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Segregation of dust and abundance inhomogeneities in globular clusters

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Summary. Segregation of dust in globular cluster protoclouds is considered as a possible mechanism for producing the observed heavy element abundance inhomogeneities within globular clusters. Heavy elements in the protocloud are locked up in dust grains. Under the influence of gravitational and radiative forces the dust grains move relative to the gas. Segregation of dust towards the protocloud centre produces a radial gradient in the dust-to-gas mass ratio within the cloud. Stars that form from material with different dust-to-gas mass ratio then have different heavy element abundances. A radial abundance gradient is thus naturally produced. If the globular cluster has a long relaxation time, the radial gradient may survive up to the present time, otherwise only star to star variations in abundance are observed. For any significant abundance variations to be produced it is required that the dust segregation time-scale be of the order of or less than the protocloud lifetime. The segregation time-scales are estimated to be $\sim 10^7$–10^8 yr, so that primordial abundance inhomogeneities can be established by dust segregation processes provided the globular cluster protoclouds had lifetimes $\sim 10^8$ yr, similar to the mean lifetime of the large interstellar clouds.

1 Introduction

Chemical abundance inhomogeneities within globular clusters are well established. These have been reviewed in recent years by Kraft (1979), McClure (1979), Freeman & Norris (1981), Freeman (1985) and Smith (1987). While the most common abundance anomalies that involve carbon and nitrogen in the cluster red giants could be understood in terms of a mixing process, in which the dredge-up of the products of nucleosynthesis in the red giant interior is the cause of the surface abundance anomalies, a number of other observed features of the abundance inhomogeneities in some globular clusters cannot be explained by the mixing hypothesis, and require a primordial enrichment process in which the inhomogeneities are introduced early in the life of the cluster. There are three main aspects of abundance inhomogeneities that require a primordial origin.

(i) *Heavy element inhomogeneities.* Inhomogeneities in Ca, Fe, Na, Al and other heavy elements in the globular clusters ω Cen and M22 as well as Na and Al variations in many other clusters (e.g. NGC 6752, M5, 47 Tuc) have been found. Globular cluster red giants are not expected to nucleosynthesize heavy elements such as Ca or Fe within their interiors. Therefore, any such heavy element abundance inhomogeneities observed now must have existed in the gas from which the cluster stars formed. Also, the CN, CH variations that are observed to be correlated with these heavy element variations must have a similar origin (Norris & Smith 1983).

(ii) *Radial gradients.* Radial colour gradients in a number of globular clusters and radial CN gradients in 47 Tuc and ω Cen have been found. The radial gradients indicate that the inner regions of the clusters are more metal rich. Interestingly, only those globular clusters that have longer than average relaxation times show the radial gradients. This is easy to understand if the gradients were primordial, so that they survive to the present time only in clusters with relatively long relaxation times (Freeman 1985).

(iii) *Variations among the main-sequence turn-off stars.* The abundance variations in ω Cen and 47 Tuc are found even among the main-sequence turn-off stars and in a number of other clusters (e.g. M13, NGC 362, NGC 6752, M3) C and N variations have been found among stars fainter than the luminosity cut-off predicted by Sweigart & Mengel (1979) for the onset of mixing. If the abundance variations were of a primordial origin there would be no difficulty in explaining these observations.

A number of hypotheses for the primordial origin of globular cluster abundance inhomogeneities have been proposed. These include: early supernova activity in the gas cloud (i.e. the globular cluster protocloud) out of which the cluster stars formed (Freeman & Rodgers 1975; Kraft 1979), sweeping up of heavy elements from the galactic disc (Iben 1980), merger of two or more protoclouds of different metallicities (Norris *et al.* 1981) and accretion on to stars of metal enriched material from stellar winds (Bell *et al.* 1981; D'Antona, Gratton & Chieffi 1983).

In this paper we propose an alternative mechanism that may operate in globular cluster protoclouds to produce the primordial abundance inhomogeneities. The physical process we consider is the segregation of dust in the protoclouds.

2 Segregation of dust in globular cluster protoclouds

The galactic globular clusters show a large spread in the mean metallicity Z (e.g. Hartwick 1976; Kraft 1979). In the metal poorest clusters [such as M92 with $[\mathrm{Fe/H}]=-2.2$, where $[X]=\log X$ (cluster)$-\log X$ (Sun)] $Z\sim10^{-4}$, while metallicities approaching $Z\sim10^{-2}$ are found in the most metal-rich clusters (such as M71 with $[\mathrm{Fe/H}]=-0.2$). Typically $Z\sim10^{-3}$. This suggests that globular clusters formed from gas that was already enriched in heavy elements to a level indicated by the observed mean metallicity. In the following discussion we assume that a significant fraction of the heavy elements in the globular cluster protocloud was in the form of dust grains as is common in the interstellar medium (e.g. Phillips, Gondhalekar & Pettini 1982).

Gravitational segregation of dust was first discussed by McCrea & Williams (1965). Settling of dust grains in a centrally condensed gas cloud has been studied by Williams & Handbury (1974). Acted upon by gravity and viscous drag forces the dust grains move relative to the gas and segregate towards the cloud centre. In the presence of an external radiation field, radiation pressure forces can also drive dust grains relative to the gas (Flannery & Krook 1978; Williams & Bhatt 1982). As a result of gravitational segregation the dust-to-gas mass ratio, visual extinction and the average dust grain size in the central regions of the cloud increases (Flannery & Krook 1978; Bhatt & Desai 1982). Such effects have been found in a number of interstellar clouds: ϱ Ophiuchi (Carrasco, Strom & Strom 1973), B361 (Clark, Martin & Biretta 1979), NGC 1333 (Turnshek, Turnshek & Craine 1980) and the dark cloud B5 for which the evidence for dust segregation is the most direct (Bhatt 1986). We first discuss the gravitational segregation of dust in the globular cluster protoclouds.

2.1 GRAVITATIONAL SEGREGATION

Consider a globular cluster protocloud of mass M and radius R with a power-law density distribution such that the density at a radial distance r from the cloud centre $\varrho(r)$ is given by

$$\varrho(r)=\varrho_0(R/r)^n \tag{1}$$

where $\varrho_0=(3-n)MR^{-3}/4\pi$ and the mass $M(r)$ within a radius r is given by

$$M(r)=\int_0^r 4\pi r^2\varrho(r)\,dr=4\pi\varrho_0R^nr^{3-n}/(3-n).$$

Initially the cloud material is homogeneous with respect to the heavy element abundance. The metallicity is Z_0 and is constant throughout the cloud. A significant fraction of the heavy elements is locked up in dust grains and the dust-to-gas mass ratio $Z_g(0)$ (which is $\sim Z_0$) is also constant throughout the cloud. For simplicity the dust grains are assumed to be spherical and single sized (radius a). Within the cloud a dust grain at a radial distance r is acted upon by two opposing forces: gravity and viscous drag. The gravitational force towards the cloud centre is given by

$$F_{\text{gravity}}=GM(r)m_g/r^2=16\pi^2G\varrho_0\sigma a^3R^nr^{1-n}/3(3-n) \tag{2}$$

where $m_g=4\pi a^3\sigma/3$ is the mass of the grain with σ as the density of the grain material and G is the gravitational constant. The viscous drag force, opposing the gravitational force, is given by

$$F_{\text{drag}}=-4\pi a^2\varrho(r)v(r)w_{\text{th}}/3 \tag{3}$$

where $v(r)$ is the speed of the grain relative to the gas and w_{th} is the thermal speed of the gas (e.g. Baines, Williams & Asebiomo 1965). The thermal speed $w_{\text{th}}=(8kT/\pi\mu m_{\text{H}})^{1/2}$ where k is the Boltzmann constant, m_{H} is the mass of the hydrogen atom, μ is the mean molecular weight and T is the temperature of the gas.

Under the balance of these two forces the dust grain settles towards the cloud centre with a speed

$$v(r)=-\frac{dr}{dt}=4\pi G\sigma ar/(3-n)\,w_{\text{th}}. \tag{4}$$

From equation (4) it follows that starting from the initial radial distance r_0 at time $t=0$ the dust grain after time t will have settled down to $r(t)$ given by

$$r(t)=r_0\exp\left[-4\pi G\sigma at/(3-n)\,w_{\text{th}}\right]. \tag{5}$$

Thus with the passage of time the dust grains segregate towards the cloud centre. This gives rise to an increase in the dust-to-gas mass ratio in the central regions of the cloud. The time-scale for this process, $(3-n)\,w_{\text{th}}/4\pi G\sigma a$, is grain size dependent. If the dust grains were single-sized there would be no grains left in the outer regions of the cloud beyond a radius $r(t)=R\exp[-4\pi G\sigma at/(3-n)\,w_{\text{th}}]$. However, in reality there is a distribution of grain sizes so that grains with different sizes settle with different time-scales, the largest settling the fastest (Bhatt & Desai 1982; Bhatt 1986). Thus dust segregation does not produce any discontinuities. In the present discussion a represents the average grain size. The relative dust concentration gradually rises towards the cloud centre. Since the heavy elements are locked up in the dust, the settling of dust grains towards the cloud centre leads to an increase in the heavy element abundance Z there. Thus a radial gradient in the heavy element abundance is naturally set up in the cloud as a result of dust segregation. After a time t the average dust to gas mass ratio $Z_g(t)$ within a radius

$r(t)=R\exp[-4\pi G\sigma at/(3-n)w_{\mathrm{th}}]$ follows from equations (1) and (5) and is given by

$$\begin{aligned} Z_{\mathrm{g}}(t)&=Z_{\mathrm{g}}(0)\,M/M[r(t)]\\ &=Z_{\mathrm{g}}(0)\,[R/r(t)]^{3-n}\\ &=Z_{\mathrm{g}}(0)\exp(4\pi G\sigma at/w_{\mathrm{th}})\\ &=Z_{\mathrm{g}}(0)\exp(t/\tau) \end{aligned} \tag{6}$$

where the time-scale $\tau=w_{\mathrm{th}}/4\pi G\sigma a=(8kT/\pi m_{\mathrm{H}}\mu)^{1/2}/4\pi G\sigma a$.

At the end of time t when star formation takes place in such a cloud, the dust containing the heavy elements is incorporated in the constitution of the stars. Stars that form at different radial distances from the cloud centre, from materials with different dust-to-gas ratios, have, therefore, different metallicities (heavy element abundances) at their birth. Thus a globular cluster with radial abundance gradients is produced. If the cluster has a long relaxation time the radial gradient may be preserved even up to the present time. For clusters with shorter relaxation times the stars would have moved considerably from their birth places, so that only star to star abundance variations would now be observed. In either case the range of logarithmic abundance variations that could be expected is of the order ΔZ given by

$$\begin{aligned} \Delta Z&=\log[Z(t)/Z(0)]\\ &\simeq\log(Z_{\mathrm{g}}(t)/Z_{\mathrm{g}}(0))\\ &=0.4343\,(t/\tau). \end{aligned} \tag{7}$$

Thus the abundance spread that can be produced depends on the time available for dust segregation prior to star formation in the protocloud. Significantly large variations ($\Delta Z\sim0.43$ dex) can be produced in a time $t\sim\tau$.

Numerical estimate of the time-scale τ could be made from equation (6): $\tau=(8kT/\pi m_{\mathrm{H}}\mu)^{1/2}/4\pi G\sigma a$, if the parameters T, μ and a characterizing the gas and dust in the globular cluster protocloud were known. As remarked earlier the observed mean metallicities of globular clusters indicate that typically the protocloud material had heavy element abundance $Z\sim10^{-3}$. Silk (1977, 1980) found that for $Z>10^{-5}$ the cooling due to heavy elements and dust grains is efficient and the protoclouds would be cool with $T\sim10$–100 K similar to the large interstellar clouds. With masses ($\geqslant$the globular cluster masses) of the order $10^6\,M_{\odot}$, the globular cluster protoclouds would in fact resemble the galactic giant molecular clouds. In the absence of any available information, we assume that the dust grains in the protoclouds were similar to the dust grains in the interstellar medium and use $a=0.1\,\mu$m and $\sigma=2\,\mathrm{g\,cm^{-3}}$ as the mean values for the dust grain parameters. For the mean molecular weight we use $\mu=2.33$ if the hydrogen in the protocloud gas were in the molecular form and $\mu=1.4$ if it were in the atomic form. The ratio He/H=0.1 is assumed. With these the time-scale τ is obtained as

$$\tau=2.9\times10^{7}\,(T/\mu)^{1/2}\,(\sigma/2\,\mathrm{g\,cm^{-3}})^{-1}\,(a/0.1\,\mu\mathrm{m})^{-1}\ \mathrm{yr}. \tag{8}$$

Thus $\tau\simeq6\times10^7$ yr for molecular gas at $T=10$ K and $\tau\simeq2.4\times10^8$ yr for atomic gas at $T=100$ K.

2.2 RADIATIVE SEGREGATION

Radiation pressure forces on dust grains (Spitzer 1941) can also cause relative motion between dust and gas in interstellar clouds (e.g. Flannery & Krook 1978; Williams & Bhatt 1982). A dust grain of radius a in a radiation field of energy density u experiences a radiation pressure force F_{rad}

given by

$$F_{\rm rad}=\pi a^2 uQ\xi \tag{9}$$

where Q is the efficiency factor for radiation pressure and the factor ξ is a measure of the anisotropy in the radiation field.

The viscous drag force $F_{\rm drag}$ opposing the radiation pressure force is given by equation (3). Under the balance of these two forces, the resulting drift speed v of the dust grains relative to the gas is therefore obtained as

$$\begin{aligned} v&=3uQ\xi/4\varrho w_{\rm th}\\ &=3uQ\xi/4\varrho(8kT/\pi m_{\rm H}\mu)^{1/2}. \end{aligned} \tag{10}$$

If the cloud size is of order L then the time required for dust segregation τ' can be written as

$$\tau'\sim L/v=4L\varrho(8kT/\pi m_{\rm H}\mu)^{1/2}/3uQ\xi. \tag{11}$$

With typical values assumed for the various parameters,

$$\tau'=5\times10^7(L/50\,{\rm pc})(n/10^2\,{\rm cm^{-3}})(T/10\,{\rm K})^{1/2}(u/10^{-12}\,{\rm erg\,cm^{-3}})^{-1}\mu^{-1/2}(Q\xi)^{-1}\,{\rm yr} \tag{12}$$

where n is the mean particle number density of the gas and $\varrho=nm_{\rm H}\mu$. The mean energy density of the diffused stellar radiation field u in the present day interstellar medium, for comparison, is $\simeq7\times10^{-13}\,{\rm erg\,cm^{-3}}$ (Allen 1973).

For the present day average interstellar conditions the radiative segregation time-scale τ' is generally longer than the gravitational segregation time-scale τ. However, situations (with stronger radiation fields on smaller length-scales, for example in the vicinity of groups of OB stars) could exist where τ' becomes comparable to or even shorter than τ. In such situations radiative segregation would be an effective mechanism for dust-gas separation. Thus if a globular cluster protocloud is optically thick and is embedded in a strong radiation field, the radiation pressure can drive the dust grains towards the cloud centre (e.g. Williams & Bhatt 1982) and produce a radial gradient in dust concentration which would result in the establishment of primordial abundance gradients in the globular cluster. Also if a protocloud is in the vicinity of an anisotropic radiation field, the dust will be transported (driven by radiation) from one region of the cloud to another and cause variations in dust-to-gas mass ratio across the cloud, leading to the observed heavy element abundance variations. In this case no radial gradients but only star to star variations will be produced.

Thus it seems possible that segregation of dust in globular cluster protoclouds produced the heavy element abundance variations in globular clusters. To produce significant abundance variations it is required that the protocloud lifetimes be of the order of or longer than the dust segregation time-scale. This is discussed in the following section.

3 Discussion

The time-scale for gravitational segregation τ was found (equation 8) to be

$$\tau=2.9\times10^7(T/\mu)^{1/2}(\sigma/2\,{\rm g\,cm^{-3}})^{-1}(a/0.1\,\mu{\rm m})^{-1}\,{\rm yr}.$$

For a typical grain size $a=0.1\,\mu$m, τ lies in the range $\sim6\times10^7$–2.4×10^8 yr. Since τ varies inversely with a, from a distribution of different grain sizes, the largest grains (which carry most of the dust mass) would segregate faster and have a smaller effective τ. We have no information about the lifetimes of the globular cluster protoclouds, but the estimates for the mean lifetime of the interstellar clouds range from 3×10^7 to $\sim2\times10^8$ yr (e.g. Bash 1979; Blitz & Shu 1980; Cohen *et al.* 1980; Solomon & Sanders 1980; Kwan & Valdes 1987), of the same order as the dust segregation time-scale τ. Therefore, if the globular cluster protoclouds had lifetimes similar to the interstellar clouds, significant dust segregation and the consequent heavy element abundance variations in the globular cluster stars can be expected.

The radiative dust segregation time-scale is given by $\tau'=5\times10^7 (L/50\,\mathrm{pc})\,(n/10^2\,\mathrm{cm}^{-3})\,(T/10\,\mathrm{K})^{1/2}\,(u/10^{-12}\,\mathrm{erg\,cm}^{-3})^{-1}\,\mu^{-1/2}\,(Q\xi)^{-1}$ yr and depends only weakly on the grain size (because of the weak size dependence of the efficiency factor Q). However, τ' strongly depends on the energy density u of the radiation field. The product Ln is the column density of the gas cloud. For the present-day galactic molecular clouds this quantity has a roughly constant value of $\simeq 10^{22}\,\mathrm{cm}^{-2}$. We have used a similar value for the product Ln in equation (12) for τ' which gives a dust segregation time-scale of the order of (or smaller than) the cloud lifetime for a radiation field energy density equal to (or larger than) the present-day mean energy density of the interstellar radiation field. Stronger interstellar radiation fields at earlier epochs in the life of the galaxy, and localized regions of interstellar space in the vicinity of luminous stars with radiation fields stronger than the mean, are quite conceivable. In such situations τ' would become small enough for the radiative segregation to be dominant. It may, therefore, be concluded that for some globular clusters the abundance variations could have been caused by radiative segregation of dust in the protoclouds.

Before concluding we note an additional factor that might play a role in producing abundance variations in globular cluster stars. The present-day giant molecular clouds are known to have subcondensations on a smaller scale within the clouds. The processes of dust segregation discussed above can operate independently in different subcondensations in a globular cluster protocloud leading to different dust-to-gas ratios in different parts of the cloud and hence abundance variations. Also, even after star formation has begun in a protocloud, radiative segregation of dust under the influence of the radiation from the newborn stars can cause abundance variations in the subcondensations on a time-scale now much reduced due to the high radiation energy density.

4 Conclusions

In this paper we have suggested the possibility that segregation of dust in globular cluster protoclouds produced the observed heavy element abundance inhomogeneities in globular clusters. Both the radial gradients and star to star variations in abundance can be produced provided the dust segregation time-scale is of the order of or shorter than the protocloud lifetime. The segregation time-scale depends primarily on the mean dust grain size for gravitational segregation, and on the radiation field energy density for radiative segregation. With reasonable values for the physical parameters of the dust grains and gas in the protoclouds, similar to the interstellar clouds, the gravitational segregation time-scale is found to be $\sim 10^7$–10^8 yr. Situations can also exist where the radiative segregation time-scale is of similar order. Therefore, if the globular cluster protoclouds had lifetimes similar to the large interstellar clouds ($\sim 10^8$ yr), it seems possible that dust segregation in the protoclouds produced the observed heavy element abundance variations in the globular clusters that require a primordial origin.

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