Galactic Disk Formation and the Angular Momentum Problem

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**Abstract.** Galactic disk formation requires knowledge about the initial conditions under which disk galaxies form, the boundary conditions that affect their secular evolution and the micro-physical processes that drive the multi-phase interstellar medium and regulate their star formation history. Most of these ingredients are still poorly understood. Recent high-resolution observations of young high-redshift disk galaxies provide insight into early phases of galactic disk formation and evolution. Combined with low-redshift disk data these observations should eventually allow us to reconstruct the origin and evolution of late-type galaxies. I will summarize some of the major problems that need to be addressed for a more consistent picture of galactic disk formation and evolution.

1. Initial- and Boundary Conditions: The Cosmological Angular Momentum Problem

Galaxy formation to some extent is an initial condition problem. Whether a galactic disk can form at all depends on the amount of angular momentum present in the infalling gas. The disk structure is determined by the gravitational potential of the baryonic and dark component of the galaxy and the specific angular momentum distribution of the fraction of infalling gas that can cool and dissipate its potential and kinetic energy while settling into centrifugal equilibrium in the equatorial plane. Once a massive disk has formed and on timescales longer than the infall timescale secular disk evolution will become important, resulting in angular momentum redistribution of gas and stars in the disk by viscous effects and gravitational torques, coupled with star formation and selective gas loss in galactic winds (Kormendy & Kennicutt 2004).

The origin of angular momentum is generally believed to be cosmological. Before and during the early phase of protogalactic collapse, gas and dark matter are well mixed and therefore acquire a similar specific angular momentum distribution (Peebles 1969; Fall & Efstathiou 1980; White 1984). If angular momentum would be conserved during gas infall, the resulting disk size should be directly related to the specific angular momentum $\lambda'$ of the surrounding dark halo where (Bullock et al. 2001)

$$\lambda' = \frac{J}{\sqrt{2} M_{\text{vir}} V_{\text{vir}} R_{\text{vir}}}$$

($1$)
with $R_{\text{vir}}$ and $V_{\text{vir}}^2 = GM_{\text{vir}}/R_{\text{vir}}$ the virial radius and virial velocity of the halo, respectively, and $M_{\text{vir}}$ its virial mass. Adopting a flat rotation curve, the disk scale length is (Mo et al. 1998; Burkert & D’Onghia 04)

$$R_d \approx 8 \left( \frac{\lambda'}{0.035} \right) \left( \frac{H_0}{H} \right) \left( \frac{v_{\text{max}}}{200 \text{ km/s}} \right) \text{kpc}$$

(2)

where $v_{\text{max}}$ is the maximum rotational velocity in the disk and $H$ is the Hubble parameter that depends on cosmological redshift $z$

$$H = H_0 \left[ \Omega_\Lambda + \Omega_M (1 + z)^3 \right]^{1/2}.$$  

(3)

Typical values for a standard ΛCDM cosmology are $H_0 = 73 \text{ km/s/Mpc}$, $\Omega_M = 0.238$ and $\Omega_\Lambda = 0.762$.

The upper panel of figure 1 shows the correlation between the disk scale length $R_{\text{disk}}$ and the maximum rotational velocity $v_{\text{max}}$ for massive spiral galaxies (Courteau 1997). There is a linear relationship which can be fitted well by $\lambda' = 0.025$ which is somewhat smaller than the theoretically predicted value of $\lambda' = 0.035$, indicating that the gas could on average have lost some amount of angular momentum during the infall phase.

This result is promising. The situation is however more confusing if we look at the recent high-resolution observations of $z=2$ star forming disk galaxies (Förster-Schreiber et al. 2006, 2009; Genzel et al. 2006, 2008; Cresci et al. 2009, Burkert et al. 2009). In contrast to their low-redshift counterparts, the high-$z$ galaxies are characterized by high gas velocity dispersions of $\sigma \approx 40 - 80 \text{ km/s}$. In addition, the sample segregates strongly into two distinct classes at a critical value of $v_{\text{max}}/\sigma \approx 3$. One can empirically define dispersion-dominated galaxies as objects with $v_{\text{max}}/\sigma \leq 3$ while rotation-dominated galaxies are defined by $v_{\text{max}}/\sigma > 3$. The lower panel of figure 1 shows the half-light radii $r_{1/2}$ of the SINS high-redshift galaxies versus their maximum rotational velocity $v_{\text{max}}$. Most of the dispersion-dominated galaxies (open triangles in figure 1) have radii of order 1-2 kpc and rotational velocities of order 100 km/s while the radii and rotational velocities of the rotation dominated galaxies (filled triangles) are on average a factor of 2-3 larger. The correlation between scale length and velocity of this sample is however very similar to the low-redshift galaxies. According to equation (1), this requires a factor 3-4 larger spin parameter (dashed curves in the lower panel of figure 1) for high-redshift disks as a result of the fact that at $z=2$ the dark halo virial radii are a factor 3-4 smaller. Burkert et al. (2009) argue that this could be explained by turbulent pressure effects in the disk and a less centrally concentrated dark halo component that did not experience adiabatic contraction during disk formation.

Simulations of galactic disk formation suffer often from catastrophic angular momentum loss which leads to disks with unreasonably small scale lengths and surface densities that are too large. The origin might be strong clumping of the infalling gas which loses angular momentum by dynamical friction within the surrounding dark matter halo (Navarro & Benz 1991, Navarro & Steinmetz 2000), low numerical resolution (Governato et al. 2004, 2007), substantial and major mergers (d’Onghia et al. 2006) and artificial secular angular momentum transfer from the cold disk to its hot surrounding (Okamoto et al. 2003). It has
Figure 1. The upper panel shows the observed scale lengths versus the maximum rotational velocities of galactic disks for the Courteau (1997) sample. The solid line shows the theoretically predicted correlation for $\lambda' = 0.035$. The dashed curve corresponds to $\lambda' = 0.025$. The lower panel shows the disk scale length versus the maximum velocity of the SINS high-redshift disk sample. Open and filled triangles correspond to dispersion-dominated and rotation-dominated galaxies, respectively. Note that here the vertical axis is plotted logarithmically for better resolution of the dispersion-dominated galaxies. Dashed curves show the Mo, Mao & White models with spin parameters as indicated by the labels.
been argued that this problem might be solved by including star formation and energetic feedback (e.g. Sommer-Larsen et al. 2003, Abadi et al. 2003, Springel & Hernquist 2003, Robertson et al. 2004, Oppenheimer & Dave 2006, Dubois & Teyssier 2008). No reasonable, universally applicable feedback prescription has however yet been found that would lead to the formation of large-sized, late-type disks, not only for special cases, but in general.

Recently Zavala et al. (2008) showed that the specific angular momentum distribution of the disk forming material follows closely the angular momentum evolution of the dark matter halo. The dark matter angular momentum grows at early times as a result of large-scale tidal torques, consistent with the prediction of linear theory and remains constant after the epoch of maximum expansion. During this late phase angular momentum is redistributed within the dark halo with the inner dark halo regions loosing up to 90% of their specific angular momentum to the outer parts which is probably related to minor mergers with mass ratios less than 10:1. It is then likely that any gas residing in the inner regions during such an angular momentum redistribution will also loose most of its angular momentum, independent of whether the gas resides already in a protodisk, is still confined to dark matter substructures or is in an extended, diffuse distribution. Zavala et al. (2008) (see also Okamoto et al., 2005 and Scannapieco et al., 2008) show that efficient heating of the gas component can prevent angular momentum loss, probably because most of the gaseous component resides in the outer parts of the dark halo during its angular momentum redistribution phase. The gas would then actually gain angular momentum rather than loose it and could lateron settle smoothly into an extended galactic disk in an ELS-like (Eggen, Lynden-Bell & Sandage 1962) accretion phase.

Little is known about the energetic processes that could lead to such an evolution. Obviously, star formation must be delayed during the protogalactic collapse phase in order for the gas to have enough time to settle into the plane before condensing into stars. However star formation is also required in order to heat the gas, preventing it from collapsing prior to the angular momentum redistribution phase. Scannapieco et al. (2008) show that their supernova feedback prescription is able to regulate star formation while at the same time pressurizing the gas. Their models are however still not efficient enough in order to produce disk-dominated, late-type galaxies. Large galactic disks are formed. The systems are however dominated by a central, massive, low-angular momentum stellar bulge component. This is in contradiction with observations which indicate a large fraction of massive disk galaxies with bulge-to disk ratios smaller than 50% (Weinzirl et al. 2008) that cannot be produced currently by numerical simulations of cosmological disk formation.

2. Energetic Feedback and Star Formation

As argued in the last section star formation and energetic feedback plays a dominant role in understanding the origin and evolution of galactic disks and in determining the morphological type of disk galaxies. Scannapieco et al. (2008) for example demonstrate that the same initial conditions could produce either an elliptical or a disk galaxy, depending on the adopted efficiency of gas heating during the protogalactic collapse phase. A consistent model of the structure and
evolution of the multi-phase, turbulent interstellar medium and its condensation into stars is still missing. This situation is however improving rapidly due to more sophisticated numerical methods and fast computational platforms that allow us to run high-resolution models, incorporating a large number of possibly relevant physical processes (Wada & Norman 2002, Krumholz & McKee 2005, Tasker & Bryan 2008, Robertson & Kravtsov 2008).

Cosmological simulations often adopted simplified observationally motivated descriptions of star formation that are based on the empirical Kennicutt relations (Kennicutt 1998, 2007) that come in two different version. The first relation (K1) represents a correlation between the star formation rate per surface area $\Sigma_{SFR}$ and the gas surface density $\Sigma_g$, averaged over the whole galaxy

$$\Sigma_{SFR}^{(K1)} = 2.5 \times 10^{-4} \left( \frac{\Sigma_g}{M_\odot/pc^2} \right)^{1.4} \frac{M_\odot}{kpc^2 yr}$$ (4)

The second relation (K2) includes a dependence on the typical orbital period $\tau_{orb}$ of the disk

$$\Sigma_{SFR}^{(K2)} = 0.017 \left( \frac{\Sigma_g}{M_\odot/pc^2} \right) \left( \frac{10^8 yrs}{\tau_{orb}} \right) \frac{M_\odot}{kpc^2 yr}$$ (5)

These relationships have been derived from observations as an average over the whole disk. They are however often also used as theoretical prescriptions for the local star formation rate which appears observationally justified if the total gas surface density $\Sigma_g$ is replaced by the local surface density of molecular gas. The origin of both relationships is not well understood yet. One can combine K1 and K2 and derive a relationship between the average gas density in galactic disks and their orbital period

$$\Sigma_g \sim \tau_{orb}^{-2.5} \sim \left( \frac{v_{rot}}{R_{disk}} \right)^{2.5}$$ (6)

where $v_{rot}$ and $R_{disk}$ are the rotational velocity and the size of the galactic disk, respectively. This result is puzzling as it is not clear why the kinematical properties of galactic disks should correlate with their gas surface densities especially in galaxies of Milky Way type or earlier where the gas fraction is small compared to the mass in stars (see e.g. Robertson & Kravtsov 2008).

3. Secular Evolution and Turbulence in Galactic Disks

Dark halos have a universal angular momentum distribution that should also be characteristic for the infalling gas component (Bullock et al. 2001). Van den Bosch et al. (2001) lateron showed that this angular momentum distribution is not consistent with the observed distribution of exponential galactic disks. One possibility is angular momentum redistribution during filamentary cold gas infall (Dekel et al. 2009). Another suggestion is viscous disk evolution. The viscosity is likely driven by interstellar turbulence which is a result of stellar energetic feedback processes or global disk instabilities (magneto-rotational instability or gravitational instability). Viscous effects will however increases the
angular momentum problem substantially as viscosity in general removes angular momentum from the dominate mass component in the disk and transfers it to the outermost parts of the disk.

Slyz et al. (2002) studied the viscous formation of exponential stellar disks from gas disks with various different surface density distributions. Their numerical simulations show that exponential disks form if the star formation timescale is of order the viscous timescale. Genzel et al. (2008) derive a timescale for turbulent viscosity in galactic disks of (see also Dekel et al. 2009)

\[ \tau_{\text{visc}} = \frac{1}{\alpha} \left( \frac{v_{\text{rot}}}{\sigma} \right)^2 \tau_{\text{orb}} \]

where \( \alpha \) is of order unity. \( \tau_{\text{visc}} \approx 10^{10} \) yrs for disks like the Milky Way with \( \sigma \approx 10\text{-}20 \) km/s and self-regulated low star formation rates. \( z \approx 2 \) star forming disk galaxies on the other hand are characterized by large random gas motions of order \( 40 \text{ km/s} \) to \( 80 \text{ km/s} \) and viscous timescales of less than \( 10^9 \) yrs (Genzel et al., 2006, 2008, Förster-Schreiber et al. 2006). Interestingly, for these objects, the star formation timescales are again similar to the viscous timescale, leading to star formation rates of \( 100 \ M_{\odot}/\text{yr} \) and confirming that galactic disk gas turbulence, star formation and secular evolution are intimately coupled.

Burkert et al. (2009) find a good correlation between the observed irregular gas motion in high-redshift disk galaxies and the theoretically expected gas velocity dispersion, adopting a Toomre Q parameter of unity. This is expected if the main driver of clumpiness and turbulence is gravitational disk instability. A disk that is kinematically too cold with small velocity dispersions is highly gravitationally unstable. Gravitational instabilities generate density and velocity irregularities that drive turbulence and heat the system kinematically. The gas velocity dispersion increases till it approaches the stability limit characterised by \( Q=1 \) where kinetic driving by gravitational instabilities saturates. A disk with even higher velocity dispersions would be stable, turbulent energy would dissipate efficiently and the velocity dispersion would decrease again until it crosses the critical velocity dispersion limit at \( Q=1 \) where gravitational instabilities become efficient again in driving turbulent motions. More simulations are required to investigate this process in greater details.

4. Summary

Many complex non-linear processes affect galactic disk formation and evolution. We are still in an early stage of understanding these processes. One of the most interesting questions is how the observations of high-redshift disk galaxies can be combined with galaxies in the local universe. The high-z disks generate stellar systems with high velocity dispersions that resemble more rotating early-type or S0 galaxies than Milky-Way type objects. Where are then the progenitors of present-day disks? In addition, why did their progenitors evolve differently with respect to the observed high-z galaxies? How do bulge-less disk galaxies form? Given the recent progress both in observations and theoretical modelling the time seems ripe to solve these questions.
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References

Abadi, M.G., Navarro, J.F., Steinmetz, M. & Eke, V.R. 2003, ApJ, 591, 499
Bournaud, F., Elmegreen, B.G. & Elmegreen, D.M. 2007, ApJ, 670, 237
Bullock, J.S., Dekel, A., Kolatt, T.S., Kravtsov, A.V., Klypin, A.A., Porciani, C. & Primack, J.R. 2001, ApJ, 555, 240
Burkert, A. & d’Onghia, E. 2004, in Penetrating Bars through Masks of Cosmic Dust: The Hubble Tuning Fork Strikes a New Note, eds. D.L. Block, I. Puerari, K.C. Freeman, R. Groess and E.K. Block, ASSL 319, 341
Burkert, A. et al. 2009, arXiv:0907.4777
Cresci, G. et al. 2009, ApJ, in press.
Courteau, S. 1997, AJ, 114, 2402
Dekel, A. et al. 2009, Nature, 457, 451
Dekel, A., Sari, R. & Ceverino, D. 2009, arXiv:0901.2458
Dubois, Y., Teyssier, R. 2008, AA, 477, 79
D’Onghia, E., Burkert, A., Murante, G. & Khochfar, S. 2006, MNRAS, 372, 1525
Eggen, O.J., Lynden-Bell, D. & Sandage, A.R. 1962, ApJ, 136, 748
Fall, S.M. & Efstathiou, G. 1980, MNRAS, 193, 189
Förster Schreiber, N. M. et al. 2006, ApJ, 645, 1062
Förster-Schreiber, N.M. et al. 2009, ApJ, in press
Genzel, R. et al. 2006, Nature, 442, 786
Genzel, R. et al. 2008, ApJ, 687, 59
Governato, F. et al. 2004, ApJ, 607, 688
Governato, F. et al. 2007, MNRAS, 374, 1479
Kennicutt, R.C. 1998, ApJ, 498, 541
Kennicutt, R.C. et al. 2007, ApJ, 671, 333
Kormendy, J. & Kennicutt, R.C. 2004, ARAA, 42, 603
Krumholz, M.R. & McKee, C.F. 2005, ApJ, 630, 250
Mo, H.J., Mao, S. & White, S.D.M. 1998, MNRAS, 295, 319
Navarro, J. & Benz, W. 1991, ApJ, 380, 320
Navarro, J. & Steinmetz, M. 2000, ApJ, 538, 477
Okamoto, T., Jenkins, A., Eke, V.R., Quilis, V. & Frenk, C.S. 2003, MNRAS, 345, 429
Okamoto, T., Eke, V.R., Frenk, C.S. & Jenkins, A. 2005, MNRAS, 363, 1299
Oppenheimer, B.D. & Dave, R. 2006, MNRAS, 373, 1265
Peebles, P.J.E. 1969, ApJ, 155, 393
Robertson, B., Yoshida, N., Springel, V. & Hernquist, L. 2004, ApJ, 606, 32
Robertson, B. & Kravtsov, A.V. 2008, ApJ, 680, 1083
Scannapieco, C., Tissera, P.B., White, S.D.M. & Springel, V. 2008, MNRAS, 389, 1137
Slyz, A.D., Devriendt, J.E.G., Silk, J. & Burkert, A. 2002, MNRAS, 333, 894
Sommer-Larsen, J., Götz, M., & Portinari, L. 2003, ApJ, 596, 47
Springel, V. & Hernquist, L. 2003, MNRAS, 339, 289
Tasker, E.J. & Bryan, G.L. 2008, ApJ, 673, 810
Van den Bosch, F.C., Burkert, A. & Swaters, R.A. 2001, MNRAS, 326, 1205
Wada, K., & Norman, C.A. 2007, ApJ, 660, 276
Weinzirl, T., Jogee, S., Khochfar, S., Burkert, A. & Kormendy, J. 2008, ApJ, 696, 411
White, S.D.M. 1984, MNRAS, 286, 38
Zavala, J., Okamoto, T., & Frenk, C.S. 2008, MNRAS, 387, 839