EARLY STRUCTURE FORMATION AND REIONIZATION IN A WARM DARK MATTER COSMOLOGY

NAOJI YOSHIDA, AARON SOKASIÀ, LARS HERNUQUIST, AND VOLKER SPRINGEL

Received 2003 March 28; accepted 2003 May 19; published 2003 June 2

ABSTRACT

We study the first structure formations in $\Lambda$-dominated universes using large cosmological $N$-body/smoothed particle hydrodynamics simulations. We consider a standard $\Lambda$ cold dark matter (CDM) model and a $\Lambda$ warm dark matter (WDM) model in which the mass of the dark matter particles is taken to be $m_\chi = 10$ keV. The linear power spectrum for the WDM model has a characteristic cutoff at a wavenumber $k = 200$ Mpc$^{-1}$, suppressing the formation of low-mass ($<10^8 M_\odot$) nonlinear objects early on. The absence of low-mass halos in the WDM model makes the formation of primordial gas clouds with molecular hydrogen very inefficient at high redshifts. The first star-forming gas clouds form at $z \approx 21$ in the WDM model, considerably later than in the CDM counterpart, and the abundance of these gas clouds differs by an order of magnitude between the two models. We carry out radiative transfer calculations by embedding massive Population III stars in the gas clouds. We show that the volume fraction of ionized gas rises up close to 100% by $z = 18$ in the CDM case, whereas that of the WDM model remains extremely small at a level of a few percent. Thus, the WDM model with $m_\chi = 10$ keV is strongly inconsistent with the high optical depth observed by the Wilkinson Microwave Anisotropy Probe satellite.

Subject headings: cosmology: theory — dark matter — early universe — stars: formation

1. INTRODUCTION

Popular cosmological models based on cold dark matter (CDM) predict that the first stars formed in low-mass ($\sim 10^5 M_\odot$) dark halos at redshifts $z \approx 20–30$ when the primordial gas condensed via cooling by hydrogen molecules (Abel, Bryan, & Norman 2002; Bromm, Coppi, & Larson 2002). Hierarchical structure formation eventually leads to the emergence of a population of early-generation stars (Yoshida et al. 2003), which may have at least partly reionized the universe soon after the end of the dark ages. The first-year Wilkinson Microwave Anisotropy Probe (WMAP) result of the measurement of cosmic microwave background (CMB) polarization implies a large optical depth of $\tau = 0.17 \pm 0.04$, indicating that reionization could have occurred as early as $z_{\text{reion}} \sim 17$ (Kogut et al. 2003). The theoretically predicted formation epoch of the first stars in CDM models thus appears plausible in light of the WMAP result and indicates that an early generation of stars may have contributed to reionization. On the other hand, from the theoretical point of view, it is intriguing and important to ask whether or not such an early-reionization epoch is compatible in detail with models other than CDM or even with CDM itself.

Warm dark matter (WDM) models predict exponential damping of the linear matter power spectrum on small length scales (Bardeen et al. 1986). The characteristic length scale is given by the free-streaming length of the WDM particle as $R_f = 0.31 (\Omega_\chi/0.3)^{1/3} (h/0.65)^{1/3} (m_\chi/\text{keV})^{-1.15} h^{-1} \text{ Mpc}$, where $m_\chi$ is the particle mass (Bode, Ostriker, & Turok 2001). Owing to the suppression of power on small scales, the abundance of low-mass halos in WDM models is considerably smaller than in CDM models, perhaps resulting in better agreement with the observed matter distribution on subgalactic scales (Bode et al. 2001). Various constraints have been placed on the mass $m_\chi$. Based on an analysis of the clustering properties of the Ly$\alpha$ forest, Narayanan et al. (2000) conclude that the lower limit on the mass is $m_\chi = 0.75$ keV. Dalal & Kochanek (2002) used lensing statistics and found that models with $m_\chi < 5$ keV are incompatible with the observed abundance of substructure in distant galaxies. Barkana, Haiman, & Ostriker (2001) concluded that models with $m_\chi < 1$ keV are likely to be ruled out, assuming the reionization redshift $z_{\text{reion}} \sim 6$. Reionization at an earlier epoch, as implied by the WMAP data, generically requires early structure formation and thus may place a more stringent constraint on the mass of dark matter $m_\chi \gtrsim 1$ keV (Somerville, Bullock, & Livio 2003).

In this Letter, we explore the formation of the first baryonic objects in a cosmological model in which dark matter is warm rather than cold. Since models with $m_\chi \approx 1$ keV appear to be inconsistent with an array of observations, we consider a model with $m_\chi = 10$ keV. Although the motivation from particle physics for elementary particles with such an intermediate mass is somewhat unclear (but see Kawasaki, Sugiyama, & Yanagida 1997), it is important to examine the effect of suppressing the linear power spectrum on early structure formation. We specifically study the formation of primordial gas clouds and of their host halos with dark masses $10^5–10^6 M_\odot$ in a $\Lambda$CDM universe and in a $\Lambda$WDM universe, and we compare the results for the two models. While the currently available observations do not directly probe structure in the redshift range that we consider here, future CMB polarization experiments will ultimately reveal how and when the universe was reionized (Kaplinghat et al. 2003) and thus will be able to distinguish the structure formation histories predicted by the two models.

2. THE $N$-BODY/SMOOTHED PARTICLE HYDRODYNAMICS SIMULATIONS

We use the parallel tree particle-mesh/smoothed particle hydrodynamics solver GADGET2 in its fully conservative entropy form (Springel & Hernquist 2002). We follow the non-equilibrium reactions of nine chemical species ($e^-, H, H^+, He, He^+, He_2^+, H_2, H_2^+$) using the reaction coefficients compiled by Abel et al. (1997). We use the cooling rate of Galli & Palla (1998) for molecular hydrogen. We study both CDM and WDM models with a matter density $\Omega_0 = 0.3$, a baryon density $\Omega_b = 0.04$, a cosmological constant $\Omega_\Lambda = 0.7$,
and an expansion rate at the present time of $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$. We set the index of the primordial power spectrum $n_s = 1$ and normalize the fluctuation amplitude by setting $\sigma_8 = 0.9$. We follow Bode et al. (2001, see their Appendix A) to set up the initial condition for the WDM model, assuming the dark matter mass $m_x = 10$ keV. In order to avoid spurious clumping in the initial particle setup (see Götz & Sommer-Larsen 2002), we use “glass” particle distributions. Further simulation details are given in Yoshida et al. (2003, hereafter Paper I). Both of the simulations employ $2 \times 324^3$ particles in a cosmological volume of 1 Mpc on a side. The mass per gas particle is then 160 $M_\odot$, whereas the mass of the dark matter simulation particles is 1040 $M_\odot$. In Paper I, we carried out numerical convergence tests using higher resolution simulations and concluded that the mass resolution adopted here is sufficient to follow the cooling and collapse of primordial gas within low-mass ($\sim 10^6 M_\odot$) halos.

3. RESULTS

Figure 1 shows the projected gas distribution at $z = 20$ for the two models. The bottom two panels show the distribution of dark matter halos in each simulation. The effect of the exponential cutoff in the initial power spectrum is evident in Figure 1; the gas distribution in the WDM model is much smoother than in the CDM case. Also, the abundance of low-mass halos crucial for the formation of primordial gas clouds is significantly reduced in the WDM model. We locate the dark matter halos by first running a friends-of-friends (FOF) group finder with the linking parameter $b = 0.164$. We discard halos that consist of fewer than 100 particles. We then use the SUBFIND algorithm (Springel et al. 2001) that identifies gravitationally self-bound sets of particles that are at a higher density than the smooth background. We carry out the latter step because, particularly in WDM models, filamentary structures tend to be identified as halos, and such objects often contain many gravitationally bound “subhalos” (Knebe et al. 2002). Using this two-step method, we can robustly identify gravitationally bound objects in our simulations. We compare the mass function of the dark halos in Figure 2. There we also show the abundance of all the subhalos identified in the simulation box as thin histograms. The mass function for the CDM simulation is well fitted by the Press-Schechter mass function (solid line), as found by Jang-Condell & Hernquist (2001). We compare this analytic mass function for the CDM model with the result of the WDM simulation (Fig. 2, right panel). The difference is nearly 2 orders of magnitude at a mass scale of $10^5 M_\odot$. Note, however, that the difference in the mass function between the two models becomes smaller on larger mass scales, confirming that the suppression of the linear power spectrum in the WDM model affects only small mass scales.

In Figure 3, we plot the number of gas clouds against redshift. We define groups of cold ($T < 500$ K), dense ($n_H > 500$ cm$^{-3}$) gas particles as “gas clouds.” In order to locate dense gas clumps, we again run an FOF group finder with $b = 0.05$ linked to gas particles. From each group, we discard gas particles that do not satisfy the above criteria. We then identify the group as a star-forming gas cloud if the cold gas mass exceeds $M_{\text{ Jeans}} = 3000 M_\odot$. The first gas cloud is identified in this manner at $z = 28$ in the CDM model, whereas it is much later (at $z = 21$) in the WDM model. The total number of gas clouds in the simulated volume differs by about an order of magnitude in the redshift range plotted. At $z = 17$, we identified 66 gas clouds in the CDM model, and there are only four gas clouds found in the WDM case. Note that the number of gas clouds does not represent the true abundance of the first stars because our simulations do not include all feedback processes from the first stars.

How does reionization by an early generation of stars proceed at high redshift in the two models? To address this question, we
carry out radiative transfer simulations for a specific model of star formation, as follows. The first stars formed out of a chemically pristine gas are likely to be very massive (Abel et al. 2002; Omukai & Palla 2003). As in Paper I, we assume that each gas cloud forms a single massive star, following the usual "one star per halo" assumption for "minihalos.” As our fiducial model, we set the mass of a Population III star to be 300 $M_\odot$ with a lifetime of 3 million years and also assume a constant photon escape fraction $f_{\text{esc}} = 1$. Although the high escape fraction might seem unrealistic, it may indeed be plausible because the gas in minihalos can be wholly ionized and photoevaporated by a single massive star assuming the gas distribution is reasonably smooth (Oh et al. 2001). We then run multisource radiative transfer simulations using the technique of Sokasian et al. (2003). Briefly, the code utilizes a postprocessed gas density field defined on a 200$^3$ grid by casting multiple rays from sources in an adaptive fashion. Photon absorption and recombination are computed along the rays, and each cell carries its own properties such as clumping factor and ionization fraction. The gas evolution between two adjacent outputs, most importantly recombination, is computed on a cell-by-cell basis using these quantities. Note that our ray-tracing simulations employ a one-step scheme (Sokasian, Abel, & Hernquist 2001) in which the gas density evolution due to radiative feedback is not taken into account. In order to mimic strong radiative feedback within H ii regions, we implemented a “volume exclusion effect” by disabling sources if they lie within already ionized regions. In practice, we turn on a source only if the ionization fraction of its surrounding gas is below 0.05. We compute the total volume filling factor of the ionized medium from the output of the ray-tracing simulation. Figure 4 shows the result for the two models. As more stars are formed, the filling factor rapidly increases close to 1.0 by $z = 18$ in the CDM model, causing complete reionization. On the other hand, due to the small number of sources, the ionized volume fraction in the WDM model remains extremely small, only up to 0.03 at $z = 18$.

4. SUMMARY AND DISCUSSION

The suppression of small-scale power in the WDM model has a significant impact on the formation of primordial gas clouds. Hierarchical growth of halos with mass $10^5$–$10^6 M_\odot$ is not seen in the WDM model, and gas cloud formation is nearly completely suppressed until halos with masses $\sim 10^7 M_\odot$ collapse at $z \sim 20$. The global star formation rate thus remains very small at $z > 17$ (see Fig. 3), regardless of the details of star formation. Our radiative transfer calculations show that reionization by early Population III stars is a very slow and inefficient process in the WDM model. To be compatible with the high optical depth observed by WMAP, the ionization fraction in the WDM model must increase rapidly at $z < 18$. As Sokasian et al. (2003) argue, the optical depth can be as high as $\tau \sim 0.15$ only if a large number of ionizing photons are
produced in (proto)galaxies at $z < 18$. Clearly the WDM model that we consider here is disfavored, if not ruled out, in light of the WMAP results. WDM models with $m_X \lesssim 1$ keV are likely to be ruled out as argued by Barkana et al. (2001) and Somerville et al. (2003), whereas models with $m_X = 100$ keV would be essentially indistinguishable from CDM models in the context of structure formation.

We now turn to the question of whether or not the CDM model is compatible with the observed high optical depth. Using the results of our ray-tracing calculation combined with that of Sokasian et al. (2003) for Population II sources, we compute $\tau_e$ as a function of redshift. We combine the contributions from the two modes of star formation in different redshift intervals assuming that the onset of Population II begins exclusively at $z < 18.5$ and that there are no Population III stars since then. While this is clearly an oversimplification, it provides a conservative estimate for the total optical depth. To this end, we rerun the $f_{esc} = 0.20$ model from Sokasian et al. (2003) with the initial condition that the intergalactic medium was fully reionized by $z \approx 18.5$ and was uniformly heated to a temperature of $1.5 \times 10^4$ K. Figure 5 shows $\tau_e$ for the CDM model computed in this manner. Note the slope of the curve decreases at $15 < z < 18$, reflecting the decline in the ionization fraction owing to recombinations at a time when the emissivity from Population II sources is still low. Population III stars in the CDM model give combinations at a time when the emissivity from Population II dominates, giving a total of $\Delta \tau \sim 0.14$, in good agreement with the WMAP result. In Figure 5, we also show $\tau_e$ for the case with only the contribution from Population II sources. The reionization history for the WDM model would be close to this case, with the contribution from Population III stars in minihalos being negligible. In a forthcoming paper, we will study extensively a number of models using a more detailed prescription of early star formation. The reionization history could be complex, as in the double-reionization scenario (Cen 2002; Wyithe & Loeb 2003), if a dramatic transition between the two modes of star formation, Population II to Population II, occurs at $z > 10$. While it is still too early to draw a definite conclusion, given the uncertainty in the WMAP measurement of $\tau_e$, future CMB polarization measurements will accurately probe the ionized hydrogen fraction at high redshift as well as the total optical depth, and thus will be able to place a strong constraint on the structure formation scenario and on the mass of dark matter.

This work was supported in part by NSF grants ACI 96-19019, AST 98-02568, AST 99-00877, and AST 00-71019.

Fig. 5.—Thomson optical depth as a function of redshift. We compute $\tau_e$ using the combined result of the present work for Population III ($z > 18$) and Sokasian et al. (2003) for Population II ($z < 15$).

REFERENCES

Abel, T., Anninos, P., Norman, M. L., & Zhang, Y. 1997, NewA, 2, 181
Abel, T., Bryan, G. L., & Norman, M. L. 2002, Science, 295, 93
Bardeen, J. M., Bond, J. R., Kaiser, N., & Szalay, A. S. 1986, ApJ, 304, 15
Barkana, R., Haiman, Z., & Ostriker, J. P. 2001, ApJ, 558, 482
Bode, P., Ostriker, J. P., & Turok, N. 2001, ApJ, 556, 93
Bromm, V., Coppi, P. S., & Larson, R. B. 2002, ApJ, 564, 23
Cen, R. 2002, preprint (astro-ph/0210473)
Dalal, N., & Kochanek, C. S. 2002, preprint (astro-ph/0202290)
Galli, D., & Palla, F. 1998, A&A, 335, 403
Götz, M., & Sommer-Larsen, J. 2002, preprint (astro-ph/0210599)
Jang-Condell, H., & Hernquist, L. 2001, ApJ, 548, 68
Kaplinghat, M., Chu, M., Haiman, Z., Holder, G., & Knox, L. 2003, ApJ, 580, 1
Kawasaki, M., Sugiyama, N., & Yanagida, T. 1997, Mod. Phys. Lett., 12, 1275
Knebe, A., Devriendt, J. E. G., Mahmood, A., & Silk, J. 2002, MNRAS, 329, 813
Kogut, A., et al. 2003, ApJ, submitted (astro-ph/0302213)
Narayan, V. K., Spergel, D. N., Davé, R., & Ma, C.-P. 2000, ApJ, 543, L103
Oh, S. P., Nollet, K. M., Madau, P., & Wasserburg, G. J. 2001, ApJ, 562, L1
Omukai, K., & Palla, F. 2003, ApJ, 589, 677
Sokasian, A., Abel, T., & Hernquist, L. 2001, NewA, 6, 359
Sokasian, A., Abel, T., Hernquist, L., & Springel, V. 2003, preprint (astro-ph/0303098)
Somerville, R. S., Bullock, J. S., & Livio, M. 2003, ApJ, in press (astro-ph/0303481)
Springel, V., & Hernquist, L. 2002, MNRAS, 333, 649
Springel, V., White, S. D. M., Tormen, G., & Kauffmann, G. 2001, MNRAS, 328, 726
Wyithe, J. S. B., & Loeb, A. 2003, ApJ, 586, 693
Yoshida, N., Abel, T., Hernquist, L., & Sugiyama, N. 2003, ApJ, in press (astro-ph/0301645) (Paper I)