論文の内容の要旨

論文題目　Kinematics of halo stars and the formation history of the Milky Way
（ハロー星の運動と銀河系形成史）

氏名　服部　公平

Kinematics and chemical abundances of halo stars have long been studied to infer the formation history of the Milky Way. In this avenue of studies, there are two, widely-accepted assumptions, namely,

- (1) the motion of halo stars observed today reflect the motion of the progenitor systems in which they formed; and
- (2) the chemical abundance of heavy elements of halo stars observed today reflect the chemical abundance of the gas from which they formed.

The assumption (1) is validated not only by theoretical argument of collisions nature of the stellar halo but also by recent numerical simulations of galaxy formations. On the other hand, the assumption (2) of constancy of stellar surface metal abundances has not been fully validated yet, although there is a possibility that accretion of metal-enriched material onto its surface enhances the surface metal content.

In the first half of this thesis (Chapter 2), we propose a purely observational test on the validity of assumption (2). The underlying idea of our method is that if both assumptions (1) and (2) are valid, we expect identical chemo-dynamical correlations for G and K type main-sequence stars, since these long-lived stars reflect the same mass-assembly and star-formation histories. We make use of the kinematical information and surface metallicity data of GK dwarfs taken from data release 8 of

Sloan Digital Sky Survey (SDSS DR8) and calculate the correlation between rotational velocity V_ϕ and stellar surface metallicity [Fe/H].

As a result, we find a statistically significant offset in [Fe/H] between the correlations of GK dwarfs in such a way that the G dwarfs have systematically higher [Fe/H] than K dwarfs do at a fixed rotational velocity. This result is consistent with the prediction from metal accretion, since G dwarfs are more sensitive to metal accretion due to their shallower surface convective envelope.

We also find that similar offset can be seen for those stars with $z_{\rm max} > 3$ kpc, while a subsample of stars with $z_{\rm max} < 3$ kpc does not show such an offset, where $z_{\rm max}$ is the maximum vertical excursion above the disk plane. According to Carollo et al. (2010), those halo stars with larger $z_{\rm max}$ are more likely to be 'outer halo' stars (those originate from small systems – such as dwarf galaxies – which have accreted and been disrupted), while those halo stars with smaller $z_{\rm max}$ are more likely to be 'inner halo' stars (those formed in the main progenitor of the Milky Way). Therefore, our results indicate that metal accretion is effective only in small progenitor systems and that metal accretion is not effective in the main progenitor of the Milky Way. This indication is favoured by metal accretion scenario, if we take into account that metal accretion is more effective in those environments where relative velocity of the accreting gas with respect to the star is smaller, since internal velocity dispersion is smaller for smaller systems.

As a complementary analysis, we also check for the correlation for blue horizontal-branch (BHB) stars. The result for BHB stars suggests that BHB stars are less affected by metal accretion, which is consistent with the prediction from metal accretion scenario.

Based on these results (as well as a set of Monte Carlo simulations that validate these results), we conclude that the metal accretion is very likely to have occurred in the formation process of the Milky Way, especially in the small progenitor systems like dwarf galaxies.

One important impact of our conclusion is that it might affect the formation scenario of Population III stars. At this moment, no metal-free stars have ever been observed. The simplest interpretation for this observational fact is that all the Population III stars have high enough mass ($M > M_\odot$) so that they have already died out. However, if metal accretion does take place, then there is a possibility that some fraction of Population III stars are low-mass enough to survive until today, disguising themselves as ordinary Population II stars due to metal accretion. Therefore, our findings leave some room for the existence of low-mass Population III stars.

Another important impact of our conclusion is that our current understanding of the formation history of the Milky Way might require modification. A large portion of observable halo stars in the Solar neighbourhood are low mass main-sequence stars, albeit their low-luminosities. If metal accretion does take place, then observed surface metal abundances of these dwarfs mean only upper limits of the original ones. Therefore, the shapes of metallicity distribution function (MDF) of halo dwarfs (especially G dwarfs with shallow surface convective envelopes) may be biased. For example, An et al. (2013) use high-Galactic latitude ($b > 35\,{\rm deg}$) main-sequence stars at the heliocentric distance range of 5 kpc $< d <$ 8 kpc and claim that the fraction of outer halo component is $\sim 20-35\%$ in this region, but this figure might need modification if the sample stars are affected by metal accretion. Also, since stellar metallicities of dwarfs are used in estimating their photometric distances, inaccurate estimate of stellar metallicity brings some systematic error in the derived photometric distance (and tangential velocity when photometric distance is used). Thus, observational studies of the spatial distribution and/or kinematics of nearby dwarfs based on photometric distances might require reconsideration of the results. For example, Carollo et al. (2007, 2010) claim that the difference in the mean metallicity between inner and outer halo components is ~ 0.6 dex, but this figure might be a lower limit, since the metallicities of outer halo stars (more metal-poor component) may be their upper limits. A good news is that our results suggest that metal accretion does not have significant impact on those stars with [Fe/H] > -1, which may be due to deeper surface convective envelope for metal-rich stars. Thus observational studies on disk stars may require minor modifications if any.

In near future, Gaia and JASMINE will provide rich astrometric data, while Gaia-ESO survey will provide much accurate stellar metallicity than SSPP metallicity. These forthcoming data will be helpful in quantifying the significance of metal accretion onto halo stars. For example, by applying similar analysis to these accurate data, we can not only test whether our results presented here are real or not, but also quantify the typical amount of mass which have accreted onto halo stars. If we can determine how the reliability of the observed metallicity depends on the stellar type, we can discuss the star formation history of the Milky Way or distant dwarf galaxies more rigorously, by using the most reliable metallicity tracers (which are presumably those stars with deep surface convective envelopes). Also, if we can estimate the typical total mass accreted onto halo stars, we can infer the environments of the progenitor systems of typical halo stars. This kind of information is beyond our reach at this moment, but might be helpful in understanding the mass assembly history of the Milky Way.

In the last half of this thesis (Chapter 3), we derive the kinematical properties of distant BHB stars and investigate their [Fe/H]-dependence. Since evolved, post-main-sequence stars are expected to be less affected by metal accretion, we assume both of the above-mentioned assumptions (1) and (2) throughout Chapter 3.

In Chapter 3, we present a model-independent analysis of the line-of-sight velocities and spatial distribution of 1865 halo BHB stars within 30 kpc of the Galactic center taken from SDSS DR8.

First, we make use of Frenk & White (1980) method to estimate the mean rotational velocity of BHB stars as a function of Galactocentric distance r. We find that the mean rotational velocity of the very metal-poor ([Fe/H] < -2.0) BHB stars significantly lags behind that of the relatively more metal-rich ([Fe/H] > -2.0) BHB stars in the Galactocentric distance range of 13 kpc $< r <$ 23 kpc. Secondly, we derive the 3-dimensional velocity dispersion of BHB stars as a function of r by making use of a new method, which corresponds to a generalization of Woolley (1978) method. We find that the relatively more metal-rich BHB stars are dominated by stars with eccentric orbits at 12 kpc $< r <$ 15 kpc, while the very metal-poor BHB stars are dominated by stars on round, low-eccentricity orbits at 13 kpc $< r <$ 18 kpc.

The derived 'mean rotational velocity curve' of halo stars above and below [Fe/H] $= -2$ is the first observational evidence for the existence of the rotational shear of halo stars outside the Solar neighbourhood. Our result suggests that the asymmetric V_ϕ-distribution of nearby halo stars claimed by Carollo et al. (2007, 2010) is reflecting the dual nature of the stellar halo, not the artefact arising from inadequate tangential velocity estimate as criticised by Schonrich et al. (2011).

Our finding that distant, very metal-poor BHB stars are dominated by round orbits poses a challenge to numerical simulations of galaxy formation, since it contradicts their prediction. All the recent simulations (as far as the author knows) predict that the orbits of halo stars in Milky Way-like galaxies are dominated by radial orbits at any Galactocentric distance r. Our result suggests that numerical simulations lack in some physical processes in which metal-poor halo stars form. As a possible explanation, we propose a scenario that these metal-poor outer halo stars with round orbits formed in gas-rich systems (similar to high-velocity clouds) whose orbits had been circularised due to inelastic interaction with other gas-rich systems.

Although our findings provide some new insights into the formation history of the stellar halo, our results have to be confirmed by future direct measurements of velocity distribution, since our results may be affected by complex structure of stellar halo. With this regard, next generation astrometric satellites such as Gaia and JASMINE will provide the best opportunity to unravel the structure and history of the Milky Way.