ACCRETION OF DUST GRAINS AS A POSSIBLE ORIGIN OF METAL-POOR STARS WITH LOW $\alpha$/Fe RATIOS

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ABSTRACT

The origin of low $\alpha$/Fe ratios in some metal-poor stars, the so-called low-$\alpha$ stars, is discussed. It is found that most of low-$\alpha$ stars in the Galaxy are on the main sequence. This strongly suggests that these stars suffered from external pollution. It is also found that the Zn/Fe abundance ratios of low-$\alpha$ stars both in the Galaxy and in dwarf spheroidal galaxies are lower than the average value of Galactic halo stars, whereas damped Ly$\alpha$ absorbers have higher ratios. This implies that some low-$\alpha$ stars accreted matter that was depleted from gas onto dust grains. To explain the features in these low-$\alpha$ stars, we have proposed that metal-poor stars harboring planetary systems are the origin of these low-$\alpha$ stars. Stars engulfing a small fraction of planetesimals enhance the surface content of Fe to exhibit low $\alpha$/Fe ratios on their surfaces, while they are on the main sequence, because dwarfs have shallow surface convection zones where the engulfed matter is mixed. After the stars leave the main sequence, the surface convection zones become deeper, reducing the enhancement of Fe. Eventually, when the stars ascend to the tip of the red giant branch, they engulf giant planets to become low-$\alpha$ stars again as observed in dwarf spheroidal galaxies. We predict that low-$\alpha$ stars with low Mn/Fe ratios harbor planetary systems.

Subject headings: galaxies: dwarf — Galaxy: halo — planetary systems — stars: abundances — stars: chemically peculiar

1 INTRODUCTION

According to the standard Galactic chemical evolution scenario, metal-poor stars have a few times higher abundance ratios of $\alpha$-elements to Fe ($\alpha$/Fe) than those of the Sun. This has been ascribed to the fact that massive stars with short lifetimes first contributed to the chemical evolution of the Galaxy by mainly supplying $\alpha$-elements, while Type Ia supernovae (SNe Ia) had to wait for their low-mass companion stars to turn off the main sequence to exclusively supply Fe-group elements to the interstellar medium (ISM; e.g., Hachisu, Kato, & Nomoto 1999). As a consequence, stars with $[\text{Fe/H}] \approx -1$ exhibit decreasing $\alpha$/Fe ratios with increasing Fe/H ratios. On the other hand, stars with $[\text{Fe/H}] \leq -1$ are expected to have $[\alpha/\text{Fe}] \sim 0.3-0.4$, reflecting yields from massive stars. Observed spectra of nearby stars have shown a correlation of $\alpha$/Fe ratios with Fe/H, supporting this scenario (e.g., Wheeler, Sneden, & Truran 1989; Edvardsson et al. 1993).

Recent spectroscopic observations of metal-poor stars have accumulated data exhibiting features of the elemental abundances that are apparently in conflict with the standard scenario: some halo stars exhibit lower $[\alpha/\text{Fe}]$ values than expected from supernova explosions of massive stars (Nissen & Schuster 1997; Carney et al. 1997; King 1997; Hanson et al. 1998). A diversity in $[\alpha/\text{Fe}]$ in a large sample of nearby stars with $[\text{Fe/H}] \leq -1$ (Fig. 1) demonstrates that stars with low $[\alpha/\text{Fe}]$ ratios are not rare in the Galactic halo (Gratton et al. 2003a).

A similar diversity in $[\alpha/\text{Fe}]$ is also seen in a different large sample of nearby stars observed by Fulbright (2000). These data still keep the essential feature that the standard scenario suggests as far as subgiants are concerned (filled circles in Fig. 1). This point will be addressed in the next section.

The origin of these low-$\alpha$ stars has been discussed in terms of their kinematic parameters (Nissen & Schuster 1997; King 1997; Fulbright 2000; Gratton et al. 2003b). These authors argued that the $\alpha$/Fe ratios correlated with the apogalactic orbit.
stars are very close to the pure r-process ratio (Shetrone et al. 2001, 2003), which implies that a few of the dSph stars had evolved through the asymptotic giant branch or supplied s-process elements to other dSph stars till the end of the star formation epoch. Thus, the timescale of the star formation in these dSph galaxies needs to be less than a few times $10^6$ yr. On the other hand, the progenitor of an SN Ia requires a longer timescale to accrete enough matter to reach the Chandrasekhar mass limit.

In this way, the origin of stars with low $\alpha$/Fe ratios in dSph galaxies is still controversial. In addition, a detailed comparison of elemental abundances of stars in the Galactic halo with those in dSph galaxies casts a doubt on the argument that low-$\alpha$ stars in the Galactic halo are originated from low-$\alpha$ stars that have once belonged to dSph galaxies (Fulbright 2002).

In this Letter, we will propose a mechanism to explain the origin of heavy elements in these low-$\alpha$ stars. There are other low-$\alpha$ stars without information on Mn/Fe ratios in young globular clusters Pal 12 and Ruprecht 106 (Brown, Wallerstein, & Zucker 1997). The proper-motion pair HD 134439/40 also exhibits low $\alpha$/Fe ratios (King 1997), although their Mn/Fe ratios have not been measured. We will also imply the origin of these low-$\alpha$ stars based on our scenario. In the next section, the surface gravities and effective temperatures of nearby low-$\alpha$ stars are investigated. In § 3, we discuss the relation between stellar elemental abundances in dSph galaxies and those in damped Ly$\alpha$ absorbers (DLAs). In § 4, a mechanism is proposed to explain metal-poor stars with low $\alpha$/Fe ratios both in the Galaxy and in dSph galaxies in a unified manner. In § 5, conclusions are presented, and we discuss some observations to test the proposed mechanism.

2. NEARBY STARS

If the nearby stars with $[\text{Fe/H}] < -1$ observed by Gratton et al. (2003a) are plotted in a log $g$–$T_{\text{eff}}$ plane (Fig. 2a), all the metal-poor stars with $[\text{Mg/Fe}] < 0.3$ would be located in a region limited by log $g > 4.1$, thus showing that these stars are on the main sequence. In the following, we will refer to subgiants as stars with log $g < 4.1$. On the contrary, stars with $[\text{Mg/Fe}] > 0.3$ reside in both dwarf and subgiant branches. As a result, the elemental abundance pattern of dwarfs in the $[\text{Mg/Fe}]-[\text{Fe/H}]$ plane (open circles in Fig. 1) has a larger dispersion than that of subgiants. The same feature is seen for other elements like Na and Zn (Figs. 2b and 2c). Stars with low Na/Fe and Zn/Fe ratios also only reside on the main sequence. These results suggest that the abundance features observed in the low-$\alpha$ stars were not solely determined by heavy elements in the ISM from which these stars were formed. Hence, some mechanisms in addition to supernova nucleosynthesis are needed to explain the observed elemental abundances. In fact, the low-$\alpha$ stars observed by Gratton et al. (2003a) have Mn/Fe ratios similar to those of the other halo stars.

Furthermore, old stars on the main sequence cannot alter the surface abundances of Mn, Fe, and Zn by nuclear reactions operating inside them. Therefore, the only mechanism to explain the observed feature would be the external pollution that brings some heavy elements into the shallow surface convection zone of a dwarf to significantly alter its surface elemental abundances. For example, the accretion of $\sim 0.1 M_\odot$ Fe would reduce the abundance ratio $[\text{Mg/Fe}]$ on the surface of a $0.8 M_\odot$ dwarf with $[\text{Fe/H}] = -1.5$ by $\sim 0.3$ dex. As the star turns off the main sequence, the mass of the surface convection zone will increase by a factor of more than 100 and reduce the influence of the external pollution to retrieve the original elemental abundances.

A certain insight into the external pollution introduced here can be obtained by comparing the abundance patterns of Galactic halo stars and DLAs. As shown in Figure 3, the Zn/Fe ratios of DLAs (Prochaska & Wolfe 2002) are, on average, larger than those of Galactic halo stars. Among the halo stars, dwarfs have, on average, lower Zn/Fe ratios than those of subgiants. Since the element Fe is thought to be heavily depleted from gas onto dust grains, the feature of Zn/Fe ratios presented in Figure 3 suggests that the dwarfs with lower Zn/Fe ratios accreted the Fe that had been depleted from gas, whereas higher Zn/Fe ratios in DLAs are the results of this Fe depletion. The accretion of the depleted Fe will also explain the features of Figure 2 since the elements Mg, Zn, and Na are inclined to remain in the gas phase rather than deplete onto dust grains as compared with Fe.

When Galactic halo stars pass through the Galactic disk, they might accrete the ISM contaminated by ejecta of SNe Ia. This process might reduce $\alpha$/Fe ratios on the surfaces of stars. However, this must increase Mn/Fe ratios at the same time.
leading to the abundance patterns that are inconsistent with observations. Furthermore, the accretion of the ISM hardly affects $\alpha$/Fe ratios on the surfaces of stars with $[\text{Fe/H}] > -2$ because the accretion rate is too small (Yoshii 1981).

3. STARS IN DWARF SPHEROIDAL GALAXIES

The observed elemental abundances of dSph stars (Shetrone et al. 2001, 2003) also show similar relations with those of DLAs for $\text{Cr/Fe}$, $\text{Mn/Fe}$, and $\text{Zn/Fe}$ (Fig. 4). Dwarf spheroidal stars have smaller $\text{Cr/Fe}$, $\text{Mn/Fe}$, and $\text{Zn/Fe}$ ratios than the average values of Galactic halo stars as well as those of DLAs. The elements $\text{Cr}$ and $\text{Mn}$ are also known to be lightly depleted from the gas phase. A sign of the depletion of Fe onto dust grains becomes prominent for $[\text{Fe/H}] \gtrsim -2$ in DLAs (Prochaska & Wolfe 2002). On the other hand, the elemental abundances of dSph stars behave in the same metallicity range as if they accrete Fe that was once depleted onto dust grains.

As discussed in the preceding section, the surfaces of some nearby low-$\alpha$ stars are affected by dust grains. On the contrary, all the low-$\alpha$ dSph stars showing features of dust grains are very luminous stars residing near the tip of the red giant branch (RGB) in the H-R diagram. In the next section, we will propose a mechanism to explain the origin of these low-$\alpha$ stars in different evolutionary stages.

4. ENGULFMENT OF PLANETS

The envelope of a star expands as it evolves along the RGB, and finally its size reaches up to a few AU. Therefore, if a star harbors planets, some of them will eventually be engulfed by their host star during the late stage of the RGB. For instance, in our solar system, the Sun is expected to eventually engulf all the terrestrial planets, although the gas giant planets will be beyond the reach of the evolved Sun. The ongoing hunt for extrasolar planets has revealed that there are some planetary systems in which massive planets orbit their host stars with semimajor axes of the order of only 1 AU. The average mass and semimajor axis of the planet orbits are found to be $3M_J$ and 1.2 AU, respectively, in a sample of 107 planets in 93 planetary systems, although these estimates probably suffer from observational bias. This leads to the implication that some fractions of stars with planets will likely engulf giant planets until the stars evolve to the tips of the RGBs.

Although the mass of the dense core in a gas giant planet such as Jupiter or Saturn in our planetary system is uncertain, a large amount of Fe is expected to be contained in their cores, compared with terrestrial planets like Earth (Guillot 1999). It is expected that Jupiter contains roughly 5 times more Fe than Earth with 0.38 $M_\oplus$ of Fe (see Table 1 in Murray et al. 2001). Thus, a giant planet with the mass of $3M_J$ is expected to contain $\sim 5 M_\oplus$ of Fe. This iron mass is in fact comparable to the mass of Fe in the convection zone of a red giant star with a mass of 0.8 $M_\odot$ and a metallicity $[\text{Fe/H}] \sim -1.5$. As a result, the engulfment of such a giant planet by a metal-poor red giant star would increase the surface metallicity by $\sim 0.3$ dex in $[\text{Fe/H}]$ and decrease the $\text{Zn/Fe}$ ratio on the stellar surface by a similar amount.

There is no information on what fraction of each element was depleted from the gas phase in the protoplanetary gas disks around metal-poor stars with a metallicity range of $-2 \leq [\text{Fe/H}] <$
[Fe/H] \approx -1. A recent observation of the ISM in the Small Magellanic Cloud (SMC) with an average metallicity of [Zn/H] \approx -1 might, however, shed light on this issue (Welty et al. 2001); Fe-group elements are depleted as much as in the Galactic ISM, whereas \( \alpha \)-elements such as Mg and Si are nearly undepleted, although Si has a higher condensation temperature than Fe. This depletion pattern would support the scenario in which nearby low-\( \alpha \) stars engulfed a fraction of dust in the protoplanetary disks and in which low-\( \alpha \) dSph stars engulfed giant planets. Of course, the physical conditions could be quite different between protoplanetary gas disks and the observed ISM in the SMC. It is crucial to understand what determines the dust-depletion pattern.

The most metal-poor star harboring planets to date is reported to have a metallicity of [Fe/H] = -0.74 (Sadakane et al. 2002). Thus, the scenario proposed here has not been fully supported by the ongoing search for extrasolar planets. Future observations will construct a much larger sample to find out whether or not there are planets orbiting stars as metal-poor as [Fe/H] \approx -2.

5. CONCLUSIONS AND DISCUSSION

We have discussed the origin of low-\( \alpha \) stars found in the Galaxy and in dSph galaxies. We have shown that the low-\( \alpha \) stars found in the Galaxy are on the main sequence and thus conclude that these stars have suffered from external pollution. A comparison of the elemental abundance pattern of low-\( \alpha \) stars with that of DLAs suggests that low-\( \alpha \) stars have accreted dust grains. On the other hand, low-\( \alpha \) dSph stars are located at the tip of the RGB. To explain the origin of these low-\( \alpha \) stars in different evolutionary stages, we have proposed that these low-\( \alpha \) stars harbor or have harbored planets and that stars engulfing planets and/or planetesimals show low \( \alpha/Fe \) ratios. However, it should be noted that there is at least one subgiant with low \( \alpha/Fe \) ratios, BD +80°245 (Carney et al. 1997). This star has \( \alpha/Fe \) approximately equal to the solar values and [Fe/H] \approx -2. If our scenario is applied to this star, it must have harbored a giant planet at a radius of \( \approx 0.014 \) AU. This does not necessarily discard our scenario. The smallest semimajor axis of planets in the present catalog of J. Schneider (see footnote 4) is \( \approx 0.02 \) AU, which is comparable to the above value.

Recently, I. I. Ivans and coworkers (see footnote 3) reported some other metal-poor stars belonging to low-\( \alpha \) stars that cannot be explained by the scenario presented here. These stars exhibit extremely large enhancements of Ti, Cr, Mn, Ni, Zn, and Ga relative to Fe and are deficient in Si and Mg. These elemental abundance features might “witness” the earliest SNe Ia as suggested by I. I. Ivans and coworkers.

We cannot expect a correlation of low-\( \alpha \) stars that have no sign of SNe Ia with any stellar kinematics from our scenario. Therefore, the relationship between low-\( \alpha \) stars and stellar kinematics mentioned in § 1 should be explained by some other mechanisms. The correlation of \( \alpha/Fe \) ratios with the galactic radii was already found in the disk stars (Edvardsson et al. 1993). According to the standard chemical evolution model, this correlation has been explained as a result of the combination of SN Ia products and the longer evolution timescales of the chemical evolution at larger galactic distances (Tsujimoto et al. 1995b). This argument could be applied to the correlation of \( \alpha/Fe \) ratios with the galactic radii found for the halo stars (Nissen & Schuster 1997; King 1997; Fulbright 2000; Gratton et al. 2003).

It is possible to test our conjecture by using two kinds of observations. One is to search planets orbiting around low-\( \alpha \) dwarfs in the metallicity range of \(-2 < [Fe/H] < -1 \) in the Galaxy. If planets are found to orbit around low-\( \alpha \) dwarfs in this metallicity range, it will strongly support our conjecture presented in this Letter. The other is to search low-\( \alpha \) stars with \(-2 < [Fe/H] < -1 \) at the tip of the RGB in the Galaxy. A few spectroscopic observations have been made for red giants with surface gravities and metallicities similar to the stars observed in dSph galaxies (e.g., Hanson et al. 1998; Fulbright 2000). A low-\( \alpha \) star was not found by these observations. The other red giants in the Galaxy observed so far are too metal-poor ([Fe/H] \approx -2) and/or have too high surface gravities (\( \log g \approx 1 \)).

The metallicity distribution function of stars with planets is shown to shift toward the metal-rich region compared with that of stars without planets (e.g., Gonzalez 1998). There have been two explanations for this fact. One is that only stars with sufficient metals can host planets, because planet formation needs dust grains (e.g., Santos et al. 2003). The other is that stars with planets tend to engulf planetesimals to enhance their metallicities (e.g., Gonzalez 1998; Murray & Chaboyer 2002). Our scenario favors the latter explanation.

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