Correlations between mass, stellar kinematics and gas metallicity in Eagle galaxies

L. J. Zenocratti,1⋆ M. E. De Rossi,2,3† M. A. Lara-López,4 T. Theuns5

1Facultad de Ciencias Astronómicas y Geofísicas, Universidad Nacional de La Plata, Paseo del Bosque s/n, B1900FWA, La Plata, Argentina
2Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales y Ciclo Básico Común. Buenos Aires, Argentina
3CONICET-Universidad de Buenos Aires, Instituto de Astronomía y Física del Espacio (IAFE). Buenos Aires, Argentina
4DARK, Niels Bohr Institute, University of Copenhagen, Lyngbyvej 2, Copenhagen DK-2100, Denmark
5Institute for Computational Cosmology, Physics Department, University of Durham, South Road, Durham DH1 3LE, UK

Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT
The metallicity of star forming gas in galaxies from the Eagle simulations increases with stellar mass. Here we investigate whether the scatter around this relation correlates with morphology and/or stellar kinematics. At redshift \( z = 0 \), galaxies with more rotational support have lower metallicities on average when the stellar mass is below \( M_\star \approx 10^{10} M_\odot \). This trend inverts at higher values of \( M_\star \), when prolate galaxies show typically lower metallicity. At increasing redshifts, the trend between rotational support and metallicity becomes weaker at low stellar mass but more pronounced at high stellar mass. We argue that the secondary dependence of metallicity on stellar kinematics is another manifestation of the observed anti-correlation between metallicity and star formation rate at a given stellar mass. We present a simple model based on self-regulation of star formation by supernovae that reproduces the trends seen in the simulation, provided that the feedback efficiency is greater in thin, rotationally supported discs and lower if the gas distribution is more spheroidal. Such a dependence of efficiency on gas morphology is expected, because cooling losses of supernova remnants are reduced in explosions that occur at the lower densities found above or below a disc.

Key words: galaxies: abundances - galaxies: evolution - galaxies: high-redshift - galaxies: star formation - cosmology: theory.

1 INTRODUCTION
The relation between stellar mass and gas-phase metallicity in galaxies (henceforth the mass-metallicity relation, ‘MZR’) has been studied extensively in the last decades from both an observational (Lequeux et al. 1979; Tremonti et al. 2004; Lara-López et al. 2010) and a theoretical (Calura et al. 2009; Yates et al. 2012; De Rossi et al. 2015; De Rossi et al. 2017—hereafter, DR17; Sharma & Theuns 2019) point of view. At redshift \( z \sim 0 \), gas metallicity, \( Z \), increases with stellar mass, \( M_\star \), approximately as a power law, \( Z \propto M_\star^{2/5} \); the slope of the correlation flattens towards higher masses. This power-law trend is also seen at higher redshifts, though possibly with a different slope and normalization (e.g. Troncoso et al. 2014).

The scatter along the observed MZR correlates with other properties of galaxies. Ellison et al. (2008) showed that, at given stellar mass, observed galaxies with smaller half-mass radii or lower specific star formation rates (sSFR) tend to have higher gas metallicity, as quantified by the oxygen abundance, \( O/H \). To account for these observations, Lara-López et al. (2010) and Mannucci et al. (2010) suggested the existence of a three-dimensional relation between \( M_\star \), \( O/H \) and star formation rate (SFR) in such a way that systems with higher SFRs tend to have lower \( O/H \) at a given value of \( M_\star \). Alternatively, this 3D relation could result from a more fundamental underlying relation between \( M_\star \), \( O/H \) and gas fraction \( (f_g) \), since \( f_g \) and SFR correlate (e.g. Bothwell et al. 2013, Lara-López et al. 2013). Deciding which relation is more fundamental could be helped by examining other correlations. Recent observations suggest that \( Z \) tends to be lower in galaxies with a higher concentration, higher Sérsic index, or higher SFR (Wu et al. 2019), at given value of \( M_\star \). Unfortunately, surprisingly large uncertainties remain in inferring physical relations from the data because different methods yield significantly different answers (e.g.
In fact, some observational studies do not find that the scatter around the MZR correlates with SFR (e.g. Sánchez et al. 2019), and some studies claim that the correlation exists but inverts at high $M_*$ (e.g. Yates et al. 2012).

In this paper we examine the scatter around the MZR in galaxies from the EAGLE cosmological hydrodynamical simulations (Schaye et al. 2015). The ‘Evolution and Assembly of GaLaxies and their Environments’ (EAGLE) suite of cosmological hydrodynamical simulations uses sub-grid models calibrated to reproduce a small set of observations at $z \approx 0$, as described in Crain et al. (2015). The simulations then reproduce a relatively extensive set of other observations, including the evolution of the galaxy stellar mass function (Furlong et al. 2015), of galaxy sizes (Furlong et al. 2017), of optical (Trayford et al. 2015) and UV and IR luminosities (Camps et al. 2018). DR17 analysed the secondary metallicity dependences in EAGLE (including the dependences on SFR, sSFR, $f_g$ and stellar age, $\tau_*$), obtaining good agreement with observed trends (see also Lara-López et al. 2019). In particular, DR17 show that EAGLE galaxies follow remarkably well the observed ‘Fundamental Metallicity Relation’ introduced by Mannucci et al. (2010). In addition, Sánchez Almeida & Dalla Vecchia (2018) show that EAGLE simulations are able to reproduce the observed secondary metallicity dependence on the size of galaxies.

In this Letter, we report new predictions of EAGLE simulations regarding the connection of the MZR scatter with the internal kinematics and morphology of galaxies. Such trends were not previously reported in MZR studies. In a forthcoming article, we address the origin of these metallicity secondary dependences by analysing the formation histories of different galaxy populations. This Letter is organised as follows. In Section 2, we briefly describe the EAGLE simulations and the galaxy selection criteria. In Section 3, we analyse the simulated MZR as a function of the morphology and kinematics of the galaxies. We summarise our findings in Section 4.

2 THE EAGLE SIMULATIONS

A full description of the EAGLE simulation suite is given by Schaye et al. (2015). Briefly, the suite was simulated with the GADGET-3 incarnation of the TREEPM-SPH code described by Springel (2005), with sub-grid modules for physics below the resolution scale whose parameters are calibrated to reproduce the $z \approx 0$ galaxy stellar mass function, the relation between galaxy mass and size, and the black hole mass - stellar mass relation (Crain et al. 2015). The adopted cosmological parameters are taken from Planck Collaboration (2015): $\Omega_m = 0.693$, $\Omega_b = 0.307$, $\Omega_b = 0.04825$, $n_s = 0.9611$, $Y = 0.248$, and $h = 0.677$.

EAGLE consists of simulations with various box sizes and particle masses. Here, we mainly use simulation labelled ‘Ref-L100N1504’ in Schaye et al. (2015), which has a co-moving extent of $L = 100$ co-moving megaparsecs (cMpc) and a baryonic particle mass of $\sim 1.2 \times 10^6 M_\odot$ (corresponding to 1504$^3$ particles). We have verified that the main trends and conclusions presented in this work are consistent with those from the higher-resolution EAGLE simulation ‘Recal-L025N0752’, analysed previously by DR17.

3 RESULTS

3.1 Correlating morphology and metallicity

EAGLE’s $z = 0$ mass-metallicity relation is plotted in Fig. 1, with galaxies binned by $\kappa_{co}$, the fraction of stellar kinetic energy in rotation: the lowest third $\kappa_{co}$ (orange), intermediate $\kappa_{co}$ (purple) and the highest third $\kappa_{co}$ (blue). Error bars encompass the 25th and 75th percentiles. Inset: as main panel, but for the higher resolution EAGLE simulation Recal-L0025N0752.

Figure 1. Black dotted line: median $M_*$ - O/H (MZR) relation in redshift $z = 0$ EAGLE galaxies from simulation Ref-L100N1504. Coloured lines: MZR relation for EAGLE galaxies binned by $\kappa_{co}$, the fraction of stellar kinetic energy in rotation: the lowest third $\kappa_{co}$ (orange), intermediate $\kappa_{co}$ (purple) and the highest third $\kappa_{co}$ (blue). Error bars encompass the 25th and 75th percentiles. Inset: as main panel, but for the higher resolution EAGLE simulation Recal-L0025N0752.

EAGLE galaxies are identified using a combination of the ‘friends-of-friends’ (FOF) and SUBFIND (Dolag et al. 2009) algorithms. This picks-out ‘self-bound’ structures of gas, stars and dark matter. Here we analyse the properties of both central galaxies (the dominant galaxies in FOF halos) and satellites$^1$. Following DR17, we measure baryonic properties within spherical apertures of 30 proper kilo-parsecs (pkpc) and characterize the ‘metallicity’ of star forming gas by its O/H abundance (EAGLE tracks 11 abundances, including oxygen and hydrogen). We analyse galaxies with at least 25 star forming gas particles (gas mass at least $5.25 \times 10^7 M_\odot$) which we found to be a reasonable compromise between numerical resolution and bias. To characterise the stellar morphology and kinematics, we use the fraction of kinetic energy in co-rotation, $\kappa_{co}$, the disc-to-total stellar mass ration, $D/T$, the ratio $V/\sigma$ of stellar rotation to velocity dispersion, the ellipticity, $\epsilon_*$, of the stellar body, and its triaxiality, $T$. These were computed by Thob et al. (2019) and can be queried in the EAGLE database$^2$ (McAlpine et al. 2016; The EAGLE team 2017).

$^1$ Our main results are unchanged if we restrict the analysis to centrals.

$^2$ http://eagle.strw.leidenuniv.nl, http://www.eaglesim.org/
Figure 2. Correlation between O/H (left panel), gas fraction $f_g$ (middle panel), and the specific star formation rate (right panel) and $\kappa_{\text{co}}$, the fraction of stellar kinetic energy in rotation, for $z = 0$ EAGLE galaxies from simulation Ref-L100N1504. Galaxies are binned in stellar mass: low stellar mass (blue), intermediate stellar mass (orange) and high stellar mass (purple), see legend. Curves represent the median relation, error bars encompass the 25th and 75th percentiles.

Figure 3. O/H metallicity as a function of stellar mass, $M_*$, for $z = 0$ EAGLE galaxies from simulation Ref-L100N1504. Bins in O/H-$M_*$ are coloured according to the median value of $\kappa_{\text{co}}$ (left panel), the stellar ellipticity $\epsilon_*$ (middle panel) and the galaxy’s triaxiality parameter $T$ (right panel).

is that O/H increases with $M_*$ for rotationally supported galaxies, but is almost independent of $M_*$ for dispersion supported galaxies. As a consequence, the trend between O/H and $\kappa_{\text{co}}$ inverts above $M_* \approx 10^{10}M_\odot$, with massive dispersion supported galaxies having lower O/H than rotationally supported galaxies of the same mass. We find similar trends in the higher resolution simulation Recal-L025N0752 (inset).

The results of Fig. 1, combined with the findings of DR17 that O/H depends on the SFR, sSFR and the gas fraction, suggest that $\kappa_{\text{co}}$ may itself correlate with these other galaxy parameters. We examine this in Fig. 2. Independent of $M_*$, the gas fraction (middle panel) and the specific star formation rate (right panel) both increase with $\kappa_{\text{co}}$, however the increase of $f_g$ with $\kappa_{\text{co}}$ is most pronounced for the lower $M_*$ galaxies (blue line), whereas the increase of the sSFR is more evident in the higher $M_*$ galaxies (purple line). The sSFR is a measure of the rate at which metals are produced, and $f_g$ a measure of the reservoir that dilutes those metals. Therefore, a consequence of these trends is that O/H decreases with increasing $\kappa_{\text{co}}$ at low $M_*$, whereas it increases for high mass galaxies (see left panel); at $M_* \sim 10^{10}M_\odot$, O/H does not depend on $\kappa_{\text{co}}$. These findings are consistent with the analysis by Correa et al. (2017) of the relation between colour and kinematics of EAGLE galaxies.

How these correlations arise is analysed in more detail in Fig. 3. At low stellar mass, $M_* < 10^{10}M_\odot$, galaxies typically have low $\kappa_{\text{co}}$, but there is a tail of galaxies with high $\kappa_{\text{co}}$ and low O/H: it is this tail that generates the anti-correlation between $\kappa_{\text{co}}$ and O/H in Fig. 2. These outliers are also gas rich and have unusually high stellar ellipticities, $\epsilon_*$, and low triaxiality parameter $T$. At high $M_* > 10^{10}M_\odot$, galaxies have usually a high value of $\kappa_{\text{co}}$, but now there is a tail of galaxies with low $\kappa_{\text{co}}$ and high $T$ - these typically are also more massive and have low O/H. At intermediate masses, $M_* \sim 10^{10}M_\odot$, there is relatively little variation in $\kappa_{\text{co}}$ or $\epsilon_*$.

Calura et al. (2009) analysed the MZR of galaxies using ‘chemical evolution’ models. They did not find a clear dependence of O/H on morphology at a given mass and $z$, which might be a consequence of the different assumptions made in their models. For example, they assume that galaxies retain the same morphology throughout their evolution and they neglect mergers. This is definitely not what happens in the EAGLE simulations, in which galaxies change morphology often as a consequence of mergers, and where discs may re-grow due to accretion (Trayford et al. 2019).

Is there a simple model that encapsulates the trends we find in EAGLE? Sharma & Theuns (2019) propose a model of

3 Similar results are obtained if using $D/T$ or $V/\sigma$ instead of $\kappa_{\text{co}}$. 

MNRAS 000, 1–5 (2019)
efficiency and the star formation rate is low. On the other hand, when $\epsilon$ is small, feedback is inefficient and the star formation rate, stellar mass, gas mass and metallicity depend on halo self-regulated galaxy formation, in which the star formation rate $\propto Z$ is high. This leads to the following scaling for the metallicities found in more prolate galaxies with lower levels of rotational support. The trends in more massive galaxies are generally less strong, with lower metallicities found in more prolate galaxies with lower levels of rotational support. These trends are consistent with the secondary dependences of O/H on gas fraction, star formation rate and stellar age, and the relation between the latter quantities with galaxy morpho-kinematics (see DR17).

At higher redshifts, the secondary O/H dependence on morpho-kinematics becomes weaker for less massive galaxies, which seems to be a consequence of the steepening of the MZR associated with systems with lower rotational support. On the other hand, for more massive galaxies, the secondary O/H dependence on morpho-kinematics becomes stronger with $z$ as a consequence of the steepening of the MZR associated with systems with higher rotational support.

Our findings regarding the O/H secondary dependences (at a fixed mass) on gas fraction, star formation rate and stellar age, and the relation between the latter quantities with galaxy morpho-kinematics Relation in EAGLE will be presented in a future article.

4 CONCLUSIONS

We analysed the stellar mass-gas metallicity relation (MZR) as function of morpho-kinematical parameters in the EAGLE cosmological hydrodynamical simulations. At $z = 0$, we found new secondary dependences of metallicity on the internal kinematics and morphology of galaxies. At low masses ($M_* \lesssim 10^{10} M_\odot$), higher metallicities are found for galaxies with more spheroidal morphologies and with lower rotational support.

We proposed a simple model based on Sharma & Theuns (2019), in which these trends are related to the efficiency of stellar feedback: when the gas is in a thin, rotationally supported disc, feedback may be more efficient, which results in lower O/H and a higher gas fraction. The trends in more massive galaxies are generally less strong, with lower metallicities found in more prolate galaxies with lower levels of rotational support. These trends are consistent with the secondary dependences of O/H (at a fixed mass) on gas fraction, star formation rate and stellar age, and the relation between the latter quantities with galaxy morpho-kinematics (see DR17).

At higher redshifts, the secondary O/H dependence on morpho-kinematics becomes weaker for less massive galaxies, which seems to be a consequence of the steepening of the MZR associated with systems with lower rotational support. On the other hand, for more massive galaxies, the secondary O/H dependence on morpho-kinematics becomes stronger with $z$ as a consequence of the steepening of the MZR associated with systems with higher rotational support.

Our findings regarding the O/H secondary dependences (at a fixed stellar mass) on morpho-kinematics and their relation with the origin of the scatter of the MZR were not previously discussed in the literature. A detailed analysis of the origin and evolution of the Mass-Metallicity-Morpho-kinematics Relation in EAGLE will be presented in a future article.

3.2 Evolution of the metallicity relations

We plot the MZR relation at different redshifts in Fig. 4. At a given $z$, the sample of simulated galaxies is separated in two sub-samples, using the median value of $\kappa_{co}$ ($\bar{\kappa}_{co}$) at that $z$. Note that the value of $\kappa_{co}$ tends to decrease with increasing $z$: dispersion-supported galaxies increasingly dominate at higher $z$. As expected, the normalization of the MZR decreases with $z$, with such evolution being independent of $\kappa_{co}$ at $M_* \sim 10^{10} M_\odot$. As we also noticed at $z = 0$, there is a clear increase of O/H with $M_*$ for galaxies with high $\kappa_{co}$, but this trend is mostly absent for the low $\kappa_{co}$ galaxies. At the low-mass end ($M_* < 10^{10} M_\odot$), the secondary dependence of O/H on $\kappa_{co}$ tends to vanish as $z$ increases, due mainly to an increase of the MZR slope for systems with $\kappa_{co} < \bar{\kappa}_{co}$ at $z < 1$. On the other hand, at high masses ($M_* \gtrsim 10^{10} M_\odot$), the secondary dependence of O/H on $\kappa_{co}$ tends to be stronger at higher $z$, which, in this case, is caused by an increase of the MZR slope for systems with $\kappa_{co} > \bar{\kappa}_{co}$ at $z \gtrsim 2$. Similar evolutionary trends are obtained if using other morpho-kinematical indicators.

\begin{figure}
\centering
\includegraphics[width=0.8\textwidth]{figure4.png}
\caption{Median $M_\star$,O/H relation of galaxies for the Eagle Ref-L100N1504 simulation at different redshifts, $z$ (solid: $z = 0$, dashed: $z = 1$, dot-dashed: $z = 2$, dotted: $z = 3$). Curves representing galaxies with rotational support below the median at $z$ are plotted in thick orange, those with higher $\kappa_{co}$ are plotted in thin blue.}
\end{figure}

\begin{equation}
Z \propto \frac{M_*^{2/5}}{\epsilon^{-1/5}} f_g \approx \frac{2^{1/2}}{3^{1/2}} \frac{\xi_a}{\bar{\kappa}_{co}} \frac{M_*}{M_\odot} \approx Z \approx \frac{0.11}{M_*^{0.17}},
\end{equation}

where $n \approx 1.4$ is the slope of the Kennicutt-Schmidt star formation law. These relations show that when feedback is efficient, $\kappa_{co}$ is high, whereas the other hand, inefficient feedback ($\epsilon \ll 1$) implies $Z$ is high and $f_g$ low. We can connect this to the morphology of the galaxy by speculating that feedback in a thin disc - corresponding to a galaxy with high $\kappa_{co}$ - is more efficient than when $\kappa_{co}$ is low (a more spheroidal gas distribution). High-resolution simulations that resolve individual supernova energy injections in gas columns suggest this type of relation between feedback efficiency and disc morphology. For example, the simulations by Creasey et al. (2013) show that supernova explosions that occur above or below the disc are more efficient at driving winds, because cooling losses are suppressed when the explosion occurs at the lower densities that prevail there (see also Girichidis et al. 2016).

ACKNOWLEDGEMENTS

LJZ and MEDR acknowledge support from PICT-2015-3125 of ANPCyT, PIP 112-201501-00447 of CONICET.
and UNLP G151 of UNLP (Argentina). MALL is a DARK-Carlsberg Foundation Fellow (Semper Ardens project CF15-0384). We acknowledge the Virgo Consortium for making their simulation data available. The EAGLE simulations were performed using the DiRAC-2 facility at Durham, managed by the ICC, and the PRACE facility Curie based in France at TGCC, CEA, Bruyères-le-Châtel. This work used the DiRAC@Durham facility managed by the Institute for Computational Cosmology on behalf of the STFC DiRAC HPC Facility (www.dirac.ac.uk). The equipment was funded by BEIS capital funding via STFC capital grants ST/P002293/1, ST/R002371/1 and ST/S002502/1, Durham University and STFC operations grant ST/R000832/1. DiRAC is part of the National e-Infrastructure.

REFERENCES

Bothwell M. S., Maiolino R., Kennicutt R., Cresci G., Mannucci F., Marconi A., Cicone C., 2013, MNRAS, 433, 1425
Calura F., Pipino A., Chiappini C., Matteucci F., Maiolino R., 2009, A&A, 504, 373
Camps P., et al., 2018, ApJS, 234, 20
Correa C. A., Schaye J., Clauwens B., Bower R. G., Crain R. A., Schaller M., Theuns T., Thob A. C. R., 2017, MNRAS, 472, L45
Crain R. A., et al., 2015, MNRAS, 450, 1937
Creasey P., Theuns T., Bower R. G., 2013, MNRAS, 430, 1922
De Rossi M. E., Theuns T., Font A. S., McCarthy I. G., 2015, MNRAS, 452, 486
De Rossi M. E., Bower R. G., Font A. S., Schaye J., Theuns T., 2017, MNRAS, 472, 3354
Dolag K., Borgani S., Murante G., Springel V., 2009, MNRAS, 399, 497
Ellison S. L., Patton D. R., Simard L., McConnachie A. W., 2008, ApJ, 672, L107
Furlong M., et al., 2015, MNRAS, 450, 4486
Furlong M., et al., 2017, MNRAS, 465, 722
Girichidis P., et al., 2016, MNRAS, 456, 3432
Lara-López M. A., et al., 2010, A&A, 521, L53
Lara-López M. A., et al., 2013, MNRAS, 433, L35
Lara-López M. A., De Rossi M. E., Pilyugin L. S., Gallazzi A., Hughes T. M., Zinchenko I. A., 2019, MNRAS, p. 2215
Lequeux J., Peimbert M., Rayo J. F., Serrano A., Torres-Peimbert S., 1979, A&A, 500, 145
Mannucci F., Cresci G., Maiolino R., Marconi A., Gnerucci A., 2010, MNRAS, 408, 2115
Mannucci F., Cresci G., Maiolino R., Marconi A., Gnerucci A., 2010, MNRAS, 408, 2115
McAlpine S., et al., 2016, Astronomy and Computing, 15, 72
Planck Collaboration 2015, A&A, 594, A13
Sánchez Almeida J., Dalla Vecchia C., 2018, ApJ, 859, 109
Sánchez S. F., et al., 2019, MNRAS, 484, 3042
Schaye J., et al., 2015, MNRAS, 446, 521
Sharma M., Theuns T., 2019, arXiv e-prints, p. arXiv:1906.10135
Springel V., 2005, MNRAS, 364, 1105
Telford O. G., Dalcanton J. J., Skillman E. D., Conroy C., 2016, ApJ, 827, 35
The EAGLE team 2017, ArXiv e-prints: 1706.09899,
Thob A. C. R., et al., 2019, MNRAS, 485, 972
Trayford J. W., et al., 2015, MNRAS, 452, 2879
Trayford J. W., Frenk C. S., Theuns T., Schaye J., Correa C., 2019, MNRAS, 483, 744
Tremonti C. A., et al., 2004, ApJ, 613, 898
Troncoso P., et al., 2014, A&A, 563, A58
Wu Y.-Z., Zhang W., Zhao Y.-H., 2019, MNRAS, 486, 5310
Yates R. M., Kauffmann G., Guo Q., 2012, MNRAS, 422, 215

MNRAS 000, 1–5 (2019)