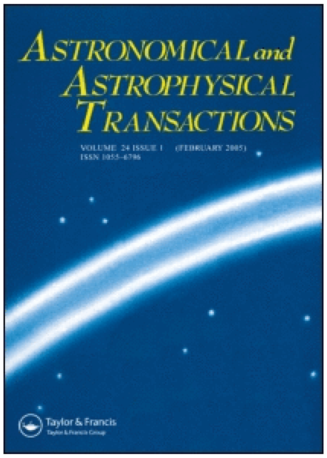
This article was downloaded by:[Bochkarev, N.]
On: 20 December 2007
Access Details: [subscription number 788631019]
Publisher: Taylor & Francis
Informa Ltd Registered in England and Wales Registered Number: 1072954
Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK



Astronomical & Astrophysical Transactions

The Journal of the Eurasian Astronomical Society

Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453505

Chemical enrichment of halo stars due to accretion of interstellar dust

V. G. Surdin [a]; P. Shah [a]
[a] Sternberg Astronomical Institute 13, Universitetski Prospect, Moscow, Russia

Online Publication Date: 01 July 1995
To cite this Article: Surdin, V. G. and Shah, P. (1995) 'Chemical enrichment of halo stars due to accretion of interstellar dust', Astronomical & Astrophysical Transactions, 8:2, 97 - 104
To link to this article: DOI: 10.1080/10556799508203300
URL: http://dx.doi.org/10.1080/10556799508203300

PLEASE SCROLL DOWN FOR ARTICLE

Full terms and conditions of use: http://www.informaworld.com/terms-and-conditions-of-access.pdf

This article maybe used for research, teaching and private study purposes. Any substantial or systematic reproduction, re-distribution, re-selling, loan or sub-licensing, systematic supply or distribution in any form to anyone is expressly forbidden.

The publisher does not give any warranty express or implied or make any representation that the contents will be complete or accurate or up to date. The accuracy of any instructions, formulae and drug doses should be independently verified with primary sources. The publisher shall not be liable for any loss, actions, claims, proceedings, demand or costs or damages whatsoever or howsoever caused arising directly or indirectly in connection with or arising out of the use of this material.

Astronomical and Astrophysical Transactions, 1995,
Vol. 8, pp. 97–104
Reprints available directly from the publisher.
Photocopying permitted by license only

CHEMICAL ENRICHMENT OF HALO STARS DUE TO ACCRETION OF INTERSTELLAR DUST

V. G. SURDIN and P. SHAH

Sternberg Astronomical Institute
13, Universitetski Prospect, Moscow, 119899, Russia

(Received November 10, 1994)

For halo stars, revolving close to the galactic plane in the direction of rotation of the Galaxy, the effect of dust accretion can considerably change their chemical composition to approach the observed lower limit of metallicity of the halo stars. The results obtained show that the effect of accretion should be studied further to explain the absence of Population III stars in the Galaxy.

KEY WORDS **Metallicity of halo stars, accretion of dust**

1 INTRODUCTION

In the early 60's astronomers studied the problem of G-dwarfs. The problem is as follows. From simple models of star formation and evolution of their chemical composition, all heavy elements originate from stars of previous generations. In comparison to this model, a considerably smaller number of old stars with low metallicity is observed. The spectral type G includes stars whose evolution time is longer than the age of the Galaxy, and they have almost not changed since the time of their birth. Theoretically, in the Galaxy, there should have existed the first generation of stars which was born from pure hydrogen-helium gas and let out the first dose of heavy elements into interstellar space. As an analogy to the Population I stars (disc stars) and the Population II stars (halo stars), the stars poor in heavy metals are called Population III stars. No stars belonging to Population III have yet been observed.

At present, the chemical composition of the interstellar medium and atmospheres of young stars is: hydrogen $X = 0.77$; helium, $Y = 0.21$; and all heavy elements, $Z = 0.02$, in terms of mass fraction. This is not far from the solar chemical composition. Older stars contain a lesser amount of heavy elements. A large number of stars of metallicity 100–200 times lower than that of the Sun are known, i.e., with metallicity $[\mathrm{Fe/H}] = -(2\div 2.3)$. Among dwarfs, the star G 64-12 has $[\mathrm{Fe/H}] = -3.5$.

The lowest metallicity is that of the giant CD-38°0245, [Fe/H] = −4.5. Stars of lower metallicity have not yet been found (Surdin and Lamzin, 1992).

To solve the mystery of G-dwarfs and to understand why Population III stars have been found, we consider the time change in chemical composition of halo stars, assuming that, while stars move in the galactic disc, interstellar dust is accreted on the star. Thus, we find the lower metallicity as a function of the orbital parameters of a star.

2 POSSIBILITY OF DUST ACCRETION INTO A STAR

It is believed that interstellar medium, particularly interstellar dust, cannot be accreted on the surface of a star due to stellar radiation and stellar wind (Bisnovaty-Kogan, 1986). But, in the recent years, it was found that the properties of interstellar and circumstellar dust are quite varied (Voshchinnikov, 1986). Dust discs have been observed in the neighborhood of main sequence stars, indicating the possibility of dust accretion on stars (Strom *et al.*, 1993). Therefore, in the above problem, we strengthen the effect of accretion to find the upper bound for changes in chemical composition of stars. If this value is too large, then the problem of accretion can be studied further. Therefore, we consider only the large factor, namely, radiation pressure.

We defined factor β as the ratio of the force of radiation pressure to the force of gravitation. It is clear that for $\beta \leq 1$ accretion takes place. If the dust particle is placed sufficiently far from a star, then the force of radiation pressure on the dust particle is

$$F_{\mathrm{pr}} = \frac{R_*^2}{cR^2} S_d \hat{Q}_{\mathrm{pr}} \sigma T_*^4, \tag{1}$$

where c is velocity of light, σ is Stephan-Boltsman constant, R_* and T_* are, respectively, the radius and effective temperature of the star, R is the distance between the star and the dust particle ($R \gg R_*$), S_d is the geometrical cross section of the dust particle, $\hat{Q}_{\mathrm{pr}}$ is the average Planck factor of the radiation pressure.

The force of gravity is given by

$$F_g = \frac{GM_* \rho_d V_d}{R^2}, \tag{2}$$

where ρ_d and V_d are the density and volume of the dust particles, respectively. Then the accretion efficiency β is

$$\beta \equiv \frac{F_{\mathrm{pr}}}{F_g} = \frac{\sigma R_*^2 T_*^4 S_d \hat{Q}_{\mathrm{pr}}}{cGM_* \rho_d V_d}. \tag{3}$$

For dust particles of graphite with a radius of 0.1 μm and $\rho_d = 2$ g/cm^3, relative values of β were calculated for stars of various spectral types (Divari and Reznova, 1970). On this basis, the absolute value of β for main sequence stars was found

(Surdin, 1973). $\beta \leq 1$ for stars of spectral types later than K7, i.e., with masses less than $0.6M_{\odot}$. Recently particles of astrosilicate are considered while modelling the properties of cosmic dust $(Mg_xFe_{2-x}SiO_4)$. For such particles, the radiation pressure efficiency is on average less by an order of magnitude than that for graphite particles. For graphite particles, $\beta = 10$ for stars of spectral type G1–G2 (Surdin, 1973). Consequently, for astrosilicate particles, $\beta \approx 1$ for such stars. Our evaluation is based on the calculated values of β for spherical and cylindrical particles with varied chemical composition (Voshchinnikov and Il'in, 1983), which show that for silicate and multi-component particles $\beta \leq 1$ for the Sun and stars of later spectral types.

In general, it is difficult to decide to what extent such values are to be believed. For example, in the paper of Il'in and Voshchinnikov (1993), values of β in the neighborhood of main sequence stars of spectral type A2 were calculated. Only for particles with a radius $r_d \geq 5$ μm is $\beta \leq 1$, i.e., gravity dominates over radiation pressure, though in the neighborhood of such stars dust discs have been observed. On the basis of models and IR spectra, these dust particles have r_d as small as 0.5 μm. For these particles, light pressure is 10–100 times (depending on their composition) greater than gravity. However, the particles do not leave stellar neighborhood. To explain this fact, Il'in and Voshchinnikov (1993) suggest a constant production of minute dust particles in the neighborhood of stars. It is obvious that the theory of interaction of dust with radiation requires correction, as the above difference of opinion can lead to an exaggerated evaluation of the role played by the radiation pressure.

From the above, we conclude that the role played by the radiation pressure is not too large, especially in the neighborhood of stars of mass less than $0.6M_{\odot}$, and for particles of the more realistic astrosilicate, for stars of mass less than $1M_{\odot}$. Considering that old halo stars have masses less than $0.8M_{\odot}$, we can conclude that practically for all these stars, the effect of radiation pressure on dust particles is much less than that of gravity.

3 DYNAMICS OF DUST PARTICLES NEAR A STAR

Limiting ourselves to the above stars, we shall try to find out if the motion of dust particles under the effect of gravity is free. We compare the mean free path length (l) to the maximum value of the impact parameter (p) of accreted particles. If $p < l$, then the motion of the particle would be Keplerian, and if $p > l$, then the motion of the particle will be hydrodynamic. Let n be the concentration of the particles in gas, μ the average molecular weight, m_H the mass of the hydrogen atom, and r_d the radius of the dust particle. From the conservation of momentum, we get:

$$l n \mu m_H = r_d \rho_d, \tag{4}$$

which gives

$$l = \frac{r_d \rho_d}{n \mu m_H}. \tag{5}$$

For a molecular medium where $\mu = 2.3$, and assuming $\rho_d = 2$ g/cm^3,

$$l = 5 \times 10^{18} \left(\frac{r_d}{10^{-5}\mathrm{cm}}\right) \left(\frac{n}{1\mathrm{cm}^{-3}}\right)^{-1} \mathrm{cm}. \tag{6}$$

On the other hand, it is easy to show that the maximum value of the impact parameter for dust falling on the surface of the stars in a hyperbolic trajectory with a velocity V at infinity is

$$p = R_* \left(1 + \frac{V_\infty^2}{V^2}\right)^{1/2}, \tag{7}$$

where $V_\infty^2 = 2GM_*/R_*$ is the parabolic velocity at the surface of the star. For all stars in the lower part of the main sequence, $V_\infty = 615$ km/s. Assuming for the Galaxy $V \leq V_\infty$, we get the following relation:

$$\frac{l}{p} = 10^5 \left(\frac{V}{1\,\mathrm{km/s}}\right) \left(\frac{r_d}{10^{-5}\,\mathrm{cm}}\right) \left(\frac{n}{1\,\mathrm{cm}^{-3}}\right)^{-1} \left(\frac{R_*}{R_\odot}\right)^{-1}. \tag{8}$$

Even in extreme cases, with slow motion of stars ($V = 10$ km/s) through dense molecular clouds ($n = 10^4$ cm^{-3}), and tiny dust particles ($r_d = 0.01$ μm), the mean free path for dust is much larger than the pericentral parameter ($l \approx 10p$) and, consequently, we can use the celestial mechanics approach to calculate the velocity of accretion.

4 AVERAGE RATE OF DUST ACCRETION ON HALO STARS

Let us consider the model in which the dust particle falls on a star with a relative velocity V at a long distance. If the maximum value of the impact parameter p satisfied (7), then the effective cross section of the star for the dust particles is:

$$\pi p^2 = \pi R_*^2 \left(1 + \frac{V_\infty^2}{V^2}\right). \tag{9}$$

The instantaneous flux of particles on the star is:

$$\dot{m} = \pi p^2 \rho V, \tag{10}$$

where ρ is the spatial density of the dust particles. We shall consider the motion of the star as in the two-body problem and consider that it moves in an elliptical orbit with an eccentricity e and inclination i. Then, from simple geometry, we can consider only the motion of the star in its two percolations through the galactic disc in the region of its pericenter. In that case, the average rate of dust accretion during an orbital period (P) is given by:

$$\dot{M} = \frac{2\dot{m}d}{PV_s \sin i}, \tag{11}$$

where d is the thickness of the disc, V_s is the velocity of the star in the region of the pericentre. We denote $\sigma \equiv \rho d$ as the surface density of dust in projection to the galactic disc and we shall assume it to be constant in time (because of the small change in chemical composition of disc stars with time). Let T be the age of the star. Then, from (9)–(11) we find the mass of dust accreted on the surface of the star:

$$\Delta M = \frac{2\pi\sigma VT}{PV_s \sin i} R_*^2 \left(1 + \frac{V_\infty^2}{V^2}\right). \tag{12}$$

The velocity of the star relative to dust is

$$V^2 = V_c^2 + V_s^2 - 2V_c \cos i, \tag{13}$$

where V_c is the circular velocity in the disc. If M_G is the mass of the galaxy bound by the apocental distance of the star (R_a), then the period of the star revolution is:

$$P = 2\pi \left(\frac{R_a^3}{GM_G}\right)^{1/2} \frac{1}{(1+e)^{3/2}}. \tag{14}$$

From the equations of Keplerian motion, we get:

$$R_a = R_p \left(\frac{1+e}{1-e}\right) \tag{15}$$

and

$$V_s^2 = V_c^2(1+e), \tag{16}$$

where R_p is the distance of the star at the pericenter of its orbit, which we take for our calculations as the distance of the Sun to the center of the Galaxy (8.5 kpc).

$$\Delta M = \frac{T\sigma R_*^2 V_c (1+e)^{1/2}(1-e)}{R_p \sin i} \left[1 + \frac{V_\infty^2}{V_c^2 \omega(e,i)}\right] \phi(e,i), \tag{17}$$

where

$$\omega(e,i) = 2 + e - 2(1+e)^{1/2} \cos i, \tag{18}$$

and

$$\phi(e,i) = \left[1 + (1+e)^{-1} - 2(1+e)^{-1/2} \cos i\right]^{1/2}. \tag{19}$$

For the calculations, we took the following values: $V_c = 220$ km/s, $T = 2 \times 10^{10}$ yrs, $R_p = 8.5$ kpc, $V_\infty = 615$ km/s. Since in the solar vicinity the average surface density of gas in the galactic disc is $5M_\odot$ pc^{-2} (Sanders *et al.*, 1984), and

2% of its mass is dust, we have $\sigma = 0.1 M_{\odot}$ pc^{-2}. We shall suppose that the dust made up of heavy elements falling into the atmosphere of the star during its lifetime mixes with it homogeneously. Since heavy elements compose 2% of the Sun, the expected metallicity of a star as a result of accretion is given by:

$$[\mathrm{Fe/H}] = \log\left(\frac{\Delta M}{0.02}\right) = 1.7 + \log \Delta M. \tag{20}$$

Taking into account (17), we get:

$$[\mathrm{Fe/H}] = -12 + 2\log(R_*/R_{\odot}) + \log F(e,i), \tag{21}$$

where

$$F(e,i) = \phi(e,i)\left[1 + \frac{7.8}{\omega(e,i)}\right](1+e)^{1/2}(1-e)\sin i^{-1}. \tag{22}$$

Within the limits of this formula's applicability (not very small i angles), for $e = 0$ the value of the function $F(e,i)$ is limited by 10^2. For $e \geq 0$, the value of this function is even less. Therefore, the expected change in chemical composition of the star of $R_* \sim R_{\odot}$ gives us nothing in excess of [Fe/H] ≈ -10. This is much less than the observed lower limit to metallicity. To strengthen our estimates, we consider the limiting case: the motion of the halo star within the galactic plane. For motion in the direction of rotation of the disc ($i = 0°$)

$$\Delta M = \pi R_*^2 T V \rho \left(1 + \frac{V_\infty^2}{V^2}\right). \tag{23}$$

In this case, $\rho = \sigma/d = 0.1 M_{\odot}$ pc^{-2}/150 pc $= 7 \times 10^{-4} M_{\odot}$ pc^{-3}. The velocity V in this case will be close to the dispersion velocity of molecular clouds (≈ 10 km/s). As a result,

$$\Delta M \approx 10^{-9} M_{\odot} \left(\frac{R_*}{R_{\odot}}\right)^2 \left(\frac{M_{\odot}}{M_*}\right), \tag{24}$$

and the expected value [Fe/H] ≈ -7, which is less than the observed limit. In the case of the star's motion opposite to the direction of galactic rotation, we get an analogous value, [Fe/H] $= -8$.

5 CONCLUSIONS

The studied effect of accretion of interstellar dust on halo stars shows that the above assumption cannot change the chemical composition of Population III stars as the effect gives [Fe/H] $\approx -(7 \div 10)$. This is considerably less than the observed lower limit for halo stars. There exists, however, a chance to strengthen the effect due to incomplete mixing of dust on the surface of stars. If we consider that, due to convection, dust would be homogeneously mixed only in the convective zone, then it would considerably increase the content of heavy metals in it. The relative mass of the convective envelope (M_{ce}/M_*) for Population II stars has been calculated by Richer *et al.* (1992). For stars of low metallicity, [Fe/H] = −2.3, its dependence on the mass of stars is as follows:

Table 1. Relative mass of convective envelopes (after Richer *et al.*, 1992)

M_{ce}/M_*	$M_*/M_\odot$
3×10^{-3}	0.80
6×10^{-3}	0.75
1×10^{-2}	0.70
3×10^{-2}	0.65
6×10^{-2}	0.60

Taking the average value $M_{ce}/M_* = 10^{-2}$, we find that it enriches the stars in heavy elements by two orders of magnitude. In this case, the expected metallicity of Population III stars is [Fe/H] = $-(8 \div 5)$.

There is yet another possible effect if dust is considered frozen in interstellar gas, i.e., it has a short mean free path due to its electrical charge. In that case, the velocity of accretion can be defined by the hydrodynamics of the medium, i.e., formation of shock waves in the he neighborhood of stars, the collection of gas by them and the capture of it by stars (Zel'dovich and Novikov, 1971). In comparison to the case of independent accretion of dust (9), this gives an additional factor V_∞^2/V^2, which in the given case, ($V_\infty = 615$ km/s, $V = 10 \div 440$ km/s), is from $2 (i = 180°)$ to 4×10^3 ($i = 0°$). The corresponding change in chemical composition of halo stars whose orbits lie in the galactic plane would be [Fe/H] = $-(5 \div 6)$ for $i = 180°$ and [Fe/H] = $-(1 \div 2)$ for $i = 0°$. For orbits with large inclinations to the plane of the Galaxy, ($i = 90°, V = 330$ km/s), we get the minimal value, [Fe/H] = $-(8 \div 7)$. In this way, a considerable change in chemical composition for Population III stars is expected only for stars with a specific range of i angle. We evaluate the limiting values for the angles which give a considerable effect. For small i, it is easy to find the following expression for the mass of dust accreted in case of its being frozen in the gas:

$$\Delta M = \left(\frac{\pi}{16}\right) R_*^2 T \sigma V_\infty^4 (\pi G \sigma_0)^{-3/2} (R_p \sin i)^{-5/2}, \qquad (25)$$

where σ_0 is the total surface density of the galactic disc, which, in the neighborhood of the Sun, is 70 $M_\odot pc^{-2}$. From (25), for typical values of [Fe/H] = −4, we get $i \approx 5°$. Consequently, for halo stars moving close to the galactic plane in the direction of its rotation, the effect of accretion of dust can considerably change their chemical composition approximately to the observed lower limit of metallicity. The above estimates shows that this effect requires deeper study in connection with the problem of Population III stars in the galaxy.

We are grateful to S. A. Lamzin and M. A. Livshits for discussions.

References

Bisnovatyi–Kogan, G. S. (1986) Accretion, *Physics of the Cosmos* (Moscow: Soviet Encyclopedia), p. 115. (in Russian).

Divari, N. V. and Reznova, L. V. (1970) *Astron. Zh.* **47**, 166.

Il'in, V. V. and Voshchinnikov, N. V. (1993) *Astron. Zh.* **70**, 721.

Richer, J., Michaud, G., and Proffitt, R. (1992) *Astrophys. J. Suppl. Ser.* **82**, 329.

Sanders, D. V., Solomon, P. M., and Scoville, N. Z. (1984) *Astrophys. J.* **276**, 182.

Strom, S. E., Edwards, S., and Skrutskie, M. F. (1993) Evolutionary time scales for circumstellar disks associated with intermediate and solar-type stars, *Protostars and Planets. III*, Levy E. H. and Lunine J. I (eds.) (Tucson: Univ. of Arizona Press), 837.

Surdin, V. G. (1973) *Photogravitational acceleration of stars*, Thesis, Moscow State University.

Surdin, V. G. and Lamzin, S. A. (1992) *Protostars* (Moscow: Nauka Publ. Co).

Voshchinnikov, N. V. (1986) Interstellar dust, *Space Research.* **25** (Moscow: VINITY), p. 98. (in Russian).

Voshchinkov, N. V. and Il'in, V. V. (1983) *Astron. Zh.* **60**, 1120.

Zel'dovich, Ya. B. and Novikov, I. D. (1971) *Theory of gravitation and the evolution of stars* (Moscow: Nauka Publ. Co.) (in Russian).