the central protostar, reaches high density. It remains to be seen whether the disks can retain stability over the many free-fall times required to really settle this key question. Another idea for disk stabilization is WIMP dark matter annihilation (DMA) heating (Smith et al. 2012). Generic models posit that WIMPs are their own antiparticle, thus being able to release large amounts of energy in regions of high DM density ('cusps'). Through complex particle-physics decay channels, this energy is eventually transformed and deposited as heat, at least in part. However, recent studies that investigate the back-reaction of the gas disk on the DM cusp indicate that any such stabilization was likely short-lived (Stacy et al. 2014).

The ultimate goal is to predict the Pop III initial mass function (IMF). To that extent, simulations need to be pushed into the late-stage, radiation hydrodynamics (RHD) regime, where the UV radiation feedback from the growing protostar(s) will act to limit the final mass of a Pop III star. It soon became clear that this radiative feedback would primarily work by evaporating the surrounding accretion disks (McKee & Tan 2008). Recently, two- or three-dimensional RHD simulations have converged on final Pop III masses of order a few tens of solar masses (Hosokawa et al. 2011; Stacy et al. 2012). Of great significance for the field of pre-galactic metal enrichment, this implies progenitor masses that would typically lead to core-collapse SNe, instead of the more extreme pair-instability supernovae (PISNe) that were preferred earlier on (see Section 3).

2.3. Rotation

Next to the mass scale of Pop III, the rotation rate of those primordial stars is the key determinant of nucleosynthetic pathways, and ultimately the modes of their demise (Maeder & Meynet 2012; Yoon et al. 2012). Rapidly rotating stars will exhibit abundance anomalies, by establishing internal circulation currents, that will mix layers that otherwise would belong to different, well-separated nuclear burning stages. In extreme cases, rapid rotation can prevent the stars from ever entering the puffed-up giant or supergiant stages, thus greatly affecting the explosion physics encountered upon their death.

Recent simulations, conducted within a realistic cosmological context, have shown that Pop III protostars were typically rapid rotators, with surface rotation speeds that are a sizeable fraction of the break-up speed (Stacy et al. 2013). The underlying reason is the well-organized nature of the gas flow in the center of the minihalo, where retrograde mergers of gas clouds, which would act to slow any rotation, are extremely rare. Important caveats, such as the impact of magneto-hydrodynamical braking, however remain, and will need more work to reach convergence.

Observations of the unusual abundance pattern in giant stars in an old globular cluster in the Galactic bulge have provided tentative evidence that the first stars were indeed rapidly rotating (Chiappini et al. 2011). Those stars simultaneously show the signature of low- (AGB), and high-mass enrichment. Since there may not have been enough time for the slow AGB (s-process) enrichment channel, the authors suggest enrichment from a single population of massive, but rapidly rotating progenitor stars, what they have termed 'spinstars'.

3. Supernova feedback

The impact of the first stars on early cosmic history sensitively depends on their mass. Regarding pre-galactic metal enrichment, the key question is the relative fraction of PISN vs. core-collapse SN progenitors. This ratio is determined by the Pop III IMF, and is still quite uncertain. However, there has been a revision in the consensus view, away from an almost exclusive PISN channel to one where core-collapse SNe dominate, as a consequence of the recent downward revision of the Pop III mass scale (see Section 2). This revision has important implications for the resulting chemical abundance pattern, as well as for the history of early cosmic structure formation.

3.1. Nucleosynthesis

A PISN, resulting from Pop III progenitors with mass $\sim 140 - 260 M_{\odot}$, is characterized by a huge yield, where almost one half of the stellar mass is transformed into metals, $y = M_Z/M_* \sim 0.5$ (Heger & Woosley 2002). This is in stark contrast with typical core-collapse yields, $y \lesssim 0.05$. It had long been argued that the observed abundance patterns in Galactic metal-poor stars do not show any signs for predominant PISN enrichment, such as a strong odd-even effect, or the absence of any neutron-capture elements (Beers & Christlieb 2005; Tumlinson 2006). Empirically, this seems to favor core-collapse enrichment, in agreement with the recent theoretical revision of the Pop III mass scale. However, it is important to keep an open mind. After all, the Pop III mass function is predicted to be broad, possibly extending to high masses in the PISN range as well. In addition, there may be observational selection effects that bias current surveys against detecting any PISN signature (Karlsson et al. 2008). Such a bias could arise since a single PISN creates a large amount of Ca, resulting in [Ca/H] values that are larger than the typical thresholds employed by surveys such as Hamburg/ESO (HES) to select candidate stars for high-resolution, spectroscopic follow-up.

3.2. Assembly of the first galaxies

The kind of explosion, PISN vs. core-collapse, encountered by the dying Pop III star governs how seriously the minihalo host is disrupted. The extreme explosion energies, $E_{SN} \gtrsim 10^{52}$ erg, associated with a PISN, result in the complete disruption of the host system with its shallow gravitational potential well (Wise & Abel 2008; Greif et al. 2010). It then takes of order a local Hubble time, $\sim 10^8$ yr, for the hot ejecta to cool, and to be reassembled into a more massive dark matter halo (Greif et al. 2010; Wise et al. 2012).

The 'recovery time', however, is much shorter for core-collapse explosions. Metal-enriched material then can recollapse, and provide the raw material for the next round of star formation, already after a few 10^7 yr (Ritter et al. 2012). Thus, the nature of the first SNe determines when and where the first *bona-fide* galaxies can form. The latter are often defined as dark matter halos that host long-lived stellar systems. PISN feedback would correspond to delayed recollapse, thus rendering the first galaxy hosts more massive, and supposedly luminous, whereas core-collapse feedback would correspond to lower-mass, fainter systems (Ricotti et al. 2008). Regardless of the nature of the Pop III enrichment channel, however, any first galaxy would already be metal-enriched, hosting Pop II stellar systems. The truly metal-free, minihalo progenitors will likely remain out of reach, due to their extreme faintness. These ultimately are questions for the *JWST*, when the metallicity and luminosity function of the first galaxies will be measured in ultra-deep field campaigns.

4. Empirical probes

4.1. High-redshift probes

The most direct way to probe the signature of the first stars is the imaging and spec-

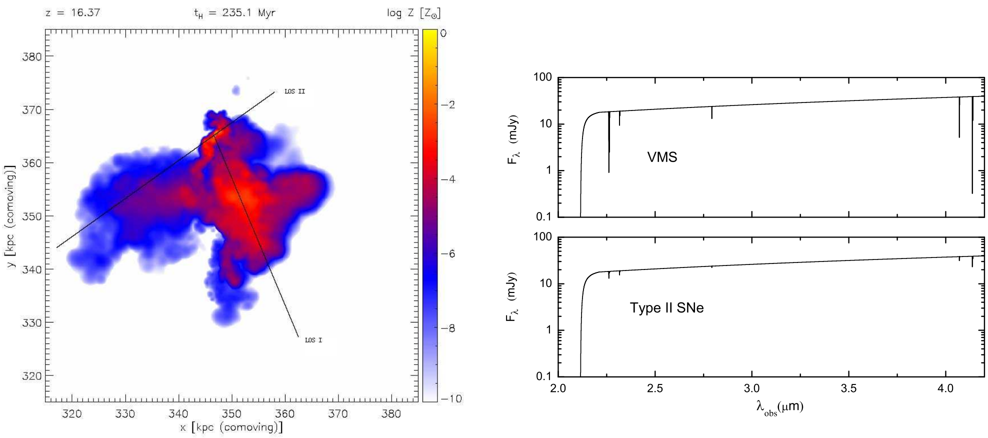

Fig. 1. Employing GRB afterglows to probe pre-galactic metal enrichment (from Wang et al. 2012). *Left panel:* Metallicity distribution in a region of clustered Pop III star formation. The box size is 70 kpc (comoving), shown at $z \simeq 16$. A GRB explodes at the intersection of the two lines. *Right panel:* Resulting near-IR absorption spectra. Two different cases for Pop III SN enrichment are considered, from conventional core-collapse (Type II) and from a very massive star (VMS) progenitor, leading to a PISN. The situation corresponds to 1 day (in the observer frame) after the GRB trigger. The absorption lines are imprinted by low-ionization species of C, O, Si, and Fe. The sharp cutoff at lower wavelengths is due to the complete absorption of Lyman-α radiation in the neutral IGM. Reproduced by permission of the AAS.

troscopy in the near-IR, possible with the upcoming frontier facilities, primarily the *JWST*. One prime avenue is to detect the emission lines emitted by the ionized regions around the first stars; emission line ratios can then serve as a diagnostic of the stellar population(s) involved, and as a tracer of the respective IMF (Johnson et al. 2009; Pawlik et al. 2011, 2013). Specifically, a strong contribution from the He II 1640 Å line would indicate a top-heavy Pop III stellar system (Schaerer 2003). The search for high-redshift galaxies has now reached a, spectroscopically confirmed, redshift of $z \simeq 7.5$ (Finkelstein et al. 2013). Even higher redshifts are expected in the ongoing Hubble Frontier Fields, exploiting the magnifying power of gravitational lensing.

A powerful probe of the metal content in pre-galactic gas clouds is provided by bright background sources, with lines of sights that intersect the intervening medium. Traditionally, quasars have served as such back-lights, now extending to $z \sim 7$ (Mortlock et al. 2011). However, quasars are getting exceedingly rare at high redshifts, rendering them ineffective to probe even earlier times. Here, GRBs take over as searchlights of the early universe (Bromm 2012). Indeed, GRBs have now been identified spectroscopically at $z \simeq 8.2$ (Salvaterra et al. 2009; Tanvir et al. 2009), and photometrically at $z \sim 9.5$ (Cucchiara et al. 2011). Their bright afterglows provide nicely featureless spectra, on top of which absorption features can be imprinted, thus probing the metal enrichment of intergalactic clouds. An example, based on a cosmological simulation, is shown in Fig. 1.

Whereas the potential for GRB cosmology still largely belongs to the future, we are already finding clues to the enrichment state of the high-z IGM, employing the traditional quasar backlights. Two new tantalizing discoveries have been made. One is the detection of seemingly completely unenriched, truly primordial material (Fumagalli et al. 2011; Simcoe et al. 2012). The presence of such islands of pristine gas at $z \lesssim 5$ indicates that pre-galactic metal enrichment was incomplete, and probably confined to the highest-density regions. The other is the detection of carbon-enhancement in low-metallicity damped-Lyman-α (DLA) clouds (Cooke et al. 2011), possibly pointing to a Pop III origin of the heavy elements found there (see Section 4.2).

Finally, there is the hunt for PISNe, triggered by the death of very massive Pop III stars. As we have seen, we do not know whether Pop III ever gave rise to these extreme explosions. It is, however, important to search for them, as any positive, or negative, result would provide us with valuable constraints on the upper-mass end of the primordial IMF. Recent RHD simulations clearly show that PISNe were sufficiently bright to be picked up by *JWST* with its near-IR camera (Pan et al. 2012; Whalen et al. 2013). The problem, however, may be that they were so very rare (Hummel et al. 2012). A survey strategy employing a wide-field mosaic, with individually only modestly-deep exposures, seems optimal. Undoubtedly, the potential for any such serendipitous discoveries in the high-redshift universe is considerable, and it will be fascinating to see this unfold.

4.2. Fossil probes

An ideally complementary probe is the near-field cosmological search for relics from the era of the first stars. These are foremost the ancient, most metal-poor stars in our Galaxy, and its dwarf satellite systems. A number of key lessons have emerged (Beers & Christlieb 2005): chemical abundance patterns in metal-poor stars can be reconciled with standard core-collapse nucleosynthesis in the majority of cases; there is currently no evidence for any true metal-free, Pop III, surviving low-mass stars, although recent simulations at least do not categorically exclude that possibility, and there is the problem that any primordial signature might be 'masqueraded' through pollution, or accretion, from the interstellar medium of the Milky Way (Frebel et al. 2009); there is currently also no hint for Pop III PISN enrichment, although we here may get fooled via a selection bias (Karlsson et al. 2008); and there is a curious trend towards carbon-enhancement towards the lowest metallicities.

The problem of C-enhancement indeed has recently become even more intriguing. Since the discovery of the two most Fe-poor stars (Christlieb et al. 2002; Frebel et al. 2005), attempts have been made to explain their peculiar abundance pattern, i.e., low in all elements with the notable exception of the ultra-enhanced light ones (C, N, O). The most convincing one is to invoke faint SNe, triggered by Pop III progenitors that are sufficiently massive to leave black holes (BHs) behind (Iwamoto et al. 2005). Basically, most of the heavy elements are then locked up in the central BH, and only the lightest ones (C, N, O) from the outer layers are expelled. Such C-enhancement nicely resonates with some theoretical predictions of cooling thresholds to enable the formation of low-mass stars (Frebel et al. 2007). However, this picture has been challenged, both on theoretical and observational grounds.

Theoretically, there is the debate whether fine-structure cooling, mostly due to C II and O I (Bromm & Loeb 2003), are driving the transition from top-heavy Pop III to low-mass dominated Pop II, or dust cooling (Schneider et al. 2006). And observationally, there is the recent discovery of the most metal-poor star, in terms of the overall mass fraction locked up in metals, yet (Caffau et al. 2011). Significantly, this star is *not* C-enhanced, but instead 'C-normal'. It thus lies in what had been termed the 'forbidden zone' of the fine-structure cooling plot (Frebel et al. 2007), thus indicating that dust cooling must have been responsible for its formation. Basically, dust operates at very high densities, thus being able to imprint sub-solar Jeans masses. The C-riddle, however, remains. There seems to be a dichotomy, 'C-enhanced' vs. 'C-normal' at very low metallicity, which has tentatively be linked to two physically distinct pathways to low-mass star formation (Norris et al. 2013; Ji et al. 2014). Basically, one pathway would be classical Jeans instability, ultimately relying on the ability of the star forming gas to cool even at high densities, since the Jeans mass scales with temperature and (number) density as $M_J \propto T^{3/2} n^{-1/2}$. This (thermal) pathway requires cooling due to dust grains, as other coolants are ineffective at high densities. An alternative pathway to low-mass stars can operate in a clustered environment, where the complex *N*-body dynamics amongst multiple protostars can lead to the ejection of some fragments from their birth cloud. Those 'ejectees', therefore, never will have the chance to accrete the full complement of their Jeans mass, as determined by the temperature and density of their initial formation site. This (dynamical) pathway suggests fine-structure cooling, since the latter has been shown to determine whether star formation happens in a clustered mode or not (Safranek-Shrader et al. 2014).

Next to individual metal-poor stars in the halo of the Milky Way, increasing attention is being paid to the newly identified ultra-faint dwarf (UFD) satellites. Each of them contains only a few hundred stars, so that, in principle, a complete census is possible, a feat that is completely out of reach for the Galaxy. Because of their shallow potential well, only a small number of SN explosions could have contributed to their enrichment. Any Pop III signature would thus be much less diluted than in systems with more complex chemical histories, such as the halo and bulge of our Galaxy. The UFDs, therefore, likely provide us with 'Rosetta Stone' systems, giving us a sporting chance to directly constrain the Pop III IMF (Frebel & Bromm 2012).

5. Outlook

The prospects for elucidating the high-redshift frontier in general, and the initial stages of cosmic chemical evolution in particular, are bright. The ultimate goal is to observationally get as close as possible to the unenriched, primordial universe that emerged from the Big Bang, and to the signposts of the first stars, their output of photons and their nucleosynthetic legacy. With the new generation of telescopes and missions, we might get closer to being able to finally answer the question of the ages: "How did it all begin?".

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