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A PANORAMIC VIEW OF THE ASTEROIDS IN THE INNER SOLAR SYSTEM WITH AKARI

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ABSTRACT

We constructed an unbiased asteroid catalog from the mid-infrared part of the All-Sky Survey with the Infrared Camera (IRC) on board AKARI. About 20% of the point source events recorded in the IRC All-Sky Survey observations were not used for the IRC Point Source Catalog in its production process because of a lack of multiple detection by position. Asteroids, which are moving objects on the celestial sphere, are included in these "residual events". We identified asteroids out of the residual events by matching them with the positions of known asteroids. For the identified asteroids, we calculated the size and albedo based on the Standard Thermal Model. Finally we had a new brand of asteroid catalog, which contains 5,120 objects, about twice as many as the IRAS asteroid catalog.

Key words: infrared; solar system: minor planets, asteroids: space vehicles; catalogs: surveys

1. INTRODUCTION

1.1. *Solar System Studies with AKARI*

Our solar system consists of eight planets, five dwarf planets, and enormous numbers of small bodies such as asteroids, comets, and interplanetary dust particles. Small bodies in the solar system are important targets to study primordial conditions, since they are thought to be remnants of the planetesimals, and contain a primitive record of the initial conditions of the solar system nebula about 4.6 Gyr ago. However, little is known about their properties, like the spatial distribution, the compositional gradient, and the variety of physical conditions. As part of the AKARI mission program entitled *"Origin and Evolution of Solar System Objects (SOSOS)"*, we aim to investigate the nature of these small bodies, which are essential to study the formation and evolution of the solar system. The AKARI All-Sky Survey has enabled us to establish a fine-scale brightness map of the zodiacal emission, and to construct the asteroid catalog on size and albedo. Moreover, AKARI's unique capabilities of spectroscopic observations, which cover a wavelength regime not available to ground-based observations, have revealed spectral features of ices and silicate materials on dozens of comets and asteroids. Three topics about small bodies in the solar system are reviewed in this volume: the zodiacal dust cloud mapping (Pyo et al., 2012), the comet spectroscopic survey (Ootsubo et al., 2012), and the asteroid survey (this paper).

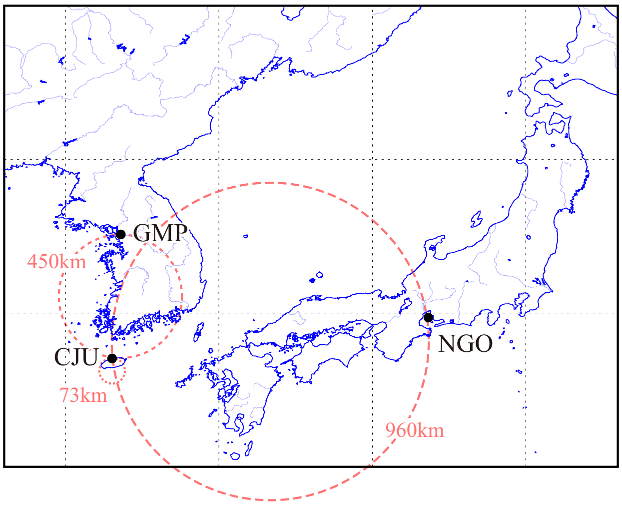

Fig. 1. Map of Korea and Japan. The black dots denote the positions of the international airports: Jeju in Korea (CJU), Gimpo in Seoul, Korea (GMP), and Chubu Centrair in Nagoya, Japan (NGO). Coastline data is taken from National Oceanic and Atmospheric Administration, National Geophysical Data Center(http://www.ngdc.noaa.gov/mgg/coast/). Asteroid (1) Ceres has the same scale as the distance between NGO – CJU, (2) Vesta's size is comparable with the distance between GMP – CJU, and (253) Mathilde is comparable to Jeju island.

1.2. *Asteroids*

Asteroids are one type of the small bodies in the inner solar system, which are orbiting mainly inside the orbit of Jupiter, and are usually composed of rocky or metallic materials. The physical properties of asteroids are fundamental to understand the formation process of our solar system. In the present solar system, asteroids are thought to be the primary remnants of the original building blocks that formed planets. They contain records of the initial conditions of our solar nebula of 4.6 Gyr ago. The composition and size distribution of asteroids in the asteroid belt provide significant information on their evolution history, although they have experienced mutual collisions, mass depletion, mixing, and thermal differentiation, that have shaped their present-day physical and orbital properties.

The size and albedo are the most basic physical quantities of asteroids. In some cases, by combining the size and the mass, which are precisely measured using modern techniques (Hilton, 2002), the bulk density of the asteroid can be estimated (Britt et al., 2002). It is a powerful indicator to investigate the macroscopic porosity and the inner structure of an asteroid. The total mass and the size distribution of asteroids are crucial to understanding the history of the solar system (Bottke et al., 2005). The mineralogy and elemental composition of asteroids can also be estimated from the albedo (Burbine, 2008).

1.3. *Scale of Asteroids*

To compare and realize the scale of asteroids in the inner part of the solar system, the map of Korea and Japan is shown in Figure 1 (1) Ceres (970 km), the largest asteroid, which is currently classified a "dwarf planet", is the same scale as the distance between Nagoya and Jeju. (2) Vesta (520 km), the second largest one, is the same as between Gimpo and Jeju. (253) Mathilde (66×48×46 km), which was explored by the spacecraft NEAR Shoemaker (Cheng et al. 1997) in 1997, is almost of the same size as Jeju island. One of the smallest asteroids ever explored is (25,143) Itokawa (0.535×0.294×0.209 km) (Fujiwara et al., 2006), which has almost the same size as a city block around the conference place in Jeju island. The asteroids cover a wide range of sizes: from a few meters up to almost a 1,000 km.

1.4. *Asteroid Surveys*

Several imaging techniques have been developed to determine the shapes of asteroids. The most straightforward and definitive approach to shape determination is by direct imaging of an asteroid, for example, by use of the Hubble Space Telescope (Thomas et al., 1997) or large ground-based telescopes with adaptive optics systems (Drummond et al., 1998). Radar observations (Ostro et al., 2002) and speckle interferometry (Drummond et al., 1985a, 1985b), as well as stellar occultation combined with lightcurve inversion techniques (Ďurech et al., 2011; Carry et al., 2012) are also very useful for resolving the shapes of asteroids; the latter is a powerful approach, which relies upon well-organized campaign observations by many participants including amateur astronomers. Although these methods are readily available, they require the convergence of critical conditions, such as the selection of large targets with trajectories approaching the Earth, and/or narrow observational windows combined with multi-epoch and multi-aspect angle datasets. The sheer number of asteroids poses yet another difficulty; as of 2012, the number of known asteroids is larger than 587,000 (see, e.g., Minor Planet Center[1] at the Smithsonian Astrophysical Observatory), a number which precludes detailed observations of all individual bodies.

One of the most effective indirect methods for measuring the sizes and albedos of asteroids is by radiometric techniques, in which a combination of the thermal infrared flux and the reflected optical flux provide unique solutions for size and albedo. The radiometric technique for determining the sizes and albedos of asteroids was developed in the early 1970s using ground-based observatories (Allen, 1970, 1971; Matson, 1971), and the approach has yielded a wealth of information both on individual objects and entire populations of asteroids (Harris & Lagerros, 2002; Dotto et al., 2002). Using radiometric measurements, a large number of objects can be observed in a short period of time, thus providing uniform data for large populations of asteroids. Although radiometry requires careful calibration, once calibrated, this method can obtain "wholesale" highly accurate measurements of the physical properties of large number of asteroids.

Infrared observations using ground-based observatories, especially in the mid-infrared range, are severely limited by moisture in the telluric atmosphere; however, infrared measurements obtained using space-borne telescopes are very reliable. Furthermore, when integrated into an all-sky survey, large number of infrared images can be obtained rapidly; moreover, the data are unbiased and uniform. The first systematic survey of asteroids using a space telescope was made by the Infrared Astronomical Satellite (IRAS; Neugebauer et al., 1984) launched in 1983. IRAS observed more than 96% of the sky in 4 bands at the mid- and far-infrared during a 10-month mission life. It derived the size and albedo of 2,470 asteroids (Tedesco et al., 2002a). Another serendipitous survey was carried out by the Midcourse Space Experiment (MSX; Mill et al., 1994) launched in 1996. It observed $\sim$ 10% of the sky in 6 bands and 168 asteroids were identified, for which the size and albedo were provided (Tedesco et al., 2002b). Also, the Infrared Space Observatory (ISO; Kessler et al., 1996) launched in 1995 made yet-another part-of-sky survey, and observed several planets, satellites, comets, and asteroids at infrared wavelengths (Müller et al., 2002; Müller et al., 2005). Despite these extensive past surveys, the asteroids with determined size and albedo were still only 0.5% of those with known orbital elements.

1.5. AKARI All-Sky Survey

AKARI, the first Japanese space mission dedicated to infrared astronomy (Murakami et al., 2007), carried out the second generation infrared all-sky survey after IRAS. The All-Sky Survey is one of the main objectives of the AKARI mission in addition to pointed observations. It surveyed the whole sky in 6 bands at the mid- to far-infrared spectral range with a solar elongation of $90^\circ \pm 1^\circ$ so as to avoid radiation from the Sun. The All-Sky Survey continued until the liquid helium was exhausted on 2007 August 26. In total, more than 96% of the sky had been observed more than twice during the cryogenic phase.

The mid-infrared part of the All-Sky Survey was conducted in two broad bands named *S9W* (6.7 – 11.6 μm) and *L18W* (13.9 – 25.6 μm) using the on-board Infrared Camera (IRC; Onaka et al., 2007), while the far-infrared part was done in four bands from 50 to 180 μm using the Far-Infrared Surveyor (FIS; Kawada et al., 2007). The IRC All-Sky Survey has advantage over the IRAS survey in the sensitivity and spatial resolution, both of which have been improved by an order of magnitude, as shown in Figure 2. Also as seen in Figure 2, asteroids inside the orbit of Jupiter are bright at the mid-infrared due to their thermal emission. These spectral features allow us to detect asteroids with the IRC All-Sky Survey.

2. CONSTRUCTING THE ASTEROID CATALOG BASED ON AKARI ALL-SKY SURVEY

Point-source detection events, 6 million sources in total, were extracted and processed in the IRC All-Sky Survey observation data, from which the IRC Point Source Catalog (IRC-PSC: Ishihara et al., 2010) was produced after checking the position of sources with multiple detections. About 20% of the extracted events in the All-Sky Survey data were not used for the IRC-PSC, because of a lack of confirmation detections. Since solar system objects have their orbital motions, detection cannot be confirmed in principle by the same positions on the celestial sphere, that is why they are not included in the IRC-PSC. Moreover, *S9W* and *L18W* observed different sky regions, $\sim 25'$ apart in the cross-scan direction from each other, because of the config-

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[1] http://www.minorplanetcenter.net.

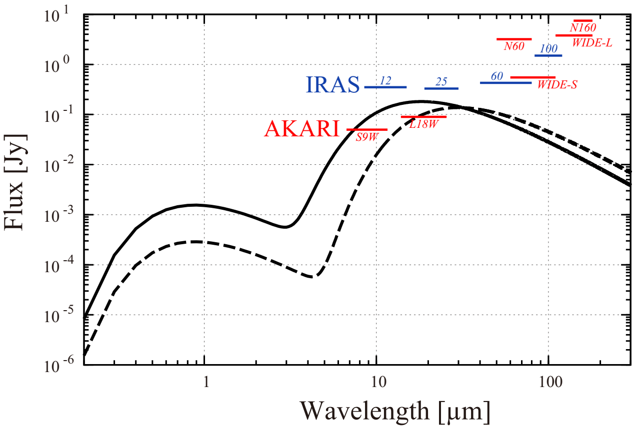

Fig. 2. Model spectra of asteroids including the reflected sunlight and the thermal emission are shown. The solid line indicates the model flux of an asteroid (representative for a small inner main-belt object) with d = 5 km, p_{v} = 0.3, and R_{h} = 1.56 AU, where d, p_{v}, and R_{h} are the diameter of the object, its geometric albedo, and the heliocentric distance, respectively. The Standard Thermal Model (Lebofsky et al., 1986) is used for the calculation. The dashed line indicates another model flux with d = 33 km, $p_{\mathrm{v}} = 0.08$, and $R_{\mathrm{h}} = 4.6$ AU, representative for a small Trojan asteroid. Each of the two asteroids represents a lower limit in the size at the corresponding distance in the AKARI survey. The horizontal bars indicate the detection limits of IRAS and AKARI.

uration on the focal plane (see, Onaka et al., 2007), and an object was not observed with both bands in the same scan orbit. Therefore, for detecting asteroids, a single event of a point source needs to be examined without stacking the maps taken at the same sky position, but at a different time. We identified asteroids out of the excluded events from the IRC-PSC. In this process, we searched for events whose positions agree with those of asteroids with known orbits. The asteroid positions were calculated by numerical integration of the orbit based on the orbital elements distributed at Lowell Observatory[2]. We have not made any attempt to discover new asteroids in this project, whose orbital elements are not archived in the orbital database. For each identified object, we calculated the size and albedo using the Standard Thermal Model of asteroids (Lebofsky et al., 1986), in which an asteroid is modelled as a spherical, non-rotating body with zero thermal inertia. The technique was calibrated against 50 large main-belt asteroids where size and albedo are known from other sources. Finally, we obtained an unbiased, homogeneous asteroid catalog (Usui et al., 2011) named the "Asteroid Catalog Using AKARI (AcuA)", which contains 5,120 objects in total (5,079 numbered and 41 unnumbered asteroids), twice as many as the IRAS asteroid catalog.

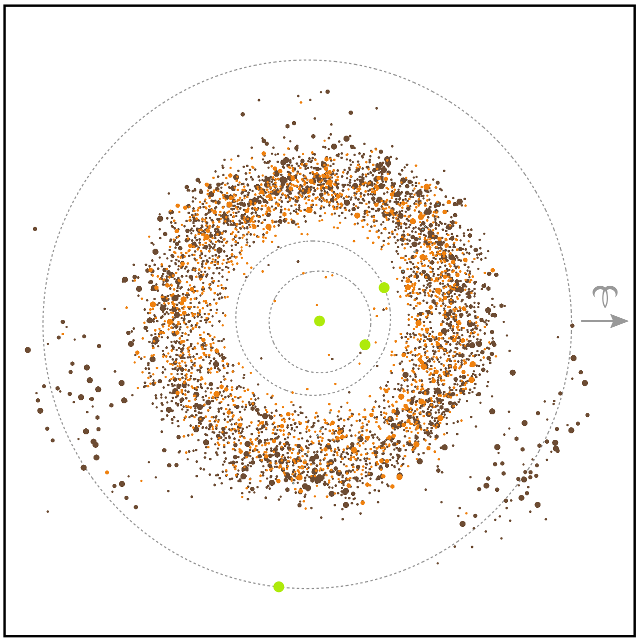

Fig. 3. Distribution of the identified asteroids in AcuA projected on the plane of the ecliptic as of 2007 August 27. The size and albedo of asteroids are distinguished by different sizes and colors of dots (orange: $p_{\mathrm{v}} > 0.1$; brown: $p_{\mathrm{v}} \leq 0.1$). The circles indicate the orbits of the Earth, Mars, and Jupiter from inside to outside. The arrow shows the direction of the vernal equinox.

3. AKARI ASTEROID CATALOG: AcuA

3.1. *Total Number and Spatial Distribution*

The number of asteroids identified in the AKARI All-Sky Survey is 2,507 in *S9W* and 5,010 in *L18W*. The total number of asteroids detected in *S9W* and *L18W* is 5,120. The number of the asteroids detected in *L18W* is larger than that in *S9W* by about a factor of 2. On the other hand, the number of the point sources detected in *S9W* in the IRC-PSC is approximately four-times as many as that in *L18W* (Ishihara et al., 2010). The opposite trend can be explained by the different spectral energy distribution of the objects; asteroids have typical effective temperatures of around 200 K and ra-

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[2] ftp://ftp.lowell.edu/pub/elgb/astorb.html.

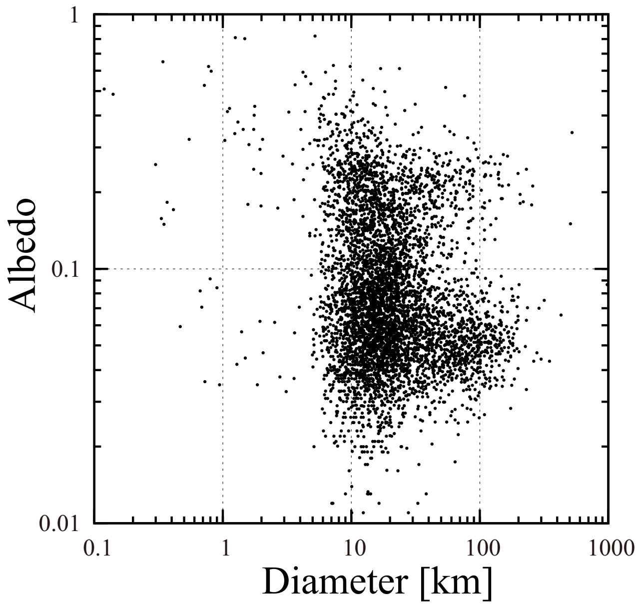

Fig. 4. Distribution of the size (diameter) and albedo of all the 5,120 asteroids in AcuA.

diate thermal emission with a peak wavelength of ∼15 μm, which can be preferentially detected in *L18W*, even when the difference in the sensitivity (in Figure 2 is taken into account. Stellar sources emit radiation with the peak wavelength at UV to optical, and are thus detected with a higher probability in *S9W*. A significant fraction of asteroids, particularly in the main-belt rather than the near-Earth, are detected only in *L18W*, but undetected in *S9W* because of the steep decrease in the thermal radiation in Wien's domain.

Figure 3 shows the distribution of the identified asteroids projected on the ecliptic (i.e., the face-on view) as of 2007 August 27. It shows the distribution of asteroids without any bias or survey gap. The catalog comprises 4,953 main belt asteroids, 58 near-Earth asteroids, and 109 Jovian Trojan asteroids, while objects beyond Jupiter's orbit, i.e., Centaurs and trans-Neptunian objects, were not detected in our survey. Several comets are also detected with the AKARI All-Sky Survey, but not included in this catalog.

3.2. Size and Albedo Distribution

Figure 4 shows the distribution of albedo as a function of the diameter for asteroids in AcuA. An outstanding feature is the bimodal distribution in the albedo. In the catalog, the smallest asteroid is the near-Earth asteroid 2006 LD1, whose size is $d = 0.12 \pm 0.01$ km. The largest one is naturally (1) Ceres of $d = 970 \pm 13$ km.

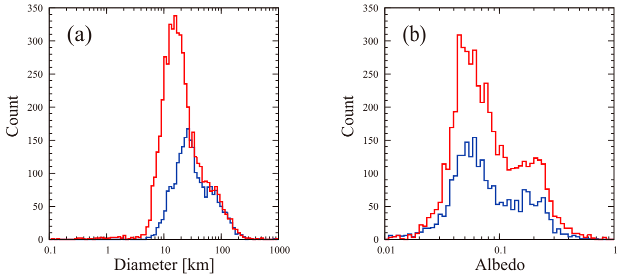

Fig. 5. Histograms of (a) the size (diameter) and (b) the albedo in AcuA. The red and blue lines indicate the results from AKARI (Usui et al., 2011) and IRAS (Tedesco et al., 2002a), respectively. The bin size is set at 90 segments for the range of 0.1 km to 1,000 km in the logarithmic scale for (a) and 60 segments for the range of 0.01 to 1.0 in the logarithmic scale for (b).

Figures 5 illustrates histograms of the asteroids in AcuA as a function of (a) the size or (b) the albedo. For comparison, the results of IRAS observations are also plotted. The IRAS catalog consists of 2,228 objects with multiple detections and 242 objects with single detection (in the 12 μm band). It clearly indicates that the AKARI All-Sky Survey is more sensitive to small asteroids than IRAS. Concerning the size distribution of asteroids, the number is supposed to increase monotonically with the decrease of the size. Figure 5 (a), however, shows maxima at $d = 15$ km for AKARI and 24 km for IRAS. The profiles of the histogram are similar to each other for those larger than 30 km, suggesting that IRAS and AKARI exhaustively detect asteroids of size $d > 24$ km and $d > 15$ km, respectively, but that the completeness rapidly drops for asteroids smaller than these values. In particular, AKARI provides a 100% complete data set of all asteroids brighter than an absolute magnitude of $H < 9$; $H < 10.3$ for the main belt asteroids and $H < 9.35$ for the Jovian Trojans, which corresponds to $d > 20$ km and $d > 70$ km, respectively. It is important to include the entire population of asteroids for investigating the mass distribution of asteroids, that is, asteroids with $H < 9$ account for more than 90% of the total mass of all asteroids. Figure 5 (b) clearly shows that the albedo of the asteroids has the well-known bimodal distribution (e.g., Chapman et al., 1975). The bimodal distribution can be attributed to two groups of taxonomic types of asteroids. The primary peak at around the geometric albedo of $p_{\rm v} = 0.06$ is associated with mainly C-type asteroids (dominating the outer part of the asteroid belt beyond 2.7 AU), and the secondary peak at around $p_{\rm v} = 0.2$ with mainly S-type objects (dominant in the inner asteroid belt within 2.2 AU).

4. CONCLUDING REMARKS

We have created an unbiased, homogeneous asteroid catalog named AcuA, down to a diameter of $\sim$ 20 km in the main belt, which contains a total of 5,120 objects based on the AKARI/IRC Mid-infrared All-Sky Survey data. This is the second generation of asteroid surveys after the IRAS observation. The present catalog revises the properties of several asteroids. The catalog data is open to the public via the Internet[3].

Recently, the Wide-field Infrared Survey Explorer (WISE; Wright et al., 2010) also completed an all-sky survey in the near- and mid-infrared 4 bands. The WISE asteroid database is only a preliminary version at present (Mainzer et al., 2011; Masiero et al., 2011; Grav et al., 2011, 2012) and further processing is currently underway before the final public version will be available. It will include more than 130,000 asteroids, which corresponds to over 20% of asteroids with known orbits. While WISE data overwhelms AcuA by number of detected asteroids, they remain $\sim$ 1,000 asteroids undetected which were detected with AKARI. This is due to the 8 month lifetime of the cryogenic tank on board WISE, which is shorter than the one year orbital period of the Earth. Additionally, WISE suffered from the saturation problem for the brightest asteroids (e.g., (1) Ceres and (4) Vesta), for which size and albedo could not be derived properly. In this sense, AcuA and WISE data complement each other.

These asteroid catalogs will be significant for various fields of the solar system science, and contribute to future Rendezvous and/or sample return missions of small objects.

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