MNRAS 000, 1–3 (2019) Preprint 10 July 2020 Compiled using MNRAS LATEX style file v3.0

On Star Formation at Dynamical Resonances of the Bar

Angus Beane[1],★ Elena D'Onghia[2,3], Lars Hernquist[1], and Federico Marinacci[4]
[1]*Center for Astrophysics | Harvard & Smithsonian, 60 Garden Street, Cambridge, MA 02138, USA*
[2]*Department of Astronomy, University of Wisconsin, 475 North Charter Street, Madison, WI 53706, USA*
[3]*Center for Computational Astrophysics, Flatiron Institute, 162 5th Avenue, New York, NY 10010, USA*
[4]*Department of Physics & Astronomy, University of Bologna, via Gobetti 93/2, 40129 Bologna, Italy*

Accepted XXX. Received YYY; in original form ZZZ

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). Given their ubiquity, it is no surprise that the Milky Way is known to host a strong bar. A full understanding of the origin of the Galaxy's structure clearly rests on the impact of the bar not just in the inner region but also near the Solar circle. Its impact on the gas phase is highly discussed in the inner regions of the Galaxy, but studies of the bar's impact on star formation at the Solar circle are less developed. In this work, we seek to contribute to our understanding of the latter topic.

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.

★ E-mail: angus.beane@cfa.harvard.edu
[1] https://arepo-code.org

2.2 Initial Conditions

The starting point for the construction of our initial conditions is the N-body model GALAKOS (D'Onghia & L. Aguerri 2020). GALAKOS has structural parameters and a circular velocity curve which are in reasonable agreement with current data. However, GALAKOS is a particularly good starting point because as D'Onghia & L. Aguerri (2020) showed, the disk forms a strong bar after 1 Gyr. The bar then grows, until at 2.5 Gyr it has grown and slowed down to a pattern speed of 40 km/s/kpc. Evidence is mounting that the Milky Way's bar is long and slow, just like that in GALAKOS.

We convert a fraction (10%) of the initial stellar disk of GALAKOS to a gas disk. As described in Springel et al. (2005), the gas disk is initially in hydrostatic equilibrium. We assumed an ideal EOS for the gas phase, consistent with our underlying physical model. We make two further modifications to this setup. First, we "core" the gas profile – instead of assuming the gas surface density profile is exponential, we assume it is a constant value within some radius R_{core}. Specifically,

$$\Sigma_{\mathrm{gas}} = \Sigma_{0,\mathrm{gas}} \times \begin{cases} e^{-R_{\mathrm{core}}/H} & R \leq R_{\mathrm{core}} \\ e^{-R/H} & R > R_{\mathrm{core}}, \end{cases} \tag{1}$$

where H is the scale length of the disk and $\Sigma_{0,\mathrm{gas}} = \frac{M_{\mathrm{gas}}}{2\pi H^2}$ is the central surface density. When $R_{\mathrm{core}}/H = 1$ and 1.4, $\sim 10\%$ and $\sim 20\%$ of the gas disk mass is removed, respectively. This mass is not returned to another component and is thus removed from the initial conditions entirely. However, since our assumed gas fraction is 10%, this only represents a total reduction in the disk mass by a few percent. The surface density profile of the stellar disk is unchanged, though its velocity distribution is suitably altered.

The second modification we make is to treat the initial disk particles as star particles. In, e.g., Marinacci et al. (2019) the initial disk is assumed to be a purely collisionless component with no feedback contributions. Instead, we assume the initial disk particles are star particles so they may contribute gas through AGB channels. This requires assigning an age and metallicity to each star particle. We randomly draw the age and metallicity of each star according to the age-metallicity-radius relation of Frankel et al. (2018). This ignores vertical variations which is implemented in other models (e.g. Sharma et al. 2020).

2.3 Gas Accretion

The method described in Section 2.2 will succesfully form a bar after a few Gyr. However, because the disk is isolated (i.e., the only gas present in the initial conditions is in the disk), there is no source of fresh gas to resupply the disk. We found in empirical tests that by the time the bar had fully formed, the disk had become significantly more quiescent than what is expected for the Milky Way, with a global SFR of < 0.5 Msun/yr and a SFR surface density at 8 kpc about two orders of magnitude less than expected. Such differences prohibit a faithful comparison to the Milky Way.

As a result, it is necessary to include a source of fresh gas to resupply the galaxy. We found this to be quite problematic because several such techniques we explored would either weaken or completely destroy the bar. We found that it was necessary to include a somewhat *ad hoc* implementation of gas accretion from the circumgalactic medium (CGM).

Our method is inspired by the picture of a "galactic fountain flow" (Fraternali & Binney 2006, 2008). In this picture, gas is launched from the central region of a spiral galaxy before falling back onto the disk at a larger radii. In these models, the gas has lower angular momentum than the disk when it rejoins the disk due to **drag interactions with the hot corona.**

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

We therefore have implemented a method to include "hoses" into AREPO. These hoses are circular regions of radius R_h placed along the x-axis at $x = \pm R$. At a fixed timestep δt each hose will spawn a number N of gas particles. The spawned gas particles have a fixed mass, a uniform initial temperature of 10^4K, and a uniform metallicity chosen to be solar.

2.4 Summary

Our goal is now to construct an initial disk galaxy with gas that, like GALAKOS, forms a strong bar. The underlying method GALAKOS uses (namely MakeNewDisk) can already convert a constant fraction of the initial stellar disk to a gas disk which is initially in hydrostatic equilibrium. However, if this setup is used na

Normally the next section describes the techniques the authors used. It is frequently split into subsections, such as Section 2.5 below.

2.5 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:

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

Refer back to them as e.g. equation (2).

2.6 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.

REFERENCES

Agertz O., Teyssier R., Moore B., 2011, MNRAS, 410, 1391
Agertz O., Kravtsov A. V., Leitner S. N., Gnedin N. Y., 2013, ApJ, 770, 25
Barnes J., Hut P., 1986, Nature, 324, 446
D'Onghia E., L. Aguerri J. A., 2020, ApJ, 890, 117
Eskridge P. B., et al., 2000, AJ, 119, 536
Frankel N., Rix H.-W., Ting Y.-S., Ness M., Hogg D. W., 2018, ApJ, 865, 96
Fraternali F., Binney J. J., 2006, MNRAS, 366, 449
Fraternali F., Binney J. J., 2008, MNRAS, 386, 935
Hopkins P. F., Quataert E., Murray N., 2011, MNRAS, 417, 950
Hopkins P. F., Kereš D., Oñorbe J., Faucher-Giguère C.-A., Quataert E., Murray N., Bullock J. S., 2014, MNRAS, 445, 581
Hopkins P. F., et al., 2018, MNRAS, 480, 800
Jog C. J., Solomon P. M., 1984, ApJ, 276, 114
Kannan R., Marinacci F., Vogelsberger M., Sales L. V., Torrey P., Springel V., Hernquist L., 2019a, arXiv e-prints, p. arXiv:1910.14041
Kannan R., Vogelsberger M., Marinacci F., McKinnon R., Pakmor R., Springel V., 2019b, MNRAS, 485, 117
Marinacci F., Sales L. V., Vogelsberger M., Torrey P., Springel V., 2019, MNRAS, 489, 4233
Pakmor R., Springel V., Bauer A., Mocz P., Munoz D. J., Ohlmann S. T., Schaal K., Zhu C., 2016, MNRAS, 455, 1134
Sharma S., Hayden M. R., Bland-Hawthorn J., 2020, arXiv e-prints, p. arXiv:2005.03646
Springel V., 2010, MNRAS, 401, 791
Springel V., Hernquist L., 2003, MNRAS, 339, 289
Springel V., Di Matteo T., Hernquist L., 2005, MNRAS, 361, 776
Vogelsberger M., Genel S., Sijacki D., Torrey P., Springel V., Hernquist L., 2013, MNRAS, 436, 3031
Weinberger R., Springel V., Pakmor R., 2019, arXiv e-prints, p. arXiv:1909.04667

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

This paper has been typeset from a TEX/LATEX file prepared by the author.