Astronomy 1Bh *The New Astronomies* **Spring 2001**

Overview

Mankind has watched and studied the heavens for thousands of years, with the help of just one 'detector' – the human eye. Our eyes respond to radiation over a very restricted range of **wavelengths** from violet to red:

$$400\text{ nm} - 700\text{ nm} \quad (400\text{Å} - 7000\text{Å})$$

Our eyes are **logarithmic detectors**, leading to the definition of the magnitude:

$$\boxed{m = -2.5\log_{10}\text{flux} + \text{constant.}}$$

The constant is set so that the brightest stars are about zero magnitude; the faintest stars we can see are about 6th magnitude, or a factor about 250 fainter.

The **telescope**, invented in the 17th century, let us see much fainter stars, on account of its bigger light-collecting area; but the detector was still the limited human eye, which only adds up light over a short **integration time** (about 1/30 second). The invention of **photography** in the mid-19th century helped astronomers to see much fainter by using long time exposures, but even these detectors failed to register most of the light they received. The ultimate limit to sensitivity comes from the quantum nature of light: energy is transmitted in discrete packets of energy called **photons**, with energy

$$\boxed{E = h\nu}$$

at frequency ν, where h is Planck's constant. Today we often use **photoelectric detectors**, in which an electron is produced by the passage of a photon. The most common device is the kind of solid-state technology found in video cameras (the **CCD**, or charge-coupled device). The best of these devices will produce an electron on more than 80% of the occasions that they are struck by a photon. The equivalent rate for photographic plates is more like 1%.

However, much of the revolutionary expansion of astronomical knowledge during the past 40 years came through the development of **new technologies**. Astronomers can now survey the Universe not only in the limited optical range of 400 – 700 nm, but over the entire range of the electromagnetic spectrum from 10^{-6} nm to 10 m. This range spans a great variety of physical processes and new kinds of astronomical sources. Some information, too, comes from other observations besides electromagnetic radiation.

In this module we shall look in turn at various phases of this astronomical revolution: the observational techniques, the physical processes involved, and the new astronomical discoveries that resulted. The recommended textbook is ZELIK: 'Astronomy – The Evolving Universe' (8th edition; Wiley 1997). More detailed suggestions for optional background reading will given at relevant places in the notes, and at the end of the module.

TEMPERATURE AND WAVEBAND

Prof Lawrence (The Scientific Style) introduced the properties of thermal (or **blackbody**) radiation at temperature T, for which the energy distribution with frequency ν is given by the **Planck Formula**:

$$B(\nu, T) = \frac{2h}{c^2}\,\nu^3 \left(e^{h\nu/kT} - 1\right)^{-1} \to \frac{2kT}{c^2}\,\nu^2 \quad \text{for small } \nu,$$

where $B(\nu, T)$ gives the amount of energy being emitted in unit range of frequency, and k is called Boltzmann's constant. *You do not need to memorise or use this formula.* You should however know that thermal radiation peaks at wavelength $\lambda_{\rm peak}/\mu{\rm m} = 2900\,{\rm K}/T$ [Wien's Law] and that the total energy is proportional to T^4 [Stefan-Boltzmann Law]. The expansion of Planck's law shows that $B \propto \nu^2$ is characteristic of the low-frequency (long-wavelength) 'tail' of thermal radiation, which cuts off abruptly at high frequencies, where the photon energy exceeds the typical thermal energy kT.

The energy distribution of astronomical objects like **stars** is only *approximately* a blackbody curve. Nevertheless, it is a good rule of thumb to say that there is a close relation between the temperature of a body and the waveband where it emits most of its energy. Thus, stars have surface temperatures of a few thousand K and all emit most of their energy in the **visible spectrum** ($0.4 - 1\mu$m). However, sources at very high or very low temperatures would not be picked out from observations in the visible region. Examples of this set of sources are:

- Very hot matter such as gas streams in a close binary star: $T \sim 10^7$ K, peaking at $\lambda \sim 0.3$ nm (X-rays).
- Very cold matter such as interstellar grains (solid particles): $T \sim 30$ K, peaking at $\lambda \sim 100\mu$m (far infrared).

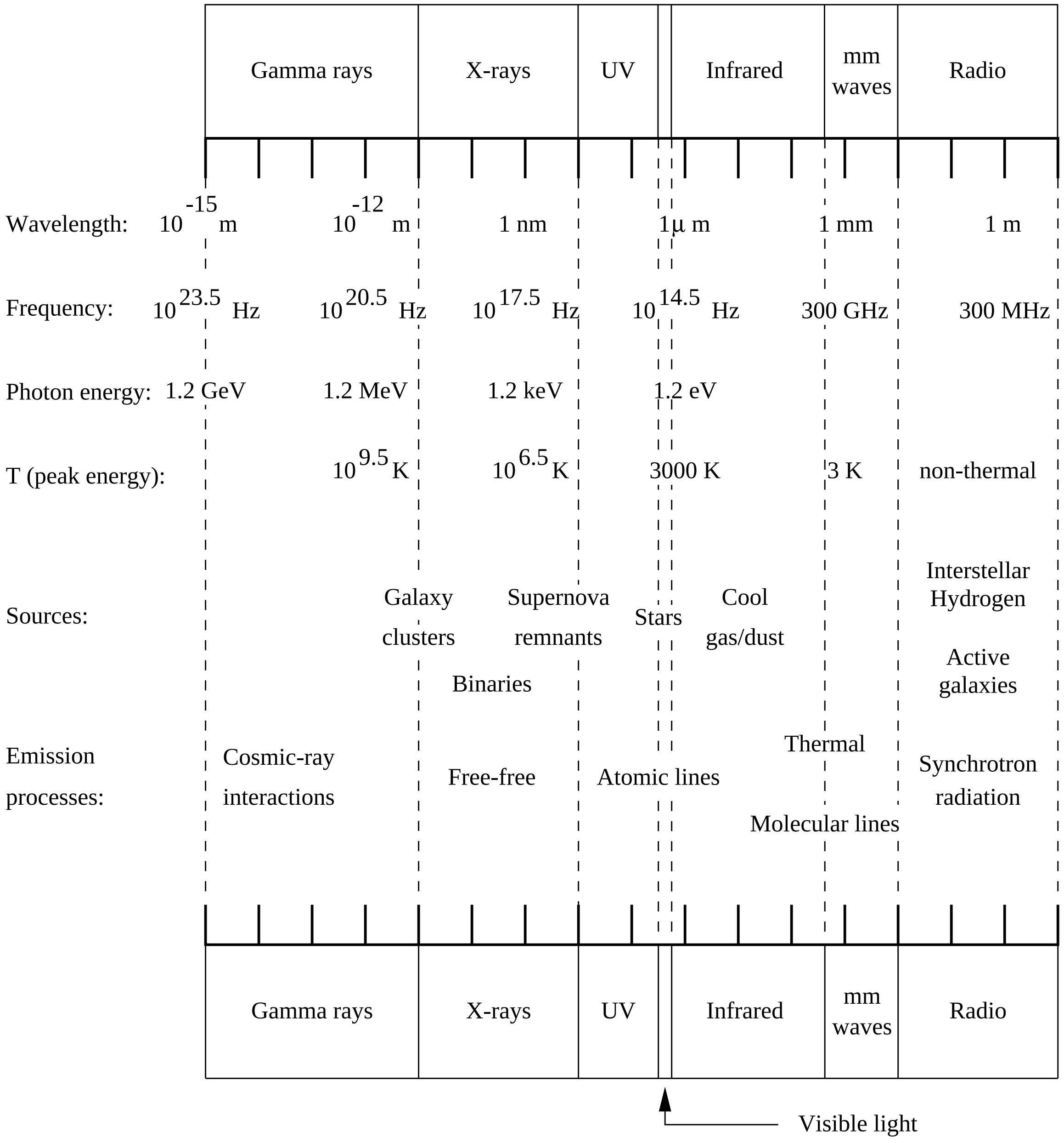
The existence of such sources, and even more exotic ones, was not revealed until the development of The New Astronomies.

SPECTRAL LINE RADIATION

The most important correction to the basic idea of smooth thermal emission is given by the narrow features that arise from transitions between discrete energy levels in atoms and molecules. These can be **emission lines**, if the dominant source of emission is a cloud of diffuse gas, or **absorption lines** if we have something like thermal emission shining through a cloud of gas. For example, the emission of the Sun contains many absorption lines owing to the thermal light from its main surface passing through its outer atmosphere.

Spectral lines are arguably the most important pieces of information in astronomy. They give important information about chemical composition, temperature, pressure, velocity (from the **Doppler shift** $\delta\lambda/\lambda = v/c$).

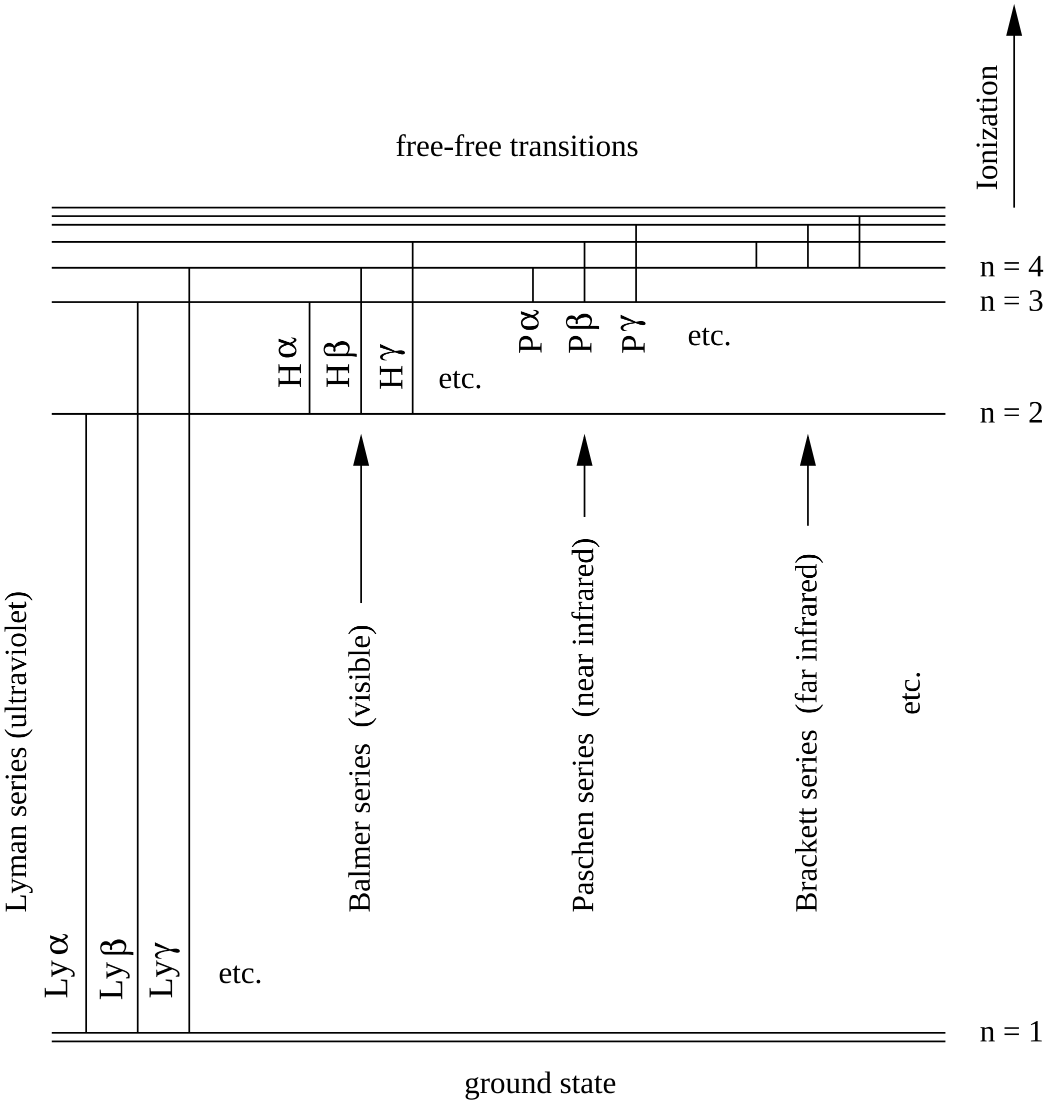
The Electromagnetic Spectrum



This diagram summarizes the range of wavelengths accessible to today's astronomers, together with some of the sources and processes that may produce the radiation we observe.

- Wavelength λ and frequency ν are related by $\lambda\nu = c$ (approximately $3 \times 10^8\,\mathrm{m\,s^{-1}}$).
- Photon energy $h\nu$ is approximately 1.25 electron volts (eV) at $\lambda = 1\mu$m.
- Planck distribution ('black body'): $T_{\rm peak} \simeq 2900/\lambda$, where T is in K and λ is in μm (WIEN displacement law).

Energy levels for the Hydrogen atom



For transition between two energy levels, $h\nu = E_m - E_n = 13.6(1/m^2 - 1/n^2)$ eV. Other atoms, and especially molecules, have more complicated energy levels.

- Cooler gas surrounding hotter star → absorption lines (↑ transitions)
- Free-space excited or ionized gas → emission lines (↓ transitions)
- In a cool gas most atoms are in ground state, $n = 1$. (N.B. 21-cm radio line of H; see below). H → H_2 in cool molecular clouds (giving more complex spectrum)

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 $10^{0.4 \times 3} = 10^{1.2} \simeq 16$) 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.

Radio astronomy

Radio astronomy spans 1 cm (upper end of mm-waves) to 30 m; longer wavelengths do not penetrate the Earth's ionosphere. Radio telescopes can see through clouds but are much afflicted by man-made interference, although certain crucial bands are supposed to be kept clear.

1933: Karl JANSKY (Bell Telephone Labs) detected radio 'noise' at 20 MHz ($\lambda = 15$ m), apparently coming from the Milky Way (he was looking for sources of 'interference'). Major development of radio astronomy did not occur until after World War 2, building on radar expertise. Pioneers included RYLE (Cambridge), LOVELL (Jodrell Bank), HEY (Malvern), and PAWSEY (Australia).

Unit of radio flux: 1 Jansky = 10^{-26} $\mathrm{Wm^{-2}Hz^{-1}}$

This was the weakest signal detectable by early radio telescopes; it is often used in the IR and optical now, although smaller units such as mJy and μJy are more practical these days.

RADIO TELESCOPES mostly paraboloid reflectors (as optical) with relaxed surface tolerance (need not even be solid). Size restricted by engineering considerations; largest steerable R.T. is the 100-m Max Planck Radio Telescope near Bonn (the much larger 1000-ft Arecibo dish is based on a natural hole in the ground). Resolution at $\lambda = 1$ m is $250,000 \times 1/100 = 2500$ arcseconds = 2/3 degree …so the biggest radio dish can't see as much detail as the human eye.

A solution is to combine telescopes over long baselines as **interferometers**. The separation d between the telescopes produces a phase difference between the signals in the two receivers. By connecting the two telescopes with a cable, their signals can be added. If the phase difference between the telescopes is a multiple of 360°, the signals add constructively; if the phase difference is 180°, the resultant is zero. In general, for a source at elevation θ, the wave-fronts reinforce if $d \cos\theta = n\lambda$, where d is the separation of the interferometer elements.

As the source moves across the sky, the combined signal therefore fluctuates as θ varies, giving rise to a characteristic pattern called **interference fringes**. This occurs only if the angular size of the source is less than λ/d (radians); if it is larger, the fringes from different parts of the source wipe out the pattern. So the technique gives information about fine structure in the source, but in a sort of tangled form. It is possible to disentangle the information about the sky brightness by using a computer to combine the fringe information taken at different interferometer spacings – although explaining how this trick works is not easy without mathematics.

If $d = 200$ km and $\lambda = 1$ m then we can detect source structure as fine as 1/200,000 radian or about 1 arcsecond, …about equal to optical resolution. Interferometry with long baselines is impossible in optical astronomy, because of phase fluctuations (distorted wave-fronts) in the Earth's atmosphere. The fluctuations are too small to affect the much longer radio waves.

APERTURE SYNTHESIS RYLE (Cambridge) showed how an array of telescopes can be used to 'synthesize' the aperture of a huge telescope. With a set of radio telescopes on an East-West railway track (left over from British Rail rationalization) plus a few on a North-South axis, we

- observe the source on successive days, with the baselines changed day-to-day;
- let the Earth's rotation change the orientation of each baseline, relative to the source, throughout each day;
- compute a map of the source from the combined data.

In this technique of Earth rotation synthesis the effect of a huge aperture is built up from successive baselines within the aperture. The Cambridge 'One-Mile Telescope' was built in 1964 and the '5km Telescope' in 1972. The biggest aperture synthesis array is the VLA (Very Large Array; built 1980 and still the best) in the New Mexico desert; it has 27 telescopes, each of 25m aperture, on a Y-shaped railway network. The VLA resolves 0.13 arcsecond at $\lambda =$ 1.3cm (23GHz).

VLBI or very long baseline radio interferometry, allows the synthesis technique to be extended to telescopes too far apart to be connected directly. The signals from each telescope are recorded on video tape and later correlated by computer, to reconstruct the effect of a very large synthesis array. The MERLIN multi-element radio-linked interferometer network based on Manchester has seven sites, from Jodrell Bank to Cambridge, contributing $(7 \times 6)/2$ $= 21$ different baselines ranging from 6km to 218km. USA has built the Very Long Baseline Array (VLBA) stretching from Puerto Rico to Hawaii, and achieving resolution of ~ 0.001 arcsecond (much better than the optical now). The EVN (European VLBI Network) is a similar arrangement in Europe (including China). The ultimate extension of this idea is to go to space; HALCA is a Japanese satellite launched in 1997, now giving VLBI resolution three times better than is possible from the Earth.

For a review of all these facilities, see Sky & Telescope, February 1997.

HOW RADIO SOURCES SHINE

- Free-free; recombination radiation; atomic and molecular lines, as for IR & mm-wave emission, but involving higher-order transitions.
- SYNCHROTRON RADIATION comes from very high-energy electrons, moving at velocities near the speed of light, and following helical paths about magnetic field lines, occurring in turbulent gas-clouds (e.g. remnants of supernova explosions). The more energetic the electron, the higher frequency radiation it emits, so the overall radiation spectrum depends on the energy distribution of the electrons. The spectral shape we typically see is rising with λ, i.e. falling with ν: $B_\nu \propto \nu^{-1}$ approximately, spread over many decades of frequency – likewise the electrons must have a huge range of energies – the gas in not in thermal equilibrium at all. How gas gets in this state, and especially how it accelerates some electrons to extreme energies, is a much debated topic.

RADIO SOURCES (MOSTLY) AREN'T STARS Because blackbody flux $\propto$ λ^{-2}, so ordinary stars are very weak at radio wavelengths. The Sun's radio flux is about 20,000 Jy at 100 MHz; at 10 parsecs, the distance of a quite nearby star, it would be $20,000 \times (10 \times 206,265)^{-2} = 5 \times 10^{-9}$ Jy . . . quite undetectable. If you lived on a cloudy planet and had to rely entirely on radio astronomy, you'd never know about the stars.

HIGHLIGHTS OF RADIO ASTRONOMY

(1) THE 21cm INTERSTELLAR HYDROGEN LINE Cold H-atoms in space sit in the ground state, but nuclear interactions split this into two states with a tiny energy gap between them. VAN DE HULST (Netherlands) predicted during World War 2 that transitions between the upper and lower levels would give a radio wavelength spectral line, at $\lambda = 21$ cm, $\nu = 1420$ MHz; it was detected in 1951. The 21-cm line can be used to map out the cold gas in our Galaxy and others, and also, using its Doppler shift, to study the rotation of galaxies. In particular, the unexpectedly large rotation of galaxies implies the existence of **dark matter**, whose nature is unknown.

(2) STAR FORMATION REGIONS Gas surrounding newly formed stars is heated and ionised by the UV light from massive young OB stars. Typical temperatures are around 10,000 K. This hot gas radiates **thermal free-free** emission over a wide range of wavelengths, but stands out clearly in the radio. Such objects are called 'HII regions' (as opposed to neutral hydrogen, which is 'HI'). Radio surveys through the plane of our Galaxy pick out many such HII regions, highlighting the places where stars formation is occurring today. However they also find larger diffuse regions which show a very different spectrum – the characteristic synchrotron spectrum, rising to long wavelengths. Recall that this is due to extremely fast ($v \simeq c$) electrons with a non-thermal energy distribution. So apparently, as well as cold gas and hot gas the interstellar medium contains relativistic plasma.

(3) SUPERNOVA REMNANTS Some supernova remnants radiate thermally: the blast wave has swept up and heated interstellar gas. But others radiate synchrotron emission – the classic example is the Crab Nebula. It seems likely that the particles are accelerated to relativistic energies in shocks caused by the blast wave – possibly this is the universal cause.

(4) RADIO GALAXIES In the 1950s radio astronomers surveyed the sky and found it peppered with bright radio sources that seemed to coincide with galaxies. They were often quite distant – so when the luminosities of these **radio galaxies** were worked out, they were much larger than that of the Milky Way, whose radio emission comes from the interstellar medium. For example, compare:

M31 (Andromeda)	200 Jy	600 kpc
CygA	14000 Jy	300 Mpc

Radio maps showed that the emission is typically coming from two giant radio lobes either side of the galaxy. Often there is also a bright and tiny spot in the very nucleus of the galaxy, and thin jet-like structures connecting the nucleus to the lobes. The radio spectrum shows synchrotron emission. Usually the nucleus also shows other signs of activity – for example strong emission lines. Overall, it seems that some sort of explosive activity has squirted out two opposite jets of relativistic plasma.

(4a) QUASARS In the 1960s quasi-stellar objects (QSOs, or quasars) were discovered. These were double radio sources like the radio galaxies, but instead of a galaxy in the middle, there was a star-like object. However the spectra of these were very surprising – they were very blue, had very broad emission lines (if this smearing is due to the Doppler effect, suggesting gas velocities around 10,000 $\mathrm{km\,s^{-1}}$), and had very large redshifts, making them more distant than all known galaxies. For example, 3C 273 has z=0.158: the recessional velocity is $cz =$

$0.158 \times 300{,}000 \simeq 47{,}000$ km s^{-1}. Dividing by a Hubble constant of 65 km s^{-1}Mpc^{-1}, the distance is approximately 730 Mpc. This is the nearest of the QSOs, They have been found out to $z > 5$ and serve as probes of the distant and early Universe.

(4b) ACTIVE GALACTIC NUCLEI We now realise that weaker quasar-like 'nuclear activity' is in fact quite common in nearby galaxies. Quasars we believe, are rare super-powerful Active Galactic Nuclei (known as AGN). Both quasars and nearby AGN have all sorts of other extra-ordinary properties – they emit X-rays and IR and ultraviolet light, and they flicker, flare and fade from day to day. Perhaps strangest of all, VLBI maps have shown 'blobs' of matter apparently moving faster than light. – this is in fact an optical/geometrical illusion – but it can only work if material is being expelled towards us very close to the speed of light.

What can explain these strange properties? Some sort of 'central engine' is producing huge amounts of energy (some of the quasars are as luminous as 100 typical galaxies) and expelling jets of plasma. However the day–to–day flickering means this is all occurring in a very small space – no bigger than our solar system! (An object can't change coherently faster than it can communicate across its parts; but the fastest this can happen is the speed of light. So if you see variations on a timescale t, you know the object cannot be bigger than size $R = ct$). The best accepted explanation is that a supermassive black hole is involved (perhaps $10^9\, M_\odot$). The lecture on X-ray astronomy will discuss how to extract energy using 'gravity power'; see also Dr Heavens' lectures later this term…

(5) PULSARS In 1967 Jocelyn BELL (at Edinburgh for most of the 1980s) discovered a radio source with 'blips' of 1.337 second period. After hectic speculation about LGM (little green men…), she and Tony HEWISH attributed the signals to a spinning neutron star – the finally collapsed remnant of a supernova explosion. Theory had predicted the existence of such objects – a solar mass compressed into 10km radius, central density $\sim 10^{14}$g cm^{-3}. Nobody had really expected to see one.

About 500 pulsars are now known. A few spin > 1000 times per second. Their rate of slowing-down, and consequent loss of energy, can be measured. They act as 'clocks' in providing useful observational tests of general relativity. See Sky & Telescope, September 1990 and April 1995.

(5) COSMIC MICROWAVE BACKGROUND RADIATION It was expected that at short wavelengths (cm) the radiation from the Earth's atmosphere, and that from the Milky Way ($\propto \lambda$), would be weak, so that the radio temperature of the sky away from the Milky Way should be ~ 0 K. But in 1965 PENZIAS & WILSON (just like JANSKY, they were Bell Telephone Lab, but these were astronomers trying to use a spare antenna to map the Milky Way) found an overall background, all over the sky, at about $\lambda = 7.5$ cm, corresponding to blackbody radiation at $T \simeq 3$ K. It is difficult to measure uniform background radiation – there is no 'empty' sky to compare it with.

Measurements at shorter wavelengths have to be made from high-flying aircraft, balloons, or spacecraft, because of variable absorption and emission in the Earth's atmosphere. They have confirmed that the spectrum of the CMB closely fits a black-body curve at 2.7 K. The radiation is highly isotropic – the same in all directions. This fits the concept of relic dilute radiation coming from the primordial fireball in the very early expansion of the Universe. Thus the CMB is key evidence for Big Bang cosmology (see later lectures), and its discovery was a major triumph of radio astronomy.

RADAR ASTRONOMY

Sound echo-location (sonar) is a technique used by a number of creatures, such as bats and dolphins. Radio echo-location was developed in World War 2, and radar echoes from the Moon were observed then. The average distance of the Moon is 380,000 km, so the out-and-back echo delay is $2 \times (380,000/300,000) = 2.5$ seconds.

Because the inverse-square decrease of signal strength applies to both the outgoing pulse and the returning echo, radar echoes are proportional to $(\text{distance})^{-4}$. So a large radar telescope is needed. The 1000-ft Arecibo radio dish has been extensively used for planetary radar. The most distant reachable object is Saturn; at its closest approach of 8.5 Astronomical Units the echo delay is $2 \times (8.5 \times 150,000,000)/300,000 = 850$ seconds.

The Doppler shift between the approaching and receding edges of a planet measures its rotation (ZEILIK p.182). Thus it was found that Mercury's rotation is faster than its orbital revolution, so it does not keep the same face towards the Sun; and that the rotation of Venus is in the reverse sense to that of other planets.

Radar mapping of Mercury and Venus has been carried out by spacecraft. Venus' surface is perpetually hidden by dense clouds of CO_2, but has been radar-mapped in great detail by the MAGELLAN spacecraft (Astronomy Now, Dec. 1991; Sky & Telescope, March 1992). The radar mapping programme terminated in 1992, and was followed by gravitational-field mapping [Sky & Telescope, January 1993].

UV & X-ray astronomy

Though we can't see much below 400 nm, the Earth's atmosphere is in fact fairly transparent down to 310 nm, so it is possible to operate ordinary photographic and photoelectric detectors in the 'near' UV. 'Real' UV, $\lambda < 310$ nm, is blocked by ozone (O_3) and other atmospheric constituents, and began to be studied only when high-altitude rockets (captured German V-2) became available after World War 2. Rockets could spend only a few minutes above the ozone layer (~ 25 km), and were eventually superseded by high-orbiting satellites that could survey the UV sky for months or years. Up to the present, these have measured the UV spectral distribution for single objects, one-by-one.

UV OBSERVATORIES IN SPACE A series of Orbiting Astronomical Observatories for UV astronomy culminated in the very successful OAO-C ('Copernicus') launched in 1972. The European TD-1 satellite (1972) carried UV photometers which contributed to an extensive all-sky UV catalogue compiled at Edinburgh and Liège. Various Shuttle-borne UV telescopes have operated. IUE, the International Ultraviolet Explorer, launched in 1978 and only closed in 1997, was arguably the most productive single observing facility of all time. It obtained high-resolution UV spectra ($\lambda = 115-320$ nm) of individual objects. IUE operated as a remote-controlled observatory in space, obeying the commands of ground-based astronomers (over 1500 individuals). (Astronomy Now, June 1992).

The Hubble Space Telescope is the first spacecraft to include UV imaging among its functions. This is a valuable contribution, in addition to the optical imaging quality, now restored to its proper capabilities.

ASTROPHYSICS IN THE UV

UV astronomy chiefly concerns hot objects ($> 10,000$ K). The photons involved have high energies, and so do serious violence to any atom or molecule that intercepts them. In the spectra of gases (stellar or interstellar) the strongest lines are the **resonance lines** involving the ground state. These involve the biggest energy transitions and are thus frequently in the UV.

UV radiation causes **photoionization**, because the photons involved often have energies above what is required to ionize atoms, removing one or more orbital electrons. For example, interstellar hydrogen gas sits in the ground state where it can absorb the Lyman lines and a continuous range of wavelengths beyond the Lyman limit ($n = 1 \rightarrow \infty$) at 91.2 nm. Thus interstellar space is expected to be rather opaque below 91.2 nm, and most UV spacecraft so far have worked in the range $100-300$ nm. NASA's EUVE (Extreme Ultraviolet Explorer) was launched in 1992 [Sky & Telescope, May 1993 and December 1994]. Once the gas is ionized, the atoms can reform, emitting **recombination radiation**; again, these lines occur principally in the UV.

Although it has been mentioned that interstellar space is rather opaque at wavelengths < 100 nm, an experiment on the joint Apollo-Soyuz spacecraft in 1975 suggested that the interstellar hydrogen is patchy enough that we may be able to see sufficient stars to probe the distribution of hydrogen clouds in the solar neighbourhood of our Galaxy. The resonance lines of some other important species, e.g. He and H_2, lie in this Extreme UV or **EUV** region. EUV telescopes require grazing-incidence optics as for X-ray telescopes (see below). Satellites that have explored this EUV waveband include the Extreme Ultraviolet Explorer (EUVE) and the X-ray spacecraft ROSAT [Sky & Telescope, August 1995].

UV ASTRONOMY

(1) STARS The Sun has been intensively observed in the UV, especially from the Skylab space station; UV pictures show the highly disturbed hot (100,000 K) region between the chromosphere (the upper atmosphere) and the corona (the even hotter extended outer envelope). UV spectra of other stars yield data on their chromospheres, and on **mass-loss** ('stellar winds') both from hot young stars and from cool stars; also on very hot **white dwarfs** soon after their formation.

(2) INTERSTELLAR MEDIUM Continuous absorption by interstellar dust rises steadily throughout the visible spectrum as λ decreases – that's why interstellar absorption is greater in the blue than in the red, so that distant stars appear **reddened**. Absorption continues to rise steadily in the UV, but around 220 nm there is a very strong 'bump' of extra absorption. Its cause is uncertain, but probably involves carbon, perhaps in the form of polycyclic aromatic hydrocarbons (carbon-ring molecules containing $\sim$ 60 C-atoms – 'buckyballs' etc). The Lyα line due to H atoms in the interstellar gas is a strong absorption feature; the corresponding weak absorption due to the rare deuterium isotope ('heavy hydrogen') gives an estimate of **deuterium** abundance which tells us the early baryon:photon ratio and hence determines a value for Ω_0 (see Big Bang course).

(3) QUASARS UV studies are important for active galactic nuclei (AGNs) and QSOs in two ways. (i) The energy output peaks in the UV, in the so-called 'Big Blue Bump'. Many people have argued this is just the spectral form you expect for an accretion disc around a supermassive black hole. (ii) In visible-region spectra of distant QSOs we see a 'Lyα forest' of dozens of Lyα absorption lines; this is of course a UV absorption line, but has been red-shifted all the way into the visible. The multiple lines probably means that the light of the quasar has been absorbed by a series of small cold gas clouds between us and the quasar. Without the quasar as a background light, we would never have known such intergalactic clouds existed [see Sky & Telescope, September 1997].

X-RAY ASTRONOMY

Röntgen discovered X-rays in 1895; he got the first Nobel Prize in Physics for his work. X-rays go through people but (fortunately) not through the atmosphere. You need rockets or spacecraft to do X-ray astronomy. The first cosmic X-rays, from the Sun's corona, were detected from V-2 rockets in 1948.

As we have seen, the EUV gap 100 – 10 nm is little explored so far. Beyond that, X-rays are conventionally divided into:

Soft X-rays	0.1 – 1 keV	(8 – 0.8 nm)
Hard X-rays	1 – 100 keV	(0.8 – 0.008 nm)

X-RAY EMISSION X-ray photons are mainly generated by a mixture of the processes discussed earlier. **Thermal free-free radiation** from gas at $10^6 - 10^8$ K is one common emission mechanism. The other is, paradoxically, the same mechanism that generates the very low-energy radio emission: **nonthermal synchrotron radiation**. The reason for this is that the ultrarelativistic electrons that generate the synchrotron emission can span a huge range of energies, thus giving contributions in all wavebands. A third possibility is a hybrid of these two: **inverse Compton emission**. Here, a low-energy photon can be struck by an ultrarelativistic electron, and kicked up to higher energies, rather like a ball being struck by a bat.

X-RAY TELESCOPES X-rays go through most materials and can't be focused by ordinary telescope mirrors. Early X-ray telescopes used grids to define the field-of-view, but of course very poor definition was obtained in this way. **Grazing-incidence** X-ray telescopes were developed in the 1970s and were used for good imaging in the highly successful EINSTEIN space X-ray observatory.

X-RAY DETECTORS X-rays would simply go through ordinary photon detectors. Instead, the ionizing energy of X-rays is used in a proportional counter. A box filled with gas (e.g. argon, carbon dioxide) is penetrated by X-ray photons entering through a metal-foil window, and their energy is absorbed by the gas atoms, producing ionization with the liberation of free electrons. These knock out further electrons, and the electron cloud is collected on a wire anode, generating a pulse whose size is proportional to the energy of the X-ray photon. (Remember the energy of a photon is proportional to its frequency – so by knowing the energy of each detected photon, you automatically get crude spectroscopy). For hard X-rays of energy > 30 keV, crystal scintillators (e.g sodium iodide) are used: incident X-rays generate light flashes that can be recorded by an ordinary phototube.

In recent years, detectors have been developed which use semi-conductors to absorb the X-rays, rather than gases or crystals. These have better energy discrimination, and so give better X-ray spectra.

X-RAY OBSERVATORIES IN SPACE After the Sun's corona, the first celestial X-ray source (Scorpius X-1) was detected from a rocket in 1962. The first X-ray satellite UHURU (1970 – 73) mapped the whole sky and located 160 sources; these were mostly concentrated towards the plane of the Milky Way, i.e. they were probably ('local') galactic objects, but a few corresponded with the positions of extragalactic objects. Sky-mapping was continued by the British ARIEL V (1974) and the American HEAO-1 (1977). Gradually the objects emitting the X-rays were hunted down. This was long hard work as the early X-ray source positions were very crude. Nearly all the objects concerned turned out to be unusual or highly energetic objects.

The EINSTEIN X-ray space observatory (1978) was a major breakthrough: 1000 times more sensitive than its predecessors and with a 58cm grazing-incidence telescope giving almost optical resolution. This has two major effects: (i) because of the accurate positions, it was now easy to identify X-ray sources, and (ii) because of the huge increase in sensitivity, X-ray astronomers could now detect relatively ordinary objects, such as stellar coronae, as well as bizarre objects like X-ray binaries. The next big advance was the German/US/UK ROSAT (Röntgen-Satellit), launched June 1990. It had an 84-cm soft X-ray telescope (0.1-2keV) and also a 58-cm wide-field XUV camera (6 – 30 nm). ROSAT mapped $\sim 250,000$ X-ray sources (UHURU found 160).

The start of the 21st Century has seen two major new X-ray observatories in space, which are set to transform the field with data of optical-like quality. NASA's Chandra (1999+) will give arcsecond-scale imaging (as good as optical). The European XMM was also launched in 1999. This has 10 times poorer resolution than Chandra, but is much more sensitive, with about 5 times the collecting area (effectively 1000 cm^2; this may not sound much, but in order to get even this XMM has to be the size of a bus).

HIGHLIGHTS OF X-RAY ASTRONOMY

(1) STELLAR CORONAE. The 'corona' of the Sun is a hot tenuous outer envelope that used to be visible only during eclipses, but it is a strong **soft X-ray** source ($T = 10^6$ K). How can the outermost part of the Sun be hotter than the 'surface' or photosphere? As well as thermal energy and radiation, energy is carried through the Sun in bulk motions (convection) and in magnetic fields; somehow this energy is released when it reaches the corona. Because the corona is so thin, even a modest heating effect leads to a high temperature. X-ray images of the Solar Corona show it is not uniform – it has loops and holes which change with time, including huge solar flares on timescales of minutes. This is all somehow controlled by unstable magnetic field patterns. Now we know that a wide range of stellar types, both cool and hot, are found to have X-ray emission from 'coronal activity'.

(2) X-RAY BINARIES: GRAVITY POWER These are very close double stars in which the more massive star has evolved into a collapsed object (a neutron star or a black hole). The two stars are so close that material in the outer atmosphere of the normal companion star can be more strongly attracted to the collapsed star, and streams down towards it. (Probably spiralling downwards in a so-called accretion disc). The gravitational potential energy lost is turned into heat, producing X-rays. For a collapsed star, energy generated this way can be more efficient than even nuclear burning. One kg of Hydrogen fusing to Helium liberates 6.4×10^{14} J; the same amount of matter falling onto a black hole should liberate roughly 10^{16} J. How do we arrive at this number?

Imagine a small amount of matter Δm falling onto a large mass M with radius R. Then the amount of energy it gains is $\Delta E = GM\Delta m/R$. So for a given mass, the more compact you can make it, the more energy you get. But the smallest something can be is a black hole with $R = 2GM/c^2$. Substituting, we find M and G cancel, and $\Delta E = \Delta mc^2/2$ – half the rest mass energy. In fact, doing this calculation properly using relativity, the energy liberated is exactly the rest-mass energy: creating matter at the event horizon of a black hole costs no energy, and this is how black holes are able to emit **Hawking radiation**. In practice, a lot of the matter will disappear down the black hole before it has time to radiate, so the true energy gain is a factor of about 10 smaller, but still many times larger than nuclear burning.

We know the sources are **binaries** because we see X-ray eclipses, as the collapsed object periodically passes behind the much larger normal star. Sometimes, where the collapsed object is a neutron star, we also see rapid X-ray pulses, as the neutron star spins. But we can actually see the pulse frequency change due to the Doppler effect as the binary orbit proceeds. Given the orbital period and velocity, we can work out the mass of the collapsed object. This is most reliable way we have of measuring the masses of neutron stars [See Sky & Telescope, May 1996].

(3) SUPERNOVA REMNANTS (SNRs) Most SNRs are X-ray sources, and as in the radio region, there are two types. Some, like Cas A, are **thermal X-ray sources**: the blast wave heats the interstellar gas to millions of degrees, which then radiates by free-free emission. In others, the SNR radiates **synchrotron emission** from particles accelerated either by turbulence in the blast wave, or by the pulsar (collapsed stellar remnant) left behind. The classic example is the Crab Nebula in Taurus (remnant of nova AD 1054), one of the first X-ray sources discovered. The spinning pulsar has rotational kinetic energy, but is slowing down. Calculations show that the rate at which rotational energy is being lost exactly matches the synchrotron luminosity of the Crab – i.e. the pulsar in this case is the direct power source for the whole nebula.

(4) AGN and QUASARS: more GRAVITY POWER? We discussed AGN and quasars earlier, in the radio section. They are very strong X-ray sources, and also rapidly variable, indicating a small size. In fact, although quasars were discovered by their radio emission, it turns out that only some of them are radio sources – but all of them are strong X-ray sources and even stronger UV sources. Following the success of the 'black hole binary' explanation of Galactic X-ray sources, it has been suggested that likewise gravity power is the explanation here. However the black hole required would be a 'supermassive object' – to explain the most luminous quasars, we probably need 10^9 solar masses.

(5) CLUSTERS OF GALAXIES Another surprise of early X-ray astronomy is that the space between galaxies in clusters of galaxies is not empty, but filled with a diffuse hot gas ($T \simeq 10^7$ K) which is emitting X-rays. In some clusters the X-rays are concentrated around individual galaxies; in others the distribution is smoother. Once again the ultimate energy source is gravity – the gas got hot as it started to collapse during the history of the Universe. Such a large mass of gas takes a very long time to cool – longer than the age of the Universe, so it is still hot today. The temperature and luminosity of this hot gas will depend on the total gravitating mass of the cluster – including the stars in the galaxies, the gas itself, and any dark matter there may be. Mapping out the cluster X-ray emission can then give us clues about dark matter, and how it is distributed. (See for example Sky and Telescope March 1992).

(6) THE X-RAY BACKGROUND Right from the earliest rocket flights it was found that there was a faint but uniform X-ray glow from all over the sky, as well as the discrete sources. In soft X-rays, we have now learned that a lot of this comes from hot gas in the plane of the Milky Way, but in hard X-rays it seems to be isotropic, and so is presumably extragalactic. For many years there have ben two rival hypotheses: (i) it comes from a hot **intergalactic gas** pervading the whole Universe, and (ii) it is actually the blurring together of many many faint sources that we simply haven't resolved yet – for example, distant quasars.

In an interesting example of the multi-wavelength nature of modern astrophysics, measurements by COBE at mm wavelengths seem to have ruled out the hot gas idea. If it existed, it should have distorted the cosmic microwave background, making it not quite a perfect blackbody... The cause of the X-ray background has to be faint active galaxies [Sky & Telescope, November 1995].

Gamma-ray & Cosmic-ray Astronomy

This is the 'last frontier' of electromagnetic radiation, comprising photon energies spanning the immense range from 0.1 MeV to 10^{20} eV or more. Gamma-rays of ultra high energy are exceedingly infrequent. There is no possibility for matter to be hot enough to radiate black-body photons of such energy. They must be generated individually by other processes, involving the release of nuclear or gravitational energy:

- transitions between nuclear (not electron) energy levels
- particle/antiparticle annihilation
- decay of elementary particles; radioactive decay
- acceleration of charged particles (by black holes?)

Most of these processes produce a wide spread of photon energies. Some however produce definite gamma-ray energies ('lines') characteristic of specific events, e.g.

- electron/positron annihilation, $e^- + e^+ \to 2\gamma$ ($h\nu = 0.511$ MeV for each photon)
- specific radioactive events, e.g. the decay of ^{26}Al, 1.808 MeV.

GAMMA-RAY DETECTORS Gamma-rays are too energetic to be focused, so there is difficulty in determining their direction.

Scintillation counters, crystals of material such as sodium iodide, emit detectable flashes of visible light when gamma-rays of low energy (< 10 MeV) are absorbed in them. Directional determination is poor – you won't see any gamma-ray pictures.

Spark chamber telescopes give fairly good directions (if you can call a few degrees good) for higher-energy gamma-rays. High voltages are applied to interleaved metal plates in a box filled with argon and neon gas. Incoming gamma-rays produce electron/positron pairs which travel through the gas and cause sparks, which are recorded, between the plates.

DISCOVERY OF COSMIC GAMMA-RAYS These were detected in various balloon and rocket experiments during the 1960s. Progress was slower than that of X-ray astronomy. The flux is weak, and there is difficulty in allowing for local gamma-rays created in and around the detector by cosmic-ray particles (see below). Military surveillance satellites (monitoring possible H-bomb tests) picked up cosmic **gamma-ray bursts** of unknown origin. The nature of these sources was destined to provide one of the longest-standing astronomical puzzles, which only began to be resolved at the very end of the 20th century, more than 30 years on.

Early gamma-ray sky mapping was done by the American SAS-2 (1972) and the European COS-B (1975-82) spacecraft, both using spark-chamber telescopes. COS-B had a spatial resolution no better than 2°, and even from a 'bright' source like the Crab Nebula (supernova remnant) the flux was only one or two γ-photons per hour. Gamma-ray detectors flew on some other spacecraft.

A major injection of new data has been coming from NASA's second 'Great Observatory', the Compton Gamma Ray Observatory (1991); at 16 tonnes, it is the heaviest scientific satellite launched by Space Shuttle. GRO's instruments, covering 20 keV to 30 GeV (3×10^{10} eV), are:

OSSE:	Oriented Scintillation Spectrometer Experiment (steerable)
COMPTEL:	Imaging Compton Telescope (multiple detectors, accuracy 1/8 degree)
EGRET:	Energetic Gamma Ray Experiment Telescope (20 MeV –30 GeV)
BATSE:	Burst and Transient Source Experiment (8 separate telescopes)

COSMIC RAYS

'Something' that makes air electrically conducting (we should say ionized) was known 100 years ago. C.T.R. WILSON (1901) found no change inside a railway tunnel near Peebles; 'something' could penetrate rock. HESS (1912) inferred cosmic rays from the increase of ionization in the upper atmosphere (balloon flights). If you don't like radiation, don't fly.

The ionization was eventually ascribed to (mainly) positively charged particles: the primary particles have energies $> 10^4$ MeV, and in traversing the atmosphere they create secondary particles, still of high energy. Spacecraft experiments of the 1970s established that the primary cosmic rays are charged nuclei of the same elements that are widespread in the Solar System, plus some electrons.

Above 5000 MeV the particle abundance at energy E is proportional to $E^{-2.6}$: at the very highest energies observed (10^{20} eV) the flux is only a few particles per square kilometre per year. Being charged particles, cosmic rays are deflected by the magnetic fields of the Galaxy (and of the Earth), so they carry no trace of their point of origin. Below 10^6 MeV they are confined by the Galaxy's magnetic fields.

Cosmic rays are also affected by the Earth's magnetic field, which traps the particles and prevents most of them from reaching the ground (a good thing for life on Earth). The VAN ALLEN BELTS were found by the first US satellite, and represent a significant hazard for manned spacecraft (or even electronic equipment on unmanned craft). There is archaeological evidence (e.g. ^{14}C in coral reefs) that cosmic-ray activity was higher 20,000 years ago, which means that the Earth's shielding magnetic field was weaker then.

Cosmic rays are interstellar gas particles that are believed to have been accelerated by supernova explosions, and possibly by pulsars and X-ray binary stars. Cosmic rays $> 10^6$ MeV would be little affected by our Galaxy's magnetic fields, and may be extragalactic. The acceleration mechanism for ultra high energies up to 10^{20} eV is unknown. If theorists had their way, such high-energy particles would not exist. The problem is that all known acceleration mechanisms involve the cosmic rays being deflected by fast-moving plasma containing magnetic fields – but the deflection produced by a magnetic field falls with increasing particle energy, so ultra high-energy cosmic rays would pass through such plasma without noticing.

COSMIC-RAY TELESCOPES

Cosmic rays are observed at ground level via the extensive **air showers** they provoke in the atmosphere. An incoming cosmic ray is a highly relativistic particle; when it hits an atom in he atmosphere, nuclear reactions readily generate many new particles (such as muons, symbolized μ – heavy versions of electrons), which are also relativistic. These in turn create further sets of particles. The result at ground level is a shower of thousands of particles, all from the one initial cosmic ray.

Arrays of particle detectors are used to detect these air showers, employing similar technology to that used in X-ray and gamma-ray satellites. The one at Haverah Park near Leeds covers 12 square kilometres. See Sky & Telescope, September 1995. By the numbers of particles detected, the energy of the initial event can be estimated. The air-shower phenomenon is also produced by gamma-ray photons; these can have energies similar to those of cosmic rays, and their effect on the upper atmosphere is similar. However, the detailed mixture of particles detected in the shower can discriminate between gamma-ray events and cosmic-ray events.

Ground-based gamma-ray & cosmic-ray telescopes can also detect **Cerenkov radiation**: this is the analogue of the 'sonic boom' from particles travelling faster than the speed of light in air, producing detectable flashes of light. This information is useful because it gives the direction of the incoming particle (by triangulation – using a number of telescopes spread out over a wide area). The most ambitious such telescope is AUGER, now under construction in Chile: this aims to study just the most energetic (10^{20} eV) events, hoping to solve the mystery of their origin.

GAMMA-RAY ASTRONOMY

(1) THE SUN while you wouldn't expect much gamma (or radio) flux from a black-body at 6000 K, gamma-rays have been detected from solar flares associated with sunspot groups. Intense local magnetic fields in flares accelerate particles to high energies. The 0.511 MeV electron/positron annihilation line has been observed. GRO has obtained detailed gamma-ray spectra of flares over the range 20 keV to 1 GeV (range of 1:50,000 in energy).

(2) THE MILKY WAY is the dominant feature of COS-B sky-maps (as it is of radio maps). Gamma-rays are generated by collisions between cosmic-ray nuclei (particles, not photons) and nuclei in the interstellar gas. The collisions produce intermediate-mass particles called neutral pions which decay into gamma-rays. [For example, $p + p \rightarrow p + p + \pi^0$, $\pi^0 \rightarrow 2\gamma$].

(3) POINT SOURCES gamma-rays from highly-accelerated particles in pulsars and supernova remnants; the Vela pulsar (neutron star) is the brightest 'star' in the gamma-ray sky. SNRs are the dispersed remnants of past supernova explosions, in which it is believed that heavy elements are created by nucleosynthesis. Gamma-ray lines corresponding to radioactive decay of specific synthesized nuclei have not yet been identified in individual SNRs. The ^{26}Al line at 1.808 MeV has however been found in the direction of the Galactic Centre; because ^{26}Al has a mean lifetime of only 10^6 years, it must have been formed in a number of 'recent' supernovae. BATSE and EGRET have recorded gamma-rays from several pulsars; these will provide clues to particle acceleration in the vicinity of neutron stars.

(4) EXTRAGALACTIC gamma-rays from active galactic nuclei and QSOs. EGRET has recorded high-energy gamma-rays form a number of distant galaxies. One QSO emits most of its energy in the X-ray/gamma-ray region. A giant elliptical galaxy emitting 10^{12}-eV gamma rays has been detected; more evidence for infall onto a back hole?

(5) GAMMA-RAY BURSTS Vela military satellites detected gamma-ray bursts in the 1960s, and it was clear even with poor directional accuracy that they were of cosmic origin. They occur randomly over the whole sky and come in many different classes, from single spikes lasting only 0.02 s, to events with complex time structure lasting up to 1000 s.

In its first year BATSE recorded positions of 261 bursts, and the surprise is that they are all over the sky. Their distribution is not associated with the large-scale structure of the Galaxy (cf. X-ray sources, many of which do concentrate towards the galactic plane). This suggests that bursters are either local, perhaps associated with the outer reaches of the Solar System (but what??), or very distant, outside our Galaxy altogether – that would make them exceedingly energetic.

In order to make the critical leap of working out what sort of objects the gamma-ray bursters are, an optical counterpart needs to be found, and this is difficult to achieve with the low-accuracy gamma-ray positions. The real breakthrough was the Italian BeppoSAX satellite. This contains a $1-200$ keV X-ray camera that is able to be pointed rapidly in the general direction of a gamma-ray burst. If a transient X-ray source is found, this is almost certainly associated with the burst; the X-ray position is good to better than 1 arcminute, so that an optical image can be taken. In this way, the optical counterparts of many gamma-ray bursts have been found, proving that the bursts take place in faint galaxies at very high redshifts. The bursts are therefore the most *visibly* energetic events in the universe: they manage to release roughly the same energy as a supernova (10^{45} J), but they put it all into radiation. A recent burst from a galaxy at redshift 1 peaked at 9th magnitude – almost bright enough for the naked eye, from the other side of the universe. We should keep our fingers crossed that one doesn't go off in the Milky Way...

The favoured theoretical idea for how gamma-ray bursts can liberate so much energy is via the merger of two neutron stars. As it happens, such an event would also be an effective source of gravity waves (see below), so there is some chance that this theory may get tested one day.

For a review of the Compton Gamma Ray Observatory's work, see Sky & Telescope, December 1992. The impact of BeppoSAX on solving the gamma-ray burst mystery is described in Sky & Telescope, February 1998.

Other messages from space

SOLAR NEUTRINOS

The Sun and stars maintain their energy output by nuclear fusion at their centres: a complicated chain of nuclear reactions, with the end result that H + H + H + H → He (4 protons → α-particle). This reaction releases a considerable amount of energy (nuclear reactions can liberate a few thousandths of the rest-mass energy of the initial particles – $E = mc^2$), but a good fraction of this output is in fact caried away by neutrinos, elementary particles with no charge and probably no mass; they would escape freely from the Sun, since matter is practically transparent to neutrinos. This creates a problem for their detection.

Several detectors, set up to look for these **solar neutrinos** are now operating, in USA, USSR, and Japan. The one at the bottom of the Homestake mine in South Dakota has been running over 25 years: in a 100,000-gallon tank of C_2Cl_4 (dry-cleaning fluid), absorbed neutrinos very occasionally convert a chlorine atom (Cl) to argon (Ar), which can be detected. N.B. Detectable neutrino fluxes are very small: the SNU (solar neutrino unit) is defined as 10^{-36} neutrino captures per target atom per second, and the observed flux at the South Dakota site is just two of these units.

Since this pioneering work, other experiments of this sort have studied neutrinos from the Sun. The GALLEX neutrino detector within an Italian mountain uses the Ga → Ge conversion. SUPERKAMIOKANDE is an underground cavern in Japan > 100 m across filled with water and lined with photomultiplier tubes (job security for research students); with such a colossal number of water molecules (10^{35}), a few rare Solar neutrinos do interact (tens of events per day). The reaction is inverse beta decay: $p + \nu \to n + e^+$. The positron takes up the neutrino momentum, and suffers relativistic recoil; this causes it to emit Cerenkov radiation, which can be detected on the walls of the cavern, and used to reconstruct both the direction of the initial neutrino and its energy (because the Cerenkov cone angle depends on the velocity of the positron). Designed as an experiment to detect proton decay, its huge mass makes it the most sensitive 'neutrino telescope' in the world. AMANDA will be a new kind of detector for high-energy neutrinos (from black holes etc.): neutrinos penetrating Antarctic ice will leave trails of Cerenkov radiation, to be detected by photon detectors buried in the ice [Sky & Telescope, July 1994]. ANTARES is a similar sort of idea, using several cubic km of Atlantic water off the coast of France.

The number of solar neutrinos found is only 30% of the number predicted by standard solar models. Is this because the astronomical models are wrong, or because our understanding of particle physics is wrong? This debate remains unresolved, but increasingly favours the latter possibility. Neutrinos come in three 'flavours', electron, muon, and tau neutrinos. An intriguing possibility is that neutrinos may 'flip' between the different 'flavours', so that we are looking for the wrong kind by the time they arrive at Earth. However particle theory says that this will only happen if neutrinos in fact have a very small but non-vanishing mass; the higher the mass difference between different neutrino species, the more rapid the oscillation between types. In order to explain the solar neutrino results, masses of a small fraction of an eV (energy units are used here: it means $mc^2 = 1$ eV) are needed. It is possible that the (so far undetected) tau neutrinos may be even more massive (just as the muon and tau particles are more massive versions of the electron). If the mass can reach about 10 eV, it is then possible that vast numbers of neutrinos spread throughout the universe could constitute the infamous dark matter.

SUPERNOVA NEUTRINOS

On 23 February 1987 a supernova (1987A) exploded in the Large Magellanic Cloud, a companion of our Galaxy. Simultaneously, and before the supernova was seen optically, the detectors in USA and Japan observed neutrino showers over a period of 10 seconds. Here was direct confirmation of nuclear processes in a catastrophically exploding star. The star's central temperature at that moment is estimated to have been 2×10^{11} K. The released energy must have been $\sim 3 \times 10^{46}$ Joules, which is about 10^{19} times the Sun's output in 10 seconds. The neutrinos carry away almost all of the energy, leaving only perhaps 1 part in 10^4 to power the fireworks. Even so, the supernova lay at a distance vast with respect to the Sun, and only a few dozen neutrinos were detected. No supernova has been seen within the Milky Way for about 400 years, whereas observations of many galaxies like our own suggest that the rate should be about one per century. It may be that we are overdue for a local supernova; it could also be that intergalactic dust in the Milky Way means that most supernovae go unobserved. In either case, the neutrino signal from a more nearby supernova would be very strong ($> 10,000$ detected neutrinos), giving us a wealth of information about the dying seconds of a star.

From the point of view of particle physics, it is significant that the neutrinos from SN1978A travelled the 160,000 light-years from the LMC and arrived at the same time, independent of energy. This limits their mass to below about 10 eV (otherwise the most energetic neutrinos would have travelled faster and arrived first).

GRAVITY WAVES

Accelerated mass should lose energy in the form of gravitational waves (a prediction of General Relativity). The argument is basically the same as for electromagnetic radiation: shaking lines of force should cause transverse displacements to propagate along the lines. The problem is that, except on the largest scales, gravitation is a weak force …only 10^{-36} of the electrostatic force between two charged particles. A propagating gravity wave will cause a relative acceleration of bodies at different positions, but the likely size of any displacements is tiny.

Early (1970s) experiments by Weber in California, looking for vibrations in large rods, turned out to be mainly sensitive to the footsteps of passing students. Since then, experiments have become much more sophisticated. Today, the preferred technology for gravitational-wave detectors consists of two large suspended masses separated by distance L, where their relative separation is measured by means of laser interferometers. The UK's main group in this are is Glasgow University, which is part of GEO-600, an interferometer under construction in Germany, with $L = 0.6$ km. The USA is constructing LIGO, which has 4-km arms. Based on existing smaller interferometers, it is expected that these experiments will measure a fractional distortion of spacetime of about $\delta L/L \sim 10^{-19}$ to 10^{-20}. This is an absurdly small number, corresponding to being able to measure a shift in the position of one of the suspended masses of about the size of the atomic nucleus. The fact that it is possible is a tribute to what can be achieved by modern engineering. The most ambitious plan of this kind is for a space project called LISA, which would involve a network of 6 satellites in orbit around the sun.

However, it is not certain whether the current ground-based detectors will see anything, because their expected sensitivity is close to the expected effect for astronomical sources. Gravity waves are emitted most strongly from massive bodies undergoing high acceleration. The best we can imagine would be the coalescence of a pair of compact massive stars – a pair of neutron stars would be ideal. Such an event would yield a characteristic 'chirp' of gravity waves as the binary loses orbital energy (through its gravitational radiation) and merges into a black hole. The peak signal for this sort of event would probably exceed the above sensitivities, even for an event at cosmological distances. Since the preferred model for gamma-ray bursts is also the merger of a neutron-star binary, it is possible to imagine a wonderful future vision in which the gamma-ray and gravity-wave signals from a single event could be studied.

Astronomers don't like to wait, and most are already convinced that gravity waves have been detected. The reason for this is a special object called the **binary pulsar**. In fact, this is a single pulsar in orbit about a white dwarf, in a rather tight orbit (8 hours period). The existence of the pulsar as a natural clock means that we are able to use the Doppler shift to measure the orbit very accurately; what is found is that the orbit is speeding up, so that the 8-hour period is reduced by about 10^{-4} seconds per year (pulsar astronomy often shows this wonderful precision). This doesn't sound much, but the orbit is losing energy, and the observed rate is exactly what would be predicted from gravitational radiation. Therefore the interferometer experiments can be fairly confident that the waves they are looking for exist – and that detecting them will open up the study of the most exotic astronomical objects yet contemplated.

SETI

Astronomy provides no clear estimate for the probability of other Earth-like planets, let alone for the emergence of life, intelligence, technology …and extinction. You can play games with

$$\boxed{\text{DRAKE'S EQUATION: } N = R f_p n_e f_l f_i f_c L}$$

This says that the number of civilizations we should expect to see at any one time is the rate of creation of stars, times the fraction that have planets, times the number of planets per star that are like Earth, times the fraction of Earth-like planets on which life gets started, times the fraction of cases where life leads to intelligence, times the fraction of civilizations that can be bothered to communicate, times the length of time each civilization lasts. The only well-known number is R, although planet searches are now making progress with f_p; there's clearly a long way to go. Perhaps the biggest uncertainty is f_l, since the origin of life is a great mystery. Some influential people, notably Fred Hoyle, have argued that life originates in space [see Sky & Telescope, March 1994 and July 1997], and is spread throughout the galaxy by comets, so that $f_l = 1$. This may seem a far-fetched idea, but we saw that millimetre astronomy has detected complex 'organic' molecules; the trouble is, whether in space or on Earth, no-one understands how to get from amino acids to life.

Returning to Drake's equation, we don't even know that $N \geq 1$, since the equation gives the *expected* number of civilizations. This number might be so small that the probability of even one civilization in the entire universe would be very close to zero. Of course, we are here; but if we hadn't been, no-one would be asking any questions. It's possible that we are the cosmic equivalent of the winner of the National Lottery, and that there are no other intelligent beings anywhere. Alternatively, the universe might be full of them; to decide, we have to look.

In an attempt to settle the question, "Is anyone there?", NASA mustered sufficient optimism to commit modest funds to its 'Search for Extraterrestrial Intelligence'. The NASA-funded programme terminated in 1993, but is continuing as a privately-funded experiment (see the web address at the end of the notes). The SETI programme is based on radio telescopes, at several sites, in the frequency range 1 to 10 GHz, that can sample up to 14 million channels simultaneously. The favoured wavelength region is the 'water hole' where the cosmic animals come to talk: the range centred on $\lambda \simeq 10$ cm, where galactic and terrestrial radio background is minimal, cosmically 'advertised' by the presence of strong radio lines of H, OH, H_2O. There is a major computing problem in handling such a huge data rate and deciding when a 'signal' may have been received. Another way of searching might be to look for waste IR radiation from aliens' colossal astro-engineering projects. See Sky & Telescope December 1998.

An awkward question is going to be, when SETI has spent $100,000,000, and it's now AD 2002, and there's no positive result – what next? Perhaps L is very small . . . if technology always leads to self-destruction . . . who knows?

FURTHER INFORMATION

In addition to the articles mentioned in the text, the following books may be helpful if you are interested in following up any of the topics in more detail:

BURKE & GRAHAM-SMITH, An introduction to radio astronomy (C.U.P.)
CHARLES & SEWARD, Exploring the X-ray universe (C.U.P.)
LONGAIR, The New Astrophysics (in DAVIES (ed.) The New Physics, C.U.P.)
SMITH, OBSERVATIONAL ASTROPHYSICS (C.U.P.)
TIME/LIFE, The New Astronomy (in Voyage through the Universe series)

There is also a lot of interesting information (and spectacular pictures) available on the web. You may like to explore some of the following addresses:

http://www.ipac.caltech.edu
http://www.sdc.asi.it
http://sofia.arc.nasa.gov
http://wave.xray.mpe.mpg.de/rosat
http://chandra.harvard.edu
http://astro.estec.esa.nl
http://www.jb.man.ac.uk/merlin
http://www.ast.cam.ac.uk/Gemini
http://info.aoc.nrao.edu
http://www-sk.icrr.u-tokyo.ac.jp/doc/sk
http://www.ligo.caltech.edu
http://www.geo600.uni-hannover.de
http://www.seti-inst.edu/science/ph-bg.html