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ACCELERATION OF INTERSTELLAR DUST GRAINS AT SUPERNOVA REMNANT SHOCKS AND POSSIBLE IMPLICATIONS FOR COSMIC-RAY COMPOSITION

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Abstract. Diffusive shock acceleration (DSA) is a well-established mechanism for energizing charged particles, such as ions and electrons, at astrophysical collisionless shocks. We study the potential for interstellar dust grains of various sizes and compositions to also undergo DSA, particularly at young supernova remnant (SNR) shocks during their free expansion and Sedov-Taylor phases. Using semi-analytical models of particle acceleration and self-similar shock dynamics, we focus on type Ia SNRs expanding in a uniform interstellar medium. Our findings indicate that dust grains can be accelerated to relativistic speeds, achieving Lorentz factors of approximately 100 and kinetic energies of around 100 GeV/nucleon for smaller grains ($\sim 5 \times 10^{-7}$ cm). Furthermore, sputtering of these accelerated grains may yield nuclei with sufficient rigidity to participate in DSA, potentially explaining the observed overabundance of refractory elements in Galactic cosmic rays (CRs). This scenario is plausible if a fraction ($\sim 10^{-3}$ to 10^{-2}) of the dust grains swept up by SNR shocks are energized via DSA.

Keywords: cosmic rays, particle acceleration, dust grains, supernova remnants

1 Introduction

Previous works have examined the role of possibility of acceleration of dust grains through diffusive shock acceleration (DSA), and how the rapid grain destruction following the acceleration could play a role in the production of cosmic rays (Epstein 1980; Ellison et al. 1997). The acceleration of dust grains, characterized by large mass-to-charge ratios, is typically limited by their rapid destruction through interactions such as thermal sublimation, sputtering, and grain collisions. The acceleration of dust grains offers a potential explanation for the observed overabundance of refractory elements (e.g., Mg, Si, Fe) in Galactic cosmic rays. These elements, typically found in dust phases, are thought to be injected into the interstellar medium by supernova remnants. In this work, we extend earlier models by reassessing the acceleration of dust grains in supernova remnant shocks, accounting for realistic grain size distributions and compositions, and examining their contribution to the cosmic-ray composition, particularly the enhanced levels of refractory elements.

2 The abundance of refractory elements in cosmic rays

A significant portion of dust grains in a supernova remnant (SNR) environment is expected to undergo destruction (Slavin et al. 2015). This also applies to accelerated dust grains, where sputtering is anticipated to play a key role. Notably, atoms sputtered from accelerated dust grains exhibit higher rigidity compared to those sputtered from thermal dust grains or grains passively carried within the plasma, and can thus acquire a sufficient rigidity to enter DSA in turn, increasing their abundance in the cosmic ray composition.

We consider the case of silicate dust grains, assuming that all silicon (Si) atoms in the interstellar medium (ISM) are locked within these grains. Observations show that the abundance of Si in cosmic rays (CRs) is approximately 20 times higher than the CR-to-solar system (SS) abundance ratio for protons (Tatischeff et al. 2021). The acceleration and sputtering of dust grains in SNR shocks has been proposed as a potential mechanism to explain the observed overabundance of refractory elements in the CR composition. We illustrate in Fig. 1 the increase of the rigidity of silicate dust grains expected due to DSA.

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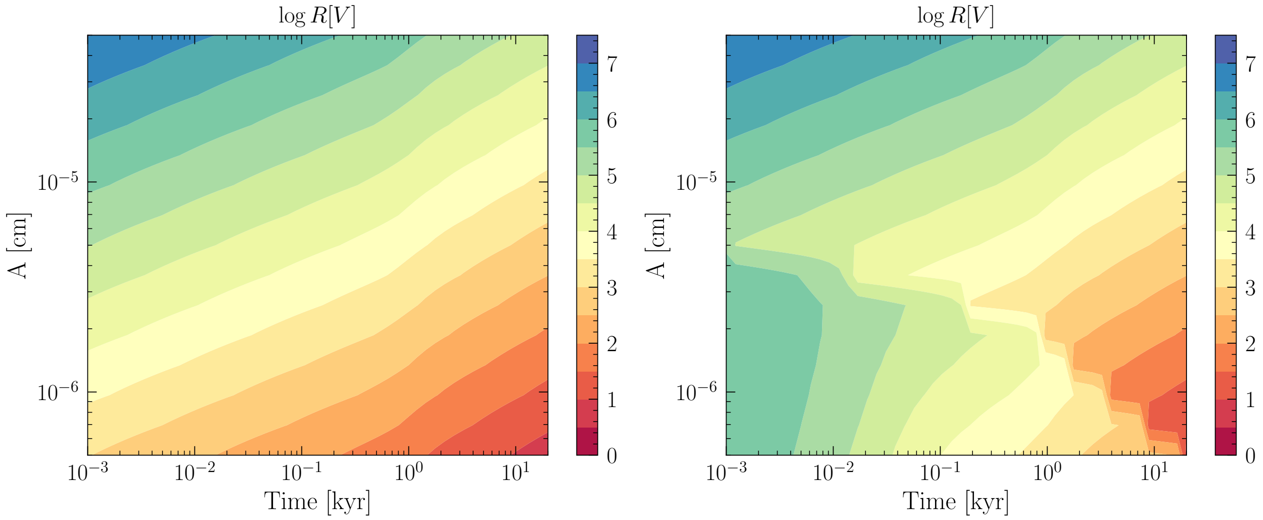

Fig. 1. Rigidity of silicate dust grains arriving downstream (top panel) and at maximum energized through DSA (bottom panel).

We calculate the number of dust grains that are accelerated and the quantity of sputtered silicon with a rigidity exceeding the minimum injection rigidity necessary for protons to enter DSA. These silicon nuclei are thus regarded as sufficiently rigid to be accelerated through DSA, thereby contributing to the CR composition. The typical rigidity of the sputtered silicon is calculated that throughout a typical Type Ia SNR's lifetime, and we found that all dust grains typically smaller than approximately $\sim 4\times10^{-6}$ can be sputtered to produce silicon capable of entering DSA.

At any given time t, the amount of sputtered silicon is estimated by comparing the sputtering timescale, to the dynamical timescale at that moment, defined as $t_{\rm dyn} = \min(t, t_{\rm adv})$, where $t_{\rm adv} \sim D_1/u_{\rm sh}^2$ and D_1 represents the diffusion coefficient of dust grains upstream. This approach implicitly assumes that all silicon sputtered upstream will be advected to the shock and can enter DSA, provided that the rigidity meets the injection criterion. Conversely, the silicon sputtered downstream is rapidly advected away and lost within the SNR.

We estimate the cumulative ratio of accelerated to swept-up silicon and protons, $R_{\rm si}$ and $R_{\rm p}$, respectively. The primary free parameter in our calculations is the fraction of dust grains energized through diffusive shock acceleration (DSA), represented by η. The scaling of $R_{\rm si}$ is proportional to η, and $R_{\rm p} \propto \eta_{\rm CR}$. To achieve a ratio $R_{\rm si}/R_{\rm p} \sim 20$ assuming a typical value of $\eta_{\rm CR} \sim 10^{-5}$, the acceleration efficiency of dust grains must be approximately of the order of $\eta \sim 5\times10^{-3}$. Assuming that the increased fraction of silicon in CRs originates from accelerated and sputtered dust grains, an acceleration efficiency for these grains of $\eta \sim 10^{-3} - 10^{-2}$ is necessary—this is two to three orders of magnitude greater than that for protons, for which $\eta \sim 10^{-5}$. The requirement for enhanced efficiency for dust grains is readily understood, as discussed in the previous section: only smaller dust grains can be accelerated through DSA (with $\beta_{\rm max}$ exceeding the shock velocity). Consequently, a substantial number of accelerated small dust grains is required to ensure that these grains can be effectively sputtered. The results of our calculation is illustrated in Fig. 2. In our simplified approach, all CR Si ions originate from the sputtering of accelerated silicate grains, which are assumed to be all destroyed at the end of the adiabatic phase (~ 20 kyr).

3 Conclusions

DSA at SNR shocks has been shown to energize dust grains to relativistic energies, with examples such as $\gamma \sim 10^2$ and $E_{\rm k} \sim 10^2$ GeV/nucleon for grains with sizes around $a \sim 5\times10^{-7}$ cm.

However, the maximum energy attainable by small grains with $a \leq 5\times10^{-6}$ cm is constrained by various loss mechanisms and destruction processes. For larger grains, specifically those with $a \geq 5\times10^{-6}$ cm, their escape from the shock precursor inhibits further acceleration.

Moreover, the sputtering of ions from accelerated dust grains contributes to the observed overabundance of refractory elements in cosmic rays (CRs). The enhanced rigidity of these sputtered ions facilitates their more

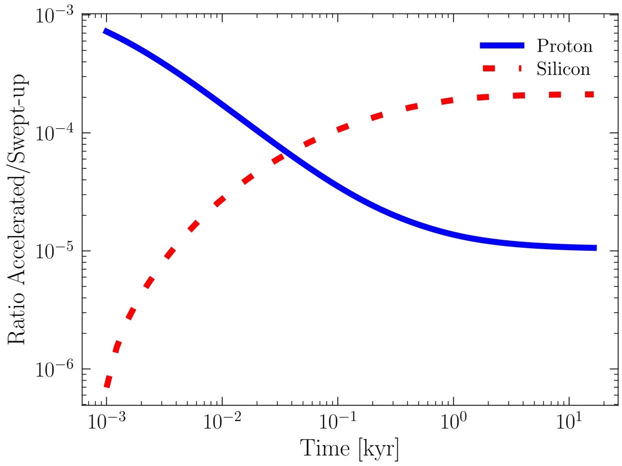

Fig. 2. Ratio of the cumulative accelerated ions to cumulative swept-up ions. The blue solid line corresponds to protons, the red dotted to silicon considering sputtering as main destruction mechanism for the dust grains. The calculation carried with the number of CRs/dust grains ($\eta_{\rm CR} = 10^{-5}$, and $\eta_a \sim 5 \times 10^{-3}$ in order to get a ratio silicon/protons of ~ 20) at the end of the Sedov-Taylor phase.

efficient injection into DSA. The observed silicon-to-proton abundance ratio of approximately 20, as reported in CR measurements (Tatischeff et al. 2021), can be explained if the acceleration efficiency of dust grains is typically around $\eta_a \sim 10^{-3} - 10^{-2}$—which is two to three orders of magnitude higher than that of protons, where $\eta_{\rm CR} \sim 10^{-5}$. This will be discussed in details in a forthcoming paper (Cristofari et al. 2025).

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