Continuum Radio Emission and Diagnostics

The Sun is a strong radio source (one of the first objects detected by radio telescopes) and radio observations can provide information on structures throughout the solar atmosphere. Radio techniques allow high–quality images with arcsecond resolution to be achieved, and different radio frequencies provide access to different layers of the solar atmosphere. This section discusses incoherent emission from thermal plasma in the non-flaring solar atmosphere; other relevant material may be found in COHERENT PLASMA EMISSION and in SOLAR FLARES: RADIO BURSTS.

Emission mechanisms

Three different emission mechanisms are the dominant sources of continuum radio opacity in the non–flaring solar atmosphere, and their contrasting properties allow them to be exploited in different ways. An important feature of radio emission from the solar atmosphere is that the presence of magnetized plasma breaks the degeneracy between the two electromagnetic modes and leads in general to very different opacities for them. In particular, the mode in which the electric vector rotates with the same sense as the gyration motion of an electron about a magnetic field (known as the *extraordinary* or X mode) interacts more strongly with radiating electrons than the mode with the opposite sense of rotation of the electric vector (the *ordinary* or O mode). Radio telescopes typically make images in the two oppositely–circularly–polarized electromagnetic modes which correspond to the natural radiation modes of the plasma: differences between the two modes result in polarized emission which reflects the conditions in the radio source and is often a valuable diagnostic.

Free–free or bremsstrahlung emission

This is the name given to the electromagnetic interaction occurring when a free electron collides with a positively–charged ion. In the solar atmosphere protons and Helium make up the bulk of the ions: at temperatures of 10^4 K and higher, all hydrogen atoms are ionized and the atmosphere is a plasma dominated by free electrons and protons. The opacity of this mechanism is proportional to the product of the electron and ion charge densities and inversely proportional to the square of frequency and to temperature to the power 1.5. It is therefore particularly effective at high densities, low frequencies and low temperatures. This mechanism can produce mildly polarized emission.

Thermal gyroresonance emission

An electron moving in a magnetic field gyrates about the field direction with a characteristic frequency called the electron gyrofrequency, $\nu_B = 2.8 \times 10^6\, B$ Hz, where the magnetic field B is measured in gauss (G). The acceleration associated with the gyromotion provides opacity in the radio regime at frequencies which are integer multiples (*harmonics*) of ν_B for magnetic field strengths in the range 10 to 3000 G, which corresponds well to the range of magnetic fields seen in the solar atmosphere above active regions. Gyroresonance opacity increases strongly with temperature, and is much larger when viewed nearly orthogonal to the magnetic field direction in the source than when viewed parallel to the magnetic field. This is the dominant source of opacity in regions of strong magnetic fields in the corona, such as above sunspots. This mechanism can produce highly polarized emission because of the large difference in the opacities of the X and O modes. Strictly speaking this is a resonant mechanism (i.e., a given radio frequency is associated with a particular value of magnetic field strength), but may be regarded as a source of continuum opacity since B varies continuously throughout the atmosphere.

Gyroresonance opacity drops dramatically as harmonic number increases. In conditions typical of the solar corona (electron densities of order 10^9–10^{10} cm^{-3}, temperatures of order 10^6 K, length scales 10^9 cm), the third (and lower) harmonic of the gyrofrequency will be optically thick in the more strongly interacting polarization (the X mode) as long as the line of sight is not nearly parallel to the magnetic field. Since magnetic field strength generally decreases with height, emission from the first and second harmonic layers originates below the opaque third harmonic layer and is not seen, although in the O mode the third harmonic layer may be optically thin and then the second harmonic layer dominates. Thus a radio image of optically–thick gyroresonance emission at a given frequency ν GHz in the polarization corresponding to the X mode can be regarded as a map of the temperature on the layer corresponding to a constant magnetic field strength of $\nu/8.4{\times}10^6$ G.

H^- opacity

As one goes deeper into the solar atmosphere the temperature drops below 10^4 K and the dominant species (H and He) become neutral. The total electron and proton densities can remain high in the chromosphere (temperatures between 5000 and 10000 K) because the total density increases rapidly with depth while the fractional ionization decreases, but below 5000 K essentially all hydrogen is neutral. Free electrons are still present at these temperatures due to ionization of metals such as sodium, but there are insufficient free protons to provide significant free–free opacity. In this situation a mechanism involving free electrons and neutral H dominates the radio opacity: the electron polarizes an H atom and the interaction between the electron and the dipolar atom provides opacity known (somewhat confusingly) as H^- opacity. From the relevant temperature range it is clear that this mechanism is only important in the lower atmosphere near the TEMPERATURE MINIMUM, probed by very high frequencies (millimeter wavelengths). Circular polarization in the radiation from this mechanism is expected to be weak.

The Appearance of the Sun at Different Radio Frequencies

The Sun can usefully be studied at all radio frequencies, from the ionospheric cutoff of order 10 MHz (wavelength $\lambda = 30$ m) up to the SUBMILLIMETER domain above 300 GHz ($\lambda \leq 1$ mm). Different frequencies penetrate to different depths in the solar atmosphere, depending on local conditions, so that the appearance of the Sun changes dramatically over the radio frequency range.

An important feature of solar radio emission is that every frequency becomes optically thick (i.e., opaque) at some point in the solar atmosphere. Just as we cannot see below the photosphere in visible light, in a radio image at a given frequency we cannot see material below the optically thick layer. Radio wavelengths lie in the Rayleigh–Jeans limit, $h\nu \ll kT$, and therefore the radio flux is proportional to the brightness temperature (see COHERENT PLASMA EMISSION). In the optically thick layer the brightness temperature is equal to the local electron temperature so that (unlike most other diagnostics of the solar atmosphere) radio images can often be interpreted directly as temperature maps. Since temperature in the solar atmosphere generally increases outwards from the temperature minimum (just above the photosphere), it is also possible for a radio image to show both the emission from the low–lying cooler optically–thick layer as well as contributions from hotter optically–thin plasma in the overlying atmosphere.

As noted above, free–free opacity increases rapidly as frequency decreases and it dominates the quiet radio Sun at low frequencies (plasma emission is also prevalent at low frequencies, and is discussed in COHERENT PLASMA EMISSION). The whole solar corona is optically thick at frequencies below 500 MHz, so that the Sun appears as a large relatively featureless source with a dimension larger than the solar radius, usually elongated in the equatorial direction due to the fact that the solar atmosphere is generally of higher density at the equator than at the poles. The fact that the low–frequency radio Sun had a brightness temperature of order 10^6K was one of the important pieces of evidence which led to the discovery of the solar corona. Propagation effects (see SOLAR RADIO BURSTS) can make

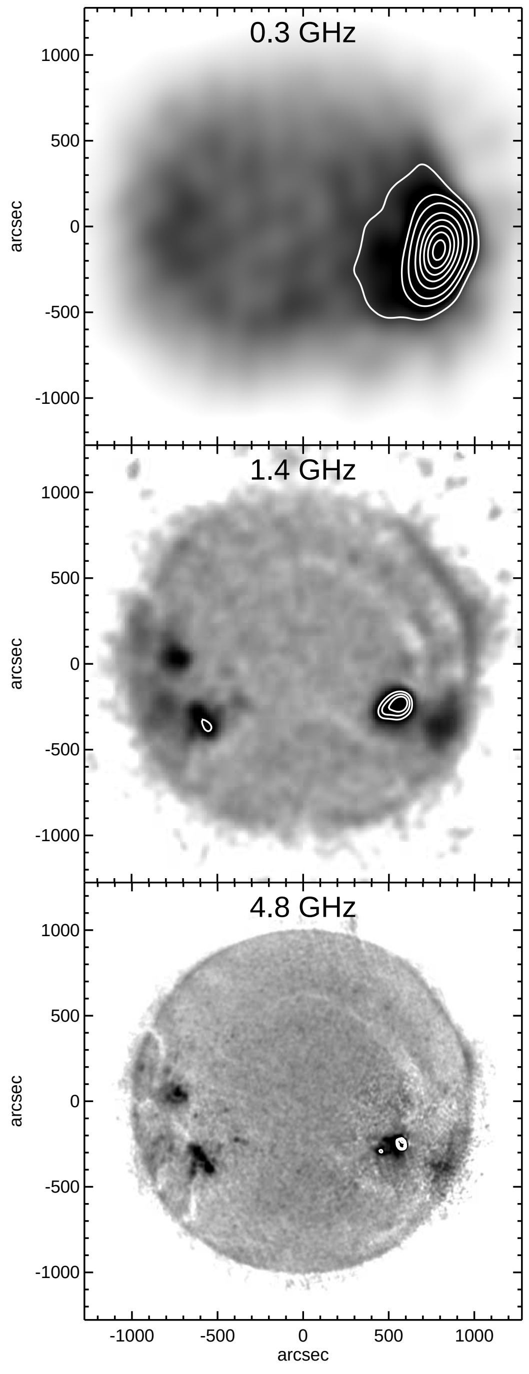

Figure 1: The appearance of the Sun at three different radio frequencies. The intrinsic resolution is different in each image: it is 220″ at 0.3 GHz (top), 50″ at 1.4 GHz (middle) and 12″ at 4.8 GHz (lower panel). These images were made with the Very Large Array radiotelescope on 1993 November 7 (courtesy S. White). White contours highlighting the brightest features are plotted at brightness temperatures of 0.8, 1.2, 1.6, 2.4, 3.2, 4.0, 4.8 and 5.6×10^6 K. The color table saturates (is black) at 0.8×10^6 K at 0.3 GHz, 0.6×10^6 K at 1.4 GHz and 0.1×10^6 K at 4.8 GHz. Solar west is to the right.

the radio Sun appear to be larger than the actual height of the optically thick surface. Scattering off small–scale turbulence in the outer atmosphere and solar wind can also supply a frequency–dependent lower limit to the spatial resolution which can be achieved in an observation. Since the whole corona is at a temperature of order 1 – 2 million degrees K, there is little contrast between quiet features on the solar disk at low frequencies. As is often the case at low frequencies, the brightest radio feature in the 0.3 GHz image shown (the feature at the right edge of the 0.3 GHz disk) is not due to free–free opacity at all, but rather is a NOISE STORM (also called TYPE I CONTINUUM, a form of broadband coherent emission commonly found over very active regions in the frequency range 200–500 MHz: see COHERENT PLASMA EMISSION).

As frequency increases above 500 MHz the quiet solar atmosphere starts to become optically thin and its brightness temperature drops, while the enhanced density in the corona above active regions maintains a high optical depth and hence high brightness temperatures. Thus at 1.4 GHz radio images of the Sun show much more contrast between features, depending on their density. The background disk has a temperature of order 10^5 K at this frequency. In coronal holes and filament channels where the density is low, the brightness temperature is below this value, while in active regions and plage the brightness temperature remains above 10^6 K. Virtually all the non–flaring radio emission seen at 1.4 GHz is believed to be produced by free–free emission. Gyroresonance emission is only rarely seen at this frequency, possibly because the gyroresonance–emitting layers lie below optically–thick free–free sources.

At 4.8 GHz, on the other hand, gyroresonance emission produces the brightest features observed in radio images. Optically–thick free–free emission has never been clearly identified at frequencies this high, so that any feature with a brightness temperature in excess of 10^6 K at frequencies of 4 GHz or higher is almost certainly a gyroresonance source. This is true in the image shown, where two sunspots in an active region south–west of disk center show up as the only features on the disk with coronal brightness temperatures. These are the only two locations in the solar corona on this particular day where the magnetic field strength exceeded the value 600 G needed to produce gyroresonance emission at 4.8 GHz. The other bright features, such as those near the east limb, are due to optically–thin free–free emission from dense structures in the corona (these also show up prominently as bright sets of loops in X–ray images), and have brightness temperatures of order 10^5 K, compared with 10^6 K over the sunspots. Low–density features clearly show up as regions of reduced brightness, e.g., within the active–region complex near the east limb, and in the filament channel stretching across the north–west quadrant. The disk at this frequency is at a brightness temperature of order 20000 K, corresponding to the lower transition region/upper chromosphere. Optically–thin coronal emission from features such as active regions appears as an additional contribution to the brightness temperature, but since it is transparent the underlying optically–thick chromospheric contribution can still be seen. The size of the radio disk at 4.8 GHz is of order 30″ larger than the optical photosphere.

The brightness temperature contribution of optically–thin free–free emission scales as ν^{-2}, so that at yet higher frequencies the optically thin contributions from hot dense coronal material diminish rapidly, while the solar disk component, being due to optically thick emission from the chromosphere, diminishes less rapidly: at 17 GHz it is 10000 K. Gyroresonance emission, on the other hand, can continue to produce features with brightness temperatures in excess of 10^6 K as long as sufficiently strong magnetic fields are present in the corona. The upper limit to coronal magnetic field strengths is not known, but may be of order 3000 G (the largest observed field strengths in the photosphere are of order 5000 G), which could produce gyroresonance emission up to 25 GHz. This results in contrasts of up to 300 between the brightest radio features and the background "disk" brightness temperature at frequencies such as 17 GHz. Above the highest frequency at which gyroresonance emission is effective, there is no form of opacity available which can make coronal features optically thick in the quiet solar atmosphere and consequently there are no features with coronal brightness temperatures: the contrast between the disk brightness temperature and the brightest features in the radio image is greatly reduced. The height of the layer in which a given frequency becomes optically thick continues to drop through the chromosphere as frequency increases: the brightness temperature of the disk component is of order 6700 K at 100 GHz and 5800 K (corresponding to the vicinity of the temperature minimum) at 300 GHz, with contrasts only of order 10% being seen in the images. At these temperatures, free–free emission is probably still the dominant source of opacity, although H^- opacity may also be contributing.

Radio continuum diagnostics

The value of radio diagnostics lies in a number of unique characteristics which complement those available in other wavelength ranges: (i) radio data provide a direct measurement of electron temperature; (ii) again in contrast to most other diagnostics which are optically thin above the chromosphere and thus show the emission integrated along the line of sight, radio emission is optically thick in the solar atmosphere and by using the fact that different frequencies become optically thick at different heights, multi–frequency observations can be used to "peel away" successive layers of the atmosphere; and (iii) the influence of magnetic fields on radio emission allows coronal magnetic fields to be measured directly. At present radio observations are the best technique available for studying magnetic fields in the corona.

Free–free emission can be used to study densities and temperatures in the solar corona. Radio observations of free–free emission complement X–ray and EUV observations of the corona well: both are sensitive to the dense loops found in the corona above active regions, but the radio data are often optically thick whereas the X–ray/EUV data are optically thin. The fact that the radio emission is optically thick makes it particularly sensitive to temperature gradients. The radio emission is weighted towards cooler plasma due to the (temperature)$^{-1.5}$ dependence of free–free opacity. Information on abundances can be derived from a comparison of the different wavelength regimes, since X–ray fluxes depend on the number densities of ions such as Fe in specific charge states, while the radio flux depends on the number density of protons.

Observations of gyroresonance emission have wide usage in the study of coronal properties above active regions, where magnetic fields are strong enough for gyroresonance emission to dominate. The fact that it is a resonant mechanism results in emission at a given frequency coming from a very thin layer of constant magnetic field strength: typically B varies by less than 2% across a gyroresonant layer. The optical depth may vary by a factor of 1000 from one harmonic layer to the next, which simplifies interpretation since it means that only one layer is likely to be contributing to the observed flux. Thus observations of gyroresonance emission pick out physical conditions in a highly localized region of the corona; changing the observing frequency picks out a different layer, so that in principle a three–dimensional picture of the corona may be developed. There are some complications, however, in interpreting gyroresonance emission: (i) the highest optically–thick harmonic layer is not known in advance: for typical conditions it occurs where $\nu = 3\nu_B$ in the X mode and $\nu = 2\nu_B$ in the O mode, but where the line of sight is parallel to the magnetic field the opacity is greatly reduced and one sees down to a lower harmonic layer; and (ii) the radio data do not contain any independent information on spatial scales, so that one does not know what the height of each gyroresonance layer is from the radio data alone.

Solar radio telescopes

The Sun was first identified as a radio source during World War II. In 1942 J. S. Hey was investigating bursty interference in meter–wavelength radar receivers in Britain when he noticed that it coincided with a solar flare. Almost simultaneously G. C. Southworth in the U.S. looked for and detected steady emission from the Sun at centimeter wavelengths. After the war years many veterans of the radar effort turned to radio astronomy. A group in Australia led by Joe Pawsey developed radio instruments for the study of the Sun and carried out pioneering work on the classification of solar radio bursts.

A number of instruments are routinely used to make radio images of the Sun at the time of writing. Solar–dedicated telescopes include the Nançay radioheliograph in France operating at frequencies in the range 150–450 MHz, the Owens Valley frequency–agile array in the USA in the range 1-18 GHz, and the Nobeyama radioheliograph in Japan at 17 and 34 GHz. In Russia the RATAN–600 telescope observes in the range 1–20 GHz and the Siberian Solar Radio Telescope at 5 GHz. Low–frequency facilities previously operated at Culgoora (40–320 MHz) in Australia and at Clark Lake (20–110 MHz) in the USA. The Very Large Array radiotelescope in the USA (0.3 - 22 GHz) is used for solar observing on an occasional basis, and provides a powerful combination of sensitivity, spatial resolution and frequency coverage.

Bibliography

Bastian T S, Ewell M W, Jr., and Zirin H 1993 The center–to–limb brightness variation of the Sun at λ=850 microns *Astrophys J.* **415** 364

Dulk G A 1985 Radio emission from the Sun and stars *Ann. Rev. Astron. Astrophys.* **23**, 169

Kundu M R 1965 *Solar radio astronomy* (New York: Interscience Publishers)

White S M and Kundu M R 1997 Radio observations of gyroresonance emission from coronal magnetic fields *Solar Physics* **174** 31

Zirin H, Baumert B M and Hurford G J 1991 The microwave brightness temperature spectrum of the quiet sun *Astrophys J.* **370** 779

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