EFFECT OF COSMIC ULTRAVIOLET BACKGROUND ON STAR FORMATION IN HIGH-REDSHIFT GALAXIES

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ABSTRACT

The effect of the cosmic UV background on star formation in high-redshift galaxies is explored by means of high-resolution cosmological simulations. The simulations include star formation, three-dimensional radiative transfer, and a highly detailed interstellar medium model, and reach spatial resolution sufficient to resolve formation sites for molecular clouds. In the simulations, the local radiation field in the Lyman–Werner band can be 50–100 times higher than at the interstellar radiation field in the Milky Way (Chen et al. 2009), but the observational constraints remain sparse.

In the interstellar medium (ISM) of local galaxies the situation appears to be reversed: the Haardt–Madau model for the UV background (Haardt & Madau 2001) predicts the z = 0 radiation field at 1000 Å (the so-called Lyman–Werner band) of about 2 × 10^3 photons cm^{-2} s^{-1} st^{-1} eV^{-1}, some 500 times smaller than the interstellar radiation field in the Milky Way at the solar circle (Draine 1978; Mathis et al. 1983).

At higher redshift the situation is, however, less clear. For example, the UV background at 1000 Å at z ~ 3 is expected to be 50–100 times higher than at z = 0 (Haardt & Madau 2001; Faucher-Giguère et al. 2009). On the other hand, estimates of the interstellar radiation field in high-redshift gamma-ray burst hosts also give some 100 times higher values than the Milky Way field (Chen et al. 2009), but the observational constraints remain sparse.

In the cosmological simulation community, the effect of the cosmic UV background is often included in the cooling rates (e.g., Cen & Ostriker 1992; Katz et al. 1996; Navarro & Steinmetz 1997; Kravtsov 2003; Ceverino & Klypin 2009; Hambrick et al. 2009; Schaye et al. 2010). However, the effect of the local interstellar radiation field (that dominates over the cosmic UV background by a larger factor at least at z ~ 0 and may be at high redshift too) has not yet been included in those simulations. In this Letter, the effect of the cosmic UV background is critically reassessed with numerical simulations that both include the full three-dimensional, time-dependent and spatially variable treatment of radiative transfer and have high enough spatial resolution to resolve the sites of molecular clouds and associated star formation.

1. INTRODUCTION

Since the end of cosmic reionization, the intergalactic space has been filled with the accumulated ultraviolet radiation from the previous generations of massive stars and quasars, the so-called cosmic UV background. The ionizing UV background completely controls the ionization state of the intergalactic medium (IGM) that manifests itself in the numerous Lyα absorption lines in the spectra of distant quasars, the Lyα forest (see, Meiksin 2009 for a recent review).

In the interstellar medium (ISM) of local galaxies the situation appears to be reversed: the Haardt–Madau model for the UV background (Haardt & Madau 2001) predicts the z = 0 radiation field at 1000 Å (the so-called Lyman–Werner band) of about 2 × 10^3 photons cm^{-2} s^{-1} st^{-1} eV^{-1}, some 500 times smaller than the interstellar radiation field in the Milky Way at the solar circle (Draine 1978; Mathis et al. 1983).

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2. SIMULATIONS AND STAR FORMATION MODEL

The physical ingredients and computational setup for the simulations used in this Letter have been recently described in great detail elsewhere (Gnedin & Kravtsov 2010a, 2010b). As a brief reminder, the simulations have been performed with the Adaptive Refinement Tree code (Kravtsov 1999; Kravtsov et al. 2002; Rudd et al. 2008) that uses adaptive mesh refinement in both the gas dynamics and gravity calculations to achieve high dynamic range in spatial scale.

The simulations include star formation and supernova enrichment and thermal energy feedback as well as a highly detailed ISM model. The three-dimensional radiative transfer of UV radiation from individual stellar particles is followed self-consistently with the OTVET approximation (Gnedin & Abel 2001), both for ionizing radiation and in the Lyman–Werner band. The simulations incorporate non-equilibrium chemical network of hydrogen and helium and non-equilibrium, metallicity-dependent cooling and heating rates, and a phenomenological model of molecular hydrogen formation on and shielding by cosmic dust as well as H2 self-shielding (Gnedin & Kravtsov 2010a, 2010b).

Particular simulations used in this Letter model a small region including a Milky Way progenitor galaxy and a number of smaller galaxies with the mass resolution of 1.3 × 10^6 M⊙ in dark matter, 2.2 × 10^5 M⊙ in baryons, and with the spatial resolution of 65 pc × (4/(1 + z)) (in physical units) within the fully refined region.

Star formation in the simulation is occurring in the molecular gas only, using the prescriptions of Krumholz & McKee (2005) and Krumholz & Tan (2007). The exact formulation of the star formation recipe is shown in Equation (2) of Gnedin & Kravtsov (2010b).

For the purpose of this Letter, two simulations are considered that differ only by the inclusion of the cosmic UV background from Haardt & Madau (2001). In the simulation without the cosmic UV background, the local radiation field produced by nearby massive stars is still included exactly in the same manner as in the simulation with the UV background. Thus, these two simulations can be used to evaluate the particular effect of the
cosmic UV background on the properties of model galaxies. Because of computational expense, the simulations are not continued beyond $z = 2$.

The simulation with the cosmic UV background is the same one as described in Gnedin & Kravtsov (2010a). That reference also shows good agreement of that simulation with several observational constraints on the properties of high-redshift galaxies.

### 3. RESULTS

A direct comparison of stellar masses and star formation rates between the galaxies in the two simulations is shown in Figure 1. In order to minimize the effect of finite numerical resolution, only highly resolved galaxies—i.e., galaxies that reach the 8th level of mesh refinement (130 pc spatial resolution at $z = 3$) within their gaseous disks—are shown in this and all subsequent figures. At this spatial resolution, the sub-cell model for H$_2$ formation performs reliably, as is demonstrated in Figure 13 of Gnedin & Kravtsov (2010b). Galaxies with masses below $M_{\text{tot}} = 10^{10} M_\odot$ are not sufficiently resolved in these simulations—none of such galaxies achieve eight levels of mesh refinement within their gaseous disks.

While the two simulations do not produce identical results, the difference between the two runs is not dramatic and is fully consistent with the timing differences in two simulations that have slightly different time steps and, hence, times of intermediate outputs. Thus, no significant effect of the cosmic UV background on the global properties of simulated galaxies is observed in these simulations.

The origin for this conclusion becomes apparent from Figure 2, where the sizes of the proximity zones—regions around model galaxies that are dominated by the local radiation from the galaxies themselves and not by the cosmic UV background—are shown together with radii containing most of the atomic and molecular gas.

A size of a proximity zone depends, of course, on the wavelength of radiation, because, in general, spectral shapes of the local interstellar radiation field and the cosmic UV background are different. Figure 2, therefore, shows two important wavelengths: the Lyman limit and $\lambda = 1000$ Å, in the middle of the Lyman–Werner band. Radiation above the Lyman limit ionizes neutral hydrogen, and so is important for determining which part of the galactic gas can cool rapidly. Radiation in the Lyman–Werner band destroys molecular hydrogen; only when gas is shielded from that radiation by cosmic dust and molecular hydrogen self-shielding, can it become fully molecular (and, hence form stars).

In a given frequency band, absorption of radiation emitted by stars in a galaxy will, generally, be different in different directions. Therefore, the proximity zone of a given galaxy is not necessarily spherical, but can have a complex shape. In order to quantify variation in the shapes of proximity zones, a HEALPix tessellation (Górski et al. 2005) of the celestial sphere (as seen from the center of a particular galaxy) with 48 pixels is constructed and the proximity zone size is measured separately for each pixel on the sky. Because HEALPix provides uniform sampling of all possible directions, it offers a convenient way to quantify variations in sizes of proximity zones in different wave bands. Error bars in Figure 2 show the 10%–90% range in the size of the proximity zone as a function of the angle on the sky.

To evaluate the effect of the local radiation field on the gas physics, Figure 2 also displays radii that contain 90% of the atomic (top) and molecular (bottom) gas in the model galaxies. As can be seen, the proximity zone in the Lyman–Werner band extends over 10 times beyond the edge of the molecular gas. That explains why the star formation in the simulations is insensitive to the presence of the cosmic Lyman–Werner background—the local radiation field in the sites of star formation.
Figure 2. Three shades of gray show three different redshifts, as marked in the UV background, at three different redshifts. Symbols and panels are similar to Figure 1. Three shades of gray show three different redshifts, as marked in the figure.

(i.e., in molecular clouds) always dominates over the cosmic background by a factor of about 100. Star formation is, therefore, regulated by the local radiation field in these simulations, and not by external radiation.

The situation appears to be reversed for atomic hydrogen. The escape fraction for ionizing radiation is small in these simulations, consistent with observational estimates (Gnedin et al. 2008). It is particularly small along the disk, so that little local ionizing radiation shines on the outer parts of H\textsc{i} disks; instead, the edges of H\textsc{i} disks are determined by the cosmic ionizing background.

Finally, to verify the robustness of these results, Figure 3 presents proximity zones and radii containing 90% of the neutral and molecular gas for the fully self-consistent run, with the UV background, at three different redshifts. Symbols and panels are similar to Figure 2. Three shades of gray show three different redshifts, as marked in the figure.

4. CONCLUSIONS

The results of this Letter can be summarized in just a few lines: the local radiation field in the Lyman–Werner band around star-forming molecular clouds dominates over the cosmic UV background (in the same band) by a factor of 100, similarly to the interstellar radiation field in the Milky Way (Draine 1978; Mathis et al. 1983) and in a few high-redshift galaxies for which measurements exist (Chen et al. 2009). The cosmic Lyman–Werner background, therefore, is essentially irrelevant for star formation in normal galaxies.

The situation is more complex for ionizing radiation—in that band the cosmic UV background may play an important role in determining the exact locations of the edges of extended H\textsc{i} disks, in agreement with the earlier results of Schaye (2004). Those outside regions of galactic disks, however, contain little molecular gas and, therefore, are inert to star formation.

The simulations presented here do not continue beyond \(z = 2\). However, if the Milky Way galaxy is a representative of low-redshift (\(z < 2\)) normal galaxies, then one may expect that even at low redshifts local radiation dominates over the cosmic background within the galactic ISM, rendering the cosmic background irrelevant for star formation. This conclusion is in stark contrast to quasar absorption systems, which are thought to be dominated by the cosmic background for column densities as high as that of Lyman limit systems (Miralda-Escudé 2005; Schaye 2006). The transition to the local-radiation-dominated regime then falls onto the damped Ly\textsc{α} systems, in agreement with observations (Wolfe et al. 2008). That conclusion is consistent with damped Ly\textsc{α} systems being outer parts of galactic disks (cf. Wolfe et al. 2005, and references therein).

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REFERENCES

Cen, R., & Ostriker, J. P. 1992, ApJ, 399, L113
Ceverino, D., & Klypin, A. 2009, ApJ, 695, 292
Chen, H.-W., et al. 2009, ApJ, 691, 152
Draine, B. T. 1978, ApJS, 36, 395
Faucher-Giguère, C., Lidz, A., Zaldarriaga, M., & Hernquist, L. 2009, ApJ, 703, 1416
Gnedin, N. Y., & Abel, T. 2001, New Astron., 6, 437
Gnedin, N. Y., & Kravtsov, A. V. 2010a, ApJ, 714, 287
Gnedin, N. Y., & Kravtsov, A. V. 2010b, ApJ, submitted (arXiv:1004.0003)
Gnedin, N. Y., Kravtsov, A. V., & Chen, H.-W. 2008, ApJ, 672, 765
Górski, K. M., Hivon, E., Banday, A. J., Wandelt, B. D., Hansen, F. K., Reinecke, M., & Bartelmann, M. 2005, ApJ, 622, 759
Haardt, F., & Madau, P. 2001, in Clusters of Galaxies and the High Redshift Universe Observed in X-rays, ed. D. M. Neumann & J. T. V. Tran (Saclay: CEA), 64
Hambrick, D. C., Ostriker, J. P., Naab, T., & Johansson, P. H. 2009, ApJ, 705, 1566
Katz, N., Weinberg, D. H., Hernquist, L., & Miralda-Escude, J. 1996, ApJ, 457, L57
Kravtsov, A. V. 1999, PhD thesis, New Mexico State Univ.
Kravtsov, A. V. 2003, ApJ, 590, L1
Kravtsov, A. V., Klypin, A., & Hoffman, Y. 2002, ApJ, 571, 563
Krumholz, M. R., & McKee, C. F. 2005, ApJ, 630, 250
Krumholz, M. R., & Tan, J. C. 2007, ApJ, 654, 304
Meiksin, A. A. 2009, Rev. Mod. Phys., 81, 1405
Miralda-Escudé, J. 2005, ApJ, 620, L91
Navarro, J. F., & Steinmetz, M. 1997, ApJ, 478, 13
Rudd, D. H., Zentner, A. R., & Kravtsov, A. V. 2008, ApJ, 672, 19
Schaye, J. 2004, ApJ, 609, 667
Schaye, J. 2006, ApJ, 643, 59
Schaye, J., et al. 2010, MNRAS, 402, 1536
Wolfe, A. M., Gawiser, E., & Prochaska, J. X. 2005, ARA&A, 43, 861
Wolfe, A. M., Prochaska, J. X., Jorgenson, R. A., & Rafelski, M. 2008, ApJ, 681, 881