The Evolution of the Low End Slope of the Schechter Function from a Cosmological Simulation

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ABSTRACT

Using an advanced, ultra-high resolution (114 h^{-1} pc) hydrodynamic simulation, we study the galactic mass function (MF) and luminosity function (LF) in various bands. We parametrize the low-end of these functions in terms of the Schechter Function (Schechter 1976) low-end slope parameter α, and find constraints on this value and its redshift evolution through our simulation. While we find evidence for the low-end slope of the halo mass function (α_{DM}) steepening from -1.9 $\rightarrow$ -2.1 as redshift increases from 0 $\rightarrow$ 4, α for various other mass and luminosity functions appears to evolve in the opposite direction, flattening over low redshifts, which may be due to downsizing.

1. Introduction

1.1. The Simulation

This summer, I worked with Dr. Renyue Cen in analyzing data from his hydrodynamic cosmological simulation (Cen 2011). This simulation uses the adaptive mesh refinement Eulerian hydrocode Enzo (Bryan & Norman 2000; Joung et al. 2009). The orignal simulation was run on a low-resolution, large-volume box with size 120 h^{-1} Mpc on a side. However, we focused our analysis on a smaller sub-volume (about 20 h^{-1} Mpc on a side) which was simulated with a significantly higher resolution. The simulation includes supernova feedback, and uses typical ΛCDM parameters: $\Omega_M = 0.28$, $\Omega_b = 0.046$, $\Omega_\Lambda = 0.72$, and $H_0 = 100$ hkm s^{-1}Mpc^{-1}.

1.2. The Schechter Function

In order to characterize the distribution of galactic properties throughout the simulation, we calculated the dark matter halo mass function (HMF), the stellar mass function (SMF), and luminosity function (LF) in various bands. Each of these represents a function for the density of galaxies with particular characteristics, such as a given luminosity. One particularly famous LF was defined by Schechter (1976), where he cataloged the galaxies in 13 clusters, and found an analytic expression to fit the data. This *Schechter Function*, as it has come to be known, gives the number density of galaxies within a given luminosity bin $\phi(L)dL$ as the superposition of a power-law and an exponential decay:

$$\phi(L)dL = \phi^* \left(\frac{L}{L^*}\right)^{\alpha} e^{-\frac{L}{L^*}} \mathrm{d}L \quad (1)$$

$$= \phi^* \left(\frac{L}{L^*}\right)^{\alpha+1} e^{-\frac{L}{L^*}} \mathrm{d}\log L \quad (2)$$

where α is the low-end slope, L^* is a characteristic luminosity where the power-law transitions into the exponential tail, and ϕ^* is an overall normalization. This Schechter form has been found to match closely to observations in many surveys, and thus can give us very useful tools to study the evolution and makeup of the universe.

2. Evolution of Low-End Slope α

2.1. In Literature

One particular value of interest is the low-end slope α, which parametrizes the steepness of the distribution in the power-law regime. The steepness of the LF tells us the relative contribution of small galaxies to the total luminosity. Since the total luminosity emitted by all galaxies with luminosity above L

$$L_T(\geq L) = \int_L^\infty L\phi(L)\,\mathrm{d}L \quad (3)$$

will go as

$$\left(\frac{L}{L^*}\right)^{\alpha+1} \quad (4)$$

in the power-law region, if $\alpha \lesssim$ -1.0, then the lower luminosity galaxies will contribue the most to the total luminosity, with these galaxies dominating the total luminosity as $\alpha \rightarrow$ -2.0 and below.
With advances in modern observation, groups such as Bouwens et al. 2012 have been able to successfully identify and classify galaxies at extremely high redshift (4<z<10) using the Lyman Break technique. By observing these galaxies in the near-IR from the Hubble Ultra Deep Field (HUDF09) data, they have been able to derive rest-frame UV LFs, and study the evolution of α. They find some evidence for a steepening of these LFs with redshift ($\mathrm{d}\alpha/\mathrm{d}z \approx -0.05 \pm 0.04$ for 6<z<8), implying that at high redshift, small, subluminous galaxies are more dominant than at later times.

2.2. In Simulation

Using our simulation, we were able to calculate the dark matter halo mass function (HMF) and apply a Schechter Function fit to the data. We found that, at low redshift (z $\lesssim$ 1) α_{DM}= -1.92±0.01, but that at redshift z=4, α_{DM} steepens to around -2.10±0.02.[1] Thus, this evolution of the low-end slope appears to be in agreement with the view of galaxy formation following a hierarchical evolution, with small halos forming earlier than massive halos (Silk & Mamon 2012).
However, when we analyzed the low-end slope of the LFs and SMF, we found that they do not match closesly to the slope of the underlying dark matter distribution. In fact, each of these slopes were significantly steeper throughout time than the HMF. (see figure 1 on page 3) The steepening relative to the HMF is more significant at lower redshifts and with younger galaxy characteristics (see description of x-axis in figure 1). This may indicate evidence for downsizing.

3. Downsizing

Downsizing is an evolutionary trend that contrasts significantly to the hierarchical process that is believed to influence the evolution of dark matter halos (Silk & Mamon 2012). Downsizing results from the trend for the specific Star Formation Rate (sSFR), or SFR per unit stellar mass, to decrease with stellar mass at low redshift. Thus, the largest galaxies will increase their stellar mass relatively less in a given interval than the smallest galaxies. If this applies as well to halo mass, then given a downsizing relation between SFR and M_h (halo mass):

$$\frac{SFR}{M_h} = M_h^{-\delta}\,,\ \delta > 0 \tag{5}$$

$$\Rightarrow M_h = SFR^{\frac{1}{1-\delta}}\,, \tag{6}$$

a HMF power-law section with slope α will result in a SFR function:

$$\begin{aligned} \phi(M_h)\mathrm{d}M_h &\propto M_h^{\alpha}\mathrm{d}M_h \qquad (7)\\ &\propto SFR^{\frac{\alpha}{1-\delta}} SFR^{\frac{1}{1-\delta}-1}\mathrm{d}SFR \\ \Rightarrow \phi(SFR) &\propto SFR^{\frac{\alpha+\delta}{1-\delta}}\,, \qquad (8) \end{aligned}$$

which, for any positive value $0 < \delta < 1$ will result in a steeper SFR function than the underlying HMF. In observational surveys such as Oliver et al. 2010, δ has been found between .25< δ <.45, which could result in a steepening of an initial slope of α_{DM} = -1.9 to a slope anywhere in the range -2.20 $\lesssim \alpha_{SFR} \lesssim$ -2.65, in agreement with the over-steepening of our SFR function. The steepening of α for each of the functions in figure 1 relative to α_{DM} could therefore be an indication that this downsizing occurs in the simulation, and that δ may become larger with time and towards the younger characteristics of galaxies, such as SFR and luminosity in blue light.

4. Conclusion

Through the study of the low-end slope of the luminosity and mass functions of galaxies in this simulation, we have been able to trace the evolution of galaxies and their properties through redshift. In particular, we are able to identify the influence of two separate evolutionary trends: hierarchical evolution, which flattens the slope of the dark matter HMF over time, and downsizing, which seems to be influencing certain baryonic properties at lower redshifts, causing them to steepen relative to the underlying dark matter. In order for our understanding of the evolution of the universe to continue to improve, we must learn more about how these two competing trends combine to influence the growth of the structure and patterns we observe in the universe today.

Many thanks go out to Dr. Renyue Cen for his guidance throughout the summer, as well as to Drs. Blake, Spiegel, and Hlozek for providing this opportunity to spend the summer with the department.

[1] At higher redshift than z∼4, the limited size of the simulation box limits the reliability of further α fitting

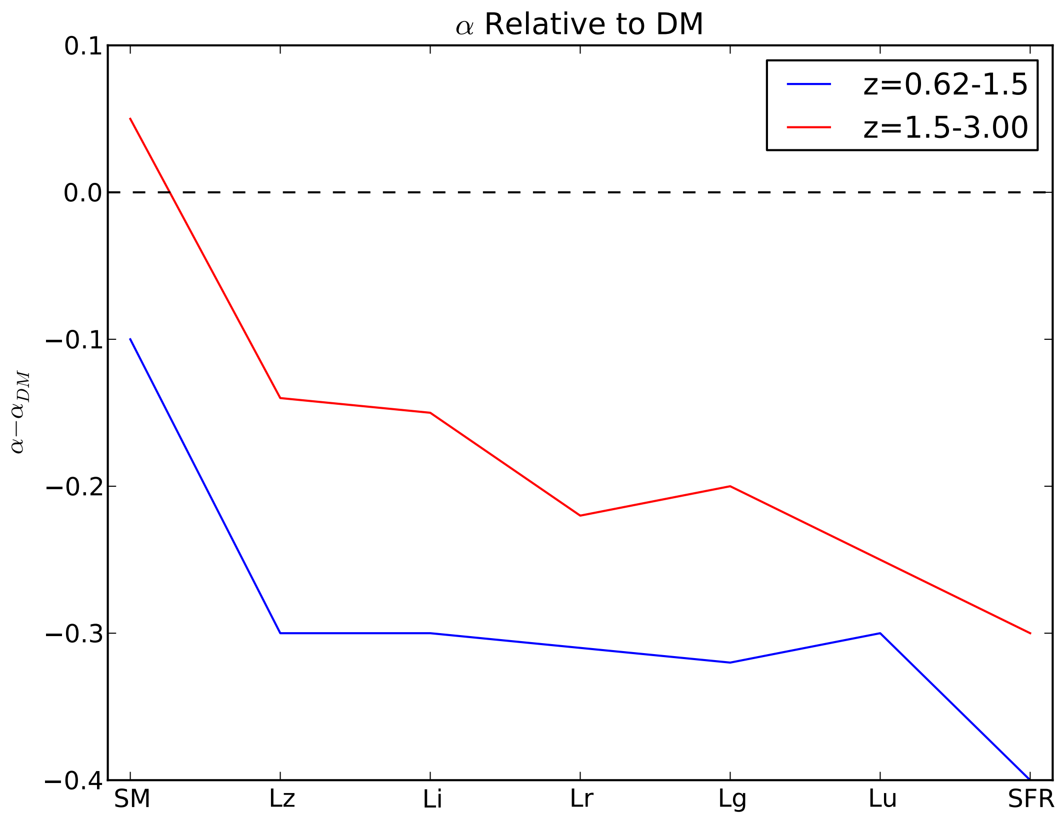

Fig. 1.— $\Delta\alpha$, the difference between the low-end slopes for the listed functions and the slope for the HMF. Values along the x-axis are grouped in terms of age-characteristics: since young galaxies will produce more luminosity in the u-band and have higher SFR and older galaxies will have higher stellar mass (SM) and produce more light in the z-band, the x-axis can act as a proxy for galaxy age. Young galaxy characteristics are towards the right edge, while older galaxy characteristics are to the left. The trend appears to be that these functions become steeper than the HMF with time (both in terms of redshift and age characteristics).

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