SPICA's Promise for Supernovae and Supernova Remnant Studies

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ABSTRACT

Spitzer and *Herschel* have started to reveal that SNe can form a significant mass of dust and molecules. The number of SNe studied so far is still limited. Moreover *Spitzer* and *Herschel* measurements have shown that multi-wavelength and monitoring observations are critical to build a comprehensive picture of dust and molecular formation in SNe. Equipped with near- to far-infrared imaging and spectroscopic instruments, the *SPICA* mission will enable a more fuller picture of supernovae and supernova remnants, potentially resolving if SNe can be a major source of dust in the interstellar medium of galaxies.

1. INTRODUCTION

In the last decade, infrared and submillimeter surveys of galaxies have found a substantial mass of dust in galaxies from the Local Universe, nearby galaxies to high-redshift galaxies (e.g. Bertoldi et al. 2003; Dunne et al. 2011). It is still unknown how the interstellar medium (ISM) of galaxies acquires such a large mass of dust. Theories of dust evolution modelling of high-redshift galaxies have suggested and proposed that a large mass of dust formation in supernovae (SNe) can explain dust in galaxies, particularly those in high-redshift galaxies. Recent observations with the *Herschel Space Observatory* began to reveal that core-collapse SNe can also form a significant mass of dust (0.1–0.7 $M_{\odot}$; e.g. Barlow et al. 2010; Matsuura et al. 2011; Gomez et al. 2012). These studies have lead us to propose major questions of dust production in supernovae:

Q1: What are the effective dust masses formed in SNe?

Q2: What is the time scale of dust formation in SNe?

Q3: What are the important physical and chemical processes involved in dust formation in SNe?

Q4: How much of dust could be destroyed by SN shocks?

Future observations with *SPICA* have a potential to answer these important questions.

2. DUST FORMATION IN SNE

Recently, far-infrared and submillimeter observations of SNe and SN remnants have found 0.1–0.7 $M_{\odot}$ of dust in core-collapse SNe. That is much larger than the previously reported dust mass found in the early epoch after the SN explosions (10^{-4} $M_{\odot}$; e.g. Wooden et al. 1993; Sugerman et al. 2006). Gall et al. (2011) reported that the inferred dust masses of SNe and SN remnants appear to have a correlation with estimated dust temperatures. Also dust mass is correlated with the wavelength where the dust thermal emission has been detected. Near- and mid-infrared observations tend to find dust-mass in the range of 10^{-6}–10^{-4} $M_{\odot}$, while far-infrared and submillimeter observations tend to find the mass range up to 1 $M_{\odot}$. The cause of this correlation is undetermined. It might suggest an increasing dust mass in time as the SNe become cooler. Multi-wavelength and monitoring observations of SNe and SN remnants from near-infrared and far-infrared wavelength is essential to find the cause of these correlations, leading us to determine the effective dust masses formed in SNe and SN remnants.

SN 1987A is the closest SN whose explosion was detected in the past 400 years, and has provided a unique opportunity to monitor the time evolution of a SN remnant after the explosion. Wooden et al. (1993) reported the detection of dust in SN 1987A at mid-infrared wavelength about 2 years after the explosion with an inferred dust mass of about 10^{-4} $M_{\odot}$. Spatially resolved Gemini mid-infrared images showed that mid-infrared dust thermal emission originated from the ring of SN 1987A, which indicated that the mid-infrared excess at d ~6000 days is from the progenitor dust rather than dust formed after the SN explosion (Bouchet et al. 2006). They also reported the dust mass of ~ 10^{-6} $M_{\odot}$ from *Spitzer* observations.

Herschel also found far-infrared dust emission from SN 1987A (Matsuura et al. 2011) during the Magellanic Cloud survey (Meixner et al. 2013). The inferred dust mass was 0.4–0.7 $M_{\odot}$, and we concluded that the only plausible explanation of such a large dust mass is dust formation in the SN ejecta, where a large mass of refractory elements became available. That assumption will be tested by an ALMA high angular resolution image.

So far SN 1987A is the only case where the time evolution of dust formation and thermal emission have been monitored. It is not yet determined why the dust mass in SN 1987A has increased: it might be gradual grain formation in time, or grains are located in clumps, which are optically thick in mid-infrared wavelength, distorting the dust masses we see today.

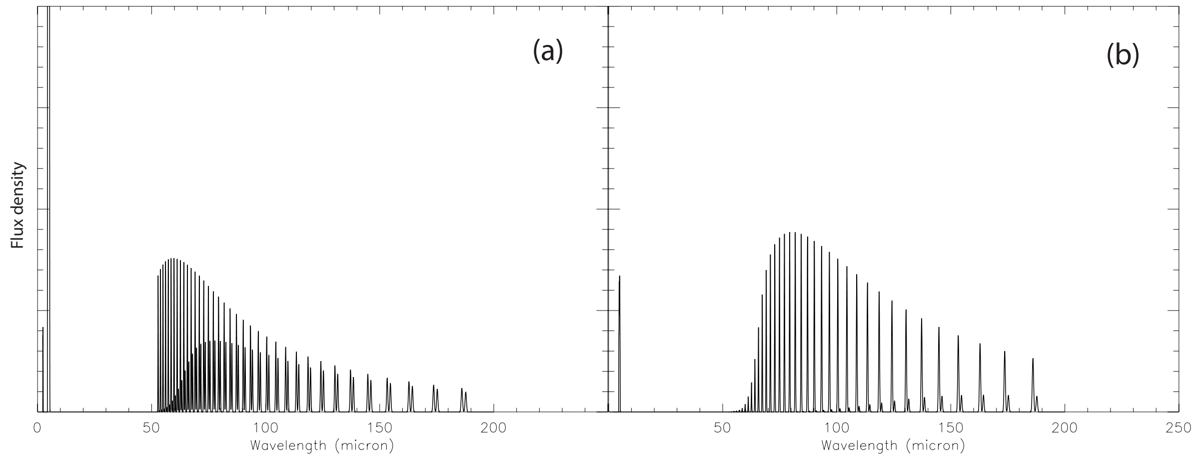

Figure 1. The demonstration of CO emissions (*Left*) at $d = 500$ days and (*Right*) at 1000 days. At $d = 500$ days, CO emissions are found at near-infrared wavelength, and $v = 1$ CO lines are strong at far-infrared wavelength, while strong CO lines are found at far-infrared wavelength at $d = 1000$ days.

Theories have proposed that dust grains condense almost instantly once the gas temperature drops to the sublimation temperature (Nozawa et al. 2003; Sarangi & Cherchneff 2013). If this theory is correct, mid-infrared observations in early days should be completely optically thick, hiding a large amount of dust, but there is no such an indication so far in SN 1987A (Ercolano et al. 2007). Future *SPICA* observations of newly exploded SNe can test these hypothesis.

MCS has potential to detect over a few hundred of SNe within 500 Mpc in 5 years. The number of far-infrared detection would be relatively modest, 7 SNe within 10 Mpc during a 5 year mission mainly due to the confusion limit, though potentially SNe up to 40 Mpc may be detected.

3. MOLECULES IN SNE

While explosions of SNe generate an enormous energy 10^{53} ergs (McCray 2003), gas in the ejecta cools down gradually, by adiabatic cooling and later with line and dust thermal emission (Jerkstrand et al. 2011). Models predicted that the gas temperature drops to 80 K only after 8 years in the case of SN 1987A (Jerkstrand et al. 2011). From molecules that have been detected SN ejecta, in early epoch in near-infrared (e.g. Spyromilio et al. 1988; Kotak et al. 2006) and in submillimeter and millmeter wavelength after 20 years of the explosions (Kamenetzky et al. 2013). Molecules have been detected in the young SN remnant, Cas A (Rho et al. 2012; Wallström et al. 2013) and they suggested that CO molecules are formed in the gas after the passage of reverse shocks. Similar to dust formation, the estimated CO mass seems to have increased in time within 25 years, but little observations of CO in between these 20 years makes it difficult to determine how molecules have formed in time. In contrast, chemical models predict CO formation is completed within 500 days after SN explosions (Sarangi & Cherchneff 2013). If that is the case, a large cold CO mass must be hidden from near-infrared observations in early epoch.

Using *SPICA* capability of detecting molecular lines from near-infrared to far-infrared, molecular chemistry in SN remnants can be investigated. Figure 1 demonstrates how the strong CO transitions can change from near-infrared to far-infrared in time. The temperature and the extent of gas were taken from the model of Nozawa et al. (2003) and the radiative transfer code from Matsuura et al. (2002) was used. These observations will reveal the time evolution of chemistry and thermal dynamical in SNe.

So far, the number of SNe where molecular lines are detected is limited. CO lines have been detected only from 9 SNe and 1 Cas A at near-infrared wavelength. Far-infrared CO lines have been detected only from SN 1987A and Cas A. Additionally SiO bands at 8 μm have been detected in 3 SNe.

The MCS on board the *SPICA* has a potential to detect SNe exploded up to 200 Mpc, providing potential of detecting near-infrared CO and SiO bands over 100 SNe. The SAFARI can detect SNe found up to 7 Mpc, and high-J CO transitions could be detected in about 5 SNe within the 5 year mission.

4. FAR-INFRARED LINES IN SNE

Models predicted that far-infrared atomic lines are important cooling lines for SN ejecta (Jerkstrand et al. 2011). Among important cooling lines, only handful lines have been observed in SN ejecta (Bouchet et al. 2006), making lack of constraints on physical process within SNe after the explosions. *SPICA* SAFARI will be able to detect these important cooling lines, such as [O I] 63 μm for the first time. The expected number of SNe is about 5 within the 5 year *SPICA* mission.

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