DISSIPATIVE PROCESSES IN GALAXY FORMATION

Joseph Silk
Departments of Astronomy and Physics, and Center for Particle Astrophysics
University of California, Berkeley

Critical Scales of Protogalaxies

Dissipation of gravitational binding energy is the key to forming cosmic structure. This process is poorly understood, insofar as issues of fragmentation and coalescence arise during the collapse of a self-gravitating primordial gas cloud. Does a protogalactic cloud form stars during its initial collapse, or did its inner regions collapse to form a central massive black hole? The nonspherical and nonlinear collapse physics defies any simple prediction. This talk will focus on the role of dissipative processes in galaxy formation, with emphasis on early star formation. For a more detailed review of galaxy formation, the reader is referred to an article by Silk and Wyse.¹

One can at least state objectively that in order for any rapid dissipative collapse to be initiated, either locally or globally, the cloud must satisfy the requirement that the cooling timescale locally be less than the free-fall collapse time. This condition is quantified by setting the cooling time-scale \( \frac{3}{2} kT[\mu \Lambda(T)n]^{-1} \), where \( \Lambda \) is the cooling rate per hydrogen nucleus in a cosmic plasma of mean molecular weight \( \mu \) and unit density, \( n \) is the density, and \( T \) is the temperature, equal to the collapse time, proportional to \((Gn)^{-1/2}\). The resulting locus in the density-temperature plane (Figure 1) may be interpreted as a restriction on the minimum mean density at the appropriate value of the virial temperature for a cloud of arbitrary mass. This condition also applies to a highly non-uniform self-gravitating cloud, since fragments will acquire the virial velocity if their density contrast is high. Note that lines of constant mass intersect the cooling locus in the vicinity of the galactic virial temperature \((10^5 - 10^7 K \) for normal galaxies) at a total (including dark) mass of about \(10^{12} M_\odot\).

The significance of this result is the following. Once a protogalaxy is capable of local cooling, fragmentation and star formation may rapidly ensue. The cooling condition is necessary for star formation, but is not sufficient to guarantee that it occurs. Angular momentum and magnetic fields provide significant barriers in regions of galactic star formation that are overcome by magnetic and gravitational torquing as well as by magnetic field diffusion. The fundamental physics is poorly understood in galactic star formation, and successful theories are semi-phenomenological. I shall adopt a similar viewpoint with regard to protogalactic star formation: stars did form, and simple physical arguments provide a crude framework for understanding galaxy formation. Once stars have formed out of the protogalactic cloud, they should subsequently conserve orbital energy and angular momentum. The oldest stars in a galaxy therefore define the protogalactic potential well.

¹ To appear in the proceedings of the National Academy of Sciences Colloquium on Physical Cosmology, Irvine, March, 1992: Physics Reports (in press)
If appreciable protogalactic binding energy was dissipated before formation of the first stars, this only hampers our ability to discern the relation between protogalaxy parameters and those of the primordial density fluctuations. If dark halos consist of cold dark matter particles, no dissipation occurred during their formation, and the parameters of dark halo potential wells can therefore be used to reconstruct, or at least constrain, the primordial fluctuation power spectrum.

It is a satisfying coincidence that the parameters of an $L_*$ galaxy are indeed on the critical locus that in effect defines the most massive systems capable of undergoing efficient star formation. The identical argument also yields a scale length of about 50 kpc that corresponds to the region within which efficient star formation occurs. One problem that arises is that excessive baryonic matter can cool within a Hubble time and further augment the derived maximum mass. This cooling catastrophe would destroy the coincidence between cooling efficiency and $L_*$.

Possible solutions are either that the cooling gas forms baryonic dark matter, or else that it is heated to about $10^6 \text{K}$ and thereby mostly remains in the intergalactic medium. The former possibility seems hard to justify given our knowledge of the inefficiency of galactic star formation, although cluster cooling flows have been argued to provide a suitable environment for almost exclusively very low mass ($\lesssim 0.2 M_\odot$) star formation. Heating of the intergalactic medium is a process that certainly occurred in galaxy clusters and may well have been prevalent at early epochs.

### Angular Momentum and Morphology

Numerical simulations of tidal torques between neighboring protogalaxies result in acquisition of angular momentum at a level $\lambda \approx 0.06$, where the dimensionless angular momentum parameter $\lambda$ has a broad dispersion and is defined as

$$\lambda = J E^{1/2} G^{-1} M^{5/2} \approx 0.3 \nu / \sigma$$

for a de Vaucouleurs density profile, in a system of mass $M$, angular momentum $J$, potential energy $E$, rotational velocity $\nu$ and virial velocity dispersion $\sigma$.

The observed $\lambda \approx 0.7$ in disks is simply explained by dissipative collapse, conserving specific angular momentum of the gas. The dark halo acquires a rotational torque as the gas contracts by about a factor of 10 in radius. The final radius of the disk, identified with the disk scale length, is in reasonable accord with $R_*$ (as inferred from the cooling diagram).

For ellipticals, the low observed $\lambda$ of about 0.07 requires that efficient angular momentum transfer must have occurred to avoid spin-up as the gas contracted towards the final high density state of the stellar component. The angular momentum transfer occurs via dynamical friction provided that stars formed sufficiently early and in massive dense clusters. Bulges should have formed in a similar manner, but most of the star formation in protodisks must have been very inefficient to avoid a similar fate.
There indeed is evidence for widely differing rates of past star formation in elliptical and disk galaxies, obtained from population synthesis and chemical evolution modelling, respectively. Star formation rates would have differed because of inefficiency if the star forming protogalactic clouds were of widely differing mass. Low mass clouds disrupt easily once a few massive stars have evolved into supernovae, whereas massive clouds tend to retain the stellar ejecta, recycling it into successive generations of stars.

Perhaps ellipticals formed via disk mergers. Enrichment results in efficient cooling, which in turn should lead to effective cloud coagulation and massive cloud formation. Simulations of mergers indeed indicate that the gas rapidly develops into a central (\( \lesssim 1 \) kpc scale) dense concentration. The central stellar cores of ellipticals are a plausible outcome of the massive central clouds. This hypothesis would naturally be consistent with the predominance of ellipticals in dense environments, where a high past rate of galaxy mergers presumably occurred. The building blocks for galaxies, in such a picture, would be gas-rich irregular galaxies, that in isolated regions have inefficiently undergone minor mergers to form spiral disks. Recent major mergers in denser regions triggered massive cloud formation that in turn led to efficient star formation and the development of elliptical morphologies.

Scaling relations

The fossilized characteristic properties of galaxies contain important information about their formation. Notable among these properties are the remarkably low dispersion scaling relations: Tully-Fisher for spirals, \( L \propto v^4 \), and the fundamental plane for ellipticals and bulges, \( L \propto \sigma^3 \mu^{-3/4} \), where \( \sigma \) is the virial velocity dispersion and \( \mu \) is the surface brightness within the half-light radius. Combination of these observed relations with the virial theorem, expressible as

\[
L \propto \sigma^4 \mu^{-1} (M/L)^{-2},
\]

leads to \( M/L \propto \mu^{-1/2} \) and \( M/L \propto L^{1/6} \), respectively, for the spiral and elliptical correlations.

These are relations between intrinsic properties that primarily involve star formation rather than structure. However star formation and morphology are inseparable. The degree of rotational support and bulge-to-disk ratio varies smoothly within the fundamental plane for the dynamically hot components, suggesting that gas dissipation is important and systematically played a larger role for the smaller systems where gas cooling was most efficient.

One can attempt to distinguish purely intrinsic star-formation-related aspects from initial conditions as follows. The initial stellar mass function determines the mass-luminosity ratio. The mean surface density of a newly formed virialised system, in the absence of any dissipation, scales with formation redshift as \( (1+z)^{2(n+2)/(n+3)} \) or roughly as \( 1+z \) for the spectral index \( n \approx -1 \) that is appropriate on galaxy scales \( 10^{10} - 10^{12} M_\odot \). Here the power spectrum of primordial density fluctuations is taken to be \( |\delta_k|^2 \propto k^n \), equivalent to a mass fluctuation spectrum \( \delta M/M \propto M^{-(n+3)/6} \).
This immediately suggests that the zero-point of the Tully-Fisher relation should depend on the redshift of galaxy formation, albeit with large dispersion, whereas that of the fundamental plane should not, if we can assume that the initial stellar mass function, and hence $M/L$, is independent of the formation epoch and environment. Indeed there is a well-known variation of zero point with Hubble type for the spiral sequence that is generally attributed to the increase in $M/L$ for the stellar population associated with increasingly bulge-dominated galaxies. One expects the large dispersion in formation redshift to lead to a large dispersion in galaxy surface brightness $\mu$ (or at least surface density). The low dispersion observed for the Tully-Fisher relation can only arise if the residuals in $\mu$ and $M/L$ are anticorrelated. Large $\mu$, early-forming galaxies (this being the sense of the correlation expected in any hierarchical scheme), should systematically have lower $M/L$. If one considers a mass sequence of disks, the late-forming, more massive disks should have progressively lower $M/L$.

This appears to be consistent with the expectation of merger-dominated formation, whereas the early-type galaxies have undergone mergers and actually "form" later than most of the gas-rich isolated systems. The age of the Milky Way suggests a relatively high epoch of formation ($z \gtrsim 1$) compared to the median redshift measured for samples of faint blue field galaxies ($z \sim 0.4$), many of which seem to be vigorous star-forming systems. Clearly, we need insight into how $M/L$ arises before hoping to understand the observed galaxy parameter correlations.

**Star formation rates in protogalaxies**

The star formation rate in a spiral galaxy is approximately proportional to its gas content. An adopted star formation rate of the form

$$\text{SFR} = \frac{c \mu_{\text{gas}}}{\tau_{\text{inst}}} \left( 1 - \mu_{\text{cr}} / \mu_{\text{gas}} \right)$$

(1)

enshrines the semi-phenomenological physics of spiral disks. Here $\tau_{\text{inst}}^{-1}$ is the disk linear instability growth rate, equal to $\pi G \mu_{\text{gas}} \sigma_{\text{gas}}^2$, $\mu_{\text{gas}}$ is the gas (HI+H2+HII) surface density, $\sigma_{\text{gas}}$ is the gas velocity dispersion, and $\mu_{\text{cr}}$ is the critical surface density above which gravitational instabilities are operative. Analyses of both axisymmetric and non-axisymmetric instabilities of thin self-gravitating gaseous and stellar disks suggest that the disk is gravitationally unstable when the mean surface density exceeds a critical value $\mu_{\text{cr}}$. For a gas disk, $\mu_{\text{cr}} \approx \kappa \sigma_{\text{gas}} (\pi G)^{-1}$, where $\kappa$ is the epicyclic frequency. I define $Q = \mu_{\text{cr}} / \mu$; in the solar neighborhood, $\mu_{\text{cr}} \approx 8 M_\odot$ $pc^{-2}$, and $\mu_{\text{gas}} \approx 13 M_\odot$ $pc^{-2}$, indicating that $Q_{\text{gas}} \lesssim 1$ near the sun. This effectively describes the ability of the gas-rich Milky Way inner disk to form both molecular cloud complexes and stars. Indeed, the rate (1) provides an acceptable description of disk star formation at late times, resembling a Schmidt law $\text{SFR} \propto \mu_{\text{gas}}^2$ in the inner disk where $\mu_{\text{gas}} \gg \mu_{\text{cr}}$. Nearby star-forming galaxies display both a nearly quadratic star formation law as well as a star formation threshold when $\mu_{\text{gas}}$ drops below the critical value.

At early times, however, one must restrict the gas consumption rate in order to reproduce the observed slow variation of star formation rate with epoch in spiral disks that results in
gas-rich disks at late times. The obvious physical mechanism is via feedback from massive star formation. The following argument is adapted from Silk\textsuperscript{9} and Wang and Silk\textsuperscript{10}.

Once massive stars form and die, the energy input from HII regions, OB star winds, and, especially, supernova remnants provides a source of momentum to the interstellar gas. I incorporate the supernova feedback by writing

$$SFR \cdot p_{SN} = \mu_{gas} \sigma_g \Omega.$$  \hspace{1cm} (2)

Here $p_{SN} = 2E_{SN}(v_c m_{SN})^{-1}$ is the final specific momentum deposited into the interstellar medium by a supernova remnant of initial kinetic energy $10^{51} E_{51}$ ergs, and

$$v_c = 208E_{51}^{1/14} Z^{-3/14} n_{1/7} \text{ km s}^{-1}$$

is the cooling velocity at which a supernova remnant expanding into a uniform medium of density $n$ and metallicity $Z$ (relative to solar) first enters the approximately momentum-conserving phase\textsuperscript{11}. The mean mass in stars that form for each supernova is $m_{SN}$, with a typical numerical value being $m_{SN} \equiv 300 m_{300} M_\odot$ with $m_{300} \approx 1$ for a present-day star formation rate of $\dot{M} \approx 100 M_\odot \text{ yr}^{-1}$ and disk supernova rate of $\approx 0.02 \text{ yr}^{-1}$. One obtains $p_{SN} = 600 E_{51}^{13/14} n_{1/7}^{-1} m_{300}^{-1} \text{ km s}^{-1}$. Equation (2) suggests that the star formation rate initially decreases in proportion to $\dot{\rho}$, as the e-folding time-scale for gas depletion is $\approx (p_{SN}/\sigma_g) \Omega^{-1} \sim 100 \sigma_{10} \Omega^{-1}$, where $\sigma_g \equiv 10 \sigma_{10} \text{ km s}^{-1}$.

The initial value of $\mu_{gas}$ is likely to be determined by cloud-cloud collisions. Consider the following simple model of identical protogalactic clouds in the protodisk. Gas dissipation is primarily due to energy loss in cloud-cloud collisions, which occur at a rate $t_{\text{coll}}^{-1} \sim (\mu_{gas} \mu_{cl})(\sigma_g/H)$ where $\mu_{cl}$ is the mean cloud surface density and the disk scale height

$$H = \frac{\sigma_g}{\pi G \left( \frac{\mu_{gas}}{\sigma_g} + \frac{\mu_{cl}}{\sigma_g} \right)}^{-1} \approx Q \sigma_g / \Omega.$$  

Clouds form at a rate $\sim \Omega$, as expected if cloud growth is driven by coagulation of smaller gas clouds in a gravitationally unstable disk. It seems reasonable to expect that a pure gas disk will be sufficiently unstable that clouds are continuously regenerated by nonaxisymmetric gravitational instabilities in the disk over a rotation period until viscous offsets play any role in redistributing the gas. In a steady state, with cloud motions being maintained by disk gravitational instabilities, $t_{\text{coll}}^{-1} \sim \Omega$ or $Q \approx \mu_{gas} / \mu_{cl}$. If self-regulation maintains $Q \sim 1$, one can thereby infer $\mu_{gas}^{(i)} \sim \mu_{cl} \sim \mu_\Omega$ as observed. In the interstellar medium of our Galaxy, molecular clouds satisfy $\mu_{cl} \approx 160 M_\odot \text{ pc}^{-2}$, and this bounds $\mu_{gas}$ early in the evolution of the galactic disk.

Implications for scaling relations

There is an important consequence of describing present inner disk star formation by a more or less quadratic law,

$$SFR \propto \mu_\Omega^\alpha,$$  \hspace{1cm} with $\alpha \approx 2;$$
note that $\alpha \approx 1.5$ may be slightly favored by the data. The present star formation rate is proportional to the current gas content. However this in turn depends on the disk age. For example, with $\alpha = 2$, we may use (1) in particular as appropriate for self-regulation by gravitational instabilities heating the disk and gas cooling providing the destabilizing mechanism. We find that in this case $\mu_{\text{gas}} = \sigma_{\text{gas}}(\epsilon \pi G \tau_d)^{-1}$, and the star formation rate $\mu_* = \sigma_{\text{g}}(\epsilon \pi G \tau_d)^{-1}$.

The feedback via supernova-driven winds specifies the normalization parameter, in effect the star formation efficiency, and prescribes the gas surface density that can be regulated by a given star formation rate:

$$\mu_{\text{gas}} = \frac{M_*}{\mu_*/M_*} \frac{\text{PSN}}{G}.$$  

This yields an efficiency $\epsilon = (\sigma_{\text{gas}}/\text{PSN})(\mu_*/\mu_{\text{gas}})$, and combination with the late time limit for $\mu_{\text{gas}}$ yields $\mu_* \approx \text{PSN}(G \tau_d)^{-1}$. Hence the mass-luminosity ratio of the star forming disk is proportional to $\mu_*/\mu_* \sim \epsilon \text{PSN} \tau_d / \sigma_{\text{g}}$.

Note that the disk $(M/L)_d$ increases with disk age, and $\mu_*$ decreases for older disks. Remarkably, the product $\mu_1^{1/2} \cdot (M/L)_d$ is independent of disk age. The zero-point of the Tully-Fisher relation is affected, insofar as the current star formation rate is not an accurate measure of current disk luminosity in the appropriate wavelength band. This should be more of a problem for bulge-dominated galaxies. In this case, $L/V_r^4 \propto (L/M)_d \mu_*^{-1} \propto L_d \tau_d^2$ increases as a function of disk age, the rate of increase of $L_d$ depending on the initial mass function $dN/dm$ of stars near the main sequence turn-off if $L_d$ is predominantly due to old stars: $L_{\text{old}} \sim t^{-(2+x)/3}$ for $dN/dm \sim m^{-1-x}$ with $x \approx 2 - 3$. There is an additional factor from the star formation threshold: since $\mu_{\text{cr}}/\mu \propto \Omega/\mu \propto v_r^{-1}$, this can result in a steepening of the $L \propto V_r^4$ relationship at low $V_r$, since $\mu_* \propto 1 - \mu_{\text{cr}}/\mu$. More important, however, is the inference of an age-dependent offset of the zero-point in the Tully-Fisher relation, especially for the near infrared I and K bands, where the young stars contribute a significant fraction of the light.

The observed dispersion in $\mu_L$ is known to be less than 10 percent, suggesting a similar limit on the dispersion in disk ages for nearby luminous spirals. Tully-Fisher offsets could therefore be as large as 5 percent, if half the light comes from the old stellar population. Residuals in $\mu_*$ and in the peculiar velocities deduced from Tully-Fisher should be anticorrelated: $\delta \mu_* \propto -\delta \tau_d$, $\delta v_{\text{pec}} \propto -\delta r \propto -\delta (L/V_r^4)^{1/2} \propto 1/2 \delta \tau_d$, that is, $\delta v_{\text{pec}} \sim -1/2 \delta \mu_*$.  

**Starbursts and ellipticals**

There are analogous implications for the fundamental plane of ellipticals, equivalent to a weak dependence of $M/L$ on $L$. However the $M/L$ for ellipticals is determined by their star formation histories, known to resemble those of starbursts. Most likely, protoelliptical starbursts are merger-induced, as is known to be the case for extreme IRAS starbursts.

Somewhat different theoretical considerations certainly apply to protogalaxies. The specific star formation rate is similar for protoellipticals and for starbursts. This had led to the suggestion that in extreme starbursts, we are seeing ellipticals in the process of
formation. The measurement of de Vaucouleurs profiles in the light both of starburst and of merging galaxies (not inevitably coincident) supports this contention.

Mergers are relatively rare today, however, although all ultraluminous IRAS galaxies show signs of recent or ongoing mergers. In the past, however, hierarchical structure formation models predict a rate that increased sharply with increasing redshift. The fragility of disks is interpreted to show that less that 4 percent of the disk mass may have been accreted discontinuously in the past 5 Gyr.\textsuperscript{13} This suggests that environments of present day disks and ellipticals are sufficiently different to have had distinctly different histories of merging activity.

One can construct a reasonably self-consistent description that appeals to major mergers of massive clouds or protodisks in dense environments as the precursors of ellipticals, with present day disks having formed via protodisks undergoing minor mergers including relatively low mass clouds characteristic of present-day gas-rich dwarf galaxies. Silk and Wyse\textsuperscript{14} develop a star formation efficiency argument that can account in this manner for many present day characteristics of galaxies.

In a star burst situation, gas inflows to the central region of the dominant galaxy are greatly enhanced by tidal interactions between the non-axisymmetric distribution of the stellar component in a merger and the gas. A dense central complex of gas rapidly develops. Clearly, the star formation rate is no longer given by a Schmidt-type law appropriate to disks. Feedback effects from massive star formation, and in particular supernova energy input, must inevitably limit the star formation rate.

I estimate the limiting star formation rate as follows.\textsuperscript{15} Let supernova remnants overlap and produce a hot coronal medium that pressurizes interstellar clouds. When the hot medium becomes sufficiently porous and dominates the volume, the cold gas fraction will diminish. Define the porosity of the hot interstellar medium by

\[ P = \frac{\rho_{\text{SN}} \nu_{\text{SN}}}{m_{\text{SN}}}, \]

where \( \nu_{\text{SN}} \) is the 4-volume occupied by an old supernova remnant halted by the pressure of the ambient medium. A spherically symmetric remnant expanding into a uniform medium of pressure \( p \equiv 10^4 p_4 \text{ k cm}^{-3}\text{K} \) and density \( n \) fills a 4-volume

\[ \nu_{\text{SN}} = 7.82 \times 10^{12} p_4^{-1.36} n^{-0.11} E_1^{1.26} Z^{-0.204} \text{ pc}^3 \text{ yr}, \]

where \( Z \) (in units of \( Z_\odot \)) is the metallicity.

The volume-filling factor of the cold medium is \( f_v = e^{-P} \), and the mass fraction is

\[ f_m = \min \left[ 1, \left( \frac{\rho_{\text{cl}}}{\rho_{\text{gas}}} \right) e^{-P} \right], \]

where \( \langle \rho_{\text{cl}}/\rho_{\text{gas}} \rangle \) is the ratio of characteristic cloud density to average density of the cold gas. The triggering of star formation drives high porosity and ensuing gas outflows via a supernova-driven wind if \( f_m < 1 \); that is if

\[ P \gtrsim \ln \left( \langle \rho_{\text{cl}}/\rho_{\text{gas}} \rangle \right), \]
one can self-regulate star formation by disrupting the gas supply. On the other hand, the porosity cannot be too large, or there will be no cold gas.

A typical value for \( \langle \rho_{\text{col}}/\rho_{\text{gas}} \rangle \) is 10, and \( \langle Q_o \rangle \) is about 0.5. I conclude that self-regulation during a starburst restricts the porosity to \( P \equiv P_o \approx 2 - 3 \).

I can now deduce the self-limiting star formation rate during a starburst with \( P \sim 1 \),

\[
M_* \propto P^{1.4} n^{-0.1} r^3 \propto v^{5.8} (M_{\text{gas}}/M_*)^{3/2}.
\]

The star formation time-scale is \( t_* = M_*^{-0.9} \rho_{\text{gas}}^{-1} (\rho_*/\rho_{\text{gas}})^{1/2} \), suggesting that low mass systems may remain gas-rich until a late epoch. A porosity larger than unity results in a wind if the star formation rate is larger than this value. However the star formation rate cannot exceed the available gas supply that can be supplied in spherically symmetric free-fall, namely \( v^3/G \), as inferred from the collapse rate of an isothermal sphere, where \( v \) is the free-fall velocity. It follows that \( v \lesssim 50 \, (M_*/M_{\text{gas}})^{1/2} \, \text{km s}^{-1} \), a condition that is necessary for a wind-driven outflow to occur and restricts such a phenomenon to gas-rich dwarf galaxies undergoing a starburst. For a wind to actually be generated, one also requires \( t_{\text{cool}} > t_{\text{dyn}} \), generally satisfied for dwarfs.

Efficient star formation as required in a starburst results if \( t_* \ll t_d \). The efficiency increases because of the deepening potential well. Relative to the dynamical time, one has for fixed gas fraction

\[
t_* / t_d \propto M^{-0.9} \rho^{-1/2}.
\]

For hierarchical clustering with \( \delta \rho/\rho \propto M^{-n/2} \), one obtains for recently virialized potential wells,

\[
M \propto (1+z)^{-6/(n+3)} \quad \text{and} \quad \langle \rho \rangle \propto (1+z)^3,
\]

where \( t_* / t_d \propto (1+z)^{-n} (1+z)^{1.4/(n+3)} \) for \( n \approx -1.4 \), or \( (1+z)^{1.2} \) to \( (1+z)^{3.9} \) for \( -1 \lesssim n \lesssim -2 \).

Hence star formation is less efficient on small mass scales and at early epochs, in a bottom-up formation model for dark matter potential wells. This is precisely what one needs to keep the universe gas-rich: one has to preserve most of the gas to a late epoch, when the largest systems form.

Implications

The large (\( \sim 10 - 30 \) percent) gas fraction in galaxy clusters directly supports the contention that early star formation was inefficient. It is tempting to infer that most of the gas in clusters would form disks in less extreme environments. For disks that undergo starbursts, the limiting star formation rate is strongly affected, at a given scale length, by external pressure, with \( M_* \propto P^{1.4} \). First infall to clusters and even to superclusters should be sufficient to give an appreciable modulation of the disk star formation rate.

To quantify this assertion, I note that tidal stirring of disk gas is important provided \( v_{\text{tidal}} \gtrsim 10 \, \text{km s}^{-1} \), the characteristic dispersion of cold interstellar clouds. Infall of a disk to a supercluster generates a tidal velocity field of order \( v_{\text{tidal}} \sim (r_g/r) \, v_{\text{infall}} \), across a
disk of half-mass radius \( r_g \) at distance \( r \) from the supercluster center. One can calculate the typical infall velocity by assuming that the galaxy-cluster correlation function

\[
\xi_{gc} = \left( \frac{r}{8.8h^{-1}\text{Mpc}} \right)^{-2.2}; \quad r \lesssim 20h^{-1}\text{Mpc}
\]

describes the enhancement in mass distribution around a cluster, in which case a spherical infall model yields

\[
v_{\text{infall}} \approx 1.5 \times 10^4\Omega^{0.6}(hr_{\text{Mpc}})^{-1.2}\ \text{km s}^{-1}.
\]

Evidently protodisks (\( r_g \approx 50 \) kpc) can undergo considerable tidal stirring out to a radial distance \( \sim 5h^{-1} \) Mpc from the supercluster. The frequency of damped Lyman alpha absorption line systems towards quasars at high redshifts implies an effective cross-section that, if interpreted as due to protodisks, yields \( r_g \sim 100 \) kpc.

Ram pressure can also be significant out to comparable distances. One can trace hot intracluster gas out to \( \gtrsim 2h^{-1} \) Mpc via its x-ray emission. Moreover one would expect that peculiar velocities \( v_{pec} \sim v_{\text{infall}} \) arise naturally in clumpy, anisotropic collapse that is expected in most clustering models and seen directly via deep x-ray imaging of clusters. The associated ram pressure on a disk galaxy amounts to \( \Delta \rho v_{pec}^2 \) and can easily exceed the mean interstellar pressure (\( \sim 3600k \text{ cm}^{-3} \)) if \( \Delta \rho \sim 100\rho_0 \sim 10^{-5} \text{cm}^{-3} \) at \( 5h^{-1} \) Mpc or further from the cluster center.

Several observations lend support to the idea that disk luminosities may be enhanced on supercluster scales. These include the enhanced correlations for luminous spirals found by Hamilton,\(^{16}\) the occurrence of post-starburst galaxies with E+A spectra\(^{17}\) with enhanced v\(_{pec}\) relative to the cluster velocity dispersion, and the apparent dominance of superclusters in pencil beam surveys\(^{18}\) and large-scale cell counts.\(^{19}\) For dwarf galaxies, obvious implications include the survival of low surface brightness gas-poor dE’s in cluster environments and the prevalence of gas-rich dwarfs in low density regions, the latter population perhaps being identifiable with the weakly clustered Lyman alpha forest clouds.

Finally, I note that systematic variations are expected from cluster to cluster in the star formation history of both disks and ellipticals. The resulting M/L variations may affect the interpretation of offsets in the Tully-Fisher and fundamental plane zero points as being exclusively due to peculiar velocities and large-scale flows.

I am indebted to Max Tegmark for preparing Figure 1, and to Rosemary Wyse and Boqi Wang for many discussions of related topics. This research has also been supported in part by a grant from the National Science Foundation.

References

Figure Caption

Figure 1: (a) The cooling rate for an astrophysical plasma of unit density, for various abundances that range from solar to depleted by up to a factor of 1000. In the depleted cases, ratios of heavy element abundances are used that correspond to the ratios measured for extremely metal poor halo stars. New cooling cross-sections have been incorporated by Sutherland (1992) to give plotted curves.

(b) As in (a), but cooling timescale is plotted versus electron temperature.

(c) Loci of the cooling conditions, cooling time-scale = free-fall time (solid lines) and cooling time-scale = Hubble time (dashed lines) for various abundances as in (a). Loci of constant virial mass (in $M_\odot$) and the condition that dynamical time equals a Hubble time are also shown.