Chapter 1

The Radio Sun

Our Sun is an ordinary star, and the nearest one to Earth. Its distance from us defines a convenient unit of measure in our Solar System, the astronomical unit, or AU. One AU is approximately 150 million km, which is the mean distance from Earth to the Sun. The solar diameter is 696,000 km, or approximately 0.7 million km, presenting an angular diameter of about 0.5° as seen from Earth's surface. Its spectral class is G2, and it lies centrally placed on the main sequence of the Hertzsprung–Russell diagram in Fig. 1.1.

Stars are composed of a mix of gases, mostly hydrogen and helium, far too hot in the center to contain solid matter. Hydrogen in the core fuses together to form helium, and in so doing it releases large amounts of energy. Gravitational forces act to compress the star into a volume with the minimum of surface area, a sphere. The dimension of a star is maintained as a stable balance between the internal pressure pushing out, caused by the high temperatures at the core due to the energy released by fusion reactions, and the gravitational force wanting to contract it. Stars maintain this equilibrium state for millions to even billions of years. The life expectancy of a star is closely related to its mass. The most massive stars live fast and die young, the smallest live a very long time.

Most ordinary stars, including the Sun, are not big producers of radio energy. The radio properties of our Sun are only significant to us due to its proximity. In order to understand the radio emission, it is first important to appreciate the structure and processes of the solar environment.

The Solar Core

The Sun is fluid object throughout; although it appears to have a clearly defined surface, known as the photosphere. This is by no means the limit of the solar environment. The photosphere merely represents that region where the gases of the Sun become opaque to radiation. Within the photosphere there are three distinct zones; working out from the center they are the core, the radiative layer, and the convective layer.

The core is where the thermonuclear reactions occur, the heart of the Sun, and where all the energy is produced. Its limit extends to 0.2 solar radii (R_0), although the bulk of energy production occurs within the central 10%of R_0.

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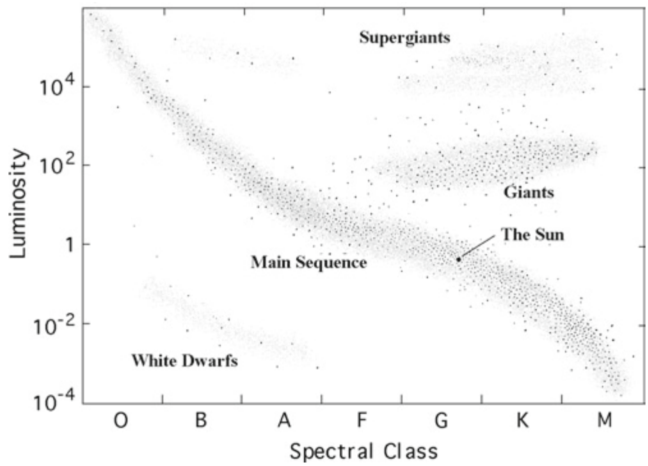

Fig. 1.1. The Hertzsprung-Russell Diagram. A plot of star colour against Luminosity. The vertical scale could be replaced by surface temperature.

In classical physics the fusion of four hydrogen nuclei to form a helium nucleus would require the particles to have sufficient kinetic energy (the energy due to their motion) to overcome the nuclear barrier forces. The kinetic energy of the atoms is largely a function of temperature, their energy increasing with higher temperatures. Hydrogen nuclei are fully ionized, which means they have no electron bound to them. Therefore they have a net positive charge. On the close approach of a pair of hydrogen nuclei they will repel each other most of the time and bounce off.

Although the core of the Sun has a temperature of 15 million K, this is insufficient to provide enough kinetic energy for the hydrogen to fully overcome the nuclear barrier forces and allow fusion. The temperature would have to be much higher. Fortunately, classical mechanics breaks down in this situation and is unable to explain nuclear fusion. Quantum mechanics can resolve this dilemma, however. Quantum mechanics is a theory that can explain many processes on the small scale of atomic structure, but fails to explain properties of the macro universe. These theories provide us with a better understanding of our universe than classical Newtonian mechanics ever could. Although quantum mechanics breaks down on the large-scale structure of the universe, and relativity breaks down at the small scales of atoms, scientists are still looking for the combined theory of everything! The process known as quantum tunneling allows a pair of atomic nuclei whose individual energies are lower than the nuclear potential energy barrier to fuse together. This is illustrated in Fig. 1.2.

The physicist de Broglie hypothesized that nuclear particles can exhibit wavelike properties. This was developed further by Schrödinger in his wave equation.

You can form a mental picture of a nuclear energy barrier by considering the rollercoaster ride pictured in Fig. 1.2.

If the car, without using an engine and ignoring frictional losses, was allowed to roll down the hill starting at point A, it would gain sufficient kinetic energy to ride over hill B but could not expect to reach a height higher than point C. If D represents the potential energy barrier between a pair of hydrogen nuclei, then it is very unlikely the pair will ever fuse unless the car tunnels through the barrier between C and E.

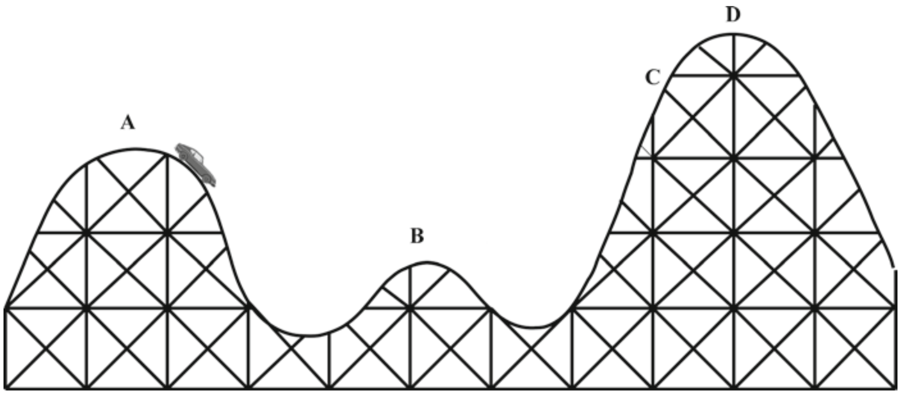

Fig. 1.2. Quantum tunneling.

The fusion process in the Sun is known as the proton-proton (PP) cycle. These PP chain reactions can take a number of routes to form helium, and which one it takes depends on the temperature of the stellar core. One of the reactions is more dominant than another for a given temperature. To take an example, the PP I chain reaction, which is dominant at temperatures from 10 million K to 14 million K, is given by these three formulae:

$$ {}_1H + {}_1H = {}_1D + e^+ + v_e $$

$$ {}_1D + {}_1H = {}_2He^3 + \gamma $$

$$ {}_2He^3 + {}_2He^3 = {}_2He^4 + 2{}_1H $$

The leading subscript refers to the number of protons in the nuclei. Note in the first reaction that one of the protons is converted into a neutron, with a consequent loss of mass. This mass is converted into energy. The positron generated here immediately combines with an electron, and the resulting annihilation generates a gamma ray photon.

In the second reaction one helium 3 isotope and a gamma ray photon is produced. In the final stage two helium 3 isotopes combine to form stable helium 4 and two protons.

The first reaction is very slow to occur, because it relies on the rare quantum tunneling process. Once this is complete the rest of the reaction occurs more quickly.

The bulk of energy production in the core of the Sun is in the form of gamma ray photons, which pass into the next layer.

The Radiative Zone

The radiative zone acts like an insulator helping to maintain the high core temperatures of 15 million °C. Here there is no major mixing of the plasma gases. The gases in the radiative zone are so opaque to radiation that the gamma ray photons are absorbed and re-emitted many times over. The average path length for a given photon before interaction is about 1 mm – this is very opaque! It can take the photon 50,000 years or more to emerge.

The Convective Zone

Finally the energy enters the convective zone. Here energy transport is achieved by warm gases rising, and cool gases falling in a cyclic pattern.

The hot gases rise towards the photosphere, cooling near the surface as energy is once again radiated from the photosphere. Rising cells of gas are visible on the photosphere surface as a granular pattern that is familiar on high resolution photographs of the Sun.

The Photosphere

The photosphere is the surface that is seen visually in optical telescopes. It is impossible to directly observe the solar interior below the surface. One of the ways astronomers can study the interior is by helioseismology. Like seismology on Earth, vibrations and oscillations in the solar surface can be observed. The telltale ripples and vibration frequencies give a lot of information about the structure of the interior layers.

It is on the photosphere that we see sunspots. These are active regions that appear dark by virtue of their cooler temperature. The black appearance is only relative to the brighter surroundings; the spot temperatures are still around 4,000 K about 2,000 K below that of the average surroundings.

Sunspots and the activity level of the Sun undergo cycles of approximately 11 years duration. At the peak of activity spot numbers reach a maximum, and when the Sun is quiet there may be long periods when no spots are seen at all.

Sunspots are a visible indication of magnetic anomalies on the surface. In spot groups the polarity of neighboring spots is often opposite. This gives rise to magnetic loops, which can enable matter to stream along the loop and back down to the surface. There are exceptions, however, where the second pole is so diffused that a single unipolar spot can exist.

Sunspots develop slowly from small pore-like structures into large spots and groups of spots. The seed pores occur on the boundaries of the granulation cells, which are manifestations of the upwelling of warm gases. Most pores simply disappear, but a few develop into large activity regions that can ultimately generate huge bursts of energy in the form of solar flares. As we shall see flares are of significant interest to the radio astronomer.

The Magnetic Dynamo

There is still much to learn to fully understand how stars and planets form magnetic fields. The mechanism by which a magnetic field is maintained is known as the dynamo process. The dynamo is a self-exciting system, where the motions of electrically charged particles flow in a conductive medium, producing circulating currents that interact with the existing field to maintain the magnetic field strength.

As mentioned previously the Sun is a fluid object that exhibits differential rotation. This means the equatorial regions rotate more quickly than the polar zones. It is thought that over the course of a solar cycle, the magnetic field gets twisted and disturbed, inducing the active regions we see. This eventually builds to a peak over the 11-year cycle and begins to settle again. This 11-year cycle is an average figure; it can be a little shorter or a little longer, but after each maximum occurs, the magnetic polarity of the poles invert. In a sense the full cycle of the sun has a mean period of 22 years.

The Chromosphere

The layer above the photosphere is the chromosphere. This is the beginning of the solar atmosphere. The matter residing in the chromosphere and the layers above it are no longer opaque to light. In this region between 5,000 and 30,000 spicules are observed at any one time. Rising to a height of 10,000 km spicules are streams of matter flowing outward at around 20 km/s, rising to a temperature of 10,000 K, hotter in fact than the photosphere. The sheer number and velocity of spicules suggest a mass flux twice that of the solar wind. By processes still not well understood a proportion of the matter streams return to the chromosphere.

The Corona

The corona is a vast rarefied zone around the Sun. There is no well-defined edge to it. In fact matter escapes the solar environment all the time in the form of the solar wind, which extends to the boundaries of the Solar System and no doubt beyond.

The temperature of the corona in the close proximity of the Sun is around 1–2 million K at quiet times, but can reach several million K above active regions. The temperature is far from uniform at any time. At these very high temperatures the matter emits a broad range of thermal electromagnetic radiation, but it is particularly interesting in the X-ray spectrum, where X-ray bright zones indicate the presence of underlying active regions. Although light is also radiated from the corona, it is weak in comparison with the emission from the photosphere, so it only becomes visible to the observer during total eclipses. All of the radio emissions from the Sun originate in the chromosphere and corona, as we shall see. So radio astronomy helps us probe and study the processes and structure of the solar atmosphere.

The question of why the corona is so hot and what heats it up has been a problem for scientists for years. It has led to many theories and is still a controversial subject. Recent observations made by James Klimchuk using instruments on board the NASA-funded XRT X ray telescope and the ultraviolet instrument EIS on board the Japanese satellite Hinode have been used to test a model that nano-flares are the prime source of coronal heating. Klimchuk investigated super hot plasmas of between 5 and 10 million K, which can only be accounted for by the bursting effect of flare activity. These super hot plasmas cool very quickly, passing on energy to their surroundings and giving rise to a general 1 million K background. We know that large flare outbursts cause significant coronal heating above them, but the relative lack of large flares for a large part of the solar cycle does not see the coronal temperature falling much below 1 million K even then. The breakthrough made by Klimchuk shows evidence of a constant rate of miniature flares occurring all the time, which is capable of maintaining the minimum temperature of the corona throughout the solar cycle.

The Quiet Sun and the Blackbody

The concept of the blackbody is fundamental to radio astronomy. It enables us to estimate the temperature of objects by observing the objects at only one wavelength of electromagnetic radiation. A blackbody is defined as a perfect absorber of radiation, as well as a perfect radiator. In other words, all radiation impinging on a blackbody will be absorbed, with no reflection or scattering; it is totally opaque. This is the theoretical ideal, of course, and nothing is perfect, but stars are good approximations of blackbodies. Despite the name, a blackbody is not always dark! After all, it has to be perfect radiator, too. Blackbodies emit a characteristic energy spectrum, defined by Planck's equation, where the peak output wavelength depends on the temperature of the blackbody. By measuring the received intensity at any wavelength, by a process of curve fitting, the whole blackbody spectrum can be derived.

Cool stars exhibit peak radiation in the infrared spectrum; hotter stars peak in the visible spectrum, and very hot objects peak in the ultraviolet. The Sun's surface temperature is approximately 6,000 K, resulting in a peak blackbody radiation wavelength in the yellow region of the visible spectrum. Hence we refer to our Sun as a yellow star. Figure 1.3 illustrates the way stellar intensity is related to its spectrum and is a plot of the Planck's equation.

By measuring a spectrum or just part of the spectrum, we can infer its temperature by fitting the data to a Planck curve. The same curve can be expressed as a graph of intensity against wavelength, or it can be calibrated as temperature against wavelength. This method is used in radio astronomy all the time to estimate an object's temperature. However the results need to be treated with extreme caution. By observing solar flare radio bursts at, say, 20 MHz, a temperature could be derived. This is almost certainly going to have a value of tens of thousands or even millions of K. By fitting this data to a Planck curve, the estimated peak output would suggest a temperature many times that which is accepted for the Sun. The quiet Sun has an immeasurably small output in the HF radio spectrum. Unfortunately the active Sun significantly deviates from the ideal blackbody spectrum in the radio region.

The answer to this problem lies in the fact that a solar flare energy output is not produced by thermal processes, so calculating a temperature from such data yields inaccurate results. Yet radio astronomers still report such results as a temperature, known as the equivalent temperature. Despite the fact that the temperature value

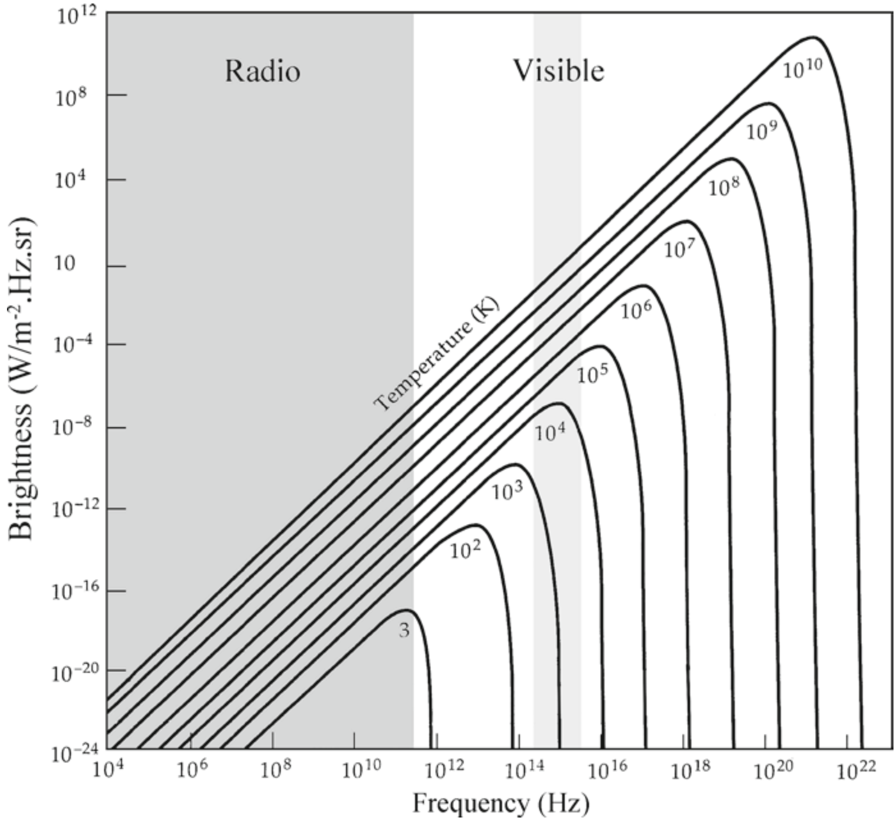

Fig. 1.3. Blackbody curves for different temperatures.

has no physical meaning, it is a useful figure that can be directly compared with other results, providing a measure of the strength of a radio signal. The equivalent temperature is therefore only valid for the frequency at which the measurement was taken, and the frequency must be quoted along with this temperature.

Solar Flares

Classification of Flares

Solar flares are classified by their size and duration, by their morphology, and by their magnetic topology. Flares are very complex phenomena, which can occur in white light, or they may be more restricted in their spectral output.

There are two basic types of flare, impulsive and gradual. Impulsive flares are of short duration, in the order of seconds to minutes. Many impulsive flares are fully contained within the Sun, although some are thought to induce mass ejection.

Gradual flares can last many minutes or even hours. This category of flare can generate huge energy output and eject matter that escapes the Sun. Fully developed flare events progress from the impulsive into the gradual phase.

Optical classification, referred to as the Hα importance, uses the scale S (sub flare sometimes also class 0), 1, 2, 3, 4, according to the area of the solar disk involved (see Table 1.1).

Today flares are routinely detected by satellite, usually in the X-ray band. The classification scheme uses one of the following prefixes – A, B, C, M, or X – X being the strongest class. The class is further subdivided and given a number such as C3, the number being an integer in the range 0–9 except for the X class, which can be any integer. The unit of measurement is W/m^2 (see Table 1.2).

For example a class C5 flare would have a strength of 5×10^{-6} W/m^2.

Radio outbursts at centimeter or meter wavelengths are classified on a scale of I–V in Roman numerals. See Table 1.3. This scheme was devised in the early days of radio astronomy, before the nature of flares was understood. The order of the numbering is relatively meaningless in the physical world.

Type III and V are associated with the impulsive flares or the impulsive phase of eruptive flares. They are generated by the acceleration of electrons along magnetic field lines into the corona.

Table 1.1. Optical classification scale for solar flares known as H α importance

Importance	Area (A) in square degrees
S	$A < 2$
1	$2.1 \leq A < 5.1$
2	$5.1 \leq A < 12.4$
3	$12.5 \leq A < 24.7$
4	$A > 24.8$

Table 1.2. Satellite based classification of solar flares based on X-Ray emission

Importance	Strength (W/m^2)
A	10^{-8}
B	10^{-7}
C	10^{-6}
M	10^{-5}
X	10^{-4}

Table 1.3. Solar radio burst classification scheme

Class	Duration	Bandwidth (MHz)	Drift rate frequency
Type I	Seconds	5	
Type II	Minutes	50	20 MHz/min
Type III	Seconds	100	20 MHz/s
Type IV	Hours	Wideband continuum	
Type V	Minutes	Wideband continuum	

Type II and IV are associated with the eruptive flares and coronal mass ejections (CME). The Type III are thought to be generated by flare-induced shock waves in the corona traveling at around 500 km/s. The Type IV is thought to be produced by magnetic reconnection following a coronal mass ejection.

How Solar Flares Form

Flares occur when charged particles are suddenly accelerated. The energy to induce the acceleration must come from the magnetic fields surrounding the active areas.

We saw earlier that groups of sunspots can be made up of pairs of spots with opposite magnetic polarity, between which there are looped magnetic field lines. Imagine a boundary line between these two spots we refer to as the neutral line. If the magnetic loop is perpendicular to the neutral line it is in the potential configuration. As the spots develop and move they can slide relative to each other along the neutral line. When this happens the field loops are no longer perpendicular to the neutral line. If this process continues to extreme levels, the field becomes nearly parallel to the neutral line, known as a sheared magnetic field. These sheared fields have more magnetic energy than the potential configuration. At this point magnetic instabilities can occur, breaking field lines and releasing energy, returning the magnetic field to the potential configuration by the process known as magnetic reconnection. The release of the free magnetic energy provides both thermal and non thermal energy to the surrounding plasma, accelerating the charged particles.

During the impulsive phase there is a rapid increase in intensity of radiation across the electromagnetic spectrum, particularly in the hard X-ray region, extreme ultraviolet, and the decimetric and centimetric radio wavelengths. These events originate in magnetic loops of the chromosphere, in the highly non-potential fields described above, where the electron densities exceed 10^{13} cm^{-3}.

The accelerated particles stream along the field loops and lose energy by electron-electron collisions and electron-ion interactions to produce the hard X-ray photons. In the low density parts of the loop ($<10^{10}$ particles per cubic meter) only a small proportion of the energy is lost, but when particles encounter the higher density regions the rate of energy loss significantly increases, stopping the electrons and heating the plasma.

Most flares are confined, impulsive types, which merely cool in the main phase by conduction into the cooler chromosphere, or by radiation. Conductive cooling is greater for long loops, although radiative cooling is lower in higher density loops. So short, dense flares dissipate first and long, lower density loops last longer.

The more powerful eruptive flares continue to emit radiation in the main phase, sometimes for several hours. It is in these eruptive flare events that the magnetic loops first break and then begin to reconnect again, releasing the free magnetic energy and heating the plasma to temperatures as high as 20 million K. Magnetic reconnection occurs quickly in the lower levels, but much more slowly at greater heights, leading to the long-duration events that we observe.

The loop heating generated by the reconnection events make the loops visible and usually appear as a pair of bright loops.

Solar Flare Radio Bursts

The Type III fast drift bursts occur whenever there are active regions present on the Sun. At decimeter wavelengths Type III bursts drift quickly from high to low frequencies, as a jet of electrons is ejected upward into lower density corona layers and about 90% of Type IIIdm bursts drift from low to high radio frequency, suggesting at times there are also jets of electrons descending into to denser regions. About half of the IIIdm bursts are associated with hard X-ray emission, suggesting a strong correlation with the impulsive phase of fully developed flares. Following the Type III bursts are often extended duration Type V continuum emissions during the main phase of the flare.

More than 90% of all Type II bursts are produced by solar flares, although not all flares generate Type II bursts. They are rarely seen in smaller flares with an optical classification less than two and occur in about one third of the flares with a Hα importance of between two and three. However they are often associated with small flares simply because small flares are far more common. About 70% of Type II events occur along with a coronal mass ejection; it is still unknown whether it is the CME or the flare blast wave that is the cause of the burst. Type IV continuum emission usually occurs alongside Type II bursts.

What, you might ask, is a Type I burst associated with? The original classification of radio flares dates back to 1963 and is based only on the morphology of the radio spectral profile, not on the physics behind the events. Accompanying Type IV continuum emission is often short, sharp, spiky noise usually classified as Type I.

At this time, not associated with flare activity, the slowly varying component of solar radio emission is prominent in the 3–60 cm wavelength band. This emission strongly follows the 11-year sunspot cycle, and not surprisingly it is associated with sunspot groups. The emission occurs in radio plages, up to 100,000 km above the active regions. High-resolution radio mapping has shown the central parts of approximately sunspot-size largely circular polarized radio energy emissions, while the surrounding plage has a more random polarization.

The Quiet Sun

At short wavelengths, those less than 1 cm, a high resolution radio telescope would show the solar disk subtends and angle of about half a degree, the same as seen visually. However at wavelengths of around 10 cm, the disk appears slightly larger, with a significant limb brightening especially in the east-west direction. While limb darkening in the optical is well known, and caused by increasingly cooler layers of gas towards the photosphere surface, limb brightening in radio is caused by the increasing temperature of the gases in the chromosphere. Observing at longer wavelengths the Sun subtends an angle of ever increasing diameter (Fig. 1.4).

From these observations it's clear that short wavelength radiation reaches us from closer to the solar surface and increasingly longer wavelengths relate to higher altitudes. The frequency of detected radiation comes from just above what is known as the critical layer for that frequency and is directly dependent on the electron density. As one would expect, the electron density decreases with

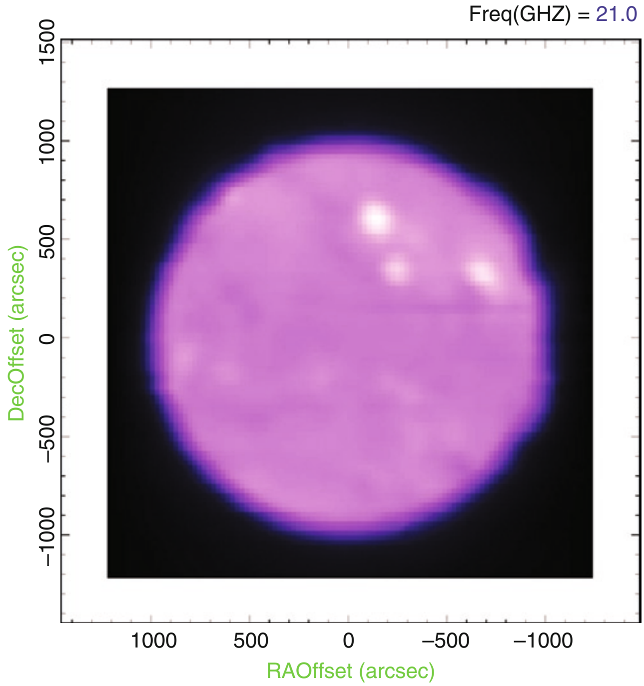

Fig. 1.4. The Sun at 21 GHz taken with the 37 m telescope at Haystack Observatory.

increasing altitude and offers astronomers a way of estimating electron densities for varying solar altitudes.

Non-outburst radio emission in the millimeter wavelength range occurs as a consequence of Bremsstrahlung thermal emission. Bremsstrahlung (breaking radiation) is caused by thermal electrons being deflected in the presence of the electric fields of ions in the chromosphere (Fig. 1.5).

At longer wavelengths of a few centimeters, gyroresonant processes are more important, whereby electrons are accelerated into spiral paths traveling along magnetic field lines. For long wavelengths, thermal emission is insignificant, and the bursting outputs of non thermal processes dominate.

The Solar Wind

The solar wind is a constant outflow of particles from the Sun. These give rise to radio bursts caused by instabilities when the solar wind encounters shock wave fronts passing through the Solar System. The shock wave fronts in turn originate in the corona of the Sun and provide us with a remote method of observing such irregularities in the Solar System, out as far as the planet Jupiter. However the frequency of the bursts is very low and is sadly not observable from the Earth's surface due to the ionospheric cut off.

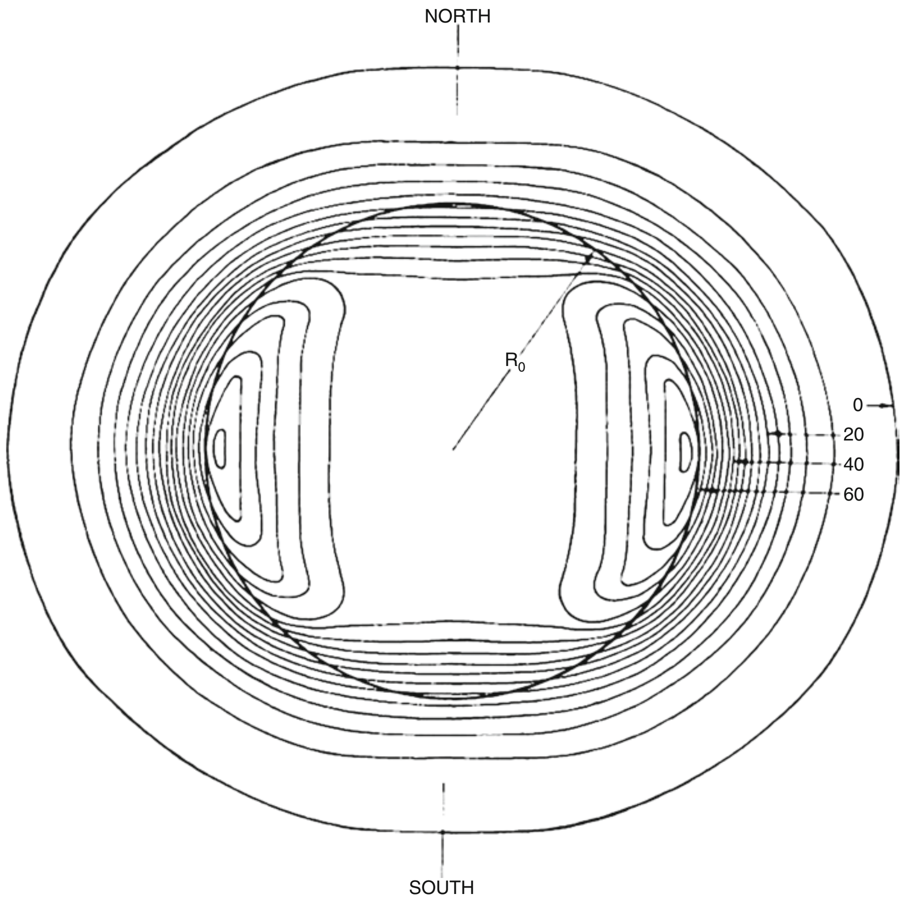

Fig. 1.5. A contour map of the Sun at 1.4 GHz. The circle of radius R_0 is the diameter of the visible Sun. (Based on data from W.N. Christiansen, and J.A. Warburton, *Australian Journal of Physics,* 1955).

Type II and III bursts are usually the only ones that can be tracked for any length of time by spacecraft into the deeper Solar System. They can be tracked for up to several hours, or maybe even for more than a day.

Interplanetary radio bursts occur at or near to the local plasma frequency. Hence they are dependent upon the electron density at the source. Once again the electron density continues to decrease with increasing distance from the Sun; therefore the critical frequency of emission decreases with distance, to the order of less than 100 kHz at about 50 AU from the Sun.

Type II bursts are seen usually only faintly at great distance from the Sun. The shock waves excite electrons to around 10 keV to produce Langmuir waves, which are converted to radio energy by a similar process as that of Type III radiation. This is particularly useful to Earth scientists tracking shock waves approaching Earth. Type III bursts are more energetic, and resulting sub relativistic jets of electrons with energy levels up to 100 keV are more commonly observed and better understood.

Amateur astronomers cannot directly observe the solar wind and its radio properties. However there are a couple of indirect means we can use to study its effects. Firstly there is the variation of long distance radio propagation of communication signals, and secondly we can check out the effects on local magnetic field.

In the project section of this book the VLF receiver is one instrument designed to monitor propagation effects, albeit in that case it's more sensitive to ionospheric X-ray exposure. It has long been known that HF radio propagation is strongly influenced by the solar cycle. While we will not be exploring HF propagation in this book in any detail, it would constitute an interesting long-term addition to a radio solar observing program to monitor the received signal strength of amateur radio beacons. The reader is strongly encouraged to get involved in amateur radio, and even progress to obtaining a transmitting license.

The use of a sensitive magnetometer can be part of the observer's arsenal of tools in order to monitor the solar influence on Earth. Charged particles of the solar wind that are captured by Earth in the magnetic polar regions not only create aurorae but also strongly influence the ambient magnetic field. Although the construction of a magnetometer is not covered in this book, the UKRAA arm of the British Astronomical Association's Radio Astronomy Group is shortly going to offer an instrument for just such observing programs.