GALAXY FORMATION AND THE COSMOLOGICAL ANGULAR MOMENTUM PROBLEM

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Abstract The importance of angular momentum in regulating the sizes of galactic disks and by this their star formation history is highlighted. Tidal torques and accretion of satellites in principle provide enough angular momentum to form disks with sizes that are in agreement with observations. However three major problems have been identified that challenge cold dark matter theory and affect models of galaxy evolution: (1) too much angular momentum is transferred from the gas to the dark halos during infall, leading to disks with scale lengths that are too small, (2) bulgeless disks require more specific angular momentum than is generated cosmologically even if gas would not lose angular momentum during infall, (3) gravitational torques and hierarchical merging produce a specific angular momentum distribution that does not match the distribution required to form exponential disks naturally; some gas has exceptionally high angular momentum, leading to extended outer disks while another large gas fraction will contain very little specific angular momentum and is expected to fall into the galactic center, forming a massive and dominant bulge component. Any self-consistent theory of galaxy formation will require to provide solutions to these questions. Selective mass loss of low-angular-momentum gas in an early phase of galaxy evolution currently seems to be the most promising scenario. Such a process would have a strong affect on the early protogalactic evolution phase, the origin and evolution of galactic morphologies and link central properties of galaxies like the origin of central massive black holes with their global structure.

Keywords: galaxies: disks, formation, kinematics and dynamics, structure - dark matter

1. Introduction

The origin of the distribution of mass and angular momentum in disk galaxies is yet an unsolved astrophysical puzzle. Eggen, Lynden-Bell and Sandage (1962) argued that spiral galaxies like the Milky Way formed by rapid infall of an initially uniform sphere of gas into a centrifugally supported disk. It was soon realized that these disks would have characteristic exponential surface
density distributions if the initial gas sphere would be in solid body rotation and if the gas would preserve its initial specific angular momentum distribution $M(<j)$ during infall (Mestel 1963, Crampin & Hoyle 1964, Innanen 1966, Freeman 1970). Here, $M(<j)$ is the cumulative mass of gas with angular momentum less or equal to $j$.

Since these first pioneering studies our insight into galaxy formation has substantially changed and improved. Current cosmological models consider a dissipationless cold dark matter (CDM) component to dominate structure formation in the Universe (Blumenthal et al. 1984). Initially small dark matter density perturbations in the early Universe decouple from the Hubble flow, collapse into virialized dark matter halos and merge into larger and larger structures. Gas accumulates within the extended dark halos, dissipates its kinetic energy and settles into the equatorial plane as soon as centrifugal equilibrium is being reached, forming fast rotating disks that subsequently turn into stars (White & Rees 1978). Fall & Efstathiou (1980) argued that gas and dark matter should initially be well mixed. In this case, the specific angular momentum distribution of the gas should be equal to that of the dark halo. If $M(<j)$ would be preserved during infall into the equatorial plane, the exponential disk scale length $R_d$ would be directly related to the specific angular momentum $\lambda$ of the dark halo. Here $\lambda$ is the dimensionless spin parameter (e.g. Peebles 1969)

$$\lambda = \frac{J|E|^{1/2}}{GM_{\text{vir}}^{5/2}}$$

where $J$, $E$, and $M_{\text{vir}}$ are the total angular momentum, energy and virial mass of the halo, respectively and $G$ is Newton’s constant. This shifted the focus to a more detailed investigation of the spin properties of dark halos and a determination of $\lambda$. Peebles (1969) suggested that halos would acquire non-negligible specific angular momentum by the gravitational interaction of their building blocks with neighboring structures. Subsequent cosmological N-body simulations (Barnes & Efstathiou 1987, Efstathiou & Barnes 1983, Zeldovich & Novikov 1983, Cole & Lacey 1996) confirmed this mechanism. They showed that prior to collapse the angular momentum of a dark fluctuation grows roughly linearly with time, as predicted by linear tidal-torque theory (White 1984) until it decouples from the Hubble flow, collapses and virializes. The $\lambda$ distribution of virialized halos turned out to be well described by a log-normal (Steinmetz & Bartelmann 1995, Cole & Lacey 1996, Gardner 2001, Bullock et al. 2001)

$$p(\lambda)d\lambda = \frac{1}{\sigma_\lambda \sqrt{2\pi}} \exp\left(-\frac{ln^2(\lambda/\lambda_0)}{2\sigma^2}\right) dln\lambda$$
with median value of $\lambda_0 = 0.042 \pm 0.006$ and dispersion $\sigma_\lambda = 0.5 \pm 0.04$. A more particulate spin parameter $\lambda'$ was proposed by Bullock et al. (2001):

$$\lambda' = \frac{J}{\sqrt{2}M_{\text{vir}}V_{\text{vir}}R_{\text{vir}}}$$  \hspace{1cm} (3)

with $R_{\text{vir}}$ the halo virial radius and $V^2_{\text{vir}} = GM_{\text{vir}}/R_{\text{vir}}$ its virial velocity. The spin parameters $\lambda$ and $\lambda'$ turn out to be very similar due to the fact that dark halos are well described by a universal density distribution (Navarro, Frenk & White, 1997, NFW) and the $\lambda'$ distribution also follows a log-normal with best fit values $\lambda' = 0.035 \pm 0.005$ and $\sigma_{\lambda'} = 0.5 \pm 0.03$ (Bullock et al. 2001).

Given $\lambda'$, and assuming that the disk gas will have the same specific angular momentum as the dark halo, the exponential disk scale length $R_d$ can be easily determined. Adopting a flat rotation curve with velocity $v_c$, the disk’s specific angular momentum is (Mo et al. 1998)

$$j_d = 2R_d v_c = \sqrt{2}\lambda'V_{\text{vir}}R_{\text{vir}}.$$  \hspace{1cm} (4)

For typical NFW halos with concentrations $c = 10$, the peak velocity of the dark matter rotation curve which is in general of order the observed peak rotation velocity is $v_{\text{peak}} = 1.2V_{\text{vir}} \approx v_c$. For a flat $\Lambda$CDM-cosmology with cosmological parameters $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ and a Hubble constant of 70 km s$^{-1}$ Mpc$^{-1}$ the virial parameters of dark halos are coupled by the relations (Navarro & Steinmetz 2000)

$$R_{\text{vir}} = 270 \times \left(\frac{M_{\text{vir}}}{10^{12}M_\odot}\right)^{1/3} kpc = 215 \times \left(\frac{V_{\text{vir}}}{100km/s}\right) kpc.$$  \hspace{1cm} (5)

Combining these questions leads to a relationship between the exponential disk scale length $R_d$ and the disk’s rotational velocity $v_c$:

$$R_d = 8.5 \left(\frac{\lambda'}{0.035}\right) \left(\frac{v_c}{200km/s}\right) kpc.$$  \hspace{1cm} (6)

A more detailed investigation which takes into account adiabatic contraction of the dark halo (Jesseit et al. 2002) and the combined gravitational force of the disk and dark halo shows that equation 6 overestimates the disk scale length by a small amount of order 10% to 20%.

Figure 1 compares the observations (Courteau 1997) with the prediction of equation 6, adopting a typical value of $\lambda' = 0.035$. Note that the slope reflects directly the spin parameter $\lambda'$. The theoretical predictions lead to a correlation that is steeper than observed. The dashed line shows a best fit model which requires a value of $\lambda' = 0.025$. If the rotation speeds of galactic disks are approximately the same as the maximum circular velocities of their
dark halos, and if the gas would have the same specific angular momentum as the dark halo, cosmological models predict disk scale lengths that are about a factor of 1.4 larger than observed. Good agreement could be achieved if the gas retained only 70% of the available angular momentum during infall. A similar conclusion was reached by Navarro & Steinmetz (2000) and Mo, Mao & White (1998) who investigated the structural properties of galactic disks within characteristic NFW-type dark halos in greater details.

2. Angular Momentum Loss during Galactic Disk Formation

Numerical simulations have become one of the most powerful tools for exploring galaxy formation. Hydrodynamical simulations of disc formation were initiated by Navarro & Benz (1991), who included radiative cooling by hydro-
gen and helium, and attempted to account for star formation and feedback processes. In contrast to the conclusion drawn in the previous chapter, the simulated galaxies however failed to reproduce their observed counterparts: the disks were found to be too small and were more centrally concentrated than actual galaxies (Navarro & White 1993). In addition, star formation in the models was overly efficient, converting gas into stars too fast. Many of the shortcomings of the early modeling could be accounted for by the limited resolution of the simulations and the way in which feedback was treated. As star formation was very efficient in low mass halos at high redshifts, a large number of dense, compact stellar systems formed that later were collected in the innermost regions of larger galaxies that formed through the merging of smaller objects. Angular momentum loss by dynamical friction drove these star clusters to the center where they formed large, dense bulges instead of extended disks.

Figure 2. The specific angular momentum $j_{disk} = R_d \times v_{rot}$ of model disks with scale length $R_d$ and rotational velocity $v_{rot}$ is compared with observational data (filled points). Figure adapted from Navarro & Steinmetz (2000).
The cosmological angular momentum problem was reinvestigated later on in greater details by Navarro & Steinmetz (2000) with high-resolution N-body/gas-dynamical simulations that included star formation and feedback to examine the origin of the I-band Tully-Fisher relation for different cosmologies. Although the slope and the scatter could be well reproduced in the simulations, the models failed to match the zero point (Fig. 2). Again, the galaxies were too compact with respect to the observations even with realistic feedback formulations that were calibrated to reproduce the empirical correlations, connecting the local star formation rate with the gas surface density (Kennicutt 1998).

A possible solution is suppression of early cooling of the gas by strong feedback from supernovae which prevents drastic angular momentum loss and produces better fits to the observations (Sommer-Larsen et al. 2003, Abadi et al. 2003). However, even in these simulations the disk systems typically contained denser and more massive bulges than observed late-type galaxies, indicating that the specific angular momentum problem is not completely solved.

3. Spin Parameter and Halo Merging History

In the Fall & Efstathiou (1980) model, the scale size of a galaxy is determined by its angular momentum, which is acquired by tidal torques from neighboring objects in the expanding universe, prior to the collapse of the halo. Recent results from numerical N-body simulations have suggested that major mergers might be especially important to increase the mean angular momentum content of the halos and their spin parameters (Gardner 2001; Vitvitska et al. 2002). This is due to the substantial amount of orbital angular momentum which a major merger adds to the system and which dominates the final net angular momentum of the remnant (Gardner 2001). Minor mergers, in contrast, have little effects on the angular momentum budget of galaxies.

Semi-analytical models of galaxy evolution (Kauffmann et al. 1993) cannot investigate the angular momentum properties of a halo self-consistently. They can however predict their merging history and by this their spin parameters, if the spin is coupled with the history of minor and major mergers. This question has been investigated in details by Vitvitska et al. (2002). They followed the evolution of the cumulative mass and the spin parameter of the major progenitors for three high-resolution halos and found that the spin parameters clearly change with time. Instead of a gradual increase, $\lambda$ is increasing with every major merger and subsequently decreasing as a result of minor merging. They proposed that the net angular momentum of dark matter halos originates from statistically random merging with preferentially the last major merger dominating. In this picture, the evolution of the halo angular momentum is quite different from the standard tidal torques scenario, in which the angular momentum grows steadily at early times and its growth flattens later on.
Figure 3. The dimensionless spin parameter $\lambda$ is shown in the upper panel for dark halos which experienced a major merger. The lower panel shows the evolution of the total angular momentum $L$, the total mass $M$ and the total energy $E_{\text{tot}}$ with time. The time axis $t'$ is centered on the epoch of major merging.

This conclusion has recently been questioned by Hetznecker & Burkert (in preparation). Figure 3 shows the evolution of the mean spin parameter $\lambda'$, averaged over a large set of dark halos that experienced at least one major merger in their lifetime. The time axis is centered at the epoch of the major merging. Note that indeed a substantial increase in $\lambda'$ is visible when the merger occurs.
However, afterwards, within the next 2 Gyrs, $\lambda'$ decreases again, approaching the same low value that had been achieved prior to the merging event. Hetznecker & Burkert argue that the temporary increase in $\lambda'$ is a result of the fact that dark halos are out of virial equilibrium during this epoch. Dark particles oscillate into and out of the virial radius and the most bound particle, with respect to which the angular momentum is typically defined, is not a good measure of the center of mass. Neglecting unrelaxed dark halos, the authors find no difference between major and minor mergers and an average $\lambda'$-distribution that is on average shifted to somewhat lower values compared with previous studies that include unrelaxed halos.

4. A Test Case: Bulgeless Galaxies

Most work has up to now focused on angular momentum properties of halos that had at least one dominant major merger during their evolution. However, major merger events tend to destroy disks, producing spheroidal stellar systems, like bulges or early-type galaxies (see e.g. review by Burkert & Naab 2003). Not much work has been devoted to explore the angular momentum properties of halos that host pure disk galaxies, or bulgeless galaxies and that never experienced a major merger.

Recently D’Onghia & Burkert (2004) performed three N-body simulations in a $\Lambda$CDM cosmological universe and explored the angular momentum properties of halos that did not experience any major merger from redshift 3 until the present time and that are in principle good candidates to host bulgeless galaxies. The authors traced each identified halo backward in time, following the mass of the most massive progenitor as a function of redshift during $0 < z < 3$ (for details, see D’Onghia & Burkert, these proceedings). They found that disk-dominated late-type galaxies inhabiting halos that have not experienced a major merger have a distribution of $\lambda'$ that peaks around a value of 0.023 which is substantially smaller than expected from observed rotation curves of bulgeless disks. To demonstrate this they compared their results with the sample of van den Bosch, Burkert & Swaters (2001) who determined spin parameters for 14 late-type bulgeless disk galaxies.

Fig.4 shows the probability distribution of the spin parameter of halos that did not experience any major mergers since $z=3$ (filled region) and compares it with the normalized probability distribution of $\lambda'_{disk}$ for the sample of galaxies measured by van den Bosch, Burkert & Swaters (2001) assuming a mass-to-light ratio of unity in the R band. The galaxies show a distribution that follows a lognormal distribution with an average value for $\lambda'_{disk} \approx 0.067$, and a dispersion of $\sigma_{\lambda'} \approx 0.31$. This is a factor of 3 larger than predicted by the numerical simulations. Again, galactic disks forming in these halos would be too small. However, this time, the problem cannot be solved by feedback processes which
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Figure 4. The distribution of the spin parameters $\lambda'$ of dark halos that experienced no major merger is shown by the filled histogram and compared to the spin distribution of observed bulgeless disk galaxies (solid line). The dotted curve shows the $\lambda'$ distribution if the spins of dark halos without major mergers would be multiplied by a factor of 3.15.

prevent the loss of specific angular momentum of clumpy infalling gas. It is remarkable that multiplying the $\lambda'$ values of simulated halos by a factor 3.15 (dotted histogram in Fig. 4) reproduces the peak and dispersion of the observed $\lambda'_{disk}$ distribution quite well. Halos without major mergers acquire their specific angular momentum through tidal torques in the early epochs of evolution (Barnes & Efstathiou 1987), when the density contrasts were small, in accordance with the prediction of the linear theory. The net result are halos with typical spin parameters of $\lambda' = 0.02$ whereas data for bulgeless galaxies indicate halos with values of $\lambda' = 0.06 - 0.07$, pointing out a new angular momentum problem, especially for bulgeless galaxies.

It’s not clear how to overcome this problem. It is known that the spin parameter distribution for the collapsed objects is insensitive to the shape of the initial power spectrum of density fluctuations, to the environment and the adopted cosmological model (Lemson & Kauffmann 1999).

In the Fall & Efstathiou (1980) model it is assumed that the gas and the dark matter in a protogalaxy have the same distribution of specific angular momentum. However the two components undergo different relaxation mechanisms: the dark matter experiences collisionless violent relaxation and the gas shocks and dissipates its kinetic energy and settles into the central regions. Van den Bosch et al. (2002) used numerical simulations in a cold dark matter cosmology to compare the angular momentum distributions of dark matter and non-radiative gas. They showed that gas and dark matter have identical angu-
lar momentum distributions after the protogalactic collapse phase if, and only if, cooling is ignored, in agreement with the standard assumptions. In addition, they found that 5% to 50% of the mass has negative specific angular momentum. Realistic disks do not typically contain counterrotating material. This suggests that during the cooling process the gas with negative specific angular momentum collides with material with positive specific angular momentum to build a bulge component. Thus, even without substructures and consequent dynamical friction a bulge would be likely to form in all galaxies due to this process, making the formation of bulgeless galaxies even more difficult.

5. The Angular Momentum Problem of Low-Mass Elliptical Galaxies

![Figure 5. Comparison of observed $v/\sigma$ (circles with error bars) and $v/\sigma$ for edge-on numerical merger remnants resulting from collisions of disk galaxies. The shaded area corresponds to the range occupied by Bendo & Barnes (2000). Both distributions are not compatible with the observed one, even in this edge-on case.](image-url)
As outlined previously, numerical simulations indicate an angular momentum problem for disk galaxy formation that results from the fact that gas loses a substantial fraction of its angular momentum while settling into the equatorial plane. Cretton et al. (2001) however also found a related problem for fast rotating low-mass elliptical galaxies. Figure 5 shows the observed radial dependence of $v/\sigma$ of their early-type galaxy sample with $v$ the observed line-of-sight rotational velocity of the stellar spheroid along the major axis and $\sigma$ the local line-of-sight velocity dispersion. The shaded region and the solid lines show the results of numerical simulations of unequal and equal-mass spiral galaxy mergers which reproduce many of the global properties of ellipticals remarkably well (Naab & Burkert 2003, Burkert & Naab 2003). Note that none of these models leads to curves that rise as steeply as observed for many cases of low-mass ellipticals which show values of $v/\sigma \approx 2$ within 1-2 effective radii. Theoretical models instead predict values of $v/\sigma \approx 1$.

Like in the case of galactic disk formation, tidal torques and dynamical friction during the major merger event efficiently remove specific angular momentum from the baryonic stellar component, leading at the end to stellar spheroids with rotational velocities that do not exceed much the velocity dispersion.

### 6. The Specific Angular Momentum Distribution Problem

Early estimates assumed that the detailed specific angular momentum distribution of dark halos is well described by a hypothetical uniform sphere in solid body rotation. This question was reinvestigated again by Bullock et al. (2001) using a large statistical sample of halos that was drawn from a high-resolution ΛCDM simulation. They found that the angular momentum distribution of dark halos has indeed a universal form which however strongly deviates from the previously expected uniformly rotating sphere. The angular momentum distribution can be well fitted by (Fig. 6)

$$M(<j) = M_{\text{vir}} \frac{\mu j}{j_0 + j}$$

(7)

where $M(<j)$ is the cumulative total mass of dark matter with angular momentum less than $j$ and $\mu > 1$ is a free shape parameter. The characteristic specific angular momentum $j_0$ is determined by

$$j_0 = \sqrt{2} V_{\text{vir}} R_{\text{vir}} \chi / b(\mu)$$

(8)

with

$$b(\mu) = -\mu \ln (1 - \mu^{-1}) - 1.$$
Figure 6. The total mass $M(< j)$ of dark matter with angular momentum less than $j$ is fitted by equation (7). Figure adapted from Bullock et al. (2001).

Note, that this formula ignores any material with negative angular momentum (Chen et al. 2003) which makes the problem of low-angular momentum gas even worse, as discussed in chapter 5.

Following Bullock et al. (2001) we explore the surface density distribution of galactic disks, adopting $\lambda' = 0.04$, a NFW halo with concentration $c = 14$ and a disk baryon fraction of $f_{\text{disk}} = M_{\text{disk}}/M_{\text{vir}} = 0.03$. We keep $\mu$ as a free parameter within the measured range of $1.01 \leq \mu \leq 2$ and study its effect on the structure of the disk. Assuming that the dark halo contracts adiabatically due to the gravitational force of the infalling gas, one can calculate the radius $r_*$ in the equatorial plane where gas of a given angular momentum $j_*$ reaches centrifugal equilibrium. $r_*$ is given by the implicit equation

$$j_* = G r_* (M_{\text{NFW}}(r_{\text{cont}}) + M_{\text{gas}}(< j*))$$  \hspace{1cm} (10)
where $r_{\text{cont}}$ is the initial radius of the dark halo mass shell that after adiabatic contraction ends up at $r_*$ (Jesseit et al. 2002; Blumenthal et al. 1984):

$$ r_{\text{cont}} = r_* \frac{M_{\text{NFW}}(r_{\text{cont}}) + M_{\text{gas}}(< j_*)}{M_{\text{NFW}}(r_{\text{cont}})}. $$

(11)

Figure 7. The predicted disk surface density distribution is shown for disks that form from gas with a specific angular momentum profile as predicted by equation 7. The dotted, dashed and solid lines show cases with $\mu = 1.06$, $\mu = 1.25$ and $\mu = 2.0$, respectively. The upper left panel shows a log-log representation. The upper right panel shows the corresponding log-linear plot and compares it with an exponential disk of scale length $0.01R_v$ and $0.02R_v$, where $R_v$ is the dark halo virial radius. The lower left panel shows the local disk scale length, normalized to the virial radius. Typical observed scale lengths are $0.01R_v$. The lower right panel shows the corresponding rotation curves adopting a dark halo mass of $10^{12}M_\odot$, which is characteristic for the Milky Way.

The upper left panel of figure 7 shows the normalized disk surface density profiles for $\mu = 1.06$, $\mu = 1.25$ and $\mu = 2.0$. The profiles agree with Bullock et al. (2001, see their Fig. 20). In this representation it is difficult to estimate
which profile, if any, would fit an exponential disk. Therefore the upper right panel shows again the same profiles, however now in a log-linear representation and focussing on the observed exponential disk regime of $r/R_d \leq 4$, where a disk scale length of $R_d \approx 0.01 - 0.02 R_{\text{vir}}$ has been assumed. An exponential disk with scale length of $0.01 R_{\text{vir}}$ or $0.02 R_{\text{vir}}$ is shown by the straight thin solid lines. Even for large values of $\mu \geq 2$ the profiles are not well fitted by an exponential. All profiles instead rise above the exponential in the inner and outer regions. The situation becomes even more clear in the lower left panel which shows the local exponential scale length defined as $r_{\text{scale}} = (d\ln \Sigma/dr)^{-1}$ for all three values of $\mu$. In all cases, $r_{\text{scale}}$ is continuously and steeply increasing with radius, with no sign of a plateau at a characteristic scale length of order $0.01 - 0.02 R_{\text{vir}}$. If one assumes that all material with small scale length $r_{\text{scale}} < 0.01 R_{\text{vir}}$ forms a bulge component one can calculate the predicted bulge-to-disk ratio as function of $\mu$. We find that for all reasonable values of $\mu$, galactic disks should harbour large bulges with bulge-to-disk mass ratios of more than 20% which is not consistent with the population of late-type disk galaxies.

Viscous effects and secular evolution might change the surface density profiles of galactic disks and redistribute their specific angular momentum distribution. It has indeed been shown e.g. by Slyz et al. (2002) that exponential stellar disks would arise naturally from rather arbitrary initial conditions if the star formation timescale is equal to the viscous timescale. It is however unlikely that viscous effects would increase the specific angular momentum of the gas in the innermost regions, by this reducing the bulge mass fraction.

7. Summary

Although, on average, cosmological models of structure formation in a $\Lambda$CDM universe generate enough spin to explain the origin of extended galactic disks several problems still remain to be solved. These include the loss of angular momentum during gas infall, the specific angular momentum distribution and exponential disk formation and the origin of bulge-less galaxies. The last problem might be even more puzzling if many bulges formed by secular processes as summarized recently in Kormendy & Kennicutt (2004). Feedback has been invoked as a mechanism to prevent the process of drastic angular momentum loss of infalling gas. (van den Bosch, Burkert & Swaters 2002; Maller & Dekel 2002; Maller, Dekel & Somerville 2002). However, D’Onghia & Burkert (2004) have shown that the dark halos that experienced no major mergers have already too low an angular momentum to produce the observed disks and it is not clear which feedback process would increase the specific angular momentum of the gas beyond that of the dark component in order to explain this result. Selective outflow of especially low-angular momentum gas
could provide another solution. Again it seems difficult to understand bulge-
less galaxies in this context as in general a bulge component would be required
to generate the kinetic energy to drive galactic winds. Another interesting sce-
nario was proposed by Katz et al. (2003) and Birnboim and Dekel (2003) who
suggested that gas in high-redshift disk galaxies is accreted cold and without
virial shocks directly from filaments. More work along these lines is clearly
required to understand the origin of galaxies and their angular momentum in
greater details.

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