Simulations of Mass Loss in Isolated Dwarf Galaxies

Robert Marcus

In this study, we examine the efficiency of mass ejection in hydrodynamic simulations of dwarf galaxies ranging in mass from 10^6-10^{11} solar masses. The energy to blow away the gas in the galaxies is supplied by supernova feedback, wherein a fraction of the energy from an exploding star is deposited into the surrounding gas.

Introduction

Since the first observation in the 1930's that galaxy clusters contained insufficient visible matter to account for observed galactic velocities, astronomers have been aware that visible baryonic matter does not constitute all of the mass in the universe. Presently, it is known that more than 85% of the matter in the universe is not visible and is commonly called dark matter. The nature of dark matter is still unknown. Dark matter interacts with baryonic matter primarily through gravity and condenses into roughly spherical halos. The presence of dark matter halos can be detected via the motions of the stars and gas in the galaxies and galaxy clusters that form within these halos.

In the cold dark matter cosmological model we have used, structure in the universe grows via a bottom-up hierarchical model, with small dark matter halos accreting mass and combining with other halos to form larger halos. Numerical simulations of galaxies and galaxy clusters reveal that dark matter substructure survives within larger structures. Thus, these simulations show that galaxies of all sizes are scaled versions of galaxy clusters. Observations of the Milky Way Galaxy contradict this result and lead to the conclusion that there are missing satellite galaxies. The simulations predict more satellites than are observed by a factor of about 50. Figure 1 shows the number of observed and simulated halos for the Virgo cluster and the Milky Way Galaxy (Moore et al. 1999). Obviously, a problem exists either with the present theory of dark matter substructure or with the theory that gas mass should map the dark matter distribution. In this study, we investigate the latter possibility.

Methods

Our simulations were run with the smooth particle hydrodynamics code Gasoline (Wadsley et al. 2003). Gasoline is a three dimensional N-body code that includes gravity and hydrodynamic forces. Gravity is implemented using a tree algorithm. For any given particle, the gravitational forces due to closely neighboring particles are summed individually, whereas the forces contributed by distant particles are combined with a single fourth order multipole moment representing a group of particles. The smooth particle hydrodynamics method represents gas as a group of particles. The mass of each of these particles is dependent on the desired resolution. These particles then interact with each other under the influence of hydrodynamic forces in addition to gravity. Gasoline also turns a fraction of the gas into stars when the gas is cold and dense enough to collapse into stars.

Gasoline not only handles star formation, but also allows for the death of stars. For stars more massive than eight times the mass of the sun, this death comes via a violent explosion known as a supernova. Inputting the energy from a supernova into the surrounding gas is an effective means of limiting the rate of star formation in simulations as it increases the temperature and decreases the density of the gas. Exactly what fraction of the energy goes into the surrounding gas is not well understood, and is parameterized in our simulations by the quantity E_{SN}. Studies of the star formation history in simulations of isolated Milky Way-like galaxies have resulted in a preferred E_{SN} value of 0.4.

In addition to curtailing star formation, injecting supernova energy into the gas surrounding the event can also increase the kinetic energy of the gas to the point where it is no longer gravitationally bound to the galaxy. Most galaxies in the universe are dwarf galaxies. Studying mass loss in these galaxies may be a means to supplying a possible resolution to the problem of the missing satellite galaxies of the Milky Way. The primary purpose of this study is to determine under what conditions gas is ejected from dwarf galaxies of total mass 10^6-10^{11} solar masses and what fraction of the gas is ejected. The simulations were run with each of eight different values for E_{SN} for each initial galaxy mass: 0.0, 0.01, 0.05, 0.1, 0.4, 0.6, 0.8, and 1.0.

Initial Conditions

Dwarf galaxies with values of m_{200} ranging from 10^6-10^{11} solar masses were simulated with a resolution of 50000 gas particles. Using Eq. 26 from Springel (1999), this mass was used to calculate v_{200}. This value for v_{200} was used as the circular velocity value in Tully-Fisher relations to calculate the baryonic mass of the galaxies. The baryonic mass was considered to consist entirely of gas with an initial temperature of 10^4 K. This temperature corresponds to a sound speed of about 10 km s^{-1}. This is also the temperature at which the hydrogen gas is neutral and cannot cool further via line cooling. The velocity v_{200} was then adjusted until the velocity given by the rotation curve matched the initial guess for v_{200} at a distance of one to ten kiloparsecs, depending on the mass of the galaxy. This amounted to an adjustment in v_{200} of approximately 10%. The new value of v_{200} was then used to fit the dark matter halo in the initial conditions file. The initial conditions were created using code from Springel (1999). The dark matter halo was created using a profile developed by Navarro, Frenk, and White (1997) during studies of dark matter halos in cosmological simulations.

Because there are no hydrodynamic interactions between dark matter and baryonic matter, the dark matter particles were removed from the initial conditions file to increase the speed at which the simulations run. The presence of the baryonic matter resulted in an increase in the dark matter halo concentration. Thus a new Navarro, Frenk, and White (NFW) profile was fit to the halo and used to define a static potential field with which to replace the dark matter particles. The potential field consisted of four parameters (softening length, halo concentration, m_{200}, and r_{200}) whose values were determined by fitting an NFW profile to the Force versus radius curve for the dark matter in each set of galaxy initial conditions.

Results

Initially, all of the gas mass in each galaxy was contained within the virial radius, a characteristic length for a galaxy, defined as the distance from the galactic center at which the density is approximately 200 times the critical density of the universe. For the purposes of comparing with observational data, the stellar mass within this radius at the end of each of the simulations was recorded. Each simulation was run for a time of 4×10^9 years.

Figure 2 shows the stellar mass remaining within the virial radius at the end of each simulation as a function of the circular velocity of the galaxy. The circular velocity is determined by the initial gas mass, with larger velocities corresponding to the more massive galaxies. Table I lists the initial gas mass and circular velocity of each of the simulated galaxies. As expected, introducing any supernova feedback greatly reduces the stellar mass formed for the smallest galaxies, as the energy from the supernovae increase the temperature and decrease the density of the surrounding gas, preventing further star formation. However, as the galaxies become more massive, the stellar mass produced in simulations with low feedback ($E_{SN} \leq 0.1$) approaches the stellar mass produced in simulations with no feedback, while about an order of magnitude less mass is in stars for simulations with $E_{SN} \geq 0.4$. For simulations with $E_{SN} \leq 0.1$, the stellar mass levels off for circular velocities greater than about 40 km s^{-1}. This is due to the fact that above this threshold, the gaseous disks are no longer unstable against the formation of spiral arms. Without spiral arms, star formation is reduced. This leveling off does not occur for the simulations with $E_{SN} \geq 0.4$, possibly because the increased feedback allows the most massive galaxies to remain unstable to spiral arm formation.

Figure 3 shows the gas mass ejection efficiency as a function of the circular velocity of the galaxy. Ejected mass is defined as the total mass of gas with positive energy. This mass is no longer gravitationally bound to the galaxy and will become part of the intergalactic medium. Almost all of the mass is ejected from the smallest simulated galaxy, of total mass 10^6 solar masses, regardless of whether or not there is any supernova feedback. This is due to the fact that the potential well created by such a small halo is not deep enough to keep gas bound even without injecting additional energy. Mass ejection becomes negligible for all galaxies with circular velocity above about 10 km s^{-1} for $E_{SN} \leq 0.1$. For larger values of E_{SN}, the ejection efficiencies remain higher than 50% up to a circular velocity of about 35 km s^{-1}. Beyond this point, supernova feedback is no longer a significant source of mass ejection.

Conclusion

According to numerical simulations, small dark matter structures survive within a hierarchical universe, leading to the conclusion that galaxies of any size are scaled models of galaxy clusters. The dark matter substructure problem arises because of the discrepancies between the results of these simulations and the observations of the Milky Way Galaxy. Figure 4 again shows the number of observed and simulated halos for the Virgo Cluster and Milky Way Galaxy, this time with a vertical line representing the point below which galaxies will lose more than 50% of their baryonic matter. For points left of this vertical line, the number of predicted satellite galaxies exceeds the observed number by a factor of 20-50. This study has shown that one possible explanation is that the baryonic matter has been ejected from these halos, leaving them unobservable.

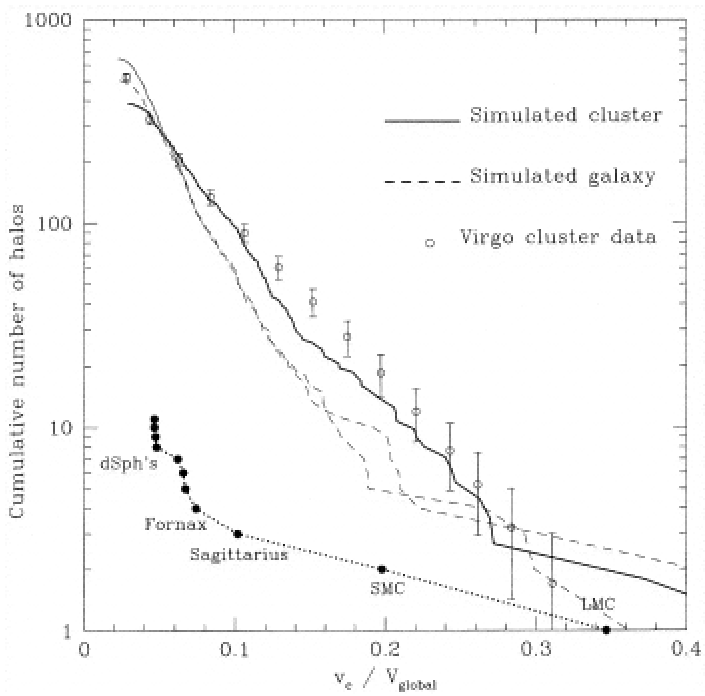

Figure 1: The number of observed satellites for the Milky Way Galaxy falls short of the predicted number from simulations by a factor of about 50.

Table I
Initial Gas Mass and Circular Velocity

Total Mass (Solar Masses)	Initial Gas Mass (Solar Masses)	Circular Velocity (km s^{-1})
10^6	3.07×10^5	1.45
10^7	1.93×10^6	3.12
10^8	1.22×10^7	6.73
10^9	7.73×10^7	14.51
10^{10}	4.87×10^8	31.26
10^{11}	3.08×10^9	67.34

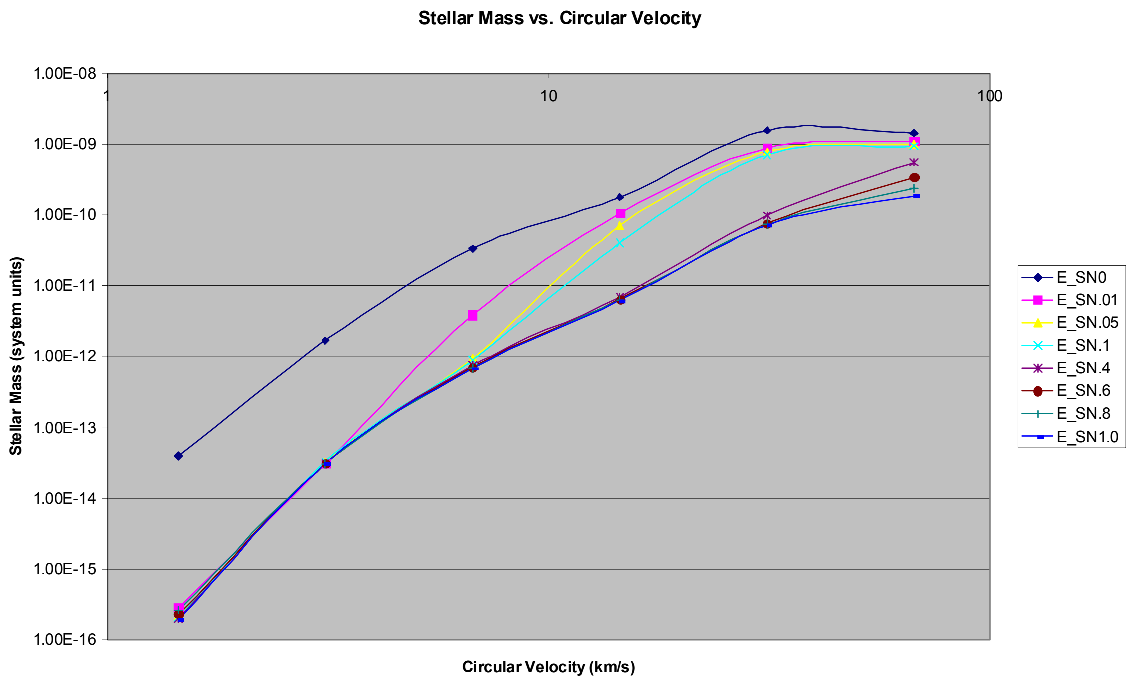

Figure 2: Stellar Mass vs. Circular Velocity for each of the eight values of E_{SN}.

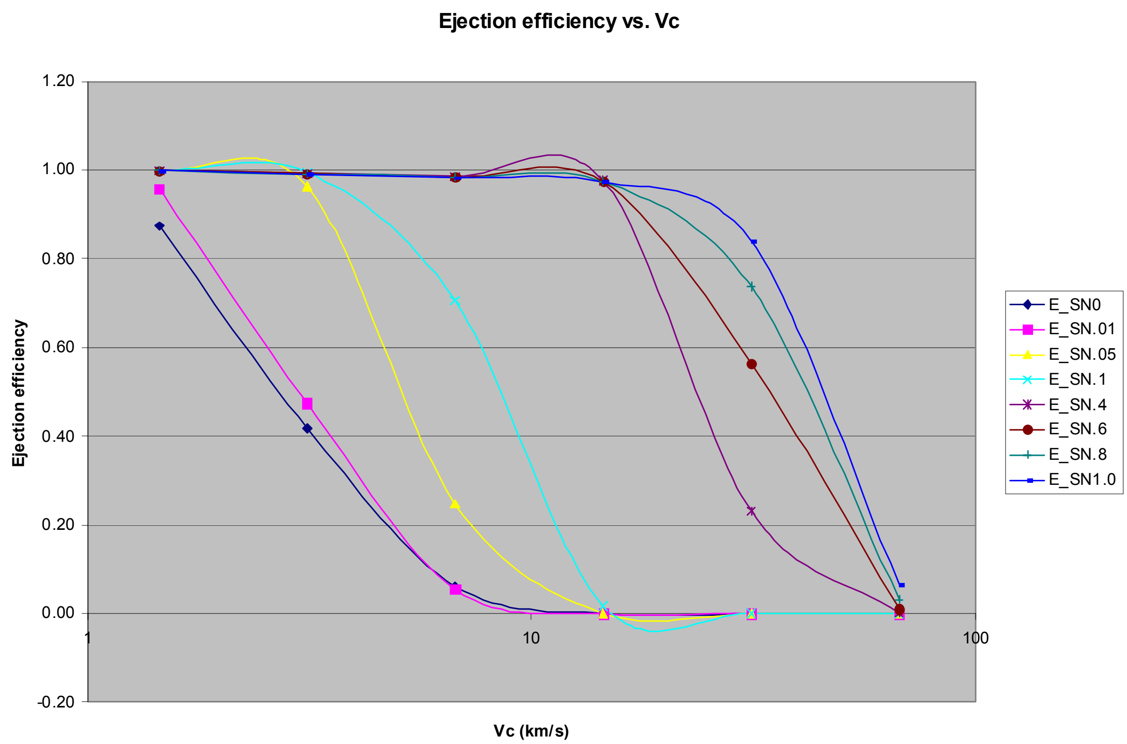

Figure 3: Mass ejection efficiency vs. Circular velocity for each of the eight values of E_{SN}

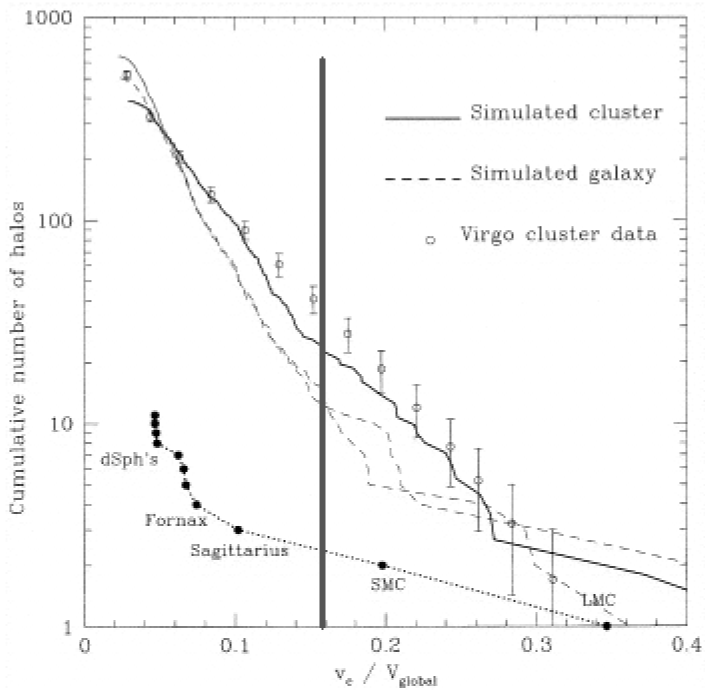

Figure 4: For values of Vc to the left of the vertical line, more than half of the gas would be ejected from the galaxy, assuming the preferred value of E_{SN} = 0.4.