COMPARISON WITH EXTERNAL GALAXIES DYNAMICS

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Many features of the Milky Way appear weird or unique, because of the peculiar point of view. However the same features are observed more easily and clearly in nearby galaxies. The Milky Way appears to cumulate many dynamical features, such as a bar, a nuclear disk, a perpendicular nuclear bar (?), lopsidedness, an inner ring (molecular ring at 5kpc), a peanut-shape bulge, a warp, and a polar ring. By comparison with external galaxies, and also results from N-body simulations, we can infer the most probable bar angular velocity and length, and interpret the ring features.

1. Bar, nuclear bar

1.1. PRESENCE OF A BAR

It is now widely recognized that our Galaxy is barred, from non-circular motions: 3kpc arm, for instance (Peters 1975, Liszt & Burton 1980), $l-v$ CO parallelogram in the Galactic Center (e.g. Binney et al. 1991), but also from its perspective view (Blitz & Spergel 1991a & b; COBE-DIRBE 2 μm survey Weiland et al. 1994, Hammersley et al. 1994), and even microlensing (Kiraga & Paczynski 1994, Stanek et al. 1994). However, the various authors don't agree on the length, and orientation of this bar (Weinberg 1992). The presence of a bar is not surprising, since the majority of spiral galaxies are barred, more than 2/3 if oval distortions are taken into account. Some bars are only visible in the old stellar component, and revealed in the near-infrared (e.g. Block et al. 1994). It is likely that our bar is not only a Pop II bar, with the Pop I component decoupled, since the bar is so obvious in the molecular component.

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1.2. BAR LENGTH AND PATTERN SPEED

According to orbits theory, the bar length can be predicted with respect to the bar resonances (corotation, Lindblad resonances). For instance, a bar cannot extend outside its corotation (cf. Contopoulos 1980). Bars can be considered as standing waves, or the eigen modes of the galaxy host: their characteristics do not depend on the triggering mechanism, for instance an external companion that helps to transfer angular momentum outwards. So the bar pattern speed, at steady equilibrium, depends only on the mass distribution of the galaxy; it slowly evolves in time with increasing mass concentration.

Within the first order epicyclic approximation, stellar orbits can be considered as ellipses precessing at the rate $\Omega - \kappa/2$ (in the rotating frame with precisely that speed, orbits are closed and run two epicycles for one turn). Since $\Omega - \kappa/2$ is a slowly varying function of radius, differential precession is not large, which helps the formation of a density wave. Self-gravity will force equality of all precessing rates. As was shown in the density wave theory (e.g. Lin & Shu 1964), the equivalent epicyclic frequency κ' is lowered by self-gravity, i.e. $\kappa' < \kappa$. This implies a larger precessing rate $\Omega - \kappa'/2$, which is indeed confirmed by N-body simulations: at the beginning of bar formation, still in the linear regime, the bar pattern speed is slightly larger than the maximum of the $\Omega - \kappa/2$ curve. During its growth, however, the bar slows down, loosing angular momentum through the trailing spiral wave. At steady state, the bar pattern speed is usually lower than the maximum of the $\Omega - \kappa/2$ curve. Then two inner Lindblad resonances exist, as testified by the presence of the perpendicular x2 orbits (Sellwood & Sparke 1988). This is always the case in concentrated mass distribution, corresponding to early-type galaxies. The bar extends then up to half the optical disk radius, where the spiral structure takes over, which corresponds to the bar ending a little inside its own corotation (CR).

But a completely different situation can occur in late-type galaxies, with no central mass concentration, where the rotation curve is very slowly rising all over the galactic disk (cf. Combes & Elmegreen 1993). The $\Omega - \kappa/2$ curve is then very flat (it is even zero for $V \propto r$, where $\kappa = 2\ \Omega$). The corresponding low bar speed pushes corotation out of the optical disk, which prevents the bar from growing, by lack of stars near CR. These bars are therefore "truncated" and much shorter relative to their corotation. Direct measurements of the pattern speed from kinematical signatures support this theory, in NGC 4321 and NGC 7479 (Sempere et al. 1994a & b).

In our Galaxy of rather early-type (Sb), the mass concentration is sufficient to be in the first category, i.e. we expect that the bar will extend up to its CR. From the observed rotation curve, the corresponding $\Omega - \kappa/2$

curve (fig. 1), and N-body simulations with stars and gas including similar bulge and disk components, we can infer a bar pattern speed of 40-50km/s, putting the CR at about 4-5 kpc. The bar length would then be 4-5kpc, which corresponds better to the Weinberg (1992) or Hammersley et al. (1994) propositions. This corresponds also to the global gas-dynamical model of our Galaxy by Mulder & Liem (1986).

1.3. NUCLEAR BAR

The much higher pattern speed inferred by Binney et al. (1991) from the CO $l - v$ diagram in the very center could be related to the existence of a nuclear bar in the center of the Galaxy. Indeed, it is very frequent, when the mass concentration is very high in the inner kpc, and when there exists a large central gas fraction (as it appears to be the case for the Milky Way), that a second bar decouples from the first one, and is amplified by non-linear interaction at a common resonance (Tagger et al. 1987): typically the corotation of the small bar is the inner Lindblad resonance (ILR) of the big one. Nuclear bars are observed in external galaxies through isophote twists. They are even more obvious at near-infrared wavelengths (cf. Shaw et al. 1993).

Two main interpretations can be proposed for these isophote twists: first, in the presence of two inner Lindblad resonances, the family x2 of perpendicular periodic orbits is the cause of phase shifts in the gas component; once enough gas is gathered in the center, a fraction of the stellar component follows its potential (Shaw et al. 1993). Second, a nuclear bar decouples from the main bar, with a larger pattern speed: it is the bar within bar phenomenon, as suggested by Shlosman et al. (1989), and demonstrated by Friedli & Martinet (1993) and Combes (1994a). This second mechanism occurs in simulations with a more viscous gas, i.e. with a large velocity dispersion. The presence of the second fast bar is difficult to predict. It is a relatively transient phenomenon, its life-time being of the order of a few 10^8 yrs, and depends on gas accretion. When gas accretion is fast enough, the consequent star formation yields enough energy in the central gas that its equivalent viscosity then can trigger the nuclear bar decoupling.

Parallel (x1) and perpendicular orbits (x2 in the notation of Contopoulos & Mertzanides 1977) are clearly observed in our Galaxy, through the $l - v$ diagram of the HI and CO emission. The x1 periodic orbits aligned parallel to the bar, and in particular, the cusped ones delineate a parallelogram in the $l - v$ plot, that is reminding of the shape of the $l - v$ CO diagram from the survey of Bally et al. (1988). The orbits x2, perpendicular to the bar between the two inner Lindblad resonances, also seem to fit the line of enhanced CO intensity following the diagonal of the parallel-

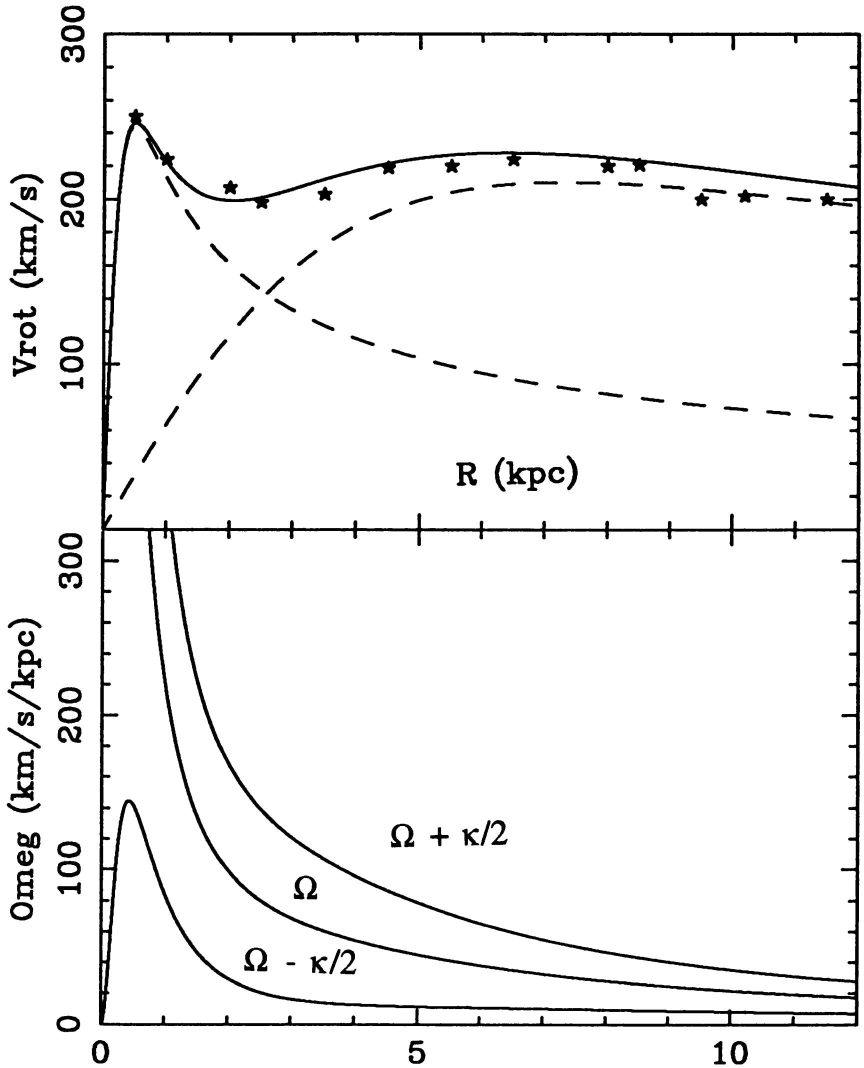

Figure 1. Rotation curve fit of the Galaxy: a) the stars are the average of observed points, as compiled by Fich & Tremaine (1991); the dashed lines represent the contributions of the bulge (1.1 10^{10} $M_\odot$) and disk (7.2 10^{10} $M_\odot$ within 12kpc). It was not necessary to add any dark halo within 12kpc. b) The corresponding frequencies Ω, $\Omega - \kappa/2$, and $\Omega + \kappa/2$, and the suggested value of the bar pattern speed Ω_p.

ogram. In early-type external galaxies possessing a nuclear bar, the latter is confined inside the nuclear ring, which corresponds to the wide location of the inner resonance; the nuclear ring is formed by the x2 orbits, which are much rounder than the x1. Since it is likely that the nuclear disk in the

Milky Way center corresponds also to orbits trapped around the x2 family, their excentricity is not large; this implies that the velocities are not highly non-circular, and supports the validity of the observed rotation curve of fig. 1.

The deformation of the parallelogram when different latitudes are taken into account in the $l - v$ diagram suggests that the elongated x1 orbits are slightly tilted, such that their extremiti ›s (at quasi zero velocity) do not lie at zero latitude. A slight tilt of 3° would be sufficient to explain the observations (Combes 1994b).

2. Nuclear disk

A nuclear disk is often apparent in galaxies as a separate dynamical component, revealed by large rotational velocities towards the center (inner kpc). It is a large mass concentration, mainly gaseous. When seen almost face-on, these objects reveal frequently a nuclear ring of star formation, i.e. the Hα regions are concentrated in an annulus centered on the nucleus. Conspicuous examples are NGC 4321 (Arsenault et al. 1988), NGC 1097 (Hummel et al. 1987). A large amount of molecular hydrogen has been traced in these galaxies, with large velocity gradients (Garcia-Burillo et al. 1994, Gerin et al. 1988).

When seen almost edge-on, these objects are peculiar from their large radial velocity gradients, as in the Milky Way (fig.2a, Dame et al. 1987). This peculiar kinematical behaviour in the center is not an exception, but is frequently encountered in external galaxies. This has been revealed by the high resolution observations in the CO emission of the central molecular component. NGC 891 (fig. 2b), which has been called the "sosie" of the Milky Way from its morphological type, presents a position-velocity diagram along the major axis very similar to the $l - v$ diagram of fig. 2a: there is a sharp velocity gradient inside the central 20"=1kpc, and the maximum apparent rotational velocity (260km/s) is reached there, while the outer disk has a flat rotation at 225km/s (Garcia-Burillo et al. 1992); it forms a separate component, in the sense that there is a shortage of CO emission between the nuclear disk (of radius 230pc) and the outer molecular ring, as in the Milky Way. The nuclear disk has a counter part in IR and radiocontinuum emission, as well as in Hα emission (Garcia-Burillo et al. 1992).

Such sharp gradients are also obtained through HI absorption in NGC 660 (van Driel et al. 1994) and NGC 1808 (Koribalski et al. 1993), as well as in the CO emission for NGC 3079 (Sofue & Irwin 1992), NGC 4945 (Dahlem et al. 1993), or even NGC 6946 (Casoli et al. 1989). Table 1 summarises the best evidences for gaseous nuclear disks in external spiral galaxies.

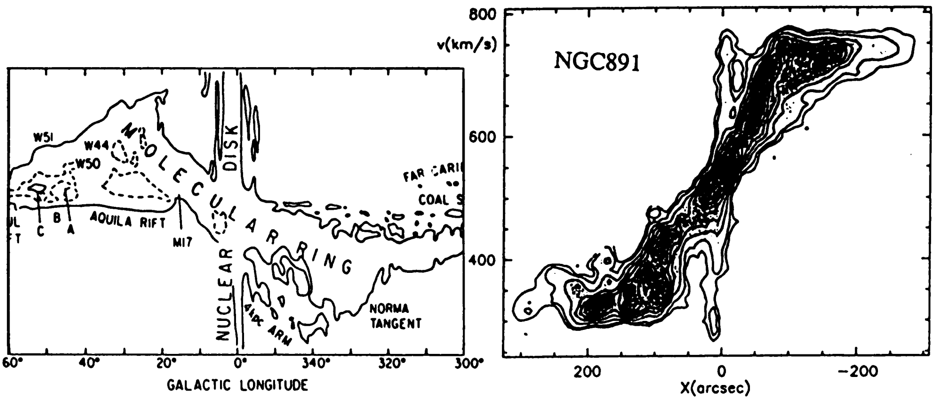

Figure 2. a) CO $l - v$ diagram of the central Milky Way, from Dame et al. (1987); b) CO(2-1) position-velocity diagram of NGC 891, from Garcia-Burillo et al. (1992).

3. Lopsidedness

The nuclear disk of the Milky Way appears strongly off-center: about 3/4th of the CO emission is at positive longitudes (and positive velocities, e.g. Bally et al. 1988). Lopsidedness is very frequently observed in external galaxies (e.g. recent images in Block et al. 1994). Already de Vaucouleurs & Freeman (1970) noticed that M33 and M101 have nuclei not-coinciding with mass centers of the galaxies. Baldwin et al. (1980) discuss properties of m=1 deformed galaxies. The nucleus of our nearest spiral neighbour M31 is displaced by 3-5 pc from the gravity center (Light et al. 1974, Nieto et al. 1986, Kormendy 1988). Recently, observations with high spatial resolution, with the 2D TIGER spectrograph, have shown that the velocity field, although regular, is displaced with respect to the light peak (Bacon et al. 1994). HST observations (Lauer et al. 1993) also suggest the presence of two components (nuclei?) in the center.

Off-centering is so frequent that it cannot be explained by transient phenomena, such as tidal effects for instance, but a physical mechanism must explain their persistence. Miller & Smith (1992) have revealed the existence in simulated disks of a density wave of the m=1 symmetry, corresponding to an oscillatory motion of the nucleus with respect to the galaxy disk. Weinberg (1994) has shown that the m=1 instability is in fact not as quickly damped as previously thought; there can exist very weakly damped m=1 modes, that persist during 10-100 crossing times, in which the peak density slowly revolves about the mass center.

This lopsidedness in the center could be related to the tilt of orbits with respect to the Galactic plane (e.g. Burton & Liszt 1993). The central gas

TABLE 1. Nuclear Disks in Spiral Galaxies

Galaxy	Type	Nuclear disk size	Ref
Milky Way	Sb	250pc	1
NGC 660	SBa	800pc	2
NGC 891	Sb	250pc	3
Maffei 2	Sbc	200pc	4
NGC 1068	Sb	1.5kpc	5
NGC 1097	SBb	800pc	6
IC342	Sc	100pc	7
NGC 1808	SABbc	250pc	8
M82	Irr	250pc	9
NGC 3079	Sc	600pc	10
NGC 3351	Sb	350pc	11
NGC 4314	SBa	350pc	12
NGC 4321	Sc	900pc	13
NGC 4945	SBc	400pc	14
M51	Sc	550pc	15
NGC 5236	SBc	200pc	16
NGC 6946	Sc	500pc	17

1- Dame et al. (1987); 2- van Driel et al. (1994); 3- Garcia-Burillo et al. (1992); 4- Ishiguro et al. (1989); 5- Planesas et al. (1991); 6- Gerin et al. (1988); 7- Ishizuki et al. (1990); 8- Koribalski et al. (1993); 9- Lo et al. (1987); 10- Sofue & Irwin (1992); 11- Devereux et al. (1992); 12- Combes et al. (1992); 13- Garcia-Burillo et al. (1994); 14- Dahlem et al. (1993); 15- Rand & Kulkarni (1990); 16- Handa et al. (1990); 17- Casoli et al. (1990)

disk might be warped, and the m=1 wave associated to a precession.

4. Inner ring

A conspicuous feature in our galaxy is the presence of the molecular ring, between 4 and 8kpc (see fig. 2a). Such rings are very precious in external galaxies as indicators of the pattern speed of the bar, since they correspond to resonances with the bar (or spiral).

Binney et al. (1991) in their fast bar model, interpret this ring as the outer Lindblad resonance (OLR), corresponding therefore to the usual outer rings observed in external barred galaxies. However, OLR in general occur at the outskirts of optical disks, and have no CO emission (because of metal deficiency), but are rich in atomic gas. The position of the OLR in the middle of the disk would then be unique. We prefer to interpret the molecular ring as the inner ring occuring at the ultra-harmonic resonance UHR, just inside the corotation region. These inner rings are frequent in barred galaxies, and encircle the bar (Buta & Combes 1994). This will correspond to the 4-5 kpc bar model. The main feature here is the depletion of the region inside CR by the gravity torques, where no molecular gas is seen (e.g. Combes 1988).

5. Box-Peanut

The COBE-DIRBE maps have revealed not only the bar (Weiland et al. 1994, Arendt et al. 1994), but also a very conspicuous box-peanut shape bulge in the center of the Galaxy. This shape is frequently observed in edge-on external galaxies (de Souza & dos Anjos 1987), and can be explained by a z-resonance effect with the bar (Combes et al. 1990). This feature confirms the existence of a strong bar in the center, and could help to determine its length. Since the box should end with the bar at R_b, its final longitude l is related to the angle θ between the bar and the Sun-Galactic Center axis, and to the solar radius R_0 by:

$$R_b = R_0 sin(l) sin(l - \theta)(sin^2 l - sin^2 \theta)^{-1}$$

If we adopt R_0=8.5 kpc, $\theta = 20°$, and $l = 21°$, this yields $R_b = 4.6$ kpc. This is only an order of magnitude, since a complete model, including the bar thickness in the plane, is necessary.

6. Warp and polar ring

The Galaxy plane appears clearly warped in the HI distribution (e.g. Burton 1992), but also in the interstellar dust layer and stellar disk, as revealed by COBE-DIRBE maps (Freudenreich et al. 1994). The stellar disk is warped at half the amplitude, which is certainly due to the radial truncation of the stellar disk. This is currently observed in external galaxies. Although almost every HI disk is warped, the stellar disks are much less frequently warped, and present only small distortions (Sanchez-Saavedra et al. 1990). The correspondence in azimuth of the stellar and HI warp indicates that the line of nodes is straight in the Milky Way, as for most of the galaxies (Briggs 1990). This straight line of nodes is still an unsolved problem, when account is taken of differential precession. The warp is however not symmetrical, being 4 times higher in the northern part (Burton 1992). This asymmetry could be attributed to the tidal perturbations of the Magellanic Clouds. Finally, the Galaxy has also a ring of matter similar to polar rings around external galaxies, orbiting around its poles: the Magellanic stream and related matter. The ring is in the settling process (Lin et al. 1993).

7. Conclusions

Our Galaxy is most probably barred, but the orientation, dimensions and pattern speed of the bar are difficult to obtain directly. By comparison with external galaxies and from the experience gained by N-body simulations, we can infer the bar length and speed from the observed mass distribution. If we believe the observed rotation curve, our Galaxy has a high central mass concentration, and the nature of its bar should correspond to the early-type barred galaxies: its pattern speed can be scaled from N-body simulations to 40-50km/s/kpc, corresponding to corotation at 4-5 kpc. The bar length is then expected to be 4-5 kpc in radius. If the molecular ring is real (i.e. not only spiral arms accumulation on the line of sight), it can then easily be interpreted as the inner ring encircling frequently the bars in external galaxies, and corresponding to UHR (ultra-harmonic resonance).

A nuclear disk component is obvious in the central gas kinematics: a large gas mass is observed with high rotation, with velocity not so far from circular. Its position corresponds to the wide region of inner Lindblad resonance, and evidence is found of x2 perpendicular orbits. External galaxies with such a nuclear disk or ring display a nuclear bar confined in the ring, aligned or not with the main bar. Because of the large mass concentration, and large gas fraction in the center, our Galaxy is also a good candidate for a nuclear bar, decoupled or not in velocity from the main one.

There is a significant lopsidedness in this nuclear component, which is not centered on the center-of-mass of the large-scale Galaxy. These asymmetries are also frequent in external galaxies. This could be related to the inner disk tilt. The box-peanut shape of the bulge might be a consequence of the bar, and gives a constraint between the bar orientation and length.

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DISCUSSION

O. Gerhard: We have recently analyzed the oval-disk galaxy of M94. This contains a nuclear bar with half-length ~20" (Mollenholft et al. AA submitted), inside the well-known inner ring at r=45" Assuming that this bar extends to somewhat inside its corotation radius we obtain a pattern speed which places the new ring at the OLR of the bar. According to your models, it is also at the ILR of the outer rotating oval. Is this ratio of pattern speeds also seen in some of your simulations? If not, what physical mechanism causes the preferred coincidence of inner bar-CR with outer bar-ILR that you described?

Combes: There are not yet enough N-body runs to have encountered all cases possible. However, I will guess that in the case you propose, the ratios of the two pattern speeds is then much larger, which necessitate a much larger mass concentration.

P. Schechter: If the orbits at the center of the arc are nearly circular, they imply a larger value for the stellar velocity dispersion than is observed. Is this cause for discomfort?

Combes: I don't think it raises a problem. The main distribution in the center, determined from stellar kinematics and IR photometry essentially, gives already rotational velocity of 200-250km/s at 100pc ($1\text{-}2\times10^9$ M$\odot$ within 100pc).