Spiral Galaxies and Tracers of Mass Accretion

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Abstract
Can the present dynamics of spiral galaxies tell us something about the merging history, the formation and evolution of disks? Galaxy interactions thicken or destroy disks; the simultaneous presence of thick and thin disks is a tracer of past accretion, and also of recent disk re-formation. Observation of a large number of counter-rotating disks is also evidence of past mergers, as well as the frequency of polar-ring galaxies. Finally, the ubiquitous presence of warps in the outer parts of HI disks might also provide a clue of how frequently disks accrete mass with different angular momentum.

1 Introduction
According to hierarchical cosmological scenarios, galaxies form through merging of smaller entities. At least the dark haloes of dissipationless matter hierarchically merge, and it is expected that some of the visible galaxies also interact and exchange mass, while spiraling in a common halo. If major mergers lead to the formation of ellipticals, and leave vestiges such as shells, ripples and loops around present-day elliptical galaxies (Schweizer & Seitzer 1988), signatures of accretion or merger are less easy to see in spiral galaxies. Yet, mass and gas accretion is required in spiral galaxies for several reasons:

- Metallicity distribution in the disk (the G-dwarf problem for instance, requires gas infall)
- Spiral formation and maintenance: episodes of spiral density waves heat the disk, and accreted fresh gas is required to trigger new instabilities
- Renewal of bars and nuclear bars, that drive mass towards the center, and self-destroy
- Reforming the thin disk after minor mergers: galaxies such as the Milky Way re-form a thin disk, while a thick one has been heated by an interacting event

In the following, the main evidences for mass accretion in spiral galaxies will be reviewed, including: the presence of thick disks, counter-rotating components, the ubiquity of warps, or the existence of polar rings.
2 Galaxy Interactions and Thickness of Stellar Disks

In hierarchical cosmologies, it is easy to estimate analytically the probability of formation of a dark halo of mass \( M \) at time \( t \) from the Press-Shechter theory (1974), revised by Bond et al (1991): a gaussian distribution of fluctuations is assumed, and structures are followed through random walk of linear overdensity with respect to smoothing scale.

From such analytical formulations of merging histories (e.g. Lacey & Cole 1993, 1994), it is possible to relate the dark haloes merger rate to the parameters of the universe (average density, cosmological constant). The merging rates for visible galaxies should follow, although the link is presently not well known (Carlberg 1991, Toth & Ostriker 1992).

For the standard CDM model (\( \Omega = 1 \)) for instance, 80% of haloes have accreted at least 10% of their mass in the last \( 5 \times 10^9 \) yrs. To reduce the merging rate today, the solution is to consider low \( \Omega \) models, for which freezing of halo formation occurs for \( z < 1/\Omega \). After this epoch, only very few haloes form, and the merger rate of visible galaxies inside haloes is expected also very low. When approximations are taken for the merger conditions of the galaxies, such as a threshold in their relative velocity \( v < v_{mg} \sim v_{escape} \) (Carlberg 1990, 91), the merger rate can be written as a power law with redshift, \( dn(mergers)/dt \propto (1 + z)^m \), with the power-law \( m \) increasing with \( \Omega \) and \( \Lambda \) (typically as \( m \propto \Omega^{0.42}(1 - \Lambda)^{-0.11} \)).

Observations support a large value of the exponent \( m \). Statistics of close galaxy pairs from faint-galaxy redshift surveys have shown that the merging rate increases as \( (1 + z)^m \) with \( m = 4 \pm 1.5 \) (e.g. Yee & Ellingson 1995). Lavery et al (1996) claim that collisional ring galaxies (Cartwheel-type) 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 (Carlberg 1991, Carlberg et al 1994).

The fragility of disks with respect to interactions can be used to constrain the merging rate. During an interaction, stellar disks can thicken or even be destroyed (e.g. Gunn 1987). Through the disk thickness of the Milky Way, Toth & Ostriker (1992) constrain the frequency of merging and the value of the cosmological parameters: from analytical and local estimations of the heating rate, they claim that the Milky Way disk has accreted less than 4% of its mass within the last 5 Gyrs. But these local calculations are only rough approximations. The first numerical simulations of the phenomenon of disk thickening through interactions (Quinn et al 1993, Walker et al 1996) appear to confirm the analytical results however: they show that the stellar disk thickening can be large and sudden.

Recently, Huang & Carlberg (1997) and Velazquez & White (1999) reconsider the problem, through numerical simulations, and find on the contrary that the heating of disks have been overestimated. In particular, prograde satellites heat the disks, while retrograde ones produce only a coherent tilt. If the halo is rigid, the thickening of the disk is increased by a factor 1.5 to 2: massive live bulges can therefore help to keep disks thin, in absorbing part of the heating. Also, there are many parameters to explore in simulations: the most important could be the compactness of the interacting companion. If the perturber has a compact core, the heating effect is important, while a more diffuse companion is destroyed by tidal shear before damaging the primary disk.

It should be however remarked that gas hydrodynamics and star formation processes can also alter significantly the processes, since the thin disk can be reformed continuously through gas infall. It is interesting to check on presently interacting galaxies whether the heating or thickening of disks is measurable. In normal galaxies, the ratio of radial scale-length \( h \) to scale-height \( z_0 \) is about constant and equal to 5 (Bottema 1993); the ratio only goes up for dwarf galaxies. Now, in a sample of edge-on interacting galaxies this ratio was found to be 1.5 to
to 2 times lower than normal (Reshetnikov & Combes 1997, Schwarzkopf & Dettmar 1999), as shown in fig 1. This is surprising, when taking into account that the visible ”interacting phase” is only transient, and on a Gyr time-scale, interacting galaxies will return to the ”normal phase”, with again a high $h/z_0$ ratio, or thin disk.

A possible interpretation of this result is that the interacting galaxies are warped, since the latter is difficult to distinguish from a thickening at any viewing angle; yet the damping of the warp will thicken the disk in any case. If the thickening is in fact transient, this indicates that the present disk galaxies come from merging of smaller units, that they acquire mass continuously: through gas accretion and subsequent star formation, disks recover their small thickness after galaxy interactions, or in other words, the disk of present day spirals has been assembled at low redshift (Mo et al 1998).

3 Counter-Rotating Components

The phenomenon of gas disks counter-rotating with the stellar component is now well known in ellipticals, where the ionised gas disks (or dust lanes) are settled in principal planes (e.g. Bertola et al 1990). Ellipticals were also first discovered with kinematically decoupled stellar cores, which are expected in merger remnants, such as NGC 7252 (e.g. Barnes & Hernquist 1992).

Counter-rotation has also been observed in many spirals during this last decade, although it is more difficult than in ellipticals, since the secondary CR component is not dominating and the primary component is strongly rotating. All possibilities have been observed, either two stellar disks counter-rotating with respect to each-other, or the gas counter to the stars, or even gas versus gas, but not at the same radii in the galaxies (see the reviews of Galletta 1996, Bertola & Corsini 1998). There is presently about 60 systems of counter-rotation recorded in the literature.

In general the counter-rotating component is not dominant, but there is a very special case, NGC 4550, where two almost identical CR stellar disks are observed (Rubin et al 1992). This case is a puzzle, since the second disk cannot have formed through subsequent accretion of gas: the two stellar disks have the same age. The only solution is through a merger of pre-existing spiral galaxies. If major mergers usually give an elliptical galaxy as a remnant, this is not the case when they have aligned direction of their angular momentum. In these rare orientation
cases, it is possible to merge two spiral galaxies in one, and reproduce the case of NGC 4550, when the momenta are opposite (Pfenniger 1998, Puerari & Pfenniger 1999).

Can one consider other explanations than mergers for CR components? It is possible to artificially simulate counter-rotation in a certain region of a galaxy, through perpendicular streaming motions due to a bar potential, for instance; but when the 2D velocity field is obtained, confusion is not possible. There are also self-consistent models of barred galaxies including retrograde orbits (Wozniak & Pfenniger 1997), but the origin of the retrograde stars is still gas accretion. A slow bar destruction can be a rare case where stars in box-orbits in a barred galaxy are scattered equally in two CR families of tube orbits, resulting in two opposite streams when the bar has disappeared (Evans & Collett 1994). But the process of bar destruction is in any case related to galaxy interactions and gas accretion.

3.1 Stability

How long such counter-rotating systems can live? Does this phenomenon favor gas fueling to the nucleus?

There exists a two-stream instability in flat disks, similar to that in CR plasmas (Lovelace et al 97). If there exists a mode in a given disk, the energy of the modes in the two streams are of opposite signs: the negative E mode can grow by feeding energy in the positive E mode, which produces the instability. There exist also many bending instabilities (Sellwood & Merritt 1994).

If there is only a small fraction of CR stars, these have on the contrary a stabilising influence with respect to bar formation \((m = 2)\); in a certain sense, they are equivalent to a system with more velocity dispersion (Kalnajs 1977).

But in the case of comparable quantities of CR stars, a one-arm instability is triggered. This is confirmed through N-body simulations: a quasi-stationary one-arm structure forms, and lives for 1–5 periods (Comins et al 1997), first leading, than trailing, and disappears. Fig 2 shows such a simulation, where the common \(m = 1\) pattern is leading for the main direct component, and trailing for the secondary retrograde one.

3.2 Counter-rotating gas

Accretion of CR gas in a lenticular galaxy deprived of gas initially is a way to form two stellar counter-rotating disks, after star formation has occurred. Thakar & Ryden (1996) have shown that both episodic or continuous gas infall are able to form a stable CR disk, without destabilising the pre-existing disk significantly. The conditions are that gas must be extended in phase space and not clumpy, which would heat too much the primary disk. For example, the merger of a gas-rich dense dwarf will have a too large heating effect, unless the mass ratio is quite small, and in such cases, only a small CR disk is produced. However, the final thickness of the disk depends drastically on the gas code used, thicker for sticky particles, and much thinner with SPH (Thakar & Ryden 1998), as well as the settling time-scales.

When gas is present in the initial disk, the presence of two CR streams of gas in the same plane will be very transient: strong shocks will produce heating and rapid dissipation will drive the gas quickly to the center (Kuznetsov et al 1999). This could be a very efficient way to fuel active nuclei. However, the gas could also infall in an inclined plane, or at different radii than those of the pre-existing gas, which can explain the observations of two counter-rotating gas systems.

Polar rings (objects similar to the prototype NGC 4650A) are such cases, where gas settles in a stable plane almost perpendicular to the primary galaxy. Polar-ring galaxies are quite rare
in the nearby universe: Whitmore et al (1990) find that about 0.5% of all nearby lenticular galaxies are observed with a polar ring. But since there are projection effects and different selection biases that prevent to see them all, they estimate to about 5% the actual present frequency of PRGs. An estimation of their frequency as a function of redshift will be a precious tool to quantify the merging rate evolution.

\section*{4 Warps as clues of matter accretion}

The majority of spirals are warped in their neutral hydrogen (HI) component (e.g. Sancisi 1976, Bosma 1981, Briggs 1990). This is a long-standing puzzle, since if the gas is considered as test-particles in the halo potential, it should differentially precess, and with a time-scale much shorter than the Hubble time the disk should end up with a corrugated shape and thicken.

Many theories have been proposed to solve the problem. Normal modes of the disk have been ruled out, since they are quickly damped (Hunter & Toomre 1969), but normal modes of the disk in the potential if a mis-aligned halo have been a possibility for a while (Toomre 1983, Sparke & Casertano 1988), until it was realized that they are quickly damped through dynamical friction (Nelson & Tremaine 1995).

The triggering of warps by tidal interaction with companions has been ruled out in the past, since the best examples of warped galaxies appeared isolated. However, this could be changing now that smallest companions can be found, or vestiges of a past merger. This is the case of the warp-prototype NGC 5907, where a conspicuous tidal loop has been observed by Shang et al (1998). It is obvious that this galaxy has accreted a small system in the recent past, and it has also a dwarf companion nearby (see Fig [3]). Regular and symmetric warps are those that have already relaxed for a while, and this could explain the apparent lack of correlation with companions.
Finally, the proposition that gas infall could maintain warps around galaxies is easily justified in the framework of hierarchical cosmologies (cf Ostriker & Binney 1989; Binney 1992). Gas infalls with slewed angular momentum with respect to the main disk. This accretion will re-align the whole system along a tilted axis. The transient state is the warped state. This hypothesis has been recently supported through numerical simulations by Jiang & Binney (1999). They show that the inner halo and disc tilts as one unit. The halo tilts first in the outer parts, and the tilt propagates then inwards; the disk is entrained and aligns with the halo, it plays the role of a tracer of its orientation. The time-scale of this phenomenon is about 1 Gyr to re-align by $7^\circ$.

5 Conclusions

In summary, there are many evidences that even spiral galaxies have experienced a large number of galaxy interactions in the past, and that their formation proceeds also through hierarchical merging and accretion: presence of thick and thin disks, growing number of observed counter-rotating disks, frequency of polar-ring galaxies, ubiquity of HI warps. Both present explanations of warps, either through tidal interactions trigger, or maintenance through gas infall, are compatible with this paradigm.

References

[1] Barnes J., Hernquist L., 1992, Ann. Rev. Astron. Astrophys. 30, 705
[2] Bertola F. Bettoni D., Buson L.M., Zeilinger W.W., 1990, in Dynamics and Interaction of Galaxies, ed. R. Wielen, Springer, p. 249
[3] Bertola F. & E. Corsini, 1998 in *Galaxy Interactions* IAU Symp. 186, Kyoto 1997, Kluwer
[4] Binney J., 1992, *Ann. Rev. Astron. Astrophys.* **30**, 51
[5] Bond J.R., Kaiser N., Cole S., Efstathiou G., 1991, * Astrophys. J.* **379**, 440
[6] Bottema R., 1993, *Astr. Astrophys.* **275**, 16
[7] Bosma A., 1981, *Astron. J.* **86**, 1825
[8] Briggs F., 1990, *Astrophys. J.* **352**, 15
[9] Carlberg R.G. 1990, *Astrophys. J.* **359**, L1
[10] Carlberg R.G. 1991, *Astrophys. J.* **375**, 429
[11] Carlberg R.G., Pritchet C.J., Infante L. 1994 *Astrophys. J.* **435**, 540
[12] Comins N.F., Lovelace R.V.E., Zeltwanger T., Shorey P., 1997, *apj* 484L33
[13] Evans N.W., Collett J.L., 1994, *Astrophys. J.* **420**, L67
[14] Galletta G., 1996, in *Barred Galaxies*, ed R. Buta, D.A. Crocker & B.G. Elmegreen, ASP Conf. Series. **91**, p. 429
[15] Gunn J.E., 1987, in *Nearby Normal Galaxies* ed. S.M. Faber, Springer New York, p. 459
[16] Huang S. & Carlberg R.G. 1997, *Astrophys. J.* **480**, 503
[17] Hunter C., Toomre A., 1969 *Astrophys. J.* **155**, 547
[18] Jiang I-G., Binney J., 1999, *MNRAS* **303**, L7
[19] Kahn A., 1977, *Astrophys. J.* **212**, 637
[20] Kuznetsov O.A., Prokhorov M.E., Sazhin M.V., Chechetkin V.M., 1999, *Astrophys. J.* preprint (astro-ph/9810429)
[21] Lacey C., Cole S. 1993, *MNRAS* **262**, 627
[22] Lacey C., Cole S. 1994, *MNRAS* **271**, 676
[23] Lavery R.J., Seitzer P., Suntzeff N.B., Walker A.R., Da Costa G.S. 1996, *Astrophys. J.* **467**, L1
[24] Lovelace R.V.E., Jore K.P., Haynes M.P., 1997, *Astrophys. J.* **475**, 83
[25] Mo H.J., Mao S., White S.D.M., 1998, * MNRAS* **295**, 319
[26] Nelson R.W., Tremaine S., 1995, *MNRAS* **275**, 897
[27] Ostriker E.C., Binney J.J., 1989, *MNRAS* **237**, 785
[28] Pfenniger D., 1998, in *Galaxy Interactions* IAU Symp. 186, Kyoto 1997, Kluwer
[29] Press W.H., Schechter P. 1974, *Astrophys. J.* **193**, 437
[30] Puerari I., Pfenniger D., 1999, in *The Evolution of Galaxies on Cosmological Time-Scales*, Tenerife, Spain, Nov 30-Dec 5, 1998, PASP Series ed T. Mahoney & J.E. Beckman
[31] Quinn P.J., Hernquist L., Fullagar D.P., 1993, *Astrophys. J.* **403**, 74
[32] Reshetnikov V., Combes F.: 1997, *Astr. Astrophys.* **324**, 80
[33] Rubin V.C., Graham J.A., Kenney J.D.P., 1992, *Astrophys. J.* **394**, L9
[34] Sancisi R., 1976, *Astr. Astrophys.* **53**, 159
[35] Schwarzkopf U., Dettmar R-J., 1999, in *Galaxy Evolution: Connecting the Distant Universe with the Local Fossil Record*, ed. M. Spite, Kluwer
[36] Schweizer F., Seitzer P. 1988, *Astrophys. J.* **328**, 88
[37] Sellwood J.A., Merrit D., 1994, *Astrophys. J.* **425**, 530
[38] Shang Z., Brinks E., Zheng Z. et al., 1998, *Astrophys. J.* **504**, L23
[39] Sparke L., Casertano S., 1988, *MNRAS* **234**, 873
[40] Thakar A.R., Ryden B.S., 1996 Astrophys. J. 461, 55
[41] Thakar A.R., Ryden B.S., 1998, Astrophys. J. 506, 93
[42] Toomre A. 1983, in Internal Kinematics and Dynamics of Galaxies, IAU Symp. 100, ed. E. Athanassoula, p. 177 (Reidel)
[43] Toth G., Ostriker J.P. 1992 Astrophys. J. 389, 5
[44] Velazquez H., White S.D.M., 1999, MNRAS 304, 254
[45] Whitmore B.C., Lucas R.A., McElroy D.B. et al: 1990, Astron. J. 100, 1489
[46] Yee H.K.C., Ellingson E. 1995 Astrophys. J. 445, 37
[47] Walker I.R., Mihos J.C., Hernquist L., 1996, Astrophys. J. 460, 121
[48] Wozniak H., Pfenniger D., 1997 Astr. Astrophys. 317, 14