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AGB Evolution and Nucleosynthesis at Low-Metallicity Constrained by the Star Formation History of Our Galaxy

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PoS(NIC XII)234

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We construct a binary population synthesis model to constrain the AGB evolution models from the star formation history of the Galaxy through the comparisons of model stars with observed extremely metal-poor stars. The binary population model includes the effects of AGB evolution and binary mass transfer for a given IMF and binary period distribution function. We discuss the origins of extremely metal-poor stars with enhancement of carbon or nitrogen, with the possible effect of mass loss at low-metallicity taken into account. Our results strongly support high-mass dominated star formation during the early epoch of the Galaxy in order to explain the observed frequency of carbon and nitrogen enhancements that are thought to result from mass transfer from a former AGB binary companion. Our model also favours the suppression of mass loss at low-metallicity to reduce the number of the possible progenitors of nitrogen-enhanced stars when we adopt a massive star dominated IMF.

PoS(NIC XII)234

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1. Introduction

Extremely metal-poor (EMP) stars (defined by [Fe/H] < -2.5) in the Galaxy can help to constrain the evolution of low-metallicity stars. Many observations have revealed a large frequency of carbon-enhanced stars among EMP stars (CEMP stars)[1]. It is also known that there is a subclass of CEMP star that does not show any enhancement of s-process elements (CEMP-no stars), which apparently contradicts the expectation of the binary pollution scenario whereby observed stars change their surface abundances by mass transfer from AGB stars with enhanced abundances of carbon and s-process elements (corresponding to CEMP-*s* stars)[2]. The apparent lack of nitrogen-enhanced EMP stars (NEMP stars) is also a problem because intermediate-mass AGB stars will contribute to the EMP population through binary mass transfer after CNO cycling during hot bottom burning, which occurs during the thermal pulsing phase.

In this paper, we explore the constraints on the evolution of EMP AGB stars using binary population synthesis. Our model includes the effect of AGB evolution and binary mass transfer for a given Initial Mass Function (IMF) and period distribution function of binaries. In particular, we emphasise the role of the suppression of mass loss at low-metallicity[3] because it significantly influences the yields of EMP AGB stars. It is currently believed that the IMF for the first stars dominates high-mass stars, which is quite different from the characteristics prescribed by the present-day IMF[4]. Our previous works suggested that there was a transition of the IMF in the early Galaxy[5, 6].

2. Models and assumptions

We modelled the stochastic formation of binary systems subject to the IMF, mass ratio function, and binary period distribution function using Monte-Carlo approach. Simulations are performed for each metallicity, from [Fe/H] $= -6$ to -1 in 0.5 dex steps. The model parameters for the binary population are the same as in [5] while the IMF is a log-normal distribution with a peak at $10M_\odot$ and dispersion of 0.4 or a power law distribution with slopes of $x = 0, -0.35, -0.85$, and -1.35. The mass ratio function is taken from the data for nearby main sequence stars [7, 8]. Period distribution functions are also taken from the literature [7, 8, 9]. The distribution of these quantities are shown in Figure 2.

AGB yields are taken from the model calculations to cover the entire mass and metallicity range[10, 11, 12]. Binary mass transfer by wind accretion or Roche-Lobe overflow is followed depending on the masses and separation of the system according to [13, 14]. For wind accretion, we assumed instantaneous mass transfer at the end of the dredge-up of carbon by the helium-flash driven deep mixing (He-FDDM) [15, 16] or the third dredge-up in the last model.

In our models, the mass and metallicity ranges of the progenitors for CEMP-*s*, CEMP-no, and NEMP stars are treated as parameters based on results of stellar evolution. For the formation of CEMP-*s*, the He-FDDM at [Fe/H] ≤ -2.5 and the third dredge-up at [Fe/H] > -2.5 are assumed to be responsible, while the third dredge-up is assumed to be the source of CEMP-no at [Fe/H] ≤ -2.5. NEMP stars are produced by the hot bottom burning at any metallicity range, while it is suppressed by the effect of mass loss at [Fe/H] ≤ -2.5. In the fiducial model, we set the lower boundary for the third dredge-up and hot bottom burning at $1.5M_\odot$ and $4.5M_\odot$, respectively, inde-

PoS(NIC XII)234

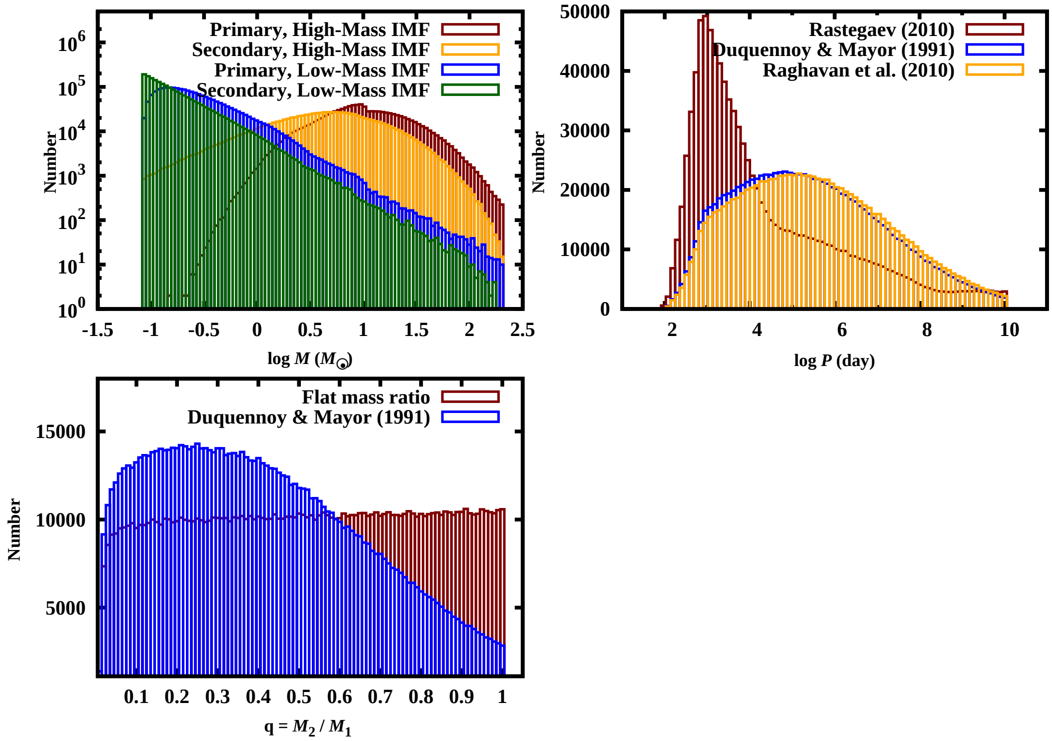

Figure 1: Demonstration of the simulation of binary systems. The total number of binary systems for given metallicity is set at one million for high-mass IMF and two millions for low-mass IMF in this figure. The distributions of the mass of primary and secondary stars are shown in the top left panel. The bottom left panel shows the distribution of the binary mass ratio. The top right panel shows the period distribution functions adopted in our simulations.

pendent of metallicity. The He-FDDM is assumed to occur for models with $0.8 \leq M/M_\odot \leq 3.5$ and with [Fe/H] ≤ -2.5. We consider the effect of type 1.5 supernovae as a result of the suppression of mass loss at low-metallicity [3]. The boundary mass and metallicity for this event are set at $5 \leq M/M_\odot \leq 8$ and [Fe/H] ≤ -2.5. A novel finding of our study is that a significant contribution from Type 1.5 supernovae is expected due to the suppression of mass loss from intermediate-mass AGB stars.

Models are compared with metal-poor giants in the SAGA database [17] and the SDSS sample [18]. We picked up comparison stars in the mass range of $0.82 \leq M/M_\odot \leq 0.83$ from our simulations that are representatives of currently surviving halo giants. The details of the models are described in a forthcoming paper (Suda et al., in prep.).

3. Results and discussion

Figures 2 shows the comparisons of the frequency of CEMP stars as a function of metallicity for different period distribution functions and for different adopted IMFs. The models show that the CEMP/EMP frequency increases with decreasing metallicity, in reasonable agreement with observations.

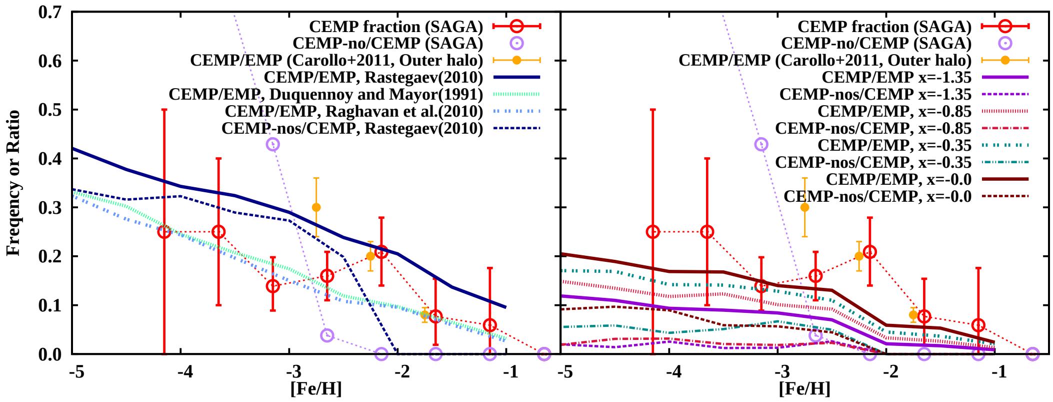

Figure 2: CEMP star frequency as a function of metallicity. Comparisons are made for different period distribution functions (left panel) and IMFs (right panel). The observed frequency of carbon-enhanced stars are taken from the SAGA database[17] and from the SDSS sample[18]. The error bars are estimated by bootstrap method. The fraction of CEMP-no to CEMP is also compared for EMP population.

The left panel of Figure 2 shows that our log-normal IMF is consistent with both the observed CEMP/EMP and CEMP-no/CEMP ratios at [Fe/H] ≤ -2. This is due to the suppression of mass loss for intermediate-mass stars, which can reduce the number of NEMP stars. As seen in the right panel of Figure 2, CEMP/EMP ratio at [Fe/H] ≤ -2 can be reproduced by a flat IMF except at [Fe/H] $= -2.5$, but the ratio of CEMP-no to CEMP disagrees with the observations. Our preliminary trial to find a solution that is consistent with observations, by changing parameters, turned out to be unsuccessful because the number of CEMP-no progenitors is too small to be consistent with observations. Our tentative conclusion is that, in any IMF we adopted, a transition of the IMF is required to account for the entire trend of CEMP frequency. This result supports the previous speculation by [19] that the IMF change should occur at [Fe/H] ~ -2.

For any choice of the IMF, mass loss at low-metallicity is a very important factor to determine the fraction of CEMP subclasses. More detailed discussions and robust conclusions will be given in a forthcoming paper (Suda et al., in prep.).

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PoS(NIC XII)234