Chapter 2
A Brief, Basic Guide to Terms and Concepts of Solar Radio Astronomy

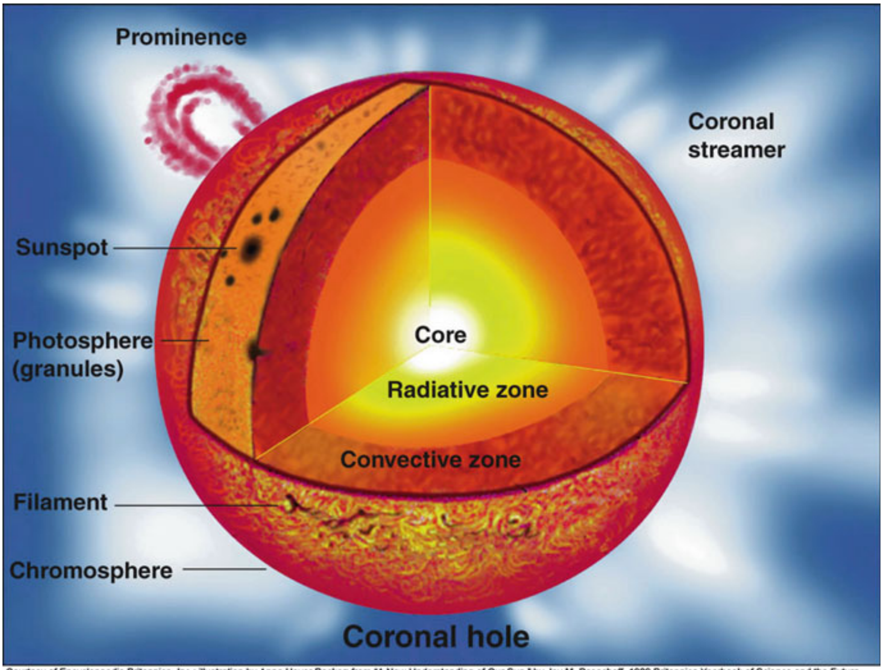
The Astronomers' Sun

Humanity has observed the sun for many centuries. Among the millions of stars observable through optical telescopes, only the sun is close enough to be studied in all of its activity, in exquisite detail. But because it is so bright, it was difficult for anyone to see features on the sun's surface until more modern times. Chinese astronomers likely observed sunspots as early as 364 BC with naked eye observations; the observations would have been at sunrise or sunset when the solar radiation is attenuated by the earth's atmosphere or even through dense terrestrial clouds. In the early seventeenth century Galileo and others began detailed studies of the sun with some of the first optical telescopes; their detection of sunspots was a major discovery that impacted the understanding of the universe. Detailed telescopic solar studies began in the nineteenth century, including spectroscopic identification of many known and even some unknown elements in the solar spectrum. The sun emits a continuum of electromagnetic radiation from X-ray, to ultraviolet, optical, infrared and radio wavelengths. In the optical wavelengths (similar to the receptivity of the human eye at 400–800 nm), the **solar spectrum** shows absorption lines that enable astronomers to determine the chemical composition of the sun. The solar spectrum and associated discoveries were made by the German astronomer Fraunhofer in 1817 using the newly invented spectroscope.

Figure 2.1 shows a three-dimensional model of the sun with sections of the solar structure from the interior to the outer solar corona. In 1939, an understanding of the energy source of the sun was made by the German scientist Hans Bethe—later a prominent physicist at Cornell University in the US—who suggested that the energy source was the fusion of hydrogen nuclei (protons) into helium nuclei in a process known as the p-p (proton-proton) chain. This process releases vast amounts of energy and is, of course, a vital source for life on earth.

Astronomers have long realised that the sun is a common type of star in the Milky Way; it has a typical size, luminosity and temperature. Due to the proximity

W.M. Goss, *Making Waves*, Astronomers' Universe,
DOI 10.1007/978-3-642-35752-7_2,



Courtesy of Encyclopaedia Britannica, Inc.; illustration by Anne Hoyer Becker; from "A New Understanding of Our Sun," by Jay M. Pasachoff, 1989 Britannica Yearbook of Science and the Future

Fig. 2.1 A schematic 3-D model of the sun showing the interior and the solar atmosphere. The solar surface is shown as it would be observed through a hydrogen H-alpha filter (Courtesy of Encyclopaedia Britannica, Inc.; illustration by Anne Hoyer Becker; from "A New Understanding of Our Sun", by Jay M. Pasachoff, *1989 Britannica Yearbook of Science and the Future*)

of the sun to the earth compared to the nearest stars (about a factor of 200,000), detailed information gathered from the relatively nearby sun has allowed scientists to extrapolate information about the structure of far more distant stars. In the early twentieth century, telescopes were used to obtain images of the sun in the visible portion of the electromagnetic spectrum (e.g., from about 3,000 to 8,000 Å or 300–800 nm, from the nearby ultraviolet to the nearby infrared). These images revealed the existence of structures in the solar atmosphere such as flares and prominences. Some of these surprising features will be described below. Later in the twentieth century, totally new solar phenomena—many of them in the tenuous solar corona—were detected using ultraviolet, X-ray or gamma ray telescopes. These wavelengths are heavily attenuated by the earth's atmosphere and thus must be observed from space using rockets or satellite telescopes.

Based on these observations, astronomers and physicists have shown how prominent effects on earth are produced by solar activity. One example is the aurosa, produced when charged particles from the earth's radiation belts are driven into the atmosphere by geomagnetic storms that occur when coronal mass ejections—something like a large bubble of plasma erupting off the sun—strike the earth. The perturbed particles impinge on the earth's upper atmosphere at altitudes above 80 km, exciting molecules at these positions which radiate over a range of visible colours.

It was during and just after World War II that physicists and radio engineers discovered radio emission from the sun; in some cases, such as with both British and New Zealand military radars, the discoveries were serendipitous. This discovery of radio waves provided a method to investigate parts of the solar atmosphere that were difficult or impossible for the optical solar astronomer to detect. Thus new information about the sun could be obtained. For example, the properties of the solar corona were much more easily determined at radio wavelengths. For the ground-based optical astronomers of that era, the corona could only be observed during infrequent, total solar eclipses.

The optical and radio investigations of the sun's atmosphere have a double significance: (1) Physical processes can be studied on a very small scale of 100–1,000s of kilometres, and extreme conditions of high temperatures and low densities are observed that would never be possible to reproduce in the laboratory. These studies have advanced the knowledge of magneto-hydrodynamic (MHD) processes in a variety of situations. In addition, strong magnetic fields are observed at the solar surface and in the corona. (2) The study of conditions and changes in the earth's outer environment due to the propagation of energetic particles in the solar wind can now be studied on a routine basis. A prominent problem that has been addressed is how solar activity impacts radio communications as the ionosphere of the earth (at altitudes above 80 km) is disturbed by temporary increases in ultraviolet radiation from solar flares.

In the immediate post-war era, the physicists and engineers at the Radiophysics Laboratory (RPL) in Australia, including Ruby Payne-Scott, played a prominent role in solving these problems. They used the techniques of WWII radar to turn the military radar systems—the "swords"—into peacetime radio telescopes—"ploughshares". *Transmission* of radio pulses in the direction of enemy aircraft (with the subsequent reception of a reflected signal) was no longer necessary. Only the receiver and the antenna were used to *receive* the strong radio radiation from the sun. By a stroke of good fortune, a prominent period of high solar activity began in 1946, coinciding with the end of WWII.

Already in 1946, the Australians were joined in a competitive race to study the radio sun by two groups in the United Kingdom at Cambridge and Manchester. Both the Australians and the British physicists and engineers had little or no astronomical experience; yet within a few years all these groups became a part of the existing solar physics communities. In Australia, the Sydney group at RPL was fortunate that Clabon ("Cla") W. Allen, a well-known optical, solar physicist working at the Commonwealth Solar Observatory (later Mt. Stromlo Observatory of the Australian National University in Canberra) became a collaborator. Cla Allen was fascinated with this new method to investigate both "solar noise" and "cosmic noise"; the latter consisted of investigations of the newly discovered "radio stars" or radio nebula as well as the background radio radiation of the Milky Way. RPL even assisted in the construction of a simple radio telescope at the solar observatory in

Canberra. The term “radio astronomy” only began to be accepted in 1948, having been invented by J. L. Pawsey at RPL and Martin Ryle at Cambridge in that year.

In the early post-war era, the rapid growth of solar noise research contributed to the development of many techniques used by radio astronomers. The solar radio groups in the UK and Australia initiated many observing modes that had lasting importance for the growth of radio astronomy in the following decades. Due to the rapid variation in the radio signals from the sun, both in time and frequency, the pioneering radio astronomers created complex instruments in the late 1940s to follow the changes in the solar radio emission over time. In addition, principles needed to interpret the radio radiation of the sun were applied in studying the radio emission from other objects in the Milky Way as well as external galaxies. A vast breadth and depth of knowledge has been gathered by astronomers about the sun and its place in the galaxy.

The following summary is intended to provide a succinct description of the current knowledge of the sun’s structure. Many details can be found in recent popular books about the sun; an excellent example is *Nearest Star*, *The Surprising Science of Our Sun*, by Golub and Pasachoff, Harvard University Press, 2001.

There are a few hundred billion stars in our galaxy, the Milky Way, and the sun is located in what is considered an outer suburb, not at all in the densely packed galactic centre. Its distance is in fact about 26,000 light years—or 8 kilo parsecs, to use the unit of distance adopted by astronomers—from the centre of the galaxy. The time for a total revolution of the sun around the centre of the Milky Way is 225 million years. Astronomers have determined that the age of the sun is 5 billion years, compared to the age of the universe which is 13.7 billion years. The mean distance between the sun and the earth is what astronomers call one astronomical unit or 1.5×10^{13} cm.

Our sun, with a surface temperature of 5,800 K, is a typical G2V star—the “G” signifies a class of moderate temperature, the “2” indicates being two-tenths closer toward the slightly cooler K class, and the Roman numeral “V” indicates a main-sequence luminosity class. (Stars on the main sequence have an approximate proportionality between temperature and luminosity, the hotter stars having a higher luminosity. Stars at birth and close to their death phase do not lie on the main sequence.) The mass of the sun is 2×10^{33} g, which is 300,000 times that of the earth. The radius of the sun is 700,000 km, more than 100 times the radius of earth. Most of the mass of the solar system resides in the sun; only about 0.13 % of the mass of the solar system is in its planets. As an example, Jupiter’s mass is 0.10 % of the mass of the sun; in comparison, Jupiter’s mass is 318 times the mass of the earth. Thus the motions of the planets, asteroids, and comets are governed by the gravitational pull of the sun. In rare cases, comets can come close to the massive planets, causing major changes in the cometary orbits.

1. The Interior and Photosphere of the Sun:

The interior of the sun can be divided into three zones: the core, from the centre to 0.25 of R_s (solar radius); the radiative zone, from 0.25 to 0.7 R_S; and then the outer convective zone, from 0.7 to 1 R_s. In the core the energy of the sun is generated by nuclear fusion while in the radiative zone the energy is carried outward by radiation. Above this region, the energy is carried by convection, a process in which the matter is heated from below, transporting energy as the matter moves outward against the pull of gravity.

The apparent, visible surface at the outer edge of the convective zone of the sun is actually a region about 400 km thick from which most of the sun's visible light is emitted. This region, called the photosphere, is where the density drops considerably and the scattering stops. The photosphere is a very small region since the radius of the sun is about 700,000 km; the photosphere extends to a point where a photon of light would experience on the average less than one scattering before leaving the star. Even though the gaseous sun does not have a solid edge, this edge is visibly well defined and considered by many as the solar surface. The density at the outer photosphere is only about 2×10^{-7} g/cm^3, or about 10^{17} protons/cm^3. In this region the effective temperature is 5,800 K.

On a scale of about one arcsec ($^1/_{1,800}$ of the solar diameter), the sun's photosphere is composed of short-lived convection cells with a typical size of 1,000 km, which produce a "salt and pepper" appearance on the solar surface. These granules carry energy from the hot interior to the base of the photosphere by convection, but only the tops of these granules are observed in the photosphere. They are dark at the edge where the cool material is flowing down and bright at the centre where the hot material is upwelling.

Major features in the photosphere are sunspots and flares.

Sunspots

Sunspots are cooler regions in the photosphere; the cooler temperature is a result of a strong magnetic field, which suppresses the upwards transport of energy by convective action and leads to decreased temperature. Different latitudes of the sun rotate at different rates (differential rotation) causing shearing. The subsequent eddies and other motions in the convective zone may give rise to the magnetic fields that cause sunspots. Sunspot temperatures are some 1,500–3,000 K cooler than the photosphere. Since they are cooler than the background they appear as dark spots (Fig. 2.2), though they would still be blindingly bright if viewed in isolation from the much hotter surrounding regions. Sunspots are regions of intense magnetic activity, usually appearing in pairs that have opposite polarity, similar to terrestrial magnets (Fig. 2.3 shows a sunspot from 4 August 2011). Sunspots occur as part of the 11-year solar cycle, with an increased number of sunspots at solar maximum and a decreased number at solar minimum. As an example a solar maximum occurred in 2001–2002, while the next predicted solar maximum will be in May 2013. The number of sunspots in the 2013 cycle is predicted to be about 30 % lower than the previous maximum. For example, on 9 May 2012 a prominent sunspot (AR1476) was detected in the new solar maximum (cycle 24). The diameter of this sunspot was about 160,000 km and its area 1,050 millionths of the solar area. This

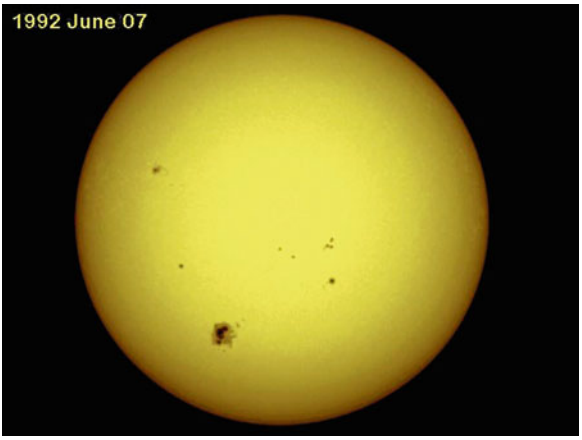


Fig. 2.2 The solar surface in visible light, near the maximum of the sunspot cycle of 1992. The small sunspots near the centre of the image are about the size of the earth (Marshall Space Flight Center Solar Physics web page "The Photosphere", http://solarscience.msfc.nasa.gov/surface.shtml)

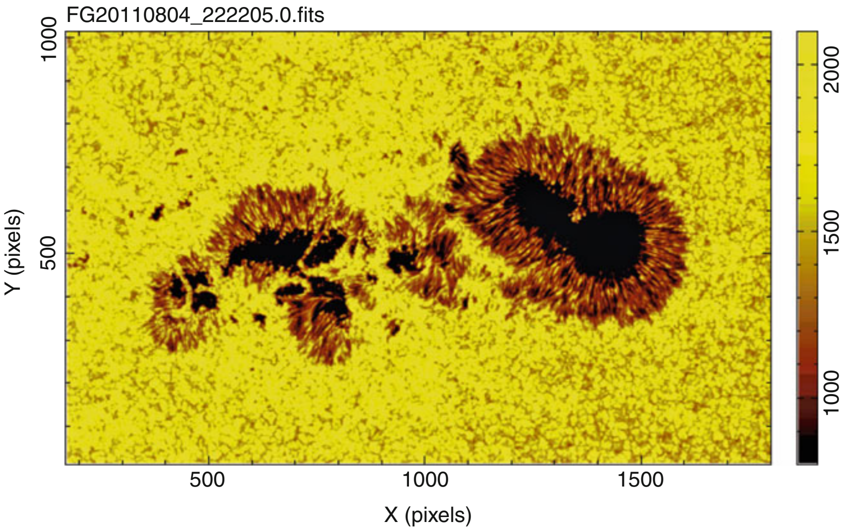


Fig. 2.3 High resolution image of a sunspot obtained with the Hinode (Japanese "sunrise") satellite, launched in September 2006. This is a cooperative mission between Japan, the US (NASA), Europe and the United Kingdom, consisting of a coordinated set of optical, extreme ultraviolet and X-ray instruments to investigate the interaction between the sun's magnetic field and its corona. This figure shows a high resolution optical (388–668 nm) image with a resolution of 0.2 arcsec. The pixel size is 0.08 arcsec; 500 pixels is thus 40 arcsec. The active region is AR 11263 from 4 August 2011. A few days later a prominent solar flare was produced (http://solarb.msfc.nasa.gov/news/12072012.html)

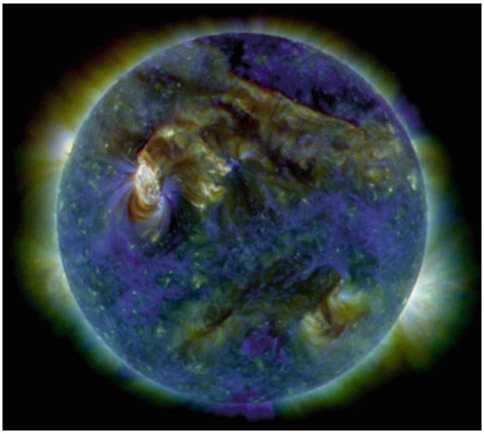


Fig. 2.4 Ultraviolet image of the entire solar surface facing the earth on 1 August 2010, obtained with the SDO (Solar Dynamics Observatory) satellite, launched on 11 February 2010 as part of NASA's "Living with a Star" program. The white area to the left centre shows a C-3 class solar flare. The colours in the image represent different gas temperatures. On 3 August 2010 prominent aurorae were observed in North America (NASA Image of the Day Gallery http://www.nasa.gov/multimedia/imagegallery/image_feature_1732.html)

size is five to six times smaller than the giant sunspots that Ruby Payne-Scott and colleagues observed during the prominent sunspot maximum of 1946–1947.

This 11-year cycle in sunspot activity was first observed by Samuel Heinrich Schwabe in the mid-nineteenth century. This German astronomer observed the solar surface for 17 years (1826–1843) hoping to discover a new planet, which was postulated to orbit the sun within the orbit of Mercury. The 11-year solar cycle of sunspots was found instead. The sunspot cycle is only a symptom of a more general activity cycle, driven by a magnetic dynamo operating in the interior of the sun.

Flares

Flares are an important constituent of solar behaviour. Figure 2.4 shows a prominent C solar flare as the white area in the upper left, while in Fig. 2.5 we see the famous "Seahorse" flare of 7 August 1972. A flare is a sudden, intense variation in brightness that occurs when magnetic energy is released. The temperature in a flare can reach 20 million K. Flare intensities are indicated—from weakest to strongest—in categories A, B, C, M and X. The scale is based on the peak rate of X-rays emitted by the flare and is logarithmic, like the Richter (earthquake) scale, thus B flares are ten times stronger than A flares, etc. Flares can originate in regions near sunspots, taking a few seconds to begin and lasting up to 4 hours. A typical flare lasts 20 min. Flares occur with rates from several per day when the sun is

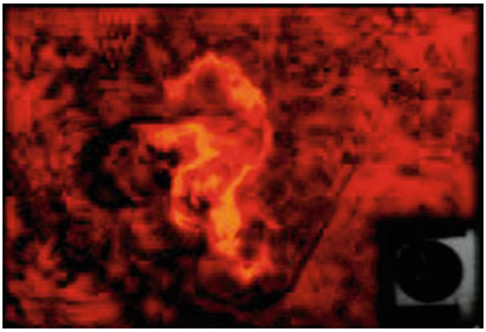


Fig. 2.5 The famous "Seahorse" flare as observed with the Big Bear Solar Observatory on 7 August 1972 in the H-alpha red line (656 nm) of hydrogen. This is an example of a "two-ribbon" flare in which the flare region appears as two bright lines threading through two sunspots (NASA "Solar Flares" http://solarscience.msfc.nasa.gov/flares.shtml)

active to less than one per week when solar activity is reduced. Many flares occur in conjunction with a coronal mass ejection (CME, see below), often likened to a large bubble of plasma erupting off the sun. (Solar fares can be observed without a CME and the latter can occur without the onset of a flare.) When the two occur simultaneously, often with large flares and fast CMEs, the event is called a "solar eruptive event" (Holman 2012).

Flares are observed at optical, radio and X-ray wavelengths. In the past, observations in the H-alpha line (the red line of the first Balmer line of hydrogen) were the most productive manner to detect solar flares. Energetic particles (electrons and protons) accelerated by the flare are detected at the earth after a delay of minutes to days following a strong flare on the sun. The radio burst connection with flares was established in the years 1946–1952 by the RPL group. The first flare in recorded history was discovered on 1 September 1859 by the English astronomer Richard Carrington. This observation was confirmed by another English observer, Richard Hodgson. About a day later a prominent geomagnetic storm was observed with auroras even at tropical locations such as Cuba and Hawaii. It is now widely believed that this flare may have been one of the most powerful flares ever observed.

2. The Outer Layers of the Sun

The solar radius extends from the centre of the sun to the top of the photosphere. The outer layers are found beyond the surface of the sun and consist of the chromosphere and the corona.

Most of the early Australian and UK observations of radio radiation arose from phenomena in the solar corona. This early, groundbreaking research made a major impact on the understanding of the outer layers of the sun. At the end of the exciting first decade of observations by solar radio astronomers, new physical processes were postulated to explain what they had found.

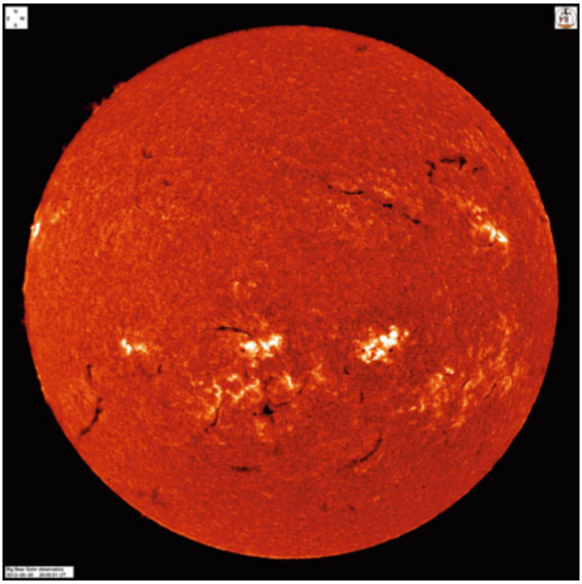


Fig. 2.6 H-alpha image of the sun's chromosphere on 30 June 2011 from the Big Bear Solar Observatory (BBSO) of the New Jersey Institute of Technology. Plages are the white area; solar filaments are also present (For latest H-alpha images from BBSO, http://bbso.njit.edu/Research/FDHA/)

Chromosphere

The **chromosphere** (the "colour" sphere) is a region 2,000 km thick that lies between the photosphere and the hotter, outer corona. In the chromosphere, the temperature rises from the photospheric temperature of 5,800 K to the one million degree temperature of the corona. The region is more visually transparent than the lower photosphere and is thus difficult to optically observe. At these higher temperatures hydrogen emits light that gives off a reddish colour (H-alpha emission); the name, chromosphere derives from this reddish colour.

Plages (French for "beaches") are bright regions of higher temperature and density within the chromosphere often close to sunspots (Fig. 2.6). In addition, plages can be present even in the absence of sunspots.

Prominences are a major component of the solar atmosphere; these are bright arch-like features that extend from the photosphere up to the corona. Prominences are stable structures with filamentary or braided shapes that appear to hang suspended above the surface (Fig. 2.7). Prominences are often associated with regions of sunspot activity, indicating that the sun's magnetic field plays a role in the formation of prominences. These features have typical time-scales of about a day and life-times of many days up to several solar rotations—one rotation being equal to about 26 days for a full rotation at the sun's equator as observed from the earth. The sizes are many thousands of km, with the largest prominences attaining sizes of up to 150,000 km. When a prominence is viewed from a different perspective, it has a different appearance. When the object is viewed face-on in the direction of the solar photosphere, the feature is darker than the surroundings (Fig. 2.6 and 2.8) and is called a **solar filament**. Prominences can become unstable

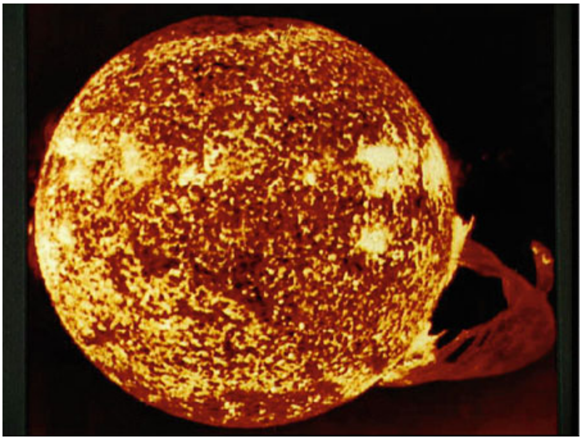


Fig. 2.7 The well-known image taken by the astronauts on Skylab 4 during the third and final mission. Image from 19 December 1973 showing a 600,000 km size prominence in the light of ionised helium (He II) in the extreme ultraviolet at 30.4 nm, provided by the U.S. Naval Research Laboratory. (Astronomy Picture of the Day, 30 August 1998, http://antwrp.gsfc.nasa.gov/apod/ap980830.html)

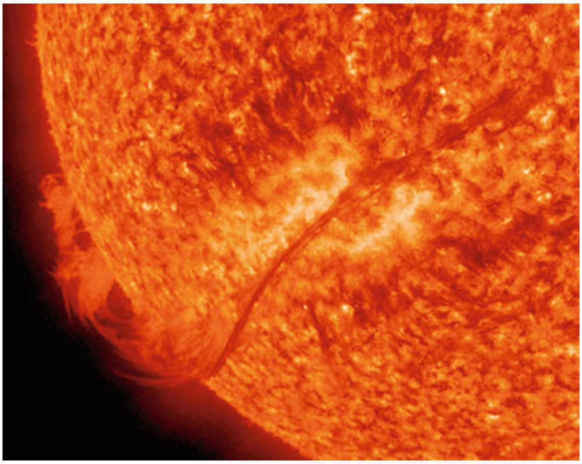


Fig. 2.8 Image of a prominence/filament from the Solar Dynamics Observatory on 6 December 2010, using the Atmospheric Imaging Assembly (AIA) at 30.4 nm in the light of ionised helium. It extends for over 700,000 km, comparable to the solar radius. This feature is called a prominence when seen bright against the dark sky above the sun's limb, and a filament when seen as a dark feature with the bright photosphere in the background, but both terms refer to the same physical feature. The SDO satellite (launched on 11 February 2010) is a part of NASA's "Living with a Star" program (http://www.nasa.gov/mission_pages/sunearth/news/News120610-filamentsnake.html)

and erupt, sending matter into space with velocities in excess of 600 km/s. These erupting filaments of gas are an impressive feature of solar activity due to their long lifetimes and energy release.

Corona

The **corona** is the extended outer atmosphere of the sun with a far larger volume than the photosphere. The typical height of the corona (depending on the 11-year solar cycle) is a few million km; in fact the corona is continuously expanding throughout the solar system forming the **solar wind**. The **heliosphere** is the region around the sun filled with solar plasma (ionised atoms); the size of the heliosphere is at least 100 AU in size based on the Voyager 1 spacecraft data. During periods of solar maximum the shape of the corona is roughly circular while during solar minimum the shape is elliptical with elongations along the solar equatorial regions.

Only in the nineteenth century was it realised that the corona belonged to the sun; earlier suggestions were made that this faint feature observed during eclipses might be a feature of the earth's atmosphere or that the features might arise from some phenomenon related to the Moon. The solar corona ("crown") is one of the more impressive components of the solar system. This extensive system occupied much of the attention of the new radio astronomers in the first decade after WWII. The temperature rises to about one million K at the base of the corona with particle densities in the range $10^{8–9}/cm^3$. This remarkable density decrease of a factor of 10 to 100 million occurs from the photosphere to the base of the corona. Within the corona, some regions with temperatures of several million K are also observed. The corona begins above the transition region, extending well beyond the solar surface. (Fig. 2.9).

Before the twentieth century the corona could only be studied during total solar eclipses. Spectra obtained in the nineteenth century showed unusual lines attributed to an unknown element, "coronium". This line at 530.3 nm is now known to arise from 13 times ionised iron (Fe XIV), (i.e., iron with 13 of the 26 electrons of the atom stripped away by intense collisions of protons in the corona). The hot corona of some millions of degrees was inferred by astronomers in the mid-twentieth century when these coronal spectral lines were identified with these highly ionised ions. Radio astronomers confirmed this hot corona a few years later by direct observations of the million degree corona.

Coronal Loops originate in the photosphere and extend through the chromosphere to the lower corona. Coronal Loops are observed in the ultra-violet (Fig. 2.10) and X-ray regimes (Fig. 2.11). These loops trace the magnetic field lines in the solar atmosphere with densities higher than their surroundings. These loops are associated with both active and quiet regions on the sun; the active regions produce the majority of the activity and are the source of flares and often a precursor of coronal mass ejections. The coronal loops are the closed magnetic flux field lines whereas open magnetic field lines result in the appearance of **Coronal Holes** (Fig. 2.12), regions of the corona that have a darker appearance due to the presence of lower density plasma.

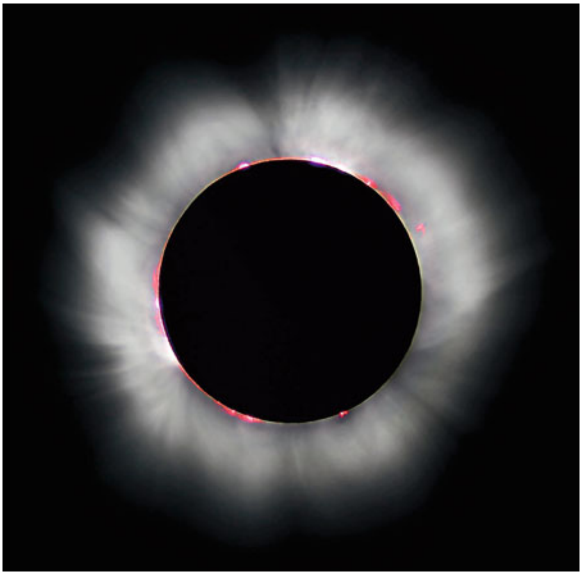


Fig. 2.9 Solar eclipse photograph of 11 August 1999 taken by Luc Viatour (http://www.lucnix.be). The diffuse corona is clearly visible when the surface of the sun is blocked by the moon. Note the red (H-alpha) prominences around the limb of the moon (© Luc Viatour [CC BY-SA 3.0])

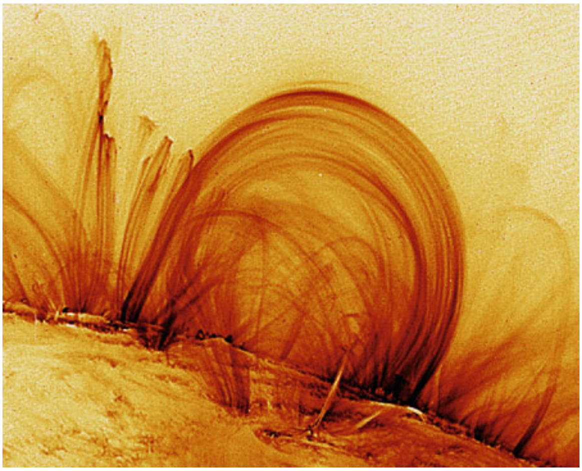


Fig. 2.10 Coronal loops observed with the Transition Region and Coronal Explorer (TRACE) at a wavelength of 17.1 nm, characteristic of hot plasma at 1 million K. Image from 6 November 1999. The satellite was launched on 2 April 1998. The Trace project is a mission of the Stanford-Lockheed Institute for Space Research and a part of the NASA Small Explorer program (http://soi.stanford.edu/results/SolPhys200/Schrijver/TRACEpodarchive.html)

Coronal mass ejections (**CME**'**s**) represent a massive release of energy into the solar wind (Fig. 2.13). Recent research suggests that CME's are caused by magnetic reconnection, the rearrangement of magnetic field lines when magnetic fields of opposite polarity are brought together. This action leads to a large release of energy. The released energy and the associated matter may expand outward, causing a CME. Typical velocities are less than 100 to some thousands of km/s with a mean velocity of about 500 km/s; the energies are up to ten times that of flares. During solar maximum, CME's occur at a rate of about 4 per day, reducing to about one per 5 days in the solar minimum period.

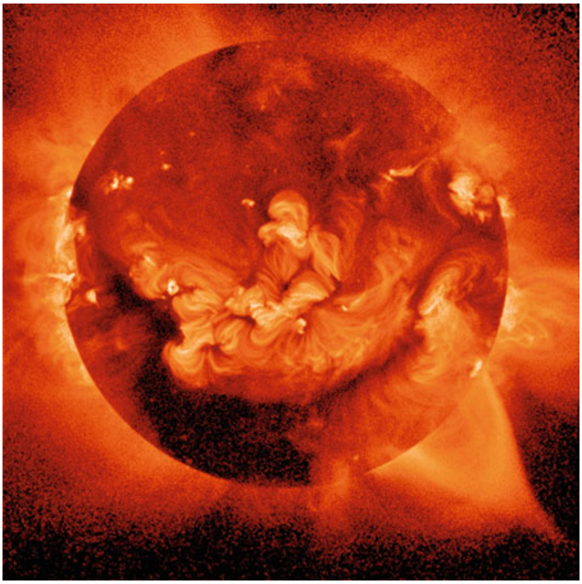


Fig. 2.11 X-ray image from the Yohkoh ("Sunbeam") solar observatory from 24 January 1992. The joint project of Japan, US and UK was launched on 31 August 2000 in Japan. The image was taken with the Soft X-ray Telescope (SXT) with an angular resolution of 2.5 arcsec in the energy range 0.25–4 keV (wavelength range 0.3–5 nm). The coronal loops represent hot (above 2 million K) and large coronal magnetic structures (http://solar.physics.montana.edu/sxt/ under "Image Galleries" and then "High-resolution SXT Full-Sun images")

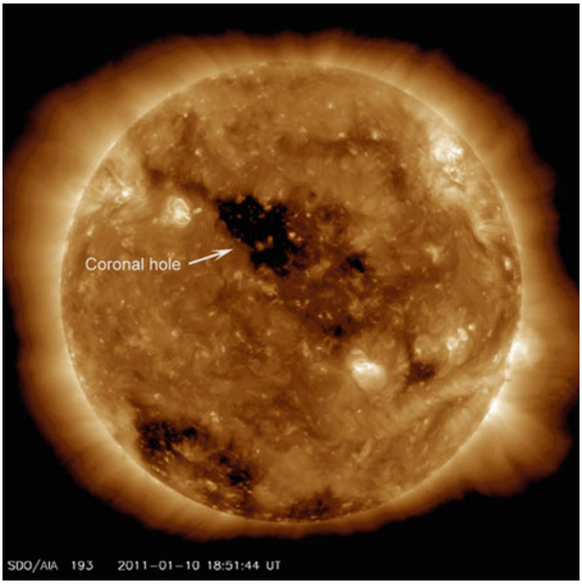


Fig. 2.12 An example of a Coronal Hole. Image from the SDO (Solar Dynamics Observatory), AIA, on 10 January 2011. The far ultraviolet image shows the dark coronal holes where the magnetic field lines are opening out to the interplanetary medium. These regions are also the sources of the fast solar wind of about 800 km/s. These particles will reach the earth in a few days, possibly causing aurorae (http://www.nasa.gov/mission_pages/sdo/news/news20110111-corona-hole.html)

As Ruby Payne-Scott and her colleagues began their exciting adventure in solar physics in 1945–1946, they could not have realised the important role they would play in the rapid advances in solar astronomy in the second half of the twentieth century. The knowledge that low frequency radio astronomy brought to understanding the physics of the solar corona had a far reaching effect. Payne-Scott's role in

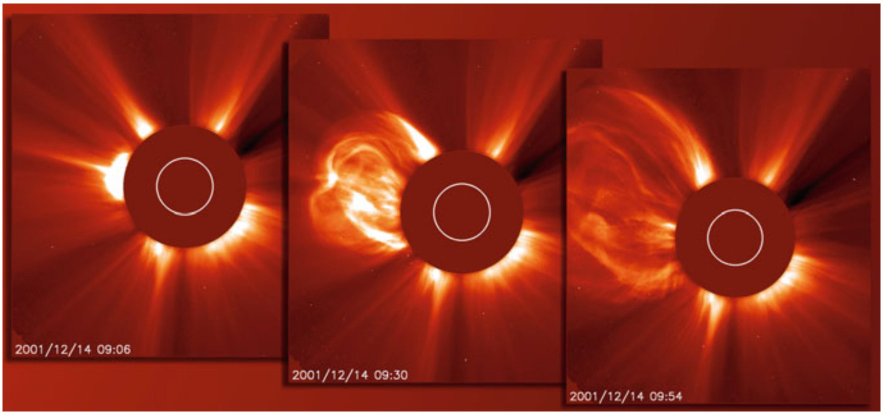


Fig. 2.13 Coronal Mass Ejection (CME). The SOHO satellite (Solar and Heliospheric Observatory, launched on 2 December 1995 and still operational in 2012) was used on 14 December 2001 to make a series of images of the sun. The LASCO (Large Angle and Spectrometric Coronograph) was used to create artificial eclipses of the surface of the sun (by blocking the bright solar image within the telescope on the satellite) enabling observations of the corona near the solar limb to a distance of 21 million km (about 1/7 of the distance from the sun to the earth). Using this instrument a number of sun grazing comets have been observed. These images were made over a 48 min interval and show a fast moving coronal mass ejection expanding at a speed of about 1,000 km/s. The sun is represented by the white circle. The field of view is 12 solar radii or 8.6 million km. This event was not directed towards the earth (http://sohowww.nascom.nasa.gov/pickoftheweek/old/17dec2001/index.html)

carrying out radio interferometry for the first time on Australia Day, 26 January 1946 has gone unrecognised. In her short period as an active radio astronomer (1944–1952), she made decisive contributions to the new field of radio astronomy. She discovered Type III bursts based on her work in 1947 at the Hornsby field station. Her understanding of these fast drifting radio bursts from the sun set the stage for the "most intensively studied form of radio emission in all of astrophysics" (Suzuki and Dulk 1985).

Tools of the Radio Astronomer

When Ruby Payne-Scott began her radio astronomy career in 1944, she was an experienced physicist who had worked on several radar research projects at the WW II Radiophysics Laboratory of the CSIR in Sydney, Australia. She was thus quite familiar with radio engineering techniques. The first radio telescopes were often radar antennas, altered only to receive radio radiation without the wartime practice of transmitting signals which were reflected from aircraft or ships. The new radio astronomers did not, in general, use the antennas as transmitters; instead they simply used the receiving equipment to detect the weak radio signals using the same antenna. There were, however, several groups working on lunar and meteor radar in the immediate post-WWII era, which did transmit signals to directly detect these objects with the radar technique.

What instruments did Payne-Scott use for her pioneering work of 1944–1951? How are these instruments related to modern twenty-first century instruments used by radio astronomers? The major research done by Ruby Payne-Scott in this era was in the VHF (Very High Frequency, 30–300 MHz or 10–1 m) range (wavelength and frequency are interchangeable; the wavelength is equal to the speed of light divided by the frequency). In this chapter, I will show a number of examples of the pioneering instrumentation used by Payne-Scott for the early solar radio noise research. I will show a few examples of twenty-first century radio telescopes that are the descendants of the post-WWII radio telescopes. The main achievement of Payne-Scott's career was the Swept Lobe Michelson Interferometer operating at a wavelength of 3 m (97 MHz) with which she recorded movies of the motions of solar bursts as they moved outwards in the solar corona. A major portion of the radio engineering planning was carried out by Payne-Scott.

Radio telescopes can be characterised by at least three attributes: (1) **sensitivity**, the ability to detect weak signals, (2) **angular resolution**, the ability to detect fine detail in the sky, and (3) **frequency response**, the determination of the intensity of the radio emission as a function of frequency or wavelength. For solar radio observations, high time-resolution (i.e. short time intervals) was essential. Payne-Scott's determination of the intrinsic frequency and time behaviour of the Type III solar bursts in 1946–1948 is an example of the latter property of a radio telescope.

The new solar radio astronomy of 1945–1951 had to address all of these attributes in order to decipher the mysteries of the radio radiation of the sun. By a stroke of good fortune, the beginning of 1946 coincided with a prominent solar maximum with large sunspots; these regions of the sun were associated with enhanced radio emission. Sensitivity was not a major limitation since solar bursts detected by Payne-Scott and colleagues had intensities in excess of a million Jansky. (**Jansky**, abbreviated as Jy, is the unit of intensity named after the American astronomer, Karl G. Jansky, who discovered radio emission from the Milky Way in 1933.) The sensitivity of her instruments was at the level of a few thousand Jansky, even enabling the quiet sun with intensities of 20–80,000 Jansky to be detected at wavelengths of 1–3 m (300–100 MHz). Modern radio telescopes such as the Jansky Very Large Array have sensitivities of a few millionths of a Jansky.

The relatively long wavelength of radio waves limits the angular resolution of the radio telescope. The radio wavelengths used in 1945 were a million times longer than optical wavelengths to which the human eye is sensitive. The typical angular resolution of a modest optical telescope is about an arcsec ($^1/_{1,800}$ of the sun's diameter, ½° as observed from the earth). The early radio telescopes had typical angular resolutions of tens of degrees, often referred to as the beam size. Thus in order to detect the details on the solar surface, the early radio astronomers needed to build special instruments called interferometers. By comparing different signal phases using an interferometer, much higher resolution (of the order of a fraction of a degree) could be achieved.

Fig. 2.14 Simple 65 MHz Yagi antenna used for routine solar radio astronomy monitoring. The antenna has an equatorial mount that enables continuous observations during daytime. The declination was set manually for each day. The antenna was located at the Potts Hill Reservoir (Chap. 10) of the Radiophysics Laboratory (RPL) of the CSIRO near Sydney Australia. The Yagi antenna was invented by Uda and Yagi in 1926 in Japan (CSIRO Radio Astronomy Image Archive B1465-1 from 26 July 1948)

In the following text, a number of radio telescopes (Figs. 2.14, 2.15, 2.16, 2.17, 2.18, 2.19 and 2.20) from the post-war era will be described. In addition, I will briefly discuss the Culgoora Radioheliograph (1967-1984); this instrument was the descendant of the ground breaking solar instruments constructed in Sydney in the post War era. In addition, two modern radio telescopes from the twentieth century will be discussed as well as a modern solar instrument planned for the second decade of the twenty-first century.

Yagi Antenna

In Fig. 2.14, we see the simplest element used by Payne-Scott in the late 1940s, the Yagi-Uda antenna, named after the discoverers of the device, Shintaro Uda and Hidetsugu Yagi of Tohoku University in 1926. It is commonly called a “Yagi” after the scientist who played the lesser role in the invention. This type of antenna is quite common for over the air VHF television and FM radio reception, whereas modern satellite television uses a high frequency, microwave dish antenna, much like modern radio telescopes.

Fig. 2.15 The 200 MHz shore defence radar at Dover Heights in Sydney during World War II. In the post-war era the antenna was converted to a radio telescope with no transmitter. In early 1946 this antenna was used for groundbreaking solar radio observations by Payne-Scott, Pawsey and McCready (Chap. 7). Payne-Scott carried out the first radio astronomical interferometry with this antenna on 26 January 1946 (Australia Day) at sunrise. See Fig. 7.2 (Copy obtained from the collection of W.T. Sullivan. Original from CSIRO Radio Astronomy Image Archive)

Broadside Array

In Fig. 2.15, the Shore Defence Radar (Sh.D.) at Dover Heights, in the eastern suburbs of Sydney is shown. This antenna was a WWII Australian Army radar used to detect enemy ships off the east coast of Sydney. J.L. Pawsey had been one of the major designers of this broadside array (200 MHz, 1.5 m wavelength) which consisted of 36 half-wave elements with a beam size of about 10°. The first use of interferometry in radio astronomy was carried out by Ruby Payne-Scott on Australia Day, 26 January 1946 at Dover Heights near Sydney using this radar antenna. This used the principle of **sea-cliff** interferometry. The antenna in Fig. 2.15 played a major role in the solar observations of 1946 and early 1947, but this instrument was scrapped by Bolton and Stanley in early 1947.

The principle of the sea-cliff interferometer is illustrated in Fig. 7.5 (see page 118). This interferometer is formed from the interference of the **direct** ray from the radiating source and the **reflected** ray from the sea; the waves from the two paths add in phase for some directions and cancel in other directions. The effective baseline of the interferometer, which determines the resolution of the interferometer, is twice the

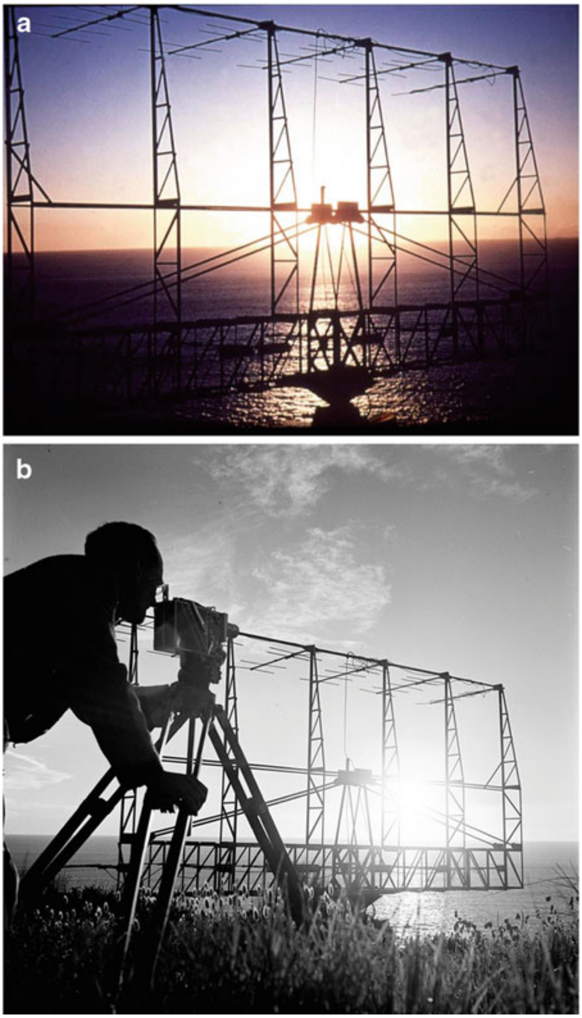


Fig. 2.16 (**a** and **b**) The 100 MHz sea-cliff interferometer used by Bolton, Stanley and Slee at Dover Heights in the early 1950s at Dover Heights, used for the study of radio sources in the southern sky. This antenna was used for a survey that detected 104 discrete radio sources (Bolton et al. 1954) (CSIRO Radio Astronomy Image Archive)

height of the sea-cliff. This type of instrument is called a "Lloyd's Mirror". In late January 1946, Payne-Scott used this interferometer at sunrise to determine the size and position of the radio bursts associated with a major sunspot. Since the resolution was set by the height of the cliff above sea level, to change the resolution another location with a different cliff height would be required. John Bolton and Gordon Stanley, two colleagues of Payne-Scott, used this technique when they travelled to New Zealand in mid-1948 where the cliff heights were 300 m compared to the less than 85 m at the Dover Heights site in Sydney. At the Dover Heights site, the resolution of the sea-cliff interferometer was about 1/3 degree much less than the beam of the single broadside array of about 25 degree.

The second generation Dover Heights sea-cliff interferometer in 1952–1953 is shown in Fig. 2.16a, b. These show the last sea-cliff interferometer built for operation at Dover Heights at 100 MHz (3 m). The 6 by 2 array of Yagi's was

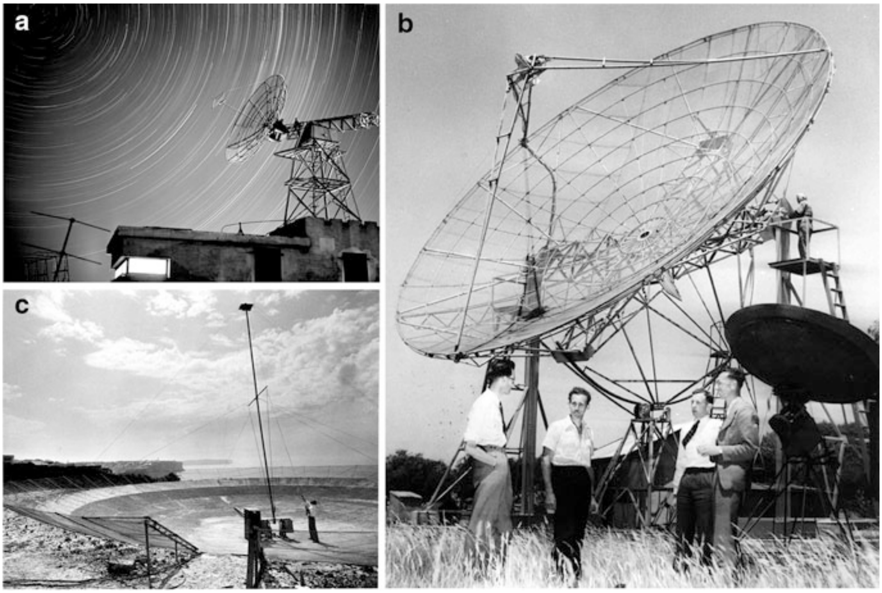


Fig. 2.17 (**a**) The 4.9 m reflector at Dover Heights used in 1950 by Stanley and Slee for an investigation of the properties of radio scintillation as a function of frequency. A striking star trail in visible light is seen during this long night time exposure from 16 July 1952. A similar photograph with John Bolton standing on the tower appears as a cover of Sky and Telescope, January 1953 (Bolton 1953). The star background includes the Southern Cross in the space between the reflector and the tower. The photograph is by the well known RPL photographer, Ken Nash who used a Rolleicord camera. A similar photograph appeared in Life magazine, November 1952 (CSIRO Radio Astronomy Image Archive, 2310-1 from 16 July 1952). (**b**) The 36 ft (11 m). transit parabola at Potts Hill. Sources were observed at transit (fixed east-west axis) with the telescope being moved in declination (north-south). The telescope was completed in 1952. The major use was for observations of the 21 cm hydrogen with an angular resolution of 2.8°. A map of the southern sky in neutral hydrogen was carried out as well as the detection of neutral hydrogen in the nearby galaxies the Large and Small Magellanic Clouds. The astronomers are left to right, Frank Kerr, Jim Hindman, Brian Robinson and Joe Pawsey. The 6 ft (1.8 m) reference antenna is in the right foreground (From W.T. Sullivan, originally CSIRO Radio Astronomy Image Archive, date circa 1953). (**c**) The 80 ft. (24 m) "hole in the ground" antenna at Dover Heights, Sydney, Australia (latitude -34° south) was completed in 1953. The survey of a limited part of the southern sky led to the radio detection of the galactic centre in early 1954. Dick McGee, one of the authors of the publication from 1954 (McGee and Bolton 1954), is shown in the photograph adjusting the mast of the telescope on 3 September 1953. With his adjustment, different regions of the sky near the zenith could be observed due to the earth's rotation. North Head at the entrance of Sydney Harbour is visible in the far distance, looking north (CSIRO Radio Astronomy Image Archive, B3150-1 from 10 Feb 1953)

mounted on an azimuth mounting and could only observe sources as they rose over the Tasman Sea. This publicity photo is somewhat ironic as this instrument was never used for solar research; likely the sun was only observed for testing purposes. Rather, a large survey of the sky from declination +50 to −50° (declination is the angular displacement with respect to the celestial equator, comparable to the latitude on earth) was carried out by John Bolton, Gordon Stanley and Bruce

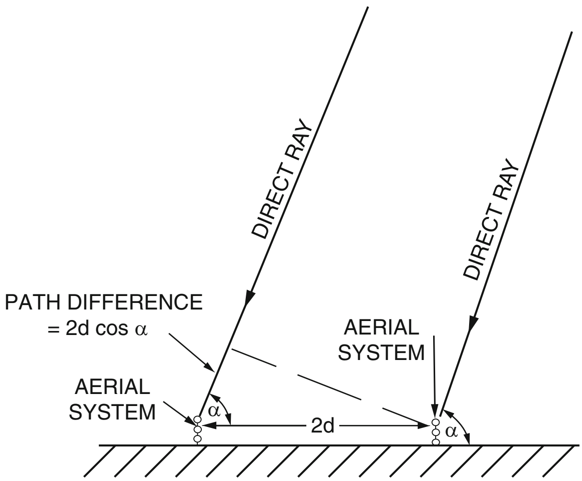


Fig. 2.18 A schematic diagram of the simple two-element Michelson interferometer, from Stanley and Slee (1950). Within a few years after 1950 most radio interferometry was done using Michelson interferometers (*Australian Journal of Scientific Research*, *Series A*, vol 3, page 234, 1950, "Galactic Radiation at Radio Frequencies, II. The Discrete Sources", Fig. 1b) (CSIRO Publishing, Copyright © CSIRO http://www.publish.csiro.au/nid.17.htm)

Slee. One hundred and four discrete sources (often called "radio stars" in this era) were detected. In reality radio nebulae were detected not the radio emission of stars.

Parabolic Reflector

For shorter wavelength observations (less than a few metres), the instrument of choice for the radio astronomer is the parabolic reflector, a paraboloid. This type of telescope was used in optical astronomy beginning in the seventeenth century; Isaac Newton is credited with building one of the first working optical reflectors in about 1668. In Fig. 2.17a, an early reflector telescope at Dover Heights is shown from 1952—a 16 ft. (4.9 m) reflector used to observe the intensity of strong radio sources at a number of frequencies; this type of observation enabled the determination of the **source spectrum**. At shorter wavelengths (for example 4 or 1.3 cm) it was necessary to use a solid surface; at 20 cm an open wire mesh was sufficient.

Also in 1952, a larger reflector was built at the Potts Hill reservoir site in the western suburbs of Sydney. This 36 ft. (11 m) transit telescope (Fig. 2.17b) was constructed mainly for 21 cm hydrogen line (the HI line arising from the neutral hydrogen atoms in the Milky Way) observations. The telescope could be positioned to detect most of the southern sky by moving the telescope only along the north-south meridian. The first HI line emission from an external galaxy was detected with this instrument. The southern Milky Way was mapped in detail, showing conclusive evidence for the spiral arm structure of the HI gaseous component of the Galaxy.

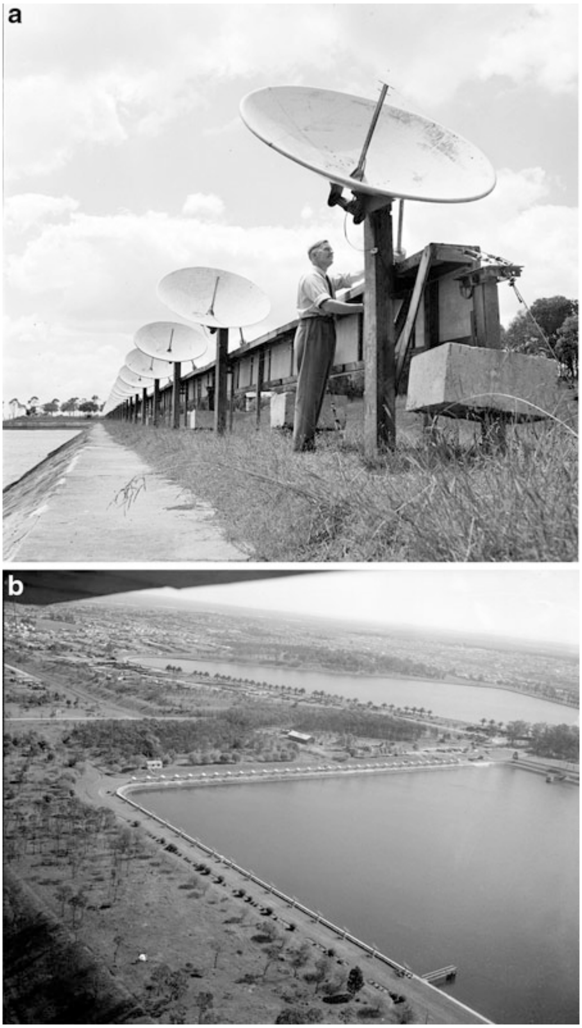


Fig. 2.19 (**a**) The 21 cm solar grating array designed by Christiansen, shown in the photograph, at Potts Hill, Sydney. The east-west array consisted of thirty-two, 1.7 m dishes providing a resolution of about 3 arcmin, a tenth of the solar diameter. The extent of the array was 213 m, and was completed in early 1952 (CSIRO Radio Astronomy Image Archive, 2976-1 from 14 January 1953). (**b**) Later in 1953, a north-south array was added to the 21 cm grading-array at Potts Hill. Sixteen elements were distributed perpendicular to the east-west array over a total extent of 160 m. Daily observations of the sun were made using both arrays from September 1953 to April 1954. The east-west array, comprised of solid surface antennas, is in the middle of the image, while the open mesh antennas extend northward, from the middle of the image to the bottom right (CSIRO Radio Astronomy Image Archive, B3475-1 from 25 October 1954)

A larger instrument was built in the early 1950s at Dover Heights with an ingenious design. This "hole in the ground" antenna could only observe close to the zenith (90° above the horizon) above Sydney, ideal for observations of the centre of the Milky Way which passed almost straight overhead. The 80 ft (24 m). diameter radio telescope (Fig. 2.17c) was used in January 1954 at 75 cm (400 MHz) to confirm that the radio source Sagittarius A was the centre of the Milky Way. This type of antenna had been invented at Jodrell Bank in the United Kingdom earlier in the 1950s. In the 1960s a large 1,000 ft. hemi-spherical "hole in the ground" antenna was built by Cornell University at Arecibo, Puerto Rico; this instrument has remained a major radio telescope into the twenty-first century.

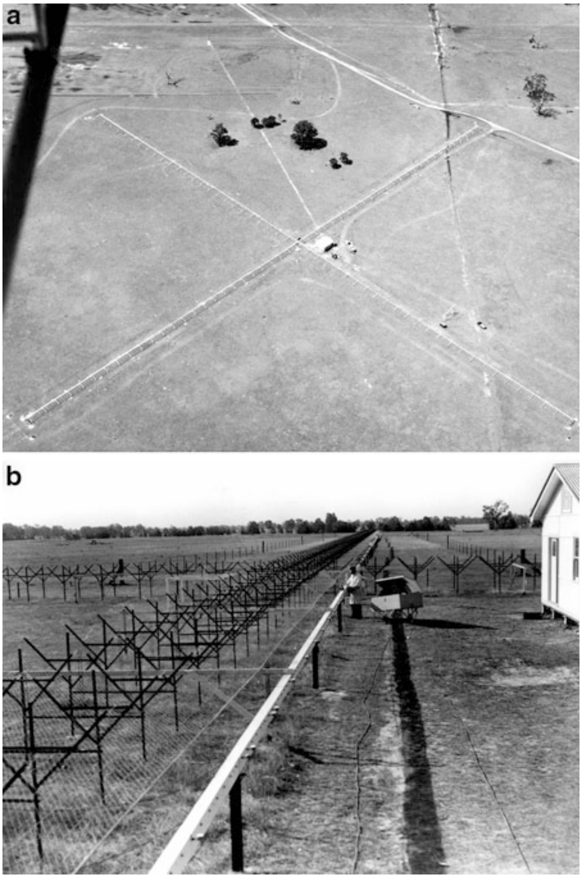


Fig. 2.20 (**a**) The Mills Cross at Fleurs designed by B.Y. Mills, completed in 1954. At the time Mills was a staff member at the Radiophysics Laboratory of CSIRO; in 1960 he moved to the University of Sydney. This instrument operated at 80 MHz with the lengths of the arms measuring 450 m. The resolution was 0.8°; an all sky image was carried out with the detection of about 2,300 sources. North is to the top left and east to the top right (CSIRO Radio Astronomy Image Archive, B3476-4 from 25 October 1954). (**b**) Details of the construction of the Mills Cross at Fleurs. The view is to the north along the north-south arm. The building to the right (east) contained the receiver and control room of the array (CSIRO Radio Astronomy Image Archive 3454-1 from 7 October 1954)

Michelson Interferometer

The sea-cliff interferometer played a key role in high-resolution radio astronomy in the late 1940s in Sydney. The instrument, however, had a number of limitations. The major problem was the limited observing time of about an hour as the source—the sun—rose in the east over the Tasman Sea. A more flexible telescope of a two element interferometer was developed in 1946 at the University of Cambridge in the UK by Martin Ryle and colleagues. This Michelson Interferometer, named after the famous American physicist, Albert Michelson (1852–1931), could observe the radio sky over many hours a day. The radio astronomers in Sydney called this instrument a "vertical interferometer", a term that did not last long (Fig. 2.18).

The resolution could be varied at will simply by changing the physical location of the antennas on the ground. Thus the inflexibility of the sea-cliff interferometer was avoided. The main advantage of the Michelson interferometer has been summarised by Buderi (1996):

> By cabling two small aerials to a shared receiver, he could achieve the resolving power [the effective angular resolution] of a gigantic antenna with a diameter as great as the distance separating the two small arrays [sic]. With his interferometer, Ryle was able to narrow in on the solar region from which radio emissions arose…

The use of the Michelson interferometer was pioneered by Sir Martin Ryle (1918–1984) and his group at the Cavendish Laboratory at the University of Cambridge (UK). Ryle was awarded the Nobel Prize in physics (1974) for his developments in the field of aperture synthesis (simulating a large radio telescope by combing the signals from a number of small antennas spaced on the ground), based on the use of the Michelson interferometer to form an imaging radio telescope.

The first Michelson interferometer developed in Sydney was planned by Ruby Payne-Scott, Alec Little and Joseph Pawsey at the Potts Hill Reservoir (Fig. 10.5), page 176 in 1948–1949. The system was an ingenious swept-lobe interferometer that could follow and, using a movie camera, record the motions of the solar bursts. The instrument operated at 97 MHz (3 m wavelength) with three elements spaced up to 280 m apart. The group of Mills and Thomas used this instrument at night to observe the intense northern radio source Cygnus A. An individual element of the interferometer is shown in Fig. 10.4, page 176.

Solar Grating-Array

A completely new development in radio astronomy occurred in 1950–1953 at CSIRO in Sydney. W. N. "Chris" Christiansen and colleagues developed a "grating-array" consisting of thirty-two 1.8 m parabolic dishes spaced at equal intervals of 7 m over a total east-west length of 213 m. This instrument enabled the astronomer to make rapid images of the sun at a wavelength of 21 cm with a one-dimensional resolution of only 1/10 of a solar diameter of ½° (Fig. 2.19a); a year later a north-south array of 16 antennas was added (Fig. 2.19b). Using this instrument a two-dimensional image of the quiet sun was made during a period of low sunspot activity in 1953–1954 with a two-dimensional angular resolution of about 1/20°; the computing to form the image was done by hand over a 6-month period! (Wendt et al. 2008a).

Mills Cross

Bernard Y. Mills and Christiansen—both of the CSIRO—had a discussion in 1953 that led to the invention of the Mills Cross. A small prototype was built at Potts Hill in 1953, followed by the complete Mills Cross (Fig. 2.20a) at Fleurs (some 40 km west of Sydney) with both the east-west and north-south arms measuring 450 m in length and set to observe at 85.5 MHz (3.5 m wavelength). The details of this image synthesis instrument are shown in Fig. 2.20b, showing the intersection of the east-west arm and the north-south arm. With an angular resolution of 0.8°, the entire southern sky (declinations from +10 to −80°) was imaged. Over 2,200 radio sources were detected; with this number of radio sources it was possible to investigate the number of sources as a function of intensity, leading to some of the first conclusions of **radio cosmology**—the study of the structure and evolution of the universe using radio sources located at great distances from the Milky Way.

Later in the mid-1960s, Mills and his group (now at the University of Sydney) built the much larger Molonglo Cross with east-west and north-south arms, with each arm measuring 1.5 km in length, observing the sky at 408 MHz or 75 cm. The Molonglo instrument has been upgraded, remaining operational in the twenty-first century.

Culgoora Radioheliograph

The Culgoora Radioheliograph was opened in 1967, representing the most advanced solar radio telescope built by the CSIRO Division of Radiophysics. The instrument operated for 17 years—until 1984–in which a number of major modifications were made to extend the frequency coverage of the solar image synthesis (creating an instantaneous narrow beam by combining the signals of all the individual telescopes) instrument. This instrument provided a wealth of new information and insights into phenomena in the solar corona. The instrument consisted of a series of aerials arranged in a circular array with a 3 km diameter (Fig. 2.21a), located at a site about 600 km northwest of Sydney. The array consisted of ninety-six, 13 m diameter paraboloids with a simple, economical design (Fig. 2.21b). The initial operating wavelength was 3.75 m (80 MHz). Later wavelengths of 6.9, 1.9 and 0.9 m were added. At 80 MHz, the resolution was 3.8 arcmin over a field of view of 2°, creating a complete image in 1 only 1 second. The instrument could make separate images using different senses of circular polarization. The instrument was able to construct a two-dimensional image over a field of view corresponding to the entire solar corona (about 2° at 80 MHz) in an almost simultaneous manner and was ideally suited to observe time-variable phenomena over a wide frequency range. Many advances in solar physics were made in the lifetime of this instrument. During its lifetime, this instrument was also used to observe non-solar radio sources such as pulsars, radio galaxies and supernova remnants.

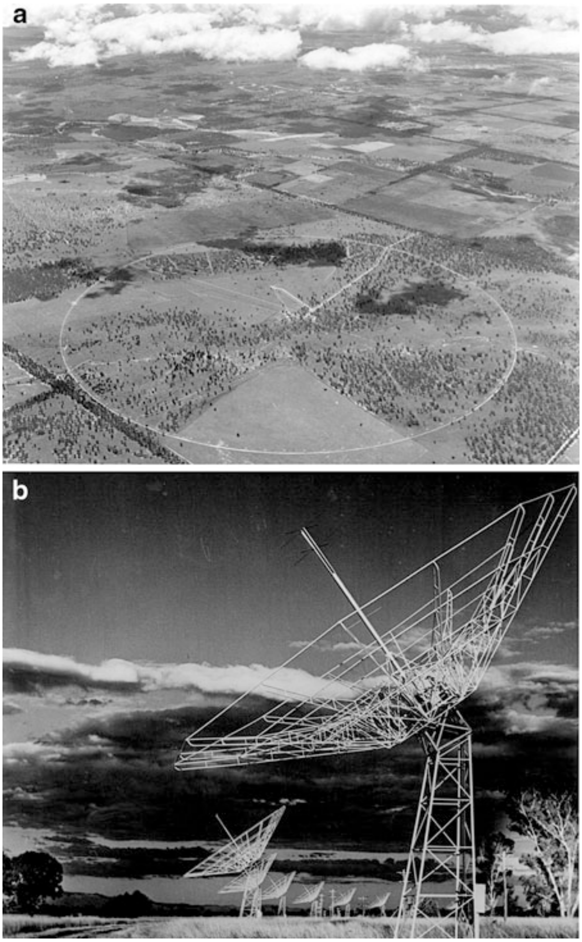


Fig. 2.21 (**a**) Aerial view from the southwest, of the Radiophysics Laboratory Culgoora Radioheliograph of CSIRO in north-central New South Wales, Australia. This instrument operated from 1968 to 1984. The 3 km diameter ring of 96 steerable 13 m paraboloids produced a beam of 3.8 arcmin over a field of 2° at 80 MHz. The instrument made images in circular polarization at intervals of 2 s, by scanning 48 beams across the sun. During the heliograph's remarkable lifetime, additional frequencies at 40,160 and 327 MHz were added. The driving force behind this project was J. P. Wild. The prominent road in this image to the centre of the array runs roughly east-west (CSIRO Radio Astronomy Image Archive, B7660-25 from 1964). (**b**) Close up of the Culgoora Radioheliograph antennas. The low-cost, 13 m antennas were characterised by simplicity. The Australia Telescope Compact Array of CSIRO (CASS) today occupies the site (J.P. Wild Observatory) near Narrabri, New South Wales, Australia. A few of the 13 m antennas remain (CSIRO Radio Astronomy Image Archive B8553-6 from 1967)

The Parkes Radio Telescope: The Dish

The Parkes 64 metre radio telescope is an icon in Australia; the dish celebrated its 50th anniversary on 31 October 2011, commemorated by Google with a Doodle of the Parkes telescope. The telescope is located near Parkes, New South Wales, Australia and is a facility of the CSIRO (Commonwealth Scientific and Industrial Research Organisation), CASS (Commonwealth Astronomy and Space Science). The importance of this instrument in the Apollo 11 lunar mission of NASA (National Aeronautics and Space Administration) during July 1969 is a well known story summarised by John Sarkissian at www.parkes.atnf.csiro.au/news-events/apollo11/. The actual moon walk by Neil Armstrong began at about 12.56 pm Australian Eastern Standard Time (AEST) on Monday 21 July 1969. The television images from the moon were shown around the world as received with the Parkes 64 m radio telescope. A fictional account of this event at Parkes has been captured in the 2000 Australian film, *The Dish*, directed by Rob Sitch and starring Sam Neill as the director of Parkes (a characterisation that bears little resemblance to the director at the time, John Bolton).

The telescope continues to maintain an outstanding research output. To date astronomers have detected about 2,000 pulsars in the Milky Way Galaxy. 1,250 of these pulsars were detected at Parkes since 1968, under the leadership of R.N. Manchester and colleagues. Numerous investigations of the interstellar medium in the Milky Way and in external galaxies have continued. The antenna was initially constructed for operation with an upper frequency of 1.4–2.3 GHz (21–11 cm wavelength). Presently the antenna is regularly used at 22 GHz (1.3 cm) for interstellar water maser and ammonia line observations; this remarkable change occurred as more accurate quality surface panels were added allowing the aerial to operate at shorter wavelengths. Fig..2.22a and c show the improved quality of the instrument from 1968 to 2011; both photographs were taken by Goss who started his career as a postdoctoral fellow at CSIRO in August 1967. Figure 2.22b is a striking publicity photo taken by Ken Nash in 1968.

Karl G. Jansky Very Large Array: The VLA

The Very Large Array of the National Radio Astronomy Observatory near Socorro, New Mexico, USA, is located on the Plains of San Augustin at an elevation of 2124 m. This aperture synthesis instrument is likely the most successful radio telescope built to date. The instrument was opened in 1980 and the completely renovated radio telescope was renamed and opened as the Karl G. Jansky Very Large Array on 31 March 2012. The updated array makes use of completely new electronics but reuses the original twenty-seven, 25 m antennas. These antennas can be moved to a number of configurations along the three railway tracks, each of length about 20 km. In 2012, the sensitivity has been increased by a factor of about ten. The renovation is a collaborative project between the USA, Canada and Mexico. The VLA covers a wavelength range from 7 mm (45 GHz) to 4 m (74 MHz)—a factor of about 600.

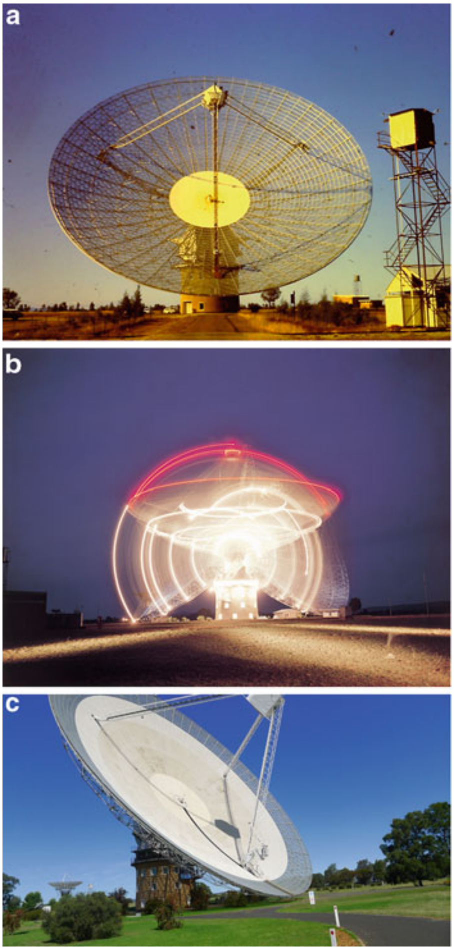


Fig. 2.22 (**a**) The Parkes 64 m radio telescope—The Dish—as photographed by Goss in 1968, after arriving in Australia as a NATO Postdoctoral Fellow in 1967. The solid inner surface has a diameter of 16.7 m. In 1968 the upper frequency limit of the telescope was in the range 6 to 3.6 cm. (**b**) The Parkes radio telescope in 1968. This Ken Nash publicity photo is a prominent icon in Australia (CSIRO Radio Astronomy Image Archive, 8886-1). (**c**) The Parkes radio telescope at the time of the 50th anniversary 31 October 2011. The new panels continue the progress over the last 50 years of improving the surface of the antenna to increase sensitivity at the higher frequencies (up to 1 cm). In order to support the NASA missions to Mars in 2003–2004 the mesh panels in the range 45 to 54 m were replaced with solid panels. After the refitting and extensive panel adjustments the roughness of the current surface of 54 m is only 0.8 mm, implying use to a wavelength of about 1 cm (Image taken by Goss, 2011)

The image in Fig. 2.23a shows the 'D' array, the smallest of the four configurations with a total extent of 1 km. In the C, B and A configurations the total length of the baseline is 3.6, 10 and 36 km respectively. The telescopes are moved from one configuration to the other about every 4 months; a double railroad

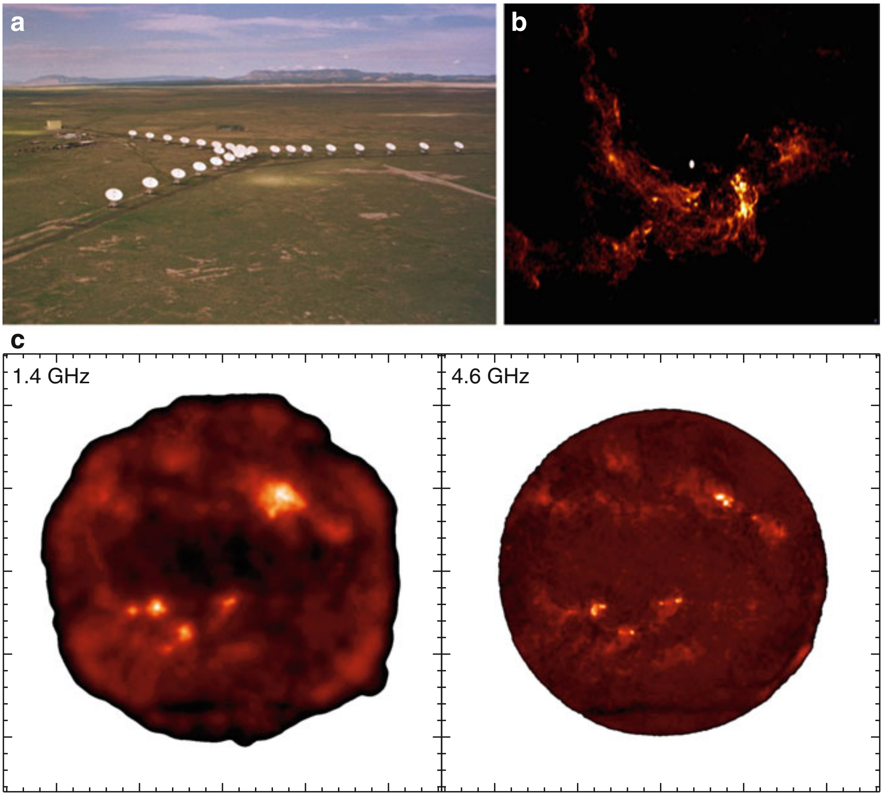


Fig. 2.23 (**a**) The Jansky Very Large Array of the National Radio Astronomy Observatory (NRAO) located on the Plains of San Augustin near Socorro, New Mexico, USA, a facility of the National Science Foundation operated under a cooperative agreement by Associated Universities, Inc. The location is at an elevation of 2,130 m. Each of the 25 m antennas can be moved along a railroad track to a number of different positions along three arms of a “Y”. There are four possible configurations; A, B, C and D. The image here is the D array with a maximum baseline of about 1 km. Each array is progressively larger by about a factor of three. In the A array the total size is about 30 km. The frequency range of the radio telescope is from about 50 MHz to 50 GHz (Associated Universities, Inc). (**b**) During the last 30 years, the VLA has produced numerous images of new features in the Galactic Centre of the Milky Way. This image is a continuum image at 1.3 cm with a resolution of 0.2 by 0.1 arcsec of Sgr A West, a region of ionised gas that surrounds the centre of the Galaxy. The compact white region is the radio source Sgr A *—Sgr A “star”-associated with the four million solar mass black hole at the centre of the Milky Way Galaxy. A prominent feature is the spiral structure in the ionised gas; this is associated with a gaseous nebula Sgr A West. The total field size is 25 arcsec, about 1 parsec or 3 light years (Zhao et al. 2009; Associated Universities, Inc). (**c**) VLA images of the sun from 11 April 1999. Left is 1.4 GHz (21 cm) and the right is 4.6 GHz (6.5 cm), with angular resolutions of 30 and 12 arcsec respectively. The field of view is about 30 arcmin. A number of active regions are shown at a time close to sunspot maximum (Image provided by Stephen M. White)

track is used, with the location of each antenna site on a railway siding. In the A array at 7 mm, the resolution is 0.04 arcsec—the size of a golf ball as viewed from a distance of 150 km. The method of operation for aperture synthesis is the scheme proposed by McCready, Pawsey and Payne-Scott in 1947.

Since 1980, about 13,000 telescope proposals have been observed, written by scientists at universities and research institutes from around the world. The scientific merits were judged by a panel of fellow scientists. About 2,500 users have utilised the VLA in its 30 year history, including many from Europe, South America, Canada, Australia, and Asia. During this period, around 200 Ph.D. candidates have completed their doctoral research at the VLA, thus earning their degrees from their respective universities. Scientists have carried out numerous groundbreaking observations of radio emission from planets, the sun, galactic nebulae, stars and molecular clouds in the Milky Way Galaxy, the Milky Way centre, nearby galaxies and distant radio galaxies. One of the more exciting fields of research in recent years has been the detection of high red-shifted (due to the expansion of the universe) molecular gas from young galaxies as observed in the distant universe. An iconic image of the region near the Milky Way centre is shown in Fig. 2.23b. The intense white dot is the radio source associated with the four million solar mass black hole at the centre of the Milky Way. The spiral structure associated with the surrounding region is a gaseous nebula. In Fig. 2.23c, two radio images of the active sun obtained by Stephen White and collaborators with the Very Large Array are shown; the images were obtained on 11 April 1991. Radio emission associated with active regions near sunspots is clearly detected at both 1.4 GHz (20 cm) and 4.6 GHz (6 cm).

Frequency Agile Solar Radiotelescope: FASR

The next generation of advanced solar radio telescopes will likely be FASR, the Frequency Agile Solar Radiotelescope project. The proposed instrument would be constructed in the US by a consortium of universities and the National Radio Astronomy Observatory; the project was one of seventeen recommended for construction later in this decade by the National Academies of Science Astronomy and Astrophysics Decadal Survey in 2010.

The instrument would consist of three sets of antennas. The log periodic dipole array of 15 elements would cover the 50–350 MHz range, while the mid-frequency range from 0.3 to 2.5 GHz would consist of fifteen, 6 m antennas and the high frequency range from 2 to 21 GHz would consist of forty-five, 2 m antennas. The instrument will produce high quality images with a resolution of 1 arcsec at 20 GHz with high time resolution of 20 ms. Major goals are the study of the nature and evolution of coronal magnetic fields, the physics of solar flares, the driving forces of space weather and the physics of the quiet sun. Figure 2.24 shows an artist's conception of the high and intermediate frequency antennas in a log spiral configuration at the proposed site at Owens Valley Radio Observatory (of the California Institute of Technology) near Bishop California, USA.

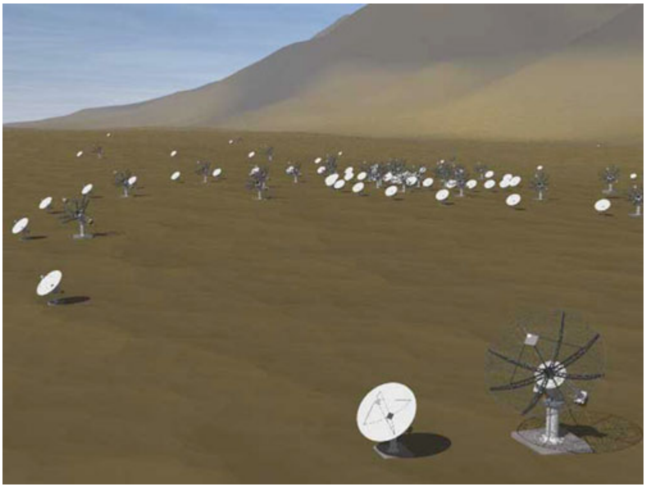


Fig. 2.24 An artist's conception of the proposed FASR (Frequency Agile Solar Radiotelescope). This is a proposed ultra-wideband imaging array operating over the frequency range 50 MHz to 21 GHz and would be the most powerful radioheliograph in the world. The instrument will image solar radio emission from the middle chromospheres to the outer corona once per second. The proposed site is the Owens Valley Radio Telescope near Bishop, California, USA (California Institute of Technology). The high and immediate frequency (open structure) antennas are shown. Looking from the SW. The FASR Project is proposed to be managed under Associated Universities, Inc. in partnership with the National Radio Astronomy Observatory, the New Jersey Institute of Technology, University of Michigan, University of Maryland, University of California-Berkeley, California Institute of Technology and the Observatorie de Paris (Image provided by Tim Bastian, National Radio Astronomy Observatory)

http://www.springer.com/978-3-642-35751-0

Making Waves
The Story of Ruby Payne-Scott: Australian Pioneer Radio Astronomer
Goss, M.
2013, XX, 262 p. 87 illus., 27 illus. in color., Softcover
ISBN: 978-3-642-35751-0