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Cosmic Chemical Evolution, r process and neutron star mergers

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Recent optical/IR/UV observations and Gamma-ray burst rate determinations have led to significant progress in constraining the star formation rate (SFR) at high redshift. The SFR is a fundamental quantity since it is used to predict, among others, the ionization history of the Universe, the evolution of the cosmic chemical abundances and the supernova rates as a function of the redshift. Such predictions are made here using a hierarchical model for structure formation. In this context, we focus our attention on the origin and evolution of a typical r process element, Europium, in two possible scenarios for the main astrophysical production site, namely core collapse supernovae (CCSN) and neutron star mergers (NSM). We find that this model favours NSM as the main r process site, specifically at low metallicity, and in addition, constrains the NSM time delay to $\sim$ 0.1–0.2 Gyr. On the other hand, the evolution of Eu abundances puts also a constraint on the merger rate, which allows an independent prediction of the expected merger rate in the horizon of the gravitational wave detectors advanced Virgo/ad LIGO, as well as a prediction for the expected rate of electromagnetic counterparts to mergers in large NIR surveys. Finally, while this model favors NSM as the main r-process site, more observations at very low metallicity and improved predictions from the nucleosynthetic evolution of massive stars are needed to confirm this result.

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1. Astrophysical and cosmological evolution

We follow the cosmic chemical evolution using a semi-analytical model for the structure formation in the cosmological context. The model is based on the standard Press-Schechter formalism [1] to account for non-linear structures. The model tracks baryons 1) in stars or their remnants within collapsed structures, 2) in gas within collapsed structures (the interstellar medium, ISM), and 3) outside of structures (the intergalactic medium, IGM). The model includes mass (baryon) exchange between the IGM and ISM, and between the ISM and the stellar component. The age t of the Universe is related to the redshift z by :

$$dt/dz = 9.78h^{-1}Gyr/(1+z)(\Omega_\Lambda + \Omega_\mathrm{m}(1+z)^3)^{0.5} \tag{1.1}$$

where we adopt for the cosmological parameters Ω_m = 0.27, Ω_Λ = 0.73 and H_0= 71 km/s/Mpc (h = 0.71). This allows to trace all the main observables as a function of the redshift. We consider here three SFR modes which are found to reproduce relatively well the main observations, i.e the SFR, the [Fe/H] evolution and the optical depth, as shown in Fig. 1. More specifically, the mode SFR1 corresponds to a standard SFR (0.1 <$M/M_\odot$< 100) with an additional Population III star component at high redshift (for stars with $M > 36M_\odot$), SFR2 to an enhanced SFR at high z and SFR3 to an upper limit of the SFR at high z. For each mode, the slope of the initial mass function is set to the Salpeter one (for more details, see [2]). As shown in Fig. 1, these three modes correspond to lower and upper values of the SFR with respect to observational data [3, 4, 5] and are all compatible with the evolution of the Fe abundance in Damped-Lyman Alpha (DLA) systems [6] and the Thomson optical depth of the cosmic microwave background (CMB) measured by WMAP [7]. Note that the population III contribution in the SFR1 mode is needed to describe the WMAP optical depth.

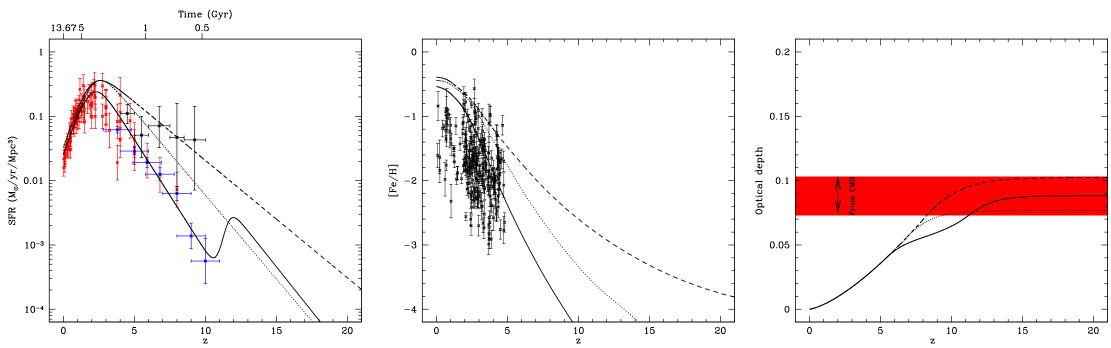

Figure 1: *Left panel*: Comparison, as a function of the redshift z, between the SFR adopted in the present work and observations from [3] (red points), [4] (cyan points) and [5] (black points). The solid line corresponds to SFR1, the dotted to SFR2 and the dashed to SFR3. *Middle panel*: Comparison between the [Fe/H] evolution predicted by the three SFR modes and DLA observations [6]. *Righ panel*: Comparison between the predicted optical depth evolution and the CMB observation by WMAP (red array) [7].

2. Cosmic evolution of Europium: CCSN vs NSM

In the past, CCSN was a promising site especially due to their potential to contribute to the galactic enrichment [8], however, they remain handicapped by large uncertainties associated mainly with the still incompletely understood mechanism that is responsible for the supernova explosion and the persistent difficulties to obtain suitable r-process conditions in self-consistent dynamical explosion and neutron-star cooling models [11, 9, 10].

More recent studies [12, 13, 14, 15, 16, 17, 19, 18] have reconsidered the chemical evolution of r-process elements in different evolutionary contexts, but have reached rather different conclusions.

More specifically, [12] explored the Eu production in the Milky Way using a local chemical evolution model. The relevance of the NSM scenario on the production of Eu has been studied by testing in particular the effect of the coalescence timescale of the binary system. Similarly, the CCSN scenario has been explored by considering different possible Eu yields. In this framework, NSM is found to be potentially a major r-process source if the coalescence timescale is short, of the order of 1 Myr.

In parallel, [13] investigated the chemical enrichment of r-process elements using a hierarchical galaxy formation model. The CCSN scenario is found to reproduce the scatter of observed r abundances in low metallicity stars if about 10% of CCSN is the dominant r-process source and the star formation efficiency amounts to about 0.1 per Gyr. For NSM, to be the main r-process site, a coalescence timescale of about 10-100 Myr with an event rate about 100 times larger than currently observed in the Galaxy need to be considered.

Finally, [19, 18] estimated the enrichment history of r-process elements in the Galaxy, as traced by the [Eu/Fe] ratio, using a high resolution cosmological zoom-in simulation. Unlike previous studies, it was found that the nucleosynthetic products from compact binary mergers can be incorporated into stars of very low metallicity and at early times, even with a minimum time delay of 100 Myr and that compact binary mergers could be the dominant source of r-process nucleosynthesis in the Galaxy.

Note that the results obtained in all these papers, in particular results related to the time delay of coalescence of NSM are somewhat different.

On the basis of the cosmic chemical evolution model described above, we now estimate the evolution of a representative r process element, Eu. In the CCSN scenario, we consider that all exploding stars eject a Eu yield of $5\ 10^{-8}\ M_\odot$. In the NSM scenario, three parameters need to be defined, namely, the amount of Eu ejected, the fraction of neutron stars (NS) in a binary system and the time delay of the merging. The Eu yield is set to $7\ 10^{-5} M_\odot$, which corresponds to a conservative value for the $7-20\ 10^{-5}\ M_\odot$ range in the different NSM models simulated in [20]; the NSM fraction is set to 0.002 and the coalescence timescale to values between 0.1 and 0.2 Gyr. As shown in Fig. 2, observations are rather well described by both scenarios, at least for metallicities [Fe/H] > -2.5. However, for [Fe/H] < -2.5, the Eu cosmic evolution clearly favours NSM as the main astrophysical site for the r process. CCSN clearly overproduce Eu at low metallicities (or high z), would it be the dominant r process source. The Population III component is seen in Fig. 2 to strongly overproduce Eu at very low metallicity ([Fe/H]<-4), though it does not affect the predictions in the NSM scenario due to the time delay of the merging. The CCSN can nevertheless be reconciled with observation if we assume that Eu is only produced in stars of metallicities $Z > 10^{-4}\ Z_\odot$.

Due to their time delay, NSM are seen to better describe the low-metallicity observations. Moreover, as shown in Fig. 2, this comparison can constrain the coalescence timescale. The

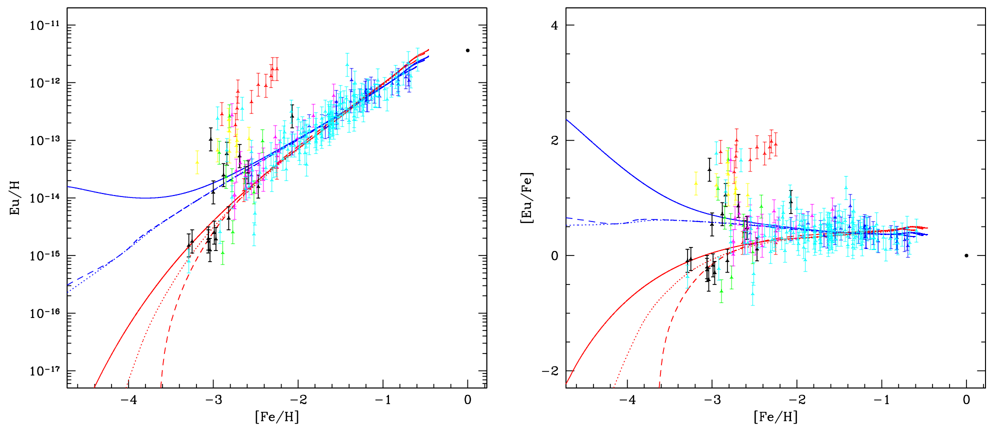

Figure 2: Evolution of Eu/H (left panel) and [Eu/Fe] (right panel) as a function of [Fe/H] for the three SFR modes and both CCSN and NSM scenarios. Blue lines represent the evolution of Eu in the CCSN progenitor case and red lines the NSM progenitor case. The solid line corresponds to SFR1, the dotted to SFR2 and the dashed to SFR3, with time delays of 0.2, 0.15, 0.1 Gyr, respectively in the NSM case. Observations are taken from Refs. [21, 22, 23, 24]. Upper limits coming from [21] and [25] are not included in these figures. For more details see [2].

timescale remains, however, rather sensitive to the early Fe enrichment in the Universe and consequently to the choice of the Fe yield coming from massive stars. The higher the Fe enrichment at early time, the shorter the time delay required. Our predictions show that the coalescence timescale is compatible with values of about 0.1 to 0.2 Gyr. Unfortunately, no Eu observations exist at [Fe/H] < -3.5 (contrary to other heavy elements like Ba); such observations could strongly help in further disentangling both scenarios and in determining the coalescence timescales. Improved predictions of Fe yields in CCSN, especially at zero metallicity, could also further constrain the cosmic evolution models.

3. Cosmological Merger Rate.

Within the same cosmic framework, it is possible to predict the cosmological NS-NS and NS-BH merger rates as a function of the redshift z and compare it to published predictions for gravitational wave detection. The merger rate within the horizon of advanced Virgo and LIGO has been studied in details in Ref. [26]. Our results, obtained in an independent method, are found to be in good agreement with these predictions, as shown in Fig. 3. For more details see again [2].

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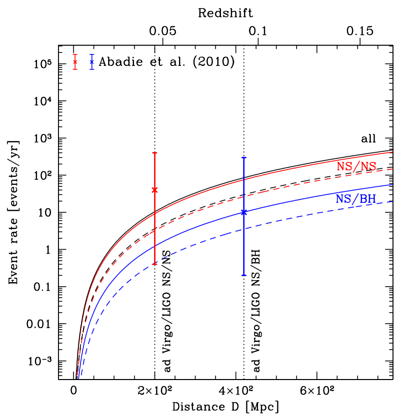

Figure 3: Integrated NS-NS (red), NS-BH (blue) and both (black) merger event rates as a function of z (or the distance D) for the three SFR modes (SFR2 and SFR3 results are very similar). Also shown are the predictions by [26].

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