FORMATION OF MASSIVE COUNTER-ROTATING DISKS: AN ALTERNATIVE SCENARIO

Ivânio Puerari (puerari@inaoep.mx)
Instituto Nacional de Astrofísica, Óptica y Electrónica, Calle Luis Enrique Erro No. 1, 72840, Tonantzintla, Mexico

Daniel Pfenniger (daniel.pfenniger@obs.unige.ch)
Observatoire de Genève, Université de Genève, CH-1290 Sauverny, SWITZERLAND

1. Introduction

The formation of massive counter-rotating disks is not yet fully understood. It is unlikely that counter-rotating systems result from the galaxy formation process, because in a uniformly rotating protogalactic cloud a subsequent splitting of the angular momentum distribution into a strongly bimodal one appears “anti-thermodynamical”. More natural is to look for a second event scenario in the form of a merger process as the origin of the formation of this kind of systems, because infalling satellites do contain much specific angular momentum with arbitrary orientation. Although only a few cases of massive counter-rotating disks are known, counter-rotation in galaxies seems to be a common phenomenon, particularly in early-type spirals (Kuijken, Fisher & Merrifield 1996; for reviews, see Rubin 1994, and Galletta 1996). So systems with heavy counter-rotation might represent the extreme case of the lighter but more frequent counter-rotating systems.

Thakar & Ryder (1996, 1998) tested some scenarios for the formation of counter-rotating disks. They investigated three mechanisms: episodic gas infall, continuous gas infall, and merger with a gas-rich dwarf companion. In all cases, some counter-rotation was produced, but in some cases they had very different characteristics when compared to galaxies like NGC 4550, the first galaxy with massive counter-rotating disks discovered (Rubin, Graham & Kenney 1992). For example, with gas infall, Thakar & Ryder were able to produce small counter-rotating disks with radial profile different from exponential. Yet, some conditions must be satisfied for producing counter-rotation, without upsetting the stability of the existing disk: e.g., the rate of infall has to be small to preclude excessive heating. The scenario with gas-rich dwarf merger is even less viable to be a mechanism to produce massive counter-rotating...
disks: only very small dwarf galaxies do not increase significantly the thickness of the pre-existing disk, and the timescale for this process is prohibitively long. In addition, merging several dwarf galaxies over several Gyr requires to adjust their angular momentum vectors relative to the moving large galaxy such that only when they merge their angular momentum vectors are well correlated, which appears highly improbable.

In this contribution we will investigate an alternative scenario: major mergers between progenitors with comparable mass. Such a scenario can be ruled out in general because they produce rather ellipticals. Yet for a narrow range of initial conditions, major mergers can nevertheless produce anyway rare galaxies such as NGC 4550, and so they are viable alternatives for the formation of these counter-rotating systems. The scenario is successful in producing a remarkably axisymmetric disk possessing strongly counter-rotating populations. Partial results were already published by Pfenniger (1997). Here, we will present results for different galaxy models and for simulations including gas.

2. Models and computational details

Fully self-consistent models with dark halo were constructed using a recipe similar to that of Barnes (1988). Firstly, we construct the spherical system following a Plummer’s density law, secondly, the disk, following a radial Kuzmin/Toomre’s law, and a sech\(^2\)\((z/z_0)\) law in the vertical direction. The next step is to tabulate the forces from the disk distribution on a grid. This force grid is slowly imposed to the spherical system. When the spheroid reaches equilibrium, we calculate the rotation curve from this evolved halo, and give velocities to the disk particles, choosing velocity dispersions (\(Q\) Toomre’s parameter equals 1, and epicyclic approximation). The asymmetric drift correction is taken into account. By superposing this disk and the evolved halo, we get an isolated galaxy model, close to equilibrium. In Table I we give the parameters for the isolated model. \(M_H\) and \(M_D\) represent the halo and disk mass, respectively. \(N\) is the number of particles, and \(b\) the radial scale length. \(R_{cut}\) is the cut-off radius, and finally \(z_0\) is the vertical scale height for the disk. With the chosen normalization \((G = 1)\), the units of length, time and mass are 3 kpc, \(10^7\) years, and \(6 \times 10^{10}\) M\(\odot\).

The binary galaxy systems are set by rotating and displacing the isolated model to get the desired configuration. We choose coplanar, antiparallel systems, since this configuration minimize the energy which would contribute to the heating of the disks. To check the effect of the
Table I. Model parameters

| Halo | Disk |
|------|------|
| $N_H$ | $M_D$ | $b_H$ | $R_{cut_H}$ | $N_D$ | $M_D$ | $b_D$ | $R_{cut_D}$ | $z_0$ |
| 30000 | 1.5 | 5.0 | 10.0 | 10000 | 0.5 | 1.0 | 5.0 | 0.1 |

orbit, we have run a parabolic and a circular encounter. The initial distance between galaxies is 22 length units, and for the parabolic orbit, the pericenter distance is 6 length units (the disk initial radius is 5). These simulations have been calculated using a parallelized version of the treecode (Barnes & Hut 1986), running on a Power Challenge Silicon Graphics. We have run also two simulations including gas. On these runs, 10% of one disk mass is treated as gas in a tree-sph code. The orbit for these simulations is parabolic. In one case, the gas is in the prograde galaxy, and in the retrograde galaxy in the second simulation. More details of the run parameters will be given elsewhere (Pfenniger & Puerari, in preparation).

3. Results and discussion

We have plotted the average line profiles as seen in the edge-on disks. The bimodal distribution is crucial in order to distinguish counter-rotating disks from hot population with a zero net rotation. It is clear from our velocity profiles (not shown here) that the distribution is bimodal, representing counter-rotating systems very well.

In Figure 1 we plot the tangential velocity (as seen in the edge-on disks) of the disk particles, in the case of a parabolic orbit. This plot can be compared to the rotation curves derived for NGC 4550 (Rubin et al. 1992) and NGC 3593 (Bertola et al. 1996). The similarity between the computed and the measured rotation curves show that a major merger scenario can reproduce very well the kinematical characteristics of the counter-rotating galaxies.

Figure 2 is similar to Fig. 1, but now for a circular orbit. The ratio between the “prograde” and “retrograde” rotation velocities seems to be related with the orbit: a more circular one tends to yield low counter-rotating velocities, while parabolic orbits yield high counter-rotation.

With respect to the density profile, our models are constructed following initially a Kuzmin/Toomre density law. This profile remains almost unchanged after the merger. So, our models have no difficulty to reproduce normal radial density profiles after the merger.
Figure 1. Rotation velocity curve of the disk particles of the merger remnant for the case of parabolic orbit to be compared with the velocity curve of NGC 4550 (see, e.g., Fig. 3 on Rubin et al. 1992) or NGC 3593 (see, e.g., Fig. 1 on Bertola et al. 1996).

Figure 2. The same as Figure 1, but now for a circular orbit. The amplitude of the counter-rotation is less marked compared to the parabolic case.
At some stage of the evolution and for some edge-on viewing angles, coplanar disks can appear as edge-on galaxies with “two-bulges”. Such a bizarre case is known in the Hercules cluster, PGC 57064. Incidentally, close-by is a pair of contact spirals (NGC 6050), which triggered for a part this work. For a comparison, we plot in Figure 3, the image of PGC 57064, taken from the Digitized Sky Survey, and a snapshot of one of our simulations. Candidates for merging coplanar-antiparallel disks such as PGC 57064 could be investigated by spectroscopy or adaptive optics photometry with large telescopes.

It is clear that the retrograde disk galaxy (with respect to the orbital spin) is less affected by the interaction: the large tail appears only in the prograde galaxy. So, the final content of gas in such interactions depends on where the gas was before the merger. In typical spirals much gas exists in the outer disks so a coplanar merger is likely to eject much of it, evacuating simultaneously the excess angular momentum.

4. Conclusions

We have shown that major mergers, involving disk galaxies with comparable masses, can reproduce very well the morphological and the kinematical characteristics of massive counter-rotating galaxies such as NGC 4550, a prototype of this kind of objects. The rotation curve, velocity dispersion and density profile of the simulations mimic those of counter-rotating systems, and these counter-rotating characteristics remain for some Gyr. The somewhat peculiar conditions for the encounters are coplanar, antiparallel disks, that should be favored by gaseous viscous processes taking place when the outer disks interact. We have tested both cases with or without hot dark halos: they don’t appear to be necessary in the scenario.

The gas content on the final merger depends on where the gas is before the interaction. If the gas is on the prograde galaxy, a large amount is expelled, while more gas remains in the merger remnant if the gas is initially in the retrograde galaxy.

Candidates where the massive counter-rotating disks are at earlier stages of the merger could be galaxies like PGC 57064 (these systems seem to be edge-on galaxies with “two-bulges”). Spectroscopy with large telescopes could check the antiparallelism of such systems and provide some hint about the frequency of such mergers events.
Figure 3. Top: Edge-on view of a simulation at some stage of the interaction, before the merger. This particular view can represent “two-bulges” galaxies like PGC 57064 (bottom).

References

Barnes J., 1988, ApJ 331, 699
Barnes J., Hut P., 1986, Nature 324, 446
Bertola F., Cinzano P., Corsini E.M., Pizzella A., Persic M., Salucci P., 1996, ApJ 458, L67
Galletta G., 1996, In: R. Buta, D.A. Crocker, B.G. Elmegreen (eds.) ASP Conf. Ser. 91, “Barred Galaxies”, ASP, San Francisco, p. 429
Kuijken K., Fisher D., Merrifield M.R., 1996, MNRAS 283, 543
Pfenniger D., 1997, In: J. Barnes, D. Sanders (eds.) IAU Symp. 186, “Galaxy Interactions at Low and High Redshift”, Dordrecht, Kluwer, p. 39
Rubin V.C., 1994, Astron J 108, 456
Rubin V.C., Graham J.A., Kenney J.D.P., 1992, ApJ 394, L9
Thakar A.R., Ryden B.S., 1996, ApJ 461, 55
———, 1998, ApJ 506, 93
