SF2A 2014
J. Ballet, F. Bournaud, F. Martins, R. Monier and C. Reylé (eds)

DISC GALAXIES: MOLECULAR HYDROGEN, STAR FORMATION AND RADIAL MIGRATION

A. Halle[1], F. Combes[2], P. Di Matteo[3] and M. Haywood[3]

Abstract. We show the importance of molecular hydrogen to simulate the evolution of disc galaxies with improved realistic interstellar medium and stellar formation. The inclusion of H_2 cooling is especially important in the low-metallicity regions such as the outer parts of discs, in which it allows for some slow star formation.

We study the evolution of the obtained stellar components of these galaxies and focus on the radial migration that occurs due to the resonances of the bar and transient spiral arms in the disc.

Keywords: Galaxies: evolution — Galaxies: ISM — Galaxies: spiral — Galaxies: star formation — Galaxies: structure

1 Introduction

The interstellar medium of disc galaxies is highly multiphase with the coldest and densest hydrogen phase consisting mainly of molecular hydrogen. This molecular phase is thus strongly correlated with star formation, as shown by Bigiel et al. (2008) in resolved observations of local disc galaxies. H_2 can play an especially important role for star formation in the low metallicity outer parts of disc galaxies. Ultraviolet observations by GALEX have shown that star formation can be active at large radii, much farther than the optical radius R_{25}, in regions where H_α observations are not able to reveal moderate-age populations of stars (Thilker et al. 2005; Gil de Paz et al. 2005, 2007). The presence of molecular hydrogen and star formation in outermost discs of spirals is also of prime importance to study cold gas accretion, which is considered one key factor in galaxy evolution (e.g. Kereš et al. 2005; Dekel et al. 2009).

We have performed simulations of isolated disc galaxies that include some detailed low-temperature cooling, especially H_2 cooling. We study the star formation and the evolution of the stellar component of the disc. Stars in galactic discs do not remain at their birth radius. In addition to epicyclic motion, the oscillations around a guiding radius, they undergo some radial migration due to angular momentum transfer (Sellwood & Binney 2002, e.g.). This radial migration impacts the stellar age and metallicity profiles. It could reconcile inside-out formation scenarios with some 'U-shaped' stellar age profiles inferred from observations (Bakos et al. 2008; Barker et al. 2007; Williams et al. 2009, e.g.) but its importance is still debated, for example in the Milky Way (Haywood et al. 2013).

2 Molecular hydrogen effect on star formation

In Halle & Combes (2013) we present simulations of Sb type disc galaxies performed with the N-body SPH Gadget-2 code (Springel 2005) to which we added some baryonic physics including some stochastic star formation reproducing a Schmidt law, kinetic core-collapse supernovae feedback, and detailed cooling including low-temperature cooling due to metals and H_2. The metallicity of the gas is assumed to decrease with radius. We computed a local mass fraction of H_2 using an adaptation of the semi-analytic recipe developed by

---

[1] Institut d'Astrophysique de Paris, 98 bis boulevard Arago, 75013 Paris, France
GEPI, Observatoire de Paris, 5 place Jules Janssen 92190 Meudon, France

[2] LERMA, Observatoire de Paris, 61 avenue de l'Observatoire 75014 Paris, France

[3] GEPI, Observatoire de Paris, 5 place Jules Janssen 92190 Meudon, France

(Krumholz et al. 2008, 2009; McKee & Krumholz 2010), using the UV flux from young stars formed in the disc. More details on the parameters of the simulations and on the baryonic physics recipes can be found in Halle & Combes (2013).

The total neutral H gas, HI and H_2 components of a simulated gas disc are shown on Fig. 1. It can be seen that the disc is much thinner in H_2 than in HI. H_2 is distributed in thin or clumpy regions (bar, spiral arms, various clumps), while the distribution of HI is more diffuse. Density peaks due to these features of the gas occur at larger radii when molecular hydrogen allows the gas to cool down in the low metallicity outer discs. Molecular hydrogen thus allows for these outer parts of discs to exhibit some slow star formation. The comparison to simulations without H_2 can be seen on Fig. 2 where the left panel shows the difference of extension of discs of formed stars and the right panel shows the SFR as a function of galactocentric radius. There is an increase in SFR at large radii for all SNII feedback efficiencies that were tested. We also show the surface SFR is more correlated with the H_2 gas than with the HI gas, as obtained in observations (Bigiel et al. 2008, e.g.) (see Fig. 25 of Halle & Combes (2013)).

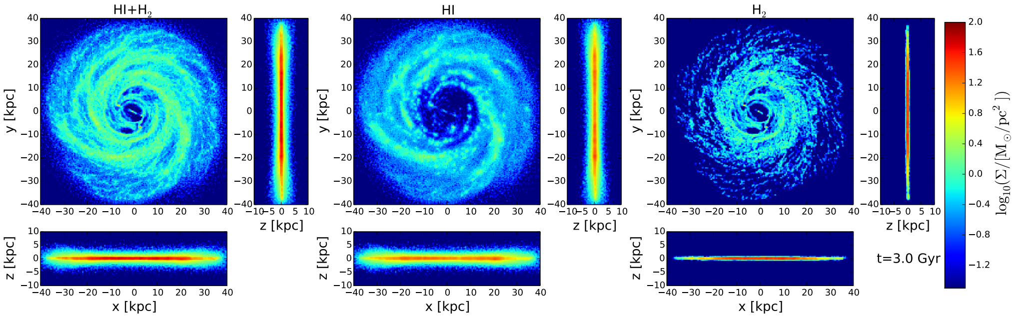

Fig. 1. Left: Surface density map of HI + H_2. **Middle:** Surface density map of HI. **Right:** Surface density map of H_2. The colour bar is the same for all plots and is shown on the right.

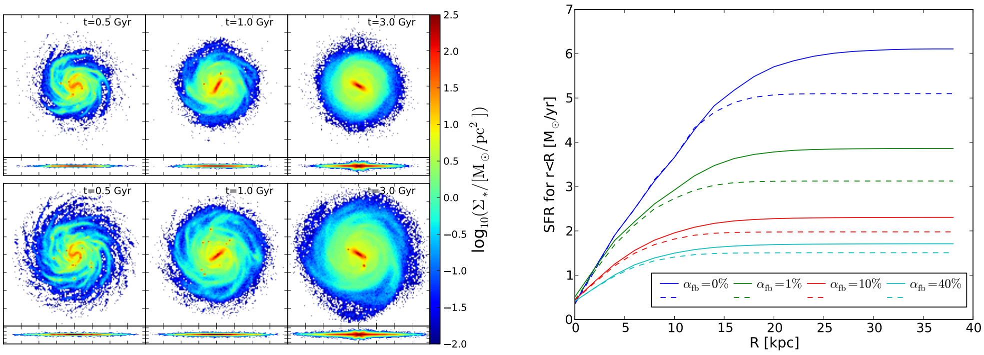

Fig. 2. Left: Surface density of stars formed during simulations after 0.5 Gyr, 1 Gyr and 3 Gyr of evolution with the same parameters except for the presence or absence of H_2. Top row: no H_2 cooling. Bottom row: H_2 cooling. **Right:** Cumulative SFR as a function of galactocentric radius, averaged on the first Gyr, for runs with varying feedback efficiencies. Solid lines: run with H_2. Dashed lines: run without H_2.

3 Radial migration

Radial stellar migration in galactic discs has been attracting an increasing attention, including some theoretical or numerical work (Sellwood & Binney 2002; Minchev et al. 2012; Roškar et al. 2012, e.g.), and studies based on observations of the stars in the Milky Way (Haywood 2008; Haywood et al. 2013, e.g.). In galactic discs where density waves such as bars or spiral arms occur, stars can gain or lose angular momentum, leading to outward, respectively inward migration. The result of this mechanism is that stars can be found at a galactocentric radius differing significantly from their birth radius. Another reason for apparent radial migration is simply the nature of orbits in axisymmetric or nearly axisymmetric potentials : Stars oscillate radially around a guiding radius.

The importance of the redistribution of stars in galactic discs having a strong bar is shown in Di Matteo et al. (2014). Stars initially at large radii are found to be parts of the central bar. This redistribution can be seen on Fig.3 where stars that are initially in 5 kpc wide annuli in one of our simulations are represented at different times. Stars migrate both inwards and outwards, and stars as far as 15 kpc from the centre can contribute (marginally) to the central bar of final size $\sim$ 8kpc.

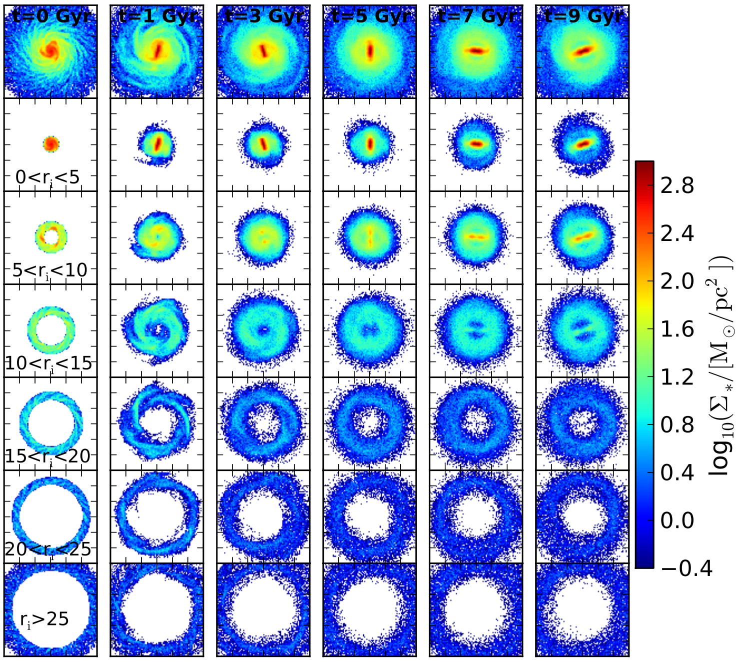

Fig. 3. From top to bottom: Face-on density distribution of stars with different birth radii. Different columns correspond to different times, as indicated. The total stellar density distribution is given in the top row. From Di Matteo et al. (2014).

We are interested in distinguishing the effects of 'blurring', that is the apparent radial migration due to epicyclic motion, from the effects of 'churning', that is the change of guiding radius (according to the terminology of Schönrich & Binney (2009)). The changes in galactocentric radius and guiding radius between two simulation times are visible in Fig. 4. The amplitude of the variations in guiding radius is significantly lower than the amplitude of variations in galactocentric radius. The vertical lines and surrounding shaded regions show the locations of the inner Lindblad resonance (ILR), corotation, and outer Lindblad resonance (OLR) of the bar. These radii shift with time because the bar slows down as it transfers angular momentum to the outer disc and to the bulge and dark matter halo. It can be seen on Fig. 4 that most of the radial migration occurs near the corotation of the bar. Transient spiral arms are also present in our simulations, and are responsible from some features visible on Fig. 4 at large radii, but the bar remains the strongest potential perturbation, and the main cause of radial migration. In the upcoming paper Halle et al. (2014), we detail the study of radial migration based on these simulations, with a quantification of the phenomenon including the fraction of migrators of several amplitudes in radial variation obtained at different galactocentric radii.

4 Conclusions

Molecular hydrogen is essential to take into account to study star formation in the outer parts of galactic discs. In the simulations of Halle & Combes (2013) we show the inclusion of H_2 cooling in simulations of isolated Sb-type galaxies with a low gas metallicity in the outer parts allows for slow star formation to occur at large galactocentric radii.

The evolution of the stellar discs (age profile and metallicity) is impacted by local star formation but also

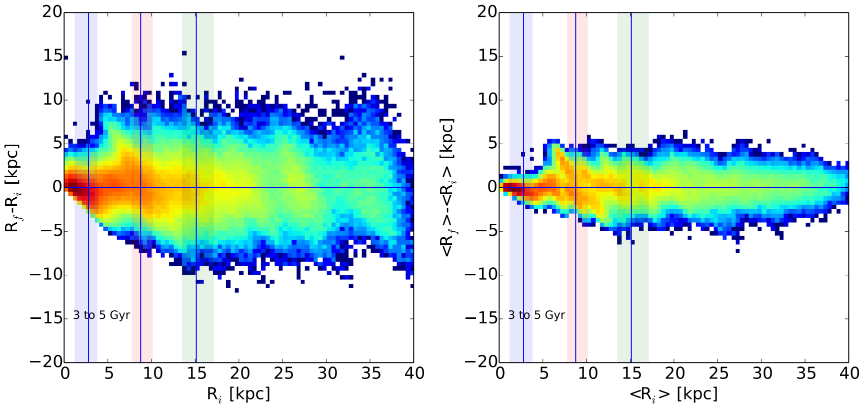

Fig. 4. Left: Distribution of the variation in galactocentric radius of the stars between 3 Gyr and 5 Gyr of evolution. **Right:** Distribution of the variation in guiding radius of the stars between 3 Gyr and 5 Gyr of evolution. The 2D histograms are mass-weighted and the colour code is logarithmic. The vertical lines show the locations of resonances of the bar as explained in the text.

by radial migration seeded by resonances in the disc. In our simulations, the bar is the main seed for stellar migration. We study this process by distinguishing the ‘blurring’ due to epicyclic motion around a guiding radius from the ‘churning’ that is a change of the guiding radius. The whole study of radial migration in our simulations will be detailed in the upcoming Halle et al. (2014).

References

Bakos, J., Trujillo, I., & Pohlen, M. 2008, ApJ, 683, L103

Barker, M. K., Sarajedini, A., Geisler, D., Harding, P., & Schommer, R. 2007, AJ, 133, 1125

Bigiel, F., Leroy, A., Walter, F., et al. 2008, AJ, 136, 2846

Dekel, A., Birnboim, Y., Engel, G., et al. 2009, Nature, 457, 451

Di Matteo, P., Haywood, M., Gómez, A., et al. 2014, A&A, 567, A122

Gil de Paz, A., Boissier, S., Madore, B. F., et al. 2007, ApJS, 173, 185

Gil de Paz, A., Madore, B. F., Boissier, S., et al. 2005, in Bulletin of the American Astronomical Society, Vol. 37, American Astronomical Society Meeting Abstracts, 178.02

Halle, A. & Combes, F. 2013, A&A, 559, A55

Halle, A., Di Matteo, P., & Haywood, M. Combes, F. 2014, A&A, in prep.

Haywood, M. 2008, MNRAS, 388, 1175

Haywood, M., Di Matteo, P., Lehnert, M. D., Katz, D., & Gómez, A. 2013, A&A, 560, A109

Kereš, D., Katz, N., Weinberg, D. H., & Davé, R. 2005, MNRAS, 363, 2

Krumholz, M. R., McKee, C. F., & Tumlinson, J. 2008, ApJ, 689, 865

Krumholz, M. R., McKee, C. F., & Tumlinson, J. 2009, ApJ, 693, 216

McKee, C. F. & Krumholz, M. R. 2010, ApJ, 709, 308

Minchev, I., Famaey, B., Quillen, A. C., et al. 2012, A&A, 548, A126

Roškar, R., Debattista, V. P., Quinn, T. R., & Wadsley, J. 2012, MNRAS, 426, 2089

Schönrich, R. & Binney, J. 2009, MNRAS, 396, 203

Sellwood, J. A. & Binney, J. J. 2002, MNRAS, 336, 785

Springel, V. 2005, MNRAS, 364, 1105

Thilker, D. A., Bianchi, L., Meurer, G., et al. 2005, in Bulletin of the American Astronomical Society, Vol. 37, American Astronomical Society Meeting Abstracts, 202.02

Williams, B. F., Dalcanton, J. J., Dolphin, A. E., Holtzman, J., & Sarajedini, A. 2009, ApJ, 695, L15