Radial migration in galactic disks caused by resonance overlap of multiple patterns: Self-consistent simulations

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ABSTRACT

We have recently identified a new radial migration mechanism resulting from the overlap of spiral and bar resonances in galactic disks. Here we confirm the efficiency of this mechanism in fully self-consistent, Tree-SPH simulations, as well as high-resolution pure N-body simulations. In all barred cases we clearly identify the effect of spiral-bar resonance overlap by measuring a bimodality in the changes of angular momentum in the disk, $\Delta L$, whose maxima are near the bar’s corotation and outer Lindblad resonance. This contrasts with the smooth distribution of $\Delta L$ for a simulation with no stable bar present, where strong radial migration is induced by multiple spirals. The presence of a disk gaseous component appears to increase the rate of angular momentum exchange by about 20%. The efficiency of this mechanism is such that galactic stellar disks can extend to over 10 scale-lengths within 1-3 Gyr in both Milky Way size and low-mass galaxies (circular velocity $\sim 100$ km/s). We also show that metallicity gradients can flatten in less than 1 Gyr rendering mixing in barred galaxies an order of magnitude more efficient than previously thought.

Key words. galaxies: evolution – galaxies: kinematics and dynamics – galaxies: evolution – galaxies: structure

1. Introduction

In the past few decades, discrepancies in the solar neighborhood age-metallicity relation have implied that effective radial migration (i.e., redistribution of angular momentum) must be taking place in the Milky Way disk (Edvardsson et al. 1993, Haywood 2008, Schönrich and Binney 2009, see Minchev & Famaey 2010 for a comprehensive discussion). In parallel, there is now considerable observational evidence that the non-axisymmetry of the Galactic potential can cause significant perturbations in the motion of stars of all ages. Evidence for this comes from, e.g., the moving groups in the solar neighbourhood (Dehnen 1998) containing stars of very different ages (Famaey et al. 2005) or the non-zero value of the $C$ and $K$ Oort constants for red giant stars in the extended local disk (Olling & Dehnen 2003, Siebert et al. 2010). All of these can be explained by the effect of resonances associated with a central bar (Minchev et al. 2010, 2007) or spiral structure (SS) (Quillen and Minchev, 2005, Quillen et al. 2010).

Until recently it was accepted that efficient radial mixing of stars in galactic disks was caused solely by transient spirals (Sellwood and Binney 2002, hereafter SB02). However, Quillen et al. (2009) showed that small satellites on radial, in-plane orbits can cause mixing in the outer disk and thus account for the fraction of low-metallicity stars present in the solar neighborhood (Haywood 2008). Moreover, we have recently demonstrated (Minchev & Famaey 2010, hereafter MF10) that a strong exchange of angular momentum occurs when a stellar disk is perturbed by a central bar and SS simultaneously; our test-particle simulations allowed us to attribute this effect to the overlap or first and second order resonances of each perturber. The presence of multiple patterns in galactic disks has been observed both in external galaxies (e.g., Elmegreen et al. 1992) and N-body simulations (e.g., Rautiainen and Salo 1999). Given that more than two-thirds of disk galaxies, including our own Milky Way, contain both central bars and SS, it is imperative to establish a strong understanding of the implications of this mechanism. Therefore, in this work we study a range of fully self-consistent, Tree-SPH simulations, as well as high resolution pure N-body simulations, searching for the signature of spiral-bar interaction in the distribution of angular momentum: MF10 predicted that when both bar and spirals are present in the disk, one finds that the changes in angular momentum form a bimodal distribution, with two local maxima close to the corotation and outer Lindblad resonance of the bar, regardless of the pattern speed of the spiral.

2. Models and results

While not self-consistent, test-particle simulations allow for a full control over the simulation parameters, such as the amplitudes and pattern speeds of bar and SS, and still provide a good approximation to self-consistent simulations. Employing this method in MF10, we were able to suppress the effect of transient spirals and thus identify the non-linear effect of resonance overlap. We showed that the most important signature of this mechanism was a bimodality in the changes in angular momentum in the disk, $\Delta L$, with maxima near the bar’s corotation and
Fig. 1. First row: Stellar disk number density contours of the isolated giant Sa galaxy simulation in GalMer for 5 time outputs as indicated in each panel. Second row: Changes in angular momentum, $\Delta L$ as a function of the initial angular momentum, $L$. Both $\Delta L$ and $L$ are divided by the asymptotic circular velocity $V_c$, thus $L$ gives approximately the galactic radius in kpc. The locations of the bar’s corotation and 2:1 OLR are indicated by the dotted and solid lines, respectively. A bimodal distribution indicating the work of resonance overlap of bar and spirals is clearly seen in each panel. Third row: The evolution of the radial profiles (left) and metallicities (right) for the stellar and gaseous disks. The initial stellar and gaseous disk scale-lengths are indicated by the dashed lines. The time steps shown are as in the first row, indicated by solid red, dotted orange, dashed green, dotted-dash blue, and solid purple lines, respectively. Fourth row: Distribution of birth radii for stars ending up in the annuli indicated by the green lines (600 pc) at $t=2.5$ Gyr.

its outer Lindblad resonance (OLR) regardless of the SS pattern speed.

Hereafter, we analyze self-consistent simulations with strong bars and spirals, therefore mixing from both transient spirals (SB02) and resonance overlap (MF10) is expected. However, we hope to be able to identify the latter mechanism by detecting the aforementioned bimodality, given that the predicted distribution of $\Delta L$ generated by transient spirals without a bar is rather smooth and not bimodal (see SB02).

2.1. Tree-SPH simulation of a giant Sa spiral galaxy

We test the predictions of MF10 by analyzing fully self-consistent simulations of isolated disk galaxies from the GalMer database\(^1\), including a gas component as well as star formation (Di Matteo et al., 2007; Chilingarian et al., 2010).

In Galmer, for each galaxy type, the halo and the optional bulge are modeled as Plummer spheres, with characteristic masses $M_H$ and $M_B$, and characteristic radii $r_H$ and $r_B$, respectively. Their densities are given by:

$$
\rho_H(r) = \left( \frac{3M_H}{4\pi r_H^3} \right) \left( 1 + \frac{r^2}{r_H^2} \right)^{-5/2}
$$

and

$$
\rho_B(r) = \left( \frac{3M_B}{4\pi r_B^3} \right) \left( 1 + \frac{r^2}{r_B^2} \right)^{-5/2}
$$

\(^1\) http://galmer.obspm.fr
On the other hand, the gaseous and stellar disks follow Miyamoto-Nagai density profiles with masses $M_g$ and $M_*$ and vertical and radial scale lengths given, respectively, by $h_g$ and $h_*$ and $a_*$:

$$
\rho_*(R, z) = \left( \frac{h_*^2 M_*}{4\pi} \right) \frac{a_* R^2 + (a_* + 3 \sqrt{z^2 + h_*^2}) \left( a_* + \sqrt{z^2 + h_*^2} \right)^2}{a_*^2 + \left( a_* + \sqrt{z^2 + h_*^2} \right)^2} \left( z^2 + h_*^2 \right)^{3/2},
$$

(3)

$$
\rho_g(R, z) = \left( \frac{h_*^2 M_*}{4\pi} \right) \frac{a_* R^2 + (a_* + 3 \sqrt{z^2 + h_*^2}) \left( a_* + \sqrt{z^2 + h_*^2} \right)^2}{a_*^2 + \left( a_* + \sqrt{z^2 + h_*^2} \right)^2} \left( z^2 + h_*^2 \right)^{3/2}.
$$

(4)

Here, we first analyze the properties of the isolated giant Sa (gSa) galaxy model: it has a total mass of $\sim 2.4 \times 10^{11} M_{\odot}$, with $M_H = 1.15 \times 10^{11} M_{\odot}$, $M_B = 0.23 \times 10^{11} M_{\odot}$, $M_g = 0.09 \times 10^{11} M_{\odot}$, and $M_* = 0.92 \times 10^{11} M_{\odot}$. The scale radii are $r_H = 10$ kpc, $r_B = 2$ kpc, $h_g = 0.2$ kpc, $a_g = 5$ kpc, $h_* = 0.5$ kpc, and $a_* = 4$ kpc. The initial Toomre parameter of both stars and gas is taken to be $Q = 1.2$ as the initial condition of the Tree-SPH simulations. Fig. 4 shows the properties of this isolated gSa model as a function of time.

2.1.1. Identification of the bimodality

In the first row of Fig. 1 we plot stellar number density contours for five time outputs up to 3 Gyr as indicated in each panel. We note that the initially strong SS disappears by the end of the simulation. The expansion of the disk is already an indication of radial migration.

The second row of Fig. 1 shows contours of the changes in the angular momentum of stars, $\Delta L$, versus the initial angular momentum, $L_0$. Both $\Delta L$ and $L$ are divided by the asymptotic circular velocity $V_c = 280$ km/s, thus $L$ gives approximately the galactic radius in kpc. The bar’s corotation and 2:1 OLR are indicated by the dotted and solid lines. A bimodal distribution becomes apparent as soon as the bar and SS form ($t \approx 0.2$ Gyr). While the peak at $L_0 \approx 4.5$ is caused by the bar’s corotation, the one at $L_0 \approx 8.5$ could only be produced by resonance overlap (see Fig. 2 in MF10). At all later times this clear bimodality remains in the distribution of $\Delta L$, thus providing strong evidence that the effect we see is caused by the spiral-bar interaction. We note also that the mixing timescale here is simply too short to be the effect of transients only.

2.1.2. Extension of the disk

The third row of Fig. 1 shows the temporal evolution of the radial density (left) and metallicity (right) profiles for both the stellar and gaseous disks. The time steps shown are as in the first row, indicated by solid red, dotted orange, dashed green, dotted-dash blue, and solid purple in increasing order.

Owing to the vigorous mixing, the disk grows rapidly with time displaying a break in the density profile that moves progressively to larger radii. At the final time (purple lines), the stellar and gaseous disks have extended to about ten and seven scalelengths, respectively, while roughly preserving their exponential profiles. This is accompanied by a strong flattening in the metallicity gradients, where at $t = 3$ Gyr one can clearly see a reversal in the metallicity gradient of stars in the outer region of the disk ($\sim 30$ kpc). The stellar metallicities at that location are similar to the initial ones at 8 kpc, suggesting that stars in the outskirts of the disk originate from regions near the bar’s 2:1 OLR, where the changes in $\Delta L$ are most prominent.

2.1.3. Birth radii of stars

The bottom row of Fig. 1 shows the distribution of birth radii for stars ending up in the annuli indicated by the green lines (600 pc) at $t = 2.5$ Gyr. The black and red histograms show stars on nearly circular orbits (of velocity dispersion smaller than 10 km/s) and the total population, respectively. In all cases, a large fraction of stars are found to originate from the bar’s corotation (dotted line), as well as an increasingly large fraction from the bar’s OLR (solid line) as larger final radii are sampled.

2.2. Tree-SPH simulations of other galaxy types

To assess how our results depend on the peculiar galaxy type we considered, we plot in Fig. 2 the changes in angular momentum for the stellar disk components of all GalMer isolated giant galaxy models available [Chilingarian et al., 2010, Table 1]. Contour levels are the same for all plots and the time is $t = 1$ Gyr. All apart from the gSd (bulgeless) model develop long-lived, central bars at the beginning of the simulation and consequently show a bimodality in $\Delta L$. When we compare the
Fig. 3 shows a power spectrum displaying the pattern speed of the $m = 2$ and $m = 4$ Fourier components, during the entire simulation, of the gSa (top) and gSb (bottom) models. Contour levels are indicated for each panel. Note that the gSa bar evolves (slows down and extends) much more and its two-armed SS is twice as strong as for the gSb model (top left). Despite the slightly stronger gSb bar, the effect on $\Delta L$ in the gSa’s outer disk is much more prominent (Fig. 2) because of the combined effect of the bar and stronger spirals.

2.3. Pattern speeds

Fig. 3 shows a power spectrum displaying the pattern speeds of the $m = 2$ and $m = 4$ Fourier components, during the entire simulation, of the gSa (top) and gSb (bottom) models. Contour levels are indicated for each panel. Note that the gSa bar evolves (slows down and extends) much more and its two-armed SS is twice as strong as for the gSb model (top left). Despite the slightly stronger gSb bar, the effect on $\Delta L$ for the gSa is much more prominent in the outer disk (Fig. 2) because of the combined effect of the bar and stronger spirals. Strong spirals are thus needed for this migration mechanism to be efficient. However, the relation between the strength of the perturbers and the angular momentum redistribution is nonlinear as previously shown by MF10.

2.4. High resolution N-body simulations

To determine whether the strong mixing we described above is caused by a deficiency in the resolution of the GalMer simulations, we ran pure N-body collisionless simulations with $10^7$ and $1.27 \times 10^7$ particles in the disk. Full description and details can be found in Wozniak and Michel-Dansac (2009). With a scale-length of 3.5 kpc, the initial conditions of the disk are comparable to those of the gSb GalMer model (Fig. 2) but lack a gas component. These simulations have no halo, which causes a ~30% drop in the RC at ~10 kpc.

Fig. 4 shows the changes in angular momentum at $t = 1$ and 3 Gyr for $1.27 \times 10^7$ (top) and $10^7$ (bottom) disk particles. At the beginning of the simulations, the effect is stronger for the low-resolution case due to the faster bar formation. However, at $t \approx 2$ Gyr both the high- and low-resolution runs yield a similar result. This suggests that the magnitude of the radial migration induced by the bar-spiral interaction and the timescale over which it is effective are not strongly dependent on the numerical resolution of the simulations. We conclude that the properties of the mixing, i.e., its magnitude and timescale, that we infer from the GalMer simulations are only weakly affected by the insufficient resolution.

2.5. Migration in low-mass galaxies

We now investigate whether the resonance overlap mechanism is also efficient in low-mass galaxies. Gogarten et al. (2010) showed that although transient spirals can explain extended disks for MW-type galaxies, this mixing mechanism is inefficient for galaxies with RCs of $V_t \sim 100$ km/s, such as NGC 300 and M33. Nevertheless, both NGC 300 and M33 are observed to have extended radial profiles of up to ten scale-lengths. We now consider the barred, dwarf Sa (dSa) simulation in GalMer (RC of 100 km/s and initial scale-length of 1.3 kpc) to see how its
density distribution and metallicity gradient evolve with time. In Fig. 5, we plot the time development of the stellar disk density and metallicity profiles, for the same time steps as in Fig. 1. We can clearly see that the stellar disk extends to more than ten scale-lengths in ~ 3 Gyr. The non-axisymmetric patterns of SB02 radial migration would be followed by a gas enrichment at each bar re-formation event resulting in the rebuilding of the gradient. The presence or not of a metallicity gradient, or its intensity, would then be an indicator of the bar/accretion phase of the galaxy.

The mechanism described in this study works even in low-mass galaxies (Fig. 5) and can thus for the first time provide an explanation for the extended disk profiles observed in galaxies with $V_e \sim 100$ km/s (Bland-Hawthorn et al. 2003, Minchev et al. 2011, in preparation).

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