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Chemical Evolution of the Galactic Halo

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A three-zone model of chemical evolution of our Galaxy is proposed to explain overall distribution of the metallicity in the Galaxy. The metallicity enrichment is strongly affected by gas flow from the outer part to the inner part of the protogalaxy during the contraction of proto-galactic gas cloud. The population in the outer halo is formed in the free-fall phase of the initial collapse of the protogalaxy, and the inner halo population is formed during the following quasistatic contraction, while the disk population is formed from the gas fallen from the halo regions.

Keywords: Chemical evolution, galactic halo/disk, protogalaxy.

§1. Introduction

The distribution of metallicity in stars and gas of our Galaxy contains information on the chemical evolution extending over the past whole history from the formation epoch to the present, and many studies have been performed, hitherto, concerning the metallicity enrichment history of our Galsxy[1,2].

It has been shown that so called "simple model" of chemical evolution for a closed system can not account for the observed metallicity distributions in our Galaxy. In the solar neighborhood there are far fewer metal-poor stars than the prediction of a simple model, and this contradiction is called the "G-dwarf problem"[1,2]. On the other hand, the distributions for tracers far from the galactic plane have higher relative content of metal poor stars than that for stars in the solar neighborhood[3], and this characteristic is much remarkable in the globular clusters[4]. In this case the simple model is discrepant with the observed distributions in the opposite sense to the G-dwarf problem in the solar neighborhood.

Since the metallicity enrichment is strongly affected by gas transport through the star forming regions, evolutionary models which allow for gas inflow or outflow have been proposed to get improved fits to the observations for respective samples. As for the globular cluster system, it's been suggested, first by Hartwick[4], that the metallicity enrichment can be reproduced by a model which allows for an outflow of gas from halo star-forming regions. The time scale of gas outflow must be a tenth of that of gas consumption due to star formation, i.e., approximately 10^8 yr in order to explain the metallicity distribution in the globular cluster system.

On the other hand, a model including infall of gas during star formation has been suggested as one of the predominant solutions to the G-dwarf problem in the solar neighborhood[2)]. Hence, if the gas outflow from halo region can play a role of gas infall to the galactic disk, the problems in both regions can be closed simultaneously. However this is not the case, because the time scale of gas infall into the galactic disk must be in an order of 10^9 yr, ten times as large as the time scale of outflow from halo region, to reproduce the observed metallicity distribution in the disk[5,6)].

This contradiction can be resolved by introduction of an intermediate component between the halo and disk regions. So, in the present paper, we propose a three zone model as follows: In the initial stage of galactic evolution star formation proceeds in a huge volume which corresponds to the present galactic halo region, and the large part of gas is removed from the halo star forming regions, following the overall contraction of the protogalaxy, towards inner region of the Galaxy. The intermediate region receives the gas flow from halo region in a time scale of approximately 10^8 yr and simultaneously flows out to the disk region in a time scale of 10^9 yr, and the disk is formed from the gas fallen from the halo and intermediate regions.

Observations also suggest the existence of a population which have intermediate characteristics between halo and disk populations, as shown by the metallicity distribution for stars more than a kiloparsec from the galactic plane[3)], and by the stellar density distributions perpendicular to the galactic plane[7,8)].

In the present paper we consider the chemical enrichment in the early stage of galactic evolution with the above-mentioned three zone model and interpret consistently the metallicity distributions observed through the galactic halo and disk.

§2. Model

The scheme of three zone model is given in Figure 1, where the Zones I, II, and III correspond to the galactic halo, the intermediate, and the disk regions, respectively. As stated in the preceding section, Zone II receives a gas flow from the halo region in a time scale of approximately 10^8 yr and simultaneously flows out to the disk region in a time scale of 10^9 yr. The disk receives just the gas flowed out from Zone II and no gas flows out from Zone III.

Our model of chemical evolution does not differ from the "simple model" except that the gas flows out from the system or flows into the system, i.e., the initial mass is metal-free, the gas is chemically homogeneous throughout the system, the instantaneous recycling approximation applies, and the initial

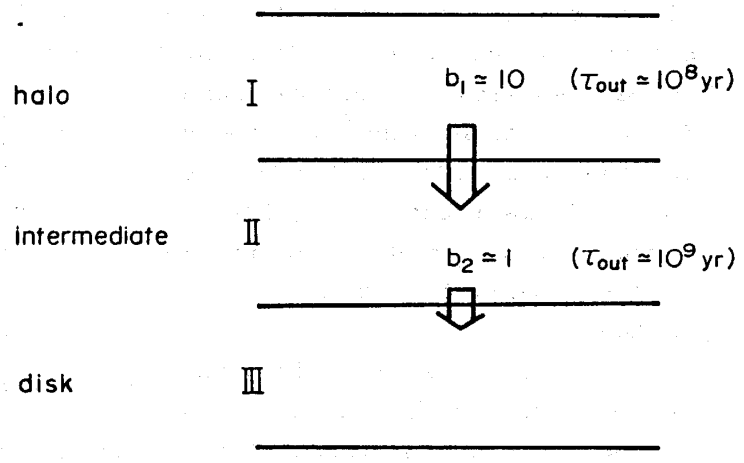

Fig. 1. Three zone model.

mass function is constant. Further, we assume that the star-formation rate is proportional to the gas mass, and the gas flows out at a rate in proportional to the star formation rate. Here and hereafter a and b denote the proportional constants for these relations, respectively.

As for the numerical values of parameters, we use the conservative values which are usually adopted for the chemical evolution in the solar neighborhood, e.g., the fraction of locked-up mass in long-lived stars in each generation of stars is taken to be 0.8, and the yield of heavy elements is 0.01[2]. The above assumptions and approximations make us capable to describe the time evolutions of gaseous and stellar masses, and metallicity in analytical form.

We adopt common values of parameters concerning the stellar formation and evolution for three zones except the outflow parameter b. The values of b are $b_1 = 10$, $b_2 = 1$, and $b_3 = 0$ for the respective three zones, corresponding to the gas outflow times, for the star formation time, a^{-1}, is 10^9 yr.

§3. Results

Figure 2 shows the time evolutions of gaseous and stellar masses for the respective zones. The mass scale in the ordinate is normalized by the initial gas mass in Zone I. In this case the initial gas mass in Zone II is set to be the same as that in Zone I. Zone I loses the gaseous mass in a time scale of 10^8 yr, as mentioned above, and Zone II receives the gas and flows out to Zone III in a time scale of 10^9 yr. The broken lines represent the time evolutions of stellar mass.

The chemical enrichments in Zone I are shown in Figure 3, where the metallicity distribution among the stars formed in Zone I is represented in a cumulative form: the abscissa gives the metallicity in [Fe/H] and the ordinate shows the fraction of stars formed with metallicity abundance less than [Fe/H]. The broken lines represent model predictions for some values of b in addition to $b_1 = 10$. The model with $b = 0$ corresponds to the "simple model", and we can see that the gas outflow has an effect to reduce the yield of heavy elements in appearance. The thick line shows the distribution for the globular clusters with galactocentric distance larger than 10 kpc, which is derived from the observational data compiled by Zinn[9]. We can see that a sufficient fit to the observed distribution is given by a model with $b_1 = 10$. This result is essentially the same as Hartwick's[4].

In this case of $b = 10$ we note that the gas outflow time, 10^8 yr is just in coincident with the free-fall time of protogalactic gas cloud, if we assume the initial radius of the cloud to be the extent of outer halo, i.e., about 30 kpc, and the mass of protogalaxy is $2 \times 10^{11} M_\odot$. So, the outflow from the halo region may be regarded as the contracting gas flow towards the inner region of protogalaxy.

The metallicity enrichment in Zones II and III are shown by the broken lines in Figures 4 and 5, respectively. Thick lines show the observed distributions for stars more than a kiloparsec from the galactic plane (Figure 4) and for stars within a kiloparsec of the galactic plane (Figure 5), respectively. The observational data are the distributions for G and K giants, which is derived from a survey at the galactic poles by Hartkopf and Yoss[3]. We can see an excellent agreement with the model prediction also in these zones.

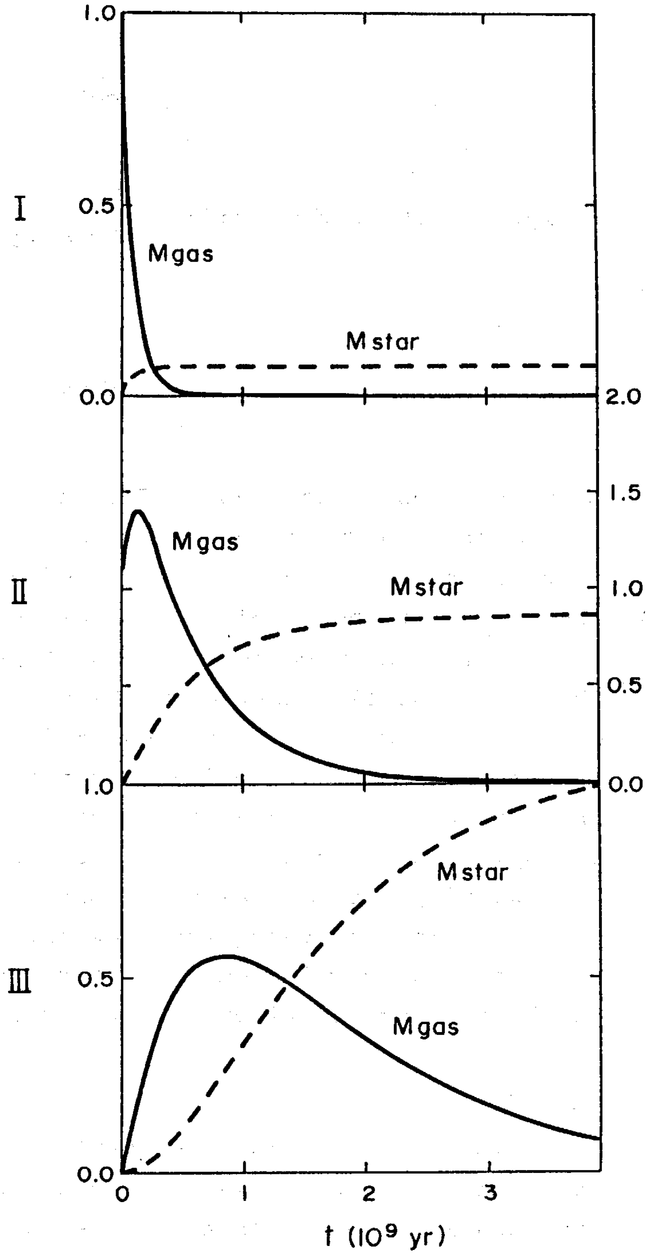

Fig. 2. The time evolutions of gaseous (M_{gas}) and stellar masses (M_{star}) for the three zones. The mass scale in the ordinate is normalized by the initial gas mass in Zone I.

Thus, as shown by Figures 3, 4, and 5 the essential characteristics of metallicity distributions for tracers throughout the whole Galaxy can be explained consistently by the present three zone model, if we adopt $b_1 = 10$ and $b_2 = 1$ for the parameters which express the efficiency of gas flow from Zone I to Zone II, and from Zone II to Zone III, respectively.

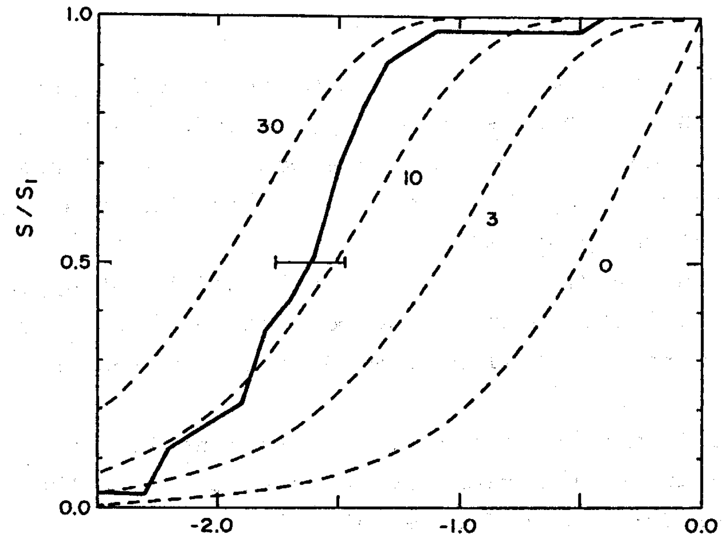

Fig. 3. The metallicity enrichments in Zone I. Metallicity distributions are represented in a cumulative form: abscissa gives the metallicity in [Fe/H] and the ordinate shows the fraction of stars formed with metallicity less than [Fe/H]. The broken lines show the distribution predicted by models with some values of b, the ratio of gas outflow rate to star-formation rate. The thick line represents the distribution for globular clusters with galactocentric distance larger than 10 kpc.

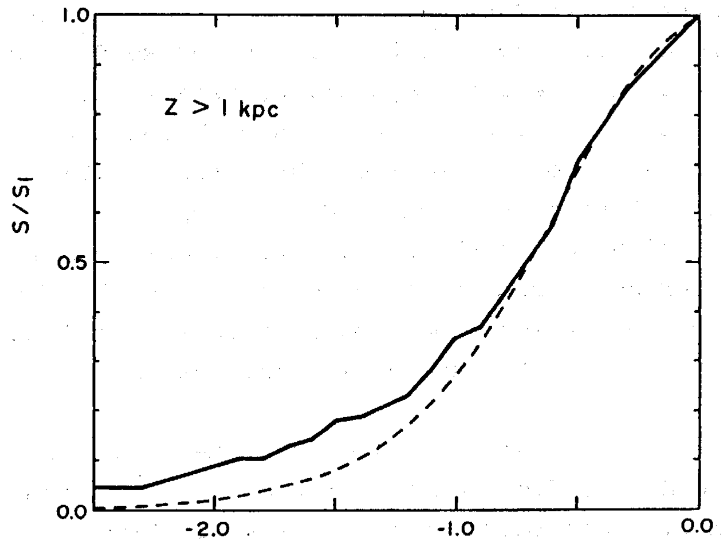

Fig. 4. The metallicity enrichment in Zone II (broken line). The thick line shows the observed distribution for stars more than a kiloparsec from the galactic plane.

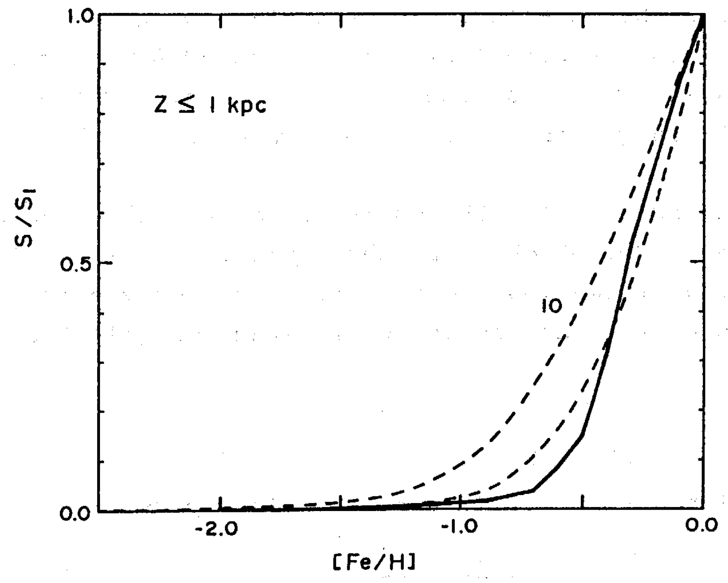

Fig. 5. The metallicity enrichment in Zone III (broken line). The thick line represents the observed distribution for stars within a kiloparsec of the galactic plane.

§4. Discussion

From the observed range of metallicity distribution the Zone I apparently corresponds to outer halo region of the present Galaxy, which has an extent of several tens kiloparsec from the galactic center. The population in this region is considered to be formed during the first 10^8 yr, in the free-fall phase of the initial collapse of the protogalaxy.

The Zone III corresponds to the disk region in a scale height of approximately one kiloparsec from the galactic plane. The population in this region is considered to be formed from the gas fallen from the outer region in a time scale of 10^9 yr.

The ratio of stellar mass formed in Zone I to that in Zone III is 1 to 13.5 in our model, and this value is approximately in agreement with the observed ratio, e.g. 1 to 20 as derived by Haud et al.10).

On the other hand, the intermediate Zone II has no definite observed candidate. The thick disk component as suggested by Gilmore and Reid7) cannot be a direct correspondence to the intermediate population, because the estimated total mass of so-called thick disk component is much smaller than the model prediction, and so it may be only a part of the intermediate population in our present model. Instead the intermediate component should be interpreted as a population which occupy the inner part of galactic halo with an extent of several kiloparsec. From the time scale of metallicity enrichment, this intermediate component would be a population formed during the quasistatic contraction for 10^9 yr after an initial collapse of the protogalaxy.

The two-stage evolution of galactic halo is also suggested by a fact that the globular clusters are divided into distinct two groups with different spatial distribution and kinematics according to their metallicities9). Our present model naturally explains the metallicity distribution of globular clusters, i.e., the metal poor clusters with [Fe/H] less than -0.8 were formed for the first 10^8 yr in the earlier stage of the halo evolution, and the metal-rich clusters with [Fe/H] larger than -0.8 were formed during the succeeding 10^9 yr11).

Thus the metallicity distributions for the whole region of the Galaxy can be reproduced by our three-zone model which adopt the common, standard values for parameters concerning stellar formation and evolution, but only allows for gas flows between the respective zones in the early stage of galactic evolution.

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