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The young SNR 1E 0102.2-7219: testing dust formation in primordial galaxies

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Abstract. We present infrared (IR) observations of the young, oxygen-rich supernova remnant 1E 0102.2-7219 (E0102) in the Small Magellanic Cloud (SMC), obtained with the *Spitzer Space Telescope.* The remnant is detected only at 24 μm and has a filled morphology with two prominent filaments. We find evidence for the existence of up to 8×10^{-4} $M_\odot$ of hot dust ($T_d \sim 120$ K) associated with the remnant. Even if *all* of the hot dust was formed in the explosion of E0102, the estimated mass of dust is at least 100 times lower that what is predicted by some recent theoretical models. The implied dust formation efficiency in the SMC is low, $< 15\%$, and challenges theoretical models for dust formation in primordial galaxies. Most of the hot dust in E0102 is located in the central region which appears significantly enhanced in IR and radio continuum emission relative to the X–ray emission. Curiously, we find a compact source of excess IR emission close to E0102's center. This could be a synchrotron jet encountering a dusty interstellar medium, or alternatively, a dust condensate embedded in a cooler interstellar cloud.

1. Introduction

Young supernova remnants (SNRs) are important physics laboratories for studying cosmic ray acceleration, nucleosynthesis, dust formation and destruction, and interstellar hydrodynamics (McKee 2001; Vink 2004). Their dynamics are driven by the interaction between the stellar ejecta and the surrounding medium, which could be circumstellar (matter ejected by the progenitor star) or interstellar. In the ejecta-dominated stage of evolution, the morphology of young SNRs is marked by two shocks: the blast-wave shock that advances into the ambient medium (the forward shock), and a reverse shock that propagates back into the ejecta and is seen in various emission lines.

Dust formation in supernovae explosions has been a highly controversial question. From a theoretical perspective, young SNRs are expected to be important sites of dust formation. Furthermore, dust injection in SNRs was thought to dominate other dust sources in the interstellar medium (ISM) (Dwek & Scalo 1980). Several recent theoretical models suggest that a large amount of dust, 0.2–2 $M_\odot$, could be formed in explosions of core-collapse SNRs even in early galaxies with very low metallicity (Todini & Ferrara 2001; Morgan & Edmunds 2003). Surprisingly, from an observational point of view, there has been evidence only for a very small amount of dust associated with SNRs, $(1-10)\times10^{-4}$ $M_\odot$. In addition, SNRs are also known to be effective at destroying dust grains, mainly by thermal sputtering, which complicates the picture of grain survival and may point to only exceptional conditions (e.g. shock velocities, grain composition, mixing of the SN ejecta with the cold ISM) that are conducive for grain production and survival. Understanding dust formation and destruction efficiencies is particularly important for the early Universe, as dust must have played the key role in early star formation (Morgan & Edmunds 2003).

Oxygen–rich SNRs comprise a small subclass of young SNRs, and are believed to be remnants of the most massive stars (typical mass of > 15 $M_\odot$). These remnants have very high–velocity debris ($V > 1000$ km s^{-1}) and high abundances of oxygen, neon, carbon, and magnesium. The oxygen–rich SNR 1E 0102.2-7219 (hereafter E0102) in the Small Magellanic Cloud (SMC), with a kinematic age of only ~ 1000 yrs, is one of the youngest SNRs known, and is commonly considered as dynamically very similar to Cas A in the Galaxy.

E0102 is a well studied object at optical, radio, and X–ray wavelengths. X–ray images of E0102 (Gaetz et al. 2000; Flanagan et al. 2004) show rich structure: a faint forward moving blast wave and a bright X–ray ring — mainly due to strong emission lines of O, Ne and Mg — marking the interaction of the reverse shock with the stellar ejecta. Infrared (IR) observations of E0102 are particularly interesting as they offer a unique test of the dust formation process in a low-metallicity environment, under conditions similar to those in primordial galaxies at high redshifts.

As a part of the *Spitzer Space Telescope (SST)* Survey of the SMC[1] (S^3MC) we have recently detected E0102 at 24 μm. The observing strategy, data processing, and detailed results are given in Stanimirović et al. (2005). In this paper we briefly summarize main results from this study, and then focus on two question: what is E0102 telling us about the dust formation efficiency in the SMC (§3), and what is the nature of the curious source of excess IR emission close to the center of E0102 (§4).

2. *SST* detection of SMC's young SNR E0102.2-7219

E0102 is the first SNR in the SMC detected at IR wavelenghts. It is prominent in the 24 μm *SST* image (see Figure 1), while it is not clearly detected in any of the other *SST* bands. At 24 μm, the remnant has an almost filled morphology, with some limb brightening along the west side, and two bright elongated knots of emission to the south. Comparing the 24 μm image of E0102 with the X–ray and 6 cm radio observations, the IR emission correlates well with the X–ray emission, but poorly with the radio continuum distribution. The position and curvature of the two IR knots agree remarkably well with filaments seen in the X–rays (Figure 1). However, some important differences are also apparent.

[1] http://celestial.berkeley.edu/spitzer

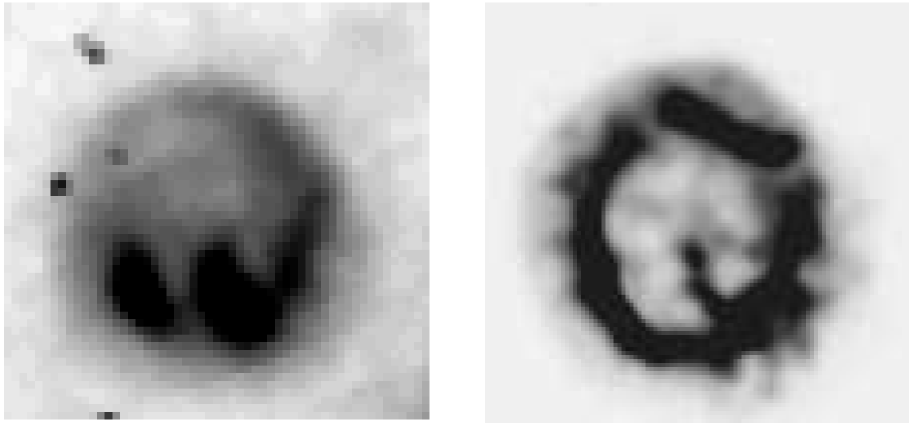

Figure 1. (left) MIPS 24 μm image of E0102, obtained by the *SST*. Several dark pixels around the SNR are affected by cosmic rays. (right) *Chandra* X–ray (0.3–10 keV) image from Gaetz et al. (2000).

For example, while the X–ray image has a high contrast, edge–brightened ring structure, the 24 μm image displays a lower contrast between the ring and the central region. In addition, the intensity of the IR emission in the limb does not decrease as sharply towards the edge of the SNR as the X-ray emission does.

For a more quantitative comparison we have convolved and regridded the X–ray and 6 cm images to match the resolution and pixel size of the 24 μm image, and then derived three ratio images: 24 μm/X–ray, 24 μm/6 cm, and 6 cm/X–ray. The 24 μm/X–ray image, shown in Figure 2 (left), confirms a good spatial correlation between the X–ray and 24 μm intensities (white pixels in this image correspond to 24 μm/X-ray$\sim 0.5-1$), however it also clearly shows that the 24 μm emission extends beyond the X–ray emission and decreases less sharply at the edges. It appears, therefore, that the IR emission is associated with both forward and reverse shocks. In addition, we have found an excess of the 24 μm emission in the SNR's center, with 24 μm/X-ray~ 2.

The noticeable excess of the IR emission relative to the bright X–ray ring suggests the presence of thermal dust continuum emission associated with the SNR and originating from the circumstellar and/or interstellar dust being heated by the X–ray emitting plasma. The measured IR flux at 24 μm and upper limits at 8 μm and 70 μm suggest the existence of hot dust, with a temperature of $T_{\rm d} \sim 120$ K. This is in agreement with expectations for the collisionally heated interstellar and/or circumstellar dust grains, with a typical size of 0.01 μm and immersed in hot gas with $n \sim 1-10$ cm^{-3} and $T \sim 10^7$ K (Dwek 1987). We estimate that the total mass of this hot dust component is $M_d = 8 \times 10^{-4}$ M$_\odot$.

However, a significant fraction of the bright X–ray ring structure correlates spatially well with the IR distribution, suggesting that a fraction of IR emission is most likely associated with the reverse shock as well, and may even be largely (up to $\sim 60\%$) due to line emission of [OIV] at 25.88 μm. Future spectroscopic observations will be able to quantify the exact fractions of emission line and continuum contributions.

3. Dust production in the SMC

Several recent theoretical models investigated dust production in early galaxies. For example, Todini & Ferrara (2001) suggested that a large amount of dust could be formed in explosions of core-collapse supernovae even in early galaxies with very low metallicity. For a progenitor star with a mass of 12–35 $M_\odot$ this model predicts $0.08 < M_d < 0.3$ $M_\odot$, and this range is expected to increase by about three times as the metallicity increases to solar values. Morgan & Edmunds (2003) showed that if a significant amount of dust is present in metal-poor galaxies it must have originated primarily from supernovae. The contribution from stellar winds is expected to be negligible, unless the star formation is extremely high.

In the case of E0102 we find evidence for up to $M_d = 8 \times 10^{-4}$ $M_\odot$ of hot dust. If *all* of this hot dust was formed in the explosion of E0102, then this amount is at least 100 times lower than the lowest predicted value by Todini & Ferrara (2001). Interestingly, this amount of dust is only a few times lower than what was found recently for Cas A (Hines et al. 2004), although the two SNRs occurred in very different interstellar environments.

We can now estimate roughly the dust production efficiency in supernovae explosions in the SMC. We assume the total dust mass in the SMC of 2×10^4 $M_\odot$ (Stanimirovic et al. 2002), and the type II SNR rate of 500 SNRs per Myr (Crawford et al. 2001). The total expected number of supernovae in the SMC is $\sim 6 \times 10^6$ over the past 12 Gyr. If each SNR produced typically $\sim 5 \times 10^{-4}$ $M_\odot$ of dust, based on what we find in the case of E0102, then the total amount of dust in the SMC produced in supernovae explosions is $\sim 3 \times 10^3$ $M_\odot$. This implies the dust formation efficiency < 15%. Similarly, Douvion et al. (2001) found the dust formation efficiency of 10% based on IR observations of Cas A. These values are at least twice lower than what some models predict (Morgan & Edmunds 2003). The low dust formation efficiency estimated from observations may suggest that a large amount of colder dust could be missed in IR observations, and/or that the dust destruction efficiency is higher than what is typically assumed. This may also imply that if early galaxies do have a significant amount of dust, then the contribution from stellar winds may be higher than what current models suggest.

4. Excess of IR emission in the center of E0102

The hot dust we find associated with E0102 is mainly located in the central region of the remnant, and appears significantly enhanced in IR and radio continuum emission relative to the X–ray emission. In Figure 2 (left), the ratio image 24 μm/X–ray has values > 1.5 in the center. Furthermore, the same figure suggests the existence of a compact region, or a knot, with a significant excess of IR and synchrotron emission relative to the X–ray emission. This IR knot is located only about $1''$–$1.5''$ east from the assumed center of the SNR's shell. The knot has an angular size (FWHM) of $\sim 5''$, which corresponds to ~ 1.5 pc at the distance of 60 kpc. Amy & Ball (1993) noticed a compact radio component in their 6 cm radio continuum image and suggested that this could be a synchrotron wind nebula powered by the rotation of an energetic young

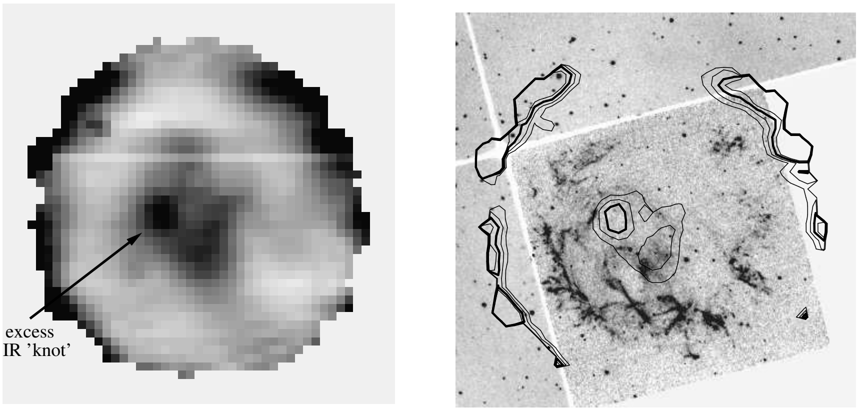

Figure 2. (left) The ratio of normalized 24 μm and X–ray images. White pixels show low ratio, $\sim 0.5 - 1$, while dark pixels correspond to high ratio of $1.5 - 2$. (right) An *HST* image from Blair et al. (2000) showing optical filaments and knots, overlaid with 24 μm/X–ray > 1.5.

pulsar associated with the SNR. Their source is roughly coincident with the SNR's center.

The compact region of excess IR and radio emission does not appear to correspond to any of optical filaments and knots seen in the *HST* image by Blair et al (2000), see Figure 2 (right). As pulsar wind nebulae are expected to be associated with strong X–ray emission this region is more likely to be an accelerated, dusty spot on the surface of the radio/IR shell. Another possibility is that this is a jet of relativistic electrons encountering a dense and dusty surrounding ISM; a similar IR arc was reported by Hines & et al. (2004) in the case of Cas A. Alternatively, this could be a fast-moving, cloud of dust-synthesized ejecta mixed with a cooler ISM gas. Future spectroscopic observations with the *SST* will be able to compare dust properties of this compact region with those found elsewhere in E0102 to check the possibility of freshly-formed dust condensates.

5. Conclusions

In the recent imaging of the SMC with the *SST* we have detected only one SNR, the oxygen-rich, young SNR E0102.2-7219. The remnant is detected only at 24 μm, and its IR distribution has a filled morphology with two prominent elongated filaments. A detailed comparison of the 24 μm image with the X–ray and radio continuum images suggests the existence of hot dust, with a temperature of about 120 K. We estimated the dust mass of up to 8×10^{-4} $M_{\odot}$, however a significant contribution (up to 60%) to our flux measurement at 24 μm could be due to the [OIV] emission line.

The amount of dust associated with E0102, under the assumption that *all* of the dust was formed during the supernova explosion, is at least 100 times lower than what is predicted by some recent theoretical models for dust production in the ejecta of core-collapse supernovae. We estimate that the dust formation efficiency in the SMC is $< 15\%$. This low observed dust formation efficiency challenges the idea that supernovae are the major dust producer in primordial galaxies. This finding also suggests that the dust destruction efficiency could be higher in metal-poor galaxies, and/or that stellar winds could be more important dust contributors in the early Universe.

The hot dust is mainly located in the central region of E0102, which appears significantly enhanced in IR and radio continuum emission relative to the X–ray emission. Close to the SNR's center we find a curious compact region of enhanced IR emission which does not have an obvious optical counterpart. This could be a synchrotron jet encountering a dusty ISM, or alternatively, a freshly-formed dust condensate embedded in a cooler ISM cloud. Future spectroscopic observations are essential to distinguish between these two possibilities.

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