The Astrophysical Journal, 511:L33–L36, 1999 January 20

ENRICHMENT OF THE *r*-PROCESS ELEMENT EUROPIUM IN THE GALACTIC HALO

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Received 1998 September 14; accepted 1998 November 20; published 1998 December 9

ABSTRACT

We investigate the enrichment of europium, as a representative of *r*-process elements, in the Galactic halo. In present chemical evolution models, stars are assumed to be formed through shock processes by supernovae (SNe). The enrichment of the interstellar medium is calculated by a one-zone approach. The observed large dispersions in [Eu/Fe] for halo stars, converging with increasing metallicity, can be explained with our models. In addition, the mass range of SNe for the *r*-process site is constrained to be either stars of 8–10 or $\gtrsim 30\ M_\odot$.

Subject headings: Galaxy: evolution — Galaxy: halo — nuclear reactions, nucleosynthesis, abundances — stars: abundances — stars: Population II — supernovae: general

1. INTRODUCTION

Recent abundance analysis of metal-poor halo stars reveals the presence of large dispersions in heavy elements. This may be interpreted as a result of incomplete mixing of the interstellar medium (ISM) at the beginning of the Galaxy (Gilroy et al. 1988). Each type of element shows a unique dispersion, which cannot be simply explained by spatial inhomogeneity of the ISM. The dispersions of neutron-capture elements like Sr, Ba, and Eu range ∼300-fold, while those of α and iron-peak elements range typically $\lesssim$10-fold (McWilliam et al. 1995; Ryan, Norris, & Beers 1996). This fact implies mixing of ejecta from small numbers of supernovae (SNe) into the parent clouds (Audouze & Silk 1995; McWilliam 1997, 1998).

In previous chemical evolution models, observed stellar compositions are taken to represent those of the ISM when the stars were formed. It may not be true, however, if star formations are mainly triggered by SNe. The composition of the formed star must be a mixture of the ISM and the individual SNe ejecta. Mathews, Bazan, & Cowan (1992) have examined the enrichment of neutron-capture elements using a chemical evolution model of the ISM. They concluded that the delayed increasing of [Eu/Fe] in terms of [Fe/H] favored origins of low-mass SNe (∼7–8 $M_\odot$). However, this might change when including the large dispersion in [Eu/Fe] for halo stars.

The excellent agreement of the neutron-capture elements in the halo stars CS 22892−052, HD 115444, HD 122563, and HD 126238 (Sneden et al. 1996, 1998) with the solar *r*-process abundance pattern implies the presence of one robust *r*-process site (Cowan et al. 1998). However, the origins of *r*-process elements are still unknown. Although the neutrino winds in SNe have been thought to be a promising site, this scenario involves serious problems, e.g., in obtaining sufficient entropy (Takahashi, Witti, & Janka 1994; Woosley et al. 1994; Qian & Woosley 1996). Collapsing O-Ne-Mg cores are also thought to be an *r*-process site (Wheeler, Cowan, & Hillebrandt 1998). The O-Ne-Mg core, as the final stage of an 8–10 $M_\odot$ star, may explode by a prompt shock (Hillebrandt, Nomoto, & Wolff 1984). The ejected shell contains a rather low electron fraction region due to electron captures, which may be a promising *r*-process site (Meyer & Brown 1997).

In this Letter, we discuss the enrichment of europium in halo stars formed through stimulated processes by SNe. Details of our models including other elements will be presented in a forthcoming paper.

2. METHODS

The evolutions of the ISM in the Galactic halo are calculated by a one-zone halo model which loses gas through accretion onto the disk. The star formation and accretion rates are assumed to be proportional to the gas fraction of the halo. The star formations obey the Salpeter initial mass function in the mass range 0.05–60 $M_\odot$. The coefficients for the accretion rate and the star formation rate are adjusted to fit to the observational data of [O/Fe] versus [Fe/H] (e.g., Barbuy 1988; Edvardsson et al. 1993) and the metallicity distribution of halo stars (Sandage & Fouts 1987). Stellar lifetimes are adopted from Schaller et al. (1992). Type Ia SNe are supposed to occur simply with a lifetime of 2.5 Gyr for ∼5% of the 3–8 $M_\odot$ stars (Ishimaru 1994; Yoshii, Tsujimoto, & Nomoto 1996).

We assume that star formation is initiated by SNe. An SN remnant is supposed to expand spherically until reaching the merge radius with the ISM (typically ∼100 pc; Cioffi, McKee, & Bertschinger 1988). The chemical composition of a formed star is assumed to be the mass average of the “snowplowed” ISM and the SN ejecta. The mass of the SN progenitor is chosen randomly but obeying the initial mass function. Further, we presume the following two cases in which the merge radii have a Gaussian distribution in the logarithmic scale within a factor of 1.5 (case 1) and no distribution (case 2).

Stellar yields for Type II and Type Ia SNe are taken from Nomoto et al. (1997a) and Nomoto et al. (1997b), respectively. The 8–10 $M_\odot$ stars are assumed to produce no iron. For simplicity, we do not take into account the metallicity effects as examined by Woosley & Weaver (1995). We do not include yields of the stars smaller than 8 $M_\odot$ either, which does not effect the results of the present study. The *r*-process elements are supposed to be produced only in Type II SNe. In this study, we examine the following three models (hereafter models 1, 2, and 3) in which europium is produced from the stars (1) 8–10 $M_\odot$, (2) $\geq$10 $M_\odot$, and (3) $\geq$30 $M_\odot$. For each model, the mass of produced europium is assumed to be constant over the stellar mass range, scaled to be [Eu/Fe] = 0.5 in the ISM at [Fe/H] = −2.

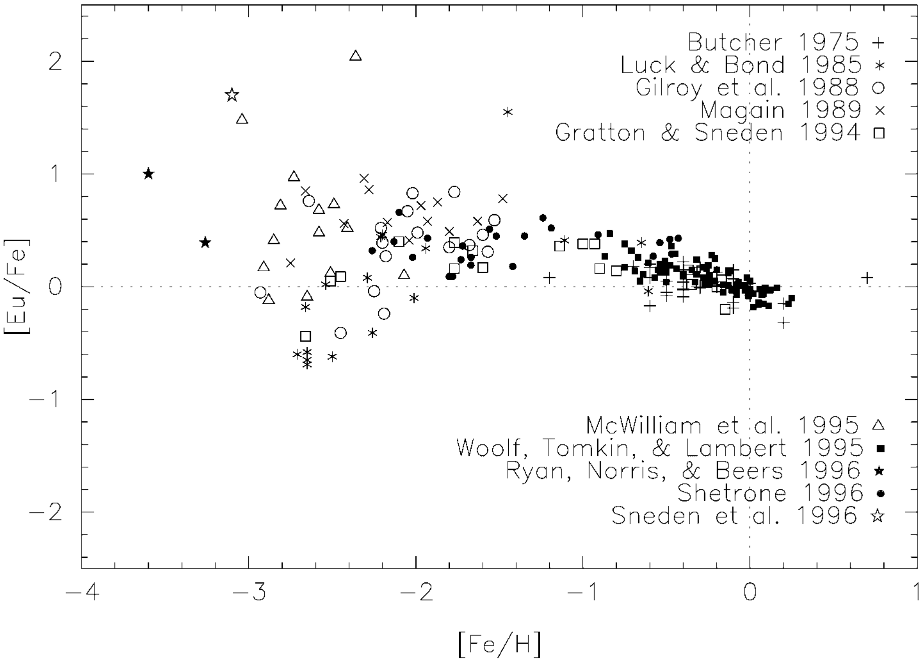

FIG. 1.—Observational data of [Eu/Fe] vs. [Fe/H] for halo and disk stars, from the data of Butcher (1975), Luck & Bond (1985), Gilroy et al. (1988), Magain (1989), Graton & Sneden (1994), McWilliam et al. (1995), Woolf, Tomkin, & Lambert (1995), Ryan, Norris, & Beers (1996), Shetron (1996), and Sneden et al. (1996).

3. ENRICHMENT OF EUROPIUM IN THE HALO

Figure 1 shows observational data of [Eu/Fe] versus [Fe/H] for halo and disk stars. Figures 2, 3, and 4 illustrate the enrichment of europium in the halo by models 1, 2, and 3, respectively. The evolution of the ISM is represented by a line, and the compositions of stars are plotted by open stars (case 1) and filled stars (case 2). As can be seen in the decrease of [Eu/Fe] for $[\mathrm{Fe/H}] \gtrsim -1$ in Figures 2–4, the iron production by Type Ia SNe has little contribution to the enrichment for metal-poor halo stars.

We see from models 1 and 3 (Figs. 2 and 4) that a large dispersion in [Eu/Fe] appears for stars at $[\mathrm{Fe/H}] \sim -3$, converging toward the value of the ISM with metallicity. These results are in excellent agreement with the observations (Fig. 1). The overproduction of europium in stars compared to the value of the ISM is due to the star formations by SNe that add europium with little or no iron to the ISM. In contrast, the underproduction is due to SNe that add iron without europium. Thus, for model 1, a significant overabundance in [Eu/Fe] appears for the stars formed by 8–10 $M_\odot$ SNe. For model 3, stars ≥ 30 $M_\odot$ are supposed to produce europium with significantly high ratios of Eu/Fe, since these stars account for only ∼15% of all SNe in number. As a result, a large dispersion also appears. In contrast to models 1 and 3, stars in model 2 (Fig. 3) show little dispersion in [Eu/Fe], since all SNe (≥ 10 $M_\odot$) produce iron and europium with similar ratios. This result is rather close to the observational data of α elements.

The distribution of merge radii of SN remnants (case 1) can be another reason for the dispersion in [Eu/Fe]. For case 2, stars show a smaller scatter due to no distribution in the merge radii and are thus clearly separated into overabundant and underabundant ones.

As can be seen in Figures 2 and 4, the number of stars overabundant in europium is smaller than those that are underabundant. This is also in good agreement with the observational results (Fig. 1). The reason is simply that the number of SNe producing europium is smaller than that of other SNe in these models.

4. DISCUSSION AND CONCLUSIONS

In this study, we find that a large dispersion in [Eu/Fe] for halo stars is mainly due to star formation by individual SNe that eject unique yields. There may be other reasons for the dispersion (e.g., a distribution of merge radii of SN remnants with the ISM [see § 3] and a spatial inhomogeneity of the ISM), which are not dealt with in this study. We should emphasize, however, that the stochastic star formation process triggered by different masses of SNe is essential to reproduce the ∼300-fold dispersions in neutron-capture elements. A dispersion caused by other factors may be ∼10-fold at most, since it must appear similarly in other types (e.g., α and iron-peak) of elements.

The results of our study indicate that the production sites of europium, as a representative of *r*-process elements, must satisfy at least one of the following two conditions: (1) europium is produced with little iron or (2) the number of SNe producing europium accounts for only a small fraction of all SNe. We suggest here a couple of possible sites for these conditions. The first is the explosion of 8–10 $M_\odot$ stars. These stars are expected to produce little iron (Hillebrandt et al. 1984). In fact, the progenitor of the Crab Nebula, which shows no significant enrichment in metal, has been suspected to be an 8–10 $M_\odot$ star (Nomoto et al. 1982). The second site is the explosion of stars $\gtrsim 30$ $M_\odot$. The subsequent neutrino winds may obtain substantially high entropy owing to the massive neutron stars (Qian & Woosley 1996). These stars account for only ∼15% of all SNe. Furthermore, the explosions of these stars may eject significantly less iron than ∼0.1 $M_\odot$ adopted in this study (Woosley & Weaver 1995). In fact, very low masses of ^{56}Ni in the ejecta of SN 1994W (∼0.0026 $M_\odot$; Sollerman, Cum-

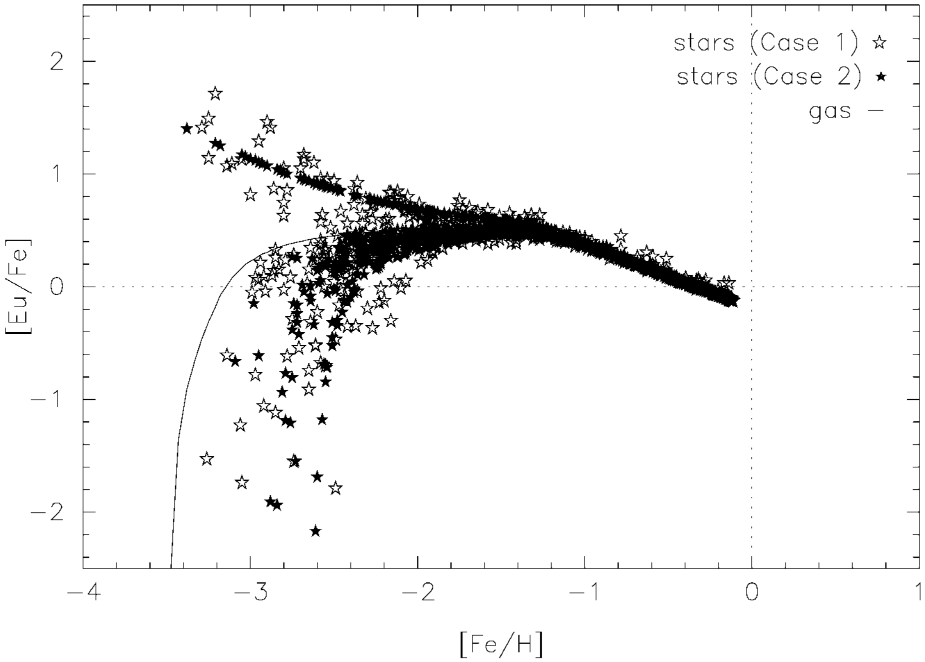

FIG. 2.—Enrichment of europium as a function of metallicity in the Galactic halo for model 1. The production site of europium is assumed to be 8–10 $M_\odot$ stars. The evolution of the ISM is indicated by a line, and the compositions of stars are denoted by open stars (case 1) and filled stars (case 2).

ming, & Lundqvist 1998) and SN 1997D (~0.002 $M_\odot$; Turatto et al. 1998) have been expected to be due to 25–40 $M_\odot$ progenitors. It should be noted that coalescing neutron stars may also produce *r*-process elements without iron (Rosswog et al. 1998). However, they may not be major sources for the large enhancement in [Eu/Fe], since their lower kinetic energies are not enough to trigger star formations.

In light of the observational results (Fig. 1), model 1 seems more likely for the following two reasons. First, in model 1 some stars show as high an [Eu/Fe] as ~1.7 at [Fe/H] ~ −3. These stars can be a possible explanation for CS 22892−052. However, model 3 would produce stars with a significantly larger dispersion in [Eu/Fe] if smaller iron yields were adopted for stars ≥30 $M_\odot$. Second, in model 1 there is no sharp peak in the distribution of stars for [Fe/H] $\lesssim -2$ (case 1) that is in good agreement with the observations. In model 3 the concentration of stars on the line of the ISM for [Fe/H] $\lesssim -2$ is due to the star formations by 8–10 $M_\odot$ stars which add neither

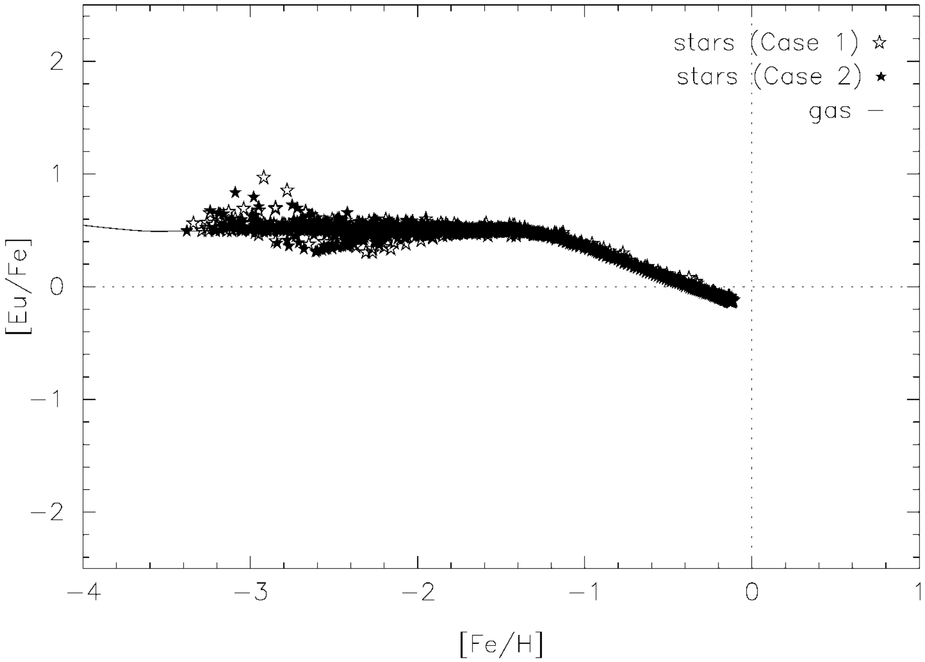

FIG. 3.—Same as Fig. 2, but the site of europium is assumed to be ≥10 $M_\odot$ stars (model 2).

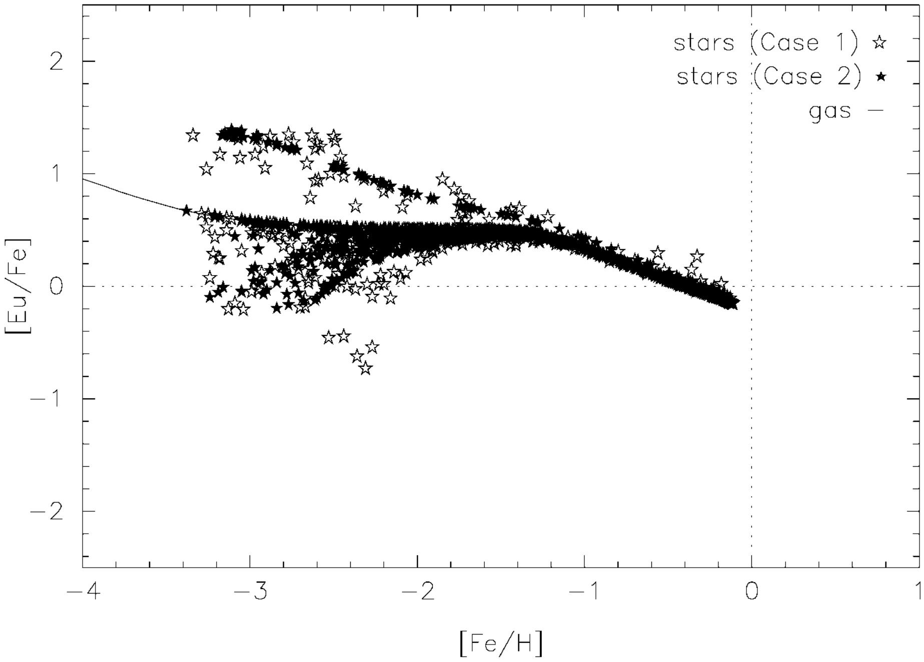

FIG. 4.—Same as Fig. 2, but the site of europium is assumed to be ≥30 $M_\odot$ stars (model 3).

iron nor europium. It should be noted, however, that the question of whether 8–10 $M_\odot$ stars explode or not is still open. Another outstanding difference between these models is that model 1 has stars in [Eu/Fe] down to ∼−2 that have not been detected by observations yet. This is a consequence of the delayed increasing of europium in the ISM due to lower mass progenitors. Hence, future surveys of metal-poor halo stars for low [Eu/Fe] will be important to distinguish the above two sites for the *r*-process. An alternative way to distinguish these sites may be to apply our models to other neutron-capture elements like Sr and Ba, which have much more data than Eu. In addition, the decreasing trend of [Ba/Fe] toward lower metallicity may support 8–10 $M_\odot$ progenitors. The future direction of this study will be one that investigates enrichment of a number of neutron-capture elements consistently.

We would like to acknowledge useful discussions with T. Young, S. Ryan, and T. Kajino. This work was supported in part by the Japan Society for the Promotion of Science.

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