THE FIRST REPORTED INFRARED EMISSION FROM THE SN 1006 REMNANT

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ABSTRACT

We report results of infrared imaging and spectroscopic observations of the SN 1006 remnant, carried out with the Spitzer Space Telescope. The 24 μm image from Multiband Imaging Photometer for Spitzer clearly shows faint filamentary emission along the northwest rim of the remnant shell, nearly coincident with the Balmer filaments that delineate the present position of the expanding shock. The 24 μm emission traces the Balmer filaments almost perfectly but lies a few arcsec within, indicating an origin in interstellar dust heated by the shock. Subsequent decline in the IR behind the shock is presumably due largely to grain destruction through sputtering. The emission drops far more rapidly than current models predict, however, even for a higher proportion of small grains than would be found closer to the Galactic plane. The rapid drop may result in part from a grain density that has always been lower—a relic effect from an earlier epoch when the shock was encountering a lower density—but higher grain destruction rates still seem to be required. Spectra from three positions along the NW filament from the Infrared Spectrometer instrument all show only a featureless continuum, consistent with thermal emission from warm dust. The dust-to-gas mass ratio in the pre-shock interstellar medium (ISM) is lower than that expected for the Galactic ISM—as has also been observed in the analysis of IR emission from other supernova remnants, but whose cause remains unclear. As with other Type Ia supernova (SN Ia) remnants, SN 1006 shows no evidence for dust grain formation in the SN ejecta.

Key words: ISM: individual objects (SNR SN1006) – ISM: kinematics and dynamics – ISM: supernova remnants – shock waves

Online-only material: color figures

1. INTRODUCTION

The supernova (SN) of 1006 C.E. is generally recognized as the brightest stellar event in recorded human history, with surviving contemporary reports from China, Japan, Korea, the Arab world, and in Europe as far north as St. Gallen, Switzerland (latitude 47°4 N), all despite the SN’s southern declination of decl. (1006) = −38:5 (Stephenson 2010). Throughout much of the twentieth century, SN 1006 languished in relative obscurity, with the exception of a short period during the heyday of cosmic-ray astronomy. It has since become a widely observed and important object: X-rays from SN 1006 were discovered by Winkler & Laird (1976), optical emission was discovered by van den Bergh (1976), and (following a somewhat checkered history) γ-ray emission was definitively detected and mapped by the H.E.S.S. Collaboration (Acero et al. 2010). Koyama et al. (1995) discovered that the NE and SW limbs of SN 1006 have a featureless, power-law X-ray spectrum, providing the first conclusive evidence that electrons can be accelerated to TeV energies in SN shocks and cementing the long-suspected connection between SNe and cosmic rays. Yet no infrared emission has previously been reported from SN 1006.

The SN 1006 remnant has a limb-brightened shell, 30′ in diameter, with strong bilateral symmetry in radio and X-rays. Its distance is well determined at 2.2 kpc (Winkler et al. 2003), and it is located high above the Galactic plane ($b_G = 14°6$, $z = 550$ pc). Its high-latitude location leads to relatively low foreground absorption. SN 1006 itself was almost certainly a Type Ia event, based on its location, environment far from any recent star formation, apparent absence of any compact remnant, and implication from Chinese records that it remained visible for several years (Stephenson & Clark 2002). The optical emission from its remnant consists solely of Balmer-dominated filaments (e.g., Schweizer & Lasker 1978; Kirshner et al. 1987; Ghavamian et al. 2002), which indicate that it is expanding into an environment with relatively low density that is at least partially neutral, another signature of SN Ia remnants.

SNe and their remnants are critical to dust grain formation, modification, and destruction. Dust grains may condense from metal-rich SN ejecta, and the fast shock waves in supernova remnants (SNRs) can lead to sputtering through collisions with shock-heated gas that erode and eventually destroy dust grains (e.g., Draine & Scalo 1980; Draine 2003; Sankrit et al. 2010). Although these processes have been observed in a number of SNRs, SN 1006 nevertheless provides a unique perspective due to its location high above the Galactic plane in a relatively pristine region of the interstellar medium (ISM). There is growing observational evidence for the formation of dust in the ejecta from core-collapse SNe, including SN 1987A (Wooden et al. 1993; de Kool et al. 1998; Matsuura et al. 2011), Cas A (Rho et al. 2008; Nozawa et al. 2010), and the Crab Nebula (Gomez et al. 2012b), and in the late-time emission from a
number of more distant SNe (e.g., Kotak et al. 2009; Szalai et al. 2011; Meikle et al. 2011).

Recent models by Nozawa et al. (2011) predict that small dust grains can also form in the ejecta from Type Ia SNe, and that $10^{-3} M_\odot$ of dust can survive for ~1000 years. However, no dust associated with ejecta has as yet been observed in any of the historical remnants of the SN Ia: Tycho (SN 1572), Kepler (SN 1604), or RCW 86 (probable SN 185 remnant), all of which have been widely observed in the infrared. Mid-IR emission from both Tycho and Kepler was detected from the Infrared Astronomy Satellite (IRAS; Braun 1987), and both have been observed in detail from Infrared Space Observatory (Douvion et al. 2001), Spitzer (Blair et al. 2007; Williams et al. 2012), Herschel (Gomez et al. 2012a), and other missions. RCW 86 was also detected from IRAS (Arendt 1989; Saken et al. 1992), and Williams et al. (2011a) have recently presented detailed observations with Spitzer. Borkowski et al. (2006) have also reported IR observations for four SN Ia remnants in the Large Magellanic Cloud. All these cases show thermal emission from dust grains and provide evidence for grain destruction in SN shocks, but none show convincing evidence for grain formation (see especially Gomez et al. 2012a).

In this paper we report the first detection of IR emission from the SN 1006 remnant. In Sections 2 and 3 we describe the results of an imaging mapping campaign with the Spitzer Space Telescope, which reveals a filament of 24 $\mu$m emission along the NW limb of the shell, plus very faint, diffuse emission elsewhere. In Section 4, we describe the spectroscopic observations from the Infrared Spectrometer (IRS) on Spitzer, and in Section 5 we present a discussion in which we fit dust models to both sets of data and assess the total dust mass and dust-to-gas mass ratio. Finally, we give a brief summary of our results in Section 6.

2. MIPS OBSERVATIONS

We mapped SN 1006 twice with the Multiband Imaging Photometer for Spitzer (MIPS; Rieke et al. 2004) as part of program 30673: on 2007 March 5 and 2007 August 22. In order to cover the entire 30$''$ shell and the surrounding background field, each observation required a pair of overlapping scan maps, which were taken consecutively. The March Astronomical Observation Requests (AORs) (18724608 and 18725120) were carried out during a “cold” campaign and included observations at 24 $\mu$m, 70 $\mu$m, and 160 $\mu$m, while the August ones (18724864 and 18725376) were during a “warm” phase of the cryogenic mission and gave only 24 $\mu$m and 70 $\mu$m data. Both pairs of scans consisted of 14 legs of length 0.75; offsets of 148$''$ were used for the March pair, while the August pair used offsets of 111$''$ to give greater exposure of SN 1006 itself at a cost of somewhat less surrounding background. We began with Basic Calibrated Data (BCD) files from the Spitzer Heritage Archive that had been processed through version 18.12 of the Spitzer pipeline, and we then performed further flat-fielding by taking a median of the hundreds of frames from each AOR and dividing all the frames from that AOR by the normalized flat. The estimated zodiacal light was then subtracted from each frame, and the maps were mosaicked together onto a standard world coordinate system, 60$''$ square with 1$''$ pixels, using the MOPEX software provided by the Spitzer Science Center. Finally, we used DAOPHOT in IRAF8 to remove the vast majority of point sources (mainly stars) from the mosaic image, in order to better assess the diffuse emission from SN 1006 itself.

The full 24 $\mu$m mosaic is shown in Figure 1, with both the original and star-subtracted versions in panels (a) and (b), respectively. These clearly show the first detection of SN 1006 in the mid-infrared. For reference, we also show images of the identical SN 1006 field in H$\alpha$, X-rays, and radio in other panels of the figure. The most prominent IR feature is the thin filament along the NW rim of the shell. Even this brightest emission is quite faint, with peak surface brightness levels above the background of 0.25–0.3 MJy sr$^{-1}$, only about 6% of the background emission and fainter than either the Tycho or Kepler SNRs by more than a factor of 20. The integrated flux from this filament in the 24 $\mu$m band is $F(24 \mu m) = 130 \pm 30$ mJy, where the precision is limited by our tracing of the filament and ability to assess the background accurately, since there is diffuse background and faint residual stars in the “star-subtracted” mosaic.

We used a similar approach for the 70 $\mu$m data, except that here the mosaic has a scale of 4$''$ pixel$^{-1}$. Despite our flat-fielding all the data using median frames for each AOR, artifacts along the scan directions are nevertheless evident in the final mosaic, shown in the bottom left panel of Figure 1. There is the slightest hint of an enhancement in the region of the NW filament, but this does not trace the narrow filament and is barely larger than background fluctuations in the vicinity. We give only an upper limit for the average surface brightness in the region of the filament: $S(70 \mu m) < 0.85$ MJy sr$^{-1}$ (3$\sigma$), and an integrated flux $F(70 \mu m) < 800$ mJy. The 160 $\mu$m images, compiled using only the two scans from 2007 March for which 160 $\mu$m are available, are quite noisy and show no discernible emission from SN 1006.

3. IMAGING ANALYSIS AND MULTI-WAVELENGTH COMPARISONS

3.1. The Northwest Filament

The NW filament corresponds closely with the optical filament that appears only in the hydrogen Balmer lines (van den Bergh 1976; Winkler et al. 2003; Raymond et al. 2007), as shown in the deep continuum-subtracted image shown in the lower right panel of Figure 1. Such “non-radiative” filaments characterize fast shocks expanding into a low-density, partially neutral environment and that are generally associated with relatively young remnants from Type Ia SNe such as SN 1006. Balmer emission from these filaments has two components, both the result of neutral H atoms that cruise through the shock. In the hot post-shock environment, the neutrals can be excited and decay to produce narrow lines (with a width characteristic of the pre-shock temperature), or they can undergo charge exchange with hot protons to produce broad lines whose width is closely related to the post-shock proton temperature (e.g., Chevalier et al. 1980; Ghavamian et al. 2002; Heng 2010). Since the lifetime of neutral atoms in the hot post-shock environment is very short, the Balmer filaments can occur only immediately behind the shock and thus delineate the current position of the shock.

To investigate the post-shock characteristics of emission along the NW filament in various bands, we have compared 24 $\mu$m, H$\alpha$, and X-ray images. We have used a higher resolution H$\alpha$ image, taken from the 0.9 m telescope at Cerro Tololo Inter-American Observatory on 2002 March 21, for which the stars were subtracted using a matched continuum image (for details, see Winkler et al. 2003), instead of the one shown in Figure 1(c).
Likewise, in X-rays we have used the 0.5–2.0 keV data from a 90 ks observation taken 2001 April 26 and 27 with the Chandra ACIS-S (for details, see Long et al. 2003), rather than the mosaic of shorter ACIS-I exposures used in Figure 1(e). We first checked the alignment of all three images using four near point sources common to all, one bright star and three distant galaxies, and found their positions in all three bands to agree within 0.5″.

To simulate images in all three bands at a common epoch, we used the $\mu = 280 \pm 8$ mas yr$^{-1}$ proper-motion rate for the NW Balmer filaments, measured relative to the center of curvature at R.A. (2000.0) = $15^h03^m16^s2^,$ decl. (2000.0) = $-42^\circ00'30''$ by Winkler et al. (2003), to extrapolate the H$\alpha$ and X-ray images from their original epochs (2002.2 and 2001.3, respectively) to the 2007.5 mean epoch for the Spitzer MIPS scans (recent measurements from Chandra find X-ray proper motions along most of the NW rim of SN 1006 that agree with those measured for the optical filaments; Katsuda et al. 2013).

In Figure 2, we show a three-color combination that compares the 24 $\mu$m (red), H$\alpha$ (green), and X-ray (blue) images of the NW filament, and in Figure 3 we plot radial profiles taken perpendicular to the filament, integrated over the four azimuthal regions outlined in Figure 2. It is clear that the 24 $\mu$m emission has a broader spatial profile that peaks 3″–5″ behind the Balmer filament, as best illustrated in region D of Figure 3, where the profiles are the cleanest. The filament is also noticeably broader in the IR than in H$\alpha$, with FWHM $\gtrsim 15''$. This is not simply a resolution effect. The resolution of the 24 $\mu$m mosaic image—measured from profiles of several isolated stars—is

For checking the H$\alpha$ image we of course used the version before continuum subtraction; the coordinates for the subtracted image are identical.

Figure 1. Images of SN 1006 in various bands. (a) Mosaic image at 24 $\mu$m, assembled from all four MIPS AORs. (b) The same 24 $\mu$m mosaic, after subtraction of most point sources, displayed with a harder stretch. (c) Deep H$\alpha$ image, after continuum subtraction to reveal the extremely faint shell of emission to the S and E (the NW filament is saturated in this display; the irregular donut-like patterns are artifacts, the residual images from bright stars—from Winkler et al. 2003). (d) Mosaic image at 70 $\mu$m, from all four MIPS AORs. (e) Chandra ACIS-I mosaic of SN 1006, from Cassam-Chenaï et al. (2008); this image emphasizes the synchrotron-dominated emission in the NE and SW. (f) 1.4 GHz radio image, from Dyer et al. (2009). All the images are aligned, with a field 40′ square and oriented north up, east left.

Figure 2. This three-color image of the NW portion of SN 1006 shows the evolution in conditions behind the shock, which is propagating toward the NW (upper right corner). H$\alpha$ filaments (green, from Winkler et al. 2003) form immediately behind the shock; 24 $\mu$m emission (red) from warm dust trails slightly behind as the dust grains are first heated and then destroyed; X-rays (blue, 0.5–2.0 keV, from Long et al. 2003) peak further behind due to the ionization time to reach the species that are most effective at producing X-ray emission. The field is 6.5 square; yellow regions indicate locations for the profiles shown in Figure 3.
Figure 3. Radial profiles of emission in Hα, 24 μm, and X-rays, taken perpendicular to the shock, for the four regions shown in Figure 2. (The data sources are the same as for that figure.) In each case, the profiles run from outside the shell inward, and the shock location is arbitrarily taken as the point at which Hα emission first rises sharply.

(A color version of this figure is available in the online journal.)

6′ (FWHM), consistent with the diffraction limit, but small compared with the width of the filament.

We attribute this IR emission to dust from the ISM that enters the shock, where it is heated through collisions with hot post-shock gas, produces IR emission, and is then destroyed. Somewhat further behind the shock, soft, primarily thermal, X-ray emission appears, rising to its peak about 10′′ behind the shock, just as the 24 μm emission is decaying away. This indicates the longer timescale for producing the highly ionized species that radiate efficiently and dominate the X-ray emission (Long et al. 2003). We can estimate the timescales through simple kinematics: the primary shock is moving outward to the NW at $\mu = 280 \pm 8$ mas yr$^{-1}$, and if we assume the nominal compression ratio of 4 between the post-shock and pre-shock densities, the post-shock material is dropping behind the shock at speed $v_s/4$, or $\mu = 70$ mas yr$^{-1}$ (relative to the shock). Therefore, the IR peak occurs some 60 years after that material was shocked, and the X-ray peak occurs $\sim 150$ years after the shock. We shall discuss the emission profiles further in Section 5.1 of this paper.

In 2012 March, all-sky survey data from the Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010) were released. Examination of data from the SN 1006 region in all the WISE bands (3.4, 4.6, 12, and 22 μm) shows emission from SN 1006 only in the 22 μm band. Not surprisingly, the WISE 22 μm image is very similar to the Spitzer 24 μm one and clearly shows the NW filament. However, the WISE data have somewhat lower angular resolution and signal-to-noise ratio than that from Spitzer. The non-detection of emission in the shorter-wavelength WISE bands is consistent with the lack of short-wavelength emission in other Type Ia remnants (Borkowski et al. 2006). Close examination of the images from the Improved Reprocessing of the IRAS Survey (IRIS; Miville-Deschênes & Lagache 2005) also shows traces of the NW filament in the co-added 25 μm image; however, it is unlikely that this faint feature would ever have been independently discovered in these low-resolution (1.5′′) maps.

3.2. Other Faint IR Emission

In addition to the narrow filaments along the NW rim of the shell, there is patchy, diffuse emission within much of the southern part of the SN 1006 shell, clearly visible in the 24 μm mosaic and less so in the 70 μm one. The morphology of this emission is similar at both 24 μm and 70 μm and is also similar to patchy emission extending well outside the SN 1006 shell, especially to the south and east. In the southern portion of SN 1006, there is also faint, diffuse emission in both Hα and

10 See http://wise2.ipac.caltech.edu/docs/release/allsky/.
Figure 4. IRS positions superposed on the 24 $\mu$m image of the NW filament of SN 1006. Red rectangles correspond to the second-order (longer wavelength) spectrographs, while yellow corresponds to first order. The three numbered slit positions are from long pointings with the IRS Long-Low instrument (14–40 $\mu$m). As we discuss in the text, we use positions 1 and 2 for our spectral modeling. The shorter, nearly vertical slit position is from the IRS Short-Low instrument, where no emission was detected.

(A color version of this figure is available in the online journal.)

X-rays (Figures 1(c) and (e)), but unlike along the NW rim, the morphology in the south is only vaguely similar to that seen in the IR. In the absence of further data, we cannot determine whether the faint IR emission is associated with SN 1006 itself or stems from cool foreground dust.

In X-rays, SN 1006 shows knots of emission interior to the shock that are thought to arise largely from SN ejecta, but there are no obvious small-scale IR features that correlate with these X-ray-emitting ejecta knots. Hence, we find no evidence for the formation of dust in SN 1006 ejecta. This is somewhat surprising in view of theoretical predictions for dust formation in SN Ia ejecta (Nozawa et al. 2011) but is consistent with observations of other Type Ia SNRs (Borkowski et al. 2006; Williams et al. 2012).

4. SPECTROSCOPIC OBSERVATIONS

We conducted IRS observations, all in Staring mode for about 90 minutes each, at three locations along the NW filament. We show the slit positions of these IRS pointings, labeled 1–3, in Figure 4, overlaid on the MIPS 24 $\mu$m image of the filament. As noted earlier, the filament is quite faint in the IR (its average surface brightness is only about 6% above the background at 24 $\mu$m), and it was undetected in the SL (5.5–14 $\mu$m) spectrum. However, faint emission is detected in the LL order 2 (14–19.3 $\mu$m) spectrum, where the dust continuum begins around 17 $\mu$m and continues to rise throughout the LL order 1 (19–40 $\mu$m) spectrum. We see no evidence for line emission anywhere in the spectrum, consistent with the non-radiative nature of the blast wave shock at this location (Dwek 1987; Dwek et al. 1996; Williams et al. 2011b).

The data used in our analysis (AOR IDs 28138240 and 24142080) were processed with Spitzer calibration pipeline version S18.7.0. Using the IDL CUBISM software (Smith et al. 2007), we assembled the 72 BCD files from positions 1 and 2 along the NW filament into two data cubes, one for LL1 and one for LL2. The IRS spectrum from position 3 is similar, but we have omitted it from our subsequent analysis because it falls on a region where different abundances were required to fit the X-ray spectrum (Long et al. 2003). Hot pixels affect the BCDs (especially beyond 35 $\mu$m), so we median smoothed the BCDs before creating the data cubes using the FILTER_IMAGE routine from the IDL Astronomy User’s library. The smoothing replaces the value of each pixel with the median of the surrounding 3 pixels in a moving box and significantly mitigates the hot pixels in the resulting data cubes. While the smoothing reduces the spatial resolution of the data somewhat, the emission from the filament is highly uniform and we expect minimal loss of information.

After combining the BCDs within CUBISM, we extracted LL1 and LL2 spectra from the NW filament using positions 1 and 2 marked in Figure 4. These two positions are only ~30″ apart, and their IRS spectra appear virtually identical; therefore, we have combined them into a single object spectrum. To estimate the sky background, we extracted separate LL1 and LL2 spectra from locations just outside SN 1006 (marked in Figure 4). We averaged the two sky spectra in each order and combined them to produce a final sky spectrum. We subtracted this spectrum from that of the SN 1006 filament to obtain the final spectrum shown in Figure 5. We describe the fits to this spectrum in the following section.

5. DISCUSSION

5.1. Model Fits to the Data

Infrared emission in typical SNR shocks is produced entirely by collisional heating of dust grains (Dwek & Arendt 1992), where energetic electrons and ions collide with the grains, heating them to temperatures of 50–100 K. Collisions with protons and heavier ions are also responsible for grain sputtering, reducing the size of large grains, and destroying many small grains entirely. We have developed models for such dust that self-consistently calculate both the heating and the destruction of grains in the post-shock gas as a function of the density of the
hot plasma, $n_p$, the electron and ion temperatures, and the shock sputtering age $\tau = \int_0^t n_p dt$ (Borkowski et al. 2006). For an arbitrary input grain-size distribution, we can use these models to calculate the IR spectrum and the post-shock profile that results as grains are heated and eventually destroyed.

The electron temperature, $T_e$, and the ionization timescale can be determined from a non-equilibrium ionization analysis of the X-ray spectra, as Long et al. (2003) did for the NW limb using Chandra data. We have revisited that analysis, taking into account hydrocarbon contamination of the ACIS detectors that was unrecognized at the time of the original analysis and using more reliable atomic data. We first redetermined the absorption column density $N_H$ from the reprocessed synchrotron-dominated eastern limb data (region NE-1 of Long et al. 2003), fit using XSPEC (Arnaud 1996) with a pure synchrotron srcut model to obtain $N_H = (8.2 \pm 0.8) \times 10^{20}$ cm$^{-2}$. We fixed $N_H$ at this value in fitting Long et al.'s region NW-1, which includes our IRS regions 1 and 2. We obtained reasonable fits using a solar-abundance plane-shock model (vnpshock) and obtained values of $kT_e = 0.9$ keV, ionization timescale $n_e t = 5.3 \times 10^9$ cm$^{-3}$ s = 170 cm$^{-3}$ yr, and emission measure $n_e M_e = 6.2 \times 10^{-3}$ $M_\odot$ cm$^{-3}$. This is a somewhat higher electron temperature than the $kT_e = 0.6$ keV found by Long et al. (2003), but it is still far below the post-shock proton temperature of $kT_p = 16$ keV, inferred from the Balmer line profiles by Ghavamian et al. (2002; Vink et al. 2003) also measured a similar value for $T_e$ at a different position along the NW rim). We then applied a Coulomb-heating model for collisions between electrons and protons behind the shock and found that, over the relatively small region we consider here, the mean proton and electron temperatures are 16 keV and 1.0 keV, respectively. We use these temperatures for the remainder of this work.

Our models also require as input a distribution of grain sizes in the ISM ahead of the shock. A commonly used distribution for the Galaxy is that of Weingartner & Draine (2001). Their models are appropriate for the diffuse ISM in the disk of the Galaxy, where the total-to-selective extinction ratio $R_V \equiv A_V/E(B-V) = 3.1$, and for dense clouds where $R_V > 3.1$. At the location of SN 1006 some 500 pc above the Galactic plane, however, the abundance of dust—both in total amount and in the distribution of grain sizes—is likely very different from that near the Galactic plane. There is significant evidence for much lower values for $R_V$ at high Galactic latitudes (Larson & Whittet 2005). Mazzei & Barbaro (2011) have calculated grain-size distributions using the same formalism as Weingartner & Draine (2001) for over 70 lines of sight to stars with “anomalous extinction sightlines.” Particularly relevant for our work, they extend these models down to low-density environments with $R_V = 2.0$. We use the model from Table 5 of Mazzei & Barbaro (2011), with $R_V = 2.0$ and $10^5 b_r = 5.0$ (this is a parameterization in their models that corresponds to the number of small carbonaceous grains). The grain-size distributions corresponding to lower values of $R_V$ are steeper than their “typical” Milky Way counterparts, i.e., they have an excess of small grains relative to large ones, resulting in a larger fraction of the total mass in grains being destroyed via sputtering for a given shock, as well as a different gas density required to produce the observed spectrum.

In our models, the spectrum from warm dust is most sensitive to the gas density in post-shock plasma, so we have used proton density $n_p$ as the principal free parameter. Using the grain-size distribution described above, we have fit the IRS spectrum over the range 21–37 $\mu$m and obtain a best fit for a density of $n_p = 1.4 \pm 0.5$ cm$^{-3}$, shown in blue in Figure 5. The 21–37 $\mu$m range comprises all the data for which the signal-to-noise ratio is high enough to be useful. The uncertainty quoted is a formal 90% confidence limit based on statistical uncertainties only, determined from the rms deviations from an arbitrary smooth polynomial fit to the spectrum in this range. We have made no provision for systematic errors in the IRS spectra, which are difficult to quantify.

There is good reason to believe that the actual density is near the lower limit of the fitted range, near $n_p = 1$ cm$^{-3}$. From an analysis of the thermal X-ray emission along the NW rim based on Chandra observations, Long et al. (2003) found a post-shock electron density $n_e \sim 1$ cm$^{-3}$. Analysis of X-ray data from XMM-Newton using a different modeling approach led Acero et al. (2007) to a pre-shock density value of $n_0 = 0.15$ cm$^{-3}$, equivalent to a post-shock density of $n_p \sim 0.6$ cm$^{-3}$ for a standard compression ratio of 4. And finally, an estimate based on the thickness of the H$\alpha$ filaments in an image from the Hubble Space Telescope by Raymond et al. (2007), and subsequently corrected by Heng et al. (2007), gave $n_0 = 0.15$–0.3 and thus a post-shock density $n_p \sim 1$ cm$^{-3}$. In Figure 5 we also show, in red, a model with $n_p = 1.0$ cm$^{-3}$, which gives an acceptable fit to the IRS data. Finally, we note that the predicted 70 $\mu$m surface brightness for any of our models is $\lesssim 0.25$ MJy sr$^{-1}$, well below the upper limit reported in Section 2.

We have also calculated the spatial profile for the decay of IR emission as grains are destroyed through sputtering in the hot, post-shock environment, assuming that the shock has been advancing through an ambient medium of constant density. In comparing the model with the observed radial profiles, we find that the observed decay is far more rapid than the sputtering model predicts, as illustrated in Figure 6. Even if we assume

![Figure 5. IRS spectrum, in black, combining positions 1 and 2 from Figure 4, and containing both orders of the Long-Low spectrograph. The points shown here, at wavelengths >21 $\mu$m, are all from order 1. The blue curve shows the nominal best-fit model and gives a post-shock density in the filament of $n_p = 1.4$ cm$^{-3}$. The red curve shows a fit with the density constrained at $n_p = 1.0$ cm$^{-3}$, within the limits of acceptable fits, and consistent with observations in other bands (Section 5.1).](image-url)

(A color version of this figure is available in the online journal.)
a grain-size distribution heavily weighted toward small grains to give \( R_F = 2.0 \), for a density of \( n_H = 1 \text{ cm}^{-3} \) the sputtering rate would need to be artificially enhanced by a factor of 6–8 to match the observed profiles.

However, it is almost certain that the shock along the NW rim of SN 1006 has nor been passing through a uniform-density environment. The ambient density to the NW is clearly higher than that around the remainder of the shell, as evidenced by the following facts: (1) the flattening of the shell to the NW; (2) the fact that the proper motion along most of the NW limb is only about 60% as high as that to the NE (Katsuda et al. 2013); (3) the density contrast around the shell required from X-ray observations (Long et al. 2003; Acero et al. 2007); and (4) the mere fact that there is significant IR emission along the NW limb, yet little or none elsewhere. Since the shell radius to the NW is only about 15% smaller than elsewhere, the shock must have encountered the denser region there relatively recently. As a result, the post-shock density profile, for both gas and dust, should drop as one moves inward from the shock. Therefore, the decrease in IR emission behind the shock is likely due in large part to the fact that farther inward the grain density has always been lower, representing an earlier epoch in the evolution of SN 1006. We suggest that this may account for the rapid drop in IR emission \( \sim 20''-35'' \) behind the shock (Figure 6). For a density \( n_p = 1 \text{ cm}^{-3} \) (equivalent to \( n_e = 1.2 \text{ cm}^{-3} \)), the shock age from X-ray spectroscopy is about 170/\( n_e \) = 140 years, suggesting that the shock was encountering considerably lower densities earlier. Detailed modeling of such a scenario is beyond the scope of the present paper.

Nevertheless, the fact that the observed post-shock drop in IR emission is so much sharper than predicted by the models, even close to the shock, probably indicates that current models significantly underestimate the actual dust sputtering rate. Effects that could be responsible include an even greater proportion of small grains, grains of high porosity, or a grain composition that leads to higher sputtering rates. Enhanced sputtering rates are not without precedent; Serra Díaz-Cano & Jones (2008) found that hydrogenated dust grains (perhaps the most common type of grains in the ISM, at least for carbonaceous materials) are sputtered at rates several times higher than their pure amorphous counterparts. The spectral data are insufficient to determine whether the carbonaceous grains in SN 1006 are hydrogenated or amorphous.

5.2. Dust Mass of the NW Filament

Almost independent of the models, we can determine the total amount of dust radiating in the NW filament, provided that the integrated IR luminosity is relatively well known. We have used the measured IR flux, \( F(24 \mu m) = 130 \pm 30 \text{ mJy (Section 2)} \), and assumed that the overall shape of the dust spectrum observed with IRS (shown in Figure 5) is applicable along the entire length of the filament to obtain \( L_{IR} = (1.7 \pm 0.9) \times 10^{33} \, d_{2.2}^2 \, \text{erg s}^{-1} \), where we have scaled to a distance of 2.2 kpc: \( d_{2.2} = d/2.2 \text{ kpc} \). Our models assume optical constants from Draine & Lee (1984) for graphite and amorphous silicate grains in the ISM, with relative proportions and grain-size distributions from Mazzei & Barbaro (2011). As in Williams et al. (2008), we then calculate the dust mass in the NW filament as \( M_{dust} = (1.1 \pm 0.6) \times 10^{-5} \, d_{2.2}^2 \, M_{\odot} \), where the uncertainty limits for both \( L_{IR} \) and \( M_{dust} \) include the overall 15% uncertainty in the Spitzer MIPS extended source flux calibration. Of course, this method of determining the total dust mass is insensitive to any cold dust—undetectable with Spitzer—but it is difficult to imagine how a significant fraction of interstellar dust (consisting almost entirely of small grains, \( a < 0.5 \mu m \)) could remain cold within the hot plasma behind such a fast shock. Our value for \( M_{dust} \) includes only the dust now radiating along the NW filament; the overall faintness of the rest of the SNR at 24 \( \mu m \), combined with the lack of detection at 70 \( \mu m \), precludes determination of a dust mass for the entire remnant.

5.3. The Ambient Dust-to-gas Mass Ratio

In previous works (Borkowski et al. 2006; Sankrit et al. 2010; Williams et al. 2011a, 2011b), we have used the density determination from IR data, combined with the X-ray emission measure, to obtain a measure of the amount of shocked gas present within a given emitting volume. We have obtained the dust mass from the overall normalization to the dust spectrum, so dividing the two gives the dust-to-gas mass ratio. In the case of SN 1006, however, the IRS spectra do not strongly constrain the density. Thus, we employ an alternative approach.

Laming et al. (1996) examined the ultraviolet spectrum of a section of the NW filament obtained with the Hopkins Ultraviolet Telescope (HUT) and measured 0.02 He II (1640 Å) photons cm\(^{-2}\) s\(^{-1}\). More recent work by P. Chayer (2012, private communication) has revised the reddening toward SN 1006 to be \( E(B-V) = 0.09 \), lowering the He II flux to 0.017 photons cm\(^{-2}\) s\(^{-1}\). According to the Laming et al. models, 0.0067 He II photons come out for each H atom crossing the shock. For the 200" section of the filament observed (corresponding to a distance of 6.5 \( \times 10^{18} \text{ cm at } d = 2.2 \text{ kpc} \)), the He II flux measured at Earth would be

\[
F_{\text{He II}} = \left( \frac{0.0067 \text{ photons}}{\text{H atom}} \right) \left( 6.5 \times 10^{18} \text{ cm} \right) \frac{n_0 v_i l}{4 \pi d^2},
\]

where \( n_0 \) is the pre-shock H number density, \( v_i \) is the shock speed, and \( l \) is the line-of-sight depth through the emitting material, all of which are presumed (for this purpose) to be unknown. Taking \( F_{\text{He II}} = 0.017 \text{ photons cm}^{-2} \text{ s}^{-1} \), we can rearrange the above equation to give \( n_0 v_i l = 2.26 \times 10^{26} \text{ cm}^{-3} \text{ s}^{-1} \). The length of the NW-1 region is 3', or 5.9 \( \times 10^{18} \text{ cm at } d = 2.2 \text{ kpc} \), so 1.3 \( \times 10^{45} \text{ H atoms per second enter the shock.} \)
If we assume a standard post-shock flow of 70 mas yr$^{-1}$, based on the proper-motion measurements of Winkler et al. (2003), then the width of the IR filament corresponds to a timescale of 150 years. During this time, the shock will have swept up $6.3 \times 10^{54}$ H atoms, or $7.6 \times 10^{-3} M_\odot$ of gas. The uncertainties in the $HUT$ measurement of the He ii flux and in the reddening correction are about 15% each, while the uncertainty in proper motion is only 3% and the uncertainty in the relative atomic rates is probably about 30%, so we estimate an uncertainty in the gas mass of $\sim 40\%$. Using the dust mass determined above, this leads to a dust-to-gas mass ratio of $(1.5 \pm 1.0) \times 10^{-3}$. The expected dust-to-gas mass ratio for the Galaxy within the model of Mazzei & Barbaro (2011) is $5.3 \times 10^{-3}$, a factor of $\sim 3$ higher than what we measure.

The dust-to-gas mass ratio in the ambient medium surrounding SN 1006 appears to be lower than that expected from dust models for the Galaxy, including those at high Galactic latitudes. This has been the case for virtually all SNRs studied, both in the Galaxy (e.g., Blair et al. 2007; Arendt et al. 2010; Lee et al. 2009) and in the Magellanic Clouds (Borkowski et al. 2006; Williams et al. 2006, 2011b). The ultimate reason for this remains a mystery, but in the case of SN 1006 specifically, its location within the Galaxy may provide a clue. At some 500 pc above the Galactic plane, SN 1006 is located at the interface between the disk and halo (see Putman et al. 2012 for a review of gaseous galaxy halos and their interfaces to galactic disks). Accumulating evidence points to a lower dust content there than in the Galactic disk (Ben Bekhti et al. 2012), coupled with a higher proportion of smaller grains (Planck Collaboration et al. 2011). An expected increase in the sputtering rate for smaller grains might better match the rapid drop-off in the 24 m profile behind the shock (Figure 6) than the current dust model, and it would also raise our inferred value of the pre-shock dust-to-gas mass ratio, bringing it even more in line with the Mazzei & Barbaro (2011) value. We further note that any dust that is too cold to be observed with Spitzer would increase the dust-to-gas mass ratio above our inferred value.

Our current determination of the dust-to-gas mass ratio is quite uncertain, as we do not know the grain-size distribution in the pre-shock gas. It is possible that models with a larger dust-to-gas ratio and a larger overabundance of small grains can be as viable as our current model with $R_V = 2.0$. This model degeneracy might be broken by future joint IR, X-ray, and UV studies focused on accurate determination of abundances of refractory elements in the post-shock gas.

6. SUMMARY

Spitzer observations of the entire region surrounding the remnant of SN 1006 show a clear detection of the NW filament at 24 m, the same filament that is prominent in Hα emission. IRS spectroscopy of this filament shows that the IR is produced entirely by continuum emission from warm dust grains, with a spectrum peaking somewhere beyond 35 m. The filament is not detected at 70 m, likely due to the significantly higher background IR emission. The IR emission from the NW filament reaches its peak just inside of the Hα emission, while the X-ray emission peaks still a little further behind. This is as expected, since Hα emission should trace the exact location of the forward shock, while dust grains require a short amount of time to be heated to temperatures observable by Spitzer and then are sputtered away, while the post-shock gas requires even longer to become ionized enough to emit strongly at Chandra energies.

Fits to the Spitzer IRS spectrum taken at two positions along the NW filament, using models of collisionally heated dust grains, do not tightly constrain the post-shock density $n_p$. The nominal best fit gives $n_p = 1.4 \pm 0.5$ cm$^{-3}$ (90% confidence); we have adopted a model with $n_p = 1$ cm$^{-3}$, the value suggested from observations in other bands, for our subsequent analysis.

The decay of the IR spatial profile behind the shock is far more rapid than expected from standard dust models. This may be due in part to a high proportion of small dust grains in the ambient ISM at the location of SN 1006, high above the Galactic plane, and probably also results in part as a relic of the shock’s having encountered a higher density region to the NW relatively recently. Nevertheless, it appears that sputtering rates significantly higher than those predicted by standard models will be required to fully explain the rapid decline in IR emission behind the shock.

Calculations of the dust-to-gas mass ratio in the ambient ISM indicate a value of approximately $1.5 \times 10^{-3}$, compared to the expected value of $5 \times 10^{-3}$ for the Galaxy at the latitude of SN 1006. This difference of a factor of several is a phenomenon seen in virtually all IR/X-ray analyses of SNRs. The remnant of SN 1006 provides a rare opportunity to study the ISM high above the Galactic plane, and further IR, X-ray, and UV studies are necessary to understand this remnant.

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REFERENCES

Acero, F., Aharonian, F., Akkheperjanian, A. G., et al. 2010, A&A, 516, A62
Acero, F., Ballet, J., & Decourchelle, A. 2007, A&A, 475, 883
Arendt, R. G. 1989, ApJS, 70, 181
Arendt, R. G., Dwark, E., Blair, W. P., et al. 2010, ApJ, 725, 585
Arnaud, K. A. 1996, in ASP Conf. Ser. 101, Astronomical Data Analysis Software and Systems V, ed. G. H. Jacoby & J. Barnes (San Francisco, CA: ASP), 17
Ben Bekhti, N., Winkel, B., Richter, P., et al. 2012, A&A, 542, A110
Blair, W. P., Ghavamian, P., Long, K. S., et al. 2007, ApJ, 662, 998
Borkowski, K. J., Williams, B. J., Reynolds, S. P., et al. 2006, ApJ, 642, L141
Braun, R. 1987, A&A, 171, 233
Cassam-Chenai, G., Hughes, J. P., Reynoso, E. M., Badenes, C., & Moffett, D. 2008, ApJ, 680, 1180
Chevalier, R. A., Kirshner, R. P., & Raymond, J. C. 1980, ApJ, 235, 186
Chevalier, R. A., Kirshner, R. P., & Raymond, J. C. 1980, ApJ, 235, 186
de Kool, M., Li, H., & McCray, R. 1998, ApJ, 503, 857
Douvion, T., Lagage, P. O., Cesarsky, C. J., & Dwek, E., 2001, A&A, 373, 281
Draine, B. T. 2003, ARA&A, 41, 241
Draine, B. T., & Lee, H. M. 1984, ApJ, 285, 89
Dwek, E. 1987, ApJ, 322, 812
Dwek, E., & Arendt, R. G. 1992, ARA&A, 30, 11
Dwek, E., Foster, S. M., & Vancura, O. 1996, ApJ, 457, 244
Dwek, E., & Scalco, J. M. 1980, ApJ, 239, 193
Dyner, K. K., Cornwell, T. J., & Maddalena, R. J. 2009, AJ, 137, 2956
Gardner, F. F., & Milne, D. K. 1965, AJ, 70, 754
Ghavamian, P., Winkler, P. F., Raymond, J. C., & Long, K. S. 2002, ApJ, 572, 888
Goldstein, B. R. 1965, AJ, 70, 105
Gomez, H. L., Clark, C. J. R., Nozawa, T., et al. 2012a, MNRAS, 420, 3557
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Gomez, H. L., Krause, O., Barlow, M. J., et al. 2012b, ApJ, 760, 96
Heng, K. 2010, PASA, 27, 23
Heng, K., van Adelsberg, M., McCray, R., & Raymond, J. C. 2007, ApJ, 668, 275
Katsuda, S., Long, K. S., Petre, R., et al. 2013, ApJ, 763, 85
Kirshner, R., Winkler, P. F., & Chevalier, R. A. 1987, ApJL, 315, L135
Kotak, R., Meikle, W. P. S., Farrah, D., et al. 2009, ApJ, 704, 306
Koyama, K., Petre, R., Gotthelf, E. V., et al. 1995, Natur, 378, 255
Laming, J. M., Raymond, J. C., McLaughlin, B. M., & Blair, W. P. 1996, ApJ, 472, 267
Larson, K. A., & Whittet, D. C. B. 2005, ApJ, 623, 897
Lee, H.-G., Koo, B.-C., Moon, D.-S., et al. 2009, ApJ, 706, 441
Long, K. S., Reynolds, S. P., Raymond, J. C., et al. 2003, ApJ, 586, 1162
Marsden, B. C. 1965, AJ, 70, 126
Matsuura, M., Dwek, E., Meixner, M., et al. 2011, Sci, 333, 1258
Mazzali, P., & Barbaro, G. 2011, A&A, 527, A34
Meikle, W. P. S., Kotak, R., Farrah, D., et al. 2011, ApJ, 732, 109
Miville-Deschênes, M.-A., & Lagache, G. 2005, ApJS, 157, 302
Nozawa, T., Kozasa, T., Tominaga, N., et al. 2010, ApJ, 713, 356
Nozawa, T., Maeda, K., Kozasa, T., et al. 2011, ApJ, 736, 45
Planck Collaboration, Abergel, A., Ade, P. A. R., Aghanim, N., et al. 2011, A&A, 536, A24
Putman, M. E., Peek, J. E. G., & Young, M. R. 2012, ARA&A, 50, 491
Raymond, J. C., Korreck, K. E., Sedlacek, Q. C., et al. 2007, ApJ, 659, 1257
Rho, J., Kozasa, T., Reach, W. T., et al. 2008, ApJ, 673, 271
Rieke, G. H., Young, E. T., Engelbracht, C. W., et al. 2004, ApJS, 154, 25
Saken, J. M., Fesen, R. A., & Shull, J. M. 1992, ApJS, 81, 715
Sankrit, R., Williams, B. J., Borkowski, K. J., et al. 2010, ApJ, 712, 1092
Schweizer, F., & Lasker, B. M. 1978, ApJ, 226, 167
Serra Díaz-Canó, L., & Jones, A. P. 2008, A&A, 492, 127
Smith, J. D. T., Armus, L., Dale, D. A., et al. 2007, PASP, 119, 1133
Stephenson, F. R. 2010, A&G, 51, 5.27
Stephenson, F. R., & Clark, D. H. 2002, Historical Supernovae and Their Remnants (Oxford: Oxford Univ. Press), 150
Szlai, T., Vinkó, J., Balog, Z., et al. 2011, A&A, 527, A61
van den Bergh, S. 1976, ApJL, 208, L17
Vink, J., Laming, J. M., Gu, M. F., Rasmussen, A., & Kaastra, J. S. 2003, ApJL, 587, L31
Weingartner, J. C., & Draine, B. T. 2001, ApJ, 548, 296
Williams, B. J., Blair, W. P., Blundin, J. M., et al. 2011a, ApJ, 741, 96
Williams, B. J., Borkowski, K. J., Reynolds, S. P., et al. 2006, ApJL, 652, L33
Williams, B. J., Borkowski, K. J., Reynolds, S. P., et al. 2008, ApJ, 687, 1054
Williams, B. J., Borkowski, K. J., Reynolds, S. P., et al. 2011b, ApJ, 729, 65
Williams, B. J., Borkowski, K. J., Reynolds, S. P., et al. 2012, ApJ, 755, 3
Winkler, P. F., Gupta, G., & Long, K. S. 2003, ApJL, 585, 324
Winkler, P. F., & Laird, F. N. 1976, ApJL, 204, L111
Wooden, D. H., Rank, D. M., Bregman, J. D., et al. 1993, ApJS, 88, 477
Wright, E. L., Eisenhardt, P. R. M., Mainzer, A. K., et al. 2010, AJ, 140, 1868