THE ORIGIN OF THE DOUBLE MAIN SEQUENCE IN ω CENTAURI: HELIUM ENRICHMENT DUE TO GAS FUELING FROM ITS ANCIENT HOST GALAXY?

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ABSTRACT

Recent observational studies of ω Centauri by the Hubble Space Telescope have discovered a double main sequence in the color-magnitude diagrams (CMDs) of its stellar populations. These observations suggest that the stellar population with the blue main sequence (bMS) has a helium abundance much larger, by ΔY ∼ 0.12, than that of the red main sequence (rMS). By using somewhat idealized models in which stars of the bMS are formed from gas ejected from stars of the rMS, we quantitatively investigate whether the helium overabundance of the bMS can result from self-enrichment from massive AGB stars, from mass loss of very massive young stars, or from Type II supernovae within ω Centauri. We show that as long as the helium enrichment is due to ejecta from the rMS formed earlier than the bMS, none of these three enrichment scenarios can explain the observed properties of the bMS self-consistently for reasonable IMFs. The common, serious problem in all cases is that the observed number fraction of the bMS cannot be explained without assuming unusually top-heavy IMFs. This failure of the self-enrichment scenarios implies that most of the helium-enriched gas necessary for the formation of the bMS originated from other external sources. We thus suggest a new scenario, in which most of the second generation of stars (i.e., the bMS) in ω Centauri could have formed from gas ejected from field stellar populations that surrounded ω Centauri when it was the nucleus of an ancient dwarf galaxy.

Subject headings: globular clusters: general — globular clusters: individual (ω Centauri)

1. INTRODUCTION

One of the most remarkable results of recent observational studies of ω Centauri is that it shows a double main sequence (DMS) in the color-magnitude diagrams (CMDs) of its stellar populations (e.g., Anderson 1997; Bedin et al. 2004). Bedin et al. (2004) proposed four possible scenarios for the origin of the DMS: (1) theoretical isochrone models or data calibration are in error; (2) stars on the bluer main sequence (bMS) of the DMS are a super-metal-poor ([Fe/H] ≲ −2.0) population; (3) the bMS represents a very helium-rich (Y ≥ 0.3) population; or (4) the bMS represents a background stellar population about 1–2 kpc behind ω Centauri. A number of recent investigations have suggested that scenario 3 (hereafter referred to as the “helium pollution scenario,” or HEPS) is the most promising among the four (e.g., Lee et al. 2005; Norris 2004; Piotto et al. 2005).

In the HEPS, there were two epochs of major star formation in the history of ω Centauri. The first generation of stars was formed from proto–globular cluster (GC) cloud(s), becoming stars on the red main sequence (rMS), while the second generation of stars was formed from gas ejected from the rMS. One of the key questions related to the HEPS is whether and how the observationally suggested large helium enrichment (ΔY ∼ 0.12) for the bMS can be obtained from the rMS with normal Y (∼0.24) in the star formation history of ω Centauri (e.g., Norris 2004). There are three candidates for the helium overabundance (Norris 2004; D’Antona et al. 2005; Piotto et al. 2005): (1) AGB stars with the masses larger than 6 M⊙, (2) stellar winds associated with massive stars during their early evolutionary phases, and (3) Type II supernovae (SNe II). It is, however, unclear which of the three is the most reasonable and realistic in the HEPS, given a lack of extensive theoretical studies of them.

The purpose of this Letter is to investigate these three possibilities in a quantitative manner and thereby discuss which is the most promising as the cause of the bMS (and the DMS) in the context of the HEPS. In this investigation, the possible Y value observationally suggested for ω Centauri (Norris 2004; Piotto et al. 2005) and the observed number fraction of the bMS (Bedin et al. 2004) are used to constrain the best possible initial mass function (IMF) of forming stars in the HEPS. In this Letter we do not extensively discuss the observed abundance pattern of the bMS and the rMS, because chemical yield tables for AGB stars with helium-rich ejecta (Y > 0.35) are not currently available. We will discuss this point in a forthcoming papers (K. Bekki & J. E. Norris 2006, in preparation; hereafter BN06). Previous theoretical studies demonstrated that if GCs lose more than 50% of their initial masses, they will disintegrate (e.g., Geyer & Burkert 2001). We also use this result as a constraint for globular cluster IMF in the HEPS. We demonstrate that none of the above three candidates can explain the observed number fraction of the bMS without the modeled ω Centauri disintegrating.

2. THE POSSIBLE THREE POLLUTERS

First we summarize the possible three “polluters” that might significantly enrich ω Centauri with helium if the second generation of stars (i.e., the bMS) were formed from their ejecta. In order to explain the observationally suggested large value of Y (∼0.35), we need to select stellar objects whose ejecta have Y significantly higher than 0.24. Figure 1 shows the helium mass fraction (Y) in the ejecta of three candidates, (1) AGB stars (van den Hoek & Groenewegen 1997, hereafter VG97; Ventura & D’Antona 2005, hereafter VA05), (2) massive stars (Schaller et al. 1992), and (3) SNe II (Woosley & Weaver 1995, hereafter...
The value of $Y$ is derived for each stellar mass based on the values listed in these papers. The theoretical predictions of $Y$ for AGB stars is at most 0.28 for VG97 and 0.32 for VA05. D’Antona et al. (2005), however, suggested that more massive AGB stars, with the masses of $6 - 7 M_\odot$, could have $Y = 0.40$ (see also Lattanzio et al. 2004). We therefore consider that massive AGB stars can be polluters in $\omega$ Cen but that lower mass AGB objects ($\lesssim 5 M_\odot$) with smaller $Y$ cannot.

The observed difference in metallicity ([Fe/H]) between the rMS and the bMS (Piotto et al. 2005) suggests that the above scenario (i) alone cannot explain the metallicity difference, because the metallicities of AGB ejecta do not differ from those of their host stars. Therefore, full chemical evolution models including the contribution of the three polluters (and mixing between the ejecta of the polluters and fresh gas) need to be considered if we are to explain fully self-consistently both the helium and metallicity in the rMS and the bMS. We discuss the advantages and disadvantages of each of the three polluters in the helium enrichment process separately. This will better permit us to disentangle the contribution of the different polluters in producing He-enhanced stars and thereby to analyze the advantages and disadvantages of each scenario in explaining the helium abundance of the bMS. The entire chemical evolution history for different elements (e.g., $^{12}$C) in $\omega$ Cen will be discussed in our future papers (BN06).

2.1. AGB Stars

The first question is whether the number fraction of the second generation of stars (i.e., the bMS fraction) can be as large as 0.25 (Bedin et al. 2004) for a reasonable IMF without $\omega$ Cen disintegrating following mass loss from massive stars and SNe II. In order to estimate the mass fraction ($f_{\text{AGB}}$) of AGB progenitor stars with masses ranging from 6 to 7 $M_\odot$ in a GC with the total mass of $M_\text{tot}$, we assume an IMF in number defined as $\psi(m_r) = A m_r^{-\alpha}$, where $m_r$ is the initial mass of each individual star and the slope $\alpha = 2.35$ corresponds to the Salpeter IMF. The normalization factor $A$ is a function of $M_\text{tot}$, $m_l$ (lower mass cutoff), and $m_u$ (upper mass cutoff), $A = [M_\text{tot}(2 - s)] / (m_u^{-s} - m_l^{-s})$, where $m_l$ and $m_u$ are set to be 0.1 and 120 $M_\odot$, respectively. Although the number fraction of low-mass stars on the bMS can depend on the forms of IMFs, we adopt the above IMF and show the results. This is mainly because we can show more clearly the roles of IMF slopes in controlling the mass fraction of AGB stars for the adopted IMF in this preliminary study. The models with the IMF proposed by Kroupa et al. (1993) show a rather small fraction ($\sim 0.1\%$) of AGB stars in comparison with the models with the above IMF.

In this AGB pollution scenario, we assume that (1) the gas ejected from AGB stars in the first generation (i.e., the rMS) is all used (i.e., a star formation efficiency of 100%) for the formation of the second generation (i.e., the bMS), and (2) the total amount of gas ejected from a AGB star is the same as the stellar mass. This second assumption is reasonable because more than 80% of the stellar mass is ejected as AGB winds for AGB stars with $m_r > 6 M_\odot$ (e.g., VG97). We also assume two different slopes $s$ of IMF for the first ($s_1$) and the second ($s_2$) generations of stars in order to investigate the maximum value of $f_{\text{AGB}}(f_1 + f_2)$, where $f_1$ and $f_2$ are the number of stars (per unit mass) with masses smaller than 0.88 $M_\odot$ (corresponding to stars older than $\sim 12$ Gyr) for the first and second generations, respectively.

Figure 2 shows that the smaller the IMF slope $s_1$ is (i.e., as the IMF becomes more “top-heavy”), the larger the number fraction of the second generation ($f_{\text{AGB}}(f_1 + f_2)$) becomes for a fixed $s_2$ of 2.35. The ratio of the final cluster mass to its initial mass ($f_{\text{run}}$), however, also becomes smaller for smaller $s_1$. As a result of this, $f_{\text{run}}$ of the models with $s_1 \leq 1.75$ becomes smaller than the threshold value (0.5) below which star clusters can disintegrate as the result of mass loss (e.g., Geyer & Burkert 2001). No models can be located within the regions with $0.25 \leq f_2 (f_1 + f_2) \leq 0.35$ and with $f_{\text{run}} \geq 0.5$, where $\omega$ Cen can...
survive possible disintegration and have the bMS fraction consistent with observations. The number fraction of the second generation cannot be larger than 0.16, even for $s_2 = 5.35$ (i.e., extremely bottom-heavy) and $s_1 = 1.95$, for which $\omega$ Cen can manage to survive disintegration due to mass loss. Thus the results in Figure 2 suggest that the observed fraction of the bMS cannot be explained simply by the AGB pollution scenario for reasonable IMFs.

If $m_\ast$ is as low as $8 M_\odot$, $\omega$ Cen cannot disintegrate owing to mass loss from SNe II for any values of $s_1$ and $s_2$. It is found that $f_2/(f_1 + f_2)$ is about 0.29 for the model with $m_\ast = 8 M_\odot$, $s_1 = 1.35$, and $s_2 = 2.35$. This result suggests that if $\omega$ Cen formed with a very unusual IMF (i.e., with no or little SNe II), the observed bMS fraction can be reproduced without disintegration of $\omega$ Cen. The above model with no or few stellar remnants (black holes and neutron stars) of massive stars, however, would not be consistent with the presence of neutron stars in $\omega$ Cen (e.g., Haggard et al. 2004).

2.2. Massive Stars

The helium mass fraction in the stellar winds of massive stars with $m_\ast > 85 M_\odot$ can become as high as 0.4, with a maximum of 0.49 for $m_\ast = 120 M_\odot$ (Schaller et al. 1992). Although there is no problem with $Y$ in this scenario, the mass fraction of massive stars with $m_\ast > 85 M_\odot$ cannot be as large as $0.25$ for reasonable IMFs ($1.95 \leq s \leq 2.35$), for which $\omega$ Cen does not disintegrate. Figure 3 shows that the mass fraction of the ejecta of the massive stars is at most 0.2 for a plausible range of IMF slopes. Given the fact that the observed star formation efficiency in the Galaxy can be at most $-0.4$ (Wilking & Lada 1983 for the $\rho$ Oph cloud), this result suggests that the observed fraction of the bMS ($\sim 0.25$) is unlikely to be explained by this scenario.

A more serious problem for this stellar wind scenario is that there would be no or little difference in the mean metallicity between the first generation of stars and the ejecta of these objects (Schaller et al. 1992; Piotto et al. 2005) demonstrated that there is a metallicity difference by $\Delta[M/H] \sim 0.3$ between the rMS and the (more metal-rich) bMS in $\omega$ Cen. Another possible problem of this stellar wind scenario is that the ejecta should be very quickly converted into stars (within less than $10^7$ yr) between the stellar wind phases of very massive stars and the onset of SNe II that can blow away the ejecta from $\omega$ Cen.

2.3. Type II Supernovae

The helium mass fraction ($Y$) in the ejecta of SNe II stars with $12 \leq m_\ast/M_\odot \leq 40$ for metal-poor stars with $Z = 0.01 Z_\odot$, ranges from 0.37 to 0.45. (WW95). Although this scenario has no problems with $Y$, the abundance by mass for heavier elements in the ejecta is too high to be consistent with observations. $^{12}$C and $^{40}$Ca in WW95 are as high as $\sim 0.01$ and 0.001, respectively, which are higher than solar values ($\sim 3.0 \times 10^{-2}$ and $\sim 6.0 \times 10^{-4}$, respectively; WW95) and thus much higher than those of $\omega$ Cen. This inconsistency with the observed metallicities suggests that the bMS cannot be formed directly from the ejecta of SNe II of the rMS. If the ejecta of SNe II mix with the primordial gas forming the rMS, the $^{12}$C and $^{40}$Ca abundance of the bMS formed from the mixed gas could be significantly reduced. However, the helium abundance would also be significantly reduced in the process of mixing. Therefore, it can be concluded that this scenario is unlikely to explain the observed abundance of the bMS. Furthermore, this scenario has difficulty in explaining the observed fraction of the bMS without assuming a top-heavy IMFs, just as the other two scenarios do.

3. DISCUSSION: ALTERNATIVE SCENARIOS

3.1. External Pollution in the Nucleus of a Dwarf Galaxy

The present study shows that the three scenarios proposed all fail to explain self-consistently the observed properties of the bMS in $\omega$ Cen. The AGB scenario appears to be the most promising among the three, although it remains unclear whether this scenario can explain the observed abundances other than helium in $\omega$ Cen. The most serious problem of the AGB scenario is that the total mass of the ejecta of more massive AGB stars from the rMS is too small to be consistent with the observed fraction of the bMS of $\omega$ Cen. If, however, we relax the adopted assumption that all stars of the bMS originate from AGB ejecta of the rMS initially within $\omega$ Cen, the problem of the AGB scenario can be significantly alleviated. The problem of the bMS fraction can be solved if the original total mass of the rMS were larger (by a factor of $\sim 10$) than the present mass (i.e., if $\omega$ Cen was a supergiant GC) and if most of the stars of the rMS were removed from $\omega$ Cen after their ejecta were used for the formation of the bMS.

We here discuss a scenario in which $\omega$ Cen was the nucleus of a nucleated dwarf galaxy (dE,N) where the AGB ejecta of the central field stellar populations surrounding the (proto-) $\omega$ Cen were consumed for star formation of the bMS. In this scenario, the ancient host dE,N of $\omega$ Cen has been completely destroyed by the Galactic tidal field so that only its nucleus (i.e., $\omega$ Cen) is now observed (e.g., Bekki & Freeman 2003). Not only the ejecta of the rMS but also the ejecta of stellar populations surrounding the nucleus can be used for the formation of the bMS, so the bMS fraction problem encountered above should not be so serious in this scenario. The bMS can be more metal-rich than the rMS if the mean abundance of the field stellar populations and gas in the dwarf is slightly higher than that of the rMS.

The key question in this scenario is how much gas ejected from the central field stars can be converted into the bMS without being removed by energetic outflow of AGB stars in the central regions of $\omega$ Cen’s host dE.N. Recent numerical simulations of transformation from a dE,N into $\omega$ Cen have suggested that $\omega$ Cen’s host dE,N had $M_\ast \sim 14$ mag, corresponding to a total stellar mass of $1.25 \times 10^7 M_\odot$ (e.g., Bekki & Freeman 2003). If the total mass of the bMS is about 30% of present-day $\omega$ Cen’s mass ($= 5.0 \times 10^6 M_\odot$; Meylan et al. 1995), it is necessary for only 1.2% of the stellar mass of the
dE,N to have been converted into the bMS. Since the mass fraction of more massive AGB stars in the dE,N (>0.02) for a reasonable IMF can be significantly larger than the above value (~0.01), the observed bMS fraction is not a problem in this new scenario.

The central escape velocity ($V_{esc}$) of this host embedded in a massive dark matter halo with the total mass of $10^9 – 10^{10} M_{\odot}$ is 50–90 km s$^{-1}$ depending on the inner profile of dark matter halo (Bekki 2005). The derived $V_{esc}$ is significantly larger than the observed maximum wind velocity of ~40 km s$^{-1}$ for AGB stars (e.g., Loup et al. 1993). Therefore, the AGB ejecta of the dE,N is highly likely to be trapped within the central region of the dE,N and consequently converted into new stars (i.e., the bMS). Although extensive numerical simulations of the central gas dynamics of a dE,N are necessary to confirm that gas ejected from field stars of the dE,N can be transferred into the nuclear region and converted into new stars there, we propose that the bMS can originate from gas ejected from stars within the ancient dE,N whose nucleus was ω Cen.

3.2. Helium Sedimentation

The local helium abundance of the remaining gas of the forming ω Cen might have been significantly higher (leading to a bMS with higher helium abundance) if helium sedimentation due to gravitational diffusion (which was originally proposed by Fabian & Pringle [1977] as a mechanism responsible for gaseous abundance gradients in clusters of galaxies) occurred in ω Cen. Chuzhoy & Loeb (2004) showed that gravitational diffusion in the interstellar medium of giant elliptical galaxies can result in the increase of helium abundance by a factor of $1 + 0.2(T/10^5)^{1/5}F_n$, where $T$ and $F_n$ are the gas temperature and the suppression factor (likely to be >5) of the gravitational diffusion by the magnetic field. These results suggest that a significant increase of helium abundance is highly unlikely within GCs, which have central velocity dispersions of order 10 km s$^{-1}$, corresponding to $T \sim 10,000$ K.

4. CONCLUSION

We have shown that the observed bMS fraction of ω Cen cannot be simply explained by any HEPS in which the bMS was formed from ejecta of the rMS. We accordingly have suggested an “external pollution” scenario in which the bMS was formed from gas that was initially within the central region of ω Cen’s host galaxy. The question yet to be answered in this scenario is how star formation could proceed within the rMS when gas was transferred to the central region. One possibility is that the bMS was formed outside yet close to the rMS as a star cluster and then merged with the rMS in the central region of ω Cen’s host galaxy.

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