# Understanding the Role of Massive Stars on the Dusty ISM Environment in Galaxies with *SPICA*

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**ABSTRACT**

In this article, some key science cases of *SPICA* are discussed focusing on (1) the dust formation associated with mass loss activities of evolved massive stars (e.g., Wolf-Rayet stars) before the SN explosion and (2) the dust formation in the ejecta of SNe and its evolution (destruction and/or grain growth) in a timescale of a few – a few tens years from its synthesis.

## 1. INTRODUCTION

Due to the short (< a few tens Myr) lifetime during the main sequence, massive stars can supply nucleo-synthesized materials into the interstellar space relatively in a short timescale and can be regarded as a strong candidate for the dust budget in the early universe. One of the major processes of dust formation by massive stars is the dust condensation in the ejecta of core-collapse supernova (SN) explosions (Kozasa et al. 1991; Todini & Ferrara 2001; Nozawa et al. 2003). Although formation of 0.1–1 solar mass ($M_\odot$) of dust per typical SN is needed to explain the dust content in the early universe (Morgan & Edmunds 2003), the amount of newly formed dust in the ejecta of a supernova obtained from the near- to mid-infrared observations of young SNe (< a few years) with *AKARI* and *Spitzer* remains only in the range of $10^{-3}$–$10^{-5}$ $M_\odot$ (Sakon et al. 2009; Mattila et al. 2008; Meikle et al. 2007; Kotak et al. 2009). On the other hand, recent far-infrared observations of SN1987A in the Large Magellanic Clouds and some Galactic SNRs by *Herschel* have revealed the presence of nearly 1 $M_\odot$ of dust in a remnant (Matsuura et al. 2011; Gomez et al. 2012; Barlow et al. 2010). There is an apparent large gap in measured dust mass between MIR observations of young SNe ($t$ < a few years) and FIR observations of young SNRs.

Recently, SNe in the "transitional" phases between the SNe younger than a few years and the young SNRs older than several tens years after the SN explosion have started gaining attention. Tanaka et al. (2012) have searched for those SNe in the "transitional" phase in the archival near- to mid-infrared imaging data of nearby galaxies obtained with *AKARI*/Infrared-Camera (IRC) and *Spitzer*. They have reported the detection of infrared emission at the position of SN 1978K ($t$ ~30 yr) in NGC 1313. They attribute this emission to $1.3 \times 10^{-3}$ $M_\odot$ of shocked circumstellar silicate dust rather than newly formed dust in the SN ejecta nor the swept-up interstellar dust.

In order to understand the role of SNe as the dust budgets in the universe, the following three dust populations that may contribute to the observed infrared spectral energy distribution (SED) of a SN should be separately examined; (1) the dust formed in the ejecta of SNe (hereafter, SN dust), (2) the dust formed by the pre-SN stellar wind, which is now located in the circumstellar region (hereafter, CS dust), and (3) the interstellar dust swept up by the SN ejecta (hereafter IS dust). In this paper, we discuss some key science cases of *SPICA* focusing on the life cycle of dust in massive stars before and after the SN explosion.

## 2. DUST FORMATION IN THE SN EJECTA AND ITS EVOLUTION

As for SNe in nearby galaxies except for those in Magellanic Clouds, we would not be able to get any spatially resolved geometric information of three dust populations (i.e., SN dust, CS dust and IS dust) even with the spatial resolution of *JWST* and *SPICA*. Under this condition, in order to carry out the spectral decomposition of emissions from those three dust populations properly, multi-epoch observations of dusty SNe on a timescale of several — a few tens years after the explosion are indispensable. It should be noted that observational simultaneity in wide spectral range from mid- to far-infrared is crucial for such time-varying phenomena and only *SPICA* can fulfill those purposes.

As discussed in Tanaka et al. (2012), SNe in the "transitional" phases in nearby galaxies will provide us unique opportunity to study the origin of dust in the early universe. Since the mass of the swept-up IS dust estimated for such "transitional" phase SNe is less than an order of ~ $10^{-6}$ $M_\odot$, *SPICA*/MCS (Kataza et al. 2012) and SAFARI (Roelfsema et al. 2012) will be able to study the properties of shocked CS dust and SN dust. If the contribution of CS dust emission is small, the SN dust will be detected at the wavelengths longer than 30 $\mu$m (see Tanaka et al. 2012). These observations will lead us to measure the reliable mass of SN dust by taking account of the possible grain growth and/or destruction that may take place in a timescale of several tens years after the SN explosion. In particular, MCS/Wide Field Camera(WFC; Wada et al. 2010) and SAFARI will be sensitive to the $10^{-1}$ $M_{\odot}$ of dust cooled below 100 K even at 25 Mpc, which will be crucial to conclusively answer to the question of whether or not SNe can be the efficient dust budget in the early universe.

Systematic spectroscopic monitoring observations of young SNe in nearby galaxies (<10 Mpc) with *SPICA*/MCS and SAFARI will be crucial to study the chemical and physical properties of newly formed SN dust and pre-existing CS dust. MCS/Medium Resolution Spectrometer (MRS; see Sakon et al. 2012a) provides us unique capability to demonstrate the process of interaction between the SN ejecta gas and circumstellar medium taking advantage of its excellent line sensitivity in wide mid-infrared spectral range from 12 $\mu$m to 38 $\mu$m. Moreover, MCS/MRS will be sensitive enough to detect $10^{-3}$ $M_{\odot}$ of dust at >150 K at a distance of 5 Mpc and will offer unique capability to diagnose the chemical compositions of the constituent dust species and to examine the temporal evolution of the physical properties of each dust component in detail.

## 3. DUST FORMATION IN THE PRE-SN STELLAR WIND

Recent observations of dust-forming type-Ib supernova 2006jc made with *AKARI* and *Spitzer* have shown that the amount of newly-formed dust in the SN ejecta of SN 2006jc is in the range of only $10^{-4}$–$10^{-5}$ $M_{\odot}$ (Sakon et al. 2009; Mattila et al. 2008). At the same time, however, they recognize the presence of pre-existing circumstellar dust possibly formed in the mass loss wind associated with the events prior to the SN explosion. These results suggest that the dust condensation not only in the SN ejecta but also in the mass loss wind during the pre-explosion phase can contribute to the process of dust enrichment in the early universe. However, it is suggested that the metal-free massive stars in the early universe may die without losing a large fraction of its mass (Baraffe et al. 2001) and the origin of dust in the early universe still remains puzzling. Although there has been no evidence, so far, of dust formation in a smooth wind flow of a single Wolf-Rayet star (Cherchneff & Dwek 2010), WR binary system, in particular WC+O systems with eccentric orbits, can periodically produce dust in two winds' collision zone whenever the secondary passes by the periastron point of the primary (Williams 1995) even in low metallicity environment. In addition, more abundant massive binary systems are expected to be born in early universe (Machida 2008). The CS dust structures around the SN progenitor must be formed and characterized as a result of the mass loss activities before the SN explosion. Therefore, dust formation history in such WR binary systems shall be clarified to understand the geometrical and compositional properties of circumstellar dust structures surrounding the type I-b/c SN progenitors.

Marchenko et al. (2002) have pointed out the survival of dust produced by WR+O binary systems for more than 100 years. If this is the case, the dust can travel farther from the WR+O core into the ISM and part of it can survive the later SN explosion event. Therefore, whether or not such WR binary systems would have made significant contribution toward supplying dust in the early universe has to be examined from the observational point of view.

For example, WR 140 is a long-period, colliding-wind binary located at the distance of 1.1 kpc (WC7 class Wolf-Rayet star+O4 type star, $P$ = 7.93 yr, $e$ = 0.881; Marchenko et al. 2003; Williams 2009). So far, interesting features in the light curves at multi-wavelengths were reported whenever the O-type companion star passed through the densest region of the carbon-rich WR wind (i.e., "spectroscopic events" in 1993, 2001 and 2009). This event is often accompanied by dust formation. Marchenko & Moffat (2007) presented the high-quality 12.5 $\mu$m image of WR 140 taken with Michelle/Gemini-North in November/December 2003. They detected the concentric dust arc-like structures, which are unequivocally linked with the 1993 and 2001 dust formation episodes (Marchenko & Moffat 2007). In the case of WR 140, the dust produced during a spectroscopic event travels 3 arcsec from the WR+O core and is cooled to 300 K after one orbital period (~10 yr) from its formation. After ten orbital periods (~100 yr) from its formation, the dust reaches at 30 arcsec away from the WR+O core and is cooled to ~100 K if grain growth is not taken into account. Therefore, sensitive spectroscopic mapping capability in wide spectral range covering from mid- to far-infrared is indispensable to understand the 100 years' scale evolution of circumstellar dust around WR 140.

There are several other WC 4-9 stars that are known as the episodic dust-makers with the recurrence period of a few — a few tens years (Williams 1995). Integral Field Unit (IFU) spectroscopic observations of those targets with MCS/MRS shall provide us valuable opportunity to investigate the properties of circumstellar dust formed around the Type-Ib/c SN progenitors. The latest specification of MCS/MRS provides us two dimensional spectroscopic capability with a wide field of view (FOV) of 12″by 8″(Sakon et al. 2013). Moreover, since the same FOV is shared between MRS-S and MRS-L by means of a beamsplitter installed in the foreoptics, the continuous 12–38 $\mu$m spectrum with moderate spectral resolution ($R$ = 1000–3000) is obtained by a single pointed observation (Sakon et al. 2012a, see Figure 1). With those capabilities, MCS/MRS, combined with SAFARI, shall give us conclusive answers to the questions of (1) if the scale of mass loss and dust formation be homogeneous at every periastron passage and (2) how the synthesized dust pass through the mass evolution and chemical composition denaturation until it reaches the interstellar space.

## 4. CONCLUSION

Some key science cases of *SPICA* focusing on the dusty SNe and their progenitors are discussed. The universe seen by *SPICA* is no longer static but dynamic. Therefore, observational simultaneity over a wide spectral range is critical for those targets. Continuous spectral coverage from the mid- to the far-infrared is essential for *SPICA*, since this cannot be

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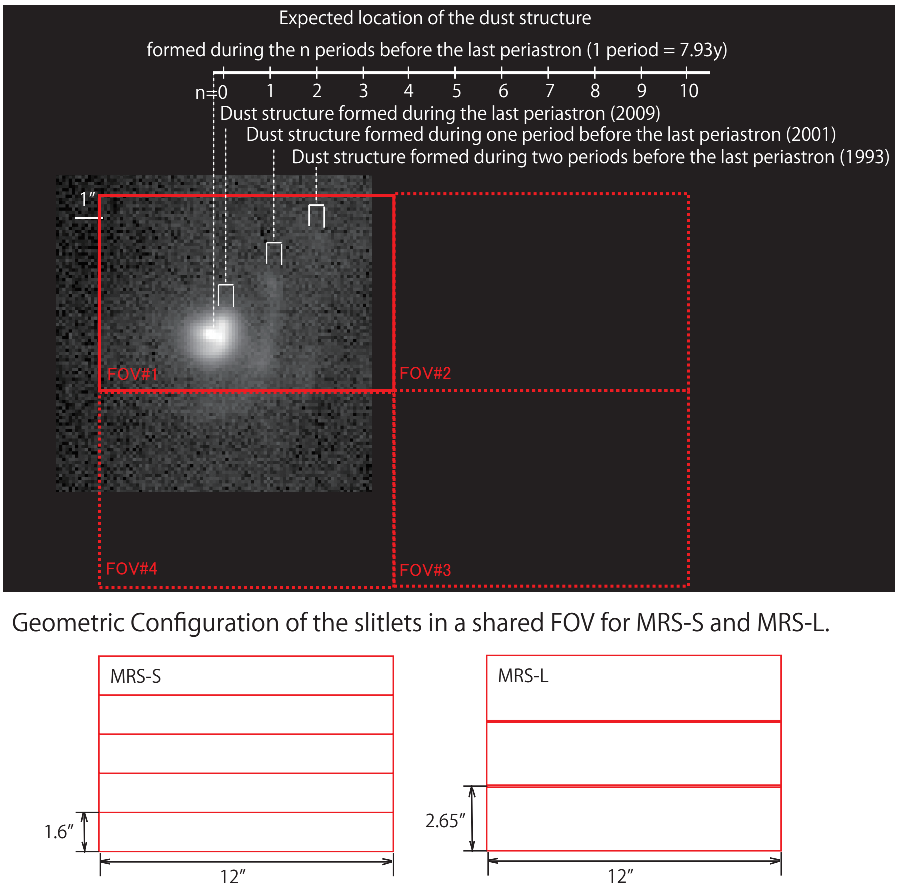


**Figure 1.** An example plan for the IFU spectral mapping observations of WR 140 with MCS/MRS. FOV positions are shown over the mid-infrared image of WR 140 obtained with Subaru/COMICS on June 2011 (Sakon et al. 2012b) to cover the whole circumstellar dust structures formed as a result of the past periastron events over ~100 years (*top*). The geometric configurations of the slitlets for MRS-S and MRS-L in a shared FOV are shown schematically (*bottom*).

achieved by *JWST*. The proposed observations should revolutionalize our understanding of cosmic dust enrichment by the massive stars that characterise the ISM environment of the early universe.

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