Properties of Infrared Emission of Novae Detected in *AKARI* All Sky Survey

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ABSTRACT

The *AKARI* all sky surveys provide us unique and independent infrared datasets of classical and recurrent novae taken with two photometric bands at 9 μm (*S9W*) and 18 μm (*L18W*) of the Infrared Camera (IRC) and four photometric bands at 65 μm (*N60*), 90 μm (*WIDE-S*), 140 μm (*WIDE-L*) and 160 μm (*N160*) of the Far-infrared Surveyor (FIS). This allows us to systematically examine the temporal evolution of the infrared spectral energy distributions (SEDs) of novae over epochs from 2006 May to 2007 August every six months. We have searched for infrared counter part of 57 targets including classical novae, recurrent novae and dusty CV, which have been observed with multi-wavelengths. In the *AKARI* IRC/FIS all sky surveys, 3 novae, V445 Pup, RR Tel, and V838 Mon, were detected both in the mid-infrared and far-infrared. Nine other novae, T CrB, DZ Cru, V2361 Cyg, V476 Sct, RS Oph, V2362 Cyg, V1065 Cen, V1280 Sco, and V745 Sco, were detected only in the mid-infrared. We have investigated the properties of infrared emission associated with those targets. In particular, for some objects, the temporal evolution of infrared emissions before and after the dust formation episode in the nova ejecta is discussed.

Keywords: Dust, Novae, *AKARI* All Sky Survey

1. INTRODUCTION

AKARI has carried out the mid- to far-infrared all sky survey from May 8th in 2006 to August 28th in 2007. It takes 6 months for *AKARI* to survey the entire sky and, therefore, *AKARI* has observed a single object three times at the maximum during its 550 days' lifetime (Murakami et al. 2007). The *AKARI* all sky survey provides us unique and independent infrared datasets of classical and recurrent novae taken with two photometric bands at 9 μm (*S9W*) and 18 μm (*L18W*) of the Infrared Camera (IRC; Onaka et al. 2007) and four photometric bands at 65 μm (*N60*), 90 μm (*WIDE-S*), 140 μm (*WIDE-L*) and 160 μm (*N160*) of the Far-infrared Surveyer (FIS; Kawada et al. 2007), which allows us to examine the temporal evolution of the infrared spectral energy distributions (SEDs) of novae over the epochs from May 2006 to August 2007 among every six months.

2. A LIST OF TARGERTS

We have examined the absense/presense of the infrared counterpart in the *AKARI* All Sky Survey Data (Doi et al. 2015; Ishihara et al. 2010) of 57 targets including classical novae, recurrent novae and dusty CV, which have been observed with multi-wavelengths. Among 57 novae examined in this study, three objects, the helium nova V445 Pup, the symbiotic nova RR Tel, and the stellar merger V838 Mon, were detected both at the mid- and far-infrared photometric bands in the *AKARI* all sky survey. The other targets were not detected in the far-infrared but nine objects, T CrB, DZ Cru, V2361 Cyg, V476 Sct, RS Oph, V2362 Cyg, V1065 Cen, V1280 Sco, and V745 Sco were detected in the mid-infrared.

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Table 1. A list of Targets

object name	outburst year	distance	*S9W*	*L18W*	*N60*	*WIDE-S*	*WIDE-L*	*N160*
T Boo	1860		—	—	—	—	—	—
T Aur	1891		—	—	—	—	—	—
GK Per	1901	—	—	—	—	—	—	—
DM Gem	1903		—	—	—	—	—	—
AR Cir	1906	—	—	—	—	—	—	—
DN Gem	1912	—	—	—	—	—	—	—
V603 Aql	1918		—	—	—	—	—	—
V476 Cyg	1920		—	—	—	—	—	—
RR Pic	1925		—	—	—	—	—	—
DQ Her	1934		—	—	—	—	—	—
RR Tel	1944	3.47 kpc	✓	✓	✓	✓	✓	✓
T CrB	1866, 1946	9 kpc	✓	✓	—	—	—	—
CT Ser	1948		—	—	—	—	—	—
EU Sct	1949		—	—	—	—	—	—
V533 Her	1963		—	—	—	—	—	—
QZ Aur	1964		—	—	—	—	—	—
HR Del	1967		—	—	—	—	—	—
FH Ser	1970		—	—	—	—	—	—
V1229 Aql	1970		—	—	—	—	—	—
V1301 Aql	1975		—	—	—	—	—	—
V1550 Cyg	1975		—	—	—	—	—	—
NQ Vul	1976		—	—	—	—	—	—
V4021 Sgr	1977		—	—	—	—	—	—
LW Ser	1978		—	—	—	—	—	—
V1668 Cyg	1978		—	—	—	—	—	—
V1370 Aql	1982		—	—	—	—	—	—
GQ Mus	1983		—	—	—	—	—	—
PW Vul	1984		—	—	—	—	—	—
QU Vul	1984		—	—	—	—	—	—
OS And	1986		—	—	—	—	—	—
V842 Cen	1986		—	—	—	—	—	—
V1819 Cyg	1986		—	—	—	—	—	—
QV Vul	1987		—	—	—	—	—	—
V827 Her	1987		—	—	—	—	—	—
V4135 Sgr	1987		—	—	—	—	—	—
V3890 Sgr	1990		—	—	—	—	—	—
V1974 Cyg	1992		—	—	—	—	—	—
V705 Cas	1993		—	—	—	—	—	—
V723 Cas	1995		—	—	—	—	—	—
V382 Vel	1999		—	—	—	—	—	—
V1494 Aql	1999		—	—	—	—	—	—
V4444 Sgr	1999		—	—	—	—	—	—
V445 Pup	2000	4.9 kpc	✓	✓	✓	✓	✓	—
V838 Mon	2002	6.2 kpc	✓	✓	✓	✓	✓	✓
V4743 Sgr	2002		—	—	—	—	—	—
DZ Cru	2003	9 kpc	✓	✓	—	—	—	—
V1186 Sco	2004		—	—	—	—	—	—
V476 Sct	2005	4 kpc	✓	✓	—	—	—	—
V2361 Cyg	2005	10.8 kpc	✓	✓	—	—	—	—
RS Oph	2006	1.6 kpc	✓	✓	—	—	—	—
V2362 Cyg	2006	7.5 kpc	✓	✓	—	—	—	—
V1065 Cen	2007	8.7 kpc	✓	✓	—	—	—	—
V1280 Sco	2007	1.1 kpc	✓	✓	—	—	—	—
V2467 Cyg	2007		—	—	—	—	—	—
KT Eri	2009		—	—	—	—	—	—
U Sco	2010		—	—	—	—	—	—
T Pyx	2011		—	—	—	—	—	—
V745 Sco	1989, 2014	7.8 kpc	✓	✓	—	—	—	—

3. THE RESULTS OF PHOTOMETRY

The results of the mid- to far-infrared photometry of 12 obejects including RR Tel, V838 Mon, V445 Pup, V2362 Cyg, V1065 Cen, T CrB, V745 Sco, RS Oph, V2361 Cyg, DZ Cru, V476 Sct, and V1280 Sco are shown in Table 2.

Table 2. The results of the photometry

object name	outburst date	*AKARI* obs.	I_{S9W} (Jy)	I_{L18W} (Jy)	I_{N60} (Jy)	$I_{WIDE\text{-}S}$ (Jy)	$I_{WIDE\text{-}L}$ (Jy)	I_{N160} (Jy)
RR Tel	1944 Oct		23.3±4.8	16.8±3.1	0.3±1.2	1.1±0.3	0.1±1.5	0.3±0.7
V838 Mon	2002 Jan 6		22.0±4.5	35.2±5.7	10.0±1.2	10.5±0.3	7.7±1.5	6.0±0.7
V445 Pup	1944 Oct	2006 Oct	12.34±0.03	40.70±0.07	15.1±3.5	4.8±0.8	< 0.3	—
V2362 Cyg	2006 Apr 2	2006 Jun 3	0.12±0.01	0.081±0.006	—	—	—	—
		2006 Dec 6	0.14±0.01	0.043±0.005	—	—	—	—
		2007 Jun 3	0.69±0.06	0.32±0.02	—	—	—	—
V1065 Cen	2007 Jan 20	2006 Jul 23	—	—	—	—	—	—
		2007 Jan 19	2.45 ± 0.2	0.24 ± 0.02	—	—	—	—
		2007 Jul 23	1.9 ± 0.1	0.8 ± 0.1	—	—	—	—
T CrB	1866 May,	2006 Aug 12	0.87 ± 0.07	0.21 ± 0.01	—	—	—	—
	1946 Feb	2007 Feb 8	0.82 ± 0.06	0.17 ± 0.01	—	—	—	—
		2007 Aug 13	0.75 ± 0.06	0.18 ± 0.01	—	—	—	—
V745 Sco	1989 Jun 30,	2006 Sep 22	0.21 ± 0.02	0.077 ± 0.006	—	—	—	—
	2014 Feb 6	2007 Mar 19	0.16 ± 0.01	0.057 ± 0.005	—	—	—	—
RS Oph	2006 Feb 12	2006 Sep 20	0.34 ± 0.02	0.17 ± 0.01	—	—	—	—
		2007 Mar 17	0.34 ± 0.03	N.A.	—	—	—	—
V2361 Cyg	2005 Feb 6	2006 May 10	0.048 ± 0.004	0.085 ± 0.007				
		2006 Nov 13	—	—	—	—	—	—
		2007 May 10	—	—	—	—	—	—
DZ Cru	2003 Aug 20	2006 Aug 1	3.3 ± 0.3	1.8 ± 0.1	—	—	—	—
		2007 Jan 28	2.96 ± 0.24	1.6 ± 0.1	—	—	—	—
		2007 Aug 1	2.5 ± 0.2	1.5 ± 0.1	—	—	—	—
V476 Sct	2005 Sep	2006 Oct 1	0.38 ± 0.03	0.6 ± 0.05	—	—	—	—
		2007 Mar 28	0.14 ± 0.009	0.19 ± 0.01	—	—	—	—
V1280 Sco	2007 Feb 4	2006 Sep 9	—	—	—	—	—	—
		2007 Mar 7	23 ± 2	6.8 ± 0.5	—	—	—	—

In the case of V2362 Cyg, the epoch of dust condensation in the nova ejecta has been identified between 2006 November 30 and 2006 December 12 (Lynch et al. 2008) and, therefore, the first *AKARI* observation epoch (2006 June 3; Day ∼60) corresponds to that before the dust condensation, the second *AKARI* observation epoch (2006 December 6; Day ∼250) corresponds to just around the dust condensation epoch, and the third *AKARI* observation epoch (2007 June 3; Day ∼430) to that after the dust condensation epoch. If the observed emission is carried by thermal emission from amorphous carbon, the data on the first epoch is consistent with the presense of pre-existing amorphous carbon dust of $T = 315$ K and of a mass $7.1 \times 10^{-8}\ M_{\odot}$. Our datasets on the second and the third ecpohs suggest that the amorphous carbon has been newly produced in the nova ejecta with $\dot{M} >\sim 10^{-9}\ M_{\odot}\ \mathrm{day}^{-1}$ during the epochs betwenn Days ∼250 and ∼430 after the nova outburst.

In the case of V1065 Cen, the first *AKARI* observation epoch (2006 July 23) corresponds to ∼180 days before the nova outburst, the second *AKARI* observation epoch (2007 January 20) corresponds to just after the outburst and the third *AKARI* observation epoch (2007 July 23) corresponds to ∼180 days after the nova outburst. The onset of dust formation in the nova ejecta was reported on 40 days after the outburst (Helton et al. 2010). Therefore, the our third observation epoch corresponds to ∼140 days after the onset of dust formation. Our datasets on the second and the third epochs suggest that the silicate dust has been newly produced in the nova ejecta with $\dot{M} \sim 2 \times 10^{-9}\ M_{\odot}\ \mathrm{day}^{-1}$ during the epochs betwenn Days ∼40 and ∼180 after the nova outburst.

As for the three recurrent novae (T CrB, V745 Sco and RS Oph) in our targets, the mid-infrared photometric data are basically consisent with those of WISE all sky survey data and the removal of photosphere component is crucial for the correct estimate of the dust properties formed in the nova ejecta.

Except for the case of the helium nova V445 Pup which has produced 1.4–1.8 × 10^{-5} $M_{\odot}$ of newly formed amorphous carbon (see Shimamoto et al. 2017, for details), the amount of the dust formed in the ejecta of each nova outburst estimated for RR Tel, DZ Cru, V2361 Cyg, V476 Sct, V2362 Cyg, V1065 Cen, V1280 Sco was basically comparable to the typical amount of dust formed in the ejecta of classical novae (e.g., 10^{-8} to 10^{-6} $M_{\odot}$; Bode & Evans 2008).

4. DISCUSSION AND SUMMARY

We have searched for infrared emission from 57 objects, including classical novae and recurrent novae, in the *AKARI* IRC and FIS all sky survey data and systematically investigated dust emission associated with nova outbursts. As a result, infrared emission at broadbands from the mid- to far-infrared (six bands of 9 μm, 18 μm, 60 μm, 90 μm, 140 μm, and 160 μm) in 2006–2007 for three objects, the helium nova V445 Pup, the stellar merger V838 Mon, and the symbiotic nova RR Tel, were detected. Moreover, the multi-epoch mid-infrared photometric data at the two bands (9 μm, 18 μm) every 6 months in 2006–2007 were detected for nine objects, T CrB, DZ Cru, V2361 Cyg, V476 Sct, RS Oph, V2362 Cyg, V1065 Cen, V1280 Sco, and V745 Sco.

(1) The multi-epoch (every 6 months) observational capabilities of the *AKARI* all sky survey have enabled us to detect dust emission associated with V2362 Cyg and V1065 Cen both before and after the onset of dust formation in the nova ejecta. From those datasets, the properties of both pre-existing circumstellar dust and the newly formed dust in the nova ejecta were constrained. The dust formation rate in the nova ejecta was estimated as $dM/dt > 10^{-9}$ $M_{\odot}$ day^{-1} (for V2362 Cyg, calculated from Days 250–430) and $dM/dt \sim 2.0 \times 10^{-9}$ $M_{\odot}$ day^{-1} (for V1065 Cen, calculated from Days 40–180).

(2) MIR photometric data of two recurrent novae (T CrB, V745 Sco) detected in the *AKARI* IRC all sky survey data is basically consistent with that detected in the *WISE* all sky survey. The removal of photosphere component is necessary to estimate the properties of dust.

(3) The amount of dust formed in the ejecta of nova outburst estimated for RR Tel, DZ Cru, V2361 Cyg, V476 Sct, V2362 Cyg, V1065 Cen, V1280 Sco, and at least at the multiple epoch of *AKARI* observations was in a range between 10^{-8}–10^{-6} $M_{\odot}$.

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