AKARI's Legacy to *SPICA*

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ABSTRACT

AKARI is the first Japanese satellite mission dedicated to the infrared astronomy. *AKARI* was launched in February 2006 and carried out an all-sky survey as well as twenty thousands of pointed observations from near- to far-IR wavelengths over four-years mission. *AKARI* operation was terminated in November, 2011. The All-Sky far- and mid-IR Point Source Catalogues, Asteroid catalogue, as well as point source catalogues from the Large Magellanic Cloud and the North Ecliptic Pole region have been published. Science targets of *AKARI* range from the solar system objects to cosmology. Science highlights from the *AKARI* data are briefly summarized. The *AKARI* project has been reconfigured in April 2013 to focus on data reduction and archiving. Revision of far-IR All-Sky Survey point source catalogue, mid- and far-IR faint source catalogues, All-Sky image maps are planned to be produced. Imaging and spectroscopic data taken in the pointed observation mode will also be archived as "science-ready" data products *AKARI* data and our experience through the mission are a legacy to promote the *SPICA* mission.

1. THE *AKARI* MISSION

The first Japanese infrared astronomical satellite *AKARI* (Murakami et al. 2007) was launched on February 22, 2006 (JST) by the 8th M-V rocket from the Uchinoura Space Center. *AKARI* was equipped with a 68.5 cm telescope cooled down to the cryogenic temperature (below 7 K) and two scientific instruments, the Far-Infrared Surveyor (FIS; Kawada et al. 2007) and the Infrared Camera (IRC; Onaka et al. 2007). The FIS covered the wavelength range between 50–180 μm by two broad and two narrow bands. The Fourier Transform Spectrometer (FTS) enabled us to carry out imaging-spectroscopic observations in the same wavelength range. The IRC observed with three cameras, namely the NIR (1.8–5.3 μm), the MIR-S (5.4–13.1 μm) and the MIR-L (12.4–26.5 μm). Each camera had three filter bands and grism/prism for low-resolution spectroscopy.

Observations were carried out in two attitude control modes; the survey mode and the pointing mode. The former was used for the All-Sky Survey. The FIS and IRC MIR-S&L were operated and scanned the sky with a speed of ~3.6 arcmin/sec. The pointing mode was used for deep imaging and spectroscopic observations of particular targets. A pointing enabled about 12 minute exposure with a cost of total 30 minutes including maneuver etc.

The scientific operation officially started on May 7, 2006. The first half year was defined as *Phase 1*, which was dedicated to the All-Sky Survey and only a small number of pointed observations were carried out in the high-visibility (i.e., high ecliptic latitude) regions. In *Phase 2*, started from November 2006, supplemental observations to complete the All-Sky Survey and thousands of pointed observations were carried out. It lasted until the liquid helium boiled off on August 26, 2007. *Phase 3* started in June 2008 with only the NIR channel of the IRC, cooled with the cryocoolers. Thirteen thousands imaging and spectroscopic observations were carried out until February 2010, when the scientific observations were suspended due to the degradation of the cryocoolers.

The *AKARI* observations were classified into several categories. The Large Area Survey (LS) included the All-Sky Survey, the Large Magellanic Cloud (LMC) Survey, and the North-Ecliptic Pole (NEP) Survey. They were conducted under responsibility of the project team. The latter two surveys were carried out in the pointing mode. Mission Programmes (MP) were proposed by the working groups consisted of the project team members. Relatively large number of pointing opportunities were allocated per programme, and the programmes were designed to produce comprehensive data-set to be the legacy to the future researches. About 30 per cent of the total number of pointed observations were opened to the astronomical communities in Japan-Korea, and the ESA supported countries. Beside them about 7 per cent of the orbits were allocated to calibration and director's discretionary time (DDT).

2. *AKARI* DATA PROCESSING AND ARCHIVING ACTIVITY

A huge amount of data taken by the *AKARI* is a legacy to the future astronomical researches and must be archived so that world-wide astronomical communities can easily access the data. Table 1 summarizes the data products so far released to the public.

The first products from the *AKARI* All-Sky Survey were the point source catalogues. The IRC Point Source Catalogue ver.1 (Ishihara et al. 2010) and the FIS Bright Source Catalogue ver.1 (Yamamura et al. 2010) were released in March 2010. Because of large differences in spatial resolution and wavelength coverage, two catalogues were provided in two separate files. The IRC catalogue contains 870,973 sources, and the FIS catalogue nominates 427,071 objects. Interestingly, we find

Table 1. Published *AKARI* Processed Data Products

Product Name	# of Sources	Release
FIS Bright Source Catalogue Ver. 1	427,071	Mar. 2010
IRC Point Source Catalogue Ver. 1	870,973	Mar. 2010
Asteroid Catalogue Ver. 1	5,120	Oct. 2011
LMC Point Source Catalogue Ver. 1	660,286	Nov. 2012
LMC Near-IR Spectral Catalogue Ver. 1	1,757	Jan. 2013
NEP-Wide Field Point Source Catalogue Ver. 1	114,793	Mar. 2013
NEP-Deep Field Point Source Catalogue Ver. 1	7,284	Mar. 2013
NEP-Deep Field Point Source Catalogue Ver. 2	27,770	Oct. 2013
Near-IR Diffuse Spectral Catalogue Ver.1	278	Jun. 2013

the fact that only 20,000–30,000 sources (depending on search radius) matches between two catalogues within positional errors. This emphasizes the difference in population in the catalogues. The catalogues have been and will be broadly used in many astronomical researches.

Usui et al. (2011) searched for signals from the asteroids in the mid-IR All-Sky Survey data by matching the scanned timestamps and positions with those predicted from the orbital elements. They succeeded to identify 5120 asteroids and catalogued their size and albedo calculated from the *AKARI* fluxes using standard thermal model of the asteroids. The catalogue is the most complete one among those has been publically used, and enables us to make more precise statistical study of the asteroids.

Catalogues from other two Large Area Surveys have also been published. The North Ecliptic Pole region survey resulted in the point source catalogues (Takagi et al. 2012; Kim et al. 2013; Murata et al. 2013). The catalogues are extensively used for the extragalactic science, for instance studies of the galaxy evolution (see Goto et al, this volume). Thanks to the continuous wavelength coverage of the *AKARI*/IRC filters precise SED analysis becomes possible.

Two products have been published from the Large Magellanic Cloud (LMC) survey. The *AKARI*-LMC point source catalogue (Kato et al. 2012) nominates 660 thousands of point sources detected in the near- and mid-IR. They are commonly observed by the *Spitzer*-SAGE survey (Meixner et al. 2006). Shimonishi et al. (2013) published near-IR spectra of 1757 sources observed in the LMC survey. These catalogues shall be useful for classification of the objects as well as the gas and solid state features of the young and evolved stars.

In addition to the data listed in Table 1, raw data of the pointed observations except for special observing modes are distributed from the ISAS data archive, DARTS[1] so that users can reduce the data with the provided toolkits. Interested users are welcome to visit the *AKARI* user support web page. [2]

Following the termination of the satellite operation, the *AKARI* project team was reconfigured in April 2013. The new team is dedicated to the data processing and archiving. The activity will continue in the next five years; the first three years for the data processing and construction of “science-ready” datasets, and the following two years for completion of data archiving and maintenance of the products. Table 2 describes the products we plan to provide. The products are prioritized by their potential impact to the researches and technical difficulties. See also Makiuti et al. and Kondo et al. (in this volume).

3. SCIENCE HIGHLIGHTS

In this section we introduce selected science highlights from the *AKARI* observations. They are only a part of the many important *AKARI* results. We draw your attention to the articles by Kaneda et al., Yano et al., Shirahata et al., Pollo et al., Małek et al., and Murata et al. in this volume.

3.1. Cosmic Star Formation History

Goto et al. (2010, see also Goto et al., this volume) measured infrared luminosity of the galaxies with the *AKARRI* All-Sky Catalogues and the North Ecliptic Pole (NEP) survey catalogue, and presented the star formation history from $z = 0$ to 2.2. Thanks to the continuous wavelength coverage the accuracy of the luminosity estimate is much better than the previous works. They found that star formation rate increases toward the past, and that the contribution of (Ultra) Luminous Infrared Galaxies (LIRGs and ULIRGs) increases more prominently.

[1] http://darts.isas.jaxa.jp/ir/akari/
[2] http://www.ir.isas.jaxa.jp/AKARI/Observation/

Table 2. Planned *AKARI* Processed Data Products

Product name	Description	Priority	Public Release
FIS Bright Source Catalogue Ver.2	Revision of the FIS BSC. Accuracy and reliability will be improved. Single-scan photometric database and scan density data will also be available.	1	Mar. 2015
FIS Faint Source Catalogue Ver.1	The catalogue improves detection limit in the high-visibility regions.	1	June 2015
FIS All-SKy image maps	All-Sky image maps in the four FIS bands (65, 90, 140, 160 μm)	2	Mar. 2016
IRC Faint Source Catalogue	The catalogue improves detection limit in the high-visibility regions.	1	Mar. 2016
IRC All-SKy Image Maps	All-Sky image maps in the two IRC bands (9 & 18 μm)	2	Mar. 2016
Asteroid Catalogue ver.2	Additional 1000 asteroids supplemental to the Ver.1 are expected.	5	Mar. 2016
FIS Slow-scan Atlas	Processed image data of individual FIS Slow-scan mapping observations.	4	Mar. 2016
FIS FTS data	Processed imaging-spectroscopic data-set observed with the Fourier Transform Spectrometer (FTS) of the FIS.	5	Sep. 2015
IRC Pointed Observation Images	Processed imaging (photometric) observation data of the IRC. Individual observation data will be processed separately. No mosaicing will be applied.	4	Mar. 2016
FIS Slow-scan Atlas	Processed image data of individual FIS Slow-scan mapping observations.	4	Sep. 2015
IRC Slit spectroscopy Data	Spectra taken with the IRC spectroscopic mode with slit (and point source aperture mask).	4	Mar. 2016
IRC Slitless spectroscopy Data	Spectra taken with the IRC spectroscopic mode on the imaging field with the objective grism/prism.	5	Mar. 2016

3.2. **Cosmic Infrared Background**

Matsumoto et al. (2011) analysed the near-IR imaging data of *AKARI*'s most frequently observed area (in the NEP survey region). They added-up the available data to produce the best sensitivity and quality image, then remove the all known point sources and smoothed the remaining "background" light. The images at 2, 3, and 4 μm data show similar structures, which the authors argued the light from the first generation stars. Matsuura et al. (2011) measured the absolute sky brightness at the far-IR wavelengths, and found that the background radiation at these wavelengths is twice as bright as the theoretically predicted values. The source of this excess is not yet known, but they argue possibilities such as radiation from black-holes in the early universe. Future follow-up observations with *SPICA* will tell us hints to further understanding of this problem.

3.3. **Dust Shell around Evolved Stars**

Izumiura et al. (2011) reported the results of far-IR mapping of dust shell around an red-giant star U Hydrae. Model analysis indicated that the star experienced a short-period, extreme mass loss (ejected dust mass was of the order of 10^{-5} $M_{\odot}$) in the past. Ueta et al. (2008) detected a bow-shock around Betelgeuse (α Ori), which was formed by interaction between stellar mass-loss wind and interstellar matter. The stream of the interstellar matter was measured from the analysis of the bow-shock shape, which was a new tool to investigate how the matter ejected from stars mix in the interstellar media. More than 100 stars were observed in the same programme and wait for detailed analysis (Tomasino et al., this volume).

3.4. **Debris Disks**

High sensitivity *AKARI* All-Sky catalogues enable us to search for stars with debris disks. Fujiwara et al. (2013) surveyed stars with infrared excess at *AKARI* 18 μm band using the IRC Point Source Catalogue and found 24 such stars in which 8 are newly detected by *AKARI*. These mid-IR excess stars have warm dust located in a terrestrial planet region, i.e., they may have information of terrestrial planet formation. Fujiwara et al. (2012a,b) found that HD 15407A posses extremely large amount of μm-size silica dust, which requires unidentified mechanism of dust trapping or continuous dust production. See also Fujiwara et al. and Onaka et al. (this volume).

3.5. **Brown Dwarfs**

One of the *AKARI*'s unique capability is the high-sensitivity spectroscopy in the near-IR region (2–5 μm). For the first time we could take spectra of brown dwarfs continuously covering 2.5–5 μm where ro-vibrational transitions of major molecules such as CO, H_2O, CH_4, and CO_2 present. Series of papers (Yamamura et al. 2010; Tsuji et al. 2011; Sorahana & Yamamura 2012; Sorahana et al. 2013) reported that; (1) detection of CO_2 and possible variation of C & O abundance in the brown dwarfs, (2) CO abundance enhancement in the coolest dwarfs, and (3) variation of radius along the brown dwarf evolution. See also Sorahana (this volume).

4. **SUMMARY**

AKARI has completed the 2nd generation All-Sky Survey in mid- and far-IR wavelength and produced the All-Sky Point Source Catalogues containing in total 1.3 million sources. The most of the sources in the catalogue have not ever been investigated in detail, and can possibly be critical objects that will open a new door of the astronomical research. Image maps and pointed observation data are also waiting for follow-up by the future facilities, such as *SPICA*. In addition, our experiences in the instruments and spacecraft development as well as operation through the *AKARI* mission will be a valuable treasure for making the *SPICA* project as successful as possible.

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