Mem. S.A.It. Vol. 85, 430

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Reconciling the chemical properties of star-forming galaxies, the Milky Way, and local ellipticals

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Abstract. We present recent results from the new galactic chemical evolution (GCE) scheme implemented into the Munich semi-analytic model of galaxy formation, which is described in detail by Yates et al. (2013). This treatment includes delayed enrichment from AGB stars, SNe-II and SNe-Ia, and a reformulation of the associated stellar feedback. We find that the model is able to simultaneously reproduce the $z = 0$ gas-phase MZR, the [Fe/H] and [O/Fe] distributions in the Milky Way disc, and positive slopes in the M_*-[α/Fe] relations of local ellipticals, without requiring a variable IMF or additional physical prescriptions at high redshift. These results are best achieved using a DTD with a small 'prompt' component, i.e. fewer than 50 per cent of the SNe-Ia exploding within 400 Myrs. These results show that a wide range of chemical observations can be simultaneously reproduced within the ΛCDM paradigm.

Key words. Galaxies: abundances – Galaxies: evolution – Methods: analytical

1. Introduction

The metal content in galaxies plays a key role in all the physical processes governing galaxy evolution, including the cooling rate of gas, the formation of stars, stellar evolution, and the yields of newly synthesised metals which are released into the ISM, CGM and IGM. However, we still have a long way to go before we fully understand how heavy elements are produced and distributed throughout the Universe. In order for significant progress to be made, a comprehensive and self-consistent model of the chemical evolution in a diverse range of galaxies is needed.

Many recent theoretical works have focused on reproducing either the chemical compositions of field stars observed in the solar neighbourhood (e.g. Minchev et al. 2013), or the chemical properties of the integrated stellar populations in local elliptical galaxies (e.g. Calura & Menci 2011). In Yates et al. (2013), we have attempted to address both of these issues together, by using a new GCE implementation in the Munich semi-analytic model, L-Galaxies. The aim is to simultaneously reconcile a wide range of chemical properties in a diverse population of galaxies at $z = 0$, with a self-consistent model that follows the ΛCDM hierarchical merging scenario of structure formation.

2. The model

L-Galaxies is a semi-analytic model of galaxy evolution which runs on subhalo merger trees built from DM N-body simulations such as the Millennium (Springel et al. 2005). Baryonic processes, such as gas cooling and star formation, are modelled analytically, according to physical laws motivated by observations and simulations. The current base model (Guo et al. 2011), which we build on in this work, is able to reproduce the stellar mass function and optical luminosity functions of galaxies at $z \sim 0$, as well as the large-scale clustering of galaxies, and the Tully-Fisher relation. Processes important for the distribution of metals throughout galaxies, such as gas stripping, tidal disruption, and SN and AGN feedback, are also included (see Guo et al. 2011, §3).

We have added a new treatment for the delayed enrichment of a number of element species by stellar winds and SNe to this base model. We assume a Chabrier (2003) IMF, *fixed in time and space*, from 0.1 to 120 $M_{\odot}$. We also incorporate the metallicity-dependent stellar lifetimes and SN-II yields tabulated by Portinari et al. (1998), metallicity-dependent AGB-wind yields tabulated by Marigo (2001), and SN-Ia yields tabulated by Thielemann et al. (2003). SN-Ia projenitor systems are assumed to live for between $\tau_{8M_{\odot}} = 35$ Myr and $\tau_{0.85M_{\odot}} = 21$ Gyr, and their formation efficiency is tuned by fixing the peak of the Milky Way disc [Fe/H] distribution to the solar value (see §4). This results in a SN-Ia formation efficiency for stellar objects within the mass range $3-16\,M_{\odot}$ of $A = 0.028$, which is in reasonable agreement with that predicted by observations of the SN-Ia rate (e.g. Brandt et al. 2010). In these proceedings, we focus on results when using the power-law SN-Ia delay-time distribution (DTD) proposed by Maoz et al. (2012). For a discussion on the effect of changing the SN-Ia DTD, and SN-II yields, in L-Galaxies, see Yates et al. (2013).

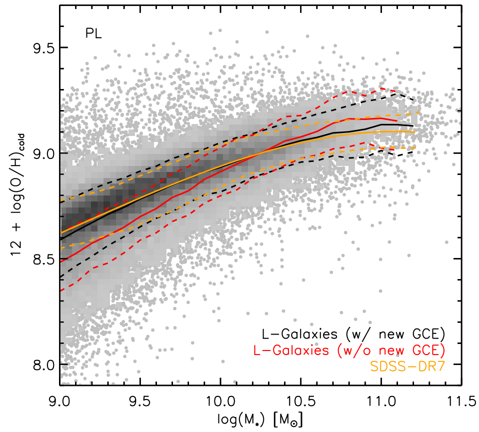

Fig. 1. The MZR for L-Galaxies with the new GCE implementation (points and black lines). This relation is compared to that of L-Galaxies prior to the new GCE implementation (red lines), and a fit to the observed MZR for emission-line galaxies from the SDSS-DR7 (orange lines) by Yates et al. (2012).

3. The mass-metallicity relation

The M_*-Z_g relation (MZR) is one of the key diagnostics used to analyse the chemical properties of star-forming galaxies. Fig. 1 shows the MZR at $z = 0$ for 94550 model, star-forming galaxies with our new GCE implementation included (points and black lines). The same model relation *prior* to the new GCE implementation (red lines), and a fit to the observed $z \sim 0$ MZR from the SDSS-DR7 (orange lines), are also shown. We can see that there is a remarkably good agreement between our new model and the SDSS observations, although we caution that the exact slope and amplitude of the observed relation is very sensitive to the metallicity diagnostic chosen (e.g. Kewley & Ellison 2008). We use the Bayesian metallicities calculated by Tremonti et al. (2004) here. The difference between the old and new model MZR at low M_* is due to a) the new input yields allowing a metallicity-dependent percentage of the star-forming gas to be recycled at a later time, and b) our new delayed SN feedback scheme, which allows the ejection of energy into the surrounding gas to occur *when SNe explode*, rather than instantaneously.

4. The Milky Way disc

The [Fe/H] and [α/Fe] ratios in the photospheres of stars in the Milky Way (MW) stellar disc place firm constraints on the likely star formation and metal enrichment history of the Galaxy. In Fig. 2, we show these key distributions for the disc G dwarfs from a sample of 4604 MW-type model galaxies at $z = 0$, and compare them to those observed by the *GCS* and *SEGUE* surveys. We can see that the *GCS* [Fe/H] distribution is well reproduced by our model. This is partly by construction, as we have tuned the SN-Ia formation efficiency in our model in order to obtain an [Fe/H]-distribution peak at 0.0. The *GCS* survey studied stars strictly within the solar neighbourhood ($7.7 \lesssim R_{\rm GC}/{\rm kpc} \leq 8.31$ and $0.0 \leq |Z_{\rm GC}|/{\rm kpc} \leq 0.359$), whereas *SEGUE* covered a wider volume of the Galactic disc, to very high galactic scale heights ($5 \lesssim R_{\rm GC}/{\rm kpc} \lesssim 12$ and $0.3 \leq |Z_{\rm GC}|/{\rm kpc} \leq 3.0$). Therefore, the *SEGUE* results contain a larger component of iron-poor, α-enhanced, thick disc stars than is seen in either the *GCS* or our chemically-averaged model.

The [O/Fe] distribution for our new model sample exhibits an extended tail up to [O/Fe]$\sim$ 0.4, although this is not as extended as that seen by *SEGUE*, for the reason described above. A high-[O/Fe] tail in the model distribution is *only* obtained if a relatively small 'prompt' component of SNe-Ia is assumed. Both a narrow Gaussian DTD centered on 1 Gyr, and the power-law DTD considered here (with fewer than 50 per cent of the SNe-Ia exploding within 400 Myrs), produce such a tail, whereas DTDs with a larger fraction of prompt SNe-Ia do not (see Yates et al. 2013).

5. Local elliptical galaxies

It has been notoriously difficult for galaxy formation models to reproduce the positive correlation between velocity dispersion (or M_*) and [α/Fe] that is seen in local elliptical galaxies (e.g. Thomas 1999). Previous GCE models working within a hierarchical merging scenario have had to invoke either a variable or adapted IMF, morphologically-dependent star formation efficiencies, or additional prescriptions to increase star formation at high redshift (e.g. Nagashima et al. 2005b; Arrigoni et al. 2010a; Calura & Menci 2011).

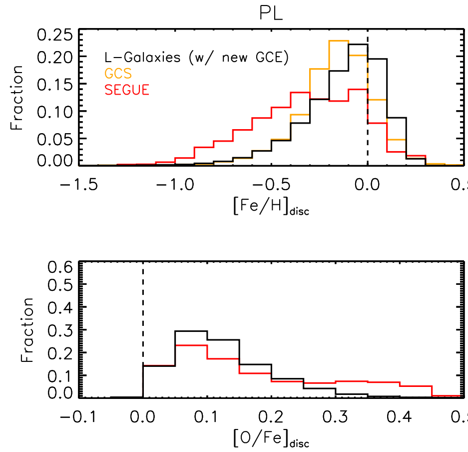

Fig. 2. [Fe/H] and [O/Fe] distributions for the stellar disc G dwarfs of our model MW-type galaxies (black). Vertical dashed lines indicate the solar iron abundance and oxygen enhancement. Similar distributions from the *GCS* (orange) and *SEGUE* (red) surveys are also plotted for comparison.

In Fig. 3, we show the M_*-[O/Fe] relation for a sample of 9605 model elliptical galaxies, selected by $M_{\rm bulge}/M_* \geq 0.7$ and (g-r) $\geq 0.051 \log(M_*) + 0.14$. Light-blue contours represent our full elliptical sample. Dark-blue, filled contours represent a sub-sample containing only those elliptcial galaxies which lie within the 1σ dispersion of the observed M_*-age relation of Johansson et al. (2012). This sub-sample is selected to account for the significant fraction of low-M_* galaxies with luminosity-weighted ages older than $\sim$ 9 Gyr in the model, which is in contradiction with observations (however, see Henriques et al. 2013).

Fig. 3 demonstrates that we reproduce a clear positive correlation between M_* and [O/Fe] in our model, although the relation flattens below $\log(M_*) \sim 10.4\,{\rm M}_\odot$ for our full elliptical sample, for the reason described above. This positive correlation is formed because high-M_* ellipticals have formed their stars more rapidly and at higher redshift than

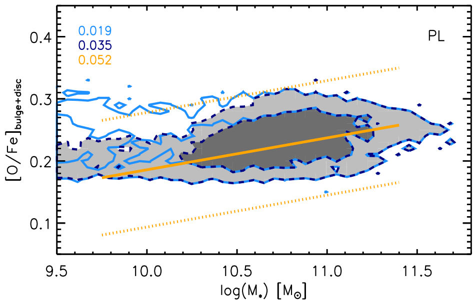

Fig. 3. The M_*-[O/Fe] relation for the bulge and disc components of our model elliptical sample. Light-blue contours represent our full elliptical sample. Dark-blue, dashed, filled contours represent a mass-age-selected sub-sample (see text). Contours represent the 68th and 95th percentiles. A linear fit to the observed relation from Johansson et al. (2012) is also shown (orange lines).

low-M_* ellipticals in our model. This means that they have had less time to get iron into their stellar populations from SNe-Ia. Such an explanation fits well with the canonical explanation for the observed M_*-[O/Fe] relation (Thomas et al. 2010).

6. Conclusions

The L-Galaxies semi-analytic model is able to *simultaneously* reproduce, with reasonable accuracy, the chemical properties of star-forming galaxies, the MW disc and local ellipticals, within the standard ΛCDM framework, and without requiring a variable IMF. This is a strong indication that the canonical thinking about the chemical evolution of galaxies in a ΛCDM cosmology can explain what is observed in the real Universe.

Acknowledgements. RMY acknowledges the financial support of the Deutsche Forschungsgesellshaft (DFG). PAT acknowledges support from the Science and Technology Facilities Council (grant number ST/I000976/1). SW was supported in part by Advanced Grant 246797 "GALFORMOD" from the European Research Council.

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