Infrared studies of AGB stars and supernovae with *AKARI* and future space missions

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ABSTRACT

This proceeding presents the progress of our understanding of asymptotic giant branch (AGB) stars and supernovae (SNe) made by the *AKARI*, the *Spitzer Space Telescope*, the *Herschel Space Observatory* and *Stratospheric Observatory For Infrared Astronomy (SOFIA)*. The *AKARI* and *Spitzer* surveys mapped the spatial distributions of asymptotic giant branch (AGB) stars in the Milky Way and Magellanic Clouds. The survey captured how much gas and dust have been returned from AGB stars into the interstellar medium (ISM). While dust return from AGB stars has been well established, dust return from high-mass stars had not been well studied. *AKARI* and *Spitzer* opened up new insight of dust condensation in the ejecta of supernovae, as well as possible dust destruction process. Finally, prospects of the research field will be discussed with future infrared space missions, the *JWST* and the *SPICA*.

Keywords: Stellar evolution, Galaxy evolution

1. INTRODUCTION

The interstellar medium (ISM) of galaxies are filled with dust and gas, however, it has not well determined how the ISM have acquired dust within. Asymptotic giant branch (AGB) stars, low- and intermediate-mass evolved stars, are well-established site of dust formation (e.g., Cox et al. 2012). It has been proposed that asymptotic giant branch (AGB) stars, low- and intermediate-mass evolved stars, are the major source of dust in the ISM of the Milky Way. In parallel, theoretical models predict very efficient dust destruction by blast waves of supernova remnants (SNRs). It is largely debate whether dust formed by AGB stars is sufficient to explain the ISM of the galaxies, or dust destruction rate exceed AGB dust formation rate, i.e. deficit in dust budget, thus, additional source of dust might be needed.

Recent development of sub-milimetre survey of distant galaxies have shown galaxies, up to redshift of $z = 8.38$, can be filled with dust (Laporte et al. 2017). Because these galaxies have much shorter timescale, shorter than the timescale of a low-mass to reach the AGB phase, dust deficit in dust budget becomes a more sever problem. In order to resolve the dust deficit problem, supernovae (SNe) have been proposed to be an additional source of dust. While the fastest part of the blast winds from SNe destroy ambient ISM dust, slower moving part of the SN winds are rich in refractory elements, which can potentially condense into dust grains.

In this review, I will report recent progresses made in dust in AGB stars and SNe/SNRs, and discuss prospects with future infrared space and airborne missions, with particular emphasis of compositions in AGB dust, and dual role of dust formation and destruction in SNe and SNRs. The key questions are listed here:

- How much dust is formed in an AGB star and a SN?
- Are dust grains formed in SN ejecta completely destroyed, and no dust input from SNe to ISM?
- How much existing ISM dust is destroyed by SN forward shocks?
- What compositions of dust are formed in AGB stars and SNe?
- How does metallicities of galaxies affect AGB dust?

2. DUST FROM AGB STARS

AKARI's one of the strengths was high sensitivity spectroscopy at 2.5–5 μm, where some of that wavelength range is not accessible from the ground, and even accessible wavelength range can not easily reach good sensitivity from the ground, due to high background of the earth atmosphere. Ohsawa et al. (2016) used this *AKARI*'s strength to investigated the

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3.3 μm feature of polycycrlic aromatic hydrocarbons (PAHs) in planetary nebulae (PNe), the evolutionary phase after AGB for low- and intermediate-mass stars. Although PAHs are thought to be formed in AGB stars, the excitations of PAHs requires UV radiation: AGB stars have very weak UV radiation, thus it is hard to detect PAHs from AGB stars, whereas hot central stars of PNe have ample of UV radiation, allowing PAH features to be identified. Ohsawa et al. (2016) found that despite PAHs are representative of carbonaceous dust grains, PAHs are found in some oxygen-rich PNe. The strengths of PAHs do not correlate with carbon and oxygen elemental ratio of the central star (Figure 1).

AKARI and *Spitzer* made surveys of the Milky Way and the Magellanic Clouds, allowing investigations of statistical studies of AGB stars. Ishihara et al. (2011) investigated the spatial distributions of oxygen-rich and carbon-rich stars, using colour classification scheme (Ishihara et al. 2011; Ita et al. 2010). Carbon-rich AGB stars distribute outer Galaxy, whereas oxygen-rich AGB stars populate more in the inner Galaxy. *Spitzer*'s surveys of the Magellanic Clouds (Meixner et al. 2006; Gordon et al. 2011) were deep enough to detect almost all dust-embedded AGB stars in these galaxies, enabling to study dust inputs from AGB stars. In both galaxies, the total dust outputs from AGB stars are dominated from high mass-loss rate ($> 10^{-5}$ $M_{\odot}$ yr^{-1}) AGB stars, which are minority (about 10 %) among the total sampled AGB stars Matsuura et al. (2013, 2009). The total dust outputs from AGB stars over ISM dust lifetime, which was the theoretical calculated form the Milky Way (Jones et al. 1994), was more than 10 times smaller than the current ISM dust mass (Matsuura et al. 2013; Boyer et al. 2011; Matsuura et al. 2009). Boyer et al. (2015) extended AGB stars into farther dwarf galaxies in the Local Group, which have range of metallicities (down to −2.2 [Fe/H]). While the theory predicts that mass-loss rate of AGB stars becomes smaller at lower metallicity, the measured total AGB mass-loss rate per stellar mass was independent of metallicity (Boyer et al. 2015). Studies of AGB stars in nearby galaxies continue with ALMA. ALMA CO J=2–1 line observations of AGB stars and red-supergiants in the Large Magellanic Cloud (LMC) found that CO lines of red supergiants are weaker in the LMC than Galactic counterparts (Groenewegen et al. 2016). It might be because ISM UV radiation is harsher in the LMC than the Milky Way, so that the CO dissociation radius of circum-stellar envelope of red-giants can be smaller in the LMC, hence CO line intensities are weaker. Alternatively, mass-loss rates of LMC red-supergiants can be lower.

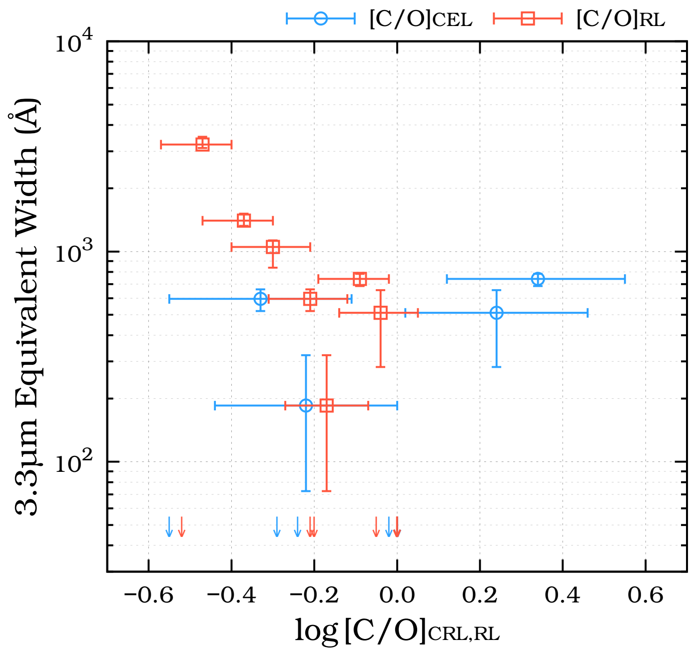

Figure 1. The equivalent width of 3.3 μm PAHs, as a function of C/O ratio (Ohsawa et al. 2016).

3. SUPERNOVA DUST

It is still largely in debate how much dust is formed by a SN. *AKARI* has made a significant contributions of measuring SN dust. Sakon et al. (2009) detected near- and mid-infrared excess from SN 2006jc at 202 days since the explosion, and inferred dust mass was 2.7×10^{-4} $M_{\odot}$. That is within the range of dust masses (10^{-5}–10^{-3} $M_{\odot}$) reported in SNe within one year after the explosion (Gall et al. 2011; Matsuura 2017).

The story changed by a detection of a large mass of ejecta dust in SN 1987A, the nearest SN explosion detected in 400 years. *Herschel* detected SN 1987A at 100–350 μm in 2010, i.e., twenty three years after the explosion (Matsuura et al. 2011). The inferred dust mass was ~ 0.5 $M_{\odot}$ (Matsuura et al. 2015), much larger than previously reported dust mass in this SN (4×10^{-6}–4×10^{-4} $M_{\odot}$; Wooden et al. 1993; Moseley et al. 1989; Ercolano et al. 2007). ALMA spatially resolved image confirmed that sub-millimetre dust emission is indeed from SN ejecta (Figure 2 Indebetouw et al. 2014). After the detection of a large mass of dust in SN 1987A, near- and mid-infrared observations SN 1987A in earlier days have been re-visited, and now there are two possibilities proposed: (1) a large mass of dust was present from early days, but the emission was optically thick, hence, the inferred dust mass was underestimated (Lucy et al. 1989; Dwek & Arendt 2015). (2) The dust mass was indeed smaller in early days, and the dust mass increased in time (Gall et al. 2014; Wesson et al. 2014; Bevan & Barlow 2016). This issue will be examined in nearby SNe in future space mission, *SPICA*, which can cover from mid- to far-infrared wavelengths (van der Tak et al. 2018).

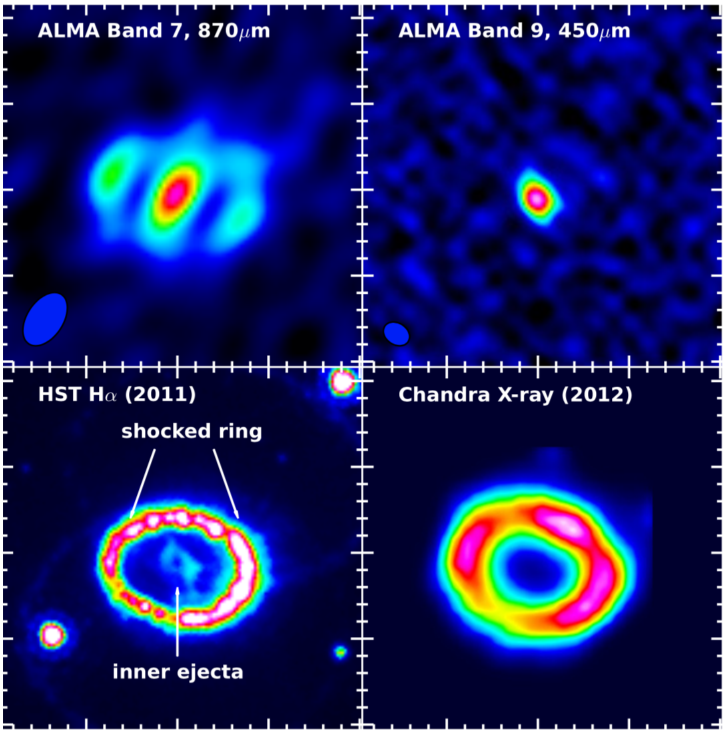

Figure 2. ALMA image of SN 1987A (Indebetouw et al. 2014). The dust emission, detected at 450 and 870 μm was detected from the inner ejecta. Note that the circumstellar ring is brighter in optical and X-ray image, and also emit synchrotron radiation at 870 μm. The ring is composed of material expelled from the progenitor when it was a red-supergiant about 20,000 years.

Dust compositions of SNe and SNRs are largely unknown — so called the 21 μm feature, which has been proposed to be associated with FeO, Mg protosilica, SiO_2, have been identified in the SNRs, Cassiopeia A and G54.1+0.3. Further, the spatial distribution of this dust is associated with distribution of [Ar II] line (Rho et al. 2008; De Looze et al. 2017). It suggests that the structure of the SNR is associated with the structure of the stellar interior just before the explosion (Fesen & Milisavljevic 2016; Wongwathanarat et al. 2015), and Ar and the composing elements of the 21 μm must have originated from the same nuclear burning zone. Future high-sensitivity infrared space missions, *JWST* and *SPICA* will contribute even further about dust compositions and spatial extent.

Historically, major role of SNe/SNRs on dust is destroying ambient ISM dust. Fast expanding blast waves from SNRs interact with surrounding ISM gas and dust, causing shocks, and destroying dust. Theoretical models predict that the dust destruction rates of 8–70 % for foward shocks (McKee 1989; Jones et al. 1996; Bocchio et al. 2014; Micelotta et al. submitted) and 1–100 % for reverse shocks (Bianchi & Schneider 2007; Nozawa et al. 2007; Nath et al. 2008; Silvia et al. 2012; Micelotta et al. 2016). It has been challenging to test these efficiencies.

Koo et al. (2016) studied infrared luminosities and X-ray luminosities of SNRs. Infrared luminosities represent dust emission, which are collisionally heated by X-ray emitting gas. They found that the correlation between X-ray and Infrared luminosities are much more diverse than the theoretical prediction (Dwek 1987). Koo et al. (2016) modelled luminosities included cooling time of X-ray radiating gas, which predict much wider luminosities of infrared and X-ray radiations than previously considered.

Theories predicts that reverse shocks destroy SN ejecta dust in a few thousand years time scale (e.g., Nozawa et al. 2007). Thus *SOFIA* detection of ejecta dust in ~10,000 years old SNR, Srg A East was surprising, suggesting less efficient dust destruction than previously thought (Lau et al. 2015). That is an important work to be done with *AKARI* archive, with on-going effort by Lee et al. (contribution to these proceedings).

4. SUMMARY

Recent infrared space and airborne missions enabled a large development of dust in and SNe/SNRs and extra-galactic AGB stars. This field expect to develop even further with future space missions, *JWST* and *SPICA*.

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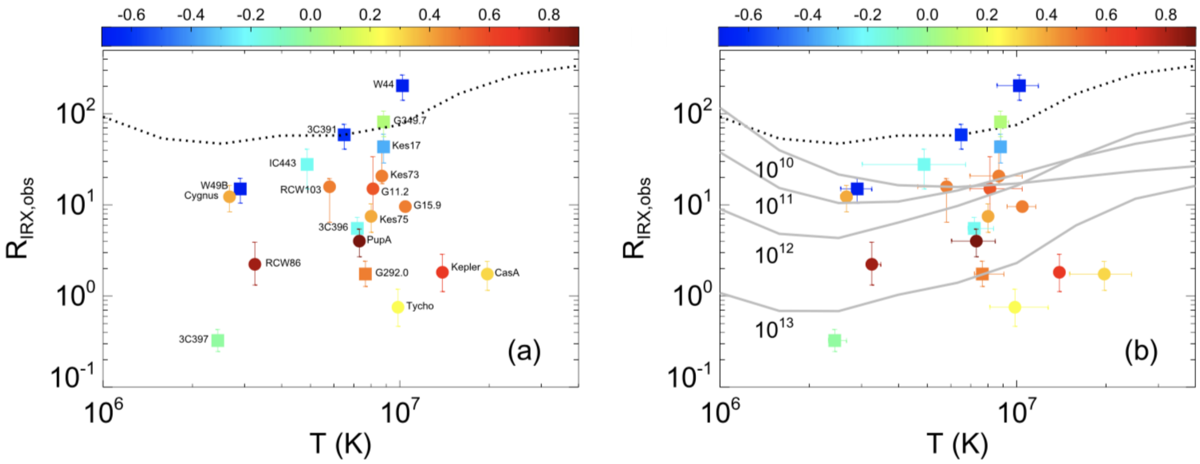

Figure 3. The infrared and X-ray luminosity ratio as a function of the electron temperature for Galactic SNRs (Koo et al. 2016) . The left panel side include modelled infrared and X-ray luminosity ration, based on (Dwek 1987). Koo et al. (2016) included the cooling time of the gas, which can explain the spread of the ratio (right panel).

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