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Dust Destruction in the Cygnus Loop Supernova Remnant

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Abstract. The Cygnus Loop supernova remnant serves as an excellent laboratory for the study of radiative and non-radiative shocks with speeds in the 150–450 $\mathrm{km\,s^{-1}}$ range. We present results on shock-excited emission and dust destruction based on Spitzer Space Telescope observations of two well-studied regions in the remnant, (i) a non-radiative shock filament along the NE limb, and (ii) the XA region, characterized by emission from bright radiative shocks.

Keywords. dust, shock waves, supernova remnants

1. Introduction

The destruction of grains in supernova remnant (SNR) shock waves is a key step in the life-cycle of dust in the Galactic interstellar medium (ISM). It regulates the dust-to-gas ratio in the ISM (Draine 2009). Within the remnants, it determines the gas phase abundances of refractory elements, which are depleted in the pre-shock gas and released as the dust is destroyed. At shock speeds greater than about 80 $\mathrm{km\,s^{-1}}$ sputtering is the dominant destruction process, while destruction by grain-grain collisions become dominant for slower shocks (Jones *et al.* 1994). Most of the dust destruction happens in middle-aged SNRs in the Sedov-Taylor phase, when the shock speeds are in the range 200–500 $\mathrm{km\,s^{-1}}$, since most of the volume swept up by a remnant happens during that stage of its evolution.

The Cygnus Loop is well suited for the study of dust destruction processes. It is nearby (540 pc, Blair *et al.* 2005), so the post-shock zone is spatially resolved by X-ray and infrared instruments. The foreground extinction is small ($\mathrm{E_{(B-V)}} \approx 0.08$), and therefore it can be observed at ultraviolet wavelengths, which allows for the determination of the shock properties (Danforth, Blair & Raymond 2001; Raymond *et al.* 2003; Sankrit *et al.* 2007). We have used the Spitzer Space Telescope (*Spitzer*) to observe a non-radiative shock along the north-east limb of the Cygnus Loop and the XA region, a radiative shock interaction region in the south-east. In §2 we summarize the main results obtained for the non-radiative shock, which have been presented in Sankrit *et al.* (2010). Then in §3 we describe the evidence for dust destruction in a slower, radiative shock in the XA region. Some possible avenues for future work are discussed in §4.

2. Non-radiative Shock

The filament observed by *Spitzer* was chosen from among the non-radiative filaments that define the edge of the Cygnus Loop because the shock parameters had been determined from observations in the optical (Ghavamian *et al.* 2001) and the far-ultraviolet (Raymond *et al.* 2003). Images obtained with the MIPS instrument showed an intensity fall-off in the 24 μm band and an increase in the 70 μm/24 μm flux ratio with distance behind the shock. Dust models using input parameters guided by prior knowledge of the shock properties were able to match the intensity profile and the variation in flux ratio. It was found that non-thermal sputtering (i.e. due to the bulk motion of the grains relative to the gas) contributes significantly to the dust destruction. Models that included only thermal sputtering were unable to reproduce the observed flux ratios for the permissible shock parameters. The models predicted grain temperatures between 30 and 60 K.

The fiducial model for the shock (post-shock temperature = 0.20 keV, corresponding to a shock speed of about 400 km s^{-1}, and pre-shock hydrogen number density = 0.5 cm^{-3}) predicted that about 35% by mass of the grains have been destroyed in the course of about 1350 yr, the age of the shock, and that in another 1000 yr about 43% of the dust will be destroyed. In order to compare the model-predicted fluxes with observations, the dust-to-gas ratio in the pre-shock gas needs to be specified. For a dust-to-gas mass ratio of 0.75%, the model reproduces the observed 24 μm flux for a path length through the emitting region of about 0.35 pc. This is considerably lower than the path length of 0.7–1.5 pc through the shock required to match the far-ultraviolet and X-ray data (Raymond *et al.* 2003). If the path length is 0.7 pc, then the dust-to-gas ratio required falls to 0.38%. It is an open question whether such a low value is permissible, but it is consistent with our earlier findings for several remnants (Borkowski *et al.* 2006; Williams *et al.* 2006; Blair *et al.* 2007).

3. Radiative Shock: the XA region

The XA region is an indentation in the X-ray shell along the southeast edge of the Cygnus Loop, and is due to an interaction between the blast wave and a cloud (Hester & Cox 1986). Danforth *et al.* (2001) analyzed optical and ultraviolet data of the region and suggested that it was a protrusion on the surface of a larger cloud. We obtained a MIPS 24 μm image of the interaction region and high resolution IRS spectra (in "stare" mode) of a few locations in the region. Images of the region are shown in Fig. 1, with IRS Long-High aperture positions overlaid. The "cusp" is the tip of the protrusion impacted by the blast wave, and the "background" lies outside the remnant. We used the "Spectroscopic Modeling Analysis and Reduction Tool" (SMART) version 8.1.2 (Higdon *et al.* 2004; Lebouteiller *et al.* 2010) to extract background-subtracted, one-dimensional, calibrated data. The resulting spectrum is shown in Fig. 2. The spectrum shows no detectable dust continuum emission, and by convolving the spectrum with the MIPS 24 μm filter response, we find that the lines contribute over 80% of the flux detected in the image.

In order to interpret the spectrum, we compare the measured line ratios with predictions from shock model calculations, using the code originally described by Raymond (1979) with updates described in Raymond *et al.* (1997). We find at least two shock speeds are required to produce the observed spectrum. The high ionization lines, [Ne V] 24.32 μm and [O IV] 25.88 μm, require a 180 km s^{-1} shock that has not recombined (otherwise it would produce too much low ionization emission) and a slower shock, about 150 km s^{-1} that produces the [S III] 33.47 μm and [Si II] 34.80 μm lines. This is consistent with the conclusions of Sankrit *et al.* (2007) who found that a range of shock speeds were required to explain the far-ultraviolet spectrum of the region.

The observed [Si II] to [S III] flux ratio is 3.4, and the shock models indicate that this cannot be obtained for depleted gas phase abundances. For a sulphur abundance [S] = 7.51 on a logarithmic scale relative to [H] = 12.00, the observed flux ratio is obtained if

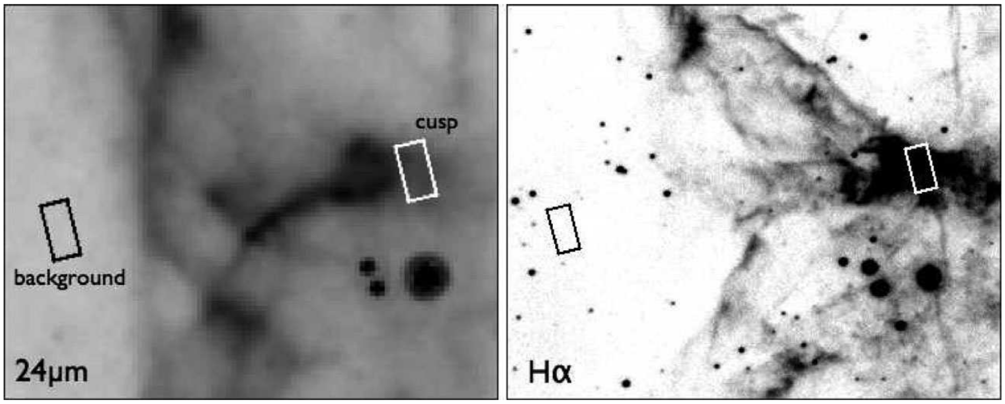

Figure 1. Images of the XA region; *left:* Spitzer MIPS 24 μm and *right:* Whipple Observatory 1.2m telescope Hα. The boxes, drawn to scale, represent the IRS Long-High aperture ($11.1'' \times 22.3''$). North is up, East to the left.

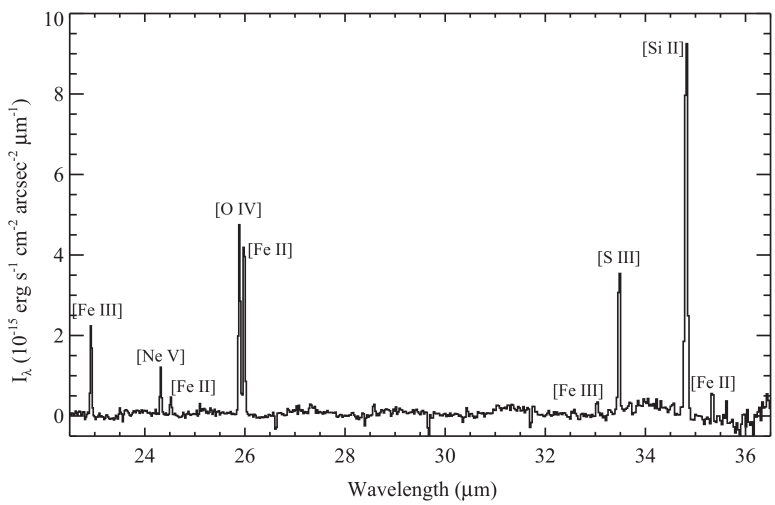

Figure 2. Background subtracted *Spitzer* IRS Long-High spectrum of the cusp (see Fig. 1).

the silicon abundance [Si] = 7.50, which is the undepleted (solar) value, and if the pre-shock magnetic field (perpendicular to the shock direction) $B_0 = 10\mu$G. The flux ratio is moderately dependent on the pre-shock magnetic field strength, with lower values of the magnetic field resulting in higher [Si II], but even for $B_0 = 1\mu$G, the silicon abundance needs to be about half the solar value. Since about 90% of the Silicon is expected to be in dust in the general ISM, our results imply that at least half of it is released into the gas phase, which in turn implies that dust has been destroyed by the shock. This conclusion is subject to the caveats that we do not have a direct measurement of the Silicon abundance in the pre-shock gas, and that we are assuming a fixed value for the Sulphur abundance. The spectrum only allows us to measure the abundance ratio in the post-shock gas.

4. Concluding Remarks

The results on the non-radiative shock presented here (and in more detail in Sankrit *et al.* 2010) suggest some avenues for exploration. To obtain a definitive answer as to the dust-to-gas ratio in the ambient ISM, it is necessary to calculate a self-consistent model of the X-ray and infrared emission. This would require following the gas phase abundances with position behind the shock. We have estimated that much deeper X-ray observations than currently available are required to reliably do so. A project currently underway is the measurement of C IV λ1550 emission in far-ultraviolet spectra, obtained with HST/COS, to examine the sputtering of Carbon atoms behind the shock front (Raymond *et al.* in preparation).

The XA region is complex, with multiple shocks present along our line of sight. The *relative* abundances of elements may be well constrained by our data, but they do not allow us to resolve the degeneracies in other parameters such as the absolute abundances, densities and magnetic fields. In our data dust destruction is addressed only indirectly via the Silicon abundance. A promising line of study both for characterizing the shock parameters and for measuring the release of refractory elements into the gas phase is the interpretation of the [Fe II] and [Fe III] lines, which requires the calculation and use of new atomic data (Bautista, in preparation). The search for cooler dust at longer wavelengths may become viable when far-infrared instruments become available on SOFIA.

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Discussion

Koo: The low dust-to-gas ratio in preshock region that you obtained seems to be common rather than unusual. Could you comment on that?

Sankrit: Yes, in all the cases we have looked at, including cygnus loop, Kepler and several LMC remnants, the inferred dust-to-gas ratio is low. This difference between SNR surroundings & Typical ISM regions is interesting and is an issue that needs to be explored at greater depth.

GREEN: Could you explain again the reasoning to choose the line of sight depth in your analysis.

SANKRIT: The line-of-sight depth chosen is approximately that of the filament length on the plane of the sky (taking into account the curvature). We expect that these brighter rims may actually have longer path lengths (selection effect). But that would drive the inferred dust density to lower values, and make the dust-to-gas ratio correspondingly lower. i.e. the deviation from the typical dust-to-gas ratio would increase.

FRANCE: Do you see low-ionization metals (e.g.; S:II 1526/1533, FeII 1608, etc) in your HST-COS spectra of Cygnus? If so, can you use these emissions to constrain dust destruction/gas liberation?

SANKRIT: No, We don't see low-ionization lines; the shock is non-radiative, and the swept-up post-shock gas has not had enough time to recombine. The only lines detected are the CIV doublet and HeII (1640 A)