Conference Summary

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Abstract. The understanding of the formation, life, and death of Population III stars, as well as the impact that these objects had on later generations of structure formation, is one of the foremost issues in modern cosmological research and has been an active area of research during the past several years. We summarize the results presented at “First Stars III,” a conference sponsored by Los Alamos National Laboratory, the Kavli Institute for Particle Astrophysics and Cosmology, and the Joint Institute for Nuclear Astrophysics. This conference, the third in a series, took place in July 2007 at the La Fonda Hotel in Santa Fe, New Mexico, U.S.A.

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1. INTRODUCTION

In July 2007, more than 130 international researchers met at the La Fonda Hotel in Santa Fe, New Mexico, U.S.A. to discuss the formation, life, and death of zero-metallicity (Population III) and very low metallicity stars, as well as the impact that these objects had on later generations of stars and on structure formation. This field has made significant theoretical and observational advances since First Stars I, which was a MPA/ESO/MPE Joint conference held in 1999 in Garching b. München, Germany, and First Stars II, which was held at The Pennsylvania State University in State College, Pennsylvania, U.S.A., in 2003. Though major advances have been made, the understanding of Population III and very low metallicity stars is still in its infancy, and many important questions remain unanswered.

Donald Rumsfeld is known for many things, but his contribution to the philosophy of science is less well recognized. In an oft-cited speech he delivered on Feb 12, 2002, he said:

There are known knowns. These are things we know that we know. There are known unknowns. That is to say, there are things that we know we don’t know. But there are also unknown unknowns. There are things we don’t know we don’t know.

He applied this to intelligence data, but one can describe our task as scientists is to uncover “unknown unknowns” by pure thought or by serendipitous observation or experiment, thereby converting them to “known unknowns;” and to then use systematic observation, experiment and theory to convert these to “known knowns.”

The study of the first stars is a new field. There are almost no “known knowns,” except for the background cosmology and an increasing set of data on abundances in very metal poor stars. There are many “known unknowns:” What is the nature of dark matter? What is the strength of the magnetic field? What are the abundance and size distribution of dust? What is the rate of mixing of metals into primordial gas? Until recently, the effect of dark matter annihilation on the first stars was an “unknown unknown,” but this has become a “known unknown” through the work of Freese and her collaborators.

We conjecture that the number of “unknown unknowns”—i.e., the discovery potential—in a field is proportional to the ratio of the number of “known unknowns” to “known knowns:"

$$UU \propto \frac{KU}{KK}.$$  (1)

If so, the study of the First Stars is an excellent field for young people—as reflected in the youth of the audience and the organizers (although not in the summarizer)!

In the following sections, we shall summarize the results presented at this conference, and raise some significant issues that have yet to be explored. In the interests of conserving space, we discuss only the results presented during First Stars III, and direct interested readers to individual contributions for more in-depth information and citations to refereed papers. In addition, we have made a concerted effort to refer only to contributions in this pro-
ceedings, and do so by the last name of one of the authors (typically the first) of each contribution.

2. A PROPOSED NAMING CONVENTION FOR PRIMORDIAL AND METAL-POOR STARS

A significant point of confusion in the literature on Population III and low metallicity stars arises from the abundance of (often contradictory and/or confusing) naming conventions. Given that essentially all researchers involved in the field were present at First Stars III, a discussion of this subject took place and the following naming convention has been proposed:

Population III: This is a blanket term that describes all stars of primordial composition (i.e., gas whose composition was determined during Big Bang Nucleosynthesis and as a result is composed almost entirely of hydrogen and helium), regardless of how, when, or where they formed. It has been found that this term is too broad, and thus the need for the existence of “Population III.1” and “Population III.2” stars, as described below.

Population III.1: These are the true “first generation” stars of primordial composition, whose properties have been determined entirely by cosmological parameters and the process of cosmological structure formation, and have not been significantly affected by previous star formation. Examples of Population III.1 star formation are shown in contributions by Norman, Turk, and Yoshida.

Population III.2: These are “second generation” stars, which still have primordial composition. Their formation, however, has been significantly affected by previous generations of star formation through the injection of kinetic energy, photodissociating or ionizing radiation, by cosmic rays, or by other as-yet-unsuggested processes, which may change the mass range of these stars. Examples of Population III.2 star formation are discussed in contributions by Ahn, Bromm, Bryan, Johnson, McGreer, Sato, Norman, Umemura and Whalen.

Population II.5: This is the suggested term for a possible class of stars with non-zero metal content where the amount of metals in the gas that the stars are formed from would not be sufficient to affect the cooling properties of the gas and thus the formation of the stars, but would play a non-negligible role in the star’s main-sequence evolution. An example of this class of object (as discussed by Meynet) is a rapidly rotating, massive star with a metallicity of $\sim 10^{-6} Z_\odot$, which would have formed in a manner identical to a star of primordial composition, but would experience enhanced mass loss relative to a Pop III star of otherwise identical properties due to the small amount of metals in the star.

Population II: These are stars whose metal content exceeds the “critical metallicity” discussed by Bromm, Glover, Omukai, Shull, and B. Smith – namely, the metallicity where the enhanced cooling properties of metal-enriched gas affects the star formation process, possibly resulting in a different IMF.

3. FORMATION AND IMF OF STARS AT ZERO AND LOW METALLICITY

The ultimate goal of the theoretical and numerical work being performed by many investigators is to gain a fundamental understanding of the Initial Mass Function (IMF) of Population III (Pop III) stars. This is also true of research relating to star formation in the present-day universe – Population III star formation, however, is considered to be a more tractable problem, given the relative simplicity of the physics involved.

In the absence of observations of Population III stars, we must rely on theory and simulations. As discussed by Norman, both theory and simulations predict that the first stars were massive, with an average mass that is much greater than stars in the Milky Way. This is consistent with the absence of observed zero-metallicity stars at the present day. Simulations show that not all Population III stars form in exactly the same fashion, however, which suggests a broad spread of masses. In addition, there is no evidence for fragmentation in extremely high-resolution simulations of Population III star formation, even when theory suggests that there should be (though note that Umemura and Suwa displayed preliminary calculations that indicate fragmentation in an asymmetric runaway collapse of primordial gas).

Turk and Yoshida presented simulations of Population III.1 star formation using different methods. Yoshida used the Gadget-2 smoothed-particle hydrodynamics code, while Turk used the ENZO adaptive mesh refinement code. Both codes have been improved in the past few years with the addition of extended-precision arithmetic, particle splitting techniques (for SPH), updated chemistry, approximations for cooling that take into account the non-negligible optical depths at high densities, and modifications to the ideal gas law equation of state at extremely high density. These improvements allow both codes to simulate large ($\sim$ Mpc) volumes of the universe while at the same time following the collapse of gas to protostellar densities, with a current maximum density of $n_H \simeq 10^{21} \text{ cm}^{-3}$! These fundamentally different methods agree quite well to sub-parsec scales – there is no evidence for fragmentation in the collapsing primordial cloud cores, and the inferred accretion rates of gas flowing onto the evolving protostellar core are extremely high, peaking at $M \simeq 10^{-2} - 10^{-1} \text{ M}_\odot / \text{yr}$. At smaller scales, some differences are apparent in their
calculations. It is unclear, however, whether this is due to numerical issues or simply due to the use of different cosmological realizations.

Glover discussed issues relating to uncertainties in the 3-body molecular hydrogen formation reaction rates. At the temperatures relevant to Population III star formation ($T < 1000 \text{ K}$), theoretical calculations of these rates vary by $2 - 3$ orders of magnitude.

Theuns showed that Pop III star formation in warm dark matter may occur in a very different manner than in a CDM universe, possibly leading to filamentary fragmentation and the formation of intermediate-mass primordial stars. Freese presented results suggesting that if neutralinos comprise a significant fraction of dark matter, their annihilation could possibly overwhelm any cooling mechanism in high-density primordial gas, and may result in a “dark star” – a massive object powered by dark matter annihilation instead of nuclear fusion. Zhao and Xu both showed preliminary results from AMR simulations including the effects of magnetic fields and their production via the Biermann battery in cosmological simulations, which may have significant effects on the formation of Pop III stars at small mass and spatial scales.

An important issue with the presented simulations of Population III star formation is that they are fundamentally Courant-limited at high densities, so that the simulations inevitably grind to a halt as the collapse proceeds. In the absence of a means to avoid this (e.g., sink particles), understanding of the shutoff of accretion onto primordial protostars can only be obtained analytically. To this end, Tan presented analytic and semi-analytic calculations of the evolution of the inner regions of primordial halos that follow the growth and evolution of the protostar, formation of an accretion disk, and feedback from the evolving protostar and main-sequence Population III star. He showed that the effectiveness of feedback processes in halting accretion onto the star (and thus determining its final mass) depend on core rotation and on the rate of accretion of gas onto the disk. Estimates of accretion rates from high-resolution cosmological simulations suggest stars with masses of $60 - 400 \text{M}_{\odot}$, with the main-sequence stellar mass in the fiducial case being $\simeq 160 \text{M}_{\odot}$.

Some aspects of Population III.2 star formation were also discussed. Bromm (Greif et al.), Bryan, Yoshida, and McGreer presented results showing the formation of primordial stars in regions of pre-ionized gas, using two different methods. All agree that significant amounts of HD form in these regions, and result in a rapid cooling of gas down to the temperature of the CMB at the redshift of formation. This lower temperature directly translates into a reduced accretion rate onto the protostellar core, suggesting that the resulting Population III.2 stars will be less massive than their Pop III.1 counterparts.

Bromm (Greif et al.) also showed that the presence of a cosmic ray background can cause the formation of significant amounts of HD in high-density primordial gas, again lowering gas temperature to that of the CMB and reducing the accretion rate. This is not to say that all Population III.2 star-forming regions are characterized by reduced accretion rates: Norman showed results from simulations of Pop III stars forming in the presence of a molecular hydrogen photodissociating (Lyman-Werner) background, which results in higher overall halo temperatures and higher inferred accretion rates onto the protostellar core.

The transition between Population III and Population II star formation was discussed at length during the conference. Bromm (Greif et al.) suggested the existence of a “critical metallicity,” or $Z_{\text{crit}}$, where metal line cooling dominates over molecular hydrogen cooling at low temperature (and hence presumably where the stellar IMF will transition from being top-heavy to a Salpeter-type function with a significantly lower mean mass), at $10^{-4} < Z_{\text{crit}}/Z_{\odot} < 10^{-3}$. Glover and Shull both suggest that $Z_{\text{crit}}$ may depend strongly on environment. Omukai showed that dust is an extremely effective coolant compared to gas-phase metals, and that the presence of a small amount of dust can radically lower the critical metallicity. The degree with which this takes place depends strongly on the abundance, type and size of the dust grains, and is highly uncertain. B. Smith used highly-resolved adaptive mesh refinement calculations to examine the fragmentation of metal-enriched gas at small scales and observed that there is not a clear relationship between metallicity and fragmentation scale – rather, the fragment scale is determined by the density of the gas when it reaches the temperature of the CMB. In this way, higher-metallicity gas may reach the CMB temperature at lower densities than lower-metallicity gas, resulting in larger overall clumps. Jappsen performed SPH simulations of metal-enriched gas collapsing in an ionized halo. She showed that, for densities $n_{\text{H}} < 10^4 \text{cm}^{-3}$, the evolution of density and temperature are not changed by metallicity for $Z < 0.1 Z_{\odot}$, because $\text{H}_2$ is the dominant coolant rather than metal fine structure lines. In addition, she does not find evidence in her calculations for the “critical metallicity” threshold proposed by Bromm (Greif et al.) Clerk, however, used high-density SPH simulations to show that fragmentation can easily occur in the high-density, dust-dominated regime at metallicities at or below $Z = 10^{-5} Z_{\odot}$. 
4. SEARCHES FOR POPULATION III AND VERY LOW METALLICITY STARS AND OBSERVED ABUNDANCE PATTERNS

4.1. The search for Population III stars

To date, no stars of primordial composition have been directly detected, either in our galaxy or in the distant universe. This may be because these stars are very massive and thus short-lived, or because surveys are looking in the wrong places. If these objects still exist, how can they be detected? And, have we already indirectly detected the traces of Population III stars?

If, as Tan suggests, Population III stars have masses of on the order of $100 - 400 \, M_\odot$, some of these stars may explode as pair instability supernovae (PISN), as described by Woosley. These objects would have unusual nucleosynthetic patterns, which have not yet been observed in abundance ratio measurements of galactic halo stars. This lack of evidence sets strong upper limits on the number of primordial stars in this mass range.

N. Smith presented observations of SN2006gy, a Type IIn supernova in NGC1260 (a S0/Sa galaxy located approximately 73 Mpc away). This was the brightest supernova known at the time of the conference, and the light curve and inferred expansion velocity are inconsistent with other Type II supernovae and cannot be explained by the interaction of a standard Type II supernova with a circumstellar medium. The observed light curve is consistent with results presented by Kasen showing theoretical predictions of pair production supernova model light curves and spectra, lending hope that Population III PISN exist. In principle, a pair instability supernovae at $z \sim 20$ would be bright enough at peak luminosity to be observable with JWST, though the time dilation of the light curve could make detection extremely difficult. This would be much less of a problem if, as suggested by Schneider, a non-negligible fraction of stars forming at $z \sim 3$ may be primordial. In addition, if a significant fraction of Population III stars are GRB progenitors (as suggested by Yoon), JWST followups of SWIFT-detected gamma ray bursts may yield direct observations of Population III supernovae. Another model for SN2006gy was presented by Woosley, a pulsational pair instability supernova of about $110 \, M_\odot$. In this scenario the supernova-like ejecta of subsequent pulses run into each other at large distance and convert their kinetic energy at almost 100% efficiency into radiation, making for a very bright display. Generally, the mass range for pulsational pair instability in non-rotation primordial composition (Pop III) stars is about $100 - 140 \, M_\odot$.

Examination of cosmic infrared background (CIB) fluctuations may yield indirect detections of Population III stars. Kashlinsky presented results from observations using the Spitzer Space Telescope, arguing that source-subtracted IRAC images contain significant CIB fluctuations that are in excess of the near-infrared background expected from resolved galaxy populations. These fluctuations appear to come from clustered sources that do not correlate with Hubble ACS source catalog maps of the same field. He claimed that this implies that the CIB fluctuations come from dim populations at high ($z > 8$) redshifts, with much lower mass-to-light ratios than current galaxies, and that have a projected number density of $5 - 10$ sources/arcsec$^2$ (within the confusion limit of present-day instruments, but resolvable by JWST), and claimed that this source population is high-redshift primordial stars. Thompson, on the other hand, claimed that the purported near-infrared background excess is due to improper modeling and subtraction of zodiacal light, and that the cosmic infrared background fluctuations detected by Kashlinsky are mainly due to low-redshift ($0.5 < z < 1.5$) galaxies and are inconsistent with galaxies at $z > 10$. Fernandez showed that metal-free stars are not the only possible source of the near-infrared background excess – her models predict that stars with metals can produce the same amount of diffuse radiation in the 1 - 2 micron band as primordial stars, because the average intensity in this waveband is determined by the efficiency of nuclear burning in stars, which is not very sensitive to metallicity.

4.2. The search for low metallicity stars

Metal-poor galactic halo stars are of great interest to the community that studies structure formation in the early universe for several reasons. Extremely metal-poor stars are possibly fossil records of the heavy element abundances produced in a single Population III supernova. The shape of the low-metallicity tail of the metallicity distribution function (MDF) has the potential to probe epochs of star formation in the early galaxy, and the change of the MDF with distance from the center of the galaxy may provide useful clues as to the assembly history of the Milky Way. In addition, the discovery of objects with enhancements of combinations of various $\alpha$-, s-, and r-process elements can probe rare events in the formation history of our galaxy. Ferrara and Salvadori, however, argue that almost no true “second generation” stars (objects that have been enriched by a single Population III supernova) should be observable at $z = 0$.

The discovery of metal-poor galactic halo stars and spectroscopic estimates of their elemental abundances has become a major industry in the past several years. The SDSS SEGUE project (as discussed by Beers) is already underway, and has discovered more than 2400 stars with $[\text{Fe/H}] < -2$ and dozens with $[\text{Fe/H}] < -3$. Over
the course of the project lifetime, SEGUE is projected to find roughly 20,000 stars with \([\text{Fe}/\text{H}] < -2\), and approximately 2000 with \([\text{Fe}/\text{H}] < -3\). The OZ Project (as summarized by Cohen) describes the discovery of more than 1500 candidate extremely metal poor stars from the Hamburg/ESO Survey, with some stars having extremely peculiar abundance ratios. The ESO LAMOST Survey and Southern Sky Survey (described by Christlieb), will begin production in the near future, will cover significantly larger areas of the sky than SEGUE (to a similar magnitude) and will, as a result, find thousands of stars with metallicities of \([\text{Fe}/\text{H}] < -3\) in the next few years.

Given the large number of extremely metal-poor stars that have been observed, and the even larger number of stars that should be found by surveys that are currently underway, a question arises – how much can we trust the elemental abundances measured in these stars? This is a crucial issue when one is interested in comparing the results from simulations (shown by Nomoto, Woosley, and others) with observationally-determined stellar abundances. Sneden discussed some aspects of this important issue, and demonstrated that correct measurement of abundances depends strongly on accurate determination of the star’s effective surface temperature, and that abundances derived from a small number of strong lines may be unreliable. In addition, laboratory data on transition probabilities of alpha elements is often contradictory or completely lacking, and that more accurate measurement of the properties of iron-peak elements is necessary in order to accurately interpret abundance data. Venn suggests that stars with the lowest [Fe/H] abundances (that have [Fe/H] < -5), which seem to be chemically peculiar, may actually appear to be that way due to dust-gas separation. If this is true, stars with \(-4 < \text{[Fe/H]} < -3\) may actually sample metal enrichment from single Population III stars. She also suggests searching nearby dwarf galaxies for single pollution event stars in addition to the halo of our galaxy.

### 4.3. Observed abundance patterns in low-metallicity stars

Much can be inferred from the observed abundance patterns of extremely metal-poor galactic halo stars, though the concerns discussed in the previous section must be kept in mind when interpreting these results.

Frebel presented an update on the abundance of HE 1327-2326 using spectra from the VLT, confirming its extremely low iron abundance and carbon enhancement \([\text{Fe}/\text{H}] = -5.7\) or \(-5.5\), depending on assumptions, and \([\text{Fe}/\text{H}] < -5.4\), and \([\text{C}/\text{Fe}]_{\text{LTE}} = 3.28\) using a 3D model atmosphere correction. This work was elaborated upon by Korn, who showed that HE 1327-2326 is a subgiant and not a main-sequence star, and that atomic diffusion may have significantly altered the surface abundances of the star (though not enough to fully explain the puzzling non-detection of lithium). Frebel also presented work using observations of carbon and oxygen-enhanced metal poor stars to examine necessary conditions for forming low-mass stars in the early universe through cooling via fine-structure lines, and showed evidence for a “transition metallicity” where the sum of the carbon and oxygen abundance is approximately \(10^{-3.5}\) the sum of the solar abundances for these elements, which supports the Bromm idea of a “critical metallicity.”

Johnson argued that carbon-enhanced metal poor (CEMP) stars are created by the pollution of a low-mass star by a companion asymptotic giant branch (AGB) star. She suggested that the observed [C/N] ratios imply that a large number of primordial stars with masses of \(2 - 3 \, M_\odot\) were created. This result was supported by Schuler, who presented observations of fluorine in a CEMP halo star. AGB stars are believed to be prodigious producers of both carbon and fluorine, suggesting that AGB stars may be the source of the observed abundance patterns in at least some CEMP stars. Both of these observational results are supplemented by Pols, who presented simulations of binary stellar evolution showing that the observed CEMP abundance ratios can be explained by binary pollution from AGB stars, and that thermohaline mixing is important in the metal-poor companion star, and by Husti, who presents similar results. This latter effect is examined in more detail by Bisterzo, who presented numerical experiments detailing the effects of thermohaline mixing on nucleosynthetic yields resulting from neutron-capture nucleosynthesis. These calculations show that the yields for CEMP stars can be well-matched when thermohaline mixing is included. Lucatello showed results from the HERES survey suggesting that there are different classes of CEMP stars, based on the presence or absence of r- and s-process elements. These stars might be enriched by different types of stars, or via different mechanisms, and the monitoring of stellar radial velocities may give some clues to their different origins. Rossi showed that estimates of carbon abundances in CEMPs may be affected by calibration problems, and presented a set of refined estimates of carbon abundances for a large sample of CEMPs.

de Mink presented results from binary evolution at low metallicity. She showed that binaries at low metallicity experience mass transfer in a very different way than solar-metallicity stars do, which may have implications for the metallicity dependence of the formation rate of various objects through binary evolution channels. She also showed that low-metallicity binaries can experience much higher rates of accretion before reaching a given size compared to solar-metallicity stars, suggesting that fewer low-metallicity binaries come into contact (and...
Masseron presented results from the high-resolution chemical analysis of a large sample of CEMP stars, and showed that these stars naturally split into two groups: stars enriched only in s-process elements, and those enriched by both r- and s-process elements. The former group is well explained by AGB mass transfer, and Masseron suggests that the latter type of star can be explained by a primordial companion with a mass of $8 - 10 M_\odot$. Tumlinson argued that the two observed hyper metal poor stars were most likely formed in mass-transfer binaries with a top-heavy IMF, and that the high frequency of CEMP stars at $[\text{Fe/H}] < -2$, and gradients with metallicity and location, suggest that the CMB sets the typical mass of early Pop II stars independent of metallicity. Komiyama also suggested that the IMF of extremely metal-poor stars is top heavy, and that this is consistent with the observed metallicity distribution function in metal-poor halo stars.

Sobeck presented results from a study of copper abundances in 50 metal-poor halo stars using the VLT UVES spectrograph. There appears to be a deficit of copper in these stars, implying the reduced extent of weak s-process in massive stars at low $[\text{Fe/H}]$ or the delayed production from Type Ia supernovae. Boesgaard discussed beryllium abundances in a sample of 51 metal-poor halo dwarf stars that have been examined at high resolution and signal-to-noise using the Keck HIRES and Subaru HDS spectrographs. There is no evidence for a beryllium “plateau” – rather, $[\text{Be/Fe}]$ remains constant with changing $[\text{Fe/H}]$ – and also no evidence for a difference in Be vs. $[\text{O/Fe}]$ in stars that are found in the halo versus those observed in the thick galactic disk, contrary to previous lower-resolution work.

Cowan presented results from HST and ground-based studies of galactic halo stars, and argued that at the time these stars formed the galaxy was chemically unmixed and inhomogeneous in r-process elements, but not in $\alpha$-elements, and suggests different environments for the synthesis of these elements. There is evidence for increasing contribution of the s-process with metallicity (and thus galactic age). Krugler presented results from autoMOOG analysis of over 6500 stars from SDSS-I and SEGUE that have estimated metallicities of $[\text{Fe/H}] < -2$ and effective temperatures of $4500 K < T_{\text{eff}} < 7000 K$. This technique produces estimates of $[\text{Fe/H}]$ and $[\text{Ce/Fe}]$ (or upper limits on these quantities). Roederer derived isotopic fractions of europium, samarium and neodymium in two metal-poor giants with apparently different nucleosynthetic histories, extending the examination of the neutron-capture origin of multiple rare-earth elements in metal poor stars to the isotopic level for the first time. The results suggest an r-process origin for the rare earth elements in one of the stars, and cannot distinguish between an r- or s-process origin in the other star. This is an important step, however, towards being able to compare nucleosynthetic predictions for the s- and r-process using this technique.

Lithium is an element of great cosmological significance. There are two stable isotopes – $^6\text{Li}$ and $^7\text{Li}$ – with $^7\text{Li}$ being formed during the epoch of Big Bang Nucleosynthesis (BBN), but not $^6\text{Li}$. There is an apparent discrepancy between the measured amounts of $^7\text{Li}$ and the predicted amounts based on recent determinations of the baryon-to-photon ratio, with the observed amount of $^7\text{Li}$ being too low. Asplund pointed out that there are actually two cosmological lithium problems – the observed abundance of $^7\text{Li}$ is inconsistent with predictions from standard BBN, and $^6\text{Li}$ is apparently inconsistent with galactic cosmic ray production. He suggests a range of possible mechanisms to cause these inconsistencies, but cautions that they state inconsistencies are based on extremely challenging observations and analysis, and should be taken with a grain of salt. Perez presented observations of two metal-poor stars suggesting isotopic abundance ratios of $^6\text{Li}/^7\text{Li} \approx 0.04 - 0.05$. In one case this is similar to results found in the literature for the same star, and in the other case her derived value is significantly higher. Perez suggested that the derived abundance ratio is extremely sensitive to parameters used in the analysis. Sbordone also found this sensitivity, and showed that effective temperature scales for extremely low metallicity stars are still poorly calibrated, leading to inaccurate determination of lithium isotopic abundance ratios.

5. STELLAR EVOLUTION, EXPLOSIONS AND NUCLEOSYNTHESIS AT ZERO AND VERY LOW METALLICITIES

5.1. Stellar Evolution and Explosions at Very Low Metallicities

In his review talk, Woosley made several points. He claims that the known abundances in low metallicity stars can be fit by “ordinary” supernovae in the $10 - 100 M_\odot$ range, and that there is no need for hypernovae or pair instability supernovae. He argues that the favored Pop III stellar masses based on nucleosynthetic predictions are $10 - 20 M_\odot$, with explosion energies of roughly $10^{51}$ ergs, and little mixing. He also suggested that metal-deficient stars will produce many more black holes than their metal-rich counterparts, with masses as high as $40 M_\odot$. Finally, he argued that the pulsational pair instability can give a wide range of light curves, from faintest to the brightest observed supernovae. Yoon presented some results based on simulations of massive stars at very low
metallicity, including rotation and binary interaction. He claims that the effects of rotation are particular important for the evolution of massive stars at low metallicity, and that a large fraction of these stars may produce GRBs or hypernovae with unique nucleosynthetic features. Additionally, he suggested that a significant fraction of massive stars may be Wolf-Rayet stars at very low metallicity, and that stars of this type in close binaries may also produce GRBs. Meynet also spoke about the evolution of Pop III and very metal poor stars, and stated that the effects of rotation on Pop III stars is significant, but less extreme than in very metal poor stars. He also suggested that a tiny amount of metals (on the order of $Z = 10^{-8}Z_\odot$) may make a big difference, and that rotation is a key parameter for very metal poor stars. Ekstrom argued that under certain conditions it may be possible for very massive primordial stars to avoid pair-instability supernovae with the help of two effects of rotation: anisotropic winds and magnetic fields. This will happen even with the assumption of reasonable initial equatorial velocities. Chiappini presented further results regarding the impact of stellar rotation on chemical enrichment at low metallicity, showing that fast stellar rotation at low metallicities is the only thing that can explain the observed abundances in metal-poor halo stars in the absence of AGB binary mass transfer. Lau presented simulation results from explosions of intermediate-mass, zero-metallicity stars, and showed that the stellar envelopes of these stars will be enriched by nitrogen, and that there is no $s$-process enrichment, owing to the lack of a third dredge-up. Gil-Pons presented results from simulations that examine the effects of overshooting in the evolution of intermediate-mass stars that agrees well with Lao’s result. Brott discussed the efficiency of rotational mixing in massive stars, and finds that while internal magnetic fields are necessary to understand angular momentum transport (and thus rotational behavior), the corresponding chemical mixing must be neglected in order to reproduce observations. She also showed that for low metallicity stars, detailed initial abundances are of primary importance, since solar-scaled abundances may result in significant calibration errors. Tsuruta presented results from simulations of the evolution of very massive ($500 M_\odot$ and $1000 M_\odot$) Population III stars, and finds that though these stars experience the pair instability, they eventually undergo core collapse and create black holes that, in the more massive star, may be up to $500 M_\odot$.

Pols presented theoretical results pertaining to carbon-enhanced metal-poor (CEMP) stars, arguing that these stars are in binary systems and have been polluted by a former AGB companion, and also suggesting that it is important to study nucleosynthesis together with binary evolution. Suda discussed the stellar evolution of low- and intermediate-mass extremely metal poor stars, and suggested that these stars may be responsible for CEMP stars. Ludwig discussed hydrodynamical model atmospheres of metal-poor stars, and showed that metal-poor stellar atmospheres are prone to exhibiting substantial deviations from radiative equilibrium. He also suggested that large abundance corrections may have to be made to take into account assumptions made in 1D atmosphere calculations. In addition, the three-dimensional effects on the effective atmospheric temperature from Balmer lines show a complex pattern, further complicating analysis. van Marle showed results from simulations of continuum-driven winds from primordial stars, and argued that continuum driving can produce strong mass loss from stars, even without metals. Krticka presented the possibility that hot Population III stars may experience significant mass loss if their atmospheres are enriched by CNO elements through metal line-driven winds, with a range of effects depending on the metallicity of the atmosphere. Mujeres presented results from simulations exploring the effect of clumping on predictions of mass-loss rate of early-type stars, and suggests that the difference between theoretically expected and empirically derived mass-loss rates may be due to inhomogeneities. She predicts that clumping leads to a higher mass-loss rate, with only modest clumping factors required to match observed values of mass-loss rates in massive stars. Onifer showed attempts to calculate the mass-loss rate of a Population III Wolf-Rayet star using a modified version of the CAK approximation. He showed that even a star with zero initial metallicity will experience significant mass loss due to radiation pressure on dredged-up nucleosynthetic products.

Church presented multidimensional simulations of primordial supernovae, which investigate the effects of Rayleigh-Taylor-induced mixing and asymmetries in the explosion on the final composition of the escaped gas. She finds that for spherically-symmetric explosions, mixing has little effect on the shells interior to oxygen, and that some asymmetry is needed in the explosion in order for elements interior to oxygen to escape from the star. Nozawa showed the evolution of dust grains that formed in Population III supernovae, and argued that dust grain size and composition strongly affects their evolution. He also demonstrated that small grains are preferentially destroyed in primordial supernova remnants, with the maximum destruction mass varying as a function of the ambient medium properties.

5.2. Nucleosynthesis at Zero and Very Low Metallicities

Qian presented a review of nucleosynthesis of metal-free and metal-poor stars. In his talk, he made several
points; he suggested that the origin of $^6$Li in low metallicity stars is still a puzzle; that the presence of nitrogen in low metallicity stars indicates rotation; and that the presence of lead in metal-poor binary members indicates that the s-process occurs at low metallicity. He also argued that the observed abundances in metal-poor galactic halo stars suggest standard supernovae rather than pair-instability supernovae, but that there are contributions from both hypernovae and faint supernovae. Nomoto discussed nucleosynthesis in massive Population III stars, focusing on hypernovae and jet-induced explosions. He showed that explosions with large energy deposition rates will create gamma ray bursts with hypernovae and that their yields can explain the abundances of normal extremely metal-poor stars, and that explosions with small energy deposition rates will be observed as GRBs without a bright supernova, and can be responsible for the formation of CEMP and hyper metal poor stars. Kratz (Farouqi et al.) presented results exploring nucleosynthesis modes in the high-entropy-wind scenario of Type II supernovae, and showed that a superposition of several entropy components can reproduce the overall solar system isotopic r-process residuals, as well as the more recent observations of elemental abundances of metal-poor, r-process-rich halo stars. Pignatari presented results of simulations examining the weak s-process at low metallicity, and showed that the s-process efficiency changes significantly as a function of both stellar mass and metallicity.

Woodward and Herwig (combined proceedings) discussed nucleosynthesis and mixing in the first generation of low- and intermediate-mass stars, with a focus on studying entrainment at convective boundaries. They point out that one feature of stars at zero and low metallicity is that convective-reactive mixing events are common, which is not true in stars of higher metallicity. They show that 1D models have difficulty simulating these evolutionary phases and the mixing that comes from them, and show 2D and 3D simulations of this process. Cristallo presented work on the evolution and nucleosynthesis of low-mass metal-poor AGB models with carbon- and nitrogen-enhanced opacities (to address observed carbon and nitrogen-rich metal poor stars), and shows that the new opacities can cause significant changes in the chemical and physical evolution of the stars, and may cause non-negligible changes in the amount of carbon, nitrogen, and s-process elements created. Campbell discussed the structural and nucleosynthetic evolution of metal-poor and metal-free low and intermediate-mass stars from ZAMS to the end of the AGB phase, and showed that many of these stars experience violent evolutionary episodes that are not seen at higher metallicities. These episodes may be coupled with strong mixing, causing surface pollution. Surman presented simulations results of nucleosynthesis in outflows from Kerr black hole accretion disks. She suggests that these accretion disks may be important contributors to the nuclear abundances in the oldest stars, particularly for rare species or those not uniformly observed.

6. EARLY FEEDBACK PROCESSES: INFLUENCE ON STRUCTURE FORMATION, REIONIZATION, AND IGM ABUNDANCE PATTERNS

The first generations of stars are potentially prodigious sources of mechanical, chemical, and radiative feedback, and may contribute significantly to the enrichment and reionization of the intergalactic medium. Reed showed that high-redshift halos are strongly biased, particularly at small scales – this effect differs from low-redshift bias, and is a function of mass. The clustering observed will significantly affect the statistical properties of feedback at high redshifts. Ciardi argued that feedback from Population III stars is generally not as efficient as one might expect from energetics estimates, and that objects with masses of $M > 10^{7-8} M_\odot$ are not greatly affected by feedback. Wise presented AMR simulations modeling the formation of a significant number of Pop III stars in a single volume, and showed that dynamical feedback from HII regions and supernovae can expel most of the gas in first-generation halos and lead to low baryon fractions in subsequent star-forming halos. In addition, he showed that metals are well-mixed within dwarf galaxies, and that ejecta from Pop III supernovae will provide a maximum metallicity of $\sim 10^{-4} Z_\odot$. Greif presented an SPH calculation of a Pop III pair-instability supernova expanding into a HII region formed by the progenitor star, and found similar results – the supernova completely disrupts the host halo and expands out to a significant fraction of the size of the HII region, ultimately polluting $\sim 2.5 \times 10^5 M_\odot$ of gas with metals. Nagakura presented 1D, spherically-symmetric simulations of the evolution of supernova remnants in the early universe, paying particular attention to the thermal and chemical evolution of the expanding dense shell of gas. He showed that at high redshift, regardless of metallicity, the minimum temperature of dense gas in the supernova remnant is limited by the CMB temperature, suggesting that fragmentation of the shell depends more critically on the density of the ambient medium and the supernova energy than on the metallicity of the gas. Nozawa discussed dust evolution in Pop III supernova remnants, and showed that the transport of dust within the evolving SNR depends strongly on the size and composition of the dust grains, and that small dust grains are preferentially destroyed in the remnant evolution. Additionally, dust can be strongly segregated from metal-rich gas, possibly explaining the
abundance patterns of iron, magnesium and silicon in the lowest metallicity stars (assuming they were formed in the shells of Pop III supernova remnants).

Whalen presented 2D radiation hydrodynamical simulations of the photoevaporation of minihalos by neighboring Population III stars, and demonstrated that, when appropriate physics and coordinate geometries are used, feedback from the I-fronts of neighboring halos will largely be positive or neutral, and that the impinging radiation drives primordial chemistry that is key to the hydrodynamics of the halo, making multifrequency radiation transport necessary. Umemura and Sato confirmed this result with 3D SPH simulations including multigroup radiation transport, and additionally suggested that the shielding due to H2 created in the ionization front may allow the formation of multiple stars in a single halo. In contrast, Ahn presented work using a 1D Lagrangian radiation transport code that suggests that the result of an impinging I-front will be roughly neutral. Bryan and McGreer showed that HD cooling can play an important role in low-mass non-pre-ionized halos, reducing accretion rates onto the protostellar cloud core. Johnson (Greif et al.) showed that primordial stars forming in relic HII regions would likely be protected from radiative feedback from neighboring halos due to the large amounts of molecular hydrogen that form even at low densities due to the high residual electron fraction.

Schneider presented a set of cosmological simulations of 5 – 10Mpc boxes that include a metallicity-dependent star formation and feedback algorithm algorithm. These simulations indicate that, due to inefficient metal enrichment, Population III star formation may continue up to z ~ 2.5 in pockets of primordial gas. The sites where Pop III stars form also change over time, moving from the centers of halos (at high redshifts) to the outskirts (at low redshifts). In addition, she suggested that only 1% of metal-enriched gas has been polluted purely by Population III supernovae, making nucleosynthetic signatures hard to identify. Pieri performed simulations of comparable volumes that also take into account photoionization suppression of halo collapse. He finds that radiative feedback has a strong impact on mechanical feedback, and reduces metal enrichment at essentially all overdensities.

Ricotti demonstrated that an X-ray background from massive Population III supernovae, supernova remnants, and from accretion onto intermediate-mass black holes may be an important source of ionization in the IGM, and that the topology of this reionization will be “outside-in,” with voids being ionized first. In addition, redshifted X-rays will contribute to HI and HeII reionization in the low-density IGM. Ferrara presented a model for reionization that includes effects from Pop III stars, Pop II stars, and AGN. This model predicts that reionization started at z ~ 20 by Population II stars and was 90% complete by z = 7, and that quasars dominate only reionization at z < 6. Additionally, the model predicts that more than 80% of ionizing photons responsible for reionization were produced at z ≥ 7 from halos with M < 10^9 M_☉, implying that the bulk of the reionization sources at high z have not yet been observed. This model is consistent with the high-redshift QSO absorption line measurements presented by Fan and with several other sets of observations, including the observed number of Lyman-alpha emitters and damped Lyman-alpha systems. Trac and Shin presented results from large volume, high-resolution dark matter-only simulations that have been post-processed to model the effects of radiative feedback from Population III and metal-enriched stars, and found results that are also in good agreement with Fan’s observations of the Gunn-Peterson trough in high-redshift quasar absorption lines, and are also consistent with the most recent WMAP electron optical depth measurements. Iocco presented results showing that Pop III stars will produce a diffuse high-energy neutrino background – the strength of this background, however, will fall below detectable thresholds for all current and planned neutrino telescopes even with highly optimistic assumptions, ruling out the neutrino background as a useful diagnostic tool for metal-free stars. This was confirmed by Suwa, who also estimated gravitational wave emission from the collapse of isolated Population III stars, and suggested that the gravitational wave background from these objects could be detectable by future gravitational wave interferometers such as BBO or DE-CIGO.

7. COMPACT OBJECTS AT HIGH REDSHIFT

7.1. Gamma-Ray Bursts and Quasars

Rockefeller showed three-dimensional simulations of the collapse of a massive Population III star, demonstrating that it is possible to create a rapidly-accreting disk of gas around the central black hole, which can then eject significant amounts of the stellar envelope. Li used these simulations as initial conditions for a three-dimensional MHD calculation of the collapsing stellar core, showing that the star’s magnetic energy can drive an outgoing shock, which leads to an explosion. In addition, the magnetic energy is primarily in “bubbles” of gas that are dominated by magnetic energy, and tend to evolve in a very inhomogeneous (and collimated) fashion. This has profound implications for Population III stars as gamma ray burst progenitors, and also for nucleosynthesis.

High-redshift gamma ray bursts have proven to be extremely useful tools for probing the ISM and IGM. Chen discussed using spectroscopy of gamma-ray burst after-
glooms to perform direct, detailed studies of the ISM in the star-forming regions of distant galaxies, which is impossible with quasars. A large sample of GRB sightlines, coupled with moderate resolution afterglow spectra and imaging of the host galaxies, will be key tools for understanding the properties of the ISM in high-redshift galaxies. Penprase showed more results related to GRB afterglows, including highly detailed estimates of the properties of star-forming regions in damped Lyman-alpha systems, and demonstrated the promise of GRBs as probes of star-forming regions in high-redshift galaxies. Yonetoku showed a strong correlation between the spectral peak energy of prompt GRBs and the peak luminosity, and used this to estimate the possible redshifts for hundreds of BATSE GRBs of unknown redshift. This analysis predicts that a large number of massive stars were formed in the early universe, assuming Pop III stars form GRBs.

Quasar absorption line studies are complementary tools to the examination of GRB afterglows, in that they are very useful probes of the IGM at high redshift. At present, measuring the Gunn-Peterson trough in QSO absorption line spectra is one of the primary methods of constraining the end of the epoch of reionization. This was shown by Fan, who demonstrated that the evolution of the ionization state of the IGM experienced a very rapid change at $z \sim 6$, increasing by an order of magnitude in $\Delta z \sim 0.5$. This implies that $z \sim 6$ marks the end of the stage of inhomogeneous, overlapping bubbles of reionizing photons. There is also evidence that $z \sim 6$ quasars are quite old, suggesting a great deal of black hole buildup and chemical enrichment at high redshift. In addition, there are far too few quasars at $z \geq 6$ to contribute significantly to reionization, suggesting that, unless the high-redshift QSO luminosity function is very steep, the dominant source of ionizing photons in the high-redshift universe is stellar populations.

### 7.2. Supermassive black hole progenitors

Can Population III stars be supermassive black hole progenitors? There are many examples of $z \sim 6$ quasars, which are believed to be black holes with masses $M_{\text{BH}} \geq 10^6 M_\odot$ sitting at the centers of massive galaxies. Trenti argued that these are extremely rare objects (one per $\sim 0.5$ Gpc$^3$ at $z = 6$), and that rare, extremely high redshift ($z \sim 40 - 50$) black hole seeds can be QSO progenitors. Alvarez, on the other hand, argued that high-redshift black holes form in halos where the progenitor star has expelled the majority of the surrounding gas, initially suppressing accretion. After gas collects in the halo again, there will be strong self-regulation of accretion by radiative feedback. As a result, black holes formed from Pop III stars will not accrete rapidly enough to be SMBH progenitors (this also has implications for the X-ray ionization scenario discussed by Ricotti).

Begelman suggested that it may be possible to form extremely massive “quasistars” by the direct collapse of gas in cosmological halos, without a stellar precursor. The required precursor object could be generated by the formation of halos with $T_{\text{vir}} > 10^4$ K, or possibly in the aftermath of a large halo merger. These objects would be radiation-dominated, and would feature the formation of a central black hole, which then becomes a source of energy that would create a convective envelope. This object could cool via thermal neutrinos, allowing it to accrete at the Eddington limit of the envelope, rather than the black hole itself. This “quasistar” would have a low effective surface temperature ($T_{\text{eff}} \sim 4000$ K), would have a lifetime on the order of $10^6$ years, and could potentially be observed by JWST.

Colgate argued that supermassive black holes form naturally as a result of cosmological structure formation – high-entropy gas creates $\sim 10^5 M_\odot$ stars, which collapse due to relativistic instabilities and become the central point of a massive accretion disk, which can then channel gas into the black hole at super-Eddington rates, using a combination of self-gravity instabilities and Rossby vortices to efficiently transport angular momentum outward.

### 8. SUMMARY

The properties of the first generations of stars, as well as their effects on later epochs of cosmological structure formation, have long been a topic of great interest to the astrophysical community. Progress in understanding these objects has been significant and rapidly accelerating in the past few years, and many insights have been obtained by theory and by large-scale numerical computations. Progress has also been made observationally, in a wide variety of settings, and many significant questions have been raised. The impressive array of new facilities and surveys that are currently running or are planned for the next few years, together with increasingly powerful simulations, should yield crucial new insights into the earliest epochs of star formation in the universe.

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