FORMING A PRIMORDIAL STAR IN A RELIC H II REGION

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ABSTRACT

There has been considerable theoretical debate over whether photoionization and supernova feedback from the first Population III stars facilitate or suppress the formation of the next generation of stars. We present results from an Eulerian adaptive mesh refinement simulation demonstrating the formation of a primordial star within a region ionized by an earlier nearby star. Despite the higher temperatures of the ionized gas and its flow out of the dark matter potential wells, this second star formed within 23 million years of its neighbor’s death. The enhanced electron fraction within the H II region catalyzes rapid molecular hydrogen formation that leads to faster cooling in the subsequent star-forming halos than in the first halos. This “second generation” primordial protostar has a much lower accretion rate because, unlike the first protostar, it forms in a rotationally supported disk of \(\sim 10–100 \, M_\odot\). This is primarily due to the much higher angular momentum of the halo in which the second star forms. In contrast to previously published scenarios, such configurations may allow binaries or multiple systems of lower mass stars to form. These first high-resolution calculations offer insight into the impact of feedback upon subsequent populations of stars and clearly demonstrate how primordial chemistry promotes the formation of subsequent generations of stars even in the presence of the entropy injected by the first stars into the intergalactic medium.

Subject headings: cosmology: theory — hydrodynamics — stars: formation

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1. MOTIVATION

Calculations performed by Abel et al. (2002, hereafter ABN02) show that rapid accretion rates driven by molecular hydrogen cooling cause the formation of solitary massive protostars in the range of \(30–300 \, M_\odot\) in minihalos of \(10^5–10^6 \, M_\odot\) at redshifts \(\geq 20\). Simulations indicate that the hard UV spectra of these \(10^5 \, K\) zero-metallicity stars will envelop them in large H II regions several kiloparsecs in diameter (Whalen et al. 2004; Kitayama et al. 2004). Over the main-sequence lifetime of the central star (on the order of 2–6 Myr for the range 30–300 \(M_\odot\)), half of the baryons within the minihalo are driven beyond its virial radius by ionized flows that quickly steepen into shocks. These shocks exhibit expansion rates of up to 10 times the escape velocity of the halo. After the death of the central star, cooling and recombination are out of equilibrium in the ionized gas, which results in significant electron fractions even after its temperature has dropped to 1000–2000 K after 20–50 Myr. One-dimensional, nonrotating calculations (Heger et al. 2003) predict two possible fates for the primordial stars themselves: complete destruction by the pair instability (140 \(M_\odot\) \(< M_\star \leq 260 \, M_\odot\)), which is very energetic and leaves no remnant, or direct collapse to black holes above and below this mass range, with the added possibility of supernova-like precollapse mass ejections by pulsational pair instabilities from these \(10^5 \, K\) zero-metallicity stars (Heger & Woosley 2002).

An important question is whether later generations of stars can efficiently form in the relatively high temperatures and ionization fractions of the relic H II regions left by the first stars. One analytical study (Oh & Haiman 2003) found that the first stars injected sufficient entropy into the early intergalactic medium by photoheating and supernova explosions to prevent further local star formation in their vicinity. Lyman-Werner soft UV background radiation is also thought to have contributed negative feedback by photodissociating primordial HII and quenching the molecular hydrogen cooling processes that allow the first stars to form (Haiman et al. 2000; Machacek et al. 2001). In this Letter, we present fully resolved simulations that show a second primordial star can form in the relic H II region of an earlier Population III star. We determine its properties, considering the effect of Lyman-Werner radiation from the resultant black hole and assuming accretion rates consistent with the density fields left by ionized outflows from the parent minihalo.

2. SIMULATION SETUP

We carried out simulations using Enzo, a publicly available Eulerian adaptive mesh refinement hydrodynamics and \(N\)-body code (Bryan & Norman 2000; O’Shea et al. 2005).\(^2\) We initialized a box of size \(300 \, h^{-1} \, \text{kpc}\) at \(z = 99\) for a cosmology with \((\Omega_m, \Omega_{\Lambda}, h, \sigma_8, n) = (0.3, 0.7, 0.04, 0.7, 0.9, 1)\). We first ran a simulation with 128\(^3\) dark matter particles in a 128\(^3\) root grid with six total levels of adaptive mesh, refinining on a dark matter overdensity of 4.0. This model was run with dark matter alone in order to identify the most massive halo that evolves in the simulation volume, which at \(z \sim 18\) had a mass \(\sim 5 \times 10^9 \, M_\odot\).

We then reinitialized the calculation in the original simulation volume at \(z = 99\) with both baryons and dark matter, using a 128\(^3\) root grid and three static nested subgrids, each of which was twice as refined as its parent grid and was centered on the Lagrangian volume of the peak that later evolved into the iden-
tified halo. The effective root-grid resolution was 1024$^3$ in this volume, which corresponds to a comoving spatial resolution of $\sim 300$ $h^{-1}$ pc and a dark matter particle mass of $1.8$ $h^{-1} M_{\odot}$ in the most highly refined region. Every dark matter particle that later enters into dark matter halos of interest was within this most highly refined grid at the start of the simulation.

We started the simulation with this set of initial conditions at $z = 99$ and followed the collapse of the first star, which occurred at a redshift of 17.76. As refinement criteria we used a baryon overdensity of 4.0 and a dark matter overdensity of 8.0. In addition, to ensure appropriate simulation resolution we mandated that the Jeans length must be resolved by at least 16 cells at all times, which exceeds the Truelove criterion by a factor of 4 along each axis (Truelove et al. 1998). At the collapse redshift, the three-dimensional structure was resolved with 8727 grids on nine levels containing a total of 49,641,744 unique resolution elements.

To compute the extent of the H$^\text{ii}$ region of the 120 $M_{\odot}$ Population III star assumed to form in the collapse, we interpolated the density, energy, and velocity fields from the entire Enzo simulation volume at the formation redshift of this star onto a three-dimensional grid of fixed resolution with 256$^3$ cells for import into a static radiative transfer code. The code utilizes the ionization-front tracking technique of Abel (2000) to calculate the boundary of the H$^\text{ii}$ region along rays cast outward from the central star by the adaptive ray-tracing technique of Abel & Wandelt (2002). Within the H$^\text{ii}$ region, we set the ionization fraction to unity and the H$_2$ and H$^+$ fractions to zero. We assume that the mean energy of ionization for the gas is 2.4 eV, which results in a post-ionization temperature of $\sim 18,000$ K when calculated in our multispecies ZEUS simulations (Whalen et al. 2004). This is somewhat cooler than one might expect from the relatively hard spectrum of massive primordial stars and is a result of our use of monochromatic radiative transfer in the ZEUS code, which underestimates the UV photoheating of the halo by not taking into account contributions from very high energy photons. Whalen et al. show that an increase in postfront temperatures results in somewhat higher sound speeds. These yield higher shock speeds that promote the photoevaporative flow of gas from the halo in which the first star is formed and could in principle affect the dynamics of nearby halos. We show below that in this case the outflow of gas has a negligible effect on the formation of a second primordial star, which suggests that our result is, at worst, only weakly affected by postfront temperature. Higher postfront temperatures will not significantly retard the cooling and recombination crucial to the formation of molecular hydrogen.

We approximated the dynamics of the H$^\text{ii}$ region by imposing the one-dimensional velocity, ionization, density, and temperature profiles for a 120 $M_{\odot}$ star at the end of its main-sequence lifetime from Whalen et al. (2004) along every line of sight from the central star. We modified baryon densities and velocities out to $\sim 120$ pc (corresponding to the location of the shock wave in the one-dimensional calculation) but changed only ionization fractions and temperatures beyond this radius out to the boundary of the H$^\text{ii}$ region determined by the ray-tracing code. We then mapped this H$^\text{ii}$ region onto the full hierarchy of grids in the Enzo calculation, centering it on the location of the first protostar. This state corresponds to only 2.5 Myr after the initial star formed ($z = 17.4$), so we assume that instantaneous ionization is a reasonable approximation for all gas outside the first halo (which has had the hydro profiles from the one-dimensional simulations imposed in it). An important question is whether the satellite halos are also ionized by the ionization front propagating outward from the first star.

3. RESULTS

The second primordial protostar forms in a neighboring mini-halo approximately 265 proper parsecs from the location of the halo in which the first star formed (and where the H$^\text{ii}$ region originated). The halo in which this second protostar forms was completely ionized by the first star to a temperature of $\sim 10^4$ K. Because of its relatively high density, the center of this halo cools very rapidly, and molecular hydrogen formation is catalyzed by the extremely high electron fraction. After only a few million years, the core of the halo has a molecular hydrogen fraction of $5 \times 10^{-3}$, well above what one would expect for a halo that has not been ionized. This halo is significantly smaller than the first: $\sim 2 \times 10^5 M_{\odot}$ rather than $\sim 5 \times 10^5 M_{\odot}$.

3.1. Comparison of the First and Second Stars

Figure 1 compares the mass accretion times of the initial and second Population III stars formed in this simulation. In addition, this figure shows the mass accretion time of the halo in ABN02 and an estimate of the Kelvin-Helmholtz timescale as a function of mass, using values of luminosity and effective temperature taken from Schaerer (2002). The upper and lower dotted lines correspond to an object with constant accretion rates of $10^{-3}$ and $10^{-2} M_{\odot}$ yr$^{-1}$, respectively. Our calculation of accretion timescales for the initial protostar agrees well with that of ABN02. The fact that the two results are in good agreement even though the ABN02 calculations assumed a lower baryon fraction supports the analysis of Ripamonti & Abel (2004) showing that all mass scales in these calculations are set by molecular physics. Comparison of the accretion rates with the Kelvin-Helmholtz timescale provides an estimate of $\sim 200 M_{\odot}$ for the upper bound of the mass of the star. The accretion timescales suggest a reasonable lower bound of $\sim 80 M_{\odot}$, since this much gas will accrete in $10^5$ yr, an insufficient time for fusion to begin. In contrast, the accretion rate of the second protostar is over an order of magnitude lower. This is because the second protostar has a much more pronounced thick disk structure than the first protostar. The disk is rotationally supported past a radius of $\sim 0.01$ pc (corresponding to an enclosed mass of $\sim 10 M_{\odot}$), whereas the disk around the first star in the volume is not. Similar accretion
timescale arguments as before suggest a mass of $\sim 5$–20 $M_\odot$ for the second star, although accretion physics will ultimately determine the true mass, particularly given the presence of this more pronounced disk.

Examination of the net angular momentum of the two halos is illuminating. The angular momentum of a cosmological halo can be described by the dimensionless spin parameter $\lambda \equiv J [E^{1/2}/GM^{5/2}]$, where $J$ is angular momentum, $E$ is the total energy, $G$ is the gravitational constant, and $M$ is the halo angular momentum. This is roughly equivalent to the ratio of the angular momentum in the halo to the angular momentum needed for the halo to be completely rotationally supported (Padmanabhan 1993). Typical values of the spin parameter for cosmological halos are $\sim 0.02$–0.1, with a mean of $\lambda \approx 0.05$ (Barnes & Efstathiou 1987; Gardner 2001). We find that the halo in which the first primordial protostar forms has a spin parameter for the gas and dark matter of $(\lambda_{\text{gas}}, \lambda_{\text{dm}}) = (0.0275, 0.0363)$, which is slightly lower than the mean. The spin parameter of the second halo is $(\lambda_{\text{gas}}, \lambda_{\text{dm}}) = (0.1079, 0.1607)$, which is atypically high. Examination of the evolution of angular momentum in the gas of the halos as the two protostars form shows that the angular momentum distributions are different in the two clouds, and if angular momentum is conserved, one would expect to see a centrifugally supported disk that is approximately 4 times larger in the second halo.

3.2. Black Hole Accretion

Here we consider whether accretion onto a relic black hole could generate enough photodissociative radiation to inhibit H$_2$ formation in the second star’s halo. We assume Bondi-Hoyle accretion (Bondi & Hoyle 1944) for the 120 $M_\odot$ black hole that forms after the collapse of the first star to estimate the Lyman-Werner flux from its accretion. This rate depends on the mass of the accretor, as well as the local gas temperatures, densities, and relative velocities it encounters. To sample the local environment the black hole would traverse over the duration of the simulation, we followed the 40 dark matter particles closest to the first protostar (within $0.1$ proper parsecs) from the end of its main-sequence lifetime until the collapse of the second protostar. We tallied the cell quantities they crossed in order to compile the accretion-rate history each particle would have if it were the black hole. The histories for the 40 black hole proxies appear in Figure 2. The mass accretion rates grow from $10^{-11}$ to $10^{-8}$ $M_\odot$ yr$^{-1}$ for most of the tracer particles.

To estimate the effect of Lyman-Werner radiation from the black hole on molecular hydrogen formation in nearby halos, we assume a canonical 10% radiative efficiency for the accretion. The uppermost accretion curve yields $2.2 \times 10^{37} [M/(100 M_\odot)]$ ergs s$^{-1}$ ($\sim 4500 L_\odot$) for an upper limit to the total luminosity (which is much lower than the Eddington luminosity of this object, $1.5 \times 10^{40}$ ergs s$^{-1}$, or $\sim 4 \times 10^8 L_\odot$). Taking this to be a blackbody spectrum, the flux in the Lyman-Werner band (11.1–13.6 eV) reaching the second protostar is $\sim 1.6 \times 10^{-23} [M/(100 M_\odot)]$ ergs s$^{-1}$ cm$^{-2}$ Hz$^{-1}$, resulting in photodissociation rates that are significantly lower than the formation rates of molecular hydrogen there. The expulsion of gas by ionized flows from the first halo prevents higher accretion rates and greater Lyman-Werner fluxes. A star in this mass range may shed its envelope just prior to collapse, resulting in a smaller black hole and making the results discussed here an upper limit.

4. DISCUSSION

This first high-resolution three-dimensional simulation of the evolution of gas within a primordial H II region demonstrates the crucial role of H$_2$ chemistry driven by photoionization in
the formation of the next generation of stars. While this has been addressed in previous work (Ricotti et al. 2002), our simulations are the first with sufficient resolution to directly examine the formation of individual stars. Further investigation will be necessary to determine if the lower accretion rates leading to the smaller mass of the second star are a coincidental effect or are a consequence of the general trend of early star formation in halos preprocessed by 

leading to the smaller mass of the second star. One possible source of error lies in the method and assumptions determining whether the neighboring halos are photoionized. While our one-dimensional results indicate that these halos will be ionized, this issue merits further investigation with fully three-dimensional simulations. We further assume that this ionization occurred instantaneously and simply ionizes the gas outside of the initial halo without changing the total density or velocity profiles of nearby halos. Instantaneous ionization appears to be a reasonable approximation, since the sound-crossing time of all of the ionized halos is longer than the main-sequence lifetime of the parent star. Again, full three-dimensional radiation photoevaporation simulations will be necessary to determine whether the hydrodynamic evolution of these halos during the main-sequence lifetime of the parent star is unimportant.

We note that our H ii region enveloped roughly a dozen minihalos similar to the one that formed the second star. More calculations will be required to see if these too form stars. The evolution of the massive disk also merits examination to ascertain whether it breaks up into a multiple system or fully accretes to form a single star. The situation realized in our cosmological simulation may lead to objects with initial conditions similar to the cases studied by Saigo et al. (2004).

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mass second-generation stars or the possibility of binaries or multiple systems of primordial stars would have strong implications for the observability of such objects and their impact upon subsequent structure formation. Less massive stars might have different nucleosynthetic signatures than those of the pair-instability supernovae that may occur in the first generation of primordial stars. The immense size of early H ii regions could also make the scenario of primordial stars forming in a relic H ii region much more common than extremely massive stars forming in pristine halos. These two facts taken together may account for the lack of detection of the characteristic odd-even abundance pattern from pair-instability supernovae expected in observations of ultra–metal-poor halo stars (Umeda & Nomoto 2005 and references therein). How H ii regions from the first stars may regulate local star formation by suppressing the collapse of gas in local halos that have not reached relatively high densities also remains to be explored.

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