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A possible solution to the [α/Fe]-σ problem in early-type galaxies within a hierarchical galaxy formation model

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ABSTRACT

The most massive elliptical galaxies apparently formed the fastest, because the ratio of α elements (such as oxygen) to iron is the smallest. In fact, iron is mainly produced from type Ia supernovae on a time-scale of ~0.1–1 Byr , while the α elements come from massive stars on time-scales of a few tens of million years. Reproducing such a α/Fe correlation has long been a severe problem for cosmological theories of galaxy formation, which envisage massive galaxies to assemble gradually from smaller progenitors, and to be characterized by a star formation history too much extended towards late cosmic times. While it has recently become clear that feedback from Active Galactic Nuclei (AGNs) activity plays a role in the late quenching of star formation, and that early star formation history in the galaxy progenitors affect the α/Fe ratio, major mergers alone cannot enhance the star formation in the high-redshift progenitors to the levels required to match the steepness of the observed α/Fe correlation. Here we report that the inclusion of the effects of fly-by 'harassments', that trigger lower level starbursts, combined with the AGN quenching of the starburst activity, considerably enhances the capability to account for the observed α/Fe ratio in ellipticals within cosmological galaxy formation models. The critical difference between the earlier work and the present result is the effect of starbursts driven by fly-by encounters that would have been very common amongst the high-redshift progenitors of massive galaxies and which would have boosted star formation in the first 2 Byr after the big bang, combined with quenching of the burst activity within the first 3–4 Gyr.

Key words: galaxies: abundances – galaxies: elliptical and lenticular, cD – galaxies: formation – galaxies: star formation.

1 INTRODUCTION

The correlation between stellar α/Fe and velocity dispersion observed in local ellipticals (Trager et al. 2000; Thomas et al. 2005; Bernardi et al. 2006; Sánchez-Blázquez et al. 2006; Graves et al. 2007; Spolaor et al. 2010; Zhu, Blanton & Moustakas 2010) is generally referred to as one of the evidences of the 'downsizing' pattern of local galaxies, a pattern which is observable up to high redshift (e.g. Cowie et al. 1996; Kodama et al. 2004; Clements et al. 2008) indicating that the more massive the galaxy, the shorter the star formation time-scale (Matteucci 1994; Renzini 2006; Rogers et al. 2010; Pipino et al. 2011).

The failure of cosmological galaxy formation models (Nagashima et al. 2005; Thomas et al. 2005; Spolaor et al. 2010) in accounting for the above correlation is in fact due to such a 'downsizing' aspect. In fact, the precision measurements of the power spectrum of the initial density perturbations (Percival et al. 2007) provide evidence for large-scale fluctuations to be smaller, on average, compared to small-scale ones – in accordance with what expected in a Cold Dark Matter (CDM) scenario; this implies a hierarchical build-up of dark matter (DM) haloes, where small-mass galaxies collapse first, and later assemble to form massive ellipticals (De Lucia et al. 2006). The deep physical origin of the disagreement between the observed and the predicted α/Fe–σ correlation has been often considered as an evidence for a fundamental flaw of cosmological CDM models of galaxy formation (Thomas et al. 2005; Baugh 2006).

To produce downsizing within standard galaxy formation models, some physical mechanisms are required which can enhance star formation in massive galaxies at early times, possibly quenching it at late times. In cosmological galaxy formation, environmental effects are likely to play a major role in producing such a scenario. The progenitors of massive galaxies formed from biased regions of the density field, and fly-by events and merging in such regions may trigger starbursts at early cosmic times ($t \leq 2.5$ Gyr), when the

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Universe was denser and the rate of galaxy encounters was at least 5–10 times higher than the present. A fundamental mechanism to quench star formation in massive galaxies is linked to their Active Galactic Nuclei (AGNs). Feedback from powerful AGN may switch off star formation when the progenitors assembled into the main progenitor of the final elliptical (Cattaneo et al. 2009).

These processes may concur in yielding stellar populations in massive galaxies characterized by a prompt star formation at early epochs followed by a quenching, in agreement with what suggested by the observed α/Fe–σ correlation. Thus, testing whether the latter processes may in fact explain the above correlation is crucial for assessing the consistency of CDM models, and requires developed modelling which includes all the physical processed detailed above.

In a previous paper (Calura & Menci 2009, hereinafter CM09), we investigated the chemical properties of local galaxies within a cosmological hierarchical clustering scenario through a semi-analytic model (SAM) of galaxy formation. We used a hierarchical SAM where chemical evolution was computed by taking into account the stellar lifetimes, a significant step forward with respect to the instantaneous recycling approximation. However, chemical abundances were computed by considering the total (summed over all progenitors) star formation history (SFH) of each model galaxy and assumed an average interstellar α/Fe. This treatment was suited to the study of interstellar abundances, comparable to the ones observed today in stars in the solar neighbourhood, but in many cases it lead us to underestimate the integrated stellar α/Fe abundances measured in local early-type galaxies.

In this Letter, by means of the same SAM, we perform a thorough study of the average stellar α/Fe in early-type galaxies, taking into account the contribution from all the single progenitors. Although computationally more expensive, this constitutes a step forward with respect to our earlier work (CM09), since thanks to the inclusion of the contribution of all the progenitors, our estimates of the integrated abundances are more accurate. A second enhancement with respect to our previous work is the calculation of the luminosity-weighted abundances (against the mass-weighted ones used in the first paper), another aspect which improves the comparison of our results to local observations.

The aim of this Letter is to show the relative roles of the various processes in shaping the α/Fe–σ correlation, stressing the importance of some processes which have been neglected in previous studies, such as interaction-triggered fly-by events and merging-triggered starbursts.

This Letter is organized as follows. In Section 2, our model is briefly described. In Section 3, we present our main results, which are then discussed in a broader context in Section 4.

2 THE MODEL

To study the integrated abundances of local ellipticals, we use the same model as described in CM09. We defer the reader to that paper for further details. Here we summarize the main features of our model.

Galaxy formation is driven by the collapse and growth of DM haloes, which originate by gravitational instability of overdense regions in the primordial DM density field, a random, Gaussian density field with CDM power spectrum within the 'concordance cosmology' (Spergel et al. 2007) for which we adopt round parameters $\Omega_\Lambda = 0.7$, $\Omega_0 = 0.3$, baryonic density $\Omega_{\rm b} = 0.04$ and Hubble constant (in units of 100 km s^{-1} Mpc^{-1}) $h = 0.7$. As cosmic time increases, larger and larger regions of the density field collapse, and eventually lead to the formation of groups and clusters of galaxies, which grow by merging with mass and redshift dependent rates provided by the Extended Press & Schechter formalism (Press & Schechter 1974).

The clumps included into larger DM haloes may survive as satellites, merge to form larger galaxies due to binary aggregations, or coalesce into the central dominant galaxy due to dynamical friction. The above complex dynamical evolution of galaxies is followed through a Monte Carlo simulation of the collapse and subsequent merging history of the peaks of the primordial density field, which enables to generate a synthetic catalogue of model galaxies and of their past merging history.

For each model galaxy, we follow the evolution of its gas and stellar content; the gas which has radiatively cooled in the galactic haloes (with mass $M_{\rm g}$) partly condenses into stars at a rate $\psi \propto M_{\rm g}/t_{\rm d}$ on long timescales, $t_{\rm d} \approx 2$–10 Gyr according to the Kennicutt law (Kennicutt 1998). Star formation can also occur through interaction-triggered starbursts (ITS), driven by merging or by fly-by events between galaxies. Such a star formation mode can convert large fractions (up to 100 per cent in major merging events) of the cold gas on short time-scales ($\approx 10^6$ yr), and provides an important contribution to the early formation of stars in massive galaxies (Menci et al. 2004).

The model also includes a detailed treatment of the growth of supermassive black holes at the centre of galaxies, of the corresponding AGN activity powered by the interaction-triggered inflow of cold gas on to the black holes, and of the AGN feedback on to the galactic gas. Due to the crucial role of AGN feedback in the affecting the SFH of massive galaxies, this sector of the model has been extensive tested; the predicted QSO luminosity function and X-ray luminosity function and emissivity have been checked against observation over a wide range of redshift $0 \le z \le 5$ and bolometric luminosities $10^{43} \le L/\mathrm{erg\,s^{-1}} \le 10^{46}$ (Menci et al. 2003, 2004); the description of the AGN feedback as resulting from the sweeping of galactic gas by the blast wave produced by the injection of the AGN radiative energy has been tested by comparing the absorption properties of AGNs (as a function of both luminosity and redshift) with recent observation (Menci et al. 2008); the consistency of the modelling of the AGN feedback with the colour distribution of galaxies has been discussed in Menci et al. (2006).

As shown in Fontana et al. (2004), the inclusion of processes such as ITS and AGN feedback within the SAM affects mostly the model rendition of the stellar mass function at high redshift. All models discussed in this Letter have basically the same stellar mass function at $z \sim 0$.

Galaxy luminosities in different bands are computed by convolving the computed SFH with synthetic spectral libraries of stellar populations (Bruzual & Charlot 2003, hereinafter BC03).

To compare our prediction to the observed α/Fe–σ relation, as performed in our previous paper, we select elliptical galaxies from the SAM synthetic catalogue on the basis of their present-day ($B - V$) colour. In specific, we consider elliptical galaxies all the systems with present $(B - V) \ge 0.85$ (Roberts & Haynes 1994). For any selected galaxy, we compute the chemical evolution a posteriori by means of detailed chemical evolution equations taking into account the stellar lifetimes, fundamental for studying the chemical evolution of Fe. Thus, the SFH, the gas content, and the gas inflow and outflow histories of all the progenitors of the considered galaxy provided by the SAM constitute the input for calculating the chemical evolution. This constitutes a step forward with respect to our earlier work (CM09), where we considered only the total (summed over all progenitors) SFH of each model galaxy and assumed an average interstellar α/Fe.

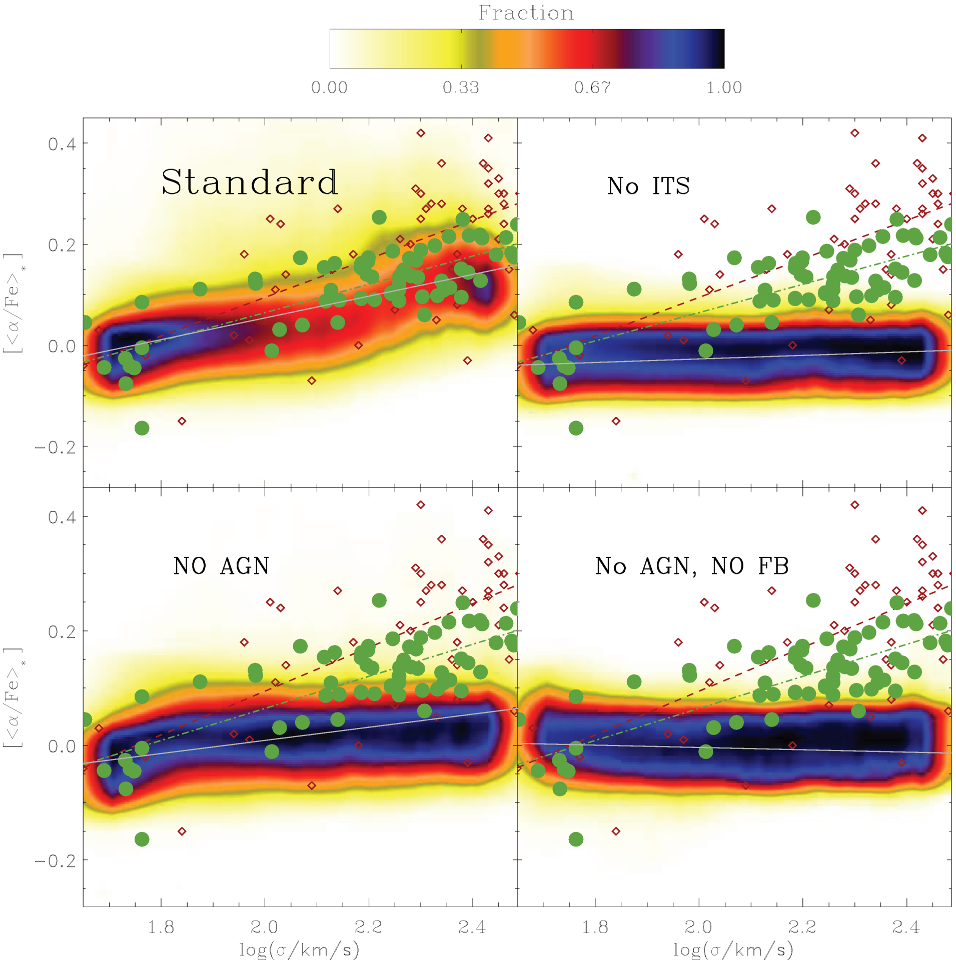

Figure 1. Stellar average α/Fe ratio versus velocity dispersion compared to local observations. The colour code represents the predicted number of galaxies with a given α/Fe and a velocity dispersion σ, normalized to the total number of galaxies with that velocity dispersion. The solid lines represent linear-regression fits to the model. The dashed line and dash dotted line represent linear-regression fits to the observational α/Fe–σ relations, as compiled by Spolaor et al. (2010; open diamonds) and Arrigoni et al. (2010; solid circles), respectively. Top-left panel: our results have been computed by means of our standard assumptions, i.e. by taking into account both ITS at high redshift and AGN feedback. Top-right panel: no ITS and fly-by interactions. Bottom-left panel: no AGN feedback. Bottom-right panel: no AGN feedback, no fly-by interactions.

3 RESULTS

The average stellar α/Fe may be calculated as:

$$\langle\alpha/\mathrm{Fe}\rangle_* \simeq \frac{\int(\alpha/\mathrm{Fe})(t)\psi(t)L_V^{\mathrm{SSP}}(t_0-t)\mathrm{d}t}{\int\psi(t)L_V(t_0-t)\mathrm{d}t} \tag{1}$$

i.e. it is the time integral of the interstellar (α/Fe) abundance over the SFH, represented by the star formation rate $\psi(t)$, multiplied by the luminosity $L_V^{\mathrm{SSP}}(t_0-t)$, which is the luminosity at epoch t_0 of a simple stellar population of unitary mass with an age of (t_0-t), and is given by SSP photometric models as a function of age and metallicity (BC03), divided by the present total luminosity.

In Fig. 1, we show the predicted α/Fe versus σ relation for our selected elliptical galaxies, considering four different cases. In Fig. 1, we report two different sets of data (Arrigoni et al. 2010; Spolaor et al. 2010), in order to have an idea on the uncertainty of the slope of the observed α/Fe–σ relation. In the standard case, we consider a model including ITS in the most massive galaxies and AGNs feedback. In the second case, we suppressed the ITS and consider AGN feedback alone. In the third case, we suppressed AGN feedback and consider ITS alone. Since the ITS consist of two components (merging and fly-by events), it may be interesting to separate these two processes in order to appreciate the importance of fly-by events. In the fourth case, we show our results obtained having suppressed AGN feedback and fly-by interactions, but considering only merger-triggered starbursts. In the standard case, the slope of the observed α/Fe–σ relation is satisfactorily reproduced. In the second and third cases, although with our model a correlation between α/Fe and σ is obtained, the predicted relation is considerably shallower than the observed one. In the fourth case, the predicted α/Fe–σ relation is overly flat with respect to the observations. The comparison between the third and fourth cases is essential to understand the major role of fly-by interactions in driving the correlation between α/Fe and σ.

4 DISCUSSION

Our results show that a standard CDM galaxy formation model including ITS, consisting in both merger-triggered and fly-by triggered starbursts, and AGN feedback can naturally lead to shorter star formation time-scales in larger galaxies, i.e. to star formation histories reversed with respect to their mass-assembly histories.

The absolute novel ingredient of our model consists in the simultaneous inclusion of both the starbursts triggered by fly-by events,

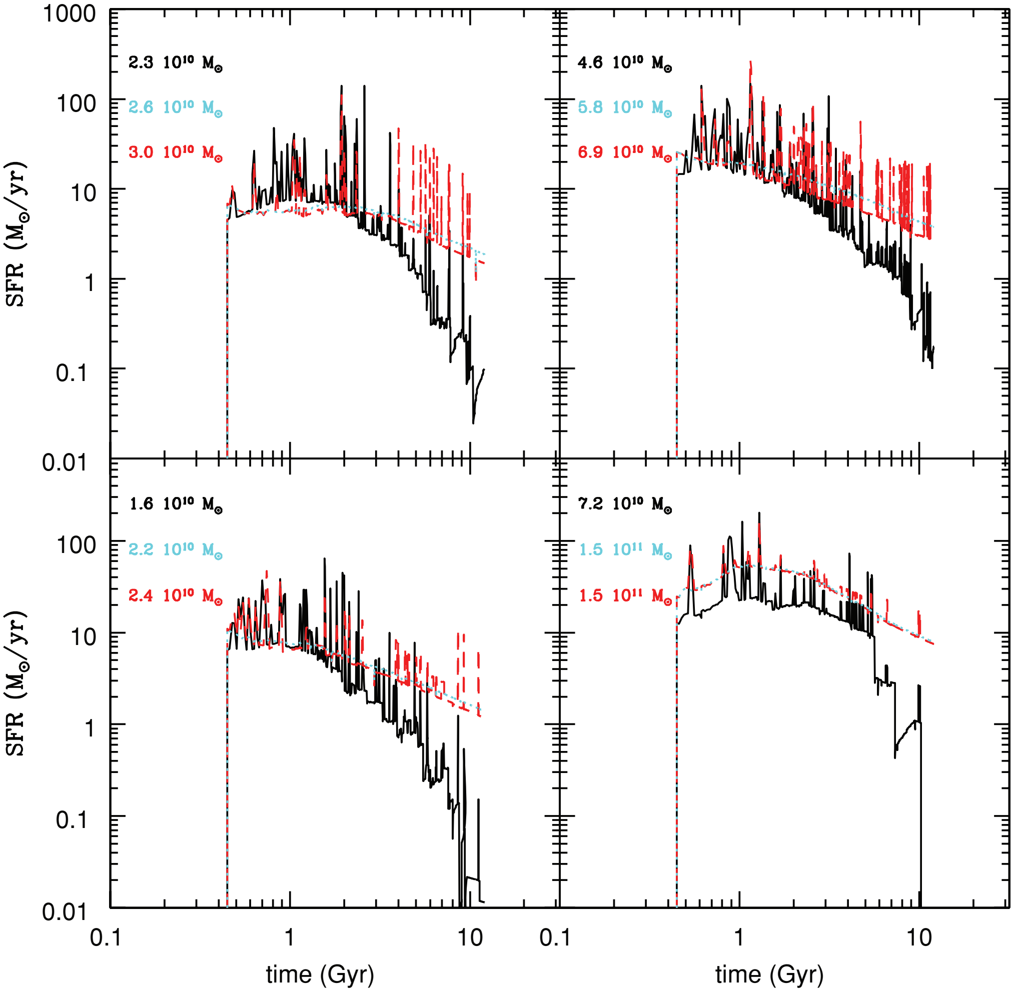

Figure 2. Star formation histories of a few early-type galaxies of our model. In each panel, we show the SFH of three galaxies drawn from the sample including ITS and AGN (solid black lines), including AGN but not ITS (cyan dotted lines) and including ITS but not AGNs (dashed red lines). In each panel, the three systems present the same merging history. The final stellar masses of the models are indicated in each panel. From top to bottom, the indicated masses refer to the standard case, the No ITS case and the No AGN case.

absent in any previous investigation of this fundamental property of early-type galaxies, and the AGN feedback related to the active Quasar phase of AGNs.

The general problem of quenching the star formation histories in massive galaxies has been investigated in several studies (e.g. Gabor et al. 2010) and is of great interest. Fig. 2 is useful to better understand how the features of our model act directly on the star formation histories of single galaxies. In each panel of this figure, we show the SFH of three galaxies drawn from the sample including ITS and AGN, including AGN but not ITS and from the one including ITS but not the effects of AGNs. The three galaxies shown in each panel present the same merger histories. It is worth to stress that in each case, the final stellar masses are not the same, since the inclusion of physical ingredient such as ITS and AGN can considerably alter the SFH and the feedback history of the systems. The final stellar mass of each model is reported in Fig. 2 (see caption for further details).

It is important to note that the suppression of ITS has effects also on the efficiency of the AGN feedback, since, according to the model used here and described in Menci et al. (2008), the cold gas which causes the ITS feeds also the nuclear activity. In fact, in every panel, both models without ITS and AGN present higher initial star formation rates with respect to the standard case. The explanation of this is that in both cases (no ITS and no AGN) the AGN is inefficient in heating and ejecting gas from the galaxies, resulting in higher amount of cold gas when the star formation has already turned on.

At the present time, the models which include ITS but without AGN feedback show SFR values larger than those shown by the ones drawn from the standard sample. Globally, their SFHs are less skewed towards early times with respect to the ones of the model with both AGN and ITS. The effects of AGNs in quenching the star formation activity within the first 3–4 Gyr is evident from this figure. Finally, the model with AGN but without ITS presents very extended SFHs, with rather flat and smooth behaviours and very high present-day values. Without the effect of ITS, gas consumption at early times is not very efficient and at later times, after a few Gyrs, the large amounts of cold star-forming gas prevent AGNs from being effective and quenching the star formation. It is therefore clear that, in order to have realistic star formation histories for early type galaxies, both effects of ITS and AGN feedback are necessary.

Both effects of AGN feedback and ITS seem to play an important role in determining galactic downsizing. However, the effect of the former seems slightly dominant, and this is supported by the fact that the predicted α/Fe–σ relation without ITS is slightly shallower than the one without AGN.

Our study of the α/Fe–σ relation tells us that our galaxy formation model can naturally account for one of the most important aspects of the 'downsizing' character of early-type galaxies. Downsizing (i.e. oldest stars are in most massive galaxies, star formation shifts to lower masses at late times) in hierarchical models will arise if there is a minimum mass required to have star formation and a maximum mass above which feedback from AGN suppresses further star formation (Sheth 2003; Croton & Farrar 2008). Together, these will also lead to an [α/Fe]–σ relation, since in principle, in such a scenario, the distribution of the formation timescales will be narrower for the stars forming in the most massive systems. In this framework, ITS help because it allows to use up more of the gas earlier, thus leaving less work to be done by the AGN feedback, and leading to a steeper [α/Fe]–σ relation. A detailed calculation of chemical abundances in more hierarchical models (such as the ones above) will be of further help in understanding the relevance of these processes with respect to the downsizing character of local galaxies.

It is important to stress that the observations can be reproduced without the modification of any fundamental chemical evolution parameter, such as the stellar IMF. However, it is worth to stress that such ingredient may play some role in determining the shape of the α/Fe–σ relation. In fact, although our unprecedented rendition of this relation, the predicted slope obtained with our standard model is slightly shallower than the observed one. This aspect will be investigated in our future work, and may have its explanation in effects such as a possible IMF dependence on the SFR and/or a flatter IMF in starbursts (Recchi, Calura & Kroupa 2009; Calura et al. 2010; Haas & Anders 2010). Some direct evidences in favour of the latter hypothesis come from observational studies of nuclear star clusters in the Milky Way (Bartko et al. 2010). Also dynamical investigations of early-type galaxies seem to require stronger baryonic feedback at the epoch of the formation of these systems, fully consistent with an IMF skewed towards more massive stars (Napolitano, Romanowsky & Tortora 2010), or from the study of local ultracompact galaxies (Dabringhausen, Kroupa & Baumgardt 2009). A top-heavy IMF at early times seems also required in order to reproduce the abundance ratios observed in the hot intracluster medium (Matteucci & Gibson 1995; Gibson & Matteucci 1997; Loewenstein & Mushotzky 1996).

In our previous work (C09), the average stellar abundance ratios have been calculated without taking into account the contribution of the single progenitors, i.e. by considering the total SFH of the selected galaxy, given by the sum of the star formation rates of all the progenitors, and considering an average interstellar α/Fe. In that paper, the observed α/Fe–σ relation could be partially explained by assuming a top-heavy IMF in the most massive galaxies, which mimics the effect of a higher star formation efficiency (or, in other words, a shorter star formation time-scale) in largest galaxies (Matteucci 1994; Matteucci, Ponzone & Gibson 1998; Ferreras & Silk 2003).

The largest galaxies have the most massive progenitors, which form all their stars in the shortest time-scales and dominate the integral of equation (1). This is the main reason why here, by considering the SFRs and the abundance ratios of each single progenitor, instead of a total SFR and an abundance averaged over all the progenitors, we can successfully reproduce the observed α/Fe–σ relation without any modification of the main chemical evolution parameters.

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