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FLY-BY ENCOUNTERS BETWEEN DARK MATTER HALOS IN COSMOLOGICAL SIMULATIONS

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ABSTRACT

Gravitational interactions — mergers and fly-by encounters — between galaxies play a key role as the drivers of their evolution. Here we perform a cosmological N-body simulation using the tree-particle-mesh code GOTPM, and attempt to separate out the effects of mergers and fly-bys between dark matter halos. Once close pair halos are identified by the halo finding algorithm PSB, they are classified into mergers ($E_{12} < 0$) and fly-by encounters ($E_{12} > 0$) based on the total energy (E_{12}) between two halos. The fly-by and merger fractions as functions of redshift, halo masses, and ambient environments are calculated and the result shows the following: (1) Among Milky-way sized halos ($0.33 - 2.0 \times 10^{12} h^{-1}\mathrm{M}_\odot$), $5.37 \pm 0.03\%$ have experienced major fly-bys and $7.98 \pm 0.04\%$ have undergone major mergers since $z \sim 1$; (2) Among dwarf halos ($0.1 - 0.33 \times 10^{12} h^{-1}\mathrm{M}_\odot$), $6.42 \pm 0.02\%$ went through major fly-bys and $9.51 \pm 0.03\%$ experienced major mergers since $z \sim 1$; (3) Milky-way sized halos in the cluster environment experienced fly-bys (mergers) $4 - 11(1.5 - 1.7)$ times more frequently than those in the field since $z \sim 1$; and (4) Approaching $z = 0$, the fly-by fraction decreases sharply with the merger fraction remaining constant, implying that the empirical pair/merger fractions (that decrease from $z \sim 1$) are in fact driven by the fly-bys, not by the mergers themselves.

Key words: dark matter — methods: N-body simulations — galaxies: interactions — galaxies: evolution

1. INTRODUCTION

Galaxies experience a number of gravitational interactions during a Hubble time. Most related studies focus on the merger phenomenon because it has the largest effect on the galactic morphology (Toomre & Toomre, 1972; White, 1978; Barnes & Hernquist, 1996; Springel et al., 2005). Here, we will focus on fly-by encounters between galaxies as these encounters can generate impulsive perturbations in their neighbors. The effects of close encounters include star formation enhancement (Patton et al., 2013), the formation of tidal tails and bridges (Toomre & Toomre, 1972), thick disks (Gnedin, 2003), and galactic warps (Kim et al., 2014).

The main goal of this study is to quantify how frequently fly-by encounters happen in the cosmic history. In this study, we measure the fly-by fraction and compare with the merger fraction. To classify two interactions, cosmological N-body simulations are performed (Section 2) and we adopt the total energy in the two-body system (Section 3).

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2. SIMULATIONS

We performed a set of four simulations using a cosmological simulation code, Grid-of-Oct-Tree-Particle-Mesh (Dubinski et al., 2004, GOTPM). The code performs the calculation of gravity by the PM method and corrects the difference between PM and Newtonian forces in the gravity by using a tree algorithm. Our simulations describe the universe with a box size of 64 h^{-1}Mpcand WMAP9 parameters ($\Omega_\Lambda = 0.7135$, $\Omega_m = 0.2865$, and $h = 0.6932$).

We adopt a halo finding algorithm, Physically Self-Bound (Kim & Park, 2006, PSB). This algorithm finds groups of particles by Friends-of-Friends (FOF). The groups have more than one peak and their member particles are defined by potential energies and tidal radii. This process makes PSB powerful for examining the interactions between dark matter halos.

3. FLY-BY ENCOUNTERS

We sample halos with mass of $0.1 - 2.0\ M_{MW}$ where M_{MW} is $10^{12} h^{-1}\mathrm{M}_\odot$. Among the halos, halo pairs are considered interacting halos when the distance between them is smaller than the sum of their virial radii in all snapshots ($r_{12} < r_{vir,1} + r_{vir,2}$). In addition, we focus

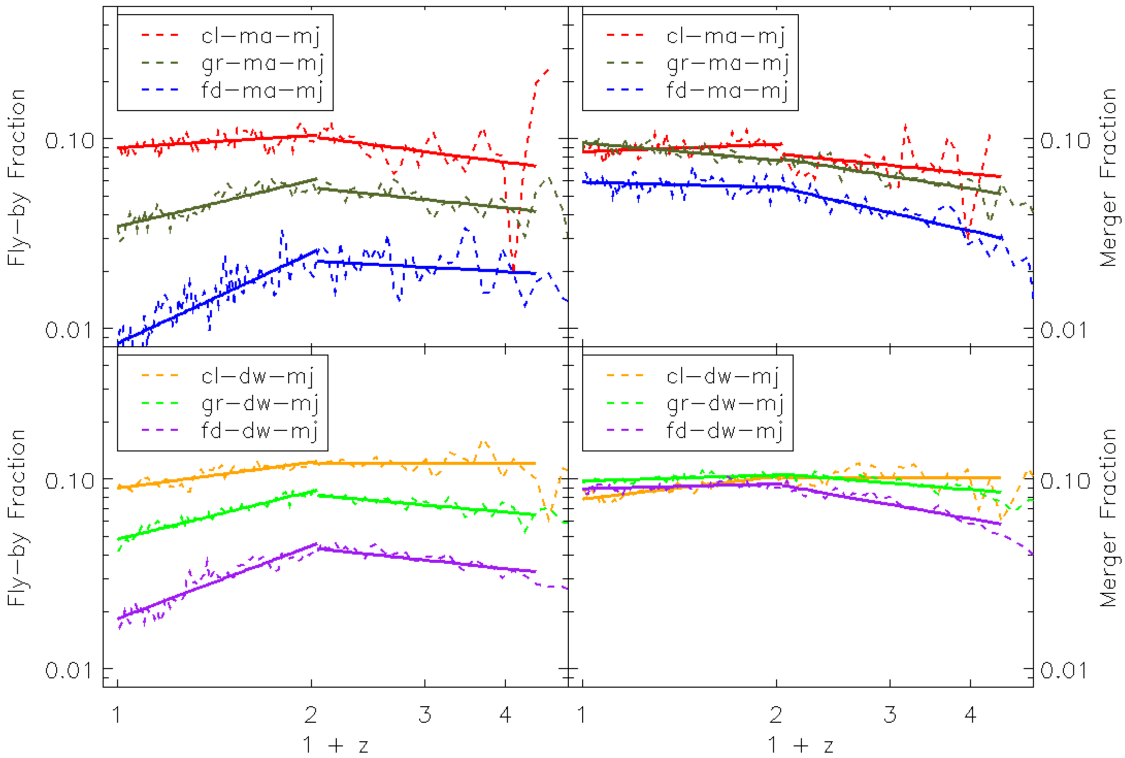

Figure 1. Fly-by (left) and merger (right) fractions as a function of redshift. Upper (bottom) panels are for massive (dwarf) halos. Colors indicate environments (red, orange - cluster / green, yellow green - filament / blue, purple - field). Solid lines are fitting functions of $F(z) = F(0)(1+z)^m$ at $z < 1$ and $z > 1$.

on major interactions with a mass ratio range from 1:1 to 1:3.

We divide galaxies into three groups (cluster, filament, and field) to find dependences on the environment. The environmental parameter is measured by counting the the number of halos within a comoving radius of 5 h^{-1}Mpc. We determine two values of the parameter through visual inspections of halo distributions at $z = 0$ and apply the values in all snapshots.

To define the fate of halo interactions, we measure the total energy to discern whether they are gravitationally bound or not. The total energy in a two-body system is given by;

$$E_{12} = M_1 M_2 \left(\frac{1}{2} \frac{(\vec{V_1} - \vec{V_2} + H(z)\vec{R_{12}})^2}{M_1 + M_2} - \frac{G}{|\vec{R_{12}}|} \right). \tag{1}$$

It includes the Hubble recession velocity in a part of the kinetic energy. If a halo pair has a positive energy, it is called a fly-by encounter.

4. RESULTS

We measure the fractions of major interactions as functions of redshift, halo masses, and ambient environment (Figure 1). The three main results are as follows:

1. All fractions have different inclinations between $z < 1$ and $z > 1$. We use a fitting function, $F(z) = F(0)(1+z)^m$ where m is an inclination index. At $z > 1$, fly-by and merger fractions decrease (negative values of m) with redshift. At $z < 1$, fly-by fractions increase ($m > 0$), while merger fractions decrease ($m < 0$) or remain stable ($m \sim 0$).
2. From $z \sim 1$, the fly-by fraction of dwarf halos ($6.42 \pm 0.02\%$) is higher than those of Milky-way sized halos ($5.37 \pm 0.03\%$) on average. In addition, dwarf halos go through more mergers ($9.51 \pm 0.03\%$) than Milky-way sized halos ($7.98 \pm 0.04\%$).
3. The fly-by fraction of Milky-way sized halos in clusters is $4 - 11$ times greater than those in fields from $z \sim 1$. In contrast, the merger fractions have a smaller difference of $1.5 - 1.7$ times between the two environments. Furthermore, halos in filaments experience more mergers than those in clusters at $z = 0$.

We suggest that the empirical pair/merger fractions (that decrease from $z \sim 1$) are in fact driven by the fly-bys, not by the mergers themselves.

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