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THE INTERPLAY BETWEEN GALAXY FORMATION AND THE IGM

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RESUMEN

Hemos desarrollado un modelo para la supresión por fotoionización de la formación de galaxias, que resulta de la reionización del Universo. Esta supresión se incorpora en el modelo de formación de galaxias de Cole et al. (2000) y produce un modelo completamente auto-consistente para la evolución del MIG y la población de galaxias. Estudiamos en detalle las consecuencias sobre la población de galaxias a una $z = 0$, haciendo hincapié en las galaxias del Grupo Local. La abundancia de satélites en el Grupo Local disminuye apreciablemente, y se predicen números comparables a los observados. La supresión de la fotoionización no produce cambios ambientales mayores en la función de luminosidad de las galaxias, en contraste con lo observado. Finalmente, demostramos que la abundancia de subestructuras predicha en los halos de materia oscura concuerda con el pequeño espesor del disco de la Vía Láctea.

ABSTRACT

We have developed a model for the photoionization suppression of galaxy formation resulting from the reionization of the Universe. This suppression is incorporated into the galaxy formation model of Cole et al. (2000), producing a fully self-consistent model for the evolution of the IGM and the galaxy population. We study in detail the consequences for the population of galaxies at $z = 0$, and focus on the galaxies seen in the Local Group. The abundance of Local Group satellites is significantly reduced, predicting numbers comparable to those observed. Photoionization suppression does not produce a strong environmental variation in the galaxy luminosity function, in contrast to observations. Finally, we demonstrate that the predicted abundance of substructure in cold dark matter halos is consistent with the thinness of the Milky Way disk.

Key Words: **COSMOLOGY: THEORY — GALAXIES: FORMATION — LOCAL GROUP — INTERGALACTIC MEDIUM**

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1. INTRODUCTION

Reionization of the hydrogen in the Universe is now known to occur at $z \gtrsim 6$ (Becker et al. 2001, Djorgovski et al. 2001). Reionization is inevitably accompanied by reheating of the intergalactic medium (IGM) and the production of an ionizing background of photons. The hot IGM has a significant Jeans mass and the ionizing background is an effective heat source for gas in low mass dark matter halos. These two effects both suppress the formation of low mass galaxies. Here, we explore the consequences of this suppression for different classes of galaxies. We will also examine the question of whether the thinness of the Milky Way disk is consistent with the abundance of substructure predicted to exist in its dark matter halo by cold dark matter models.

2. MODEL AND RESULTS

The temperature and ionization state of the IGM is evolved for a range of density contrasts in the presence of an ionizing background emitted by stars (computed by our model of galaxy formation) and quasars (from Madau, Haardt & Rees 1999). We obtain the temperature of the IGM as a function of time allowing us to infer the filtering mass (the mass scale below which gas is unable to accrete efficiently into dark matter halos; Gnedin 2000). Galaxy formation is strongly suppressed in halos below this mass. We also compute, at each redshift, the cooling rate of gas in the presence of the ionizing background. Cooling is suppressed (or stopped altogether) in low-temperature halos further inhibiting galaxy formation. To accurately determine the properties of satellite galaxies we solve the orbit equations for each satellite, accounting for the effects of dynamical friction, stripping of material by tidal forces, and heating via gravitational shocks. This more detailed model of satellite orbits and mass loss prevents the formation of super-massive galaxies at the centres of clusters through overmerging, resulting in galaxies with masses closer to those actually observed. Simultaneously, the amount of energy deposited by satellites into vertical motions of stars in the disk

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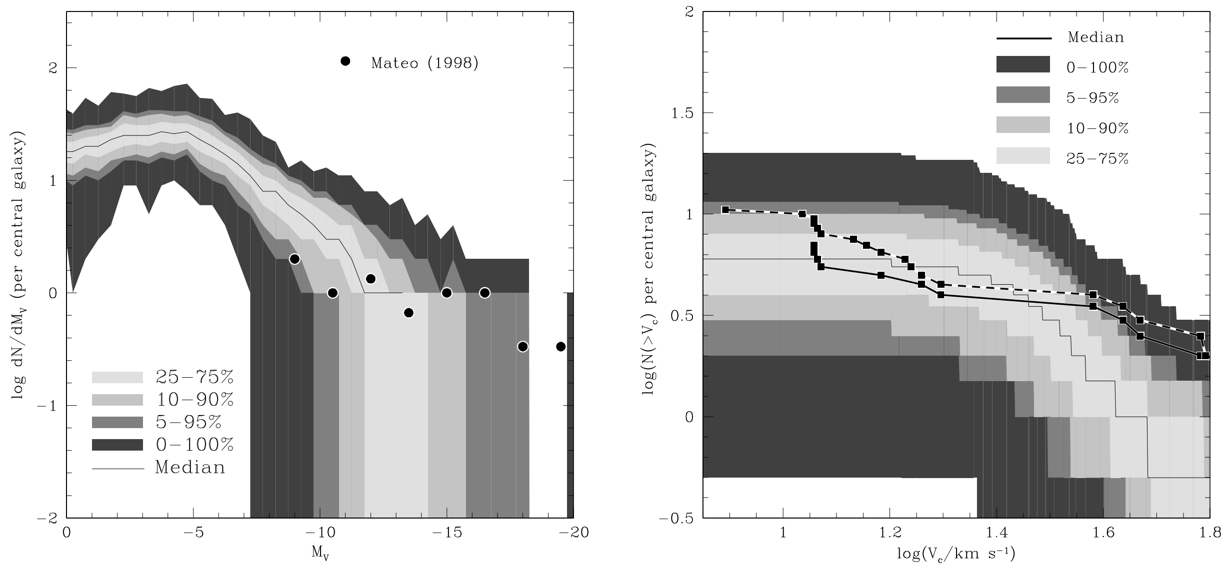

Fig. 1. *Left-hand panel:* The V-band luminosity function (per central galaxy) of satellite galaxies in the Local Group from Mateo (1998) (filled circles). Only satellites within $R_{\rm MW} \approx 272$kpc (the virial radius of the Milky Way's halo) of the Milky Way or M31 are included. The median luminosity function for galaxies in pairs of Milky Way-like model halos is shown as the solid line, with shaded regions indicating various intervals of the distribution of model results. *Right-hand panel:* The cumulative velocity function of satellites brighter than $M_{\rm V} = -9$ per central galaxy (filled squares connected by the solid line; the dashed line shows the result of assigning galaxies with no measured $V_{\rm C}$ a value based on their luminosity). The model result is shown by the solid line, with shaded regions again showing intervals of the model distribution. We plot the circular velocity at the half-mass radius of the combined disk and spheroid system after accounting for tidal limitation.

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of each galaxy is computed. Here we will focus on just a few of the most significant results from this work.

The star formation rate per unit volume is affected by reionization. Before $z \approx 10$ our model predicts a rate identical to that of Cole et al. (2000) who did not include the effects of reionization on galaxy formation. Once the first episode of reheating due to reionization of HI begins at $z \approx 10$ our model predicts a small suppression of star formation rate compared to Cole et al. (2000) as galaxy formation is shut off in low mass halos. As larger structures form the star formation rate recovers to the Cole et al. value. A second episode of reheating due to reionization of HeII at $z \approx 4$ has a similar effect. This suppression in the star formation rate is a small effect, since the low mass halos affected by photionization suppression are already inefficient at forming galaxies in our model due to supernovae feedback. If we excluded supernovae feedback from our model photoionization suppression would result in a factor of 2–3 reduction in the star formation rate.

We generate a large sample of dark matter halos and select those containing a central galaxy similar to the Milky Way (in terms of rotation speed and morphological type). We then study the population of satellite galaxies found in these halos. The left-hand panel of Figure 1 shows the V-band luminosity function of satellite galaxies (per central galaxy, which we assume there are two of in the Local Group, namely the Milky Way and M31). Points indicate the observed luminosity function of satellites within the virial radii of the Milky Way or M31. Photoionization significantly reduces the number of satellites expected (with minor assistance from tidal limitation of satellites), resulting in reasonable agreement between model and data. At the brightest magnitudes, the model appears to underpredict the number of satellites, while at the faintest magnitude the model appears to overpredict the observations (although here incompleteness in the observational dataset may be a problem). Consequently, although the total number of satellites is comparable to that seen, the luminosity function remains too steep.

The cumulative velocity function of satellite galaxies for the same model is shown in the right-hand panel of Figure 1. Only galaxies brighter than

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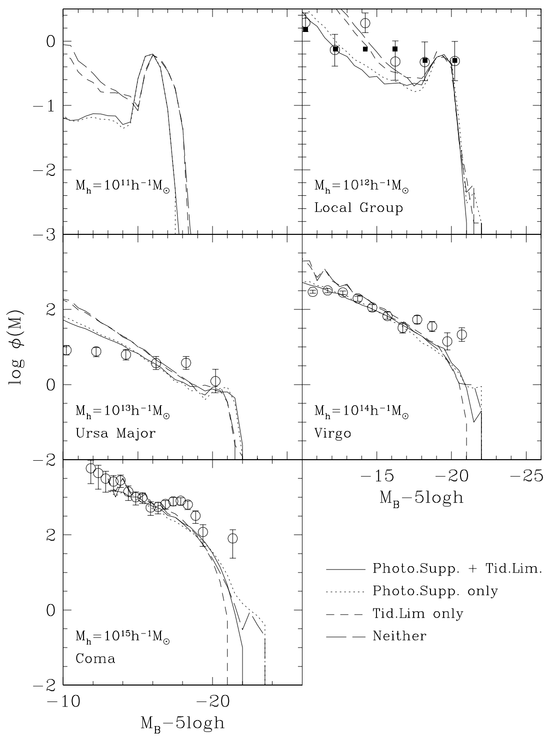

Fig. 2. B-band galaxy luminosity functions in different environments. Each panel shows the mean predicted model luminosity function in an ensemble of dark matter halos with mass as given in each panel (ranging from small galaxies to clusters). Solid lines include photoionization suppression (Ph.S.) and tidal limitation (Ti.L.), dotted lines have Ph.S. only, short-dashed lines have Ti.L. only, and long-dashed lines have neither. Open circles show observed luminosity functions from the compilation of Trentham & Hodgkin (2002); the origin of each observational dataset is given in each panel. These have been normalized arbitrarily to permit easier comparison of their shapes with the models. Filled squares in the $10^{12}h^{-1}M_{\odot}$ panel show the luminosity function from Fig. 1, which includes only galaxies classed as lying within the virial radii of the Milky Way's or M31's dark halos.

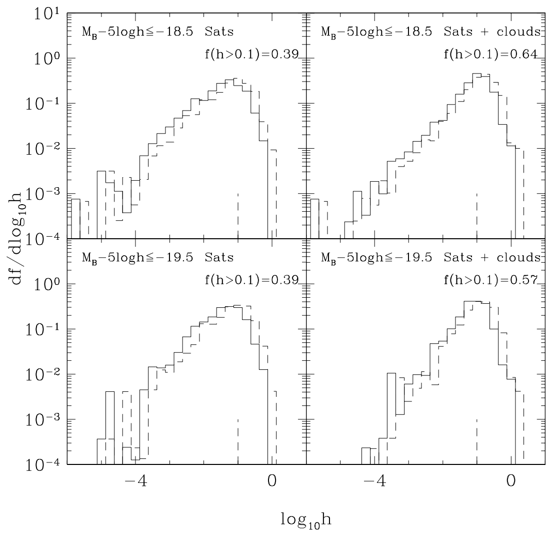

Fig. 3. Normalized disk scale-height distributions for field galaxies. Upper panels show S/S0 galaxies brighter than $M_{\rm B} - 5\log h = -18.5$ while lower panels show S/S0 galaxies brighter than $M_{\rm B} - 5\log h = -19.5$. Left-hand panels show results for heating by substructure only, while right-hand panels show results when heating due to star-cloud scattering is included as well.

$M_{\rm V} = -9$ are included, which roughly corresponds to the luminosity of the faintest known Local Group satellites. Again, a large reduction in the number of satellites is achieved by reionization, producing good agreement between model and data. We have used our model to explore many other properties of the satellites finding generally good agreement with observations.

We have also studied the influence of the reionization of the Universe and the resulting suppression of galaxy formation on the luminosity function of galaxies in different environments. Here, by "environment" we mean the mass of the dark matter halo in which the galaxy lives at $z = 0$. The mass of this halo is indicated in each panel of Fig. 2. We show results both with and without the effects of photoionization suppression and tidal limitation of galaxies (resulting in four sets of results) as indicated in the figure. Results from this work are shown in Fig. 2. Photoionization suppression has been proposed as a natural means to produce an environmental variation in luminosity functions due to preferential suppression of dwarf galaxy formation in low density environments. However, we find that this process leads to a small flattening of the luminosity function in all environments, but does not produce any significant environmental variation in the slope, in contrast to the observational result. This can be understood as a result of competing effects of this suppression mechanism, which preferentially inhibits low mass galaxy formation, but also produces new low mass galaxies by partially inhibiting the formation of previously higher mass galaxies.

We have enhanced our calculations of satellite orbits under the influence of dynamical friction to calculate the rate at which galaxy disks are heated by dark matter substructures orbiting in their halo. The resulting model has been calibrated against the best available N-body simulations (Velázquez & White 1999). We find that it is then able to reproduce the N-body heating rates to within a factor of two. Applying these calculations within our semi-analytic model of the cosmological growth of disk galaxies in a cold dark matter universe we can predict the distribution of disk scale heights. Results of these calculations are shown in Fig. 3, where we plot the distribution of scale heights normalized to the radial scale-length of the disk, h. We find that only 40% of bright galaxies should have a scale-height in excess of 10% of their radial scale length (the height corresponding to the Milky Way's disk), if substructure is the only source of heating. Accounting for heating due to stars scattering from molecular clouds using the formalism of Lacey (1984) increases this number to 60%. Thus, the observed thickness of the Milky Way's disk is consistent with the abundance of substructure in dark matter halos predicted by cold dark matter models.

3. CONCLUSIONS

We have developed a model for the coupled evolution of the IGM and galaxies. This model traces the average thermodynamic properties of the IGM as it is reionized and reheated by photons emitted by stars and quasars. This photoionization suppression alone seems unable to explain the observed environmental variation in the galaxy luminosity function, but does flatten the slope of the global luminosity function resulting in good agreement with the observational data. The effects of reionization significantly reduce the abundance of Local Group galaxies, predicting numbers comparable to those observed, implying that there may be no need for alternative dark matter scenarios to explain the satellite abundance.

Our detailed model of satellite orbits removes the overmerging problem found using simpler estimates of galaxy merger rates and which resulted in the production of super-massive galaxies at cluster centres. This same model has been used to compute the degree of heating experienced by galactic disks due to orbiting satellite halos. We find that the observed thinness of the Milky Way's disk is not atypical in a ΛCDM universe.

REFERENCES

Becker R. H. et al., 2001, AJ, 122, 2850
Cole, S., Lacey, C. G., Baugh, C. M., & Frenk, C. S., 2000, MNRAS, 319, 168
Djorgovski S. G., Castro S. M., Stern D., Mahabal A., 2001, ApJ, 560, 5
Gnedin, N. Y., 2000. ApJ, 542, 535
Lacey C. G., 1984, 208, 687
Madau, P., Haardt, F., & Rees, M. J., 1999, ApJ, 514, 648
Mateo, M. L., 1998, ARA&A, 36, 435
Trentham N., Hodgkin S., 2002, submitted to MNRAS (astro-ph/0202437)
Velázquez H., White S. D. M., 1999, MNRAS, 304, 254

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