Lecture 14 : Formation of galaxies; evolution of Milky Way

It is now believed that galaxies, as well as other structures in the universe, have been formed out of primordial density fluctuations due to gravitational instability. The prevalent notion is that mass in the universe is dominated by **cold dark matter**, and the models are generically known as CDM models. In these models a power spectrum of density fluctuations are predicted, which has more power for smaller structures. As density fluctuations grow with time, one then expects small scale fluctuations to grow non-linear first. These structures then merge with one another to form bigger structures, and this scenario is known as the **hierarchical scenario** of structure formation.

The gravitational potential for these structures are mainly provided by dark matter, and baryonic gas is expected to fall into these potentials soon after recombination era. Baryons are different from dark matter in that they dissipate, primarily through radiation. It turns out that dissipation is at the heart of the question if and when a structure is going to form stars, be luminous and essentially form a galaxy.

1 Gas cooling

It was argued by (Hoyle ?; Rees & Ostriker 1977, Silk 1977) that stars can form in a structure if the gas cooling time scale is smaller than the dynamical time scale. Gas will be able to fragment only under this condition, with the fragments forming stars later. Otherwise the gaseous cloud will remain hot, as it collapses under gravity, and will not form stars.

Homework on limits of galaxy mass and size from cooling argument

The cooling timescale is defined as $t_c = nkT/(n^2\Lambda(T))$ where $n^2\Lambda(T)$ is the volume cooling rate of gas at temperature T (erg/cc/s). This timescale therefore depends on the density and temperature of the gas. One can also predict from structure formation theories, given a power spectrum of fluctuation, the typical mass and size of objects collpasing at a given epoch (that is 1-σ fluctutations). One can find the gas density in this object, assuming a dark matter to baryon density ratio. One can also assign a temperature to the gas, equating it the virial temperature of the system. One can then draw a limiting curve in the $n-T$ parameter space for which $t_{cool} \leq t_{dyn}$. Here the dynamical time could be the free-fall time scale of the collapsed object.

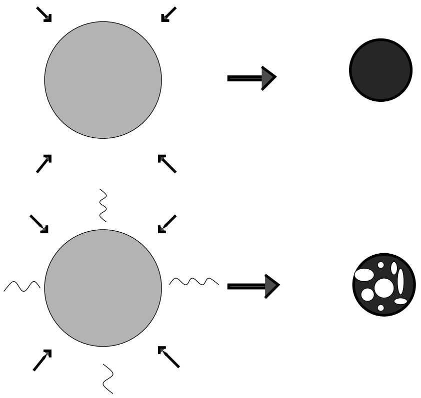

Figure 1: Cartoon to explain the importance of dissipation for galaxy formation.

When the density and temperature of real objects are superposed in this diagram one finds that galaxies fall in the $t_{cool} \leq t_{dyn}$ space, and clusters are outside the limiting curve. It is clear that galaxies have suffered dissipation whereas groups and cluster have not.

1.1 Molecular hydrogen cooling

When the temperature of the gas is $\geq 10^6$ k, the cooling function is dominated by free-free radiation, where it is dominated by atomic line cooling for $T \geq 10^4$ K. Below this temperature, cooling is dominated by molecular line transitions. If we want to find out when the first structures formed, we must then determine the cooling efficiency due to hydrogen molecules. In the absence of dust grains in the early universe, the only way to form molecular hydrogen is to use the residual free electrons after recombination to form $H + e^- \rightarrow H^- + \gamma$. The negative ion then forms molecular hydrogen through $H^- + H \rightarrow H_2 + e^-$. The negative ion is however vulnerble to the CMBR radiation, until about $z \leq 100$, after which some amount H_2 can form in small clumps of matter.

This calculation was done in detail by Tegmark et al (1997, ApJ, 474, 1) and according to these calculations, the first luminous objects in the universe could have formed as early as $z \sim 30$ with baryonic masses of order 10^5 solar masses.

The fate of these objects and how they affected the ambient medium is an active field of research at present.

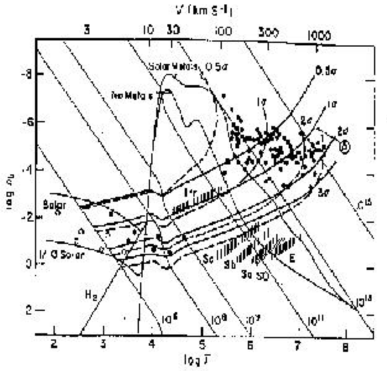

Figure 2: The cooling diagram (Blumenthal et al 1984, Nature) is divided by the cooling criteria. Dots at upper right represent alll groups and clustes of galaxies within 5000 km/s in the CfA catalogue. The shaded regions at lower right denote the various types of galaxies. Dwarf spheroidal galaxies are plotted at lower left. The model curves assume a power spectrum with $n = 1$.

2 Evolution of Milky Way

Let us begin our discussion on the evolution of galaxies with our own Galaxy. In a classic paper in 1962, Eggen, Lynden-Bell and Sandage (ApJ, 136, 748) studied the motion of a sample of high-velocity stars. They found a correlation between metallicity and orbital eccentricities and angular momenta, and argued that the Galaxy formed quickly, through the collapse of a uniform, isolated proto-galactic cloud.

The basic idea of ELS was that stars formed in the early stage of the collapse of a protogalactic gas cloud retained the motion of the inward falling gas and are seen today as randomly oriented, elliptical oribiting halo stars. Therefore one expects the oldest, lowest metallicity stars, with largest ultraviolet excess, to have the highest eccentricity orbits. They also have the lowest angular momenta. Angular momenta and eccentricity are adiabatic invariants; their values do not change significantly if the potential changes slowly. They advocated the following scenario of Milky Way formation : a near-spherical spinning protogalactic cloud collapsed to form MW. ‘Initially this cloud was metal poor and in near free-fall. As it collapsed, its rate of spin increased to conserve its angular momentum, and from it condensed the most metal-poor stars and halo globular clusters. The present eccentric orbits of these objects were a direct consequence of the free-fall

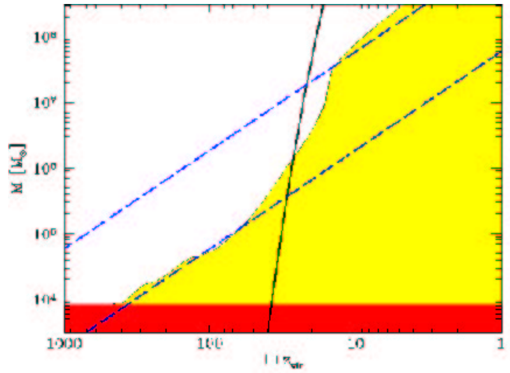

Figure 3: The minimum mass of clumps that can form stars with molecular hydrogen cooling as a function of collapse redshift in the standard CDM. The dashed lines corresponding to $T_{vir} = 10^4$ and 10^3 K are shown for comparison. The No cooling can help in the red region since $T_{vir} \leq T_{CMB}$. The solid line shows the 3-σ peak in standar CDM with $\sigma_8 = 0.7$. Such objects can form with baryonic mass $\Omega_b \times 2 \times 10^6 \sim 10^5$ $M_\odot$ can form at $z \sim 30$.

of the proto-galactic cloud....Supernova increased the metallicity of the cloud as it collapsed. After shrinking in radius by a factor of order 10, the cloud became metal-rich and flattened into a centrifugally supported disk. At this point disc formation commenced and the Milky Way settled down to something like its present configuration.' According to them the collapse was quick, with a timescale of order a Gyr. This however predicted that globular clusters should have a small spread in age.

Another competing scenario was proposed in 1978 by Searle and Zinn (ApJ, 225, 357) whose study of Galactic globular cluster showed that there is no metallicity gradient. They inferred from their observation of a large age spread in the halo stars that the halo was built from independent low-mass fragments on a timescales of a few Gyrs, and not in a monolithic collapse as suggested by ELS. This idea got a boost when Majewski et al (1994, ApJ, 427, L37) found strong evidence of mergers of substructures, in the form of coherently moving group of halo stars (also the discovery of Sagittarius dwarf galaxy, which is being devoured by Milky Way, in 1995, whose tidal arms wrap 360° around Milky Way).

Elemental abundances can also give clues to the history of Milky Way. The halo stars have [0/Fe] ratio close to 3, indicative of enrichment from high mass Type II supernovae (like other α particle elements, like Mg), with lifetime less

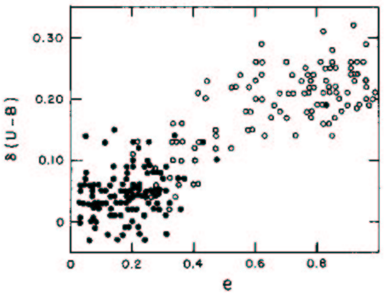

Figure 4: Correlation between ultraviolet excess and eccentricity (ELS).

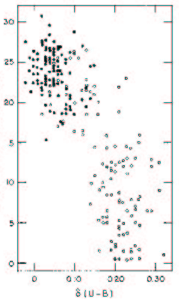

Figure 5: Correlation between the angular momentum and the ultraviolet excess (ELS).

than 0.1 Gyr. When plotted against [Fe/H], say, one sees a plateau for metal poor, halo stars, which deviates when SN Type I from disk stars begins to contribute. This could have been used to *date* the formation of disk stars, but the lifetime of Type I supernovae is still uncertain. It is still interesting to note that this life time is roughly close to the formation epoch of the galactic disk! If this life time is about a Gyr, then the halo also formed on the timescale of a Gyr. This is roughly consistent with the estimate of the Galactic age from cosmology of about 13 Gyr and a disk lifetime, from white dwarf luminosity functions, of 10-11 Gyr.

Theories of hierarchical structure formation advocates a Searle-Zinn type of scenario, with galaxies being formed out of many subclumps. A sure sign of a past significant merger in Milky Way (and in many other galaxies) is the presence of the *thick disc*, discovered in 1983 by Gilmore & Reid, whose member stars have kinematics and metallicities intermediate between that of halo and (thin) disc stars. It is believed that the thick disk stars were created by the infall of a substructure (satellite galaxy) which dynamically ‘heated’ the population of stars

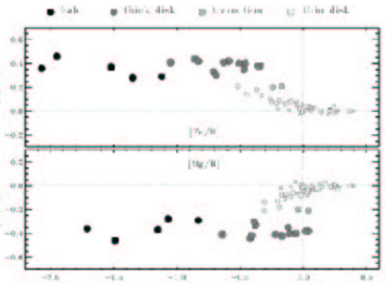

Figure 6: Filled black circles denote halo stars in this plot between [Mg/Fe] and [Fe/H] (Fuhrmann 1998, AA, 338, 161)

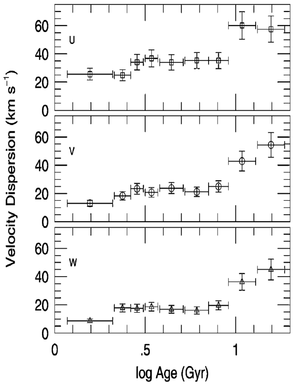

Figure 7: from Freeman and Bland-Hawthorn (2002 ARAA).

which had formed a disc by then. Edvardsson etal (1993) found a correlation bewteen velocity dispersion in u,v,w direction of thick disc stars, and their age. One finds that stars older than 10 Gyr has very high velocity dispersion, which perhaps indicates that thick disc was formed by a single merger event around that time.

It therefore appears that a disc appeared around 10-12 Gyr ago ($2 \geq z \geq 1.5$), which suffered a major merger creating the thick disc. The majority of the stars formed out of gas accreted during this merger event.