Infrared and Millimetre Astronomy

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

(a) Earth's atmosphere is not transparent at all wavelengths; there are **atmospheric windows** between heavy absorption bands of H_2O and other constituents (these IR absorption bands are responsible for 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 $1-10\mu$m (with gaps). Millimetre-wave telescopes, like the James Clerk Maxwell Telescope, also in Hawaii, pick up the spectrum again from 350μm onwards.

Aircraft (12 km+) carry smaller telescopes but get much better transparency above most of the H_2O: NASA is building 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. IRAS (Infrared Astronomy Satellite) was launched in 1983 and used a 60-cm telescope to map the whole sky at wavelengths 10μm -100μm. This is still the best survey at these long wavelengths.

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

$$\boxed{\text{Resolution / arcseconds} = 250{,}000 \times (\text{wavelength / aperture})}$$

(remember 1 degree = $3600''$). Thus for 4-m telescope in visible light, e.g. $\lambda = 0.5\mu$m, theoretical resolution = $0''.03$. Atmospheric blurring ('**seeing**') due to turbulence actually limits resolution to $\simeq 1''$ (10p coin at 3 miles). But at $\lambda = 30\mu$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.

MILLIMETRE-WAVE ASTRONOMY

The region between IR and radio wavelengths was one of the last to be explored by astronomers: radiation is generally weak (N.B. blackbody flux density $\propto \lambda^{-2}$), atmosphere is absorbing, detection technology is difficult, at the borderline between optical and radio techniques. Discovery of many interstellar lines from **molecules** in the 1960s encouraged construction of special telescopes for the mm/sub-mm region. With the discovery of lines at or below $\lambda = 1$ mm, telescopes began to be designed with very high surface accuracy to work efficiently in this region.

Most precise is the 15-m JCMT (James Clerk Maxwell Telescope) on Mauna Kea, Hawaii. To focus radiation efficiently at $\lambda = 300\mu$m, surface accuracy of the 276-panel metal reflector has to be $\pm 20\mu$m, or better than 1/1000 inch – remarkable engineering. Applying the angular resolution formula to the JCMT, we see the penalty for working at longer wavelengths:

at $\lambda = 300\mu$m: $250{,}000 \times 0.3/15{,}000 = 5$ arcseconds
at $\lambda = 3$ mm: $250{,}000 \times 3/15{,}000 = 50$ arcseconds

IR & MM-WAVE EMISSION 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. This is also known as **bremsstrahlung** – German for 'braking radiation'. This arises from electrons being accelerated by the electrostatic field of nuclei in low-density clouds of hot ionized gas ('plasma'). The spectrum of radiation from this process looks very different from black-body radiation; it is flat (same flux at all frequencies) up to a maximum photon energy, which is of order the typical thermal electron energy (kT).

(3) **Spectral line emission** (or absorption) by interstellar molecules and atoms. Atomic signatures are found in the optical/UV and IR. Especially important is **recombination radiation**, where the separate electrons that constitute a plasma come together to make an atom. Longer-wavelength emission comes from molecules, of which H_2 is the most important. These have two reasons for emitting: changes in their rotational or their vibrational energy state. Rotational energy levels are more closely spaced, and tend to produce millimetre emission, whereas vibrational changes are associated with infrared photons.

(4) **Radiation from 'ordinary' stars** seen through clouds of cool interstellar grains. The grains are $< 1\mu$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 'cocoons' 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.

IR & MM-WAVE OBSERVING TECHNIQUES

(1) PHOTOCONDUCTORS Low-energy (< 1 eV) photons of IR radiation can release electrons in the crystal lattice of some semiconductors, such as 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 λ) can release **photoelectrons**.

(2) IR CAMERAS These are based on (expensive) arrays of (typically) 256×256 detectors-on-a-chip, analogous to the CCD array detectors used in optical astronomy. These obtained the first IR 'pictures'; 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]. The solid-state technology is more exotic than the Silicon used in optical CCDs: common combinations are InSb (Indium Antimonide) or HgCdTe (Mercury–Cadmium–Tellurium). This is because the photon energies are much lower than in the optical; the energy needed to excite an electron in Silicon is too large to detect IR photons.

(3) BOLOMETERS These are a kind of thermometer, which work best at the longer IR wavelengths, 10μm 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 N_2 (77 K) or liquid He (4 K), to reduce noise due to thermal agitation.

(4) HETERODYNE TECHNIQUES Bolometers detect radiation over a very broad frequency range. To obtain high spectral resolution at short wavelengths, it is possible to use the same method as in optical astronomy and disperse the light with a diffraction grating. At longer wavelengths (above 1 mm $\leftrightarrow$ 300 GHz $\leftrightarrow 3 \times 10^9$ Hz), it is better to use a technique that is common in radio astronomy. The signal is mixed with a **local oscillator** at frequency ν_L to produce difference frequency $\nu - \nu_L$ that lies in low GHz range (typically 1% of ν) and is detected by ordinary radio techniques. This is the method used to detect the narrow line radiation from interstellar molecules.

(5) BACKGROUND SUBTRACTION 300 K blackbody radiation peaks at $\lambda = 10\mu$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**: a wobbling secondary mirror 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.

(6) CRYOGENICS With such detectors, IR astronomy becomes more like optical astronomy. Not only can direct images of the sky be obtained, diffraction-grating **spectrometers** can be used to study IR spectra. However, it is important not to inject unwanted background radiation into the detector. This means that all the components of the instrument have to be mounted inside cryostats, cooled perhaps to liquid Helium temperatures (4 K).

Some of the basic principles important in the IR were established quite early on. In 1800, Sir Wm HERSCHEL discovered IR radiation by placing thermometers beyond the red end of the Sun's spectrum. In 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.

TOPICS OF IR & MM-WAVE 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 ~ 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 2.2μm the absorption is only 3 magnitudes (absorption factor $10^{0.4\times3} = 10^{1.2} \simeq 16$) and the GC is readily mapped showing intense radiation sources and complex velocities. The Brackett-γ 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-γ 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'. In our Milky Way galaxy the nearest 'star nurseries' lie in the constellation of Orion, about 1500 light-years away. The dust itself is heated as stars form and glows ($T < 1000$ K) in the mid-IR (e.g. 10μm 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 (9.7μm), H_2O ice (3.08μm), solid CO (4.67μm); others remain unidentified. Submillimetre radiation can penetrate the dust-clouds, revealing very young stars and **protostars**. Highly supersonic and chaotic gas-flows of order 8 kms^{-1} are revealed by the widths of the molecular lines. In the vicinity of highly-luminous newly formed stars (e.g. in the Kleinmann-Low Nebula in Orion) molecular lines show velocities $\sim 100\,\mathrm{km\,s^{-1}}$ in vigorous outflows.

(3) **Giant Molecular Clouds** (GMCs) are huge cool (10 – 100 K) clouds of gas and dust-grains, with total masses of order $10^5 - 10^6$ suns. Since the dissociation energy required to break up molecules is only a few eV (corresponding to light of visible wavelengths), 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. At such low temperatures, and densities of order 300 molecules per cm^3 (mean free path of millions of km between collisions), chemistry is very different from laboratory chemistry; for example, only 2-body interactions need be considered. Free radicals (e.g. OH) and ionized molecules (e.g. CH^+) can persist. Catalysis on the surface of dust grains is very important in forming more complex molecules: this is where ingredients of molecules can accumulate until they are able to combine. Within the GMCs are hotter regions (30 – 100 K) where star formation is probably occurring. The dust-shielded environment was probably essential in order to give these denser clouds time to collapse. The residual dust around the protostar is of course what gives rise to planetary systems around stars, which are now known to be very common.

(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 2μm pictures of galaxies show up the smoother distribution of the older star population.

(6) The peak region of the spectrum of cosmic microwave background radiation at 2.7 K is measured in the millimetre range. This radiation, highly significant for our understanding of the early history of the Universe, is considered in a later lecture.