THREE-DIMENSIONAL ORBITS OF METAL-POOR HALO STARS AND THE FORMATION OF THE GALAXY

MASASHI CHIBA
National Astronomical Observatory, Mitaka, Tokyo 181, Japan

AND
YUZURU YOSHI
Institute of Astronomy, University of Tokyo, Mitaka, Tokyo 181, Japan

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ABSTRACT

We present the three-dimensional orbital motions of metal-poor stars in conjunction with their metal abundances, for the purpose of getting insight into the formation process of the Galaxy. Our sample stars, which include metal-deficient red giants and RR Lyrae variables observed by the HIPPARCOS satellite, are least affected by known systematics, stemming from kinematic bias, metallicity calibration, and secondary metal contamination of stellar surface. We find, for the stars in the metallicity range of $[\text{Fe/H}] \leq -1$, that there is no evidence for the correlation between $[\text{Fe/H}]$ and their orbital eccentricities, $e$. Even for $[\text{Fe/H}] \leq -1.6$, about 16% of the stars have $e$ values less than 0.4. We show that the $e$ distribution of orbits for $[\text{Fe/H}] \leq -1.6$ is independent of the height $|z|$ away from the Galactic plane, whereas for $[\text{Fe/H}] > -1.6$, the stars at $|z| \geq 1$ kpc are systematically devoid of low-$e$ orbits with $e \leq 0.6$. This indicates that low-$e$ stars with $[\text{Fe/H}] \leq -1.6$ belong to the halo component, whereas the rapidly rotating thick disk with a scale height of $\sim 1$ kpc has a metal-weak tail in the range of $-1.6 < [\text{Fe/H}] \leq -1$. The fraction of this metal-weak thick disk appears to be less than 20%. The significance of these results for the early evolution of the Galaxy is briefly discussed.

Subject headings: Galaxy: formation — Galaxy: halo — Galaxy: kinematics and dynamics — stars: Population II

1. INTRODUCTION

The most useful diagnostics for probing how the Galaxy has formed lie in the relationship between metal abundances, $[\text{Fe/H}]$, and orbital eccentricities, $e$, of stars (see, e.g., Freeman 1987; Majewski 1993). For example, if the Galaxy underwent a monolithic, rapid collapse, the orbits of stars that have formed from free-falling gas clouds were made highly eccentric in the course of a rapid change of the Galactic mass concentration. The aftermath of collapse therefore prohibits the existence of metal-poor stars having nearly circular orbits. On the other hand, if the mass concentration occurred slowly in a manner of either a quasi-static contraction or merging/accretion of numerous fragments, some fraction of metal-poor stars are inevitably expected to hold nearly circular orbits, where the eccentricities have been approximately preserved up to the present epoch.

However, our knowledge of the Galactic past still remains far from reaching general consensus since the pioneering work by Eggen, Lynden-Bell, & Sandage (1962, hereafter ELS). ELS showed, on the basis of the kinematically selected sample of stars, evidence supporting the picture of a rapid Galaxy collapse from their finding of a strong correlation between $[\text{Fe/H}]$ and $e$. In contrast, Yoshii & Saio (1979) and Norris, Bessell, & Pickles (1985, hereafter NBP) demonstrated the existence of low-$e$, low-$[\text{Fe/H}]$ stars and argued that the ELS result is an artifact of selecting metal-poor stars with high eccentricities. This divergence of results stems from how well the existing systematics are controlled when selecting samples for the analysis. In particular, the systematic biases inherent in the samples either create or diminish a correlation between $[\text{Fe/H}]$ and $e$ of stars in a nontrivial manner so that the picture for the initial contraction of the Galaxy is drastically changed.

It has recently been claimed that a nonnegligible fraction of low-$e$, low-$[\text{Fe/H}]$ red giants obtained by NBP are dropped out because of their underestimated calibration of $[\text{Fe/H}]$ (Twarog & Anthony-Twarog 1994; Ryan & Lambert 1995). In Figure 1a, we reproduce their result of the relation between $[\text{Fe/H}]$ and planar $e$ projected onto the Galactic plane, for dwarfs (crosses) and red giants (filled symbols), where the revised $[\text{Fe/H}]$ for the latter stars are used if they are available from either Anthony-Twarog & Twarog (1994, hereafter ATT) or Ryan & Lambert (1995). It is suggested that the revision of $[\text{Fe/H}]$ of some red giants turns out to decrease a number of low-$e$, low-$[\text{Fe/H}]$ stars, thereby weakening the conclusion of NBP.

In this Letter, we attempt to settle this long-standing issue on the basis of a mostly unbiased sample of stars and a technique devised to analyze the orbital distribution of stars. Our sample stars, which contain metal-deficient red giants and RR Lyrae variables in the vicinity of the Sun, are expected to provide precise chemokinematical properties of old stellar populations compared with those used by ELS and NBP, because of their selection without kinematic bias and of their well-determined metal abundances and distances from recently revised spectrophotometric calibrations (ATT; Layden 1994, 1996). Further advantage of using these sample stars is offered by their homogeneity in the data of proper motions, which are accurately measured by the HIPPARCOS satellite (ESA 1997), and their insensitivity to the effects of metal accretion due to encounters with interstellar clouds because of their deep convection zone (Yoshii 1981). In order to clarify the global orbital properties of these metal-poor stars in the Galactic space, we adopt, in contrast to most previous studies, a realistic, three-dimensional Galactic potential (Sommer-Larsen & Zhen 1990) that allows us to establish the three-dimensional orbital motions.

1 Also at Research Center for the Early Universe, Faculty of Science, University of Tokyo, Bunkyo-ku, Tokyo 113, Japan.

2 Whether or not the subdwarf studies (e.g., Carney, Latham, & Laird 1990) are subject to the effects of metal accretion is yet to be settled.
of stars in conjunction with their metal abundances. The extensive analyses and results are reported elsewhere (Chiba & Yoshii 1997).

2. METHOD AND RESULTS

We have selected 122 red giants from the kinematically unbiased sample of metal-deficient red giants surveyed by Bond (1980) and 124 RR Lyrae stars from the catalogs of variable stars compiled by Kukarkin et al. (1969–1976). The proper motions of the sample stars have been observed by the HIPPARCOS satellite, accurate to ~1 mas yr\(^{-1}\), which were allocated to the senior author’s proposal submitted in 1982. The radial velocities and their errors are assembled from a number of published works. The data on distances and metallicities are taken from the spectrophotometric studies by ATT for 188 red giants, Bond (1980) for four other red giants, and by Layden (1994, 1996) for all RR Lyrae stars. The full listing of all data and literature that we have used will appear in Chiba & Yoshii (1997). A majority of the sample stars are located within about 2 kpc from the Sun and have metallicities, [Fe/H], less than –1 dex. We note that the distribution of their metallicities in the range of [Fe/H] \(\leq -1\) is in good agreement with the likely true metallicity distribution of halo derived from subdwarf stars (Laird et al. 1988).

For the purpose of enlightening the orbital properties of these stars combined with their metallicities, we calculate the eccentricities, \(e\), of orbits by assuming a Galactic potential. We adopt the three-dimensional Stäckel-type potential constructed by Sommer-Larsen & Zhen (1990), which reproduces well the mass model of Bahcall, Schmidt, & Soneira (1982). Since orbits with this potential are generally not closed, we arbitrarily define \(e\) by \(e = (r_p - r_a)/(r_p + r_a)\), where \(r_p\) and \(r_a\) denote the apogalactic and perigalactic distances, respectively. It is worth noting that use of other axisymmetric potentials does not modify the essential results explained below.

In Figure 1b, we plot the relation between [Fe/H] and \(e\) for RR Lyrae stars (open circles) and red giants (filled circles). It is apparent that while the stars with [Fe/H] > −1 have nearly circular orbits with \(e < 0.4\), those with [Fe/H] \(\leq -1\) have a diverse range in orbital eccentricities, i.e., there is no correlation between [Fe/H] and \(e\). Even for [Fe/H] \(\leq -1.6\), about 16% of stars have \(e < 0.4\). The primary reasons for the change from Figure 1a include (1) sampling the stars almost completely in accord with the halo’s metallicity distribution, especially those for [Fe/H] \(\leq -1.6\), whereas the number of such metal-poor stars in NBP is insufficient, and (2) adopting a more realistic, three-dimensional Galactic potential including a massive halo in order to properly take into account their large vertical velocities above and below the Galactic plane (see Fig. 3 below), whereas \(e\) based on a two-dimensional potential adopted by ELS and NBP is overestimated (Yoshii & Saio 1979). We note that the diverse \(e\) distribution for [Fe/H] \(\leq -1.6\) is not affected by the systematic underestimation of [Fe/H] for metal-rich stars with disklike kinematics (see Twarog & Anthony-Twarog 1994 for details).

It has been discussed by recent workers that low-\(e\), low-[Fe/H] stars may belong to the metal-weak tail of the rapidly rotating thick disk that dominates at [Fe/H] = −0.6 to −1 (NBP; Beers & Sommer-Larsen 1995). If this is the case, many low-\(e\) stars in the [Fe/H]–\(e\) diagram ought to disappear when we restrict to the larger height from the Galactic plane than the scale height of the thick disk with \(\sim 1\) kpc (Freeman 1987). In Figure 1b, the domain enclosed by dashed lines shows where low-\(e\) stars are selectively excluded at \(|z| \geq 1\) kpc. It is clear that in the intermediate metallicity range of \(-1.6 < \text{[Fe/H]} \leq -1\), the thick disk overlaps with the halo at \(e \leq 0.6\), but this metal-weak tail of the disk does not extend down to [Fe/H] \(\leq -1.6\). We have found that such a division between the halo and thick disk components at [Fe/H] \(\sim -1.6\) is rather sharp (Chiba & Yoshii 1997).

The above indication that low-\(e\) stars in the range of [Fe/H] \(\leq -1.6\) belong to the halo component is also supported from the following analysis of orbital distributions. Figures 2a and 2b show the cumulative \(e\) distributions of orbits \(N(< e)\) for [Fe/H] \(\leq -1.6\) and \(1.6 < \text{[Fe/H]} \leq -1\), respectively. Various histograms show how the distribution changes when we set limits on the range of the height \(|z|\). For [Fe/H] \(\leq -1.6\), the overall \(e\) distribution of stars remains essentially unchanged with increasing \(|z|\). Thus, the stars in the range of [Fe/H] \(\leq -1.6\) belong to the halo component, where a nonnegligible fraction (\(\sim 16\%–20\%\)) of stars have nearly circular orbits with \(e < 0.4\). On the other hand, the number of low-\(e\) stars in the range of \(-1.6 < \text{[Fe/H]} \leq -1\) shows a sharp drop at \(|z| \sim 1\) kpc and then remains unchanged at higher \(|z|\) (Fig. 2b). This

\(^3\) It is also remarked that NBP selected the stars with probable errors for \(e\) less than 0.1. This selection of stars, however, creates an extra bias in the sample (Twarog & Anthony-Twarog 1994; Chiba & Yoshii 1997).
suggestions that the stars with these intermediate metallicities are contaminated with the thick disk component with a scale height of ~1 kpc, except for those stars having high $e$ at high $|z|$. The halo is thus well separated from other disk components if we set the restriction $|z| \geq 1$ kpc.

Figure 3 further presents the distribution of vertical velocities $V_z$ above and below the Galactic plane for [Fe/H] $\leq -1.6$ (Fig. 3a) and $1.6 < [\text{Fe/H}] \leq -1$ (Fig. 3b). Dotted lines correspond to a typical vertical velocity dispersion of the thick disk in the $z$-direction. The symbol designation is the same as in Fig. 1b.

of [Fe/H] $\leq -1.6$ allows us to obtain $F \sim 0.1$ for $-1.6 < [\text{Fe/H}] \leq -1$, and this value is increased to only even for $-1.4 < [\text{Fe/H}] \leq -1$ (Chiba & Yoshii 1997). Thus, in contrast to earlier results suggesting a large $F$ (e.g., $F \sim 0.72$ by Morrison, Flynn, & Freeman 1990; $F \sim 0.6$ by Beers & Sommer-Larsen 1995), the fraction of the metal-weak thick disk is found to be small.

3. DISCUSSION AND CONCLUSION

Using a mostly unbiased sample of red giants and RR Lyrae variables, we arrive at the conclusion that orbital eccentricities of metal-poor halo stars are no longer correlated with their metallicities. This result is virtually in contrast to the ELS result but is in agreement with other studies using subdwarf stars (Carney et al. 1990). A detailed analysis of the eccentricity distribution of orbits, which is made possible for the first time by the accurate HIPPARCOS proper motions (ESA 1997) and well-calibrated metal abundances of the almost complete halo sample (ATT; Layden 1994, 1996), allows us to conclude that (1) low-$e$ stars in the range of [Fe/H] $\leq -1.6$ belong to the halo and (2) the metal-weak thick disk constitutes a small fraction down to its boundary at [Fe/H] $\sim -1.6$. Our sample stars are also less sensitive to the effects of secondary metal accretion onto the surface of stars (Yoshii 1981); therefore, the currently observed metallicities of these stars can be regarded to retain the fossil records for those when the stars were formed.

The above conclusions set constraints on the scenarios for the contraction of the Galaxy at high redshifts. The absence of a correlation between [Fe/H] and $e$ suggests that the Galaxy has not experienced a free-fall monolithic collapse (ELS) unless otherwise there remain no metal-poor, high angular momentum stars after collapse. Alternatively, the Galactic spheroid may have been assembled from merging or accretion of numerous fragments (Searle & Zinn 1978), such as dwarf-type galaxies, but whether or not the aftermath reproduces the observed kinematical distribution of stars is yet to be explored (e.g., Steinmetz & Müller 1995). The early evolution of the Galaxy also involves the stage of the thick disk formation. It is also still unsettled whether a leading merger scenario for forming thick
disk (e.g., Quinn, Hernquist, & Fullagar 1993) reproduces our finding of only few stars with disklike kinematics in the range of $[\text{Fe/H}] \leq -1$.

Therefore, the comprehensive understanding of the observed chemokinematical properties of metal-poor stars demands more advanced approaches to studying Galaxy formation, perhaps guided by both extensive numerical simulations of a collapsing galaxy and kinematical data of more stars in the whole region of the Galactic space provided by next generation of astrometric telescopes.

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