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On Star Formation at Dynamical Resonances of the Bar

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ABSTRACT
Long-term, secular processes can be important drivers of present-day galactic properties. The Milky Way is known to host one and perhaps multiple bars whose gravitational influence has observable consequences on both stellar and gaseous components. It has long been known that along the major axis of a bar gas can be driven towards the galactic center, fueling, e.g., the Central Molecular Zone and nuclear activity. On the other hand, stars are known to congregate near Lagrange points (i.e., minimums in the galactic potential), forming known moving groups such as Hercules. We report the results of isolated simulations incorporating both a state-of-the-art star formation and feedback model (in which a multi-phase interstellar medium is generated self-consistently) and a model of the Milky Way which forms a strong bar with a pattern speed matched to current observations. We are able to show, for the first time, that an enhancement of star formation may occur at the Lagrange points. We derive a collisional analogue of the theory of dynamical resonances and

Key words: Galaxy: disc – Galaxy: kinematics and dynamics – stars: kinematics and dynamics

1 INTRODUCTION

Roughly two-thirds of spiral galaxies are known to host bars in the near-infrared, about half of which are strong (e.g. Eskridge et al. 2000).

2 METHODS

2.1 Numerical Methods and Physical Model

We perform our simulations using the moving-mesh code Arepo. Gravity is solved using a standard oct-tree algorithm (Barnes & Hut 1986). Hydrodynamics is modelled with a finite volume solver over an unstructured Voronoi mesh allowed to move in a quasi-Lagrangian fashion (Springel 2010; Pakmor et al. 2016). A concise summary of this core functionality of Arepo is available with its public release[1] (Weinberger et al. 2019).

In our simulations we will reach $\sim 10^3\,\mathrm{M}_\odot$ mass resolution. As a result, the cold phase of the interstellar medium (ISM) is well-resolved (cite), and an appropriate physical model which account for the processes occuring at these scales must be used. In this vein, we use the state-of-the-art model SMUGGLE (Marinacci et al. 2019). A detailed description of the model is presented in Marinacci et al. (2019), but we summarize the salient components here.

Standard cooling processes are accounted for using tabulated cloudy calculations, described in detail in Vogelsberger et al. (2013). In addition to standard channels, metal line, fine-structure, and molecular cooling processes are also accounted for, allowing the gas to reach $\sim 10\,\mathrm{K}$, as well as self-shielding for high-density gas. Cosmic ray and photoelectric heating are also taken into account. Star formation follows a standard probabilistic approach (Springel & Hernquist 2003), with the star formation efficiency (ϵ) set to 0.01 and additional density and viriality conditions. Finally, stellar feedback is accounted for in three different channels: supernovae, young massive stellar radiation, and stellar winds from OB and AGB stars.

The model used here is similar to the one used first by Agertz et al. (2011, 2013) and by the Feedback In Realistic Environments (FIRE) collaboration (Hopkins et al. 2011, 2014, 2018), with some key differences discussed in Marinacci et al. (2019). One drawback of the SMUGGLE method is that radiation is not self-consistently tracked and evolved, and therefore radiation feedback must be implemented in an approximate manner. An extension of SMUGGLE which explicitly tracks the radiation field as an additional fluid component (Kannan et al. 2019a) based upon Arepo-RT (Kannan et al. 2019b) is available. We plan to use this module in the future.

Normally the next section describes the techniques the authors used. It is frequently split into subsections, such as Section 2.2 below.

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[1] `https://arepo-code.org`

Figure 1. This is an example figure. Captions appear below each figure. Give enough detail for the reader to understand what they're looking at, but leave detailed discussion to the main body of the text.

Table 1. This is an example table. Captions appear above each table. Remember to define the quantities, symbols and units used.

A	B	C	D
1	2	3	4
2	4	6	8
3	5	7	9

2.2 Maths

Simple mathematics can be inserted into the flow of the text e.g. $2 \times 3 = 6$ or $v = 220\,\mathrm{km\,s^{-1}}$, but more complicated expressions should be entered as a numbered equation:

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}. \tag{1}$$

Refer back to them as e.g. equation (1).

2.3 Figures and tables

Figures and tables should be placed at logical positions in the text. Don't worry about the exact layout, which will be handled by the publishers.

Figures are referred to as e.g. Fig. 1, and tables as e.g. Table 1.

3 CONCLUSIONS

The last numbered section should briefly summarise what has been done, and describe the final conclusions which the authors draw from their work.

ACKNOWLEDGEMENTS

The Acknowledgements section is not numbered. Here you can thank helpful colleagues, acknowledge funding agencies, telescopes and facilities used etc. Try to keep it short.

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APPENDIX A: TWO-COMPONENT TOOMRE INSTABILITY CRITERION

The Toomre instability criterion for a two-component fluid was first derived by Jog & Solomon (1984). For a mode of wavenumber $k = 2\pi/\lambda$ to be stable against gravitational collapse, the criterion for the two fluids in an infinitesimally thin disk is that,

$$Q_2(k) = \left(Q_g^{-1}(k) + Q_s^{-1}(k)\right)^{-1} > 1, \tag{A1}$$

where $Q_2(k)$ is the two-component Toomre parameter and,

$$Q_g(k) = \frac{\kappa^2 + k^2 c_s^2}{2\pi G k \Sigma_{g,0}}, \tag{A2}$$

where κ is the radial epicyclic frequency, c_s is the sound speed of the gas, and $\Sigma_{g,0}$ is the surface density of the gas. $Q_s(k)$ can be obtained by replacing c_s by σ_R (the radial velocity dispersion) and $\Sigma_{g,0}$ by $\Sigma_{s,0}$ (the stellar surface density). Note that the familiar one-component Toomre criterion can be obtained by minimizing $Q_g(k)$ as a function of k.

We denote the minimum of $Q_2(k)$ as a function of k by Q_2. We consider only physically plausible values of k between 0.06 and $6000\,\mathrm{kpc}^{-1}$ (corresponding to modes of wavelength $\lambda \sim 100\,\mathrm{kpc}$ to 1 pc). The equivalent of the one-component Toomre stability criterion is that $Q_2 > 1$, such that the disk is stable against collapse of modes of all wavelengths.

APPENDIX B: `mwib` RESOLUTION LEVELS

We set a series of standard resolution levels similar to those in the Aquarius convention. Due to the isolated nature of our simulations, it is convenient to tune the particle mass to a specific number.

resolution level	m_{DM} [$M_\odot$]	m_{b} [$M_\odot$]	ϵ [pc]
5	2.4×10^6	4.8×10^5	80
4	3×10^5	6×10^4	40
3	3.75×10^4	7500	20
2	4690	938	10
1	586	117	5

resolution level	m_{DM} [$M_\odot$]	m_{b} [$M_\odot$]	ϵ [pc]
5h	2.4×10^6	4.8×10^5	80
4h	3×10^5	6×10^4	40
3h	3.75×10^4	7500	20
2h	4690	938	10
1h	586	117	5

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