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Accretion Processes onto Globular Cluster Stars

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Abstract: We have observed strong correlations between the r-process and s-process elements abundances and the α elements abundances in field metal-poor stars. We explain those correlations with the EASE scenario, which closely links the origin of these stars to globular clusters. According to this scenario, thick disk and field halo stars were born in globular clusters from which they escaped, either during an early disruption of the cluster (forming Pop IIa) or through a later disruption or an evaporation process (Pop IIb). We assume that before escaping from the globular cluster the PopIIb stars will accrete some of the s-process elements matter which is ejected by the intermediate-mass stars when they reach the Asymptotic Giant Branch. Here we examine and compare three different accretion situations. If the globular cluster's binding potential is strong enough, the gas ejected by the AGB stars can sink to the cluster's center and form a reservoir from which the lower-mass stars can accrete matter. If the binding potential is not strong enough, the gas will flow out of the cluster, and the stars can accrete from this flow. And, finally, main sequence stars in the cluster can accrete gas during close encounters with mass-losing AGB stars.

1 Introduction

We have obtained accurate relative abundances for a sample of 21 mildly metal-poor field stars from the analysis of high resolution, high signal-to-noise spectra (Jehin et al. 1999a). Looking for correlations between the element abundances, we found that the α-elements and the iron-peak elements are well correlated with each other, and the abundances of the rapid neutron-capture elements (r-process elements) are well correlated with those of the α-elements, which is in agreement with the generally accepted idea that those elements are produced during the explosion of massive stars. For the slow neutron-capture elements (s-process elements), we find that the stars can be separated into two subpopulations. For those in PopIIa, the abundances of the s-process elements vary little while that of the α elements increases up to a maximum value. The stars in PopIIb show a large range in their s-process elements abundances, while they show a constant and maximum value for the abundances of the α elements. We called this behavior the "two-branches diagram". To explain this result, we have developed the EASE

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scenario, which links the metal-poor field stars to the globular clusters. The observations and the EASE scenario are described in more details in Jehin et al. (1999a, 1999b).

One crucial piece of this scenario consists in explaining how unevolved stars (PopIIb) can get enriched in s-process elements while the α elements abundances remain constant. The s-process elements are mainly produced in asymptotic giant branch (AGB) stars, where they are brought to the surface through dredge-up processes. The AGB stars lose a large fraction of their mass through stellar winds or superwind events, releasing the s-process elements enriched gas in the interstellar medium. Main sequence stars can accrete this matter, thereby enriching their surface abundances in those elements.

The idea that the gas ejected by the AGB stars in globular clusters can be accreted by other stars in the cluster is not an entirely new one. Observations of globular clusters show that they contain much too little gas or dust, compared to what is lost by their AGB stars, and globular cluster stars also show many abundance anomalies. Many authors have been intrigued by the fate of the gas in globular clusters, and among them, Scott & Rose (1975), Faulkner & Freeman (1977), VandenBerg & Faulkner (1977), VandenBerg (1978), and Scott & Durisen (1978), and accretion has already been suggested as a plausible mechanism to explain abundance anomalies (D'Antona et al. 1983, Faulkner 1984, Faulkner & Coleman 1984, Smith 1996).

In order for accretion to be efficient, the gas density should be as high as possible, the relative velocity of the accreting star with respect to the gas should be low, and the time during which the accretion takes place should be long.

2 Mass Lost by AGB Stars

When a star reaches the AGB phase it will lose a large fraction of its mass. We assume here that those stars lose their mass instantaneously, so that the rate of mass injection in the cluster is given by

$$\frac{dM_g}{dt} = -M_{ej}\frac{dN}{dt}, \tag{1}$$

where M_{ej} is the mass ejected by a star reaching the AGB, and dN/dt is the rate at which the cluster stars reach the AGB. It can be rewritten in terms of the mass spectrum dN/dM and the rate dM/dt at which stars leave the main sequence:

$$\frac{dN}{dt} = \frac{dN}{dM}\frac{dM}{dt}. \tag{2}$$

We assume a power-law mass spectrum,

$$\frac{dN}{dM} = (\alpha - 2)(M_l^{2-\alpha} - M_u^{2-\alpha})^{-1} M_{cl,0} M^{-\alpha}, \tag{3}$$

where α is the power-law index of the initial mass spectrum, M_l and M_u are its lower and upper mass limits, and $M_{cl,0}$ is the globular cluster's initial mass. The rate dM/dt can be derived from the following equation, relating the mass M of a star (in units of $1M_\odot$) to its lifetime on the main sequence t (in years) (Bahcall & Piran 1983)

$$\log t = 10 - 3.6 \log M + (\log M)^2. \tag{4}$$

For the mass ejected by each star as it reaches the AGB, we fitted the results from Weidemann & Koester (1983):

$$M_{ej} = -1.5625 \times 10^{-2} M^2 + 1.04375 M - 0.528, \tag{5}$$

where the masses are again expressed in units of $1M_\odot$.

Finally, we have

$$M_g(t) = \int_{t_1}^{t} \frac{dM_g}{dt'} dt' \tag{6}$$

where t_1 is the time at which the highest mass star ($M = M_u$) reaches the AGB.

Using typical values for the parameters, $M_u = 10M_\odot$, $M_l = 0.1M_\odot$, and $\alpha = 2.35$ (the Salpeter's IMF), we obtain that about 20% of the cluster's initial stellar mass is returned to the cluster as gas in 10 Gyrs. Most of the gas is ejected into the ISM within the first Gyr.

3 Fate of the Gas in Globular Clusters

Smith (1996) has derived criteria for the fate of the ejected gas in globular clusters. By comparing the stellar-ejecta speed to the cluster's escape speed, he obtained the following criterion for retention of the gas in the cluster:

$$\log(M_{cl}) - \log(r_{eff}) > 3.72 + \log(1 - f_c) + 2\log v_{10} \tag{7}$$

where M_{cl} is the mass of the cluster (in units of $1M_\odot$), $r_{eff} = \sqrt{r_c r_t}$ is the cluster's effective radius (in parsec), r_c and r_t are the cluster's core and tidal radii, f_c is the fraction of the initial ejecta energy lost via radiative cooling and v_{10} is the stellar-ejecta speed in units of 10 km/s. He also shows that many Galactic globular clusters obey this relation, using present-day parameters. Therefore, in tightly bound globular clusters, the gas released by the AGB stars can be retained in the cluster's center, forming a central reservoir of gas. The gas will accumulate in the cluster's center between passages through the galactic plane, at which time the cluster will be swept clean of the gas.

If the cluster is not dense enough to retain the gas, it can escape from the cluster either through a continuous wind, when the cluster crossing time for individual ejecta shells is long compared to the average time between individual mass-loss episodes, or through stochastic mass loss events. The criterion for establishing a continuous wind is

$$\log(M_{cl}) + \log(r_{eff}) > 6.96 - \log\alpha_{19} + \log(M_{ej}) + \log v_{10} \tag{8}$$

where $\alpha_{19} = (dM/dt)/M$ is the inverse characteristic time of mass loss in units of 10^{-19}s^{-1}.

4 Accretion of Gas in Globular Clusters

The accretion rate is determined by the Bondi's formula (Bondi, 1952):

$$\frac{dM_s}{dt} = 4\pi\lambda(GM_s)^2\rho_g(v_{rel}^2 + c_s^2)^{-3/2} \tag{9}$$

where M_s is the mass of the accreting star, ρ_g is the unperturbed gas density, v_{rel} is the relative velocity of the star with respect to the gas, c_s is the sound speed in the gas, and λ is a parameter of order 1.

4.1 Accretion from a Reservoir of Gas

If we assume that the accretion takes place from a reservoir of gas, and that the density is homogeneous within the gas reservoir, we have

$$\rho_g(t) = \frac{M_g(t) - M_a(t) - M_{esc}(t)}{4\pi r_g^3/3} \tag{10}$$

where M_g is the total (integrated) mass of gas ejected by the AGB stars in the globular cluster, M_a is the mass of gas which has been re-accreted by cluster stars, M_{esc} is the mass of gas lost from the cluster when crossing the galactic plane, and r_g is the radius of the gas reservoir. The mass of the accreting star, $M_s = M_{s,0} + M_{s,a}$, where $M_{s,0}$ is its initial mass and $M_{s,a}$ is the mass it has accreted. A given star will only spend a fraction γ of its lifetime inside the gas reservoir, as its orbit in the cluster will take it out of the gas reservoir. We therefore write

$$M_{s,a}(t) = \gamma \int_{t_1}^{t} \frac{dM_s}{dt'} dt'. \tag{11}$$

The total amount of gas which is accreted by the cluster stars is obtained by integrating the mass accreted by each star over the mass spectrum:

$$M_a(t) = \int_{M_l}^{M_{TO}} M_{s,a} \frac{dN}{dM} dM \tag{12}$$

where M_l is the lower limit of the mass spectrum dN/dM, and M_{TO} is the turn-off mass.

Assuming that the radius r_g of the gas reservoir is given by the core radius of the cluster, and taking the ratio of the number of stars in the core to the total number of stars in the cluster for the parameter γ, we find that stars in large and tightly bound clusters (47Tuc, M15, ...) can re-accrete up to 90% of the ejected gas. Individual stars in the cluster can therefore accrete a significant fraction of their initial mass.

4.2 Accretion from a wind

Smith (1996) has shown that accretion from a wind is much less efficient than accretion from a central reservoir. Indeed, even though in this case we have $\gamma = 1$, the gas density will be several orders of magnitude lower, leading to a much smaller accretion rate.

4.3 Accretion during Close Encounters

Main sequence stars can also accrete matter during close encounters with mass-losing AGB stars. In this case, the accretion time will be much smaller, but the gas density will be much larger. Here, it will be given by

$$\rho_g = \frac{\dot{M}_g}{4\pi r^2 v_g} \tag{13}$$

where $\dot{M}_g$ is the AGB star mass loss rate, v_g is the ejected gas velocity, and r ($r > R_{AGB}$) is the distance to the star. Replacing ρ_g into Eq. (9), we have

$$\frac{dM_s}{dt} = \lambda G^2 \frac{M_s^2 \dot{M}_g (v_{rel}^2 + c_s^2)^{-3/2}}{r^2 v_g}. \tag{14}$$

For an order of magnitude result, we use $r \sim b$ (b is the impact parameter), $v_{rel} > c_s$, and the interaction time $\Delta t \sim b/v_{rel}$. We get

$$M_{s,a} \sim \frac{G^2 M_s^2 \dot{M}_g}{b v_g v_{rel}^4}, \tag{15}$$

which gives $M_{s,a} \sim 10^{-5} M_{s,0}^2$ for $\dot{M}_g \sim 10^{-6} M_\odot/\mathrm{yr}$, $v_g \sim 10\mathrm{km/s}$, $v_{rel} \sim 10\mathrm{km/s}$ and $b = 1\mathrm{au}$. This result should be multiplied by the number of encounters the main sequence star will have with AGB stars during its lifetime. We expect however the accretion through this process to be much less efficient than the accretion from a central reservoir of gas.

5 Conclusions

We have investigated different gas accretion processes in globular clusters, namely, accretion from a central reservoir of gas, accretion from a cluster wind, and accretion during close encounters with mass-losing stars. By far the most promising process is the first one.

We argue that accretion of gas by globular cluster stars has to take place, at least to some degree, and that it could be large in some cases. Furthermore, even a small amount of accretion will affect the surface composition of main sequence stars. The amount of accretion will depend on many parameters, such as the stellar initial mass, velocity, and orbit in the cluster, the cluster's core radius, concentration, mass, and orbit in the Galaxy, the AGB ejecta speed, etc... so that the accretion will be highly variable from star to star.

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Discussion

I. Iben: Are you now able to explain the failure of observers to find hydrogen (neutral on ionized) in GCs ?

A. Thoul: The upper values I find are not much higher than the upper limits determined from observations, at least for some clusters. For other clusters, such as ω Cen for example, you still need another process to expell some of the gas.

F. D'Antona: Regarding the UV field which would expell the globular cluster gas, we must remember that during the evolution of the most massive AGB stars, which are in any case the best pollutors, there are no blue HB stars. Furthermore, the post AGB evolution is fast, it lasts probably a few years in the planetary nebula hot regime before the massive core remnant becomes a white dwarf. So accretion is favored at these early times. It may well be that it stops when the planetary nebula evolution begins to last for a longer time.

R. Gratton: The concentration of M15 and 47 Tuc you use are the present values. Concentration was likely smaller in the past. How will the results change if values more appropiate for the early phase where most of the accretion might have occured are used ?

A. Thoul: Of course I know that the parameters must have been different in the past. The cluster core was probably larger (i.e. cluster less concentrated). On the other hand, the velocity dispersion was maybe smaller, which would favor accretion. It would be nice to have values for these parameters at earlier times but we don't have them. Maybe that will become possible with the results of simulations of globular clusters dynamical evolution.

R. Kraft: One needs to look carefully at the composition of the ejected material as a function of mass of original star, both at the end of AGB and also at the end of first ascent. If this material is still H-rich, then it won't change composition in the low mass (MS) stars very much. So relative abundances need to be considered as a function of input abundance.

A. Thoul: I agree with you.

R. Cayrel: Bondi's accretion formula does not take into account the fact that a star has a corona and a wind, probably much more important in a young star than in the present Sun.
I think that the competition between mass loss and accretion should be studied to clarify which one wins !

A. Thoul: I agree. In fact we also expect to have both gas, ionized or not, and dust in the intracluster medium. Those components may be acreted differently. The composition of the accreted material will depend on that effect.

R. Gratton: The mass of the Hyades (7 x 10^7yr) giants is similar to those of turnoff stars : this supports the assumption that most mass loss in intermediate mass stars occurs on the AGB.

M. Hilker: How often do you expect a removal of the retained gas due to the passage of the cluster through the galactic plane ?
(One should expect to see differences for clusters that are crossing the disk more often than others).

A. Thoul: I have taken this effect into account. The period of the cluster's orbit in the galaxy is one of the input parameters, and it does of course affect the results as you expect.

S. Ryan: If some stars accrete a large fraction of their initial mass, their evolutionary rates would change. Does the observed spread in turnoff colors provide any constraints on the amount of mass accretion that has occured ?

A. Thoul: Actually no, because most of the accretion takes place during the first 10^9 years, and therefore it does not change today's turnoff mass.