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the plasma density is very small. This outer layer has been clearly identified in the saturnian magnetosphere but at Jupiter the evidence is less clear, probably because the flux tubes are more rapidly refilled by diffusion. In both magnetospheres this transition region is characterized by a more dipolar field orientation, with large fluctuations of magnetic field and plasma density.

The outer boundary of any planetary magnetosphere is the magnetopause which separates solar wind plasma from magnetospheric plasma. At the magnetopause the magnetic field changes from its magnetospheric value to the, usually, smaller magnetosheath value. The stronger magnetospheric magnetic pressure is balanced by the pressure of the magnetosheath plasma which is solar wind plasma heated in the bow shock that exists in front of the magnetopause (see Fig. 1). Because of the internal plasma sources, the magnetospheres of the giant planets are inflated and the magnetopauses are usually much further away from the planets than at the Earth. At Jupiter the magnetopause has been observed as far out as $120 R_J$. Thus the jovian magnetosphere can be 10 times larger than the Sun. If it could be seen with the naked eye, it would appear bigger than the Sun. On the other hand, these magnetospheres can be more easily compressed by solar wind pressure increases and the jovian magnetopause has been observed as close in as $50 R_J$. At the Earth such large variations of the magnetopause position are not observed.

These giant magnetospheres display a remarkably complex topology and dynamics. They generate radio waves, synchrotron radiation, and particles with energies in excess of several megaelectron volts which populate the entire solar system. As such they resemble stellar magnetospheres more than the Earth's magnetosphere. It is a triumph of technology that we have made in situ observations of these objects; it is an equal triumph of space plasma physics that we understand at least the fundamental processes that shape them.

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See also **Interplanetary and Heliospheric Space Missions; Outer Planets, Space Missions; Planetary Magnetism, Origin; Planetary Radio Emissions.**

Planetary Radio Emissions

Donald A. Gurnett

A wide variety of planetary radio emissions are known to be generated in our solar system. For our purposes, the term *planetary radio emission* is defined to be any naturally occurring electromagnetic emission that can propagate freely away from the planet. This definition excludes various types of waves known as plasma waves that are generated in planetary ionospheres and magnetospheres, but which cannot escape because of propagation constraints. It also excludes radio emissions produced by radio transmitters and other human activities.

Planetary radio emission can be conveniently classified into two types: thermal and nonthermal. Thermal radio emissions are simply part of the thermal radiation spectrum emitted by the planet. Thermal radiation is usually strongest at infrared frequencies and is very weak and difficult to detect at radio frequencies. Nonthermal radio emissions are caused by nonequilibrium charged-particle distributions in the atmosphere, ionosphere, and magnetosphere of the planet. Nonthermal radio emissions are classified into two types, incoherent and coherent, depending on whether the charged-particle motions are uncorrelated or correlated. For incoherent radiation, the electric fields of the individual particles add randomly. The total radiated power is then the sum of the powers radiated by the individual particles (i.e., proportional to N, the number of radiating particles). For coherent radiation, the electric fields of the individual particles add in phase. The total radiated power is then proportional to N^2, which increases very rapidly as N increases. Because of the N^2 dependence, coherent radiation is generally much more intense than incoherent radiation. However, some mechanism is required to produce correlated motions. For planetary radio emissions, this mechanism usually involves a plasma instability or an impulsive phenomenon such as lightning.

THERMAL RADIATION

Thermal radiation has been detected from all of the planets. At radio wavelengths the spectrum follows the Rayleigh–Jeans law,

$$B = \frac{2kT}{\lambda^2}, \tag{1}$$

which gives the brightness of the source (in W m^{-2} Hz^{-1}), as a function of the temperature T and wavelength λ. The quantity k is Boltzmann's constant. Although the thermal radiation is stronger at infrared wavelengths, infrared radiation is absorbed by clouds and sometimes does not give a reliable measurement of the surface temperature. Because planetary atmospheres are generally transparent at radio wavelengths, measurements in the radio part of the spectrum provide the best method for determining the surface temperature of a planet. The best known example of the use of radio measurements to determine the surface temperature of a planet occurred at Venus, when Cornell H. Mayer and collaborators, using microwave measurements, estimated the surface temperature to be nearly twice as hot as on Earth. These very high temperatures were later confirmed by the *Venera* 7 lander, which measured a temperature of 740 K on the surface of Venus. If the planet does not have a solid surface, as is the case at Jupiter, Saturn, Uranus, and Neptune, then the spectrum gives the temperature deep in the interior of the atmosphere. An example of the thermal spectrum of Jupiter is shown in Fig. 1. The thermal spectrum can be seen on the right-hand side of the plot, at frequencies greater than about 10 GHz. The straight dashed line labeled "thermal" shows the $1/\lambda^2$ variation predicted by the Rayleigh–Jeans law. The effective disk temperature of Jupiter at these frequencies ranges from about 200–320 K.

INCOHERENT NONTHERMAL RADIATION

Although several types of incoherent nonthermal radio emissions can occur, the only planetary radio emission of this type that has been observed is synchrotron radiation. Synchrotron radiation is caused by the accelerated motion of charged particles moving in a magnetic field. The radiated power increases rapidly as the particle speed approaches the speed of light. Because of their smaller mass, electrons are much more effective radiators than ions. If the motion is circular, with no motion along the magnetic field, then the radiation occurs at harmonics of the cyclotron frequency, and extends up to a critical harmonic number, above which the inten-

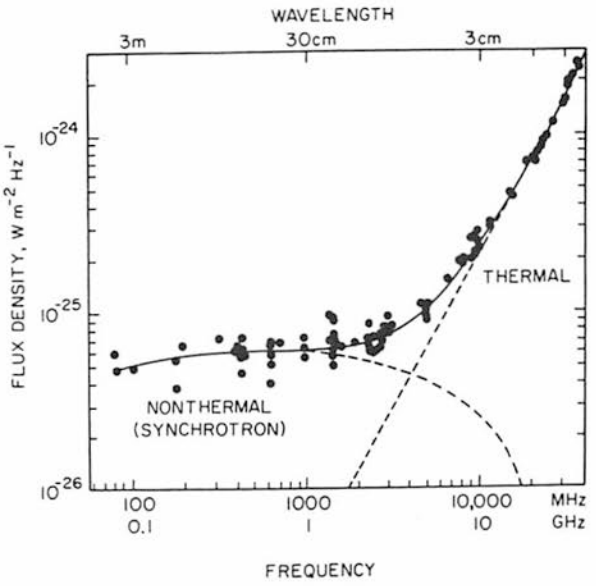

Figure 1. The thermal radiation and synchrotron emission spectrum of Jupiter. [*From Carr et al. (1983).*]

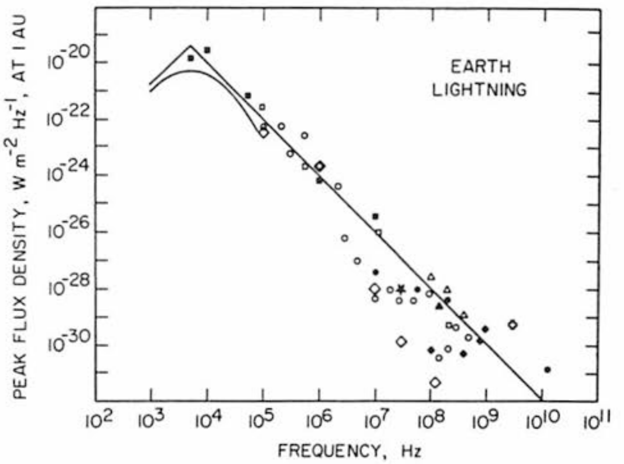

Figure 2. The spectrum of terrestrial lightning, adjusted to a distance of 1 AU. This radiation can only escape through the ionosphere at frequencies above about 10^7 Hz. [*From Pierce (1977).*]

sity decreases rapidly with increasing frequency. The critical harmonic number varies approximately as E^3, where E is the particle energy. The total power radiated is proportional to E^2B^2, where B is the magnetic field strength. Thus both a strong magnetic field and high energies are required for efficient generation of synchrotron radiation. When a distribution of velocities exists along the magnetic field, as is normally the case, the discrete harmonic spectrum is converted to a continuum. This process is called Doppler broadening. For nonrelativistic energies most of the radiation is concentrated near the first few harmonics. This type of radiation is usually called gyrosynchrotron radiation.

The only known example of planetary synchrotron radiation occurs at Jupiter. This radiation was first discovered by Russel M. Sloanaker in 1959. A spectrum of the jovian synchrotron radiation is shown on the left-hand side of Fig. 1. As can be seen, the synchrotron radiation is stronger than the thermal spectrum at frequencies below about 3 GHz, and has a broad peak centered on about 1 GHz. Because the highest intensities occur at wavelengths in the decimeter range, this radiation is often called jovian decimetric radiation.

Jupiter is an intense synchrotron source because the planet has a strong magnetic field and a very intense, energetic radiation belt. Measurements by the *Pioneer 10* and *11* spacecraft showed that the surface magnetic field of Jupiter is about 10 G and that the inner region of the magnetosphere is populated with intense fluxes of electrons with energies up to 40 MeV.

COHERENT NONTHERMAL RADIATION

Several types of coherent nonthermal planetary radio emissions have been identified. Compared to the thermal and incoherent nonthermal emissions described in the previous sections, coherent emissions are more highly structured and vary considerably from planet to planet. The basic mechanisms involved in the generation of coherent radio emissions are also more complex and poorly understood. At present, three distinct types of coherent nonthermal radio emissions are known to exist: lightning, cyclotron maser radiation, and mode conversion from electrostatic waves.

LIGHTNING

Radio signals from lightning have now been detected at six planets: Earth, Venus, Jupiter, Saturn, Uranus, and Neptune. At Earth, lightning discharges can be heard on a simple AM radio receiver. At Venus, lightning was first detected by a low-frequency (10–80 kHz) receiver on the *Venera 11* probe which entered the atmosphere of Venus on December 21, 1978. At Jupiter, impulsive very low frequency (1–10 kHz) signals called whistlers, which are known to be produced by lightning, were detected by the plasma wave instrument on the *Voyager 1* spacecraft which flew by Jupiter on March 5, 1979. Whistlers were also observed by the *Voyager 2* spacecraft as it flew by Neptune on August 25, 1989. At Saturn and Uranus, impulsive high-frequency radio signals, believed to be caused by lightning, were detected by the radio astronomy instruments on *Voyager*.

Lightning generates coherent radio emissions because the electrical breakdown initiates an impulsive, highly correlated motion of electrons along the discharge path. The coherence is very high at low frequencies (~ 10 kHz) and decreases at higher frequencies. On Earth, the discharge produces a spectrum that has a peak at about 5 kHz, decreasing approximately as f^{-2} with increasing frequency. A spectrum of terrestrial lightning is shown in Fig. 2. The energy emitted per discharge varies over a wide range. The high-energy terrestrial discharges are often referred to as "superbolts." Because of the limited amount of data available at other planets, it is difficult to carry out quantitative comparisons with terrestrial lightning. The comparisons that have been made suggest that lightning at the outer planets is considerably more energetic than terrestrial lightning, possibly comparable to terrestrial superbolts.

Cyclotron Maser Radiation

Five planets, Earth, Jupiter, Saturn, Uranus, and Neptune, are known to produce powerful radio emissions via a mechanism known as the cyclotron maser instability. This radiation was first observed from Jupiter by Bernard F. Burke and Kenneth L. Franklin in 1955 at a frequency of 22 MHz using a ground-based radio receiver. Further studies showed that the jovian radio emissions occurred over a broad range of frequencies extending up to about 40 MHz. Because the maximum intensities occurred at decameter wavelengths, this radio emission is called jovian decametric radiation (DAM). About 10 years after the discovery of the jovian decametric radiation, a similar type of radio emission was detected from the Earth's magnetosphere by the *Electron-2* satellite. Subsequent studies using a variety of Earth-orbiting spacecraft showed that the terrestrial radio emission is very intense (total radiated power ~ 10^7–10^9 W) and is generated at high altitudes over the

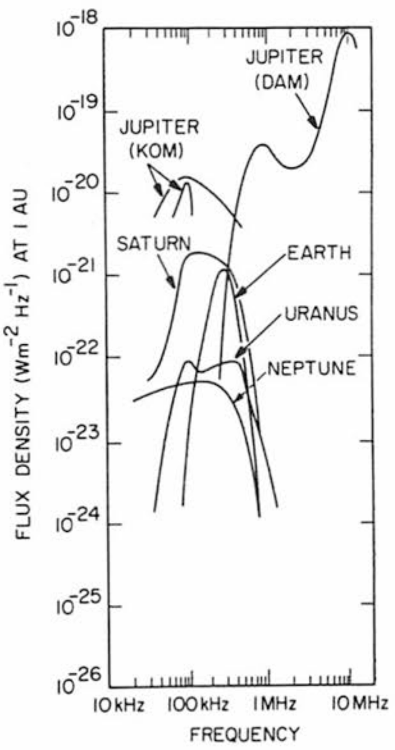

Figure 3. A comparison of the radio emission spectrums of coherent radiation from Earth, Jupiter, Saturn, and Uranus, adjusted to a distance of 1 AU. [*Provided by Michael L. Kaiser (1990).*]

evening auroral zone in association with discrete auroral arcs. The frequency range of the intense terrestrial radio emission typically extends from about 100–500 kHz. Because the maximum intensities occurred at kilometer wavelengths, the radiation is called terrestrial kilometric radiation, or auroral kilometric radiation. Similar types of radio emissions were also discovered from Saturn, Uranus, and Neptune by the *Voyager 2* spacecraft, which flew by these planets in the mid and late 1980s. A comparison of the radio emission spectra of Jupiter, Earth, Saturn, Uranus, and Neptune is shown in Fig. 3.

After several years of study, it is now clear that the intense radio emissions from these five planets have several common characteristics. First, in all cases the radiation is associated with a strong planetary magnetic field. Second, the emission occurs at a frequency very close to the electron cyclotron frequency, $f_c = (1/2\pi)eB/m_e$, where e is the electronic charge, B is the magnetic field strength, and m_e is the electron mass. Third, the polarization of the emitted radiation is primarily right-hand polarized with respect to the magnetic field in the source region. Fourth, the emission usually occurs in regions of very low plasma density. These characteristics are all consistent with a plasma instability called the cyclotron maser instability. For this instability an electromagnetic wave acts to organize the phase of the cyclotron motion in such a way that the electrons radiate in phase with the original wave. In this respect, the mechanism is similar to stimulated emissions from an optical laser. However, the free energy is not of atomic origin, as in a laser, but rather from anisotropies in the electron velocity distributions. At Earth, it is estimated that as much as 0.1–1.0% of the energy of the auroral electron precipitation is converted to radio emission via this process. Such high conversion efficiencies can only be obtained from a coherent process.

Mode Conversion From Electrostatic Waves

In addition to the cyclotron maser radiation, a wide variety of much weaker radio emissions are observed that are believed to be generated by mode conversion from electrostatic waves. These radio emissions were first discovered at Earth by the *IMP-6* spacecraft, and then were later discovered at Jupiter, Saturn, Uranus, and Neptune by the *Voyager* spacecraft. At Jupiter, this radiation occurs at kilometer wavelengths and is called jovian kilometric radiation (KOM). A typical spectrum of KOM is shown in Fig. 3. This type of radiation often consists of many narrowband emission lines that sometimes merge into an essentially continuous spectrum that has been called by various names, including "continuum radiation," "myriametric radiation," "narrowband electromagnetic emissions," and "narrowband kilometric radiation." In specific cases it can be shown that the radiation originates from localized electrostatic waves generated by intense fluxes of low-energy (few kiloelectron volts) electrons. The association with electrostatic waves strongly indicates that the radiation is produced by a mode conversion process that transfers some of the electrostatic energy to escaping electromagnetic radiation. Usually the electrostatic waves occur near half-integral harmonics of the electron cyclotron frequency, $(n + 1/2)f_c$. These waves become particularly strong when the emission frequency is near a characteristic frequency known as the upper hybrid resonance, f_{UHR}. Although many details are poorly understood, the mode conversion process appears to be most efficient in regions with steep density gradients.

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See also **Earth, Aurora; Interplanetary and Heliospheric Space Missions; Mercury and Venus, Space Missions; Outer Planets, Space Missions; Planetary Magnetospheres, Jovian Planets.**

Planetary Rings

Laurance R. Doyle

When Galileo first spotted the rings of Saturn in 1610, he thought they might be "handles" or large moons on either side of the planet. He was perplexed, however, years later when he viewed the planet again and found that the rings had disappeared (were edge-on). In 1655 (based on the vortex theory of René Descartes),