TIME-SCALE FOR ACCRETION OF MATTER

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1. Abstract
Mass accretion is the key factor for evolution of galaxies. It can occur through secular evolution, when gas in the outer parts is driven inwards by dynamical instabilities, such as spirals or bars. This secular evolution proceeds very slowly when spontaneous, and can be accelerated when triggered by companions. Accretion can also occur directly through merging of small companions, or more violent interaction and coalescence. We discuss the relative importance of both processes, their time-scale and frequency along a Hubble time. Signatures of both processes can be found in the Milky Way. It is however likely that our Galaxy had already gathered the bulk of its mass about 8-10 Gyr ago, as is expected in hierarchical galaxy formation scenarios.

2. Introduction
There are two essential processes for a galaxy to accrete mass: either it accretes gas regularly, through internal dynamics, producing radial flows, from gas in the outer parts (the reservoir could be in the Local Group); or the accretion occurs in more violent events, galaxy interactions or mergers. The first process, that will be called secular accretion, can also be triggered and enhanced by the passage of companions, so that the two processes are in fact inter-related. Let us try to estimate the corresponding time-scales involved.

3. Secular evolution
The galaxy can be considered as a giant accretion disk: to minimise its energy, it has the tendency to concentrate, and accrete gas from the outer
parts towards the center. But the angular momentum is a barrier: only through tangential forces, creating torques, can the angular momentum be exchanged and transferred outwards in order that the mass flows inwards. One can apply an analog of the theory of viscous disks (Lin & Pringle 1989). In that frame, viscous torques are the way to re-distribute angular momentum. If the time-scale for this re-distribution, $\tau_{\text{vis}}$, is of the same order of magnitude as the time-scale to form stars $\tau_*$, then an exponential stellar disk is created, and this generates also an exponential distribution of metallicity (Tsujimoto et al 1995).

3.1. GRAVITY TORQUES

What is the nature of the viscosity, effective in galactic disks? Normal viscosity is not efficient, due to the very low density of the gas. One could think of macroturbulent viscosity, but the time-scales are longer than the Hubble time at large radii, and could be effective only inside the central 1kpc. Instead, if the galaxy disks develop non-axisymmetric density waves such as spirals or bars, gravity torques are then very effective at transferring the angular momentum outward. This led Lin & Pringle (1987) to propose a prescription for an effective kinematic viscosity for self-gravitating disk undergoing gravitational instabilities.

The basis of this prescription is described in Figure 1. Gravitational instabilities are suppressed at small scales through the local velocity dispersion $c$, and at large scale by rotation. The corresponding limiting scales are the Jeans scale for a 2D disk $\lambda_J \sim c^2/(G\mu)$, and $\lambda_c \sim G\mu/\kappa^2$, where $\mu$ is the disk surface density, and $\kappa$ the epicyclic frequency. Scales between $\lambda_J$ and $\lambda_c$ are unstable, unless $c$ is larger than $\pi G\mu/\kappa$, or the Toomre $Q = \frac{c\kappa}{G\mu}$ is larger than 1. If the disk is cold at the beginning (general case for the gas), instabilities set in, which heat the disk until $Q \sim 1$, and those instabilities provide the necessary angular momentum tranfer, or viscosity, to concentrate the mass. Since the size of the region over which angular momentum is transferred is $\sim \lambda_c$, and the time-scale is a rotation period, $2\pi/\Omega$, the effective kinematic viscosity is $\nu \sim \lambda_c^2 \Omega$, and the typical viscous time $\tau_\nu \sim \lambda_c^2 \Omega^3/(G^2 \mu^2)$.

Why should there be approximate agreement between the two time-scales, viscosity and star-formation? This comes from the fact that the two processes depend exactly on the same physical mechanism, i.e. gravitational instabilities. As shown empirically by Kennicutt (1989), the Toomre parameter $Q$ appears to control star-formation in spiral disks. Therefore, if the regulating instabilities have time to develop, one can expect that $\tau_\nu \sim \tau_*$, as required for exponential light and metallicity distribution.

In summary, if the gravitational viscous time-scale is governing the mass
Figure 1. Gravitational instabilities regulate the transfer of angular momentum, through a feedback process, so that we can talk of "gravitational viscosity": when fresh gas has been accreted, or radially transported inwards, the disk becomes cold ($Q < 1$); the disk then develops waves, that create non-axisymmetry and gravity torques; they transfer the angular momentum outwards (trailing waves), and matter is driven inwards. The waves heat the disk, until $Q \sim 1$. The disk needs the presence of gas to cool down again, and close the loop.

accretion, the time-scale for accretion by secular evolution is of the order of a few dynamical times. But there must exist a reservoir of gas in the outer parts. Evidence that such accretion exists can be found in present day galaxies: the strong frequency of large-scale asymmetries of gas observed in the outer parts, or lopsidedness, cannot be explained without continuous or repeated accretions (e.g. Richter & Sancisi 1994). The presence of gas warps in almost every disk galaxies observed in HI cannot be explained by a persistant mode, but is likely to be the manifestation of gas accretion with a different angular momentum orientation than the normal to the galaxy disk (Binney 1992).

4. Galaxy Interactions

There is plenty of evidence that the Milky Way has accreted mass or has even encountered merging events in the past (e.g. Searle & Zinn 1978, Zinn 1993). Moving groups are detected in the halo (Majewski 1993, and this volume), and the thick disk is best explained by an interaction event (Bienaymé, this volume). This is in line with hierachical formation.

In hierarchical cosmological scenarios, galaxies have formed by succes-
sive mergers of larger and larger entities. Primordial fluctuations of dark matter exist at all scales, but small-scale perturbations become non-linear and collapse first, and are then incorporated in larger structures collapsing later on. Small halos then merge into larger ones; the baryonic structures that had condensed in the halos potential well, can also merge, with some delay. While the merging scenario of dark halos is quite well understood and reproduced in simulations, or quantified analytically by Press-Schechter formalism, the scenario concerning the baryonic component, i.e. galaxies, is less known, because complex physics intervenes (cooling, star formation, feedback, IMF, metal abundance..) in supplement to gravity. As a general statement, it is thought that galaxy merging directly follows dark halos merging, as soon as the virial velocities inside the merged dark structure is below a certain threshold (roughly equal to the escape velocity for individual galaxies, from dynamical friction efficiency). Since structures forming now have quite large virial velocities, galaxy merging becomes less and less efficient.

Galaxy interactions were undoubtedly more frequent in the past, and many groups have tried to quantify the effect. Already Toomre in 1977 has estimated the number of mergers from their observed frequency at $z = 0$ just taking into account the probability of eccentricities of binary orbits. Statistics of close galaxy pairs from faint-galaxy redshift surveys have shown that the merging rate increases as a power law with redshift, as $(1 + z)^m$ with $m = 4 \pm 1.5$ (e.g. Yee & Ellingson 1995). Lavery et al (1996) claim that ring galaxies are also rapidly evolving, with $m = 4 - 5$, although statistics are still insufficient. Many other surveys, including IRAS faint sources, or quasars, have also revealed a high power-law. Governato et al (1998) from numerical simulations of standard ($\Omega = 1$) and open ($\Omega_0 = 0.3$) CDM models find that the number density of interacting binaries is proportional to $(1 + z)^{4.2}$ and $(1 + z)^{2.5}$ respectively.

The number of mergings for a given galaxy is still quite uncertain observationally; the merger frequency, and the peak merging epoch are very sensitive to the values of universe density ($\Omega$) and the cosmological constant ($\Lambda$, see e.g. Carlberg 1991). The observation of relatively thin stellar disks has been advanced as a constraining argument.

4.1. THICKENING OF DISKS

Galaxy interactions can easily thicken or even destroy a stellar disk (e.g. Gunn 1987). The fragility of stellar disks with respect to thickening has been used by Toth & Ostriker (1992) to constrain the frequency of merging and consequently the value of the cosmological parameter $\Omega$. They claim for instance that the Milky Way disk have accreted less than 4% of its mass
within the last $5 \times 10^9$ yrs. Numerical simulations have tried to quantify the thickening effect (Quinn et al 1993, Walker et al 1996). They show that the stellar disk thickening can be large and sudden, but it is strongly moderated by gas hydrodynamics and star-formation processes, since the thin disk can be reformed continuously through gas infall. Velazquez & White (1998) through N-body simulations find that analytical derivations overestimate by factors 2-3 the disk heating and thickening; while prograde satellites do heat the disk, retrograde ones produce essentially a coherent tilt of the disk. Companion accretions therefore cause stellar warps and asymmetric disks.

Galaxies presently interacting have their ratio $h/z_0$ of the radial disk scalelength $h$ to the scaleheight $z_0$ 1.5 to 2 times lower than normal (Bottema 1993; Reshetnikov & Combes 1997). However, since galaxies have experienced many interactions in the past, including the presently isolated galaxies, all these perturbations, thickening of the planes and radial stripping, must be transient, and disappear after an interaction time-scale, i.e. one Gyr. Present galaxies are thought to be the result of merging of smaller units, according to theories of bottom-up galaxy formation; a typical galaxy has accreted most of its mass, and the existence of shells and ripples attests of the frequency of interactions (Schweizer & Seitzer 1992). This implies that the global thickness of galaxy planes can recover their small values after galaxy interactions. Or in other words, the disk of present day spirals has been essentially assembled at low redshift (Mo et al 1998).

4.2. MERGING HISTORY OF THE MILKY WAY

Since the number of galaxy interactions and mergers were much larger in the past, it is likely that most accretion events occured long ago in the Milky Way. This is compatible with the observation of globular clusters for example: Unavane et al (1996) conclude that there has not been more than 10% of the mass accreted over the last 10 Gyr. The same is true for many galaxies of the Local Group, except maybe for the SMC (Sarajedini et al 1998).

Although we are still witnessing the on-going mergers of some dwarf galaxies bound to the Milky Way (Sagittarius dwarf, Ibata et al 1994; Magellanic Clouds, Lin & Lynden-Bell 1977, Putman et al 1998), the bulk of the mass must have been accreted some Gyrs ago. Many debris stay coherent as tidal streams for the Milky Way life-time: Johnston (1998) estimates that up to 10% of the sky is covered by those debris, and this could have consequences for microlensing experiments (Zhao 1998). If the time-scale for mixing after stellar accretion can be long, more than a Hubble time, the time-scale for gas accretion and processing is quite short (less than a
Figure 2. Indicative accretion rate as a function of time, for a structure of the Milky Way mass ($10^{12} \, M_\odot$ halo). Full line: normalised accretion rate, as expected from the Press-Schechter formalism (standard CDM model) for the dark halos, and modified for baryonic systems merging; Dashed line: power law $m = 4.5$ as a function of $(1+z)$ for comparison; Dash-Dotted line: corresponding fraction of the present mass assembled as a function of time.

Gyr). High velocity clouds (HVCs) could represent a huge reservoir of gas around the Milky Way, if we interprete correctly their distance. If the latter is around 40kpc from the center, they correspond to a total of $10^{11} \, M_\odot$ of HI gas (Blitz et al 1998). Simulations of the clouds infalling towards the Local Group gravity center are compatible with the observations. HVCs will then be the analog of the Lyman-limit absorbing clouds in absorption in front of quasars. Embedded in dark mini-halos, they could be the building blocks of the Galaxy (Blitz et al 1998).

To have a statistical estimate of these accretion times, we can use the empirical law of interactions increase with redshift, in $(1+z)^m$ as described earlier. An other approach is to consider the probability of formation of halos of mass $M = 10^{12} \, M_\odot$, such as the Milky Way. This is obtained through the well-known Press-Schechter (1974) formalism, or "excursion set" derivation (Bond et al 1991). The model is based on the existence of a Gaussian random field for initial density fluctuations, on the follow up of their linear growth, and on spherical collapse theory. This leads to the
differential mass function:

\[ f(\sigma(M), t) = \frac{\delta_c}{\sqrt{(2\pi)D(t)\sigma^3}} \exp\left[-\frac{\delta_c^2}{2D(t)^2\sigma^2}\right] \]

where \( \sigma(M) \) is the mass variance, \( D(t) \) the linear growth factor and \( \delta_c \) the critical overdensity \( \delta_{\rho} \) for collapsed structures (extrapolated in linear theory = 1.69). The derivative of this formula with respect to time (or redshift) gives the rate of change of density of halos of a given mass \( M \). But this is the difference between their increase as the result of mergers of smaller halos, and their decrease due to combining into halos of larger masses (and can become negative). To have the rate of merging, Carlberg (1990a) assumes that the halos of mass larger than \( M \) come essentially from merging masses between \( M/2 \) and \( M \); a more exact calculation is derived by Lacey & Cole (1993), and leads to an analytical expression for the merging or accretion rate as a function of time, to form the Milky Way halo, for example. This analytical expression is in very good agreement with N-body simulations (Lacey & Cole 1994).

Once the rate of merging of halos is estimated, the probability of merging the baryonic systems must be taken into account, to compare with observations, and this introduces large uncertainties. Carlberg (1990b) proposes a simple criterion for baryonic systems to merge: either they merge in a dynamical time-scale if their relative velocity is lower than the escape speed from the systems, or they never merge in a Hubble time. He then derives the baryonic merging rate by considering only the fraction of the Maxwellian distribution for velocities less than the threshold for merging. Lacey & Cole (1993) show that the merging efficiency depends strongly on the eccentricity of the initial orbits, through dynamical friction. The results between circular orbits and highly elongated ones (pericenter = 5% of apocenter) can vary by factors 3 or more. An average estimate of the accretion rate as a function of time for baryonic matter is plotted in fig 2. It is very close at low redshift to a power-law of power \( m = 4.5 \), the value expected for this model universe, through numerical simulations. In this scenario, it can be seen that most of the Galaxy (90% of the mass) was built 9 Gyr ago (if \( t_0 = 15 \) Gyr).

5. Conclusion

Mass accretion can be considered to occur through two processes: a secular accretion from gas in the outer parts of galaxies, or in the near halo (may be HVCs), that occurs on a dynamical time-scale; and through galaxy interactions and mergings, that has progressively built the galaxy in the past. Both processes can occur on widely different time-scales, according
to the environment. For instance, Low Surface Brightness (LSB) galaxies appear unevolved systems, with large gas fraction, low mass concentration, and their long evolution time-scale is attributed to their poor environment (Bothun et al 1997). The Milky Way on the contrary, as an HSB, had a very rapid evolution time-scale, and is likely to have accreted the bulk of its mass 8-10 Gyr ago. Its evolution is compatible with the statistical mean obtained in hierarchical scenarios, from the Press-Schechter formalism for the dark halos merging, implemented with simple recipes for the merging of baryonic systems.

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