Invisible Major Mergers: Why the Definition of a Galaxy Merger Ratio Matters.

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Abstract. The mapping between dark matter halo mass, galaxy stellar mass, and galaxy cold gas mass is not a simple linear relation, but is influenced by a wide array of galaxy formation processes. We implement observationally-normalized relations between dark matter halo mass, stellar mass, and cold gas mass to explore these mappings, with specific emphasis on the correlation between different definitions of a major galaxy merger. We always define a major merger by a mass ratio $m/M > 0.3$, but allow the masses used to compute this ratio to be defined in one of three ways: dark matter halo masses, galaxy stellar masses, or galaxy baryonic masses (stars and cold gas). We find that the merger ratio assigned to any particular merger event depends strongly on which of these masses is used, with the mapping between different mass ratio definitions showing strong evolution with halo mass and redshift. For example, major dark matter mergers ($> 0.3$) in small galaxies ($M_{DM} < 10^{11} M_\odot$) typically correspond to very minor stellar mergers ($< 1/20$). These mergers contain significant dark matter mass, and should cause noticeable morphological disruption to the primary galaxy, even though there is no observable bright companion. In massive galaxies, there is an opposite effect, with bright companion galaxies corresponding to only minor dark matter mergers. We emphasize that great care must be taken when comparing mergers based on different mass ratio definitions.

1. Introduction

In the cold dark matter (CDM) model of structure formation, galaxy mergers are believed to play an important role in galaxy evolution. Typically, these mergers are divided into two categories. “Minor” mergers (with mass ratios $< 1/3$) are often thought to trigger moderate bursts of increased star formation and/or morphological disturbances, as well as contributing to the deposition of diffuse light components of galaxies. “Major” mergers (with mass ratios $> 1/3$) are likely to influence stronger morphological disturbances responsible for the transformation from disk-dominated to bulge-dominated morphologies, in addition to triggering stronger starburst and AGN activity.

Despite this commonly adopted distinction between major and minor mergers at merger mass ratios of $\sim 1/3$, there is still ambiguity in what mass is used to define this ratio. Theoretical investigations of dark matter halo merger rates typically define merger ratios in terms of dark matter halo masses, the most theoretically robust prediction from cosmological N-body simulations (e.g. Stewart et al. 2008, and references within). But because estimates of dark matter halo masses are difficult to obtain observationally, it is also common to define
merger ratios by comparing the stellar masses or the total baryonic masses of galaxies.

In attempting to compare theoretically derived merger statistics (in terms of dark matter mass ratios) to observational investigations of galaxy mergers (in terms of stellar or galaxy mass ratios), it is important to understand the mapping between these definitions. Galaxy merger rates, for example, are quite sensitive to the merger mass ratio being considered (Stewart et al. 2009a). In order to explore the fundamental differences between major mergers as defined by dark matter halo, stellar, and galaxy merger ratios, we adopt a semi-empirical methodology to estimate the stellar and cold gas content of dark matter halos as a function of halo mass and redshift. We give a very brief overview of this method before presenting our findings, but we refer reader to Stewart et al. (2009b) for a more in-depth discussion of this method.

2. Assigning Baryons and Defining Masses

In order to assign stars to our halos, we assume a monotonic relationship between halo mass and stellar mass. Using this technique, provided we know \( n_g(> M_{\text{star}}) \) (the cumulative number density of galaxies with stellar mass more massive than \( M_{\text{star}} \)) we may determine the associated dark matter halo population by finding the halo mass above which the number density of halos (including subhalos) matches that of the galaxy population, \( n_h(> M_{\text{DM}}) = n_g(> M_{\text{star}}) \). Specifically, we adopt the relation found by Conroy & Wechsler 2008 (interpolated from the data in their Figure 2). Of course, a simple relation of this kind cannot be correct in detail, but in an average sense, it provides a good characterization of the relationship between halo mass and galaxy stellar mass that must hold in order for LCDM to reproduce the observed universe.

In order to assign gas to the central galaxies within our halos, we quantify observationally-inferred relations between gas fraction and stellar mass. Specifically, we characterize the data from McGaugh 2005 (disk-dominated galaxies at \( z = 0 \)) and Erb et al. 2006 (UV-selected galaxies at \( z \sim 2 \)) with a relatively simple function of stellar mass and redshift (see Stewart et al. 2009b), and find that this adopted characterization is also consistent with a number of other observationally motivated works (e.g., Kannappan 2004; Baldry et al. 2008).

Having estimated the stellar and cold gas content of dark matter halos as a function of halo mass and redshift, we define three different means of identifying the mass of a galaxy (and thus, define merger mass ratios):

1. The mass (or mass ratio) of each dark matter halo, \( (m/M)_{\text{DM}} \). We will refer to these as the DM mass (ratio) of a galaxy (merger).

2. The mass (mass ratio) of the stellar mass of each dark matter halo’s central galaxy, \( (m/M)_{\text{star}} \). We refer to this definition as the stellar mass (ratio).

3. The mass (mass ratio) of the total baryonic mass of each dark matter halo’s central galaxy, \( (m/M)_{\text{gal}} \). In this case, we define a galaxy’s baryonic mass as a combination of its stellar mass and cold gas mass \( (M_{\text{gal}} = M_{\text{star}} + M_{\text{gas}}) \). We refer to this definition as the galaxy mass (ratio).

Using these mass definitions, we show the stellar and galaxy mass of a dark matter halo’s central galaxy as a function of halo mass (and normalized by halo
Figure 1. A comparison of the baryonic properties of central galaxies to their dark matter halo masses. Left: Ratio of stellar mass to dark matter halo mass, as a function of halo mass. Right: Ratio of total baryonic mass (stars and cold gas) to halo mass, as a function of halo mass. In both panels, the solid and dashed lines correspond to $z = 0$ and $z = 1$, respectively. Note that these relations vary significantly with halo mass and redshift.

mass) in Figure 1, where solid and dashed lines represent galaxies at $z = 0$ and $z = 1$, respectively. We emphasize that these mass fractions are a strong function of halo mass, and evolve with redshift. It is clear from this figure that a single merger event between galaxies may have a drastically different mass ratio in dark matter compared to its mass ratio in stars (or baryons). This could have important implications for observational efforts to measure the merger rate: morphological disturbances will be affected by high total mass ratio events, while pair count estimates will be more sensitive to the mass ratio in visible light.

3. Mapping Between Mass Ratios

We explore the various mappings between major mergers using different mass definitions in Figure 2. In the top panels we focus on mergers with $(m/M)_{DM} = 0.3$ (henceforth major DM mergers), with the dashed and dotted lines showing the corresponding stellar and galaxy mass ratios of these mergers. In the bottom panels, we instead focus on major stellar mergers, defined by $(m/M)_{star} = 0.3$. In these panels, the solid and dotted lines correspond to the DM and galaxy mass ratios of these mergers. The left and right panels show relations at $z = 0$ and $z = 1$, respectively.

We emphasize that, in general, the DM mass ratio between two galaxies is not the same as the stellar (or galaxy) mass ratio. Specifically, major DM mergers (top panels) correspond to stellar mass ratios ranging from $\sim 5 - 60\%$ (5 - 50%) and galaxy mass ratios of $\sim 20 - 60\%$ (35 - 50%) for $10^{11-13} M_\odot$ halos at $z = 0$ (1). Similarly, major stellar mergers (bottom panels) correspond to DM mass ratios from $\sim 10 - 55\%$ (15 - 65%) and galaxy mass ratios of $\sim 30 - 45\%$...
Figure 2. Conversion between major merger ratios defined by dark matter halo mass ($M_{\text{DM}}$), stellar mass ($M_{\text{star}}$), or galaxy (baryonic) mass ($M_{\text{gal}}$). In the top panels, the dashed and dotted lines show the stellar and galaxy mass ratios of major DM mergers with ($m/M_{\text{DM}}$)\text{}$=0.3$, as a function of halo mass (lower axis) and stellar mass (top axis). Similarly, the solid and dotted lines in the bottom panels show the DM and galaxy mass ratios corresponding to major stellar mergers with ($m/M_{\text{star}}$)\text{}$=0.3$. The left and right panels give these relations at $z=0$ and $z=1$, respectively.

(35 – 75%) for 10$^{11-13}$\,M$_{\odot}$ halos at $z=0$ (1). Indeed, the only broad regime where different mass definitions result in similar merger ratios is for stellar and galaxy merger ratios of massive galaxies, where galaxy gas fractions are typically low enough that $M_{\text{star}} \sim M_{\text{gal}}$.

Note that in $M_{\text{DM}} < 10^{11}$\,M$_{\odot}$ halos, major DM mergers should contain stellar mass ratios $< 1/20$. The smaller galaxy in these mergers contain significant mass in dark matter, and should be capable of triggering severe morphological disruption in the primary galaxy, but they are observationally “invisible,” with
negligible luminous content with respect to the primary. The existence of these “invisible” major mergers is a robust, testable prediction of LCDM.

4. Example Consequence: Measuring the Merger Rate

While theoretical investigations into dark matter halo merger rates define mergers by DM mass ratios, observed merger rates (specifically, those based on close-pair counts of galaxies) typically select pairs based on luminosity (stellar mass), and should thus constitute major stellar mergers. The mapping between stellar and DM mass ratios has two important qualitative effects in this case. First, for smaller halos, major DM mergers should correspond to substantially smaller stellar mass ratios, and may not be distinguishable as a luminous close-pair when observed (ie. faint/invisible major mergers). Second, for massive halos, some observed close-pairs with comparable luminosities (major stellar mergers) may correspond to substantially smaller DM mass ratios, and would be counted as minor (not major) mergers in theoretical predictions from N-body simulations (ie. bright minor mergers).

For a more quantitative analysis, we adopt the fitting function for $dN/dt$ from [Stewart et al. 2009a] (Table 1, infall, “simple fit”), which provides the rate of mergers more massive than ($m/M$)$_{DM}$ into dark matter halos of mass $M_{DM}$ (per halo, per Gyr) as a function of redshift, mass, and mass ratio. For $10^{11}M_{\odot}$ dark matter halos and DM merger ratios > 30% at $z = 0 - 1$, the merger rate increases from $\sim 0.015 - 0.075$. Now consider an identical halo mass, but for mergers selected on stellar mass ratios > 30%, corresponding to a DM mass ratio of $\sim 7\%$ (4%) at $z = 0$ (1). Because of the minor DM mergers being considered, this selection would result in an artificial increase of the observed merger rate by a factor of 3 - 4 compared to DM merger rates ($\sim 0.05 - 0.30$ from $z = 0 - 1$), with a redshift evolution that is too steep (and does not appear to fit well to $dN/dt \propto (1 + z)^{\alpha}$; see [Stewart et al. 2009a]). Thus, using different mass ratios to define mergers has a substantial effect on predictions of galaxy merger rates, and great care must be taken when comparing studies of galaxy or halo mergers, if the merger mass ratios have been defined by different criterion.

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