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Evolution and nucleosynthesis of primordial very massive stars

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Abstract. We present evolutionary models of zero-metallicity (Pop-III) very massive objects (VMOs) , with initial masses in the range 120 $M_\odot$ – 1000 $M_\odot$. In the attempt of exploring the possible occurrence of mass loss by stellar winds, calculations are carried out with suitable formalisms for the mass-loss rates driven by radiation pressure and stellar rotation. The corresponding wind chemical yields are presented. Finally, with the aid of a simple chemical model, the primordial helium and metal enrichments, and the resulting $\Delta Y/\Delta Z$ ratio are discussed.

Key words. stars: evolution – stars: mass loss – cosmology: early Universe

1. Evolutionary calculations

This work (see also Marigo et al. 2002, in preparation) completes the analysis of zero-metallicity stars started with Marigo et al. (2001), to whom we refer for all the details. Suffice it here to recall a few relevant prescriptions:

- An initial helium content of $Y = 0.23$
- Overshooting from stellar convective cores
- The network of nuclear reactions (pp-chain and CNO tri-cycle, and the most important alpha-capture reactions) is implicitly solved without any assumption for nuclear equilibria
- Evolutionary calculations cover the nuclear phases of H- and He-burning up to central carbon ignition.

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2. Mass loss

We consider two possible stellar-winds driving mechanisms, namely:

- Radiation-driven mass loss following Kudritzki's (2002) prescription

  $$\dot{M}_{\rm rad} = func(L, T_{\rm eff}, Z, {\rm fms}) \qquad (1)$$

  that expresses the rate as a function of stellar luminosity, effective temperature, metallicity, and force multipliers (fms) of the Castor et al. (1975) formalism.
- Rotation-driven mass loss according to Maeder & Meynet's (2000) recipe

  $$\dot{M}(v_{\rm rot}) = F_\Omega \times \dot{M}_{\rm rad} \ , \qquad (2)$$

  with the enhancement factor defined by

  $$F_\Omega = \frac{(1-\Gamma)^{\frac{1}{\alpha}-1}}{[1-(T_\Omega+\Gamma)]^{\frac{1}{\alpha}-1}} \ , \qquad (3)$$

Γ is the Eddington factor for electron screening opacity, Ω is the angular velocity, and α is the force multiplier describing the slope of the line-strength distribution. The effect of rotation is contained in the term

$$T_\Omega = func\left(\frac{v_{\rm rot}}{v_{\rm crit}}\right) \,, \qquad (4)$$

where $v_{\rm rot}$ is the rotational velocity, and $v_{\rm crit}$ is the break-up velocity.
At each time step, the current $v_{\rm rot}$ is derived under the assumptions of rigid-body rotation and conservation of the current angular momentum. The critical condition of $\Omega\Gamma$-limit corresponds to the vanishing of the net acceleration due to gravitational, radiative, and centrifugal forces. In this case F_Ω diverges, implying extremely high $\dot{M}$. We assume $\dot{M}_{\rm crit} = 10^{-3}\,{\rm M}_\odot\ {\rm yr}^{-1}$.

3. Yields and primordial chemical enrichment

As by-product of our calculations, we have estimated the wind ejecta in the form of newly synthesised He and CNO elements. It turns out that the yields expelled through radiative/rotational winds are practically negligible for all masses, except for $M = 750,\ 1000\,{\rm M}_\odot$. By combining the supernova yields available in the literature with our predicted wind contributions, We have calculate the helium and metal enrichments (ΔY and ΔZ) produced by a population of (very) massive zero-metallicity stars, with $M \geq 10\ M_\odot$, i.e. assuming that the primordial IMF favoured the formation of massive stars, as supported by current models of primeval cloud fragmentation (e.g. Bromm et al. 2002). A very simple chemical model is assumed: stars formed in a single burst from a primeval cloud, that is assimilated to a closed box system, chemical enrichment is considered instantaneous with the burst and homogenised throughout the gas.

4. Conclusions

- Line-radiation transfer, usually at work in massive stars of 'normal' chemical composition, should be a little efficient mass-loss driving mechanism in (very) massive primordial stars, except at the largest masses, say $\gtrsim 500\ {\rm M}_\odot$.
- Stellar rotation, instead, could cause the ejection of significant amounts of mass in correspondence to the $\Omega\Gamma$-limit, that is more easily reached at zero metallicity. However, the net impact on mass loss should be quite limited, given the extremely short time during which these critical regimes can be maintained.
- Pop-III MOs and VMOs may have produced a significant helium enrichment, $\Delta Y \sim 0.01$, if the fractional mass of the primordial gas converted into stars was of the order of few 0.01 up to 0.1. These values are consistent with indications from dynamical models of galaxy formation and chemical evolution of the IGM. The corresponding metal enrichment would be $\gtrsim 10^{-3}$, consistent with metallicity determinations in high-redshift Lyman-break galaxies.
  On the other hand, assuming an upper limit $Z_{\rm max} \approx 10^{-5}$ as suggested by Pop-II Halo stars, a much lower star formation efficiency, of the order of 10^{-4}, seems to be required in order to prevent an overproduction of metals.

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