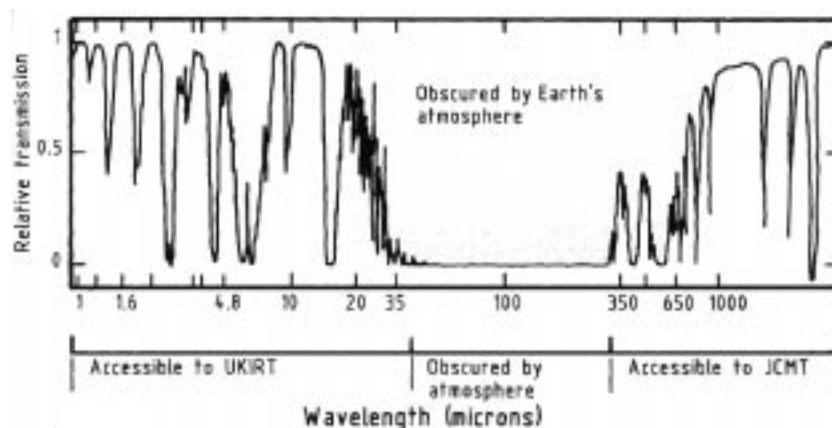


## Infrared Astronomy

There are two consequences of moving astronomical observations to longer wavelengths:

(a) **Earth's atmosphere** is not transparent at all wavelengths; see diagram below, showing **atmospheric windows** between heavy absorption bands of  $\text{H}_2\text{O}$  and other constituents. (Do you understand the connection between IR absorption bands and the 'greenhouse effect'?). Best IR sites are high, dry mountain tops, e.g. Mauna Kea (4200 m) in Hawaii. Effective range for ground-based IR astronomy is  $1-3\mu\text{m}$  (with gaps!). Millimetre-wave telescopes, like the James Clerk Maxwell Telescope, also in Hawaii, pick up the spectrum again from  $350\mu\text{m}$  onwards (see later lecture). Note that IR does not penetrate clouds.



This diagram shows how the Earth's atmosphere defines a set of atmospheric 'windows' through which radiation can penetrate.

Aircraft (12000 m+) carry smaller telescopes but get much better transparency above most of the  $\text{H}_2\text{O}$ : NASA had the Kuiper Airborne Observatory (KAO) dedicated to astronomy, now to be replaced by SOFIA (Stratospheric Observatory for Far-Infrared Astronomy) – a 2.5-m telescope in a Jumbo Jet!). Perfect (but expensive!) sky transparency is available from spacecraft: e.g. ISO, the Infrared Space Observatory, was launched in 1995.

(b) **Resolution** of fine structural detail decreases as  $\lambda$  increases. This is because light gets blurred as it is **diffracted** through the telescope aperture. The key formula is:

$$\text{Resolution / arc-seconds} = 250,000 \times (\text{wavelength / aperture})$$

Thus for 4-m telescope in visible light, e.g.  $\lambda = 0.5\mu\text{m}$ , theoretical resolution =  $0''.03$ . Atmospheric blurring ('**seeing**') due to turbulence actually limits resolution to  $\simeq 1''$  (10p coin at 3 miles!). But at  $\lambda = 30\mu\text{m}$  the above formula gives  $1''.8$ , which is worse than the 'seeing' limit. Resolution gets much worse as we move through millimetre waves towards the radio region, so bigger telescopes are needed.



**1800: Sir Wm HERSCHEL** discovered IR by placing thermometers beyond the red end of the Sun's spectrum.

**1856: C PIAZZI SMYTH** (Professor of Astronomy at Edinburgh) used an electrical IR detector at a high, dry site in Tenerife to measure the IR radiation of the Moon. He pointed his detector at the Moon and then at the clear sky near the Moon, in order to compensate for the IR radiation from the Earth's atmosphere; thus he pioneered sky subtraction, now a standard technique of IR astronomy. Lack of really sensitive IR detectors prevented any major advance in IR astronomy during the next 100 years.



**1963-68: NEUGEBAUER & LEIGHTON** used home-made 60-inch telescope at CalTech, with PbS (lead sulphide) detector, to make the first infrared sky catalogue of  $\sim 5600$  objects. Most were 'ordinary' cool stars – but there were some surprises!

**1970s:** many specialised **infrared telescopes** were installed at dry mountain sites, for example UKIRT (UK Infrared Telescope) at 4200 m on Mauna Kea, Hawaii.

**1983:** IRAS spacecraft with 60 cm telescope made all-sky survey at wavelengths  $10\mu\text{m}$  –  $100\mu\text{m}$  inaccessible from ground-based telescopes.

**1986:** IRCAM infrared camera using array detector was commissioned on UKIRT by Edinburgh team.

**1995:** ISO launch, next-generation infrared space observatory.

**1997:** 2MASS; all-sky infrared imaging survey over  $1 - 2\mu\text{m}$ .

**2001?:** SIRTF, NASA Space Infrared Telescope Facility (like ISO, but bigger).

**2007???:** FIRST, ESA far-IR & sub-mm mission.

In 1963 the sensitivity limit of the  $2\mu\text{m}$  sky survey was magnitude 3. Today objects of magnitude 18 or fainter are routine to image: a gain of 15 magnitudes or ONE MILLION TIMES fainter. This gain is due principally to advances in detector/electronics technology.

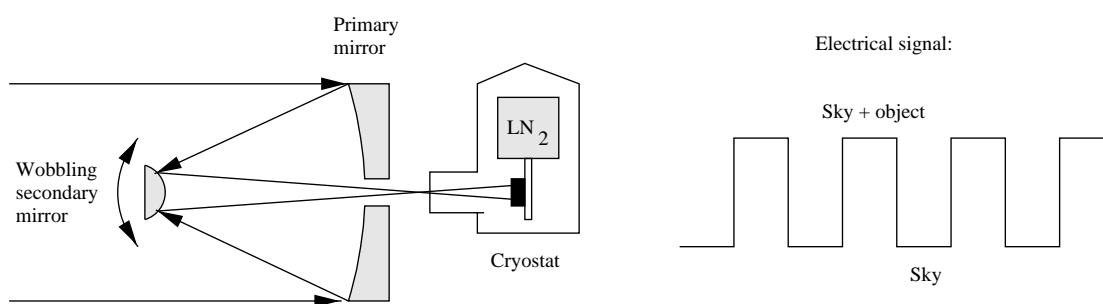
## IR DETECTORS

**(1) PHOTOCONDUCTORS:** Low-energy ( $< 1$  eV) photons of IR radiation can release electrons in the crystal lattice of some semiconductors, such as Si (silicon) and InSb (indium antimonide). These free electrons increase the electrical conductivity of the material and the resulting current flow can be measured. These detectors are selective; only photons of sufficient energy (short enough  $\lambda$ ) can release **photoelectrons**.

**(2) BOLOMETERS:** These are a kind of thermometer, which work best at the longer IR wavelengths,  $10\mu\text{m}$  onwards. They measure the increase in electrical current due to the heating effect of absorbed IR radiation. Modern bolometers use semiconductors such as Ge:Ga (gallium-doped germanium).

IR detectors are mounted in a **cryostat** (cooling vessel) filled with liquid  $\text{N}_2$  (77 K) or liquid He (4 K), to reduce noise due to thermal agitation.

**(3) IR PHOTOMETERS:** 300 K blackbody radiation peaks at  $\lambda = 10\mu\text{m}$ , which means that IR observations are made in the presence of overwhelming background from the atmosphere, telescope, etc. In day-time the Sun contributes only a modest increase to the thermal background, so day-time IR observations are possible! The background radiation is subtracted by **sky-chopping**, as used by Piazzzi Smyth over 100 years ago. The best method is a wobbling secondary mirror that flicks the image of the IR source on-and-off the detector, giving an oscillating signal that can be detected by a phase-sensitive amplifier.



Cooled diffraction-grating **spectrometers** (CGS), to study IR spectra, can be mounted inside (fairly large!) cryostats. Alternatively, narrow-band **interference filters**, isolating a spectrum pass-band such that  $\delta\lambda/\lambda \simeq 0.01$ , are used for mapping IR objects at a single wavelength (e.g.  $\text{H}_2$  line).

**(4) IR CAMERAS:** These are based on (expensive!) arrays of (typically)  $256 \times 256$  detectors-on-a-chip, analogous to the CCD (**Charge-Coupled Device**) array detectors used in optical astronomy (and in domestic video cameras). These obtained the first IR 'pictures' and are enormously more efficient than the previous process of scanning an area with a single detector, or scanning a spectrum line by line. Edinburgh's IRCAM was first to go into regular service. IR arrays up to  $1024^2$  pixels now exist, and  $2048^2$  detectors are expected soon [Sky & Telescope, June 1995].



## IR SOURCE MECHANISMS:

- (1) **Blackbody radiation** from interstellar solid particles ('dust' or 'grains'). Temperature ranges from 1000 K very close to stars, to 10 K in the interior of dense dust-clouds, shielded from star radiation that could heat the grains.
- (2) **Free-free emission** from ionized gas-clouds ('HII regions') bombarded by energetic photons from young, hot stars.
- (3) **Spectral line emission** (or absorption) by interstellar molecules and atoms. Found mostly in the millimetre region, but a few, e.g. H<sub>2</sub>, in near IR.
- (4) **Radiation from 'ordinary' stars** seen through clouds of cool interstellar grains. The grains are  $< 1\mu\text{m}$  in diameter and absorb visible light much more strongly than IR (see below). Most stars, if more than 100 light-years away, suffer some absorption (typically half a magnitude per 1000 light-years); others sit inside 'cocoon' of dust and are quite invisible in optical radiation but easily observed in the IR. 'Seeing' otherwise invisible stars is a major benefit of IR astronomy.

## SOME IR ASTRONOMY

(1) IR radiation 'sees through' very dense circumstellar/interstellar **dust clouds**. A striking example is the centre of our Galaxy (the Milky Way), which is a complex and rapidly evolving region. At visible wavelengths the absorption towards the Galactic Centre is  $\sim 30$  magnitudes (a factor of  $10^{12}$  or one million million); the GC is completely invisible, and ordinary photographs show only relatively nearby star-clouds. But at  $2.2\mu\text{m}$  the absorption is only 3 magnitudes (absorption factor  $10^{0.4 \times 3} = 10^{1.2} \simeq 16$ ) and the GC is readily mapped showing intense radiation sources and complex velocities. The Brackett- $\gamma$  line of hydrogen atoms can be observed, and the Doppler-shift (formula:  $\delta\lambda/\lambda = v/c$ ) of Br $\gamma$  gives velocities. (can **you** work out the wavelength of the Brackett- $\gamma$  line?).

(2) The study of star formation is a major aim of IR astronomy. Star formation (recall 'Star Birth' in Astronomy 1Ah) occurs in clouds of gas and dust that are visible, if at all, only as dark patches seen against the Milky Way star-clouds. IR lets us see into these 'star nurseries'. The dust itself is heated as stars form and glows ( $T < 1000$  K) in the mid-IR (e.g.  $10\mu\text{m}$  at 300 K), emitting huge quantities of previously unsuspected energy. Dust grains emit fairly narrow spectral 'features' (broader than atomic/molecular lines), e.g. from silicates ( $9.7\mu\text{m}$ ), H<sub>2</sub>O ice ( $3.08\mu\text{m}$ ), solid CO ( $4.67\mu\text{m}$ ); others remain unidentified.

(3) **Giant Molecular Clouds** (GMCs) are huge cool clouds of gas and dust-grains, in which star-forming regions occur locally. Since the dissociation energy required to break up molecules is only a few eV (corresponding to light of visible wavelengths – check this!), molecules can survive only deep inside clouds where the grains shield them from ambient starlight. Millimetre-wave astronomy has revealed an astonishing variety of organic molecules in these regions. The cool grains (10–15 K) radiate in the far-IR, best studied from spacecraft (e.g. IRAS). Within the GMCs are hotter regions (30–100 K) where star formation is probably occurring. Whereas cold hydrogen radiates only in the radio region, molecular hydrogen (H<sub>2</sub>),



whose dissociation energy is  $4.5\text{eV}$ , can form in large quantities in dust-clouds, and its spectral lines are observable in the  $2\mu\text{m}$  region.

(4) **Star formation in external galaxies** is indicated by strong IR radiation from the dust-clouds in which stars are forming (at a later stage, their increasing radiation evaporates the dust). While ordinary galaxies like our Milky Way emit about half of their energy as IR radiation, the IRAS survey found many spiral galaxies that emit 95% of their radiation in the IR, implying a stage of very vigorous grains heated by newly formed stars). Calculations show that the available material could not sustain such high energy output for more than a few  $\times 10^8$  years, whereas galaxy ages are of order  $10^{10}$  years. Such starburst galaxies must represent a transient phase in a galaxy's evolution. It is an open question whether all galaxies go through a starburst episode.

(5) **Star Populations in Galaxies:** Optical photographs of galaxies tend to show the 'frosting on the cake', the spiral arms outlined by chains of young, bright, blue stars. Nevertheless, the older, fainter, yellower stars (like our Sun) comprise most of the (observable!) mass of the galaxy and dominate its dynamics near the centre (dynamics in the outer regions is however dominated by dark matter, whose true nature is perhaps the biggest mystery in astronomy). IRCAM  $2\mu\text{m}$  pictures of galaxies show up the smoother distribution of the older star population.

In our Milky Way galaxy the nearest 'star nurseries' lie in the constellation of Orion, about 1500 light-years away. We shall look at a series of pictures of Orion at different wavelengths, concentrating on the star-forming regions.