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Globular cluster formation from cloud-cloud collisions

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Abstract. Hydrodynamic evolution of supernova remnants in collided proto-cluster clouds is investigated in the frame work of a supernova-driven star formation scenario. It is found that the relative velocity of proto-clouds must be greater than a certain value, which is a function of the mass of each proto-cloud, to produce a stellar cluster with little dispersion of Fe/H ratios among the member stars. The metallicity distribution function for globular clusters in the Galactic halo is calculated from a simple model. This calculation shows that cloud-cloud collisions can reproduce the observed metallicity distribution function for globular clusters. Before cloud-cloud collisions, each cloud has been enriched with heavy elements according to a supernova-driven star formation scenario that reproduces the observed abundance distribution function for the Galactic halo field stars.

Key words. globular clusters: general – Stars: formation – ISM: supernova remnants

1. Introduction

The fact that there is no extremely metal-poor star with [Fe/H]< -2.5 in globular clusters (GCs) suggests that the proto-cluster clouds already possessed a certain amount of heavy elements. A mechanism to form such clusters is cloud-cloud collisions in which each cloud undergoing star formation (Murray & Lin 1993). Cloud-cloud collisions can leave shocked gas with some heavy elements and without either stars or dark matter. In this shocked gas, star formation commences. We will discuss the influence of subsequent supernova explosions on the shocked gas in some detail and obtain a condition to break up the gas cloud.

This merging scenario must be reconciled with the observed metallicity distribution function (MDF) for the Galactic GCs. Lee, Schramm, & Mathews (1995) tried to reproduce the MDF with a merger model and succeeded in reproducing a certain feature. However, their age-metallicity relation is different from ours that reproduces the observed MDF for the halo field stars (Tsujimoto, Shigeyama, & Yoshii 1999). Thus it is not clear if the model of Lee et al. (1995) can explain the MDFs for the field stars and GCs at the same time. We have performed some calculations similar to Lee et al. (1995) to reproduce MDFs for both field stars and GCs.

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2. Cloud-cloud collisions

Suppose that identical star forming clouds move in the halo under its gravitational field. Then the formation rate of GCs $dN_{\rm gc}/dt$ through cloud-cloud collisions will be written as

$$\frac{dN_{\rm gc}}{dt} = f\sigma n_{\rm cl}^2 vV, \tag{1}$$

where $f\sigma$ denotes the effective cross section for GC formation through cloud-cloud collisions. Each cloud has a geometrical cross section of σ and moves at speed v in the halo with the volume of V. The radius of each cloud is assumed to be 40 pc. Clouds are uniformly distributed in the halo with the number density $n_{\rm cl}$. The evolution of $n_{\rm cl}(t)$ is described by the differential equation

$$\frac{1}{V}\frac{dn_{\rm cl}V}{dt} = -2\sigma n_{\rm cl}^2 v - \frac{n_{\rm cl}}{t_{\rm SN}}\theta(t - t_{\rm SF} - t_0), \tag{2}$$

where the second term in the r.h.s. denotes the destruction of a cloud due to SNe at the end of star formation. Here two time scales $t_{\rm SF}$ and $t_{\rm SN}$ have been introduced to describe the duration of star formation in each cloud and the time scale of SN contribution, respectively. The initial total number of proto-clouds is assumed to be 16,000 so as to give the total mass of the baryon component of the Galaxy. The duration of star formation is specified by our chemical evolution model for the halo field stars as $t_{\rm SF} = 0.3$ Gyr. The time scale of SN contribution is determined by the life time of massive stars as $t_{\rm SN} = 10$ Myr. The time when the star formation starts is denoted by t_0. As discussed in Lee et al. (1995), the volume V of the galaxy also evolves according to the self-gravity as

$$\begin{aligned}\frac{dV}{dt} &= 4\pi r^2\frac{dr}{dt}\\ &= -4\pi r^2\sqrt{\frac{2GM_{\rm MW}}{R_{\rm max}}\left(\frac{R_{\rm max}}{r} - 1\right)}.\end{aligned} \tag{3}$$

Here G denotes the gravitational constant, $M_{\rm MW}$ the mass of the Milky Way, and $R_{\rm max}$ is the maximum radius of the halo. This equation describes the Milky Way shrinking from its maximum size. Thus the time is measured from when the halo has its maximum size ($R_{\rm max} = 270$ kpc is used as a fiducial value). The cloud velocity is given by the virial velocity as $v = \sqrt{0.4GM_{\rm MW}/r}$. The resultant MDF is shown in Fig. 1 and compared with the observations. The free parameters of $f = 0.13$ and $t_0 = 2.02$ Gyr give the best fit to the halo component of the observed MDF. The shape of the MDF is found to be sensitive to the value of t_0. Thus it is expected that different galaxies have quite different MDFs of metal-poor GCs. The collapse needs to halt when $r = 40$ kpc to reproduce the metal-poor end of the MDF irrespective of $R_{\rm max}$. Otherwise, there would be too few GCs with [Fe/H]< -1.8. The subsequent star formation needs to finish soon after the first SNe explode in order to account for no dispersion in the metallicity of the cluster stars (see Tsujimoto & Shigeyama 2003).

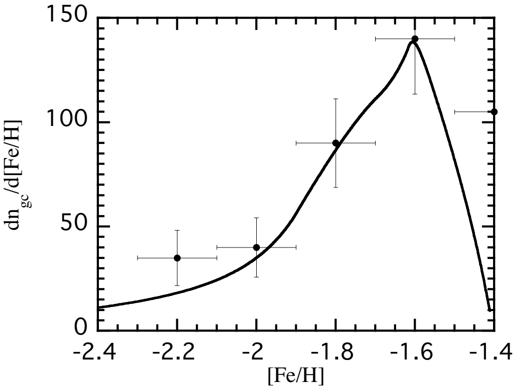

Fig. 1. The MDF for globular clusters in the Galactic halo (Filled circles: observations (Harris 1996); solid curve: a result from calculations based on a merging scenario). See the text for details.

3. Star formation after merging

After two clouds collide, a strong shock wave is formed and compresses the gas to leave a dense cloud. From this compressed gas, stars are assumed to form with the metallicity inherited from the gas. In our SN-driven star formation scenario, the star formation history is determined by the evolution of SNRs that is affected by the environment. A critical condition to show a sign of chemical evolution is whether the star formation proceeds for generations or quit with a single or a few generations at most. This condition is given by comparing the maximum size of an SNR and the cloud. If the size of an SNR exceeds that of the cloud, the SNR cannot assemble the gas necessary to form stars of the next generation. The resultant GC contains a single generation of stars showing no dispersion in Fe/H ratios. Otherwise, the cloud contains multiple generations of stars with different Fe/H, that might resemble ω Cen stars (Tsujimoto & Shigeyama 2003). An additional condition for the formation of multiple generations of stars is that the mass fraction $X_{\rm init}$ of stars in a cloud at the beginning should be less than 1 %, as was already discussed in Tsujimoto et al. (1999).

For a quantitative but simple discussion, we shall consider a head-on collision of two identical clouds. Suppose that each cloud moving at the speed v_1 is spherical and uniform with the mass $M = 10^6\,M_\odot$ and the radius $R = 40$ pc. This mass corresponds to the Jeans mass soon after the recombination. The velocity dispersion σ of $\sim$ 10 km s^{-1} that accounts for the elemental abundance patterns of extremely metal-poor field stars (Shigeyama & Tsujimoto 1998) has enabled us to estimate R. The density ρ_2 of the strongly shocked region is given by the formula

$$\rho_2 = \rho_1\left(1 + \frac{2}{\sqrt{1+\frac{4P_1}{\rho_1 v_1^2}} - 1}\right),$$
$$\sim \rho_1\left(\frac{\rho_1 v_1^2}{P_1}\right), \qquad (4)$$

where $P_1 = 2\sigma^2\rho_1/3$ is the pressure in the pre-shocked gas and the initial mean density of the cloud is denoted by ρ_1. Here the shock is assumed to be isothermal because the cooling time is several orders of magnitude shorter than the sound crossing time. As a result, the collision leaves a cloud with a disk-like shape with the half width of $W = 2R \times (\rho_1/\rho_2) = 4GM/(3v_1^2)$. The shocked cloud may not feed an SNR because the maximum size of an SNR given by $R_{\rm SNR} \sim 0.9\,{\rm pc}\left(v_1/(200\,{\rm km\,s^{-1}})\right)^{-2/3}$ (Shigeyama & Tsujimoto 1998) exceeds the width of the cloud. Thus the cloud with $R_{\rm SNR} > W$ will produce a GC with a single generation of stars while $R_{\rm SNR} < W$ will lead to a GC with multiple generations. The criterion gives the maximum velocity

$$v_{1,\,\rm max} \sim 33\,{\rm kms^{-1}}\left(\frac{\sigma}{10\,{\rm km\,s^{-1}}}\right)^{\frac{37}{28}} \times \left(\frac{M}{10^6 M_\odot}\right)^{\frac{1}{4}}, \qquad (5)$$

that can produce a GC with some dispersion in Fe/H. Since clouds move at $\sim$ 200 km s^{-1} in the gravitational potential of the Milky Way, it is rare to collide with such a low velocity. In fact, if all the clouds move at 200 km s^{-1} and their distribution is isotropic in the velocity space, then the fraction of collisions with $v_1 < 33$ km s^{-1} is ~ 0.027. Note, however, that the total mass and the velocity dispersion of the proto-cluster clouds generating ω Cen must be significantly greater than those assumed here, which lead to a greater $v_{1,\rm max}$ (Eq. (5)).

4. Final stage

When SNe from the first generation stars break up the gas, it is likely that the available energy from SNe exceeds the gravitational binding energy of the cloud. Since the dynamical timescale of the cloud discussed above (∼4 Myr) is shorter than that for the evolution of massive stars, the stellar component with the velocity dispersion much smaller than that of the gas will shrink to form a bound system before SNe expel the remaining gas. In fact, the virial theorem implies that the half mass radius $R_{\rm h}$ of the newly-formed GC is $R_{\rm h} \sim GM_{\rm GC}/(4\sigma^2) \sim 2.2$ pc. This value is significantly smaller than the initial radius and is in accordance with the observation. When the star formation repeats for generations as in the ω Cen proto-cloud, the available energy from SNe must be counted to specify the time of gas removal as was done in Tsujimoto & Shigeyama (2003). This energy was found to be insufficient for gas removal. The passage through the Galactic gaseous disk might strip the remaining gas.

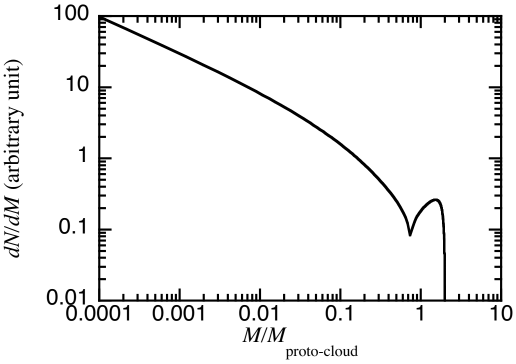

Fig. 2. The mass function given by Eq. (7).

5. Mass function

It is not an easy task to derive globular cluster mass function from the first principle, because it involves star formation processes as well as other complicated thermal processes. Thus we simply calculate the mass distribution function of the overlapped region of colliding two identical clouds. If the star formation efficiency is approximated to be constant, this mass distribution function would give the form of globular cluster mass funciton. Suppose two identical clouds with the mass M and radius R collide with an impact parameter b. The density distribution of each cloud is given by $\rho(r) = M/\left(4\pi R r^2\right)$, where r denotes the distance from the center of the cloud. The mass m of the overlapped region at collision is given by a function of non-dimensional parameter $\xi = b/R$ as

$$m(\xi) = \frac{M}{2}\left\{\frac{(\xi^2-1)}{\xi}\ln|\xi-1| + 3 - \frac{3}{2}\xi\right\}, \quad \text{for } 0 \le \xi < 2. \tag{6}$$

Thus the mass spectrum $dN(m)/dm$ of the overlapped region becomes

$$\frac{dN(m)}{dm} = 2\pi R^2 n v \xi \frac{d\xi}{dm} = \frac{4\pi n v R^2}{M} \times \frac{\xi}{\left\{\frac{1}{\xi} - \frac{1}{2} + \left(1 + \frac{1}{\xi^2}\right)\ln|\xi - 1|\right\}}, \tag{7}$$

where n denotes the number density of proto-clouds, v their mean velocity. The shape of this function is given in Fig. 2.

6. Summary

We have discussed star formation driven by supernovae after two proto-clouds collide. Intense collisions are preferred for globular cluster formations without significant dispersion in Fe/H ratios among the member stars. Less intense collisions would lead to subsequent star formations to make clusters like ω Cen. A collision of massive clouds inclines to the formation of such a cluster according to Eq. (5).

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