First stars as a possible origin for the helium-rich population in ω Cen

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ABSTRACT

The most massive Galactic globular cluster ω Cen appears to have two, or perhaps more, distinct main sequences. Its bluest main sequence is at the centre of debate because it has been suggested to have an extremely high helium abundance of $Y \sim 0.4$. The same helium abundance is claimed to explain the presence of extreme horizontal branch stars of ω Cen as well. This demands a relative helium to metal enrichment of $\Delta Y/\Delta Z \sim 70$; that is, more than one order of magnitude larger than the generally accepted value. Candidate solutions, namely, AGB stars, massive stars, and supernovae, have been suggested; but in this study, we show that none of them is a viable channel, in terms of reproducing the high value of $\Delta Y/\Delta Z$ for the constrained age difference between the red and blue populations. Essentially no populations with an ordinary initial mass function, including those candidates, can produce such a high $\Delta Y/\Delta Z$ because they all produce metals as well as helium. As an alternative, we investigate the possibility of the stochastic “first star” contamination to the gas from which the younger generation of ω Cen formed. This requires the assumption that Population III star formation episode overlaps with that of Population II. While the required condition appears extreme, very massive objects in the first star generation provide a solution that is at least as plausible as any other suggestions made before.

Key words: galaxies: globular clusters — individual (ω Centauri)

1 INTRODUCTION

The most massive Galactic globular cluster, ω Cen, shows a double (or more) main sequence in the colour-magnitude diagrams (CMD), with a minority population of the bluer main sequence (bMS) and a majority population of redder MS (rMS) stars (Anderson 1997; Bedin et al. 2004). The interpretation of the bMS by a huge excess in the helium abundance ($Y \sim 0.4$) has been suggested via CMD fittings (Norris 2004) and supported by the spectroscopic study on the bMS stars (Piotto et al. 2005). The extreme helium abundance is claimed to explain the extremely-hot horizontal-branch (HB) stars of ω Cen as well (Lee et al. 2005).

The helium-enhancement parameter $\Delta Y/\Delta Z$ required to explain the sub-population of ω Cen are $\sim 70$, more than an order of magnitude larger than the currently-accepted value, 1–5 (Fernandes et al. 1996; Pagel & Portinari 1998; Jimenez et al. 2003). To explain this, several possible polluters, i.e., AGB stars, stellar winds associated with massive stars during their early evolutionary phases and type II supernovae (SNe II) have been suggested (e.g. Norris 2004; D’Antona et al 2005). However, Bekki & Norris (2006) show that these candidates cannot reproduce such a high helium abundance for reasonable initial mass functions (IMFs) within the scheme of a closed-box self-enrichment.

The acute point is not the high helium abundance itself but the high value of $\Delta Y/\Delta Z$, because populations containing those candidates produce a large amount of metals as well as helium according to canonical stellar evolution models. Maeder & Meynet (2006) have recently suggested that “moderately” fast-rotating massive ($\sim 60 M_\odot$) stars expel helium-dominant gas into space and thus could provide a solution to this problem. We show that this scenario provides a viable solution only if additional conditions on the mixing and escaping of metals are invoked.

As an alternative solution, we investigate the possibility that the late generation of “the first stars” (Population III) might affect the chemical mixture of the minority of Population II stars. We are particularly inspired by the work of Bromm & Loeb (2006) that suggested an overlap between the Population III and II star formation episodes. The chemical yields of such supposedly-heavy, zero-metal stars have been computed by Marigo, Chiosi, & Kudritzki (2003). We present in this Letter the result of our investigation.
2 CHEMICAL EVOLUTION MODELS

In order to investigate the pattern of the helium enhancement in a population, we employ a simple chemical evolution code and a realistic initial mass function (IMF). We describe a simple chemical enrichment model essentially following the formalism of Ferreras & Silk (2000) and reduce a set of a few parameters following the formalism of Tinsley (1980) and reduce a set of a few parameters following the formalism of Tinsley (1980). A two-component system is considered, consisting of cold gas and stellar mass. The net metallicity \( Z \) and helium content \( Y \) of two systems are traced. We assume instantaneous mixing of the gas ejecta from stars and instantaneous cooling of the hot gas component. The mass in stars, \( M_s(t) \) and in cold gas, \( M_g(t) \), are normalised to the initial gas mass,

\[
\mu_s(t) = \frac{M_s(t)}{M_s(0)} \quad \mu_g(t) = \frac{M_g(t)}{M_g(0)}
\]

where the initial states of the galaxy is assumed to be completely gaseous without stars: \( \mu_s(0) = 0 \).

A Schmidt-type star formation law (Schmidt 1963) is assumed:

\[
\psi(t) = C_{\text{eff}} M_s^p(t)
\]

where the parameter \( C_{\text{eff}} \) implies the star formation efficiency. We assume \( n = 1 \), that is, a linear law \( \psi(t) = C_{\text{eff}} M_s(t) \).

Exponential infall of primordial gas is assumed:

\[
f(t) = \Theta(t - \tau_{\text{inf}}) A_{\text{inf}} e^{-(t - \tau_{\text{inf}})/\tau_{\text{inf}}}
\]

where, \( \Theta(t) \) is a step function. The parameters \( A_{\text{inf}}, \tau_{\text{inf}}, \) and \( \tau_{\text{inf}} \) are the infall rate, timescale, and delay, respectively. In order to explain the G-dwarf problem (Tinsley 1980), gas infall has been considered as a solution (Larson 1972).

Some cold gas is heated to high temperature by supernovae and/or AGN and can be driven out: outflows. It is also an important factor to the final chemical properties of galaxies (Larson 1974; Arimoto & Yoshii 1987). We use a free parameter \( B_{\text{out}} \) that represents the fraction of gas ejected following the formalism of Ferreras & Silk (2000). This parameter should be a factor of the mass of the galaxy, whose potential well determines whether the winds are strong enough to escape its gravitational potential.

There are five input parameters: \( C_{\text{eff}}, B_{\text{out}}, A_{\text{inf}}, \tau_{\text{inf}}, \tau_{\text{lag}} \) with the following initial conditions: the initial metallicity \( Z_0 = 10^{-4} \) and the initial helium of stars and gas \( Y_0 = 0.235 \), the IMF slopes and cutoffs.

2.1 Mass Evolution

The evolution of gas mass is given by

\[
\frac{dM_g}{dt} = (1 - B_{\text{out}}) E(t) - C_{\text{eff}} \mu_g(t)
\]

\[
+ \Theta(t - \tau_{\text{lag}}) A_{\text{inf}} e^{-(t - \tau_{\text{lag}})/\tau_{\text{inf}}}
\]

where the stellar mass ejecta \( E(t) \) is defined as

\[
E(t) = \int_{m_1}^{\infty} dm \phi(m) (m - w_m) C_{\text{eff}} \mu_g(t - \tau_m).
\]

for a star with main sequence mass \( m \), \( w_m \), is adopted from Ferreras & Silk (2000).

2.2 Chemical Evolution

The chemical evolution of gas is given by

\[
\frac{d(Z_{\mu_g})}{dt} = -C_{\text{eff}} Z_g(t) \mu_g(t) + (1 - B_{\text{out}}) E_Z(t)
\]

\[
+ \Theta(t - \tau_{\text{lag}}) Z_f A_{\text{inf}} e^{-(t - \tau_{\text{lag}})/\tau_{\text{inf}}}
\]

\[
E_Z(t) = \int_{m_1}^{\infty} dm \phi(m) C_{\text{eff}} [(m - w_m)(Z_g\mu_g)(t - \tau_m)]
\]

\[
+ m_p \mu_g(t - \tau_m),
\]

where \( p_m \) denotes the mass fraction of a star of mass \( m \) that is newly converted to metals or helium and ejected. We approximate it by a polynomial fit to the \( p_m \) prediction of Maeder (1992). In Figure 1, we show Maeder’s chemical yields for metal-poor (\( Z = 0.001 \)) stars and our fitting functions. For our reference model, we use these chemical yields.

We also show the metal yields of extremely metal-poor (\( Z = 0.00001 \)) rotating stars (Maeder & Meynet 2006) in dotted line. Maeder & Meynet computed the yields for 60 \( M_{\odot} \) stars, and in order to demonstrate their effects to the \( \Delta Y/\Delta Z \) of an integrated population, we set up an extreme assumption that the newly-proposed metal yields may be applicable to all heavy stars of \( M \geq 50 \).

The crucial point shown here is that canonical stellar models produce and spread into space metals as well as helium. No combination of these stars can produce \( \Delta Y/\Delta Z \) that exceeds the value of the constituent stars. The rotating metal-poor massive star models by Maeder & Meynet (2006) are exception and indeed can produce high values of \( \Delta Y/\Delta Z \). So we explore below whether a population including such stars can indeed present a solution to our problem.

SN Ia are generally considered important in chemical evolution studies because they eject a considerable amount of iron-peak elements: \( \sim 0.7 M_{\odot} \) (Tsujimoto et al. 1995). For our exercise, we have tried the most up-to-date SN Ia rate of Scannapieco & Bildsten (2005), consisting of two components: star formation rate and the total stellar mass of the system. The contribution by SN Ia is negative to our study because they are copious producers of metals. We remove its effects for simplicity.

We have found that gas infall or outflows of the processed material have negligible impacts on \( \Delta Y/\Delta Z \) unless specific chemical elements alone (e.g., helium or metals) are affected. Hence, only the closed-box model is considered.

The star formation efficiency parameter \( C_{\text{eff}} \) has a small effect. When a range \( C_{\text{eff}} = 0.1 \) – \( 5.0 \) Gyr\(^{-1} \) is considered, a population can reach \( \Delta Y/\Delta Z \approx 1 - 2 \) after a 1 Gyr evolution. We show a typical case of \( C_{\text{eff}} = 1 \) in Figure 2 as a solid line. The value of our reference model is consistent with the most recent observational mean value of the helium enrichment parameter of the galactic gas.

Having failed to recover the high \( \Delta Y/\Delta Z \) in the standard chemical enrichment model, we consider the stochastic effect in the helium yields \( p_{m,Y} \). We assume that the stars in a specific mass range can have larger values of \( p_{m,Y} \) than the current stellar physics suggest.

Fig. 2 presents part of the result of the stochastic-effect test, where \( C_{\text{eff}} = 1 \) is assumed; (1) when \( p_{m,Y} \) is doubled...
for all the stars, (2) when \( p_{m,Y} \) is doubled for 6–10 \( M_\odot \) stars, maximising the AGB effect, and (3) when \( p_{m,Y} \) is doubled for 40–50 \( M_\odot \) stars, allowing the SN II effect to dominate. Lastly, the triple-dot dashed line is for the model where all heavy stars (\( M \geq 50 \)) are fast-rotating showing yields of Maeder & Meynet (2006). Because instant recycling of chemical elements is unrealistic, we use the chemical mixing time scale of 50 Myr.

The \( \Delta Y/\Delta Z \) after a 13 Gyr evolution of the AGB-dominant system is merely ~ 2 times greater than that of the reference system. The effect is even smaller for the SNe II dominant system. Even if we double the values of \( p_{m,Y} \) for all stars, the system could attain only \( \Delta Y/\Delta Z \approx 4 \). But of course, for our purpose, we need a much higher helium enrichment within a much shorter timescale (\( \approx 1 \) Gyr).

Doubling the helium yields is ad hoc and hard to justify in terms of nucleosynthesis. Even in this unphysical test, however, the stochastic effect does not help us achieve the high \( \Delta Y/\Delta Z \). This is because (1) ordinary stars produce and spread into space not only helium but also metals and (2) most notably in the case of the “Maeder & Meynet case”, there are many more low-mass stars in the ordinary IMF than massive stars.

Other possible contributing factors, e.g., IMF slope and the remnant mass \( m_w \), also have some influence. One may wonder about the effect of radically-different IMFs (e.g., with a reversed slope). This indeed would produce more helium but even more metals in ordinary stellar populations, hence in fact lowering the resulting value of \( \Delta Y/\Delta Z \). On the other hand, a reversed IMF slope would dramatically increase \( \Delta Y/\Delta Z \) in the “Maeder & Meynet case”. However, this should not be common because otherwise all populations with massive stars should have enhanced helium.

When assuming that the helium enrichment of bMS of \( \omega \) Cen is due to the ejecta from the rMS formed earlier, the candidate solution is even more severely constrained. For example, low-mass stars which produce mainly helium can generate high values of \( \Delta Y/\Delta Z \) up to \( \approx 8 \) but they take much too long to spread the processed materials into space, when compared to the age difference between the two subsystems in \( \omega \) Cen, i.e., 1–2 Gyr (Lee et al. 2005). Any star whose lifetime is longer than this would have no impact at all.

The “Maeder & Meynet case” is noteworthy as it is the only scenario where high values of \( \Delta Y/\Delta Z \) can be achieved during a short period of time. Assuming all stars form simultaneously in a population, \( \Delta Y/\Delta Z \) can be as high as we need during the first few Myr until intermediate-mass stars begin to spread a large amount of gas into space. In this sense, this scenario provides a solution if the bMS population of \( \omega \) Cen is only slightly younger than its rMS population. However, the time window (\( \sim 10^7 \)–\( 10^8 \) yr) for this to happen is very small compared to the constraint from CMD studies (Lee et al. 2005). The possibility of difference in the effect of stellar wind for helium and metals demands further studies, and the role of the local black hole accretion on metals may also be noteworthy (Maeder & Meynet 2006).

3 VERY MASSIVE OBJECTS

We finally explore the plausibility of the “first” Pop III star pollution. The first stars in the universe are thought to have formed out of the metal-free gas at redshifts \( z \geq 10 \) (Bromm & Larson 2004; Ciardi & Ferrara 2005). These Pop III stars are often predicted to be very massive, \( M \gtrsim 100 \) \( M_\odot \) (Bromm, Coppi & Larson, 2002; Abel, Bryan & Norman...
Figure 3. (Top) Filled circles represent the $p_{m,Y}$, $p_{m,Z}$, newly synthesized and ejected helium or metal mass fraction, calculated from yields of Marigo et al. (2003) for 120, 250, 500, 750 and 1000 $M_\odot$ VMOs. Dotted line implies linear interpolation of given 5 points in logarithmic scale. (Bottom) The $\Delta Y/\Delta Z$ of each mass of VMOs

We have calculated the chemical enrichment evolution of the closed-box system made only of VMOs. Marigo et al. (2003) give the evolutionary properties of VMOs including lifetime, helium and metal yields, carbon and helium cores at central C-ignition and mass loss for 120–1000 $M_\odot$. Two different mass loss rates are considered by them: the radiation-driven mass-loss model and the rotation-driven model. The yields and mass loss rates of the two models are slightly different from each other, and we use the rotation-driven model because it produces a larger amount of helium. We find linear fits to these yields in the logarithmic scale (Fig. 3) and show the resulting $\Delta Y/\Delta Z$ for each mass of VMO. The helium enrichment parameter of VMOs ranges 63 – 1.6×10^7!

Figure 4. The mass-cut dependence of $\Delta Y/\Delta Z$ of the ejecta from VMOs. We constrain high mass cut of IMF as 1000 $M_\odot$ and IMF slope as canonical value, $x = 1.35$. The system consisting of 120–1000 $M_\odot$ VMOs with Salpeter IMF slope results in $\Delta Y/\Delta Z \sim 520$ and 995–1000 $M_\odot$ system produces $\Delta Y/\Delta Z \sim 72$.

We have calculated $\Delta Y/\Delta Z$ for a population of VMOs with various mass cuts and IMF slopes. The $\Delta Y/\Delta Z$ value after the 1 Gyr evolution in a closed-box system varies with IMF slope and mass cut. The values of $\Delta Y/\Delta Z$ as a function of lower mass cut are shown in Fig. 4. We fix the high mass cut as 1000 $M_\odot$ assuming the Salpeter IMF. The resulting range of $\Delta Y/\Delta Z$ after 1 Gyr of evolution is two orders of magnitude higher than that of an ordinary system. Our model matches the values of both $Y$ ($\sim 0.4$) and $\Delta Y/\Delta Z$ ($\sim 70$) at age $\sim 1$ Gyr suggested for the bMS sub-population, as marked in Fig. 5. Interestingly the solution suggests $M(VMO) \sim 995–1000 M_\odot$; but considering the uncertainty in the VMO yields, it may not be significant.

Figure 5. Chemical evolution in the gas of the VMO system for different values of star formation efficiency. The values of helium and $\Delta Y/\Delta Z$ of the bMS population of $\omega$ Cen are marked (squares) in each panel.

4 DISCUSSION

By means of a simple chemical evolution test, we conclude that ordinary populations cannot produce $\Delta Y/\Delta Z$ much greater than 4. None of the candidates succeeds in reproducing the large helium enrichment claimed for the blue MS stars of $\omega$ Cen. The reason for this is simple: the evolution of ordinary stars result only in a modest value $\Delta Y/\Delta Z \sim 1–5$. We confirm the result of Karakas et al. (2006) who rejected the AGB solution on a similar ground. The massive rotating star models of Maeder & Meynet (2006) reach high values of $\Delta Y/\Delta Z$, but it is difficult to maintain the high value longer than a few Myr in a population with a realistic mass spread.
We present Pop III very massive objects (VMOs) as an alternative solution. They produce both the helium abundance and the helium-to-metal ratio searched for at the age $t \approx 1$ Gyr demanded by the observational constraint. This scenario requires an overlap between the star formation episodes of Pop III and Pop II. Suppose that $\omega$ Cen formed in the era of overlap of Pop III and Pop II formation. Earlier generations of Pop III stars form and their mass ejecta are mixed in the short timescale of roughly $10^{-8}$ yrs. First generation of Pop II stars start forming globally (this is not part of $\omega$ Cen) and the processed gas gets recycled and mixed in the proto-system until the gas reaches $<Z> \sim 0.001$. By now, the mixed mean helium abundance is not any more extraordinary but with severe irregularities. The $rMS$ population of $\omega$ Cen forms with the mean chemical composition. A group of Pop III VMOs form in the tail of the Pop III episode nearby out of a pristine (irregularity) gas cloud. Soon after this, that is, before their ejecta are mixed fully, the younger stars of $\omega$ Cen ($bMS$) form under the heavy influence of this helium-rich ejecta. After the dynamical relaxation, the two chemically-distinct populations could be in one system. Since this is a geographic and chronological stochastic effect, it would not be significant in the galactic scale.

The plausibility of our scenario strongly depends on the validity of Marigo et al.’s yields. Other groups have computed the yields for zero-metallicity VMOs (e.g. Bond et al. 1984; Ober et al. 1983; Klapp 1984), and Marigo et al.’s yields are not in a smooth continuation with the yields of low-mass zero-metal stars given by Limongi & Chieffi (2002). The discontinuity may not be a big issue if the mass loss in VMOs may happen in an extreme fashion (Smith 2006). Considering the acute dependence of our conclusion on the reliability of the chemical yields, it is urgent to perform detailed independent stellar evolution modelling for VMOs.

The second question about this scenario is on the condition of VMO formation. The Pop II star formation is allowed in the broad regions of Pop III objects (Tsujimoto et al. 1999; Susa & Umemura 2006). The $bMS$ population of $\omega$ Cen has $\sim 30\%$ of the cluster mass (Lee et al. 2005). Assuming $M_{tot} \sim 10^5 \, M_{\odot}$, the helium-rich population mass would be $M_{bMS} \sim 3 \times 10^5 \, M_{\odot}$. Assuming the primordial helium abundance is $23\%$, $17\%$ of the $bMS$ population mass, $M_{Hel} \sim 5 \times 10^4 \, M_{\odot}$, is the newly-generated helium mass. To generate $5 \times 10^4 \, M_{\odot}$, pure helium from $1000 \, M_{\odot}$ VMOs, we need at least $\sim 200$ VMOs simultaneously. However, Abel, Bryan, & Norman (2002) suggest that metal-free stars form in isolation due to the immense radiation from the first-forming star. Moreover, such a large number of Pop III stars forming close to each other, if that is possible at all, would make the site extremely hostile for the younger generation of $\omega$ Cen to form. This poses serious challenges to our scenario. By definition, this stochastic effect works only on small scales and not in the galactic scale. But the number of VMOs required would be smallest in the deepest local gravitational potential, which means that this rare event of achieving a high $\Delta Y/\Delta Z$, would prefer larger gravitationally-bound objects, such as massive globular clusters rather than small ones.

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