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THE HIGH RATIO OF $^{44}$Ti/$^{56}$Ni IN CASSIOPEIA A AND THE AXISYMMETRIC COLLAPSE-DRIVEN SUPERNOVA EXPLOSION

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ABSTRACT

The large abundance ratio of $^{44}$Ti/$^{56}$Ni in Cassiopeia A is puzzling. In fact, the ratio seems to be larger than the theoretical constraint derived by Woosley & Hoffman. However, this constraint is obtained on the assumption that the explosion is spherically symmetric, whereas Cas A is famous for the asymmetric form of the remnant. Recently, Nagataki et al. calculated the explosive nucleosynthesis of axisymmetrically deformed collapse-driven supernova. They reported that the ratio of $^{44}$Ti/$^{56}$Ni was enhanced by the stronger alpha-rich freezeout in the polar region. In this Letter, we apply these results to Cas A and examine whether this effect can explain the large amount of $^{44}$Ti and the large ratio of $^{44}$Ti/$^{56}$Ni. We demonstrate that the conventional, spherically symmetric explosion model cannot explain the $^{44}$Ti mass produced in Cas A if its lifetime is shorter than ~80 yr and the intervening space is transparent to the gamma-ray line from the decay of $^{44}$Ti. On the other hand, we show that the axisymmetric explosion models can solve the problem. We expect the same effect from a three-dimensionally asymmetric explosion, since the stronger alpha-rich freezeout will also occur in that case in the region where the larger energy is deposited.

Subject headings: nuclear reactions, nucleosynthesis, abundances — supernovae: general — supernovae: individual (Cassiopeia A, SN 1987A)

1. INTRODUCTION

Cassiopeia A (Cas A) is a young supernova remnant that is located relatively close to us (2.9 ± 0.1 kpc; Braun 1987). There is an old record that J. Flamsteed observed this supernova phenomenon (1680 AD?) and that the new star had an apparent brightness of the 6th magnitude (Ashworth 1980). The mass of the progenitor is estimated to be 15–30 $M_\odot$ (Hurford & Fesen 1996), which implies that Cas A is the remnant of collapse-driven supernova explosion. Recently, Cas A was observed by the COMPTEL telescope aboard the Compton Gamma Ray Observatory, and the gamma-ray line (1.157 MeV) from $^{44}$Ti decay was detected at the significance level of ~4 $\sigma$. The measured line flux was $(7.0 \pm 1.7) \times 10^{-3}$ photons cm$^{-2}$ s$^{-1}$ (Iyudin et al. 1994). However, this flux measurement was revised to $(4.8 \pm 0.9) \times 10^{-3}$ photons cm$^{-2}$ s$^{-1}$ by further analysis (Iyudin et al. 1996). On the other hand, OSSE observations reported that the flux is $(1.7 \pm 1.4) \times 10^{-3}$ photons cm$^{-2}$ s$^{-1}$ (The et al. 1996). At the 1 $\sigma$ level, the revised COMPTEL observation and the OSSE result are in agreement near $3.5 \times 10^{-3}$ photons cm$^{-2}$ s$^{-1}$ (The et al. 1996). The inferred amount of $^{44}$Ti is larger than $1 \times 10^{-4}$ $M_\odot$, although this estimate depends on the distance and the age of Cas A, and especially on the half-life of $^{44}$Ti, which is still very uncertain (it is difficult to measure the half-life of an element of the order of the human lifetime; we also note that the half-life is equal to the lifetime times ln 2, by way of precaution). It is reported to fall in the range from 39 ± 4 yr (Meiβner 1996) to 66.6 ± 1.6 yr (Alburger & Harbottle 1990). This range corresponds to 50–98 yr in the lifetime.

The observed mass of $^{44}$Ti in Cas A is large compared with the theoretical prediction (Woosley & Weaver 1995; Timmes et al. 1996), even if we adopt the lower limit of the COMPTEL observation ($1 \times 10^{-4}$ $M_\odot$). Moreover, this amount of $^{44}$Ti is accompanied by the ejection of at least 0.05 $M_\odot$ of $^{56}$Ni, if we assume that the theoretical prediction for the ratio of mass fractions, $X(^{44}$Ti)/$X(^{56}$Ni) $\leq 1.89 \times 10^{-3}$ (Woosley & Hoffman 1991), is correct. However, this much $^{56}$Ni would have led to the peak absolute magnitude of ~4, and it would have been much brighter than the recorded 6th magnitude of the apparent brightness. This is the puzzling abundance problem of Cas A.

Although the possibility of extinction of ~10 mag is proposed to solve this problem (Timmes et al. 1996), it is yet to be confirmed observationally (Predehl & Schmitt 1995). In the present Letter, we propose another explanation, i.e., the effect of asymmetry of the supernova explosion.

Historically, all explosive nucleosynthesis calculations with the use of a large nuclear reaction network have been performed for spherically symmetric explosion models. On the other hand, both the image of Cas A inferred from optical and X-ray observations and the velocity distribution inferred from optical observations show that the remnant is not spherically symmetric. Particularly in optical images, a remarkable jetlike feature is present at the east side (e.g., Fesen & Gunderson 1996). The fact that no pulsar has been found yet in Cas A might imply that the jet did not originate from the pulsar but was caused by the core-collapse dynamics, i.e., the explosion itself would have been asymmetric (e.g., Burrows & Hayes 1995).

Recently, Nagataki et al. (1997) calculated for the first time explosive nucleosynthesis in axisymmetrically deformed, collapse-driven supernovae using a large nuclear reaction network (see Bazán & Arnett 1997 for two-dimensional nucleosynthesis calculations in the presupernova stages, and refer also to Müller, Fryxell, & Arnett 1991 for explosive nucleosynthesis with the Rayleigh-Taylor instability). They found that the ratio...
$X(\text{^{44}Ti})/X(\text{^{56}Ni})$ can be significantly larger than that of the spherical explosion. The reason is given in the following paragraph.

Since $^{44}$Ti is synthesized through the alpha-rich freezeout, high entropy is needed for the synthesis of this nucleus. The relation between the energy density and the temperature behind the shock wave is approximately $E \equiv a T^n$, where $a$ is the radiation constant. Since the axisymmetric explosion generates a stronger shock wave in the polar direction, a higher temperature is reached in this direction, resulting in much higher entropy per baryon than that for the spherical explosion. It should be noted again that it is this stronger alpha-rich freezeout that yields the higher ratio of $X(\text{^{44}Ti})/X(\text{^{56}Ni})$ for the axisymmetric explosion beyond the constraint for the ratio in the spherical explosions (Woosley & Hoffman 1991).

In the present Letter, we investigate whether this mechanism can explain the mass of $^{44}$Ti and the high ratio of $X(\text{^{44}Ti})/X(\text{^{56}Ni})$ observed in Cas A. In § 2, we summarize the results of Nagataki et al. (1997). A comparison with observations is presented in § 3. A summary and discussion are given in § 4.

2. EXPLOSIVE NUCLEOSYNTHESIS FOR AXISYMMETRIC SUPERNOVA EXPLOSIONS

In this section, we summarize the results of Nagataki et al. (1997). They performed two-dimensional hydrodynamical calculations and studied the changes of the chemical compositions using a large nuclear reaction network containing 242 nuclear species. The location of the mass cut was not determined from the hydrodynamical calculation but from the amount of $^{56}$Ni in the ejecta. We note that all material inside the mass cut is assumed to fall back onto the central compact object (this is the definition of the mass cut). For example, the mass cut for the model of SN 1987A was determined so as to contain 0.07 $M_\odot$ of $^{56}$Ni in the ejecta, which is the value inferred from the light curve. In Figure 1, we show the relations between the ejected mass of $^{56}$Ni and that of $^{44}$Ti for four models: S1, A1, A2, and A3. Model S1 is a spherical explosion; models A1, A2, and A3 are models of axisymmetric explosions in an increasing order of the degree of asymmetry. For the axisymmetric models A1–A3, the initial velocity behind the shock wave is assumed to be radial and proportional to $r [1 + \alpha \cos(2\theta)/1 + \alpha]$, where $r$, $\theta$, and $\alpha$ are the radius, the zenith angle, and the model parameter that determines the degree of asymmetry, respectively. In this study, we take $\alpha = 0$ for model S1, $\alpha = 1/4$ for model A1, $\alpha = 1/2$ for model A2, and $\alpha = 1/3$ for model A3. The larger $\alpha$ gets, the more asymmetric the explosion becomes. We assumed the same distribution for the thermal energy also. Half of the total energy appears as kinetic energy, and the other half appears as thermal energy. Once the position of the mass cut is determined, the mass of $^{44}$Ti is also obtained for each model, as is seen from Figure 1.

3. COMPARISON WITH OBSERVATIONS

The amount of $^{44}$Ti synthesized in Cas A is estimated from the observed flux by using the following equation, which holds if the intervening matter is transparent to the gamma-ray line:

$$M_\odot(^{44}\text{Ti}) = 1.38 \times 10^{-4} \frac{F_g}{1 \text{ cm}^{-2} \text{s}^{-1}} \times \left( \frac{d}{1 \text{ kpc}} \right)^2 \left( \frac{\tau}{1 \text{ yr}} \right) \exp(t/\tau),$$

where $M_\odot(^{44}\text{Ti})$, $F_g$, $d$, $M(^{44}\text{Ti})$, $\tau$, and $t$ are the amount of $^{44}$Ti (in solar mass) synthesized in Cas A, the gamma-ray flux, the distance, the mass of $^{44}$Ti, the lifetime of $^{44}$Ti, and the age of Cas A, respectively.

We show in Figures 2 and 3 the amount of $^{44}$Ti as a function of the lifetime. Since the age of Cas A is uncertain, we study three cases: 300, 315, and 335 yr (van den Bergh & Kamper 1983). We set other parameters so as to be modest for the spherical explosion model. As one can see from this equation, the lowest amount of $^{44}$Ti allowed by the observation is obtained by choosing the smallest values for the flux and the distance within the uncertainties. Therefore, in this Letter, we adopt the lowest flux of the COMPTEL telescope ($3.9 \times 10^{-5} \text{ cm}^{-2} \text{s}^{-1}$) and the nearest distance ($2.8 \text{ kpc}$). We will see that the spherical explosion model cannot explain the amount of $^{44}$Ti even with these modest parameters.

For comparison, we give the amount of $^{44}$Ti ejected from the four models. Since the amount of $^{56}$Ni in Cas A is unknown, unlike SN 1987A, we investigate the mass of $^{44}$Ti for two mass cuts (M.C (A) and M.C (B) in Fig. 1) to see its effect. In case of M.C (A), 0.05 $M_\odot$ of $^{56}$Ni is ejected, and 0.1 $M_\odot$ in M.C (B). The results are shown in Figures 2 and 3 by the horizontal lines.

We can see from these figures that the spherical explosion cannot produce a sufficient amount of $^{44}$Ti even if the youngest age, the nearest distance within uncertainty, and a rather larger amount of $^{56}$Ni are used. Therefore, we conclude that the spherically symmetric explosion model is unlikely to explain the
44Ti mass observed in Cas A if the lifetime is shorter than ~80 yr and the intervening matter is transparent to the gamma-ray line. On the other hand, it is shown that the axisymmetric models can produce larger amount of 44Ti than the spherical explosion. It should be noted that no spherically symmetric explosion models calculated so far predict more than ~1.5 × 10^{-4} M_{\odot} of 44Ti, in agreement with our model S1 (Woosley & Weaver 1995; Hashimoto 1995).

4. SUMMARY AND DISCUSSION

We have tried to explain the observation of the large amount of 44Ti and the high ratio of 44Ti/56Ni in Cas A using the results of the axisymmetric explosive nucleosynthesis by Nagataki et al. (1997). We have found that the spherically symmetric explosion model is unlikely to give an explanation of such a high ratio of 44Ti/56Ni if the lifetime of 44Ti is shorter than ~80 yr and the intervening matter is transparent to the gamma-ray line from the decay of 44Ti. Although a large extinction of ~10 mag due to the intervening matter was proposed as a solution to the problem of the observed low apparent brightness, this remains to be confirmed observationally (Predehl & Schmitt 1995). Instead, we based our model on the observational fact that the shape of Cas A is far from spherically symmetric (e.g., Fesen & Gunderson 1996), and we found by two-dimensional calculations that the axisymmetric explosion models can also solve this problem. We think it is qualitatively correct that the ratio of 44Ti/56Ni is enhanced by axisymmetric explosion, since larger energy is deposited near the rotational axis and a higher entropy per baryon is reached there, resulting in stronger alpha-rich freezeout and yielding the larger amount of 44Ti and higher ratio of 44Ti/56Ni. Quantitatively, however, there are uncertainties in the location of the mass cut as well as in the initial degree of asymmetry, both of which are difficult to derive from analytical studies or numerical simulations, at least at present. In spite of these quantitative difficulties, we believe it is worthwhile for our scenario to be studied further, since it results in a solution to the Cas A problem.

In this Letter, we used only one progenitor model, where the He core mass is 6 M_{\odot}, which corresponds to 18–21 M_{\odot} in the main-sequence stage. Since the progenitor of Cas A is thought to be 15–30 M_{\odot}, one may need to examine the dependence of our conclusion on the progenitor mass. However, we think the qualitative tendency for the ratio of 44Ti/56Ni will not be changed for the following reason. The entropy per baryon after the passage of the shock wave is approximately proportional to \frac{T}{\rho}, where T and \rho are the local temperature and density, respectively. This means that the entropy per baryon depends more strongly on the temperature than on the density. The temperature depends significantly on the strength of the initial shock wave, while the density depends on the initial structure of the progenitor. Since the iron cores of the presupernova models have similar structures (Hashimoto 1995), the qualitative tendency for the ratio of 44Ti/56Ni will be unchanged even if the mass of the progenitor is changed.

The essential point of our results is that the explosion energy is localized in a small region near the rotation axis, leading to the stronger alpha-rich freezeout there. Therefore, we expect that the same mechanism will also work for three-dimensionally asymmetric explosions, where the explosion energy is deposited in some small regions.

There are two main possibilities conceivable that make the shock wave asymmetric in the collapse-driven supernova explosion. One is the effect of rotation (and/or magnetic field) of the progenitor, which causes the shock wave asymmetry (Müller & Hillebrandt 1981; Symbalisty 1984; Mönchmeyer & Müller 1989; Yamada & Sato 1994). The other is the effect of neutrino-driven convection (Shimizu, Yamada, & Sato 1994; Burrows & Hayes 1995), which causes high-speed “fingers” in the mantle, resulting in a more complex asymmetric explosion.

Although, in this Letter and in Nagataki et al. (1997),
have shown the effect of the strong alpha-rich freezeout for the two-dimensional axisymmetric explosion, we also want to stress the necessity of explosive nucleosynthesis calculations with a large nuclear reaction network for the “finger-like” explosion. Although it requires very high mesh resolution and CPU time, we think such a calculation will be necessary to explain the observed complex structure of Cas A. We are planning such a calculation in the near future.

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