ASTR 288C – Lecture 12
Monday, 30 November 2009

Low Energy Telescope Design and Instrumentation

Optical Astronomy

Introduction

Optical astronomy is the study of ultraviolet, visible, and infrared light. The term visual astronomy is sometimes used to refer to the study of just visible light, but professional astronomers tend to use the term optical astronomy to refer to wavelengths between approximately 3500 Å and 8000 Å, which roughly corresponds to the range of light that the human eye can see. Optical observations include:

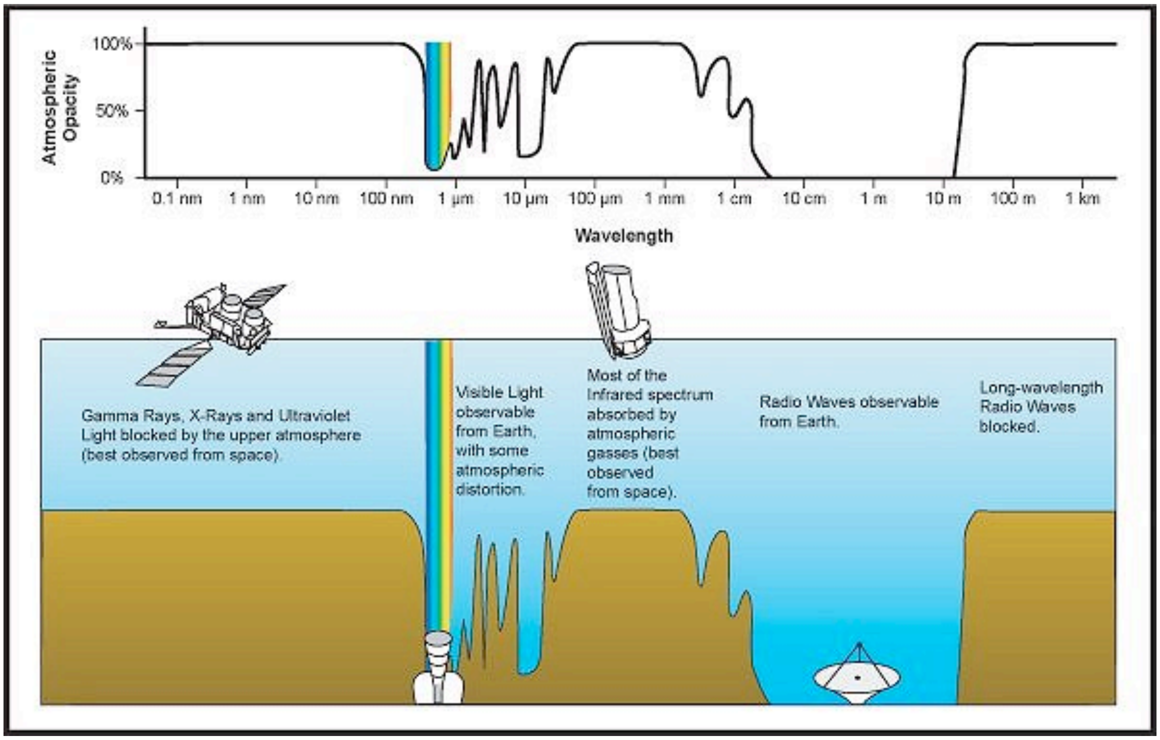
- imaging, where a two-dimensional image of a field on the sky is created;
- photometry, where the flux or intensity of the electromagnetic radiation created by an astronomical body is measured;
- spectroscopy, where the spectrum of a source is recorded and analysed; and
- polarimetry, where the polarization of the light from a source is measured and analysed.

Optical astronomy is the oldest branch of astronomy because optical astronomy corresponds to the wavelength range that the human eye can detect. . Astronomical observatories and records date back to Neolithic times.

Stonehenge.

Anasazi rock painting depicting SN1054 and the Moon.

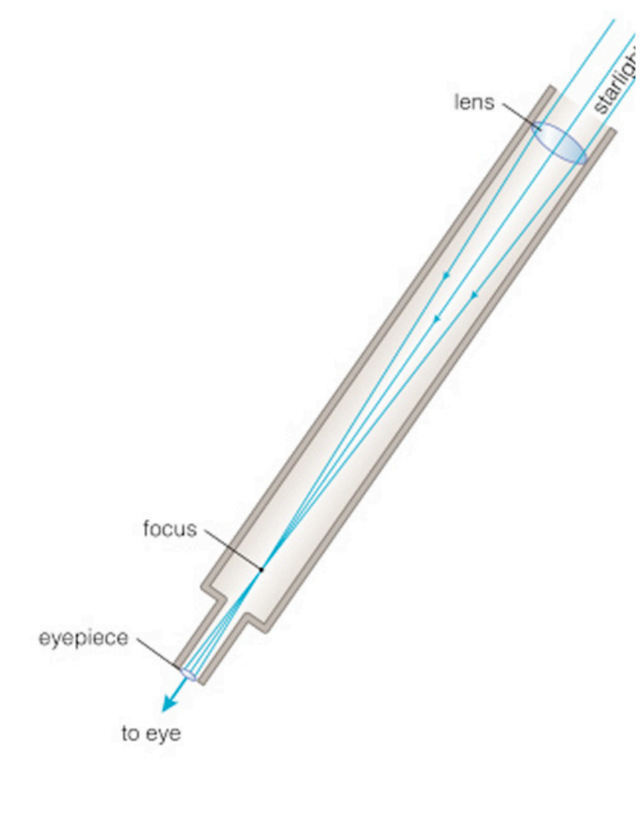
The Earth's atmosphere is opaque to most of the electromagnetic spectrum with windows of transparency in the optical, infrared, and radio régimes.

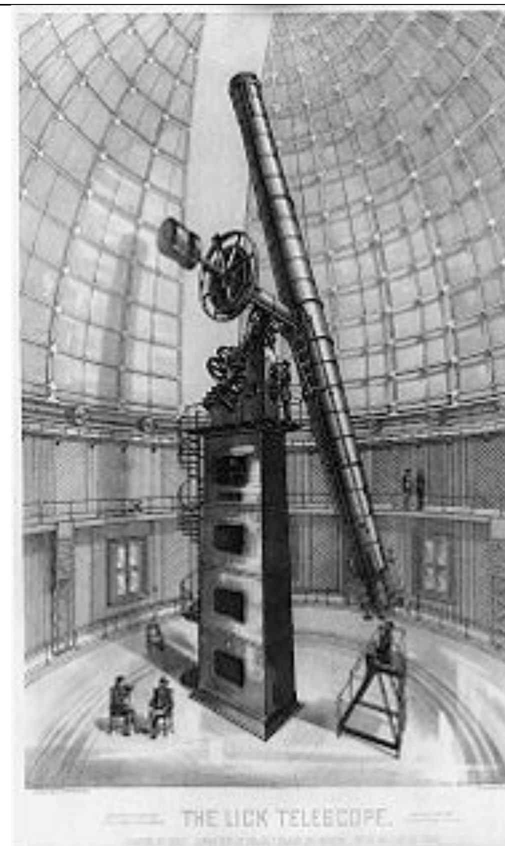


Although the optical window is fairly narrow most astronomy is still done at optical wavelengths. This is because most thermal processes, which have blackbody spectra, peak in or near the optical band.

Optical Telescope Design

There are two basic designs that are used for optical telescopes, with many different variations. The earliest telescopes were **refracting telescopes**. All refracting telescopes use the same basic optical principles. The combination of an objective lens at one end of a tube and some type of eyepiece at the other end is used to gather more light than the human eye could collect on its own, focus the light, and present the observer with an image. Refracting telescopes come in many different configurations to correct for image orientation and various types of aberration.

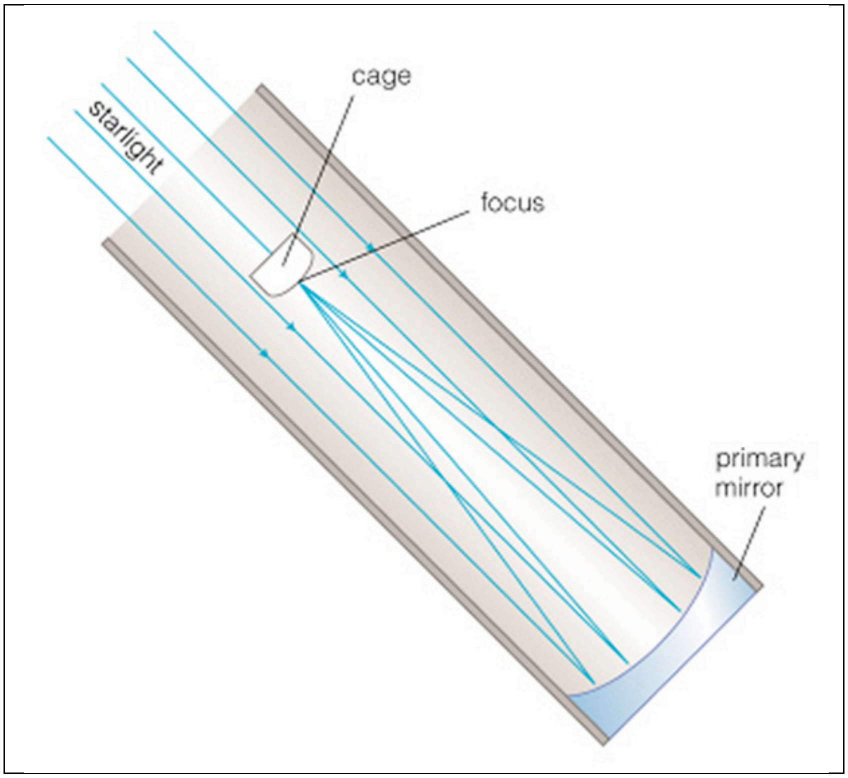




Refractors are no longer used much in professional astronomy. Some of the problems with refractor telescopes are

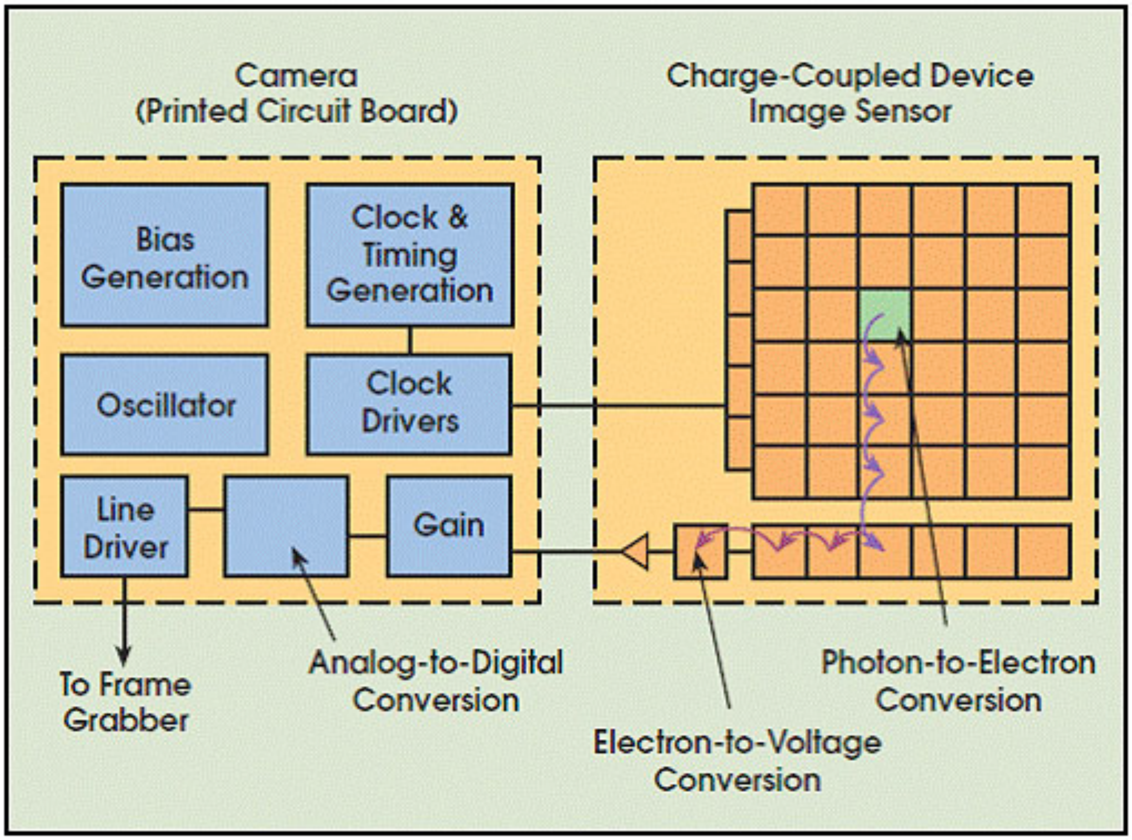
- They are susceptible to chromatic and spherical aberration.
- It is difficult to make very large refracting telescopes since the lenses become very heavy. The largest refracting telescopes have objective lenses about 1 m in diameter.
- It is difficult to avoid contamination in the lens.

The other major telescope design in use is the **reflecting telescope**. This is an optical telescope that uses a single mirror, or combination of mirrors, that reflects and focuses light to form an image. The reflecting telescope was invented in the 1663 by James Gregory as an alternative to the refracting telescope. Reflecting telescopes allows for very large diameter objectives, and thus much greater light-gathering capabilities, than refracting telescopes do. Reflecting telescopes come in many design variations and may employ extra optical elements to improve image quality or place the image in a mechanically advantageous position.



Instrumentation

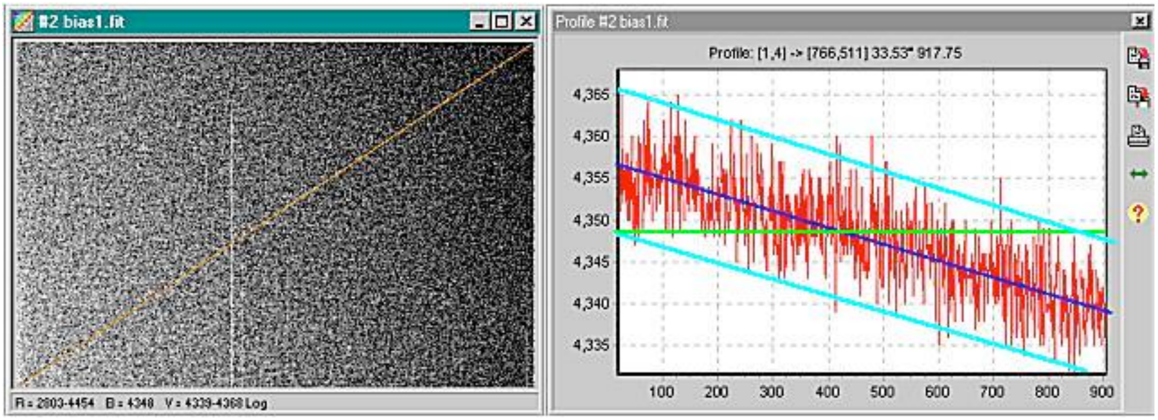
There are too many different types of optical instruments to discuss them all. However, they all share a common property of needing to detect and record incoming photons. One of the most common types of optical detectors is a **charge-coupled device** (CCD). The CCD consists of a photoactive region and a transmission region made out of a shift register.



An image from the telescope is projected onto the CCD where it falls on an array of silicon pixels (the photoactive region). This causes each pixel to accumulate an electric charge proportional to the light intensity at that location. A two-dimensional array of pixels captures the image. Once the exposure is complete a control circuit causes each pixel to transfer its contents to its neighbor below it in the same row. The last pixel in the row dumps its charge into a charge amplifier, which converts the charge into a voltage. By repeating this process for each row, and tracking the timing, the controlling circuit is able to convert the entire detector array to a sequence of voltages, which it samples, digitizes and stores in memory.

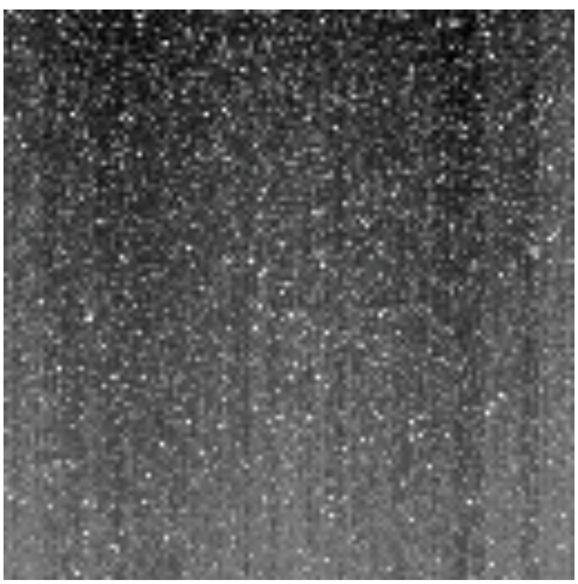
There are several effects that need to be considered when using a CCD for astronomical observations. Bias, dark current, and pixel-to-pixel sensitivity variations may affect the pixels in the CCD. To counter these effects, one needs to take a series of control exposures.

- **Bias**



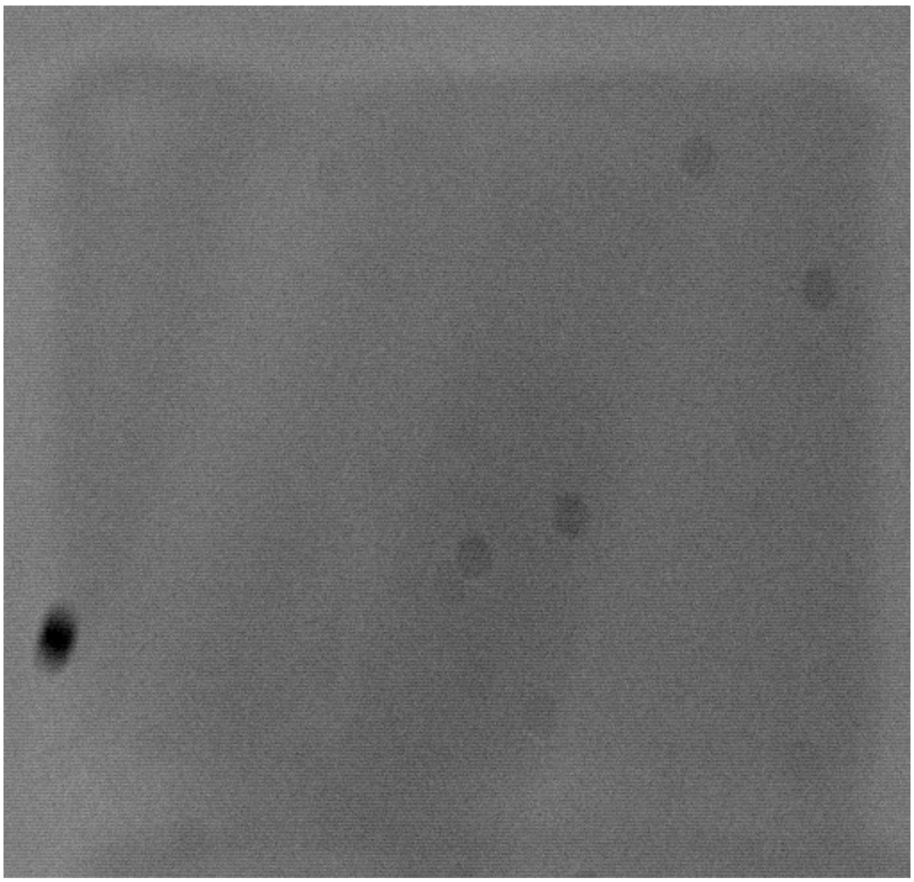
A CCD operates at a pedestal voltage that results in a pre-exposure signal of several hundred electrons on each pixel. The exact number of electrons varies with telescope position and the CCD operating voltage, and it can vary slightly from pixel to pixel. This bias signal needs to be subtracted from the CCD before the data can be used. To do this take a series of 0-second exposures with the shutter closed and average them to get a reasonable estimate of the bias in each pixel. Subtract this bias image from the CCD data image.

- **Dark Current**



Dark current is caused by random motion of electrons in the CCD array. In modern CCDs the dark current is very small, usually measured in electrons per hour, so it can often be ignored for short exposures. However, for long exposures, or exposures of fields with very low count rates, dark current can be a significant source of noise in an image. To correct for dark current take an exposure with the shutter closed for the same length of time as the data exposure. For example, if you exposed on NGC 205 for 3600 s then take a 3600 s dark exposure. The dark current changes with time and temperature so one should take dark exposures either shortly before or shortly after the data exposures. The dark exposure is subtracted from the bias-subtracted data exposure.

- **Pixel-to-Pixel Variations**



Each pixel in a CCD array will have a slightly different sensitivity. There are several ways to correct for this, and seasoned optical astronomers tend to develop their own arcane methodologies. The basic idea is to take an exposure of a uniform field, such as a blank region of sky, the twilight sky, or an illuminated screen on the side of the observatory dome, to measure pixel-to-pixel variations in the recorded intensity. Several exposures are taken and averaged, then the averaged exposure is normalized so that the mean signal in a pixel is unity. The bias-subtracted, dark-subtracted data image is divided by this flat-field frame to correct for the pixel-to-pixel sensitivity variations.

Detailed information about how to preprocess optical CCD data is available in *A User's Guide to CCD Reductions with IRAF*, which is available at http://iraf.noao.edu/docs/photom.html. Although this guide is intended for use with the IRAF software package the basic information is general to all astronomical CCDs.

Composite optical image of M31.

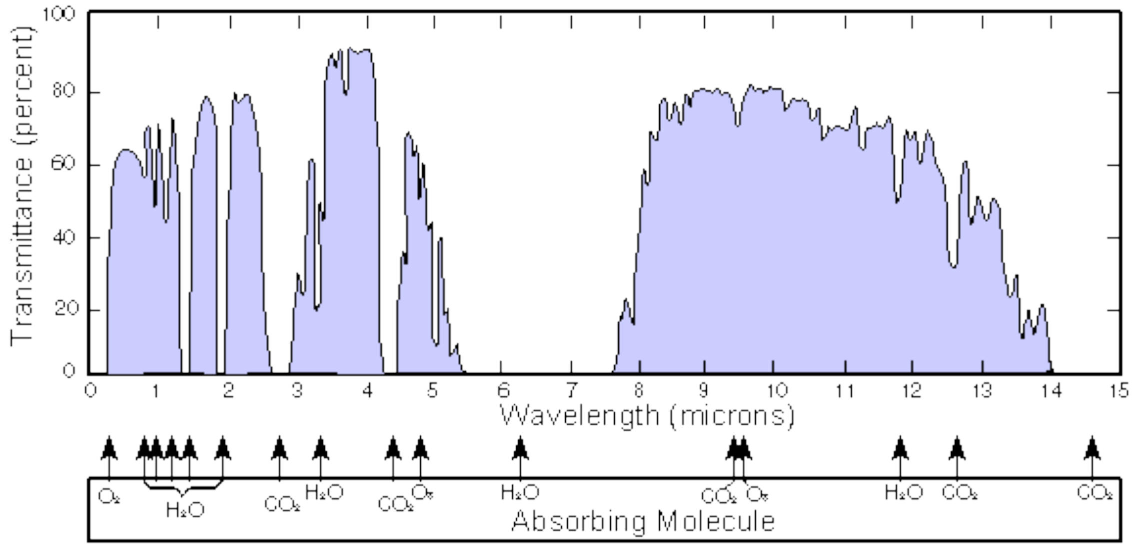
Infrared Astronomy

Introduction

Infrared astronomy is the study of astrophysical sources between wavelengths between approximately 8000 Å and 1 mm. The main infrared bands are

Wavelength (μm)	Band	
0.65–1.0	*R* and *I*	All major optical telescopes
1.25	*J*	Most major optical telescopes and most dedicated infrared telescopes
1.65	*H*	Most major optical telescopes and most dedicated infrared telescopes
2.2	*K*	Most major optical telescopes and most dedicated infrared telescopes
3.45	*L*	Most dedicated infrared telescopes and some optical telescopes
4.7	*M*	Most dedicated infrared telescopes and some optical telescopes
10	*N*	Most dedicated infrared telescopes and some optical telescopes
20	*Q*	Some dedicated infrared telescopes and some optical telescopes
450	Sub-mm	Sub-millimetre telescopes

The wavelength regions between these bands tend to have low atmospheric transmission, so they need to be observed from space. Dedicated infrared and sub-millimetre telescopes tend to be located at very high altitude sites so that they are above the bulk of the Earth's atmosphere. The atmospheric transmission in part of the infrared, along with the main absorbing molecules, is shown below.



Astronomers tend to divide the infrared spectrum into three regions based on the transmission properties of the atmosphere and the type of telescopes and instrumentations that are needed.

- **Near-Infrared**
  7000 Å – 5 μm
- **Mid-Infrared**
  5 μm – 40 μm
- **Far-Infrared**
  40 μm – 350 μm

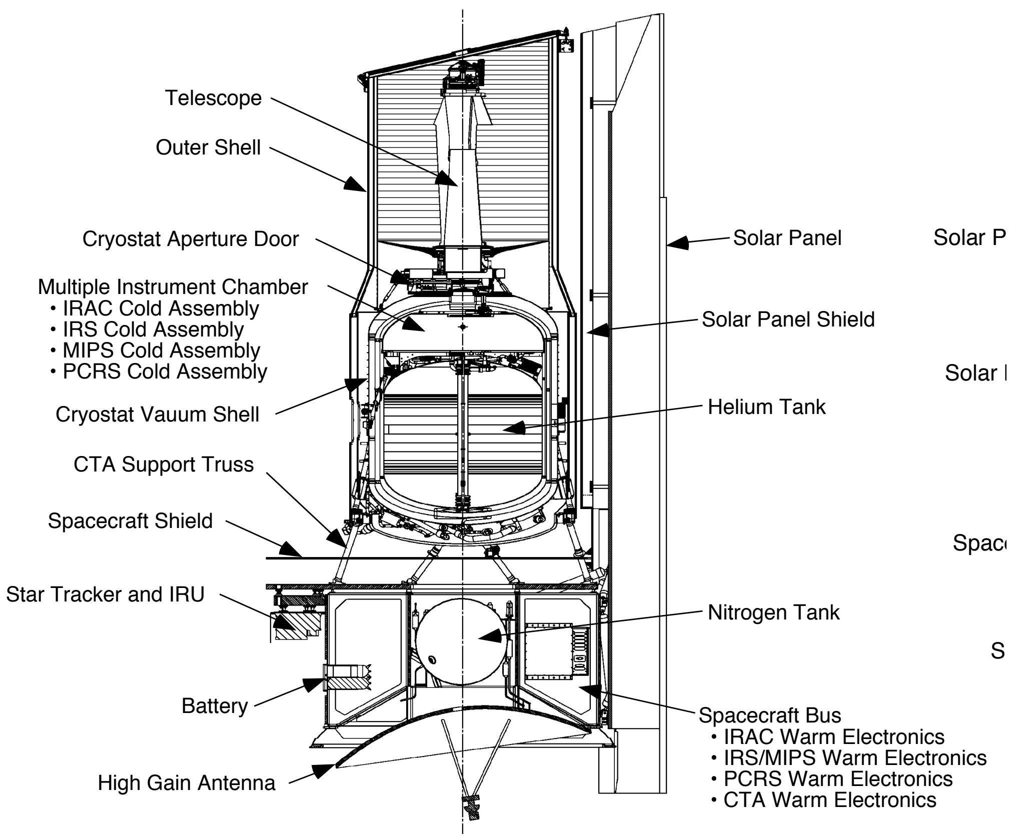
The infrared portion of the spectrum can provide a good deal of information that is not available at optical wavelengths. Cold, dark molecular clouds of gas and dust in the Galaxy radiate primarily in the infrared. Infrared can also be used to detect protostars on the Hayashi track before they begin core fusion. Stars emit a smaller portion of their energy in the infrared spectrum, so cool objects such as exoplanets can be more readily detected as they are brighter relative to their parent stars in the infrared than they are in optical.

Infrared light is also useful for observing the cores of active galaxies, which are often cloaked in gas and dust. High-redshift galaxies have the peak portion of their spectrum redshifted toward longer wavelengths, so they are more readily observed in the infrared.

Telescopes

Near- and mid-infrared telescopes are essentially the same as optical telescopes and operate on the same principles. The details of the instrumentation differ, but the basic steps for making images and spectra are the same.

Below is a schematic diagram of the *Spitzer Space Telescope* showing the critical components. *Spitzer* operates in the mid-infrared.



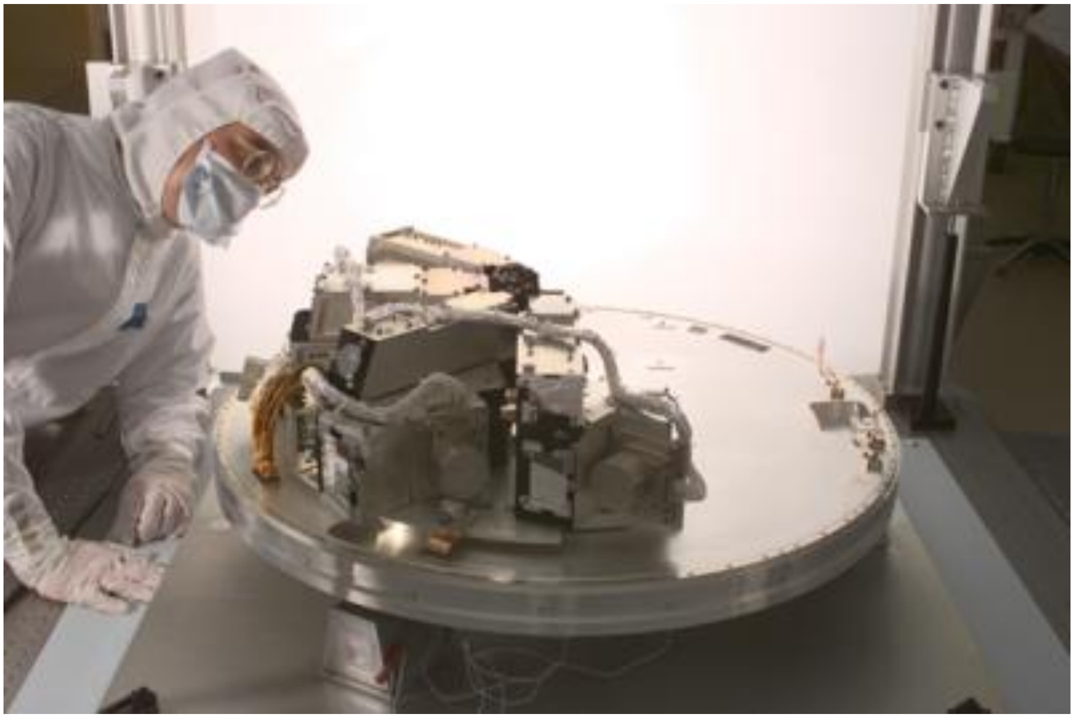
Notice that a significant portion of the structure is devoted to coolant (the helium and nitrogen tanks). Thermal noise can be a major problem with mid- and far-infrared observations, so it important to keep the telescope and instruments cooled. To help with this *Spitzer* was placed at the Earth–Sun L2 point and always points away from the Sun. *Spitzer* also has active cooling which maintains an operating temperature of approximately 4 K. *Spitzer* exhausted its on-board supply of cryogen in May 2009 and since then has been running a warm mission that allows some of its instruments to continue to return scientific data.

Spitzer has three instruments on-board:

- IRAC (**I**nfra**r**ed **A**rray **C**amera)

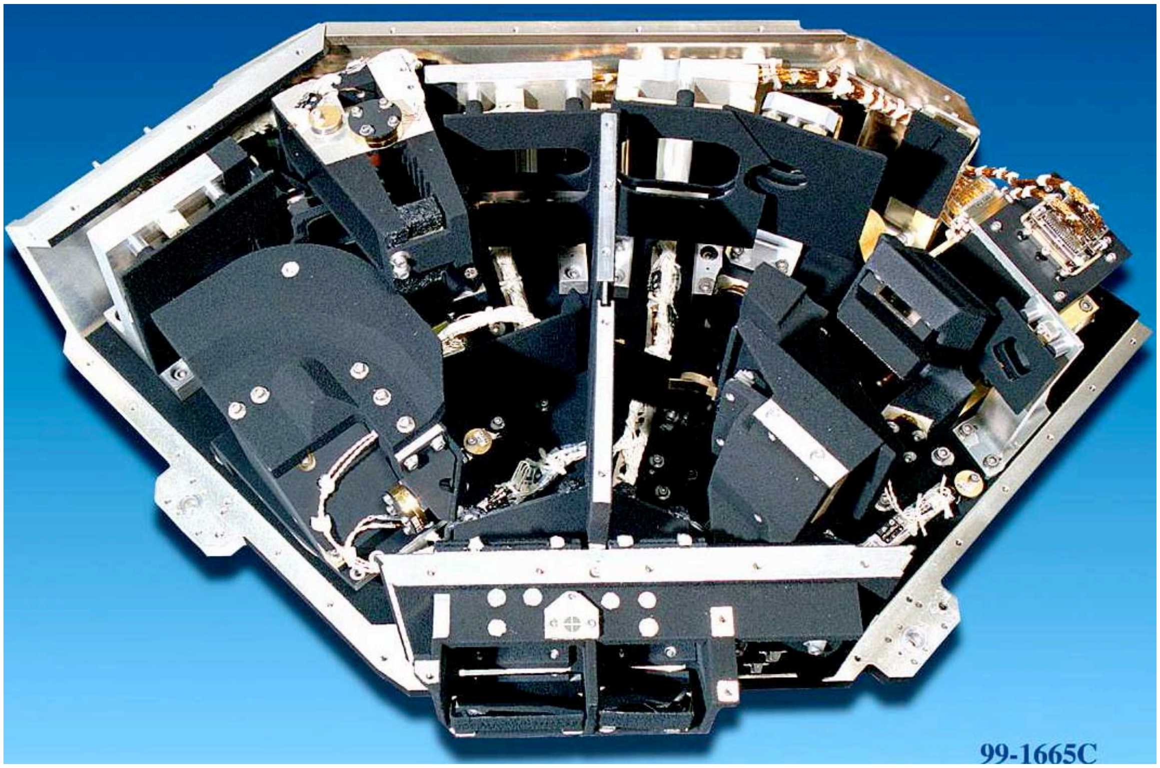
IRAC is an infrared camera that operates simultaneously at four wavelengths (3.6 μm, 4.5 μm, 5.8 μm and 8 μm). Each module uses a 256 × 256 pixel detector – the short wavelength pair use indium antimonide technology, the long wavelength pair use arsenic-doped silicon impurity band conduction technology.

- IRS (**I**nfra**r**ed **S**pectrograph)

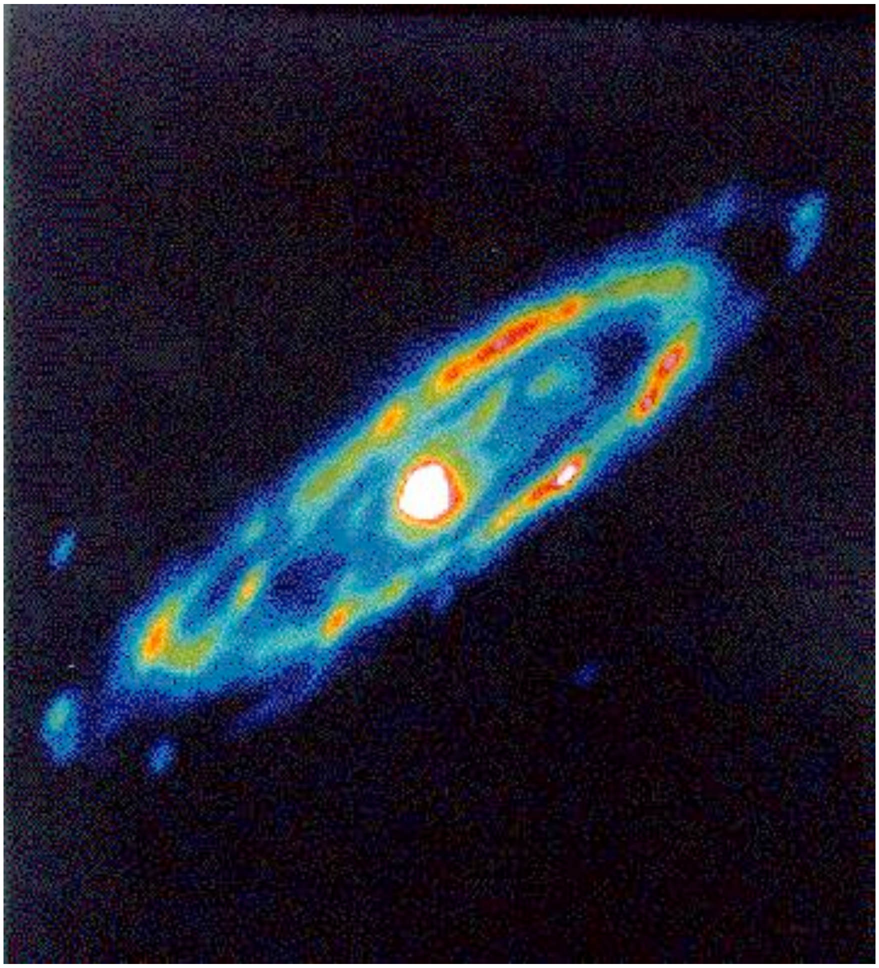


IRS is an infrared spectrometer with four sub-modules that operate at the wavelengths 5.3–14 μm (low resolution), 10–19.5 μm (high resolution), 14–40 μm (low resolution), and 19–37 μm (high resolution). Each module uses a 128 × 128 pixel detector. The short wavelength pair use arsenic-doped silicon blocked impurity band technology, the long wavelength pair use antimony-doped silicon blocked impurity band technology.

- MIPS (**M**ultiband **I**maging **P**hotometer for **S**pitzer)



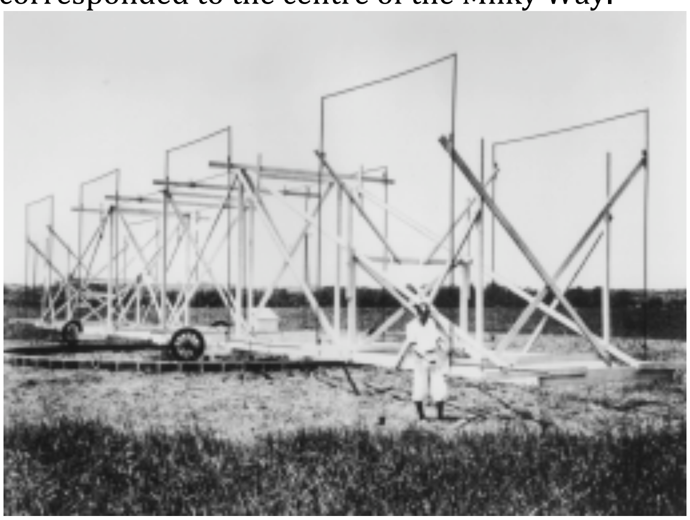
MIPS has three detector arrays in the far infrared (128 × 128 pixels at 24 μm, 32 × 32 pixels at 70 μm, 2 × 20 pixels at 160 μm). The 24 μm detector is identical to one of the IRS short wavelength modules. The 70 μm detector uses gallium-doped germanium technology, and the 160 μm detector also uses gallium-doped germanium, but with mechanical stress added to each pixel to lower the band gap and extend sensitivity to this long wavelength.


Composite infrared image of M31.

Radio Astronomy

Introduction

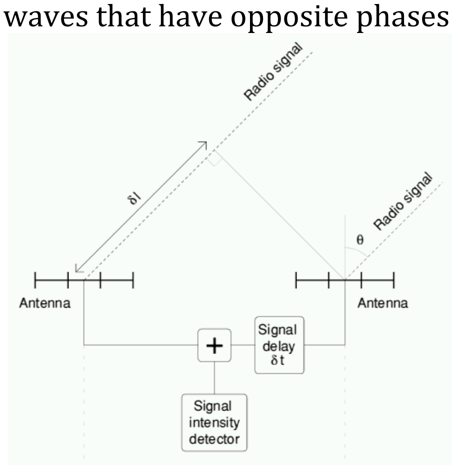
Radio astronomy works at wavelengths longer than approximately 1 cm. The first identified astronomical radio source was discovered serendipitously in the early 1930s when Karl Jansky, an engineer with Bell Telephone Laboratories, was investigating static that interfered with short wave transatlantic voice transmissions. Using a large directional antenna, Jansky noticed that his analogue pen-and-paper recording system kept recording a repeating signal of unknown origin at 20.5 MHz. Since the signal peaked once a day, Jansky originally suspected the source of the interference was the Sun. However, continued analysis showed that the source was not following the 24 hour Solar day but instead repeating on a cycle of 23 hours and 56 minutes, which matches the sidereal day. Since Jansky's array was directional he was able to localize the source in the sky and found that it corresponded to the centre of the Milky Way.



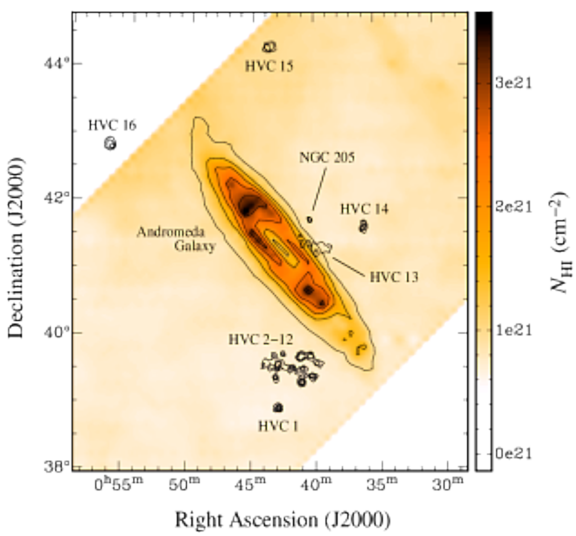
Radio Telescopes

There are two broad categories of radio telescopes. The first is the standard dish antenna. This is of a parabolic dish (or mesh) that focuses radio waves onto a receiver. The basic principle is similar to that of an optical reflecting telescope. Dish antennae are usually directional and can produce radio maps of the sky.

The second type of radio telescope is an array of dish (or mesh) antennae that are linked together to form an interferometric array. All of the telescopes in the array are widely separated and are connected together using coaxial cable, a waveguide, optical fiber, or some other type of transmission line. Having multiple antennae not only increases the total signal collected, it can also be used for aperture synthesis, which vastly increases resolution. Aperture synthesis can yield angular resolution of 1 milliarcseconds, or better. This technique works by combining the signals from the different telescopes in a coherent way so that the wavefronts that are recorded by each antenna can be matched. The result is that that waves that coincide with the same phase will add to each other while two waves that have opposite phases will cancel each other out.



This creates a combined telescope that is the size of the antennas furthest apart in the array. In order to produce a high quality image, a large number of different separations between different telescopes are required. The Very Long Baseline Array telescope uses antennae in Hawai`i, the continental US, and the Caribbean to construct a radio telescope with a baseline that is approximately 5000 km long.



Radio image of M31.