Cosmological Simulations of MW-like galaxies

https://doi.org/10.1017/S1743921317008572 Published online by Cambridge University Press

Else Starkenburg, Ivan Minchev and Marica Valentini

https://doi.org/10.1017/S1743921317008572 Published online by Cambridge University Press

Rediscovering our Galaxy
Proceedings IAU Symposium No. 334, 2017
C. Chiappini, I. Minchev, E. Starkenburg & M. Valentini, eds.

doi:10.1017/S1743921317008572

Simulations of MW-mass galaxies in the cosmological context

Cecilia Scannapieco[1,2]

[1] Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Departamento de Física. Buenos Aires, Argentina
email: cscannapieco@df.uba.ar

[2] CONICET. Buenos Aires, Argentina

Abstract. During the last three decades simulations of the formation of galaxies have made fantastic progress, overcoming problems such as the angular momentum catastrophe and producing galaxies that resemble disk-bulge systems similar to those observed. In this work, I discuss such progress focusing on the formation and evolution of disks in galaxies similar to our Milky Way, and on the effects of different feedback processes that affect galaxies through cosmic time.

I also present the results of simulations that use constrained initial conditions of the Local Group, and discuss environmental effects that might play a role in the formation and evolution of our Galaxy.

Keywords. Galaxy: formation, Galaxy: formation, Galaxy: disk, Galaxy: kinematics and dynamics, cosmology: theory, methods: numerical

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1. Introduction

Numerical simulations are the most powerful tool to study the formation and evolution of galaxies in the context of a cosmological model. In the Λ-Cold Dark Matter (ΛCDM) cosmological paradigm, galaxies form as gas cools down and condenses within dark matter haloes, which grow hierarchically through mergers and continuous mass accretion. The growth of galaxies and of the dark matter haloes where they reside is a highly non-linear, multi-scale process free from any simplifying symmetry, and numerical simulations have become the standard tool to follow such complex process through cosmic time. Hydrodynamical simulations follow the evolution of matter in the dark and gaseous components, including also sub-grid recipes to describe the transformation of gas into stars, the cooling of gas and feedback from stellar evolution and/or other sources.

Over the last three decades, numerical simulations in a cosmological context have made spectacular progress. While a first generation of simulations suffered from the angular momentum catastrophe (Navarro & Benz 1991), being unable to reproduce the formation of disk galaxies when the proper cosmological setting was considered, more recent models succeeded to produce extended, rotationally-supported disk-like components with properties that resemble those of real Spirals. The success of these models relies on the inclusion of an efficient modelling of feedback processes, which decouple the early cooling/condensation phase that brings gas to the inner regions of the host dark matter haloes from the star formation activity which takes place from this gas (e.g., Scannapieco *et al.* 2008).

Feedback, i.e. the injection of mass and radiation – and thus of energy and momentum – into the interstellar and intergalactic media, is a fundamental process in galaxy evolution: the interplay between feedback heating and radiative cooling is what ultimately determines how star formation proceeds in galaxies and how mass accretion onto galaxies is regulated. While feedback from stellar evolution is believed to be the dominant process in intermediate and low mass galaxies, the effects of black hole feedback are probably dominating in massive (bulge-dominated) galaxies and galaxy clusters (e.g. Springel, Di Matteo & Hernquist 2005), where black holes are more massive.

The most important feedback channel from stellar evolution comes from supernova (SN) Type II explosions. During these events, the chemical elements synthesized in stellar interiors are ejected into the interstellar medium, affecting the cooling of gas which depends strongly on the chemical abundances. Moreover, SN explosions eject significant amounts of energy which provides heat and pressure to the surrounding gas, eventually transporting a fraction of it to the outer regions of galaxies and even to the intergalactic medium in the form of a galactic wind.

While SN feedback was quickly identified as a relevant mechanism for galaxy formation, it was only in the early 2000's that this process was implemented in numerical codes such that its expected effects at galaxy scales were reproduced (e.g., Okamoto *et al.* 2005, Scannapieco *et al.* 2006, Stinson *et al.* 2006). These models were able, for the first time, to form galaxy disks from cosmological initial conditions, and confirmed the importance of the timing of star formation for galaxy morphology: while stars formed during the early, violent phases of galaxy growth populate mostly a bulge component, the disk is almost entirely composed of young stars. Despite the significant code-to-code variations that appear when SN feedback is implemented in different ways (Scannapieco *et al.* 2012), all models agree on the importance of galactic winds for forming disks, as winds circulate gas within the haloes, ejecting low-angular momentum material at early times, and favoring its (re-)accretion as high-angular momentum gas later on (Brook *et al.* 2011). Winds shift the onset of star formation, being thus key to the formation of extended, high-angular momentum, young galaxy disks.

This second generation of models progressed rapidly, and showed that, despite their individual successes, it was in general extremely hard to produce galaxies that, at the present time, did not have a significant bulge component in addition to the disk (Scannapieco *et al.* 2012). As a result, other forms of feedback started to be explored, focusing on those that would provide a prompt effect on star formation, as to prevent the formation of (old) stellar bulges. Among them, "radiation pressure" feedback – i.e. momentum transfer by the ionizing radiation of young stars (see Haehnelt 1995) – appeared promising as it would act prior to SN explosions, right after the onset of star formation. In the last years, several works have implemented radiation pressure feedback models (e.g. Hopkins *et al.* 2011, Agertz *et al.* 2013, Aumer *et al.* 2013, Stinson *et al.* 2013), and have shown to be quite successful in producing more disk-dominated galaxies. However, a number of caveats are still present, mainly resulting from our limited knowledge on how the radiation emitted by the stars is coupled to the surrounding gas, and on the relative importance of radiation pressure and photoionization effects on the molecular clouds (see, e.g. Sales *et al.* 2014). Other physical processes affecting galaxy evolution at the MW scales are being currently investigated, such as magnetic fields and cosmic rays (e.g. Booth *et al.* 2013, Pakmor *et al.* 2016), and AGN feedback (e.g. Vogelsberger *et al.* 2013), although this process seems less important than the others in determining the internal properties of galaxies.

In the particular case of the Milky Way, environmental effects might also play a role. The Milky Way lives in a rich environment, with Andromeda, another Spiral galaxy of similar mass, at less than a Mpc from it. Although environment is known to shape the properties of galaxies in clusters and groups (see, e.g. Girardi *et al.* 2003 and references therein), environmental dependencies at the MW-scales are still controversial (see, e.g., Ziparo *et al.* 2013). Simulations of the formation of loose groups are ideal to investigate

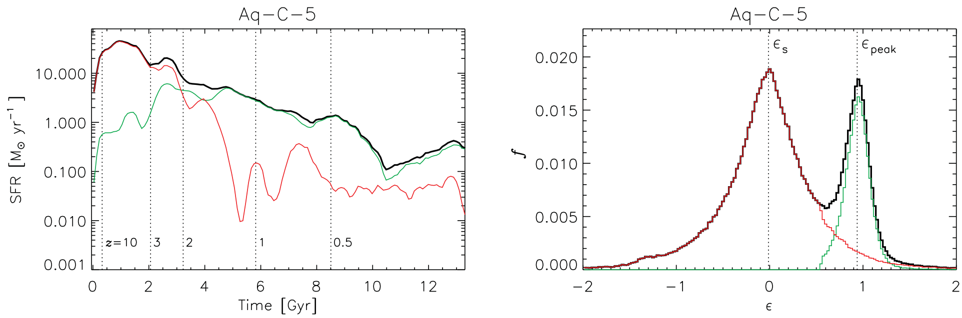

Figure 1. The star formation rate of a galaxy simulated in cosmological context (black thick line), divided into spheroidal (red line) and disk (green line) components. The right-hand panel shows the distribution of circularities $\epsilon \equiv j_{\rm z,i}/j_{\rm circ}$ which measure the rotational support of each star ($j_{\rm z,i}$ and $j_{\rm circ}$ denote the angular momentum of each star perpendicular to the disk, and the angular momentum expected for a circular orbit at the same radius, respectively). $\epsilon \sim 1$ corresponds to approximately circular orbits (Scannapieco *et al.* 2009).

such dependencies (Few *et al.* 2012, Garrison-Kimmel *et al.* 2014), as well as simulations using constrained initial conditions of the Local Group which by construction reproduce the dynamical properties of our Local Volume, forming Local Group-like systems with two main constituent galaxies, similar to the MW and Andromeda (Nuza *et al.* 2014).

Here we discuss the problem of galaxy formation in the cosmological context, focusing on the effects of feedback (Section 2) and on the physical processes that induce morphological transformations as galaxies evolve (Section 3). In Section 4 we present results of constrained initial conditions of the Local Group and discuss environmental effects that might be relevant for the formation of our Galaxy, and in Section 5 we discuss future perspectives.

2. Disk formation and feedback processes

2.1. *Supernova feedback*

The dominant feedback process for low- and intermediate-mass galaxies (up to the MW scales) is believed to originate in Type II SN (SNII) explosions, which heat up and pressurize the interstellar gas, triggering galactic winds and fountains. SN feedback has a critical role in galaxy formation; however, its implementation in simulations has proven to be complicated, both due to uncertainties in the physics of SNe – e.g. the efficiency of the coupling between the SNe energy and the surrounding gas – and to numerical limitations – the physical scales over which SNe act are unresolved in galaxy simulations. Early models showed that a simple injection of energy into the interstellar medium had little influence on the evolution of simulated systems, while the dumping of SNe energy as a momentum input produced a larger effect (Navarro & White 1993) but still of insufficient impact. A second generation of codes included efficient SN feedback treatments, implementing either thermal (i.e. energy injection) or kinetic (i.e. momentum input) models, or a combination of both (e.g. Okamoto *et al.* 2005, Scannapieco *et al.* 2006, Oppenheimer & Davé 2008, Stinson *et al.* 2006, Dalla Vecchia & Schaye 2012). These models demonstrated that SNe reduce the star formation levels and, more importantly, delay the onset of star formation. SN-triggered galactic winds were found to preferentially remove low-angular momentum gas right after star formation sets on, which can be later (re-)accreted in higher-angular momentum orbits (Brook et al 2011). Together, the shift towards later star formation and the redistribution of angular momentum produced by SNe, facilitate

https://doi.org/10.1017/S1743921317008572 Published online by Cambridge University Press

the formation of extended, rotationally supported disks, as the bulk of late star formation almost exclusively contributes to the disk component of a galaxy (Fig. 1).

2.2. *Radiation pressure feedback*

During the last few years, a third generation of numerical models were developed, with the aim of better describing the effects of feedback at galactic scales, and of minimizing the number of assumptions and input parameters. These efforts have been motivated by the need to better understand the impact of various feedback processes on the formation of disks and of galaxies with very small bulges. In this context, special attention has been given to the possible effects of the early phases of the evolution of massive stars which, through the radiation pressure they exert into the surrounding medium, could act as a first, faster regulator of star formation compared to SNe (e.g. Hopkins *et al.* 2011, Aumer *et al.* 2013, Agertz *et al.* 2013, Stinson *et al.* 2013). Some of these models have shown to be very successful in producing galaxies with high disk-to-total ratios and realistic galaxy properties; however, it is not yet clear that they provide a good physical description of the effects of young stars on the interstellar medium (see, e.g. Sales *et al.* 2014) and this is in fact a matter of intense debate. It is expected that the large efforts currently underway will allow a better understanding on the effects of young stars at galaxy scales.

Several groups are also exploring the effects of other possible feedback channels on MW-mass galaxies, which are believed to also contribute to shape the star formation activity such as black holes (e.g. Vogelsberger *et al.* 2014) and cosmic rays (e.g. Booth *et al.* 2013).

3. Disk evolution and disk survival

The ability to reproduce the formation of disks in cosmological simulations allowed to identify various physical processes that are key to disk formation and evolution. While the overall feedback effects of regulating star formation occur similarly for galaxies of similar mass, much more difficult is to predict the evolution of their disks, due to the great variety of possible merger and accretion histories in a ΛCDM model. This requires the simulation of a representative sample of galaxies, and at relatively high resolution. By studying the evolution of eight MW-mass, mildly isolated galaxies (dubbed Aq-A to Aq-H) from the Aquarius Project (Springel *et al.* 2008), Scannapieco *et al.* (2009) found that disks can be formed at relatively early epochs, but also easily destroyed/disrupted during evolution, producing a wide variety of final morphologies. Fig. 2 shows that not only the relative importance of the disk in each galaxy changes significantly with cosmic time, both for galaxies that have or lack a significant disk component at the present time, but also that there is large galaxy-to-galaxy variation in the disk-to-total (D/T) evolution. Furthermore, these simulations show that not only mergers can affect disk evolution (note however that these galaxies do not experience major mergers since $z = 3$, except for Aq-F-5), but more important is that the D/T ratios decrease significantly during periods of misaligned gas accretion, when the angular momenta of accreted gas and of the pre-existing stellar disks are not closely aligned. This shows that the accretion of gas has also a significant role in the growth and survival of galaxy disks.

A similar result was obtained by Sales *et al.* (2012), who used a sample of ∼100 MW-mass galaxies to study the evolution of angular momentum until the turn around epoch, where most of it has already been acquired. They found that the coherence of the angular momentum of gas that will be accreted by a galaxy is key to forming surviving disks (Fig. 3). In this work, galaxy morphology is quantified in terms of the parameter

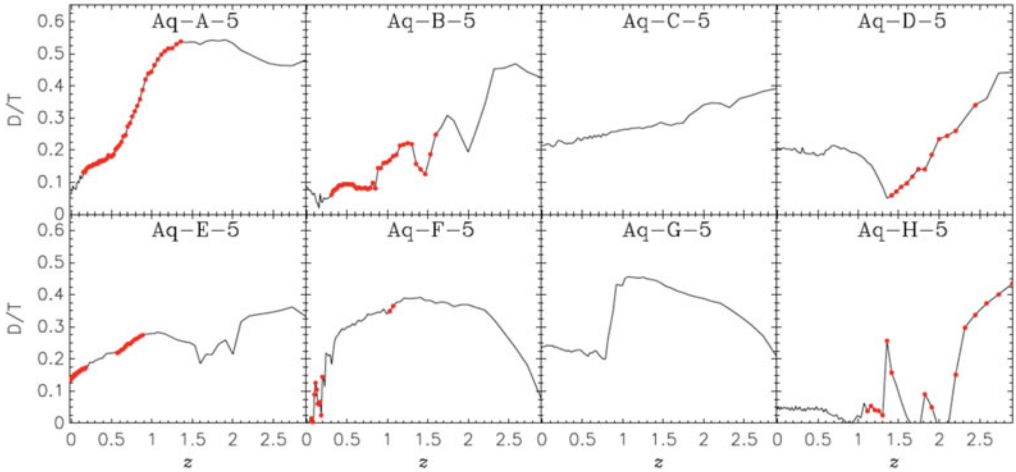

Figure 2. Disk-to-total mass ratio as a function of redshift (lines) for the eight simulated galaxies of Scannapieco *et al.* (2009). Solid circles indicate periods of strong misalignment between the cold gaseous and stellar discs: $\cos\beta < 0.5$.

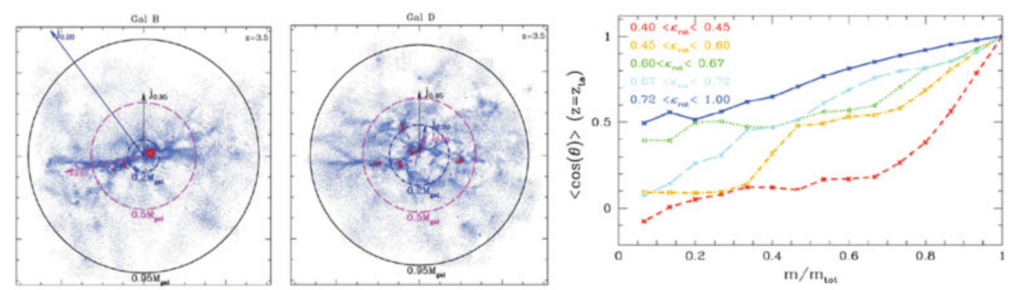

Figure 3. *Left:* Projected particle distribution at $z = 3.5$ (i.e. near turn-around) of all baryons that collapse to form galaxies named B and D at $z = 0$. Concentric circles enclose 20, 50 and 95% of the mass, and the arrows denote the angular momentum of matter within them. Galaxy D has acquired its angular momentum coherently and ends up as a disk-dominated galaxy, while strong misalignment of the different shells is detected for galaxy D, which lacks a significant disk component at the present time. *Right:* The angle between the angular momentum enclosed within a given mass fraction ($m/m_{\rm tot}$) and the total angular momentum of the system at turn-around, as a function of $m/m_{\rm tot}$, averaged over all galaxies grouped in bins of the $z = 0$ $\kappa_{\rm rot}$ values. (Adapted from Sales *et al.*, 2012.)

$\kappa_{\rm rot}$ defined as the fraction of kinetic energy invested in ordered motion ($\kappa_{\rm rot} \sim 1$ for disks in perfect circular motion and $\kappa_{\rm rot} \sim 0$ for non-rotating systems).

4. The Milky Way as part of the Local Group

Understanding the formation of our own Galaxy constitutes an area of particular interest in studies of galaxy formation. While the ability to form galaxy disks in simulations opened up the possibility to study the formation of the various stellar components in MW-mass galaxies, the simulated systems are in general chosen to be relatively isolated and with no significant merger activity, at least in the recent past, to favour the formation of disk-dominated galaxies. However, the MW and its neighbour Andromeda inhabit the Local Group (LG) of galaxies, a richer environment compared to more isolated regions of the Universe.

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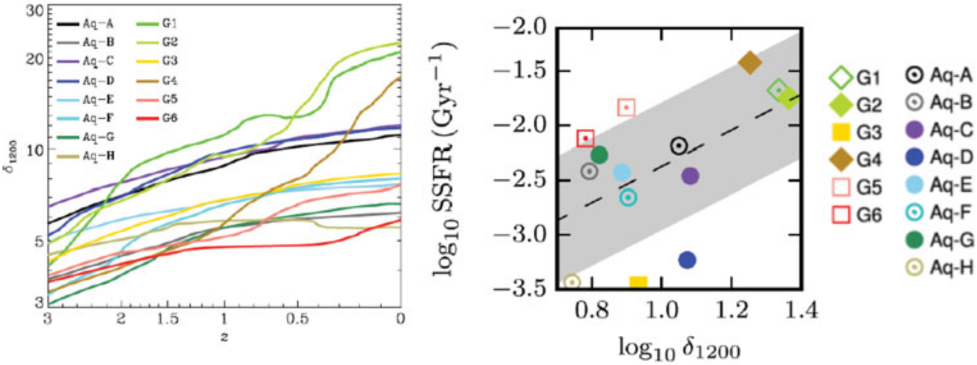

Figure 4. *Left:* The evolution of the environmental density ρ_{1200} for the six galaxies in the Local Group simulation, as well as for the eight Aquarius galaxies of Scannapieco *et al.* (2009). *Right:* The relation between the specific star formation rates of the same galaxies, as a function of δ_{1200}. Filled symbols indicates galaxies with significant disks at $z = 0$, and the grey-shaded regions indicate the significant linear regressions with $\pm\sigma$ errors. (Creasey *et al.* 2015).

Simulations of the LG that use constrained initial conditions which, by construction, reproduce the large-scale ($\gtrsim$ Mpc) dynamical properties of the Local Universe, are a promising tool to investigate possible environmental effects taking place in our Galaxy. Creasey *et al.* (2015) analysed the properties of six galaxies formed in the (10 Mpc)^3 high-resolution region of a simulation using the CLUES (Constrained Local UniversE Simulations) initial conditions for the LG. In order to measure the richness of the environment, they defined the environmental overdensity, δ_{1200}, as the ratio between the mean density of matter within 1200 comoving kpc from the center of a galaxy and the mean matter density of the universe. δ_{1200} as a function of time was calculated for the six LG galaxies (referred to as G1-G6, where G1 and G2 are, respectively, the candidates for the MW and Andromeda), and also for the eight Aquarius galaxies of the previous Section. All galaxies are found to inhabit similar environments at $z \sim 2-3$; however, G1, G2 and G4 exhibit stronger evolution after $z \sim 2$ and are the galaxies with the highest overdensity at $z = 0$, approximately twice as overdense as the remaining galaxies (Fig. 4, left-hand panel). Two of these galaxies (G1 and G2) have the highest star-forming gas mass and star formation rates (SFR) of the sample and, if we only consider SFR, then the three galaxies with higher δ_{1200} (G1, G2 and G4) are extremal.

In fact, when the specific SFR of the galaxies is plotted against δ_{1200}, a significant correlation is detected, and the null hypothesis is rejected at 2.6σ (Fig. 4, right-hand panel). A similar behaviour is found for the SFR-δ_{1200} relation (with slightly higher correlation of 3.8σ). These results suggest the possibility that galaxies in richer environments are contributing to higher SFRs compared to galaxies with lower δ_{1200}. There does not appear to be corresponding trends with the morphology (i.e. whether the stellar component lies in a disk) as was also noted by Few *et al.* (2012) and, indeed, in Scannapieco *et al.* (2015) we find morphology to be largely determined by the merger history.

Interestingly, the δ_{1200}-SSFR correlation appears only at late times ($z < 1$); for higher redshifts all galaxies live in sparser environments and G1, G2 and G4 have similar SSFRs than the remaining galaxies in the sample. The fact that the correlation appears when these galaxies increase their δ_{1200} suggests that the cold gas is driven by the richness of the environment, and that galaxies in richer environments could replenish faster such that higher SFRs continue until $z = 0$. As discussed in Nuza *et al.* (2014), the MW and Andromeda galaxies seem to share the gas halo and an excess of gas between them,

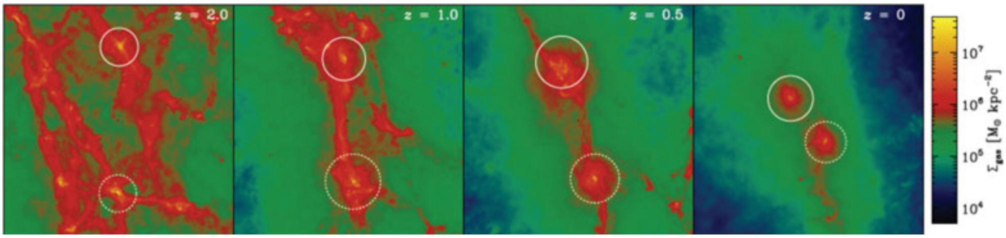

Figure 5. Spatial distribution (in an arbitrary projection) of the gas in a constrained simulation of the LG, at various redshifts. The plot focuses on the region inhabited by the MW and Andromeda, indicated respectively at their virial radii with dashed and solid circles. (Scannapieco *et al.* 2015).

with respect to any random direction, is detected, which is also suggestive of possible environmental effects at the scales of the LG (Fig. 5).

5. Discussion

The cosmological simulation of MW-mass galaxies has significantly progressed during the last decades; current simulations reproduce the formation of disk-bulge systems with properties similar to those observed. This success has mainly resulted from the inclusion of models for stellar feedback, which shifts the onset of star formation to later epochs, facilitating the formation of young, rotationally-supported, surviving disks. Zoom-in state-of-the-art simulations of individual galaxies (e.g. Grand *et al.* 2017) have reached sufficient resolution to allow for detailed studies of the chemical, dynamical and structural properties of galaxies, providing important clues to the formation of the various stellar components of galaxies, as well as the characteristics of the interstellar gas.

One limitation of such studies is that their success is usually decided on the basis of galaxy morphology – i.e. the prominence of the disks. However, the disk formation process is not yet fully understood, and we do not know in advance whether a given halo should harbour a disk. On the other hand, we do know what the galaxy population looks like, and thus the simulation of large, representative samples of galaxies – albeit at lower resolution – complements studies based on simulations of individual galaxies, allowing a better judgement on the success of a model. A few large-volume simulation suites have already been presented (Schaye *et al.* 2014, Vogelsberger *et al.* 2014, Khandai *et al.* 2015); these simulations will help us better understand the relevance of the various physical processes occurring as galaxies evolve, and the relative importance of the different feedback channels.

The future looks promising for simulations as the variety of models, together with the possibility to reach very high resolutions and simulate large numbers of galaxies, will allow to scrutinize the galaxy formation process with an unprecedented level of detail. Real progress will however only be possible if, as a community, we work together to understand the numerical effects that affect the codes, and to identify the sources of discrepancy, as to be able to provide simulations with predictive power, independently of the particular simulation code used.

Acknowledgments

C.S. thanks the Deutsche Forschungsgemeinschaft (DFG), the IAU and the LOC of the meeting for their support. C.S. also thanks Laura Sales, Michael Aumer, Peter Creasey and Sebastián Nuza for sharing their results and allowing their reproduction in this paper.

https://doi.org/10.1017/S1743921317008572 Published online by Cambridge University Press

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