GRAIN SURVIVAL IN SUPERNOVA REMNANTS AND HERBIG-HARO OBJECTS

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ABSTRACT

By using the [Fe ii] \( \lambda 8617/ \lambda 6300 \) flux ratio, we demonstrate that most of the interstellar dust grains survive in shocks associated with supernova remnants and Herbig-Haro objects. The [Fe ii]/[O i] flux ratio is sensitive to the gas-phase Fe/O abundance ratio but is insensitive to the ionization state, temperature, and density of the gas. We calculate the [Fe ii]/[O i] flux ratio in shocks and compare the results with the observational data. When only 20% of iron is in the gas phase, the models reproduce the observations most successfully. This finding is in conflict with the current consensus that shocks destroy almost all the grains and that >100% of metals are in the gas phase. We comment on previous works on grain destruction and discuss why grains are not destroyed in shocks.

Subject headings: dust, extinction — ISM: abundances — shock waves — supernova remnants

1. INTRODUCTION

For interstellar dust grains, the predominant destruction process is shocks driven by supernova explosions. In the postshock cooling gas, a charged grain is accelerated around the magnetic field line (betatron acceleration), collides with other grains and gas particles, and thereby loses its mass. Generally, it is believed that almost all the grains are destroyed in a single shock. The references are summarized in Savage & Sembach (1996) and Jones (2000). However, we would like to argue that the actual efficiency of grain destruction is as low as ~20% by mass in representative shock-heated nebulae, i.e., supernova remnants (SNRs) and Herbig-Haro (HH) objects.

The relative intensity of the emission lines [Fe ii] \( \lambda 8617 \) and [O i] \( \lambda 6300 \) is used to estimate the gas-phase Fe/O abundance ratio. In the usual interstellar medium, iron is depleted into grains by a factor of \( \geq 100 \) as a major dust constituent, while oxygen is largely undepleted (Savage & Sembach 1996). Thus, the gas-phase Fe/O ratio is proportional to the mass fraction of destroyed grains. The [Fe ii]/[O i] flux ratio is sensitive to the gas-phase Fe/O ratio but is insensitive to the ionization state, temperature, and density of the gas. This is because the same physical conditions are required to generate the [Fe ii] and [O i] emissions. They are excited by electron collisions. Since the ionization potentials of Fe II and O I are only 16.2 and 13.6 eV, respectively, both the [Fe ii] and [O i] emissions are generated in a partially ionized zone. The excitation energies of the [Fe ii] and [O i] lines are 19,000 and 23,000 K, respectively. Their critical densities for collisional de-excitation at 10^4 K are \( 3.5 \times 10^3 \) and \( 1.8 \times 10^5 \) cm^{-3}, respectively, which are well above the typical electron density in shocks. Moreover, the [Fe ii] and [O i] lines are prominent in shocks. The grain destruction is expected to have been completed in their emission region, which is far downstream from the shock front.

We calculate the [Fe ii]/[O i] flux ratio in shocks and compare the results with the observational data of SNRs and HH objects. The analysis and subsequent discussion employ the same values for atomic constants and interstellar abundances, the references of which are given below.

2. OBSERVATIONAL DATA

Figure 1 shows the number distribution of the [Fe ii] \( \lambda 8617/ \lambda 6300 \) flux ratio in SNRs (filled areas) and HH objects (open areas) in our Galaxy and in Magellanic Clouds. We do not include young SNRs, in which supernova ejecta dominate the line-emitting gas. The total (gas + dust) abundances of metals in our sample are hence equal to those of the usual interstellar medium. The possible scatter of the total abundances among objects would be too small to affect the present analysis. For reference, we also show the flux ratios in H II regions M8 and M42 (arrows). The data were taken from the literature and are described in the figure caption.

The distributions of SNRs and HH objects seem to be the same. Their [Fe ii]/[O i] flux ratios are higher than those of H II regions by factors of 2–3. Since the gas-phase fraction of iron in H II regions is \( 5\%–10\% \) (Baldwin et al. 1996; Esteban et al. 1999), the grain destruction efficiency in SNRs and HH objects seems to be 20%–30%. This result is confirmed by the following numerical calculation.

3. NUMERICAL CALCULATION

Our numerical calculation was based on the code MAPPINGS III, version 1.0.0g (Dopita & Sutherland 1996). To study [Fe ii] and [O i] emissions in detail, we included the charge exchange reaction \( Fe^{++} + H^o \rightarrow Fe^+ + H^+ \) (Neufeld & Dalgarno 1987), updated the collision strengths of \( Fe^+ \) and \( O^+ \) with the values of Pradhan & Zhang (1993) and Berrington & Burke (1981), and updated the radiative transition probabilities of \( O^+ \) with the values in Osterbrock (1989). Careful analytic fits were made to the temperature dependence of those collision strengths.

The most important parameter for our calculation is the gas-phase elemental abundances. We included 11 elements: H, He, C, N, O, Ne, Mg, Si, S, Ar, and Fe. Formerly, the solar values had been used for the total (gas + dust) abundances of metals in the interstellar medium. Recently, however, studies of elemental compositions in nearby stars revealed that the Sun is enhanced anomalously in metallicity by a factor of \( ~1.5 \) (Snow & Witt 1996). Since no reliable data of the interstellar abun-
dances are currently available, we used the solar values of Anders & Grevesse (1989), with the abundances of metals being lowered by 0.20 dex (Savage & Sembach 1996). The gas-phase fraction of iron $\delta_{Fe} = n_{Fe}/n_{Fe} (gas + dust)$ was set to be 0.1, 0.2, 0.3, or 1.0. We accordingly changed the gas-phase fractions of C, O, Mg, and Si by assuming that the grain composition is always equal to that observed toward the reddened star $\xi$ Oph (Savage & Sembach 1996). When $\delta_{Fe} = 0.2$, for example, 68% of C, 64% of O, 22% of Mg, and 26% of Si are in the gas phase.

The other parameters are the shock velocity $v_s$, the preshock hydrogen nucleon density $n_{H,0}$, and the preshock magnetic field $B_0$. We set $v_s = 50$–150 km s$^{-1}$, $n_{H,0} = 10$ or 100 cm$^{-3}$, and $B_0 = 3$ $\mu$G. These parameter values are typical of radiative shocks in SNRs and HH objects: $v_s \geq 100$ km s$^{-1}$ in SNRs and $v_s \leq 100$ km s$^{-1}$ in HH objects (Russell & Dopita 1990).

We assumed a plane-parallel geometry and a steady flow. The preshock ionization state was determined in an iterative manner. Since the ionized zone in the preshock gas is practically absent at $v_s \leq 150$ km s$^{-1}$ (Dopita & Sutherland 1996), we ignored the contribution of the preshock gas to the emergent spectrum. The calculation was terminated when the ionized hydrogen fraction $n_{HI}/n_{HI}$ fell below $\sim 0.01$. Beyond this point, the gas becomes too cool and neutral to excite the [Fe II] and [O I] emissions. We also ignored grain opacity, heating, and cooling. Their natures in shock-heated gas are quite uncertain.

They should nonetheless be unimportant to the [Fe II] and [O I] excitations (see Shields & Kennicutt 1995).

Figure 2 shows the cloud structure for $\delta_{Fe} = 0.2$, $v_s = 100$ km s$^{-1}$, and $n_{H,0} = 10$ cm$^{-3}$ as a function of the hydrogen nucleon column density from the shock front: (a) temperature and densities, (b) ionization fractions, and (c) line emissivities per hydrogen nucleon of [Fe II] $\lambda\lambda 6617, [O I] \lambda 6300, [O I] (\lambda 3726 + \lambda 3729)$, and [O III] $\lambda 5007$. These emissivities are normalized by their peak values.
v_s \geq 70 \text{ km s}^{-1} \text{ depends only on the gas-phase iron fraction } \delta_{Fe}. \text{ Although this is not the case at } v_s < 70 \text{ km s}^{-1}, \text{ such slow shocks are unimportant. They do not generate the } [\text{O III}] \lambda5007 \text{ emission, which is observed in all of our SNRs and HH objects. We also show the median and maximum values of the observed } [\text{Fe II}]/[\text{O I}] \text{ ratios (arrows). These values are reproduced by the models for } v_s \geq 70 \text{ km s}^{-1} \text{ with } \delta_{Fe} = 0.2 \text{ and } 0.3, \text{ respectively. The preshock gas has } \delta_{Fe} = 0. \text{ Hence, as suggested from the comparison with } \text{H II} \text{ regions (Fig. 1), the grain destruction efficiency is 20\%, on average, and 30\%, at most, in radiative shocks associated with SNRs and HH objects.}\)

4. DISCUSSION

Although shocks destroy grains in SNRs and HH objects, the destruction is far from complete. Typically, 80\% of iron is still locked into grains. However, many observational studies of shock-heated nebulae conclude that the grain destruction is almost complete, as reviewed by Savage & Sembach (1996) and Jones (2000; see also references for the data used in Fig. 1). In the usual interstellar gas, heavy metals such as Fe and Ca are depleted by factors of $10^2$–$10^4$ (Savage & Sembach 1996). If only a small fraction of the grains is destroyed, emission and absorption lines of those metals are greatly enhanced (Fesen & Kirshner 1980). The observer is easily misled to consider that a large fraction of the grains is destroyed. Moreover, owing to wide variations of physical quantities across the gas (Fig. 2), it is generally difficult to determine elemental abundances in shocks.

Nevertheless, conclusions similar to ours were obtained in some of the past observations of SNRs. Phillips & Gondhalekar (1983) and Jenkins et al. (1998) observed ultraviolet absorption lines of stars behind S147 and the Vela SNR, estimated the column densities of gas-phase ions across these SNRs, and found depletion of Al. Raymond et al. (1988, 1997) observed ultraviolet and optical emission lines of the Cygnus Loop and the Vela SNR, compared their relative strengths with predictions of shock models, and found depletions of Fe and of C and Si. Oliva, Moorwood, & Danziger (1989) observed near-infrared emission lines of RCW 103, compared their strengths with model predictions, and found depletion of Fe. Reach & Rho (1996) detected continuum emission from grains in the far-infrared spectrum of W44. It should be noted that our result is more reliable than these previous ones. The Fe/O abundance ratio estimated from the [Fe II] and [O I] fluxes is robust with respect to the shock velocity and preshock density (Fig. 3).

Since we studied the Fe/O abundance ratio alone, the grain survival probability estimated here is applicable, strictly speaking, only to Fe-bearing grains. There could exist several types of grains and subgrains that have different survival abilities. Of importance is a careful analysis of emission and absorption lines of the other elements. The present conclusion is nonetheless general. Observations of various Galactic interstellar clouds indicate that Mn, Cr, Ni, and Ti always have the same dust-phase fraction as Fe (Savage & Sembach 1996; Jones 2000). Although the major dust constituents Mg and Si appear to be more easily liberated to the gas phase than Fe, large fractions of Mg- and Si-bearing grains survive in shocks. The above observations indicate that, when 80\% of Fe is locked into grains, ~50\% of Mg and Si are in the dust phase.\footnote{These dust-phase fractions were adapted from Savage & Sembach (1996).}

The present conclusion is, at least qualitatively, consistent with theoretical models. Jones, Tielens, & Hollenbach (1996) predicted that 60\% (by mass) of silicate grains survive in a shock with $v_s = 100 \text{ km s}^{-1}$, $n_{H,0} = 25 \text{ cm}^{-3}$, and $B_0 = 3 \mu$G. This predicted probability of grain survival is somewhat low, but we could increase it. The above model assumes that grains are solid and homogeneous. If the grains are porous, e.g., consisting of several types and sizes of subgrains, they undergo less destruction (Jones et al. 1994). This is because their effective cross section is large. The resultant large gas drug prevents efficient betatron acceleration. Such porous grains are the natural result of the coagulation of small grains into larger ones and are found as interplanetary dust particles. The presence of porous grains is also suggested by the recent finding that the Sun is overabundant in heavy elements (Snow & Witt 1996). The amount of metals available for grains in interstellar space is much less than had been estimated from the solar abundances. However, the observed interstellar extinction per unit length puts a lower limit on the volume fraction of space occupied by grains. This situation calls for porous grains that have high volume-to-mass ratios (see also Jones et al. 1996 and Mathis 1990, 1998).
of interstellar grains. We estimate the grain lifetime in our Galaxy (Tielens 1998). The gas mass shocked by a supernova to a velocity equal to or greater than \( v \), is 2500 \( (v/100 \text{ km s}^{-1})^{9/7} M_\odot \). Since the effective supernova rate is \( 8 \times 10^{-2} \text{ yr}^{-1} \) and the mass of diffuse gas is \( 5 \times 10^3 M_\odot \), the time interval for a grain to experience a supernova-driven shock with \( v > 100 \text{ km s}^{-1} \) is \( \frac{1}{2} \times 10^9 \text{ yr} \). If each of the shocks destroys 20% of the grains, their mean lifetime is \( \frac{1}{2} \times 10^9 \text{ yr} \). The lifetime of the gas parcel itself is much longer, i.e., \( 2 \times 10^9 \text{ yr} \), which is estimated from the total gas mass of \( 8 \times 10^9 M_\odot \) and the star formation rate of \( 5 \times 10^{-5} \text{ yr}^{-1} \). Since interstellar grains are actually present, there has to exist some growth process, e.g., accretion of gas particles onto grains in dense gas (Jones et al. 1994). Tielens (1998) obtained a similar grain lifetime from the metal depletions observed in diffuse and dense gases and the timescale for cycling the material between them.

Finally, we underline that dust depletion is crucial to understanding spectra of shock-heated nebulae. Their gas-phase abundances are often assumed to represent the total (gas + dust) abundances of the preshock gas. This assumption could be wrong. For example, near-infrared [Fe ii] emission lines at 1.257 and 1.644 \( \mu \text{m} \) are more prominent by factors of \( >500 \) in SNRs than in \( \text{H II} \) regions (Graham, Wright, & Longmore 1987). This fact is often explained by the shock destruction of Fe-bearing grains. However, Mouri, Kawara, & Taniguchi (2000) found that with the code MAPPINGS III, the [Fe ii] 1.257 \( \mu \text{m}/\text{Pa}\alpha \) flux ratio observed in SNRs is reproduced only when the gas-phase iron abundance is as low as in the \( \text{H II} \) region M42. The flux ratio predicted for the solar abundance is too high. This finding motivated the present work. We adopted the [Fe ii] \( \lambda 8617/\lambda 6300 \) flux ratio as a more reliable diagnostic, conducted numerical calculations in more detail for gas-phase metallicity, and thereby determined more precisely the gas-phase iron abundance.

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Note added in proof.—Physical processes of dust grains in shocks, e.g., betatron acceleration and collisions with gas particles, are explained by B. T. Draine (Ap&SS, 233, 111 [1995]) and Jones et al. (1994, 1996).