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Infrared Astronomy for Infrared Engineers

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Abstract

Astronomical observations at infrared wavelengths are important because they provide information about celestial sources that is inaccessible at visible wavelengths. Here I discuss the main factors contributing to the importance of infrared astronomy, and present an overview of some of the recent and future observational efforts.

1. Introduction

Practically all our knowledge about celestial sources (planets, stars, galaxies,interplanetary, interstellar and intergalactic material) is based on the detection and analysis of electromagnetic radiation. With a few exceptions (e.g. F.W. Herschel's discovery of infrared radiation in 1800), the pre-XX century astronomy was essentially confined to the visible (0.4-0.7 micron) wavelength range. The full range of electromagnetic radiation (see Figure 1) was open to astronomers during the second half of the XX century. Observations at infrared wavelengths (0.7 micron to about 100 micron) are especially informative, and infrared astronomy has enjoyed fast, and still ongoing, progress. In Section 2 I discuss the main factors contributing to the importance of infrared astronomy, and in Section 3 I review some the current resources and upcoming infrared missions.

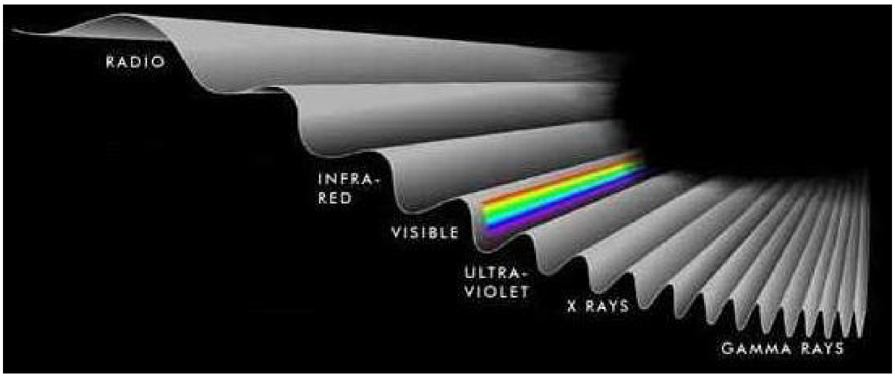

Fig. 1*. A schematic view of the electromagnetic spectrum. Astronomical sources radiate at all the marked wavelength ranges, and astronomy is often divided using the same nomenclature (e.g. radio astronomy, X-ray astronomy, infrared astronomy).*

2. The Motivation for Infrared Astronomy

If the radiation from celestial sources followed the Planck law, it would be sufficient to observe those sources at only two wavelengths in order to constrain their temperature and bolometric flux (total flux, integral of the specific flux over all wavelengths). However, due to several effects described below, the radiation from celestial sources rarely follows the Planck law, and often the crucial information about a source is obtained at wavelengths other than visible. In addition to intrinsic deviations from the Planck law, the interstellar

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material can alter the radiation on its way from the source to the detector. Finally, the cosmological redshift effect shifts the overall spectrum towards the redder, longer wavelengths, and can make objects at the edge of the currently observable Universe practically invisible at optical wavelengths.

In this section I illustrate these three major drivers for infrared astronomy.

2.1 Deviations of Astronomical Radiation from the Planck Law

Even in stable stars (not too young, not too old), whose spectral energy distribution resembles the Planck law with temperatures ranging from about 1,000 K to about 100,000 K, there are absorption lines due to radiative transfer effects in their atmospheres. The top panel in Figure 2 shows the spectrum of a fairly cold star (about 2,000-3,000 K) observed by the Sloan Digital Sky Survey (hereafter SDSS, for more details see Stoughton et al. 2002, and www.sdss.org). Many molecules can exist at these low temperatures, and they produce the prominent absorption features, resulting in a non-Planckian spectrum. Molecules cannot survive in very hot stars, and in these stars only strong absorption lines are the hydrogen Balmer lines, as seen in the middle panel in Figure 2 (most stars, including our Sun, are mainly composed of hydrogen). Sometimes stars are bound in a close binary system, and the spectrum shows both types of features, as displayed in the bottom panel in Figure 2.

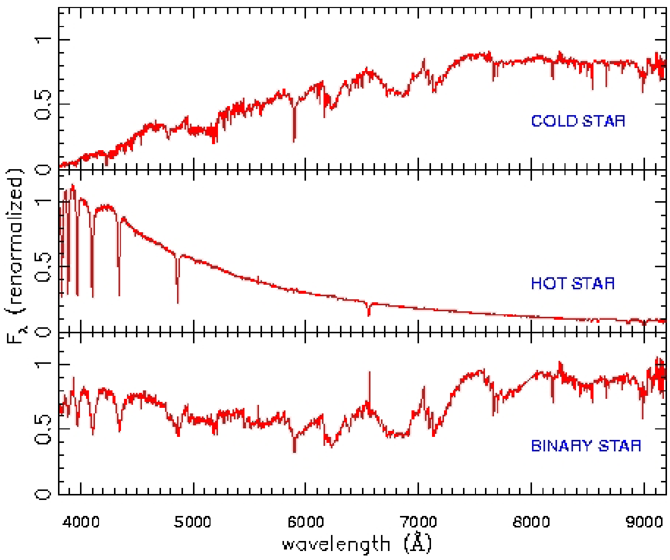

Fig. 2. *Examples of stellar spectra observed by the Sloan Digital Sky Survey. The top panel shows the spectrum of a fairly cold star (about 2,000-3,000 K), and the middle panel shows the spectrum of a hot star (about 10,000 K). The absorption features visible in the top panel are due to various molecules in the star's atmosphere, while those in the middle panel are the hydrogen Balmer lines. The spectrum shown in the bottom panel is a binary star system that contains one hot and one cold star.*

Close to the end of their lifes, many stars become unstable. The increase in the energy output during this phase is often sufficient to eject parts of their atmosphere away from the star (for a detailed review see Habing 1996).

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As the material flows away from the star, it cools down, and once its temperature drops to below about 1,000 K, the solid particles condense out from the outflowing gas. These particles, known as ``astronomical'' dust, are very efficient at absorbing radiation and re-radiating it at longer infrared wavelengths. A fascinating image of such a star obtained by the Hubble Space Telescope is shown in Figure 3. The star is actually obscured by an optically thick dusty disk whose silhouette is visible in the center. The bright parts of the image are the radiation scattered off the dust grains in the circumstellar envelope which surrounds the star.

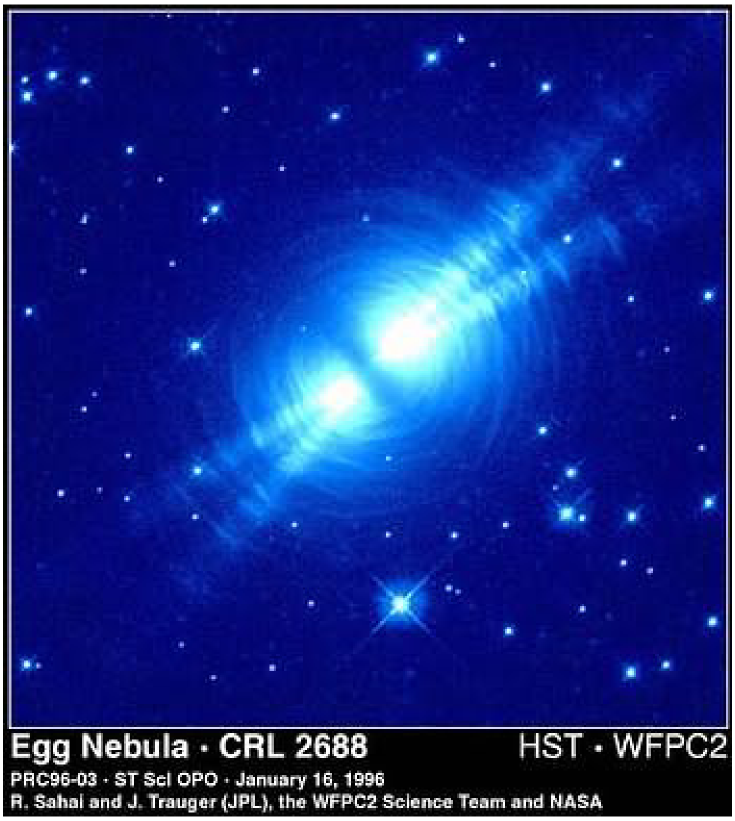

Fig. 3. *The Hubble Space Telescope image of a dying star surrounded by dusty envelope (the so-called Egg Nebula). The shell-like structure around the star is due to episodes of mass loss, and is visible because the photons emitted by the star are scattered by the dust grains towards the observer.*

Most of radiation from such stars, after reprocessing by the circumstellar dust shell, is detected at infrared wavelengths. The interpretation of this radiation offers important clues about the usually invisible dying star and the properties of obscuring circumstellar shell. As an example, Figure 4 shows the observed spectrum (spectral energy distribution) of one such star, named CW Leo.

The radiation emitted by this star, which peaks around 1 micron, is completely absorbed by dust, and reradiated at infrared wavelengths. Using a radiative transfer model for the transfer of radiation through circumstellar shell, Ivezic & Elitzur (1996)

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demonstrated that the dust around CW Leo is composed mainly of amorphous carbon and SiC grains (our radiative tranfer code, DUSTY, which was used to compute the model spectra is publicly available from http://www.pa.uky.edu/~moshe). Such a detailed inference about an object hundreds of light years away would not be possible using only the visible wavelengths data.

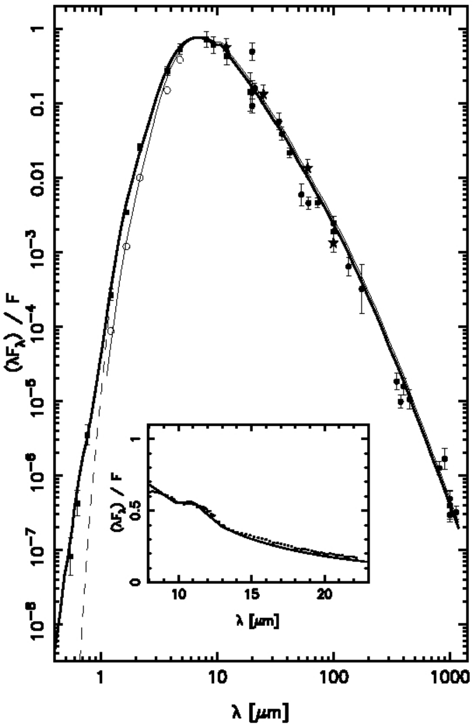

Fig. 4. *An example of a star whose radiation is detected mostly at infrared wavelengths. The data are shown by symbols, and the lines show a model which is in a good agreement with observations (Ivezic & Elitzur, 1996).*

2.2 The Effects of Interstellar Dust

The space between stars is not entirely empty. While the mean density of interstellar material is extremely low by engineering standards (about 1 particle per cc, i.e. lower than the best laboratory vacuum), this material can have profound influence on the radiation transfer because of enormously large distances between stars. For example, the density of interstellar dust is sufficiently high that we can't see the center of our Galaxy at visible wavelengths (total optical depth is over 20). The absorption of radiation by dust is a strong function of wavelength and generally decreases with wavelength. Thus, infrared radiation can be seen through a much thicker layer of dust than visible radiation. An example of an object obscured by dust at visible wavelengths is shown in Figure 5. As the wavelength of observation increases, the object becomes more and more visible. This effect is another reason to perform infrared observations.

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Fig. 5. *The dependence of dust absorption on wavelength. The left panelshows a visible light image of a region in Orion. The famous Horse Head Nebula is visible in the lower right corner, and is due to a cloud of interstellar dust obscuring background stars. The middle panel shows an near-infrared image (1 micron) of the same region, and on the same scale. The dust obscuration effects are practically negligible. The right panel shows a far-infrared image (100 micron) which demonstrates that the radiation absorbed by dust at shortwavelengths is reradiated at longer, infrared wavelengths.*

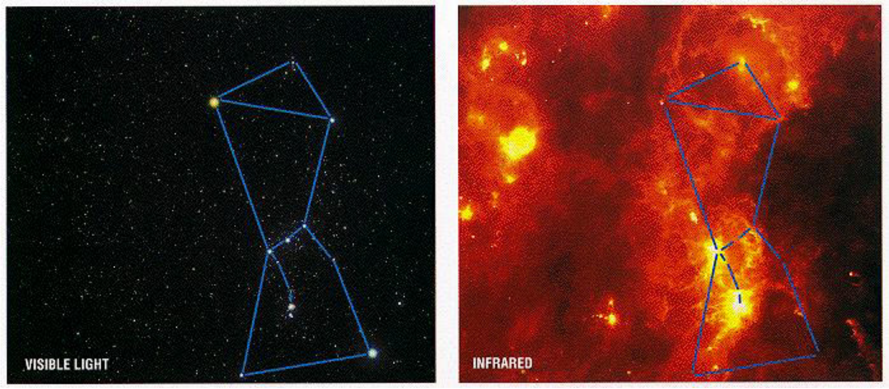

Fig. 6. *An example of a region with strong dust emission, as visible in the right panel. The bright region in the lower right panel is a star forming site, which looks rather ordinary in the visible light, shown in the left panel. nothing special is apparent in this visible light image. However, this dust emits strongly at infrared wavelengths, as is vividly demonstrated by the infrared image of the same region displayed in the right panel.*

The radiation absorbed by dust heats the dust to temperatures ranging from a few hundred K to a few K. Because of this range of temperatures, most of the reradiated energy is emitted at infrared wavelengths. The left panel in Figure 6 show the Orion constellation (the blue lines are added to guide the eye), a region known to contain significant amount of dust, although the appearance of that region at the visible wavelengths is quite ordinary.Sometimes the radiative transfer effects couple with the dynamics of interstellar gas and dust to produce very complex environments. A spectacular example of such a region is shown in Figure 7.

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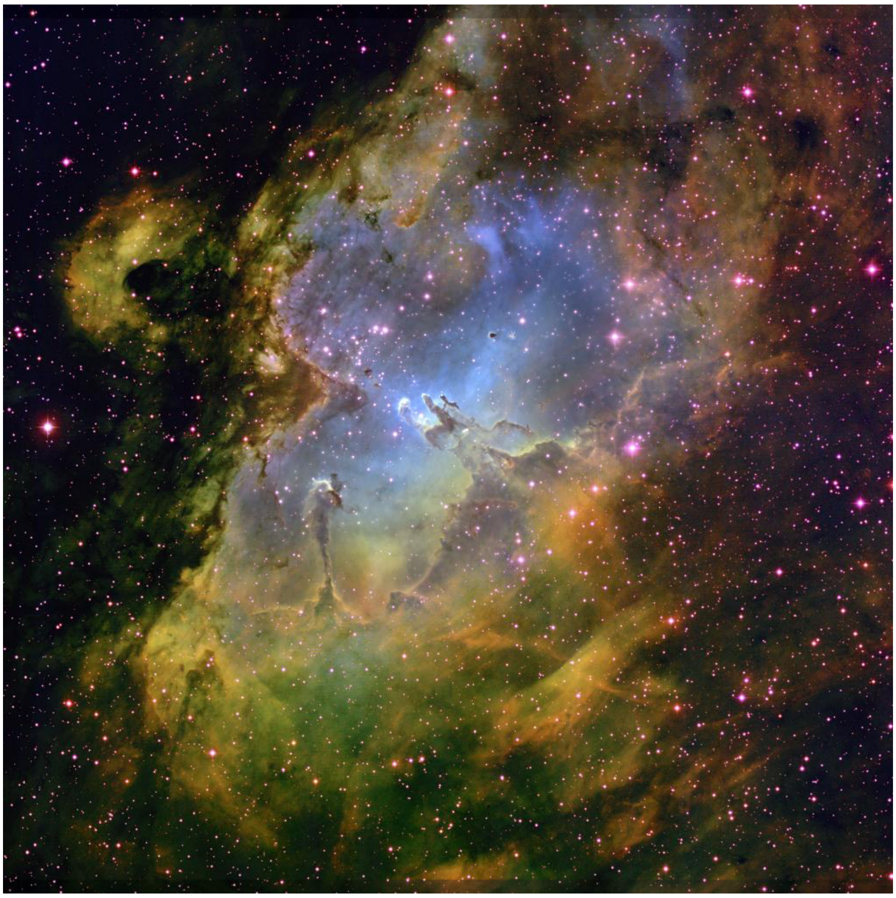

Fig. 7. *The Hubble Space Telescope image of the Eagle Nebula. The dots are stars, and the extended regions of emission are radiation from stars scattered by interstellar gas and dust. The shell-like appearance is real, and is due to clearing of the central region by radiation pressure acting on interstellar material.*

2.3 The Cosmological Redshift

Similar to a decreasing pitch of an ambulance moving away from the listener, the light waves emitted by a receding source also shift towards longer wavelengths. This effect is usually negligible in engineering environments because typical source velocities are much smaller than the speed of light, but on cosmological scales it may have profound effects. The Universe is expanding, and the speed of any object observed by us is proportional to its distance. Very distant objects have substantial recession velocities, and their intrinsic spectra are shifted to longer wavelengths by a large factor. Figure 8 shows spectra of a few most distant quasars (extremely luminous objects due to prodigious accretion of material onto a black hole, which thus can be seen to great distances) whose spectra were shifted by about a factor of 7 from the original wavelengths. Actually, a more correct

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term would be “stretched” because observed wavelength is equal to (1+z) times the so-called rest-frame wavelength, where z is the redshift (proportional to distance via Hubble law).

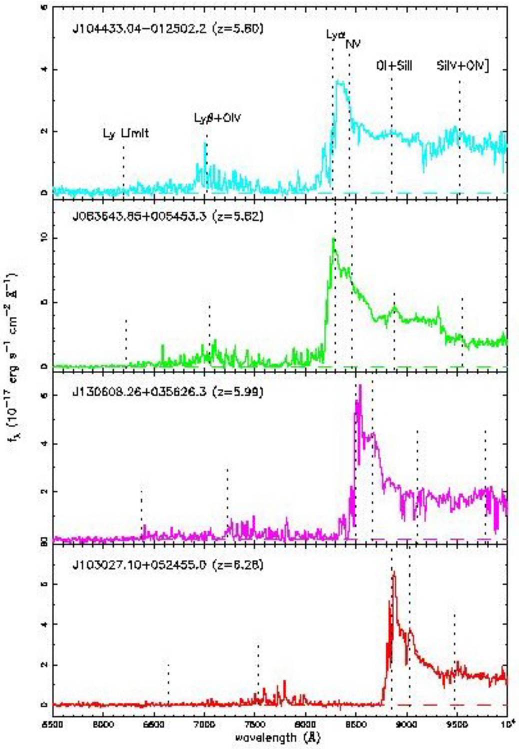

Fig. 8. *Examples of spectra of some of the most distant known objects in the Universe (the bottom one is the most distant known quasar). The spectra of these quasars were shifted by about a factor of 7 towards redder wavelengths by the cosmological redshift effect. Their discovery was based on infrared light because they emit very little light at the visible wavelengths.*

All spectra shown in Figure 8 contain practically no light at the visible wavelengths. We discovered them using infrared images obtained by the SDSS (Fan et al. 2001), like those shown in Figure 9. This figure vividly illustrates the need for infrared observations in order to discover objects at the edge of observable Universe.

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Fig. 9. *Two images obtained by the Sloan Digital Sky Survey of a region that contains the most distant known quasar. The left image is obtained at visible wavelengths, while the right image also includes infrared light. This quasar is only detected in the right image (the tiny red dot slightly towards the right from the center) because its intrinsically blue spectrum was moved towards longer wavelengths by cosmological redshift.*

3. The Current Status of Infrared Astronomy and Upcoming Surveys

3.1 The Past and Present

Infrared astronomy has enjoyed a fast and steady progress since 1960s, mostly due to commensurate development of infrared detectors (which went from PbS and Ge devices, to InSb and HgCdTe devices), and rocket technology. Major infrared sky surveys can be divided into two types: ground based, and space missions.

The ground based observations are usually done from very high altitudes (in addition to mountains, balloons and rockets are used to elevate telescopes) in order to avoid the absorption of infrared radiation by the Earth's atmosphere (see Figure 10). Space missions fully avoid atmospheric absorption, and also benefit from cold environment.

The largest and most accurate ground-based infrared survey is the recently completed 2MASS (Two Micron All-sky Survey, www.ipac.caltech.edu). This survey has detected and measured fluxes for over 300 million sources at three wavelengths ranging from 1 to 2 micron. The 2MASS database has not yet been fully explored, but it is practically certain that such an enormous resource will result in many scientific results. For observations of individual sources, the best telescopes and instruments are situated on the summit of Mauna Kea, a dormant Hawaii volcano (see Figure 11).

The most successful space infrared survey to date was Infrared Astronomical Satellite (IRAS) launched in 1983. It detected over 100,000 sources at wavelengths ranging from 10 to 100 micron, which at that time nearly doubled the number of all cataloged astronomical sources. The IRAS mission has had a major impact on almost every area of astronomy. For example, IRAS revealed for the first time the core of our Galaxy (which is heavily obscured by dust at visible wavelengths), and established that Milky Way is a barred spiral galaxy – a galaxy which has an elongated central bar-like bulge from which its spiral arms unwind.

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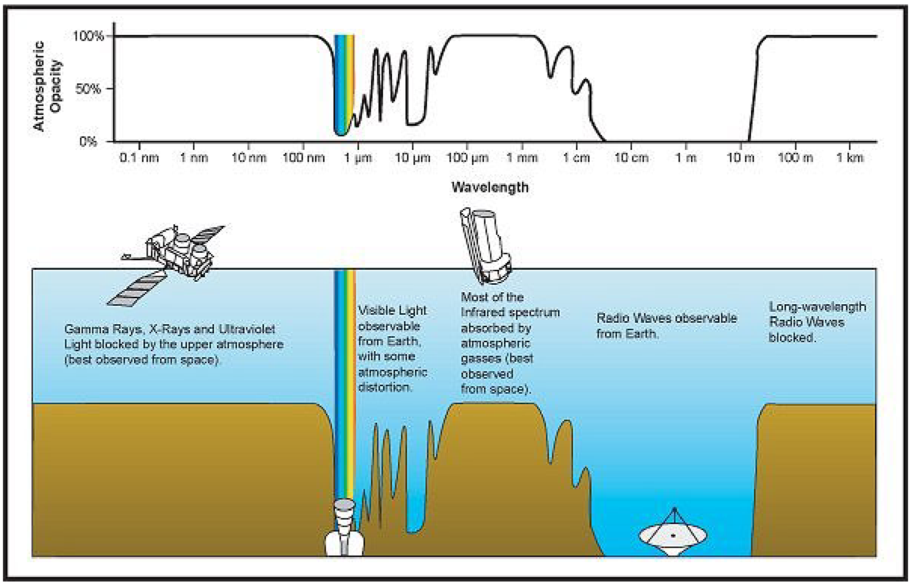

Fig. 10. *A schematic view of the wavelength dependence of the atmospheric opacity. The infrared range from 1 micron to 10 micron is accessible from high-altitude ground based observatories, but at longer wavelengths spacecrafts are required to detect radiation from celestial sources.*

3.2 The Future

Several upcoming space missions demonstrate the importance of infrared astronomy. The SIRTF (NASA's Space Infrared Telescope Facility) spacecraft, about to be launched, will carry the most sensitive infrared telescope ever built. It will be more sensitive than IRAS by over a factor of 1000, and is expected to revolutionize many areas of astronomy.

Another exciting facility is pursued by the European Space Agency: The Herschel Space Observatory. It will be launched in 2007, and will perform photometry and spectroscopy over a wide range of infrared wavelengths. A similar mission, also by the European Space Agency, PLANCK, which may reach wavelengths as long as 1 cm (these two missions may be eventually be merged together).

The James Webb Space Telescope is a planned successor to the Hubble Space Telescope, and is scheduled for launch in 2011. It will be Sensitive to wavelengths up to 20 micron, and will have extremely good sensitivity and resolution. Last, but not least, the Terrestrial Planet Finder is a major long-baseline space interferometer mission, with the aim of finding Earth-like planets around other stars. Although many technical challenges are unsolved yet, NASA plans to launch in 2012. If successful, this mission will provide an unprecedented glimpse of other worlds similar to ours.

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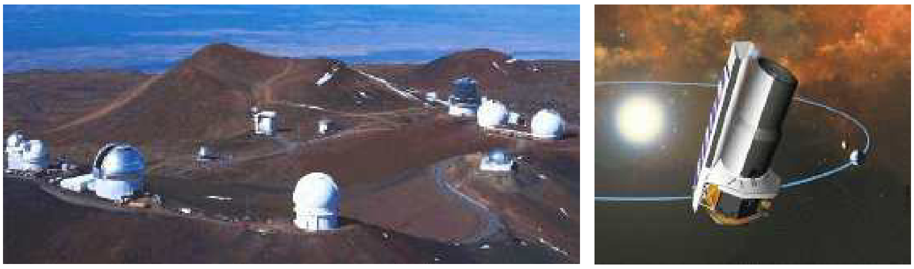

Fig. 11. *The leading approaches to infrared astronomy. The left panel shows the summit on Mauna Kea, Hawaii, where the high altitude and dry air allow for efficient observations. The right panel shows SIRTF (NASA's Space Infrared Telescope Facility) spacecraft which carries the most sensitive infrared telescope ever built.*

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