Review

A half century of infrared astronomy — A personal recollection of the footprints in Japan

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Abstract: Since the new era of infrared astronomy was opened by the Two Micron Sky Survey by Neugebauer et al. in the early 1960s, about a half century has passed. During this time, observations have expanded rapidly and widely, to almost every field of astronomy, to reveal new perspectives on the universe. As a result, infrared astronomy has become one of the major branches of astronomy, along with optical, radio, X-ray as well as high-energy particle astronomy. In Japan, we started our infrared astronomical activities at a rather early time, under relatively poor technical and environmental conditions, and using somewhat unconventional methods to overcome these difficulties. Here, a brief survey is presented of developments concerning infrared astronomy during the past half century, while mainly recollecting our footprints in the stream of world activities.

Keywords: infrared astronomy, history, Japan, space and ground-based

1. Birth of infrared astronomy

In 1800, Sir William Herschel reported that some component sensitive to a thermometer was present in sunlight, extending beyond the red edge of the spectrum, by splitting the sunlight with a prism.1)–3) Although there had been several relevant studies that showed similar facts, indicating the existence of radiation sensitive as heat, called ‘radiant heat’,4) Herschel’s work was very systematic and comprehensive and hence might be called a discovery. In fact, this was the first astronomical observation in the infrared region.

However, because the sensitivity of the thermometers was so low, it was hardly applied to observations concerning other celestial objects for a long time afterward. Even after a thermocouple was invented by T.J. Seebeck,5) and a bolometer by S. Langley,6) observations had been limited to bright sources, such as our Moon, other planets, and some bright stars as well as the Sun. In the early 1900s, William W. Coblenz attempted to measure stellar fluxes,9) but most of the early work was attempted mainly by people in the U.S.A.; Gerald P. Kuiper was the first person who noticed the potential of this new detector, and used it to observe the infrared spectra of the bright planets.10) Note: Infrared radiation is generally defined as electromagnetic radiation at wavelengths of between 0.8 µm and 1000 µm and is subdivided into near (0.8–5 µm), mid (5–30 µm) and far (30–1000 µm) infrared. This division is rather arbitrary, and ‘far infrared’ near 1 mm is often called ‘submillimeter radiation’.

2. New start

2.1. Ground-based observation. During W.W.II, a new type of detector, the so-called PbS (lead sulfide) detector, was developed in Germany for military purposes. It was a photoconductor with far more sensitivity than that of thermocouples and was first used as ‘a viewer in the dark’. As the War ended, scientists having been engaged in military research returned to their usual work and some scientists paid attention to astronomical applications. Peter Felgett in Britain was one of the first to apply this detector for measuring stellar fluxes,9) but most of the early work was attempted mainly by people in the U.S.A.; Gerald P. Kuiper was the first person who noticed the potential of this new detector, and used it to observe the infrared spectra of the bright planets.10) Harold Johnson used it to extend his UBVR (visible) photometry system to JKL bands in the near-infrared.11) In the early 1960s, Frank Low, originally...
a solid-state physicist, invented a liquid helium-cooled Ge bolometer while working at Texas Instruments Inc. They built a bolometer, having a sensitivity of many orders of magnitude higher than the previous ones, opened up observations in the mid and far-infrared regions.

In the Soviet Union, V.I. Moroz had made pioneering studies, already in the early 1960s: some spectral observations of the Moon and the big planets as well as the Crab Nebula in the near-infrared region with a PbS detector. 

Upon the advent of sensitive detectors, astronomical observations were attempted by several groups mainly in the U.S.A. Gerry Neugebauer and Robert Leighton at Caltech conducted an unbiased sky survey at 2.2 microns, while constructing a special telescope, with an ingenious technique of making an inexpensive parabola mirror with epoxy resin based on the principle that a spinning liquid surface forms a paraboloid. The survey was made at the Mount Wilson Observatory from 1965 to 1968. Against predictions by astronomers in general, that the survey would provide fewer than 100 new sources, they found a number of unknown sources with extremely red colors, such as NML Cyg and NML Tau.

They detected more than 20000 sources which were published as the Two Micron Sky Survey (TMSS) catalog with about 5000 sources brighter than K = 3 mag. The catalog has been used as a standard database for later work. Frank Low with Harold Johnson at Univ. of Arizona extended his observations to increasing wavelengths of mid-infrared, the N band at 10.2 microns, and the Q band at 21 microns, while observing the quasar 3C 273.

As described above, once sensitive sensors had become available and infrared observations had been shown to be useful and powerful for exploring new fields of astronomy, these activities spread quickly and widely in the world. Due to technical familiarity, they were generally undertaken by physicists. The Univ. of Minnesota and UCSD group led by Ed Ney made ground-based observations with the dedicated telescope (O’Brien Observatory) and Mt. Lemmon Observing Facility, and discovered silicate features in circumstellar dust.

Such observations were expanded rapidly to a variety of Galactic and extragalactic objects. An ice band feature at 3 microns was found in the BN object, hydrogen recombination lines in the near-infrared range (Brackett, Paschen and Pfund series) were observed in late-type stars, and the fine-structure line of ionized Ne+ (12.8 microns) was observed in planetary nebulae and the Galactic center. This line was used to disclose the kinematics of the Galactic center region, and the kinematics later led to the suggestion of a massive BH (black hole) in the Galactic Center. The hydrogen molecule which is inert in the optical range was directly detected by its vibration/rotation lines in the near-infrared by Gautier et al., while the distribution of hydrogen molecules had been studied indirectly only through the radio CO emission so far. As spectroscopic observations provide more physical information (composition, density, temperature, motion etc.) of objects, major activities shifted to spectroscopic observations.

2.2. Balloon and rocket experiments. The biggest nuisance and annoying problem for infrared observations is the presence of the atmosphere, a strong absorber and emitter of infrared radiation. Ground-based observations are severely limited only in several wavelength windows in the near- and mid-infrared regions, due to the absorption by such molecules as CO2, CH4, and H2O. In particular, the far-infrared region is completely blocked by the absorption of H2O vapor.

Not only absorption, but also the emission of the atmosphere is serious, since both peaks at the far-infrared regions. The latter is extraordinary strong, by many orders of magnitude compared to the emission of astronomical origin. Since the responsible emitters are concentrated in the lower layer of the atmosphere, the condition is rapidly improved as one goes up to higher altitudes, of a high mountain, an airplane, or a balloon, but going out to space by using a rocket or satellite is ideal to be completely free from such effects.

Despite technical difficulties, it is remarkable that space observations were started almost simultaneously with ground-based observations.

In the mid-1960’s, Frank Low built an airborne telescope having a 30 cm aperture, onboard a Lear Jet of NASA Ames, which opened up observations in the mid- and far-infrared regions. He and his colleagues made the first observation of the Galactic Center in the far-infrared region and extended it to extragalactic sources. The telescope was later used by Harwit’s group of Cornell Univ., which led to the discovery of such far-infrared fine-structure lines as O+ (51.8 µm, 88.4 µm), O (63.2 µm, 145.5 µm), and C+ (157.7 µm). NASA provided a more advanced airborne telescope, having a 90 cm aperture, named KAO (Kuiper Airborne Observatory), which was used for a
variety of observations (photometric, imaging, spectroscopic and polarimetric), and worked as a very active and productive facility for mid- and far-infrared observations for 20 years during 1974–1995.

If we go up to balloon altitudes as high as 30–40 km, the atmospheric absorption is almost negligible at all infrared wavelengths. W.F. Hoffmann, NASA New York undertook far-infrared observations with a simple balloon-borne telescope with a 1-inch quartz lens bathed in liquid helium, and succeeded to detect a very strong emission in the Galactic Center region, diffusely distributed in several degrees.\(^3\) The observed emission was too strong to be easily believed, but it was definitely confirmed by a galactic-plane survey later done by Hoffmann et al. using a 30 cm balloon telescope with finer resolution and higher detectivity.\(^2\) A more detailed far-infrared red map of the Galactic Center was made by Giovanni Fazio, SAO (Smithsonian Astrophysical Observatory), using a 102 cm balloon telescope.\(^3\) To check the blackbody spectrum of the cosmic-background radiation in the submillimeter range, balloon experiments were undertaken by Muehlner and Weiss\(^2\) and by Woody and Richards.\(^3\) In Europe, Furniss et al. in Britain, undertook a far-infrared survey by balloon.\(^4\) French group made a galactic-plane survey to map 3.3-µm PAH emission.\(^5\) A Dutch group at Groningen Univ. and a German group at MPE also made balloon observations in the far-infrared region.\(^6\),\(^7\)

Even at balloon altitudes, thermal emission of the atmosphere with a temperature of about 200 K, peaking at the mid-infrared range, is still extremely strong, many orders of magnitudes higher than the emission of astronomical origin. This should fatally limit the detector’s sensitivities due to statistical noise produced by impinging background photons onto the detectors, which is the so-called photon noise limit. This obstacle is completely removed if we make observations in space by using rockets or satellites. Martin Harwit at Cornell Univ. was intrigued by its potentialities, abilities and advantages of infrared observations to exploit new fields of astronomy, a summary of which was reviewed in the book and papers of “Infrared Astronomy by J.E. Beckman and A.F.M. Moorwood”,\(^8\) “History of British Infrared Astronomy since the Second World War by R.E. Jennings”,\(^9\) “The Beginning of Modern Infrared Astronomy by Frank Low et al.”,\(^10\) and “Early Infrared Astronomy by James Lequeux”.\(^4\)

3. Footprints in Japan

3.1. Initiation in Japan. Based on a suggestion of Prof. Satio Hayakawa, a theoretical physicist, of Nagoya Univ., who inspired modern astrophysical activities in Japan, such as cosmic ray, X-ray, as well as gravitational wave astronomy, several volunteers in the Department of Physics (Matsumoto, T., Sugimoto, D. and Okuda, H.) started preliminary studies of infrared observations in the mid 1960s. First, they investigated and argued about the possibilities, abilities and advantages of infrared observations to exploit new fields of astronomy, a summary of which was reviewed in the 天文月報 (Tenmon Geppo; Astronomical Herald Japan),\(^11\) which is briefly summarized as follows:

Following Wien’s law, infrared emission ranging from 1 and 1000 microns corresponds to the blackbody temperatures of between 3000 K and 3 K. This means that infrared observations would be useful for studies of low-temperature objects such as late-type stars, the early stage of star formation; i.e., the contraction of low-temperature gases and dust particles, as well as planetary objects.

The energy range of infrared radiation is situated between 0.3 and 0.003 eV, which corresponds to the energy levels of recombination lines emitted between high quantum levels, Brackett,
Paschen, Pfund series of hydrogen atom or fine-structure lines of heavy atoms (*e.g.* Ne*, S, O, O*++, C*, N* etc.) as well as molecular lines (hydrogen molecule vibration and rotation transitions, water vapor bands).

The infrared-energy level also corresponds to the energy bands of solid materials. These energy bands are substantially broad and, hence, dust particles act as a major agency in energy transfer in interstellar space. This would indicate that infrared emission would be the strongest energy carrier in interstellar space, and that infrared observations are extremely powerful to probe objects even at cosmological distances. The temperature range where solid materials can exist is lower than a few thousand K. This means that celestial bodies in a solid can only be probed by infrared emission, although they have been so far observed as reflection nebulae or dark nebulae silhouetted against bright background emission.

One of the useful advantages of infrared observations is its high transparency in interstellar space. Usually, light in the optical range is weakened by absorption and scattering (so-called interstellar extinction) of dust particles while propagating through interstellar space. The extinction rate in the galactic plane on the average is about 3 mag (about one order of magnitude) per kpc at visual light. By this effect, distant stars or objects embedded in dense interstellar clouds are completely invisible. The interstellar extinction is substantially reduced as the wavelength increases; the extinction rate at 2 µm is almost one tenth of that of visual light, *i.e.* 0.3 mag per kpc. This means that we can look into dense molecular clouds completely obscured visually, such as protostars embedded in molecular clouds or the Galactic Center situated at a distance of 8 kpc, which corresponds to a reduction of 25 mag (10^-10) at visible and 2.5 mag (10^-1) at 2 µm emission, respectively.

Not as a direct property, but infrared observations are favorable also for cosmological research, since the light emitted at the early universe should have shifted to the infrared region due to a large Doppler effect.

### 3.2. Early days of ground-based observations

Inspired by these expectations, we started preparatory work since 1965, the year when the first report on the NML Cyg and NML Tau, discovered in the Two Micron Sky Survey by a Caltech group appeared in a letter of Astrophysical Journal.15 However, the first and most serious problem was how to obtain a sensitive infrared detector. At that time, only a PbS detector packed in a glass tube used for security guards was available. Due to the severe regulations of military activities, infrared technology in Japan had been poorly advanced, and also, we could not import highly sensitive infrared detectors from the U.S.A.

By making a simple photometer with a PbS detector, we started our observations from the Moon, a unique target bright enough for our instrument. From the phase variation of the infrared brightness, we inferred the characteristics of the regolith of the lunar surface.49 In 1967, the author moved to a cosmic-ray physics group led by Prof. H. Hasegawa in Kyoto Univ., and started up a new group, and continued observations in collaboration with the Nagoya group.

By that time, the activities in the U.S.A. had expanded to a variety of fields and objects, as described in subsection 2.1.

In the meantime, liquid nitrogen-cooled PbS tips became available from Santa Barbara Inc., by which we could have expanded the possibility of advanced observations. However, since our technical level was still low, we considered that it would not be wise to follow similar work made in the U.S.A. Concerning this idea, we started some polarimetric observations by building a simple photopolarimeter with a rotating sheet polarizer (HR polaroid). Polarimetry is a comparative measurement of two light modes, being robust against the unstable sky condition in Japan. It was lucky that we soon succeeded in observing the large and peculiarly behaved polarization in VY CMa, a bright late-type supergiant, at the H and K bands (1.6 and 2.2 µm), which was the first successful work concerning our polarimetric observations.50 The observed polarization showed a peculiar behavior, as reproduced in Fig. 1, which we showed to be explained by the superposition of two kinds of polarization, one peaking in the optical range and the other peaking in the infrared range, each being perpendicularly polarized. If the star is surrounded by a dense dust disk, the star light in the disk plane could be strongly absorbed and only infrared light scattered and polarized perpendicularly to the plane could come out. The optical light that escaped favorably to the direction perpendicular to the disk plane is polarized parallel to the plane. The addition of the two components peaking in the visible range and the infrared range, but each being perpendicularly polarized, makes a dip in the middle of the wavelength at around 1 micron, where the two components cancel out each other. This can explain
the behavior of the observed polarization and would suggest the presence of a disk-like dust layer around the central star.

Encouraged by this success, we chose the Galactic Center source as a next target. However, the emission was so weak, only barely visible in the signal, even using the 188 cm telescope in Okayama Astrophysical Observatory, the largest telescope in Japan at that time. Upon repeating hundreds of measurements, about 5% of the polarization in the K band buried in much noise, was detected. The polarization vector was almost parallel to the Galactic plane. A preliminary result was reported at the Liège conference, while being half in doubt.51) This was because the polarization was parallel to the Galactic plane, similar to that found in the polarization of stars at the optical band.52)

The infrared polarization would presumably be caused by the same mechanism as the interstellar origin, i.e. asymmetrical scattering by needle-like dust particles aligned by a magnetic field. Later, the polarization in the H band was measured and found to be as large as about 10%,53) which is consistently explained by the hypothesis of interstellar origin.

These results suggested that the similar configuration of the magnetic field as observed in the solar neighborhood is extended far to the Galactic Center region. One motivation to make the polarimetric observation was to infer about the emission mechanism of the near-infrared emission in the Galactic Center, discovered by Becklin and Neugebauer,54) i.e. whether it is stellar emission (thermal), polarized by interstellar extinction or synchrotron emission (nonthermal), being controversial at that time. Our observations showed that the former process was responsible.

Dyck et al. measured a polarization of about 3% in the longer wavelength of the N band, dominant in thermal emission, the vectors of which were almost perpendicular to the Galactic plane.55) This can be explained as being asymmetric thermal emission preferentially polarized parallel to the aligned dust particles similarly explained for the far-infrared polarization observed by Hildebrand, R. et al.56) They are consistent with our conclusion.

The observations of infrared polarization in the Galactic Center region are collected in Fig. 2(a), (b), (c).
As shown in these examples, the polarimetric observation can be useful to obtain information about any unresolvable structure in the source or emission process, and/or the same modulation process in the propagation of light.

3.3. Expansion in ground-based observations.

3.3.1. Construction of a dedicated infrared telescope, AIRO. Observations of the early days were made by using the 91 cm and 188 cm telescopes of Okayama Astrophysical Observatory belonging to Univ. of Tokyo, which had been opened to common use for nationwide universities. They were located near to sea level (at an altitude of 370 m), not so suitable for infrared observations, in addition, they were very busy telescopes, and hence only one or two weeks in a year could be assigned to a single group. This was a very severe condition to cultivate a new field by developing observational instruments and testing their performances. Wishing to improve the situation, we applied for Grant-in-Aid funds of Monbusho (MOESS, Ministry of Education, Science and Sport), which was rarely granted at that time. Luckily, and surprisingly, we were given a grant of 17 million yen (50k US$). However, this amount of money was never enough to build an astronomical telescope, probably being too costly by more than ten times, if we were to build it in a conventional way. In order to overcome this difficulty by introducing a new idea, we decided to build a 1 m telescope with a Kanigen (Ni-P alloy)-coated aluminum mirror, in a small machining factory. Through devoted efforts of the boss of the factory, Mr. Sojiro Norizuki, together with the enthusiastic support of the young students of Kyoto Univ. and Nagoya Univ., a 1 m infrared telescope was completed in 1972 on a meadow hill in Kiso Agematsu, Nagano pref., at an altitude of 1200 m. This was named AIRO (Agematsu InfraRed Observatory) of Kyoto Univ. The AIRO telescope is shown in Fig. 3.

Fig. 2. (Color online) Infrared polarization in the Galactic Center. (a) The first detection in the K- (2.2 µm) and H- (1.6 µm) bands, black bold lines. Dotted lines are those at 3.4 and 11 microns, observed by Dyck et al. (b) Polarization of discrete infrared sources. The object marked by Q was later discovered as the Quintuplet. (c) Detailed map of K-band polarization. The background image is a map of CO molecular clouds.
Based on this undertaking, the observational condition has been substantially improved with a reduction of background radiation due to the high altitude, and adopting secondary mirror chopping; in addition to that, much of observational time became available. As a result, we were able to expand the observations on a variety of objects and increased the observing quality.

Particularly, easy accessibility to the observational time allowed us to make observations of spontaneous phenomena, such as novae and comets. Extensive observations of Nova Vulpeculae 1976 (NQ Vul) for over 200 days after its discovery allowed us to trace the dust-formation process in the nova explosion in real time. The observed light curves are shown in Fig. 4.

Using a low-resolution spectrometer with a circular variable interferometric filter, Noguchi et al. made a spectral survey of 22 carbon stars and 23 M-type stars, and found that the 3-micron absorption band was exclusively present in carbon stars but not in M-stars, which was explainable by a C-H bond origin.

The polarimetric observations were inherited and advanced by Sato, Tamura, and Yamashita, who studied the magnetic configuration in many molecular clouds (dark nebulae) and its relationship to the star-formation processes.

Another idea, to escape the high atmospheric background, was to reduce the so-called photon noise by narrowing the spectral bandwidth by which we...
could expect a substantial improvement in the detector sensitivity. Based on this idea, a Fabry-Perot spectrometer in the near-infrared bands was developed by Tanaka et al. With this spectrometer, a map of the Orion KL nebula using the $\text{H}_2$ molecular line at 2.12 microns was drawn, using the 1.5 m telescope built by Hiromoto, N. et al. in the NICCT (National Institute of Information and Communications Technology) for testing communication in space by employing light waves. The map was later refined as a beautiful picture by the SUBARU telescope.

3.3.2. Observations at oversea sites. Although the observational conditions had been somewhat improved by these facilities, we could not be satisfied with them, and longed for observations at overseas sites with excellent conditions.

Around the 1980s, many ground-based telescopes optimized to infrared observations, such as UH88 (2.2 m), NASA-IRTF (3 m) and UKIRT (3.8 m), were built on Mauna Kea in Hawaii with excellent environmental conditions, and were working very actively in the 1980s.

Since 1979, using the “Overseas Scientific Research Program” of Monbusho’s Grant-in-Aid support, and the JSPS’s bilateral collaboration program between Japan and U.K., the Kyoto Univ. group got the opportunity to send young students to the overseas observatories of Mauna Kea, Wyoming in the U.S.A. and Siding Spring in Australia, in order to make extensive observations by using the full advantages of their excellent observational conditions.

Using these opportunities, they made various observations; for example, in the Galactic Center region, a source counts in the galactic plane in near-infrared by using the USAF 60 cm telescope on Mauna Kea, by which it was found that the space density of M-giants showed enhancements in the 5 kpc arm as well as the Galactic Center region similarly as observed in our near-infrared diffuse emission survey by balloon, to be mentioned later.

Kobayashi, Y. et al. made more detailed polarimetric observations of near-infrared sources of discrete and diffused emission in the Galactic Center resolved by Becklin and Neugebauer using the 5 m Palomar telescope. by using a more sophisticated polarimeter incorporated with a half-wavelength plate, developed by Kobayashi, Y. The observed polarizations of every source showed similar behaviors as the diffuse component, and confirmed the previous results made before with a diffused field both in degree and vector of polarization.

Intrigued by the finding that one of these sources, 12' apart from the Sgr A*, was resolved into two identical sources, having identical properties of brightness, polarization, and spectrum, we made further investigations, and finally found that it was composed of five identical objects, which we named “Infrared Quintuplet”. Later, it has been identified to be a cluster of super-massive stars of the Wolf-Rayet type. The Infrared Quintuplet, originally observed and a photo taken by NICMOS are shown in Fig. 5.

Using the 1 m telescope of the Siding Spring Observatory in Australia, Nagata et al. made a multi-color infrared survey in the Galactic Center region, and found another similar source associated with the Radio-Arc source in the neighborhood of the Galactic Center, and named it “Arch cluster”. It has not been well understood yet why such clusters of young and massive stars are concentrated in the central region of the Galactic Center, generally thought to be an old-population region.

It should be recalled, however, that dedicated programs with small-scale facilities also opened new fields of astronomy. The Two Micron All Sky Survey (2MASS) provided the first deep and comprehensive infrared source catalogue, and its advanced program, the Sloan Digital Sky Survey (SDSS), led a revolution in an exploration of the early history of galaxy formation. This should be a good lesson to be recalled by us, to whom no big budget or organization is available.

In Japan, Sato’s group at Nagoya Univ. built a 1.4 m telescope (IRSF) in South Africa in 2000. Due to advantages of good weather and good location of the southern hemisphere, the telescope has been used for a variety of observations as well as for the education and training of young researchers. As a dedicated telescope with plenty of observational time, the IRSF could be used for extensive and systematic survey observations, such as a polarimetric survey in the Galactic Center region, by which the magnetic-field configuration in the region was clarified in detail, which is shown Fig. 2(c). It was also used for extensive point-source surveys in near-infrared region of the Large and Small Magellanic Clouds, including their bridge region. They published their catalogues with more than 14 million sources, providing a standard data set of the stellar system in the Magellanic Clouds. It was also used for the development of a circular polarimeter system by Kwon and Tamura. Matsumaga et al. made long-term monitoring of Cepheid and Mira variables.
in the Galactic Center region. Nishiyama has determined the wavelength dependence of interstellar extinction in the near-infrared bands, and also succeeded to improve the distance scale of the Galactic Center.

In 2017, it was successfully used for follow-up observations of the electromagnetic counterpart of the recently detected gravitational wave source GW 170817, generated by a neutron star merger. From the observed light curve in the J-, H- and K-bands, it was suggested that the r-process nuclear synthesis worked in the explosion process of the source.

From these examples, we have learned that the telescope has worked very powerfully and efficiently when it is put at a good site, and used properly, even if it is small.

Another example of a dedicated facility was the MAGNUM (Multicolor Active Galactic NUclei Monitoring) telescope planed by Y. Yoshii of Univ. of Tokyo. It was a 2 m telescope installed on the Haleakala summit in Maui of Hawaii, which was automatically operated from Japan by the faculty of Univ. of Tokyo. The telescope had been used specifically for measurements of the time lag of the brightness variation at visible and infrared bands, from which the distances to AGN sources were estimated. It represents a new method for measuring extragalactic distances.

3.3.3. Foundation of SUBARU telescope. Because Japan is located in a semi-tropical region with much rain and a humid climate, no good site for infrared observations is available in this country. Thus, it was urgent to have our own facility located at a good site for making advanced observations. In the early 1980s, the Kyoto group started to study the possibility of building a telescope on Mount Haleakala, discussing with Donald Hall, the director of IfA (Institute for Astronomy), Univ. of Hawaii. However, we experienced many obstacles to build a facility in a foreign country, because of the lack of a legal system for putting national property abroad; also the anticipated cost would not be easily acceptable for a single university.

However, owing to the enthusiastic wishes of the astronomical community, an 8.2 m telescope, called “SUBARU”, was finally built on Mauna Kea in Hawaii. This was the first experience not only for the academic society but also for the government, to put a national property of such a big and costly facility in a foreign country as a permanent base. Even an arrangement of a new law was necessary as well as negotiations with the partner countries. These difficulties were solved by enormous efforts of the members of the Tokyo Astronomical Observatory and government agencies. The telescope started being constructed in 1991 and celebrated its first
light in 1999. The detailed story of the telescope construction and the early observations appears in a special issue of the Publication of Astronomical Society of Japan. This is indeed the biggest enterprise the Japanese astronomical society has ever experienced in its history.

Four kinds of instruments were implemented for infrared observations to cover various kinds of observations. They were IRCS (InfraRed Camera and Spectrograph), OHS/CISCO (OH-Airglow Suppressor/Cooled Infrared Spectrograph and Camera for OHS), COMICS (COoled Mid-Infrared Camera and Spectrometer) and CIAO (Coronagraphic Imager with Adaptive Optics) for infrared observations.

For optical observations, three instruments, Supreme-C (Supreme Cam), HDS (High Dispersion Spectrograph) and FOCAS (Faint Object CAmera and Spectrograph) were implemented. An AO (Adaptive Optics) system was also developed in parallel and used effectively for refining the angular resolution as well as improving the detectivity of faint objects. It was an epoch-making event in the history of Japanese astronomy, that we could have a first-class facility both in observational power and in observing condition. The telescope has been used for a variety of observations and has been opening new horizons of astronomy. It has become one of the most active and productive telescopes in the world, such as the Keck telescopes, Gemini telescope on Mauna Kea and the VLTs on Mt. Paranal in Chili.

A picture of SUBARU is shown in Fig. 6.

3.4. Early space observations by balloon and rocket experiments. As reviewed briefly above in subsection 2.2, a variety of attempts were undertaken for developing infrared observations in space. The complete freedom from atmospheric absorption and emission as well as from instrumental emission by cryogenic cooling provides ideal conditions to obtain the ultimate power of detectors free from photon noise and allowing all band observations from near infrared to submillimeter range. The ISAS (Institute of Space and Aeronautical Science) was founded in 1964, which first belonged to Univ. of Tokyo and was later reorganized as a sub-division of the national space agency named ISAS/JAXA (Japan Aerospace Exploration Agency) in 1981. Starting with the development of a small rocket, called ‘pencil rocket’, space experiments were initiated at the time of IGY (International Geophysical Year, 1977–1978), and have been undertaken for geophysical and astrophysical research by using balloons, sounding rockets and satellites.

3.4.1. Balloon observations. Because the ground-based observations are limited by the high humidity of the Japanese climate, and a lack of dedicated telescopes, we were interested in making space observations freed from these handicaps. However, it was not easy to design the experiments in those early days, under the constraints of a small launching power and a coarse attitude control system; moreover, the recovery of payloads was only possible in the ocean which caused serious damage or complete loss of the valuable instruments. Hence, only light payloads with simple systems were allowed.

To overcome the various problems, we chose a strategy for making observations of diffuse radiations. A wide field of view could be easily available with small-aperture telescopes, and high-precision attitude control system would not be required in such observations. The author's group at Kyoto Univ. intended to map the galactic plane in a near-infrared band by using a balloon-borne telescope with an
ambient temperature 20 cm reflector. For the first flight in 1971, because we used a rather wide-band filter centered at 2 µm, the signal was seriously contaminated by strong OH airglow emission, and thus failed in detecting of the Galactic emission. However, we instead found that the OH airglow emission was distributed nonuniformly, and changed its configuration rapidly with time, which was later used as a probe for studies of the upper atmosphere by geophysicists. Since the second flight in 1975, we narrowed the band width to 0.08 µm centered at 2.4 µm, a band gap of the OH airglow, we succeeded to detect the Galactic emission.

On the other hand, the Nagoya Univ. group led by Matsumoto started with observations of the atmospheric CO₂ emission in the mid-infrared range, by a 23 cm liquid nitrogen-cooled telescope with a HgCdTe detector onboard a balloon. Later, they shifted to a near-infrared survey of the galactic plane at 2.4 microns by a liquid nitrogen-cooled telescope with an 8 cm Si-lens, and succeeded to obtain near-infrared map of the northern Galactic plane. In the same year, the author’s group also succeeded in drawing a 2.4 µm map of the central region of the Galaxy. The maps obtained by both groups showed good consistency, and first revealed the distribution of the stellar component in the central region of the Galaxy, which had been hidden by strong interstellar dust extinction. From these projects, we could draw a general scheme of the global distribution of the stellar component in the central region of the Galaxy, the bulge and 5 kpc arm structure.

The Nagoya group extended the survey to the southern hemisphere, sending campaigns to Mildura Australia in collaboration with Prof. John Thomas of Australian National Univ. They succeeded in drawing a beautiful and comprehensive map of the near-infrared emission in both the northern and southern sky of the Galactic plane as shown in Fig. 7. This was the first perspective view of the Galaxy, revealing its global structure; the largest edge-on galaxy in the sky. As can be seen in the figure, the bulge structure is well closed up, having a somewhat rectangular shape, and a dark lane was still left due to the strong interstellar extinction. An identical map was obtained by the DIRBE (Diffuse InfraRed Background Experiment) in the COBE (COrnic Background Explorer) mission in greater detail, as shown in the same figure. It was indeed a beautiful and impressive map, but the essential behaviors had been similarly seen in the balloon observation.

![Fig. 7. (Color online) Milky Way as seen by near Infrared. (a) Balloon observation by Nagoya Univ. 1980. (b) Satellite observation by COBE, DIRBE, 1991. Provided by NASA.](image-url)
As a counter work to the near-infrared surveys, a simple balloon telescope with a Ge bolometer set at the direct focus of an off-axis 8 cm parabola mirror was flown to make a galactic-plane survey at 100 microns by Maihara, T. et al. It provided the first two-dimensional map of the far-infrared emission in the galactic plane, which was later improved by the finer maps made by the balloon flights of Low and Nishimura and the French group. The observed far-infrared emission of dust, acted as an absorber, is silhouetted over the near-infrared background of the stellar light component, as can be seen in Fig. 8.

Since the early 1970s, a Univ. of Tokyo group, led by Keiichi Kodaira, also attempted to make photometric and spectroscopic observations of late-type stars by balloon-borne telescopes with apertures of 15 cm (BAT-I) and 30 cm (BAT-II) in the near-infrared region. The observed results were shown to be in good accord with a theoretical model proposed by T. Tsuji. As a successive work of the Galactic plane surveys in near- and far-infrared, the Kyoto group investigated the possibility of a spectroscopic observation of diffuse galactic emission. After the author moved to ISAS, and organized a new infrared group in 1981, he started a balloon project to make a far-infrared line spectroscopic observation in collaboration with the Kyoto Univ. group. Because a satellite mission, IRAS (InfraRed Astronomical Satellite), dedicated for a four-band photometric infrared survey, was running as a U.S., Dutch and U.K. joint mission, and soon to be launched, we thought the photometric survey would be no more worth to do. Although the atmospheric emission is still very strong and hazardous for detector performance, the effect should be substantially reduced by narrowing the bandwidth of the spectrometer. For such an attempt, we developed a cryogenically cooled Fabry Perot spectrometer to make spectroscopic observations of fine-structure lines in the far-infrared region. Using a metal-mesh etalon, we made a simple Fabry-Perot spectrometer with a resolution as high as $\lambda/\Delta\lambda = 1800$, which was cooled by liquid helium down to 2 K at the balloon altitudes. Using this tactic, the background radiation onto the detector could be reduced substantially and the detector performance was greatly improved. As for the detector, a G-doped Ge photoconductor, which was developed independently by Hiromoto was used. Despite the first production trial of the detector, it had achieved the highest sensitivity available in the world.

In the far-infrared region, there are a number of fine-structure lines of heavy atoms, neutral and ionized, such as [OI], [OIII], [CII], [NI] (emission lines by O, O$^{++}$, C$^{+}$, N$^{+}$ atom and ions), etc. These lines are useful to diagnose the physical and chemical conditions of interstellar space. Among them, the [CII] line was presumed to be the strongest, and worked as the major coolant of the interstellar medium. We first built a 50 cm balloon telescope BIRT (Balloon InfraRed Telescope) incorporating an offset guiding system and a star tracker. In a test flight, from Alice Springs, Australia, in 1985, we used a grating spectrometer and observed [OIII] lines of 51.8 and 88.4 µm in RCW 38, in collaboration with John Thomas. After replacing the spectrometer by a Fabry-Perot one, balloon flights were continued in
collaboration with Frank Low of Univ. of Arizona. After overcoming a number of ballooning failures, we could obtain useful data in 5 flights involving 3 campaigns to Palestine, Texas, and Alice Springs, Australia, from 1985 to 1992. In the first campaign, we observed some discrete sources such as M 17, NGC 6334 and the Galactic Center region, we also tried a zigzag scan of the galactic plane sampling at several galactic longitudes, by which we found that the [CII] line was ubiquitously distributed along the Galactic plane as well as the HII regions. The distribution of the [CII] line emission and its kinematic behavior in the Galactic Center region were derived from detailed analyses of the intensity distribution and the spectral profiles. To make an extensive survey in the Galactic plane more efficiently, we replaced the telescope by an off-axis telescope BICE (Balloon Infrared Carbon Explorer) with a smaller aperture of 30 cm, widening the field of view and reducing spurious radiation from the secondary mirror on the detector. Instead of the conventional sky-chopping method (spatial modulation), we introduced a wavelength sweeping method (frequency modulation) to eliminate the background emission. This worked very effectively for sorting the line-emission component from the background emission, particularly concerning diffuse emission. Using these methods, an extensive survey of the [CII] emission along a wide range of the northern and southern Galactic planes was made. Some discrete areas of the rho Ophiuchi cloud and the LMC regions were mapped at the same time. A brief summary of these observations was given in the review by Okuda, H. et al.

The intensity map of the [CII] line emission along the Galactic plane thus observed is shown in Fig. 9. By this work, we found that the [CII] line emission was very strong and efficiently observed for a wide area of the Galactic plane. Since it is line emission, we could obtain kinematic information concerning relevant gas clouds, as shown in the

Fig. 9. [CII] line emission map of the Galactic Plane. (a) Intensity map (b) Radial velocity variation with the galactic longitude (l-v diagram). (c) Balloon Infrared Carbon Explorer (BICE).
same figure. It would be useful to study the spatial distribution of the [CII] emission in the Galaxy, as has been done by the 21 cm line of hydrogen gas and the 2.6 mm line of CO molecules. [CII] emission is mainly generated in the intermediate region between a highly ionized HII region and a cold HI region or molecular-cloud region, the so-called photo-dissociation region. It is important for understanding the physical condition in interstellar space comprehensively. In addition, the observations would be easily made by small facilities and expected to be extended to extragalactic objects at long distances, as the emission rate of the [CII] line is a thousand and a million-times stronger than those of the CO line and the HI line, respectively.

3.4.2. Rocket observations. The Nagoya group started a series of rocket experiments from the late 1960’s. In the beginning, they observed airlight and zodiacal light in both the near and mid-infrared ranges by utilizing solid N2-cooled telescopes onboard K-9M rockets of ISAS. Since the early 1980s, they shifted their target to background radiation in the near and far-infrared regions, and undertook pioneering work involving observations of the cosmic-background radiation.

Firstly, they undertook rocket experiments to search for extragalactic background radiation in the near-infrared range with a liquid nitrogen-cooled telescope. After subtracting the zodiacal component, they found some excess or residual component at between the 1- and 2-micron region, which was substantially stronger than the integrated brightness of stellar origin. Intrigued by the idea that it might be the emission of first-generation stars borne in the early stages of the universe, they have repeated the rockets experiments to remove the ambiguity of a correction for the strong foreground emission. The expected component of the extragalactic background is so subtle that subtracting the foreground radiation of the zodiacal light is crucial, but also estimating the emission of the stellar component is important, which can be hardly discriminated by rocket observations with a low angular resolution. As shall be mentioned later, they used every chance to improve the conditions, by using satellite observations, such as IRTS and AKARI.

Meanwhile, they developed basic cryogenics techniques, such as the handling of liquid He under the zero-gravity condition and manufacturing of a light-weight cryostat, etc. They also undertook measurements of the cosmic background in the submillimeter range to check the 3K blackbody hypothesis in collaboration with the P. Richards group of UC Berkley. They found a marginal excess in the Wien wing of the 3K blackbody spectrum, which was later corrected in the COBE mission.

4. Satellite missions

In balloon experiments, the atmospheric windows are almost completely open from near infrared to submillimeter, although strong emission still remains. If we can get out of the atmosphere by using rockets, the atmospheric emission that is fatally hazardous for detector performances can be almost completely removed. However, their observing times are limited, typically to within a few tens of hours, and a few tens of minutes in the observations by balloons and rockets at most, respectively. Moreover, the launching risks are rather high in balloon experiments. The success rates were generally less than 50%, particularly in the case of big and heavy instruments. In rocket experiments, the payload masses were severely limited. As a result, they were not cost effective. The best solution should be available by satellite experiments.

4.1. The first satellite mission, IRAS and COBE. Since the mid-1970s, Reiner van Duinen of Univ. Groningen in the Netherlands started to investigate a satellite mission for infrared observations, as a follow-on mission of the ANS (Astronomical Netherland Satellite) dedicated for X-ray and UV observations, which was in 1974 successfully launched. In the U.S.A., Martin Harwit, a pioneer of infrared experiments by rocket, showed a strong interest in satellite experiments from the early 1960s, but it took a long time to assure a consensus among U.S. astronomers. After many efforts over a few years by almost all leading astronomers who had developed infrared observations, a consolidated mission, called IRAS, was proposed as a joint mission by a U.S., Dutch and U.K. consortium. A detailed story of the circumstances was written in the article by Martin Harwit.

After solving large numbers of complex technical problems by tremendous efforts, it was successfully launched into a Sun-synchronous orbit at the day-night terminator in 1983 by a NASA Delta rocket. The mission was a spectacular success.

IRAS was a cryogenically cooled 57 cm infrared telescope dedicated for unbiased all-sky surveys in 4 wavelength bands (12, 25, 60 and 100 µm). It was also incorporated with a low-resolution spectrometer and a chopped photometric channel provided by the
Dutch group. All instruments worked perfectly for about 10 months, succeeding in obtaining complete sky maps of the infrared intensity in the 4 bands, together with a catalogue of some 250,000 celestial sources.109 Among many discoveries, typical highlights were as follows:

1. Infrared cirrus; the interstellar dust clouds shine brightly in the far infrared over all the sky, not homogeneously, but rather fibrously, and thus dubbed as “infrared cirrus”.110

2. Infrared galaxies; there exist a number of galaxies which are emitting hundreds and thousands of times more strongly than the Milky Way galaxy, dominantly in far-infrared region.111

3. Dust disks orbiting around ordinary stars, like Vega; these disks are thought to be remnant of circumstellar gas and dust from which the planetary system had been formed.112

4. Linear band structures in zodiacal light seen in mid infrared; they seem to be formed by young dust particles generated by collisions of asteroids or comets, and not yet diffused widely.113

These discoveries were remarkable and unprecedented; however, the most important contribution of the mission to the astronomical community is manifested in the fact that the uniform and reliable database of celestial objects obtained in the survey issued as ’IRAS Catalog’,114 have been continuously used in almost every field of astronomical works up to now. It was indeed an epoch-making event, which opened up a new era of infrared astronomy.

The observation of the cosmic background radiation had also been an important issue in the early stage of a definition study of the IRAS. However, it was dropped because it was difficult to accommodate the two kinds of observations being different both by subject and technically in the same mission. A separate mission, optimized for observations of diffuse emission, named COBE, was launched in 1989.115 The three instruments on board, DIRBE (Diffuse InfraRed Background Experiment), FIRAS (Far InfraRed Absolute Spectrometer) and DMR (Differential Microwave Radiometer) worked perfectly. DIRBE made a complete all-sky map of diffuse infrared emission from near- to far-infrared.116 FIRAS observed a precise spectrum of the cosmic background in the full range and showed that it was beautifully matched with a single black-body spectrum with a temperature of 2.73 K.108 It was also used for observations of far-infrared line emissions by carbon [CII], nitrogen [NI], [NII] and carbon monoxide (CO) diffusely distributed in the Galaxy.117

The DMR observation showed the existence of some inhomogeneity in microwave radiation as small as of the order of $10^{-5}$.118 This is thought to be the seeds of later formed galaxies. John Mather and George Smoot were awarded Nobel prizes for these achievements in 2006.

4.2. Japanese first trial satellite experiment, IRTS mission. The great advantage of the space mission was fully proved by the success of the IRAS mission. However, it was not easily allowed for us to plan such a mission because of technical and budgetary problems. Unlike the space missions of X-ray or optical observations, infrared satellites should demand a difficult technique of cryogenic cooling, using easily vaporizable cryogens, which require the use of a heavy and bulky cryostat (a vacuum tank) with extremely low thermal dissipation. The smaller is the cryostat the worse is the cryogen keeping efficiency, since the cryogen heat capacity is proportional to its volume, while the incident heat is proportional to its surface, making a small telescope inefficient. As a result, the infrared satellite should have been heavy in mass, bulky in volume and costly from the beginning. The M3S-II rocket of ISAS, only available in the years of 1980s, was not powerful enough to launch such a satellite.

In the meantime, NASA (NAtional Space Development Agency of Japan), the previous space agency before the reorganization into JAXA, which had been concerned with national projects such as meteorological and communication satellites, was planning participation in the U.S. Space Shuttle program, and was organizing a recovery mission, called SFU (Space Flyer Unit). It was designed as a platform for multi-purpose experiments, launched by a NASDA H-2 rocket and to be recovered by the Space Shuttle after completion of experiments. Since it was an omnibus platform, not necessarily designed for infrared observations, we proposed a small infrared telescope IRTS (InfraRed Telescope in Space), mostly dedicated to simple sky surveys of infrared emission with a moderate spatial resolution and medium spectral resolution, covering a wide wavelength range from 1.4 to 800 µm.119 In a sense, this was culmination work of the observations so far made by balloons and rockets. The onboard telescope was a Ritchly-Chretian type, that was 15 cm in aperture, and incorporated 4 focal plane-instruments; NIRS (Near InfraRed Spectrometer), a grating spectrometer, covering wavelengths from 1.4–4 µm, with a resolution of 0.13 µm, MIRS (Mid InfraRed Spectrometer), a grating spectrometer, covering wave-
lengths from 4.5–11.7 μm, with resolution of 0.23–0.36 μm, FILM (Far Infrared Line Mapper), a grating spectrometer with narrow slits, centered at the [CII] and [OI] lines with a resolution of about 400 as well as a continuum band of 155–160 μm, FIRP (Far Infrared Photometer), a 4-channel photometer centered at 150, 250, 400, 700 μm. The beam sizes of the former three instruments were 8′ × 8′ and the latter was 30′. The detectors were InSb for NIRS, Si:Bi for MIRS, a Ge-Ga photoconductor developed by Hiromoto for FILM and a closed-cycle 3He cooled bolometer at 0.3 K for FIRP.

The SFU was launched by NASA’s H-2 rocket in Mar. 1995. All instruments of IRTS worked perfectly and provided high-quality data in every channel of the instruments for a period of 4 weeks with a life time of 120 litters of liquid helium. The following are typical examples of their results;

1. MIRS made spectral measurements of diffuse galactic emission and provided valuable data concerning the PAH components.120)

2. FILM made the [CII] and [OI] lines survey extending to high galactic latitudes.121),122)

3. The extragalactic background light (EBL) in the near infrared was examined in detail, and carefully by NIRS under substantially better conditions than the previous rocket experiments, having a longer observational time and a wider sky coverage. The contributions of zodiacal light and stellar light components could be assessed in greater detail by the finer spectral and spatial resolutions. The EBL thus-attained spectrum was consistent with results obtained by the previous rocket experiments, although slightly reduced in intensity.123)

Some of these results are shown in Fig. 10.

Besides these observations, spectroscopic observations of stars were made by NIRS and MIRS, and their collected data were given as a catalogue compiled by a collaboration with IPAC. A symposium dedicated to IRTS was held in ISAS in 1996 and its proceeding was published in an ASP conference series, Vol. 124.124)

Despite that IRTS was a small and narrowly defined mission, it worked very well and provided much valuable data; there was, however, some regret that the observations were limited to a short time, only 7% of the sky was surveyed, since the SFU mission was shared by many other experiments, both technical and scientific. If it had achieved a full sky survey, the IRTS would be a legendary mission as a wide-range infrared spectroscopic survey satellite of diffuse infrared emission.

Although IRTS was a small and limited mission, its success has left us valuable experiences and technical expertise of space missions, which had given us a strong confidence to make an advanced mission in later years. It should be mentioned that IRTS was undertaken in friendly collaboration with Thomas Roellig, Martin Cohen and Minoru Freund of NASA Ames Institute in California with the support from NASA.

4.3. First observatory-type satellite, ISO.

Following the IRAS and COBE missions, extensive and general use of an infrared satellite, called ISO (Infrared Space Observatory), was launched in 1995 by ESA.125) It was equipped with 4 instruments; ISOCAM, ISOPHOTO, SWS (Short Wavelength Spectrometer), and LWS (Long Wavelength Spectrometer). These covered a variety of observations, imaging, photometric and spectroscopic measurements in all ranges of wavelengths from near- to far-infrared. All of these instruments worked perfectly, and provided a tremendous amount of valuable data during its life time of 28 months. The observations covered almost all kinds of objects from planets, comets in the solar system to stars, interstellar matter as well as Galactic and extragalactic objects, made with all kind of instruments, as done by ground-based observatories. It is by no means possible to show all, but here we introduce only a few legendary highlights.

Since ISO was equipped with powerful spectrometers, covering a wide range of wavelengths with both moderate and high resolutions, it had opened a new field of spectroscopic studies of chemical and material properties of various kinds of astronomical objects. High-resolution spectroscopy succeeded in resolving the complicated water-vapor spectral lines, which showed a ubiquitous presence of water in low-temperature astronomical objects and many fine-structure lines in interstellar and gaseous nebulae.126)

The observations of dust-origin-band structures of various kinds gave valuable information concerning solid-state materials, as well as refractory interstellar and circumstellar dust. The similarity between the absorption spectra in young stars and the Hale-Bopp comet suggested a link between interstellar and interplanetary dust.127) Many kinds of ice that were the origins of spectral bands (H₂O, CO, CO₂, CH₄ etc.), in both emission and absorption, were found. A series of vibrational and ro-vibrational lines of H₂ were also observed, H₂ molecules are inert in the low-temperature state, and do not appear in the optical spectral range, and thus this has provided...
direct information concerning the molecular state of hydrogen in stellar atmospheres as well as interstellar space.126)

A number of fine-structure lines in the far-infrared range, such as [OI], [OIII], [NII] and [CII], were observed in both Galactic and extragalactic objects, and were used for inferring the physical conditions in low and high-temperature gasses present in highly and partially ionized regions. These lines are very efficient in interstellar gas cooling, and hence emitted very strongly in far-infrared range, and are easily observed even in galaxies at far distance. They were used to diagnose ULIRG (Ultra Luminous InfraRed Galaxy), distinguishing between black holes and starburst origins.129)

Using the extremely high sensitivity available only in space observations, deep surveys of faint galaxies at cosmological distances were made in the near, mid and far-infrared ranges, by which it was shown that the star-formation rates in galaxies had substantially increased in the past, i.e. increasing with the distance as far as $z \sim 1.5$, the observable limit by ISO.130)

ISO was the first observatory-type satellite dedicated to infrared astronomy, and was used by worldwide astronomers. It was an extremely success-
ful mission, and the observed data had been archived and opened for usage by astronomers throughout the world. A number of symposia and workshops were held, and their proceedings were published. It was indeed a legacy-making mission of infrared astronomy.

4.4. Participation in the ISO mission. Meanwhile, we were solicited by ESA to support the ISO mission. As the IRTS was designed only for observing of diffuse radiation, we wished to use it for work complementary to the IRTS. As a return of the support to data receiving at the Villafranca station in Spain, we were given 5% of the total guaranteed observation time. The author and Takashi Tsuji of Univ. of Tokyo served as members of the ISO science committee. Kimiaki Kawara and Yasunori Sato worked at the station as coordinators of the observation programming, data receiving as well as liaison duties with Japanese observers. We assigned the guaranteed time primarily to three categories: 1) Cosmology, 2) Interstellar Matter, 3) Stars and Circumstellar Dust.

Concerning the first category, we made an extremely deep survey of galaxies in the Lockman Hole, the least-obscured area of the sky by interstellar clouds, in a mid-infrared band (6.7 µm) and far-infrared bands (95 and 175 µm). These were the deepest surveys so far made by that time, by which we got some evidence of a rapid increase in the star-formation rate in galaxies toward $z = 1.5$.

In the second category, the UIR bands of PAH origin were studied in relation to the UV radiation environment in interstellar space, while in the third category, the dust shell around the evolved carbon star, Y CVn, was detected distinctly in far-infrared photometric images at 90 µm and 160 µm, which was explained as being a remnant of explosive mass ejection in the past, showing a history of past phenomena that I have to leave those other topics to review recent activities, widely and rapidly progressing, here we only briefly touch on some limited topics.

5. Expansion, advancements, progresses in the new millennium

The potential and importance of infrared observations are now well recognized, and the variety of observations has expanded rapidly into every field of astronomy. Since it is no longer possible to review recent activities, widely and rapidly progressing, here we only briefly touch on some limited topics.

5.1. Ground-based observations by big telescopes. On the ground, since the late 1990s, many 8- to 10-m class telescopes were built and are now fully used for a variety of infrared observations. They are powerful tools for investigating faint objects, such as exploring distant galaxies born in the early phase of cosmological evolution, reaching as far as $z \sim 8$, or about 10 billion light years. Incorporated with the adaptive optics technique, the angular resolution of ground-based telescopes has been substantially improved. By this technique, the proper motions of the stars in the central core of the Galactic Center were measured with extreme precision. From their Keplerian motions, an extremely strong mass concentration in the core, 4 million solar masses in 0.01 pc, presumably of black-hole origin, was derived.

The Subaru telescope long-awaited earnestly by the Japanese astronomical community was completed with a great deal of expectation in 1999 and used for a variety of observations. It is a common-use facility, open to every Japanese astronomer, and partly to international members too. Equipped with various instruments described before, a number of interesting observations have been performed. In particular, using the Supreme CAM, a CCD camera with a substantially wide field of view, an exploration of extremely deep space was made, and gave valuable information concerning the dark-matter distribution in space. Another remarkable example is a program for exploring of exoplanetary system, using the near-infrared coronagraph (CHAO and Hi-CHAO) incorporated with the AO system, in which they got direct images of a number of planetary systems and remnant dust layers around main sequence stars or dwarf stars. The observations by SUBARU have covered so many kinds of objects and phenomena that I have to leave those other topics to be reviewed by someone else.

As a faculty facility, Univ. of Tokyo group is building a 6.5 m telescope on a point as high as 5640 m near the ALMA site in Chili. From the advantage of the highest altitudes for ground-based observatories, together with its large aperture, it is expected to achieve the best condition for observations in the mid-infrared region.

5.2. Advanced observations in space.

5.2.1. Sophisticated space missions: SST, WMAP, Herschel and Planck. As for space observations, a big and consolidated mission, called SIRTF (Space InfraRed Telescope Facility) was proposed as a Space Shuttle experiment by NASA in rather early years of 1980s, but it was once suspended due to the tragic
Shuttle launch accident of as well as the situation that the initial payload was a little too bulky and heavy. However, it was smartly reborn by introducing an interplanetary orbit as well as implementing some size reduction by taking the telescope out of the cryostat, based on Frank Low’s idea. The new version could substantially reduce the thermal load from Earth radiation and increase the freedom of telescope pointing as well. It was launched in 2003 and renamed as Spitzer Space Telescope (SST).

An advanced version of the COBE, called the WMAP satellite was launched in 2001 and beautifully confirmed COBE's discovery of an anisotropic distribution of microwave cosmic background radiation, from which detailed cosmological parameters were derived. WMAP demonstrated that the Lambda-CDM (Cold Dark Matter) model best reproduces the observed fluctuation pattern of the cosmic microwave background (CMB) radiation.

Two European missions, Herschel and Planck, were launched in 2009 simultaneously by the same rocket, and sent into the so-called second Lagrangian point of the Sun-Earth system (L2). This is an excellent location for sheltering the satellite from solar radiation and infrared emission from Earth. It is very hard for the author to mention these follow-up missions in detail, and thus someone else should write about them. Here, we only briefly refer to our own mission of concern.

5.2.2. **First Japanese full-size infrared satellite, AKARI.** Encouraged by the success of the IRTS mission, we wished to have our own satellite mission with full capability. An advanced mission called ASTRO-F (renamed as AKARI after launch) had been investigated from the late 1990s. In 1996, Matsumoto moved from Nagoya Univ. to ISAS in order to promote the new mission. However, it was not so easy to manage the mission even by using the newly developed M-V rocket of ISAS with a launching power of about one-ton payload to be sent to a polar orbit as IRAS’s. To realize the mission within the limited capability, we had to attempt some new techniques never experienced before. For a light weight mirror, we developed a SiC mirror. To reduce the heat load to liquid-helium cryogen, we introduced a tandem 2-stage Stirling-cycle mechanical cooler. By these developments, we could accommodate a 70 cm telescope within the payload mass limitation, and lengthened the lifetime of the 180-liter liquid-helium cryogen to one and a half years. With these severe limitations on the resources in technique and human power, we could not complete an observatory-type mission; instead, we adopted an all-sky-survey-type mission. We had made our best efforts to reach higher sensitivities and resolutions as much as possible, compared to that of IRAS. For near and mid-infrared observations, we used two-dimensional arrays, covering the wavelength bands from 2.4 to 4.1 microns by InSb detector arrays and from 7 to 24 microns by Si:As detector arrays. For far-infrared observations, we used two-dimensional arrays of Ge:Ga detectors, non-stressed and stressed, to cover the wavelength bands from 65 to 160 microns, developed by Fujiwara, M., Doi, Y., and Hirao, T. By incorporating of prism and grism dispersers to the near- and mid-infrared channels, and of a Fourier-transform spectrometer in the far-infrared, we also added spectroscopic capabilities covering the entire infrared range. By using these various equipments, we improved the spatial resolutions to a few seconds in the near and mid-infrared range, and to a few tens of seconds in far-infrared range, much higher than those of IRAS’s. The detection limits substantially exceeded those of the IRAS by factors of tens to hundreds as well. A picture of the AKARI and an all-sky map of the-infrared emission are shown in Fig. 11.

Due to some technical problems, the launch was delayed to February, 2006, which had been originally scheduled to be at the same time of Spitzer. After the launch, it was renamed AKARI, a light to illuminate the dark universe. The mission was highly successful, and all devices and instruments worked perfectly during the lifetime of the liquid helium for one and a half years. After exhaustion of liquid helium, the cryocooler worked well, and observations in both near- and mid-infrared regions were extended for another 8 months. Most of the time was dedicated to the all-sky non-bias survey by continuous scanning along the day-night border zone of the sky, though some time was granted intermittently to pointing observations of discrete sources, making detailed mappings of selected areas and spectroscopic measurements of individual sources. The observed data was enormous; very uniform and homogeneous data were obtained for 96% of the entire sky in six wavelength bands (9, 18, 65, 90, 140, and 160 μm). In pointing-mode observations, high-sensitivity imaging and spectroscopic observations were carried out for thousands of selected areas or discrete sources. These data are to be released as archival data for use by worldwide astronomers. Due to missing an efficient data-processing center, such as IPAC, data analyses...
have been slow and not yet fully completed. The archival data so far released are summarized in a report by Yamamura et al. at the AKARI symposium held in 2017.\textsuperscript{150} We hope that the AKARI data will be used as an advanced version of the IRAS work. The AKARI mission was undertaken in collaboration with U.S., European, Korean and Taiwanese astronomers as well as with the support of NASA and ESA.

As a smaller project, Shibai, H. et al. of Osaka Univ. have challenged themselves to make observations by a far-infrared interferometer onboard a balloon, with a span of 8 m,\textsuperscript{151} spending almost 20 years under very poor supporting conditions. They have not succeeded so far in obtaining data. Interferometric observations would be a unique or ultimate method to achieve high resolution, as was done in radio astronomy, thus of extreme importance in the future for far-infrared observations.

5.2.3. Search for extragalactic near-infrared background. As for the intriguing emission found in the near-infrared part of cosmological background radiation, various trials have been attempted to confirm the excess emission by using the data obtained with IRTS and AKARI missions. Matsumoto, T. et al. reanalyzed in great detail the near-infrared background data that covered a wider area of the sky, assessing zodiacal light, integrated star light and diffuse Galactic light with great care. They confirmed the existence of the residual emission to be attributed to being of extragalactic origin.\textsuperscript{152} They further applied another method, so-called the fluctuation analysis proposed by Kashlinsky et al.\textsuperscript{153} to estimate any excess emission component, and obtained consistent results, as obtained by the photometric survey. They are continuing a new series of rocket experiments (CIBER: Cosmic Infrared Background ExpeRiment) as a Japan/U.S. joint project, by extending the observations to shorter wavelengths, and with the finer spectroscopic resolution, so as to obtain more informative data to discriminate zodiacal radiation even more precisely.\textsuperscript{154} Latest data of the near-infrared extragalactic background light is summarized in Fig. 12.

6. A future prospect

As we anticipated in our assessments of the potential of infrared astronomy at our starting time, modern infrared astronomy rapidly developed and expanded to every field of astronomy or astrophysics in the past half century. The legacy of infrared observations is enormous and covers almost every object from the solar system to cosmology. Now, in every field of astronomy we cannot tell a story
without referring to achievements obtained by using infrared observations. Already, in 1980, when the first IAU symposium on infrared astronomy was held in Kona, Hawaii, it was said that the symposium was the first and the last symposium titled as “Infrared Astronomy”. It would be too big of a subject to be organized in a single symposium in the future. Certainly, no symposium titled as “Infrared Astronomy” has ever been held since then. So far, our prospects anticipated in our assessments made at our start of infrared observations have been fully proven.

As mentioned above, our trials in the early phase were mostly successful, although they were all made under the strong limitations in technical and financial resources, particularly human resources. In fact, we have been able to conduct some unique studies that were feasible with relatively small and simple instruments in the early stage of infrared astronomy. However, we could hardly develop them to higher levels, once they had entered advanced and large-scale enterprises, particularly concerning space research.

AKARI achieved a good success in multi-band all-sky surveys, with high sensitivity and fine resolution, providing basic data concerning the astronomical objects, as well as discrete and diffuse sources. They are generally very valuable and useful data as a base of astronomical research. Regretfully, however, we were poorly cared for concerning post-mission supports, such as data analysis and archival work. We could not organize a data-analysis center for AKARI, such as the IPAC in JPL, despite that the AKARI data are far more abundant than those of IRAS. As a result, we have not been able to conduct any data analysis quickly, leaving valuable data unanalyzed, and unavailable (within a reasonable time) to the worldwide community.

In addition, since the mission was mostly dedicated to general survey works, the results would not necessarily satisfy individuals who want specific information. In this mood, a more general-use observatory-type telescope was desired, and a study was started in parallel with the development of the AKARI mission.

In a new mission, named as SPICA (SPace Infrared telescope for Cosmology and Astrophysics),155) it is aimed to make the most advanced observations in the mid and far-infrared regions, where photon noise due to environmental thermal emission peaks. To avoid such noises, the telescope has been generally cooled by liquid helium, while installing the whole telescope and instruments in a
bulky and heavy cryostat, which inevitably limits the telescope size available. On the other hand, in the far-infrared region, the angular resolution is limited by diffraction, so it is essential to make the telescope aperture as large as possible for improving the resolution. In the case of the Herschel mission, a telescope with an aperture as large to be as 3.5 m was available, but it could be only cooled to as low as 50 K by radiation cooling; liquid helium was used only for cooling the detectors.

To satisfy both requirements, large aperture and low temperature, we investigated the feasibility to introduce the full use of mechanical cryocoolers, without using liquid helium with a finite lifetime. We have had successful experiences of using mechanical coolers involving double-stage Stirling coolers, at 20 K in the previous AKARI mission, and a Joule-Thomson cooler at 4.5 K in the SMILES (SubMillimeter Limb-Emission Sounder) mission.\(^{156}\) operated onboard the International Space Station. Based on these experiments and expertise, we could succeed in designing a large aperture (2.5 m) telescope cooled down below 8 K, using only mechanical cryocoolers, while eliminating any heavy and bulky cryostat. Reducing the payload mass by this method, the SPICA has proved to be a realistic mission and proposed for a next-generation infrared observatory dedicated to the mid and far-infrared region, the least advanced wavelength area in infrared astronomy. A lower-temperature performance would improve the detection limit by almost two orders of magnitude than those achieved by Herschel. The mission is highly evaluated worldwide, and has been selected as a candidate for the ESA M-5 mission as an ESA/JAXA joint program. It was originally started by ISAS/JAXA as the host institute with the collaboration of European groups, but it is now being promoted as a joint mission of ESA and ISAS/JAXA, with the full support of the Japanese astronomical community and endorsed by the Science Council of Japan. It is of an even larger-scale mission than Herschel or Planck, a three-ton satellite to be sent to the L-2 orbit.

As for ground-based facilities, a number of gigantic telescopes have been proposed, and some are under construction. The European community is building a 40 m telescope (ELT) in Cerro Amazones in Chile. The 30 m telescope (TMT) is under a promotion with collaboration among the U.S.A., Japan, Canada, China and India to be built on Mauna Kea in Hawaii. The mounting system of these telescopes, weighing up to 3000 tons, is comparable to the weight to that of a battle cruiser, should be driven and controlled with a precision of a few tenths of a second of arc. The primary mirrors are to be composed of several hundreds, or almost a thousand aspherical mirror segments, which should be actively supported to keep them shaped as a single mirror with optical precision, continuously. These techniques are extremely challenging and hence their costs would be enormous. Japan is expected to share development concerning the telescope mounting system and the mirror system. Another type big telescope, the GMT (Giant Magellan Telescope, 25 m in aperture) composed of seven 8.4 m circular mirrors is now being built at Las Campanas, Chile, expecting its first light in 2024. With the extraordinary light collection power available by the large apertures and the refinement of angular resolution, they should open up a new era of astronomy, such as exploring the early history of the universe, the fundamental nature of black holes and dark matter/energy as well as the origin of life. These projects are promoted through wide-range international collaborations to overcome many financial and technical difficulties.

Now, infrared astronomy has been plunged into a typical world of big sciences, either demanding the big cost of more than a billion dollars and large organizations on the order of hundreds or more people each. The latter problem is particularly more serious in our country. Compared to the U.S.A. and European countries, our proper concern is that we could hardly obtain the supports of professional engineers and technicians, which is indispensable in developing big missions. In our country, most research should be shared by the scientists themselves along with doctoral or postdoctoral students. Under these conditions, most researchers had to spend most of their energy for implementing and operating the missions, so that it happened that they could hardly find enough time to conduct full analysis of the observed data, while deepening scientific discussion.

For the large projects or missions mentioned above, they should take a long time, as long as 10 years or longer, for their development and operation. Such a burden might not be withstood, particularly by students in such long-term missions. This is a serious issue, indispensable to be solved in the future projects or missions.

In the case that improvements might not be easily anticipated, it should be worth investigating some heterogeneous strategy, such as challenging a new field or a new technique, to attack the new
field, which is still in a primitive stage of evolution and hence does not demand a high cost or big organization.

At the same time, it should be requested for scientists to consider more seriously how to aim the most important science in the given environmental conditions by undertaking more strategic considerations.

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Profile

Haruyuki Okuda was born in Aichi pref. in 1935. Graduated from Nagoya Univ. in 1958, he majored in cosmic ray physics in the post graduate course of the same university, in which he engaged in search for cosmic ray sources by building an air Cerenkov telescope under Prof. Y. Sekido, and making some theoretical works of estimation of the electronical composition in cosmic ray under Prof. S. Hayakawa, by which he took a Ph.D. in 1963.

He stayed for one year from 1966 in the Leiden Observatory in the Netherlands as a guest researcher, under Prof. H.C. van de Hulst. In 1967, he moved to the Department of Physics in Kyoto Univ. as an associated professor in the cosmic ray group led by Prof. H. Hasegawa and started infrared astronomical observations, that had been initiated by the suggestion of Prof. Hayakawa when he was in Nagoya Univ., first from the ground, by building a 1 m infrared telescope, and in parallel from space, by using balloons. The observations were devoted mostly uncultivated areas, such as polarimetric observations of infrared stars and the Galactic Center or global surveys of diffuse Galactic emissions in near- and far-infrared. In 1981, he moved to the Institute of Space and Astronautical Science (ISAS) as a professor to initiate a group of infrared astronomy group, where he organized several inter-university missions by satellite experiments, in collaborations with Nagoya Univ., Univ. of Tokyo, Osaka Univ. as well as NASA and ESA, such as the IRTS (1995), ISO (1995), and AKARI (2006) in its initial phase of planning.

He served as the president of the Astronomical Society of Japan from 1997 to 1998, and as the president of the Division XI (Space and High Energy Astrophysics) of the IAU from 2003 to 2006.