

Title : will be set by the publisher
Editors : will be set by the publisher
EAS Publications Series, Vol. ?, 2018

arXiv:1009.5079v1 [astro-ph.GA] 26 Sep 2010

RADIAL MIXING DUE TO SPIRAL–BAR RESONANCE OVERLAP: IMPLICATIONS TO THE MILKY WAY

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Abstract. We have recently identified a previously unknown radial migration mechanism resulting from the overlap of spiral and bar resonances in galactic discs (Minchev & Famaey 2010, Minchev *et al.* 2010b). This new mechanism is much more efficient than mixing by transient spirals and its presence is unavoidable in all barred galaxies, such as our own Milky Way. The consequences of this are a strong flattening in the metallicity gradient in the disc, an extended disc profile, and the formation of a thick disc component, all taking place in only a couple of Gyr. This timescale is drastically shorter than previously expected and thus can put strong constraints on the longevity, strength and pattern speeds of the Galactic bar and Spiral Structure.

1 Introduction

In the last decades discrepancies in the solar neighborhood age-metallicity relation have conclusively demonstrated that effective radial migration (i.e., redistribution of angular momentum) must be taking place in the Milky Way disc (e.g., Haywood 2008, Schonrich & Binney 2009). Until recently it was accepted that such mixing was solely caused by transient spirals (Sellwood & Binney 2002). However, Quillen *et al.* (2009) showed that small satellites on radial, in-plane orbits can cause mixing in the outer disc and thus account for the fraction of low-metallicity stars present in the solar neighborhood Haywood (2008). Note that the Milky Way (MW), as well as more than 2/3 of disc galaxies contain central bars. Are bars important for the process of radial migration?

2 Resonance overlap of multiple patterns

We have recently shown (Minchev & Famaey 2010, hereafter MF10) that a strong exchange of angular momentum occurs when a stellar disc is perturbed by a cen-

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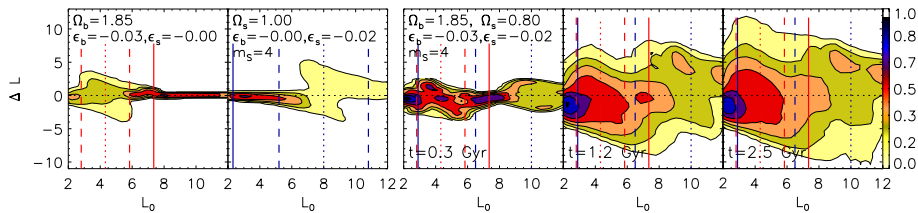


Fig. 1. Changes in angular momentum, ΔL , as a function of the initial angular momentum, L_0 . From left to right the first 2 panels show the effect of a bar or a SS only, respectively, with parameters consistent with the MW. The simultaneous propagation of the same perturbers is shown in the following 3 panels for $t = 0.3 - 2.5$ Gyr. The dotted lines show the corotation radii. The 2:1 and 4:1 LRs are indicated by the solid and dashed lines respectively (bar=red, spiral=blue). Figure is from MF10.

tral bar and spiral structure (SS) simultaneously (see Fig. 1). By using test-particle simulations, we attributed this effect to the overlap or first and second order resonances of each perturber. Both bars and spirals can participate to this overlap of resonances. The efficiency of this mechanism was later confirmed in fully self-consistent, Tree-SPH simulations, as well as high-resolution pure N-body simulations Minchev *et al.* (2010b) (see Fig. 2).

3 Implications for the Milky Way

To illustrate the effect of this migration mechanism in the MW we use a bar pattern speed of $\Omega_b = 1.85\Omega_0$, where Ω_0 is the angular velocity at the solar circle r_0 , consistent with recent pattern speed estimates (Minchev *et al.* 2007, 2010a; Dehnen 2000). For the bar amplitude we use a value derived by Rodriguez-Fernandez & Combes (2008). The MW SS parameters are much more uncertain. A detailed discussion can be found in MF10 for the motivation of our choice of parameters.

The last 3 panels of Fig. 1 show the resonance overlap induced migration for a bar and SS consistent with the MW. As one can see, since this is a nonlinear effect, depending on the perturbers' amplitudes, strong mixing could occur in a short period of time. While there is no doubt that the MW has been affected by this process, it may be difficult to estimate exactly how. This migration mechanism is a strong function of the strengths of the MW bar and SS. However, it may be incorrect to use the currently observed spiral and bar amplitudes since most likely they have not been the same throughout the lifetime of the Galaxy. Since resonance overlap also induces stellar heating (Minchev & Quillen 2006), we can put constraints on the amount of radial migration that has taken place in the MW by requiring that we do not overheat the Galactic disc.

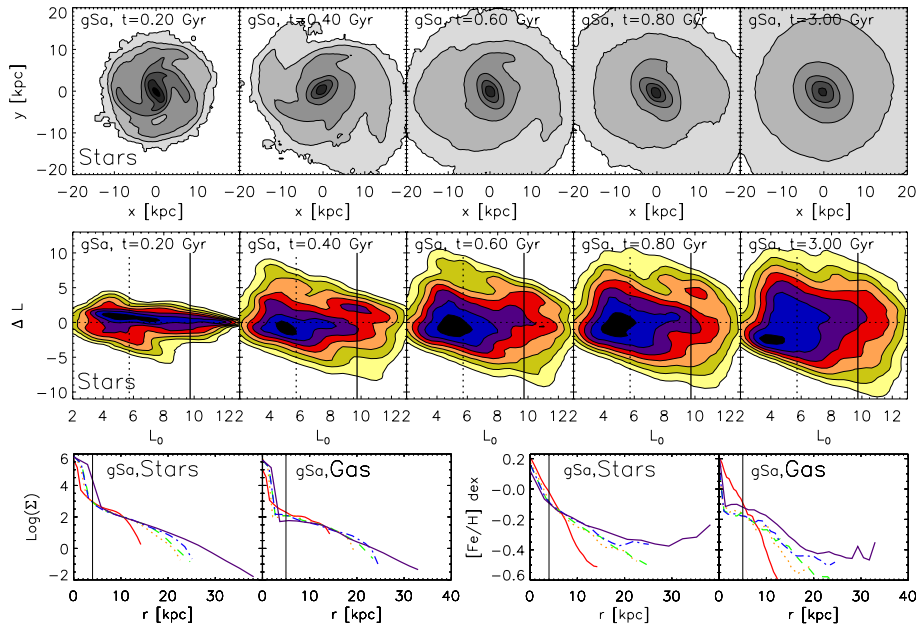


Fig. 2. Results of a Tree-SPH simulation, studying the exchange of angular momentum due to resonance overlap of bar and SS. **Top row:** Time development of the stellar disc density contours of a giant Sa galaxy. **Second row:** ΔL as a function of the initial angular momentum, L_0 . **Bottom row:** The evolution of the radial profiles of surface density (left) and metallicity (right) for the stellar and gaseous discs. The initial disc scale-lengths are indicated by the solid lines. The 5 time steps shown are as in the top row, indicated by solid red, dotted orange, dashed green, dotted-dash blue and solid purple, respectively, from Minchev *et al.* (2010b).

4 Conclusions

Radial mixing caused by the resonance overlap of multiple patterns could be up to an order of magnitude more effective than the transient spirals mechanism. This effect is non-linear, strongly dependent on the strengths of the perturbers. The signature of this mechanism is a bimodality in the changes of angular momentum in the disc with maxima near the bar’s corotation and its outer Lindblad resonance (Figs. 1 and 2). This is true regardless of the spiral pattern speed. This migration mechanism can create extended discs in both MW-mass (Fig. 2) and low-mass galaxies, such as NGC 300 and M33 (Minchev *et al.* 2010b, Fig. 4). It can also be responsible for the formation of a thick disc component early on in the galaxy evolution (Minchev *et al.* 2010, in preparation).

For bar and spiral parameters consistent with MW observations we find that it takes ~ 3 Gyr to achieve the mixing for which transients require 9 Gyr (cf., MF10). In addition to radial mixing, spiral-bar coupling can account for the age-

velocity relation (AVR) observed in the solar neighborhood. Note however that the estimates for the MW spiral and bar strengths derived from observations *now* may simply be irrelevant for our understanding of the current state of mixing in the Galactic disc.

Ongoing and planned large Galactic surveys, such as RAVE, SEGUE, SIM Lite, GYES, LAMOST and GAIA, can search for signatures of the mechanism (cf, Minchev & Quillen 2008). However, the most promising technique to put constraints on this mechanism in the MW is "chemical tagging" (Freeman & Bland-Hawthorn 2002) which will become possible with the forthcoming spectroscopic survey HERMES. Therefore, in the next couple of years we may be in a position to directly measure the spread of open clusters across the Galaxy as a function of age, thus providing direct constraints on the amount of mixing in the MW (Bland-Hawthorn *et al.* 2010).

We are grateful to the organizers for a very interesting conference and a traveling grant. Special thanks to Catherine Turon.

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