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EARLY STRUCTURE FORMATION AND REIONIZATION IN A WARM DARK MATTER COSMOLOGY

Naoki Yoshida, Aaron Sokasian, Lars Hernquist
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138
Volker Springel
Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-str. 1, Garching bei München
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ABSTRACT

We study first structure formation in Λ-dominated universes using large cosmological N-body/SPH simulations. We consider a standard ΛCDM model and a ΛWDM model in which the mass of the dark matter particles is taken to be $m_X = 10$ keV. The linear power spectrum for the ΛWDM model has a characteristic cut-off at a wavenumber $k = 200\ \mathrm{Mpc}^{-1}$, suppressing the formation of low mass ($< 10^6 M_\odot$) 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 $m_X = 10$ keV is strongly inconsistent with the observed high optical depth by the *WMAP* satellite.

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

1. INTRODUCTION

Popular cosmological models based on Cold Dark Matter (CDM) predict that the first stars form in low mass ($\sim 10^6 M_\odot$) dark halos at redshifts $z \approx 20-30$ when primordial gas condenses 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 *WMAP* result of the measurement of CMB polarization implies a large optical depth $\tau_e = 0.17 \pm 0.04$, indicating that reionization could have occurred as early as $z_{\rm reion} \sim 17$ (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 warm dark matter particle as, $R_{\rm f} = 0.31(\Omega_X/0.3)^{1/3}(h/0.65)^{1.3}(m_X/\mathrm{keV})^{-1.15}\ h^{-1}\mathrm{Mpc}$, where m_X 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 sub-galactic scales (Bode et al. 2001). Various constraints have been placed on the mass m_X. Based on an analysis of the clustering properties of the Ly-α forest, Narayanan et al. (2000) conclude that the lower limit on the mass is $m_X = 0.75$ keV. Dalal & Kochanek (2002) used lensing statistics and found that models with $m_X < 5$ keV are incompatible with the observed abundance of substructure in distant galaxies. Barkana, Haiman & Ostriker (2001) concluded that models with $m_X < 1$ keV are likely to be ruled out *assuming* the reionization redshift $z_{\rm reion} \sim 6$. 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 $m_X \gg 1$ 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 $m_X \lesssim 1$ keV appear to be inconsistent with an array of observations, we consider a model with $m_X = 10$ keV. Although the motivation from particle physics for elementary particles with such an intermediate mass is somewhat unclear (but see Kawasaki, Sugiyama & Yanagida 1997; Bode et al. 2001), 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 ΛCDM and in a ΛWDM universe, and compare the results for the two models. While the currently available observations do not directly probe structure in the redshift range 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.

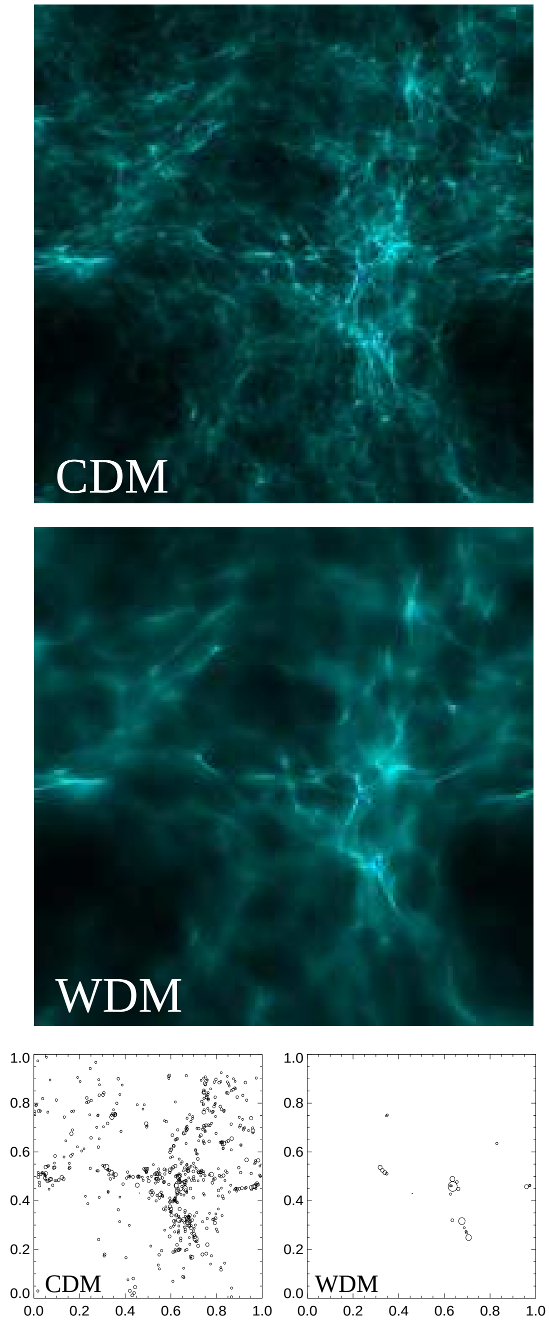

FIG. 1.— The projected gas distribution in the CDM (top) and the WDM (middle) simulations at $z = 20$. Figures in the bottom portion show the distribution of dark halos with mass greater than $10^5 M_\odot$ for the CDM (left) and for the WDM (right) model.

2. THE N-BODY/SPH SIMULATIONS

We use the parallel Tree-PM/SPH 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^{++}, H_2, H_2^+, H^-) 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 matter density $\Omega_0 = 0.3$, baryon density $\Omega_b = 0.04$, cosmological constant $\Omega_\Lambda = 0.7$ and expansion rate at the present time $H_0 = 70\text{km s}^{-1}\text{Mpc}^{-1}$. 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 set-up (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 2×324^3 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.

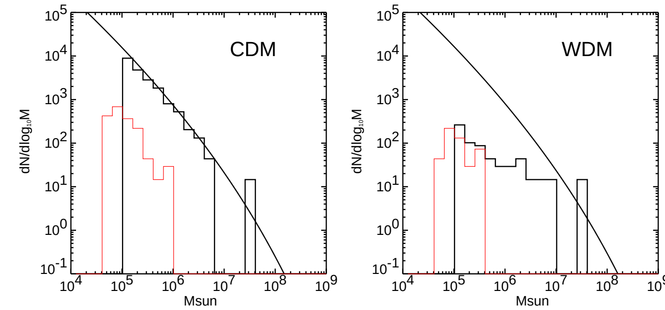

FIG. 2.— Mass function of dark matter halos at $z = 20$. The solid line is the Press-Schechter mass function computed for the CDM model, which agrees remarkably well with our CDM simulation. The thin histograms show the abundance of all the subhalos found in the simulation box.

3. RESULTS

Figure 1 shows the projected gas distribution at $z = 20$ for the two models. Panels in the bottom portion show the distribution of dark matter halos in each simulation. The effect of the exponential cut-off 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) groupfinder with linking parameter $b = 0.164$. We discard halos which consist of fewer than 100 particles. We then use the SUBFIND algorithm (Springel et al. 2001) which 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 by 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

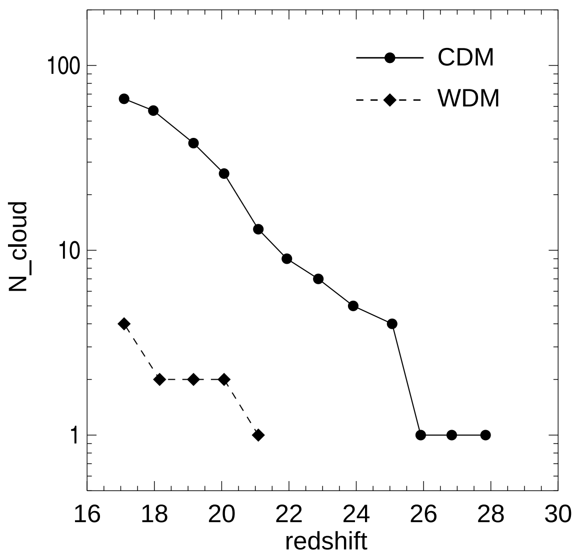

FIG. 3.— The number of star-forming gas clouds as a function of redshift.

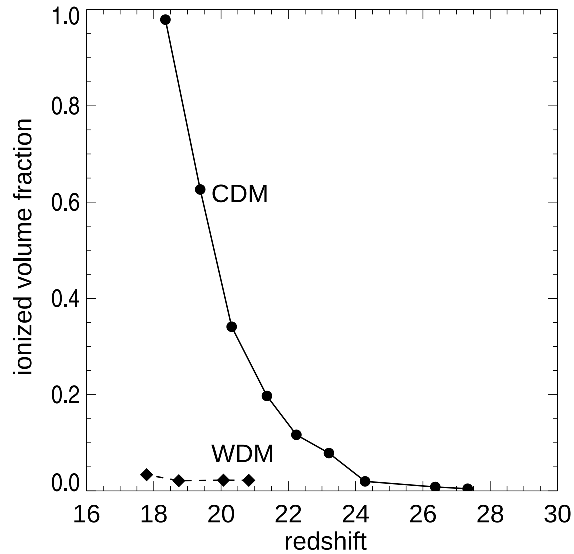

FIG. 4.— The volume fraction of ionized regions.

with the result of the WDM simulation (right panel). The difference is nearly two 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 ($n_{\rm H} > 500{\rm cm}^{-3}$) gas particles as "gas clouds". In order to locate dense gas clumps, we again run a FOF groupfinder with $b = 0.05$ to gas particles. From each group we discard gas particles which do not satisfy the above criteria. We then identify the group as a star-forming gas cloud if the cold gas mass exceeds $M_{\rm Jeans} = 3000 M_\odot$. 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 $z = 20$, we identified 26 gas clouds in the CDM model, and there are only 2 gas clouds found in the WDM case. The corresponding numbers at $z = 17$ are 66 and 4 for the CDM and WDM models, respectively. 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.

An important question is how reionization by an early generation of stars proceeds 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 "mini-halos." 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 $f_{\rm esc} = 1$. Although the high escape fraction might seem unrealistic, it may indeed be plausible because the gas in mini-halos can be wholly ionized and photo-evapolated by a single massive star assuming the gas distribution is reasonably smooth (Oh et al. 2001). We then run multi-source radiative transfer simulations using the technique of Sokasian et al. (2003). Briefly, the code utilizes a post-procesed 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 et al. 2001) in which the gas density evolution due to radiative feedback is not taken into account. In order to mimic strong radiative feedback within HII 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 evolution of the volume filling factor computed in this manner for the two models. Initially, there is only a single HII region and so the filling factor is very small. 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 mass $\sim 10^7 M_\odot$ collapse at $z \sim 20$. The global star-formation rate thus remains very small at $z > 17$ (see Figure 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 observed high optical depth of 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 $\tau_e \sim 0.15$ only if a large number of ionizing photons are produced in (proto-)galaxies at $z < 18$. Clearly the WDM model 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 τ_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 over-simplification, it provides a conservative estimate for the total optical depth. To this end we re-run the $f_{\rm esc} = 0.20$ model from Sokasian et al. (2003) with the initial condition that the IGM was fully reionized by $z \simeq 18.5$ and was uniformly heated to a temperature of 1.5×10^4 K. Figure 5 shows τ_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 a $\Delta\tau \sim 0.05$ whereas the ordinary stellar populations contribute $\Delta\tau \sim 0.09$ at $z < 15$, giving a total of $\tau \sim 0.14$, in good agreement with the *WMAP* result. In Figure 5, we also show τ_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 mini-halos 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, Pop III to Pop II, occurs at $6 < z < 18$. While it is yet too early to draw a definite conclusion, given the uncertainty in the *WMAP* measurement of the optical depth, future CMB polarization measurements such as *Planck* will probe the ionized hydrogen fraction at high redshift as well as the total optical depth accurately (Kaplinghat et al. 2003), and thus will be able to place a strong constraint on the structure formation scenario and on the mass of dark matter.

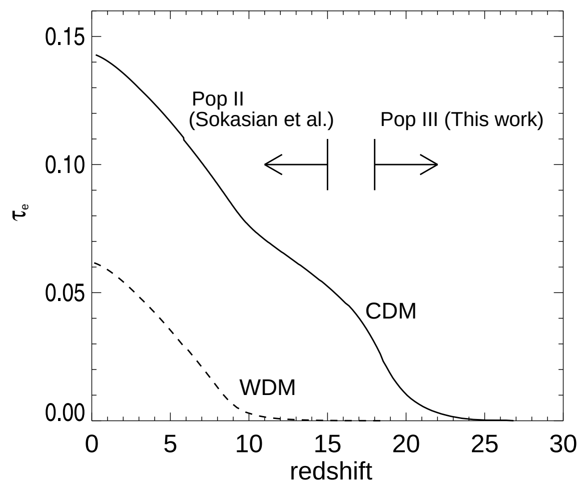

FIG. 5.— Thomson optical depth as a function of redshift. We compute τ_e using the combined result of the present work for Pop III ($z > 18$) and Sokasian et al. (2003) for Pop II ($z < 15$) .

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