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 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].