Chapter 2

Jupiter

Jupiter is one of the most interesting Solar System objects to observe, whether that's with an optical or radio telescope, as well as one of the easiest. Jovian radio emission is very strong, at times (at HF radio frequencies) rivaling if not surpassing the Sun in signal strength.

The Structure of Jupiter

Spacecraft studies of small gravitational effects on spacecraft trajectory suggest that Jupiter has a small solid core of around 20 times that of Earth's mass, and a radius of around 0.2R_j where R_j is the Jovian planetary radius of 69,084 km (Fig. 2.1).

The layer surrounding the core is highly compressed liquid metallic hydrogen, which extends to a distance of 0.78R_j. Above this lies a still dense atmosphere of mostly molecular hydrogen.

How can hydrogen be metallic, you may ask? Natural hydrogen atoms consist of a proton orbited by a single electron. Metallic hydrogen is formed when the atoms are compressed at very high pressures. This pressure is enough to reduce the average distance between hydrogen nuclei to less than the Bohr radius (the smallest orbital diameter for the electron). At these pressures the electrons become unbound from the protons and are free to move around, making the hydrogen electrically conductive, like a metal. At even more extreme pressures hydrogen would crystallize into a solid metallic lattice, although this is not the case for Jupiter, as indicated by the amount of polar flattening due to rotation.

The fluid conductive hydrogen layer plays an important role in generating the dynamo effect and the strong magnetic field we observe around the planet. The magnetic field plays an important role in the generation of radio emissions.

Jovian Magnetic Field

The dynamo effect in planets is similar to the dynamo effect in stars we saw earlier and is again a self-exciting system, which means it functions without any external input. Planetary dynamos are still not well understood, but to get some idea of how we think they work consider Fig. 2.2.

J. Lashley, *The Radio Sky and How to Observe It*, Astronomers' Observing Guides,
DOI 10.1007/978-1-4419-0883-4_2, © Springer Science+Business Media, LLC 2010

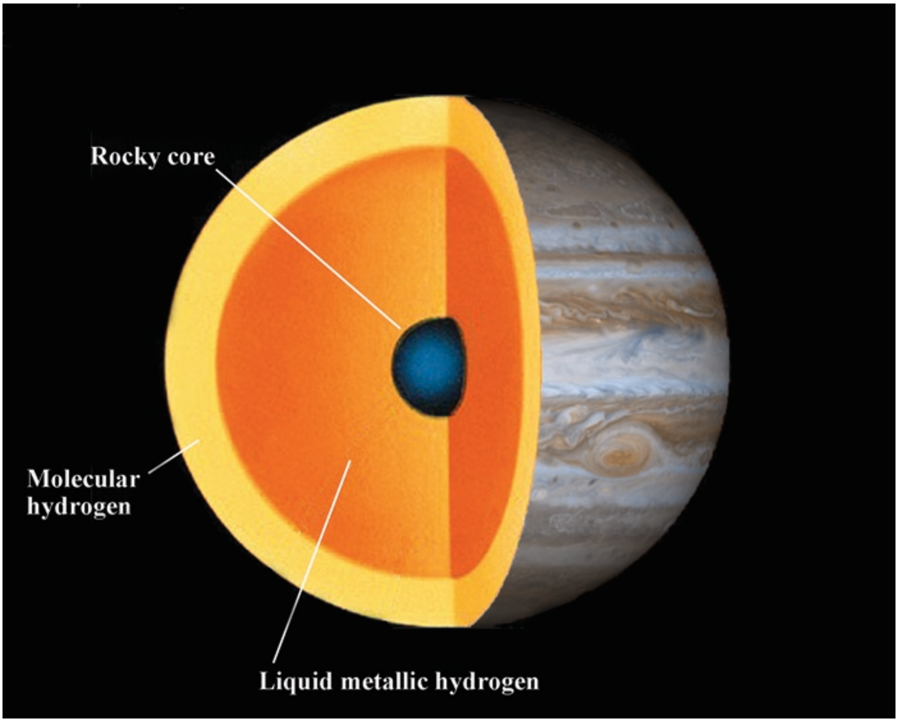


Fig. 2.1. The internal structure of Jupiter.

The conductive disk is rotating about an axis. A current loop is formed between the disk and the axis, the loop being completed by conduction through the disk itself. The current loop generates magnetic flux, which is intercepted by the disk generating more current. The conductivity of the disk is not perfect; in fact it is relatively poor, and hence it has considerable resistance. The current growth in the Jovian dynamo is counteracted by retarding Lorenz forces acting on the disk. In this way the system settles into an equilibrium state.

The Jovian Magnetosphere

From the earliest days of the detection of radio waves from the planet Jupiter in the 1950s, it was known there must be a significant magnetic field surrounding Jupiter. The bursting nature and strong output of radio energy in the HF spectrum, up to a sharp cut off at almost 40 MHz, equated to a temperature of about 3×10^{15} K, assuming it was due to blackbody radiation and was evenly distributed across the Jovian surface. Visible evidence alone clearly shows Jupiter cannot be that hot. The radio-generating process must be of non thermal origin. In order to begin to understand the radio output of Jupiter we need to build up a picture of the Jovian magnetosphere.

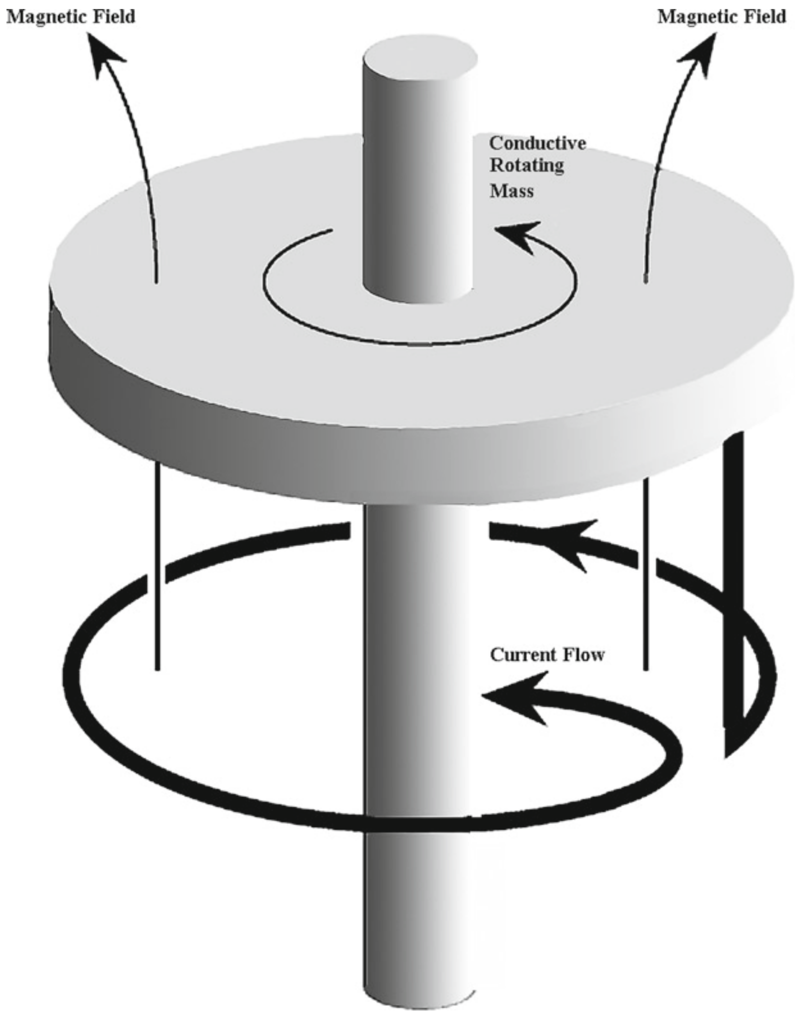


Fig. 2.2. A model of a planetary dynamo. A disk rotating at speed ω through a magnetic field B inducing a current I to flow.

The magnetosphere is the envelope surrounding Jupiter where the magnetic fields influence the motion of charged particles. It is both extensive and complex. It is convenient to discuss the Jovian magnetosphere in three parts: the inner, middle, and outer magnetosphere. This is because the dominant processes are different in each zone.

The Inner Magnetosphere

This region extends out to about six Jovian radii and is controlled by the predominantly dipole magnetic field generated within Jupiter. Studies carried out by *Pioneer 10* and *11* and *Voyager 1* and *2* show there is a significant asymmetry in the magnetic field, where the north pole has a magnetic field strength of 14 Gauss, and the south pole only 10.4 Gauss. The field is a dipole (a simple two-pole system,

Table 2.1. The longitude coordinate of Jupiter is broken into three systems, each based on a slightly different rotation period

System	Relevance	Rotation period
I	Cloud tops within ±10° of equator	$9^h\ 50^m\ 30^s$
II	Cloud tops north or south of the 10° latitudes	$9^h\ 55^m\ 40.6^s$
III	The magnetosphere	$9^h\ 55^m\ 29.7^s$

like a bar magnet), which is tilted with respect to the planet's rotational axis by approximately 9.6°, toward a system III longitude of 202°. You may be familiar with the System I and II coordinate systems used for defining the position of cloud features on the visible surface of Jupiter. The system III was developed for use in radio astronomy, as a more accurate means of monitoring the motion of features in the magnetosphere. The different systems are detailed in Table 2.1.

The inner magnetosphere consists of a cloud of trapped charged particles. To understand why the particles are trapped, and don't simply get absorbed into the atmosphere, consider the motion of an electron inside the field. If an electron is traveling perpendicular to the field lines, a force known as the Lorenz force is induced by the magnetic field and deflects the electron into a circular orbit. The radius of the orbit is proportional to the velocity of the electron, and inversely proportional to the magnetic flux density. The rate of rotation around the magnetic field line is known as the cyclotron or plasma frequency. It is proportional only to the magnetic flux density.

On average, however, the random motions of the electrons will mean they enter the magnetic field at an angle. They are forced to move in a spiral pattern along the field towards one of the poles. On approaching the poles the field strength increases, forcing the cyclotron frequency to increase and its rotational diameter to decrease, by the increasing Lorenz force on the electron but at the expense of its forward velocity. The sense of direction of the Lorenz force is parallel with the magnetic field and acts towards the region of least field strength. The forward velocity eventually reaches zero at a point known as the mirror point, when reflection occurs, and the electron reverses direction and proceeds the other way until encountering the opposite pole, where it is reflected back again. The result of this is why planetary radiation belts are doughnut-shaped toroidal regions centered on the magnetic equator.

Since circular motion created by a force involves acceleration, the electrons emit radio energy. The frequency of the emission for these relatively slow non-relativistic particles is close to or equal to the cyclotron rotation frequency. For fast relativistic particles, the radio emission also occurs at higher harmonics of the cyclotron frequency, and we call this synchrotron radiation. The radiation pattern is beamed in a thin-walled conical distribution in the same direction as the instantaneous velocity, tangential to the curve of motion (Fig. 2.3).

Radio emission from cyclotron and synchrotron sources is polarized; however, the type and sense of polarization depends on the observer's line of sight. Equatorial emission is linearly polarized where the line of sight is parallel to the electron circular motion, while near the poles the emission is more nearly circular, either left or right hand, depending on the direction of movement of the electron along the field lines. For most emissions, the viewing angle is somewhere in between these extremes, producing left- or right-handed elliptical polarization.

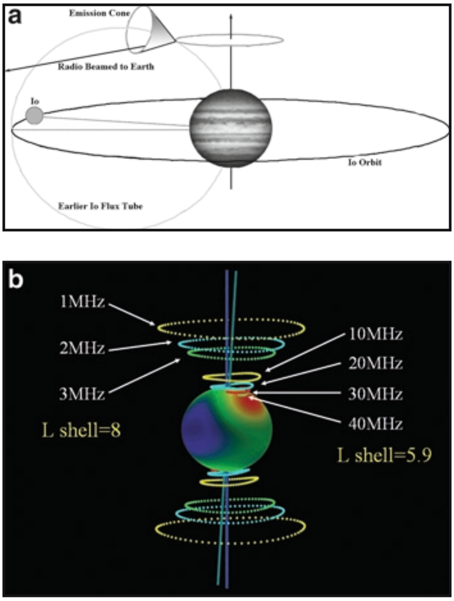


Fig. 2.3. (**a**) Drawing of the decametric radio beam emission from Jupiter. (**b**) This shows the spatial distribution of the radio spectral output. (Image credit Imai Lab, Kochi National College of Technology).

The inner magnetosphere is the source of all the strong decametric (tens of meters wavelength) radio emission, with an interesting relationship to the moon Io. Since the magnetic field is rotating with Jupiter, the field sweeps past and overtakes Io; in so doing a voltage of 500,000 V is induced between Io's inner and outer faces. In turn this leads to currents flowing in a magnetic flux tube, which connects Io to the polar ionosphere of Jupiter. The estimated current amounts to 2.8 million amperes, with a power of approximately 10^{12} W. For reasons still uncertain, plasma instabilities can occur, resulting in the strong outbursts at frequencies up to a cut off at 40 MHz. These outbursts are modulated somewhat by the motion of Io, and its mutual location with respect to Jupiter and Earth. This modulation is not completely predictable, although it helps to provide a probability of being able to detect decametric radio bursts for a given date and time.

The 40 MHz cut off is quite sharp. This is because the electrons involved in the emission process encounter their strongest magnetic field near the mirror points, after which they reflect back into weaker magnetic fields again.

The Middle Magnetosphere

The middle magnetosphere extends from $6R_j$ to in around $50R_j$. It is bound on the inside edge by the region where the influence of the planetary magnetic field is no longer dominant, and on the outside by the region where the influence of the magnetopause and solar wind is small. The dominant feature driving the field is an equatorial current sheet called the magnetodisc. Although the outer boundary of this region is largely symmetrical, the magnetodisc is thickened in the sunward direction.

The Outer Magnetosphere

This zone is significantly compressed on the sunward side due to the influence of solar wind pressure. The boundary between the interplanetary environment and the magnetosphere is known as the magnetopause. Once again the field is driven by currents flowing in the plasma within.

The thickness of the dayside outer magnetosphere is very variable, depending upon solar activity. There is also a huge difference in shape between the day and night sides. There exists a huge antisolar magnetotail. It is not known how long the tail actually is, as no direct measurements have yet been possible, but it is believed the tail reaches as far the orbit of Saturn. If we could see the extent of the magnetosphere with our eyes, it would appear a few degrees across as viewed from Earth's surface. It would certainly be an impressive sight.

Jovian Radio Emissions

Radio emission from Jupiter has been detected from as low as 10 kHz and as high as 300 GHz. The spectrum can be broken up into three parts, which relate to three distinct mechanisms involved.

The high end of the radio spectrum is dominated by thermal blackbody radiation, while synchrotron output from trapped high-energy relativistic particles accounts for the spectral region from 4 GHz down to around 40 MHz. The cyclotron process is responsible for the low-frequency output. This is one of few objects in the universe where cyclotron emission is easily observable to us.

Often in the literature acronyms such as KOM, HOM, DAM, and DIM are used, referring to the wavelengths of the radio output as detailed in the Table 2.2.

Kilometric and hectometric emissions are unable to penetrate the ionosphere of Earth, as they are reflected away and can only be studied using spacecraft. Much of this radiation is highly directional and is beamed from the polar regions, in such a way that Earth does not even intercept it. Study at these wavelengths has been carried out by spacecraft such as *Pioneer 10* and *11*, *Voyager 1* and *2*, *Galileo*, *Ulysses*, and *Cassini*, in close proximity to Jupiter

Decametric wavelengths below about 20 m and decimetric radiation can easily be observed from Earth's surface. Decametric studies are well within the capabilities of basic amateur-built equipment.

Although Earth's ionosphere always reflects long wavelength radiation, the ionospheric cut off is somewhat variable, depending on solar activity and time of day. At times of high solar activity the cutoff point is at shorter wavelengths near 10 m, and when quiet or at night the cutoff point is at much longer wavelength, around 30 m. Jovian decametric noise is known to peak around 8–10 MHz (roughly 30 m)

Table 2.2. Nomenclature of radio emissions based on their wavelength

Kilometric (KOM)	Thousands of meters wavelength
Hectometric (HOM)	Hundreds of meters wavelength
Decametric (DAM)	Tens of meters wavelength
Decimetric (DIM)	Tenths of a meter wavelength (cm)

but is still potentially very strong in the 12.5–16.5 m (18–24 MHz) band that is more accessible to a radio telescope.

Decametric Radio Bursts

When observing with a single radio telescope, due to the poor resolution compared with optical telescopes, it is not possible to resolve fine details on the surface of Jupiter. The beam width of a single HF antenna is likely to be at least several degrees wide. Even using interferometers would not provide resolutions good enough without huge baselines and aperture synthesis techniques.

In order to try and determine more information about the source location of decametric emission, shortly after their discovery, a neat trick was used. By plotting the occurrence of decametric emission against central meridian longitude (CML) over a period of a few years, an interesting profile appeared. The resulting graph, Fig. 2.4, provides a probability of being able to observe decametric emission for a given CML. The various peaks were given identification labels A, B, and C, and with later studies D. Although this technique helps to get around the poor resolution of a single receiver, it provides no information on the latitude of the source.

Although the pattern observed is repeatable year after year, even the principal peak A only occurs in about one out of three of the expected times.

In addition to the CML, it was also noticed that the phase angle (the angular separation from CML) of the moon Io had an influence on the probability of receiving HF radiation. By re-plotting the occurrence of decametric radiation with Io phase against CML the results are again interesting; see Fig. 2.5.

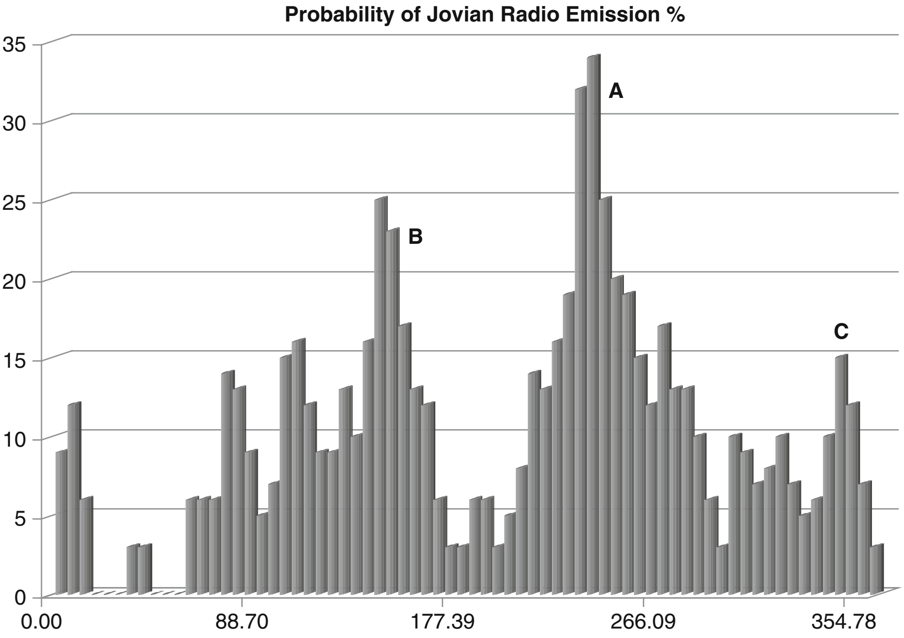
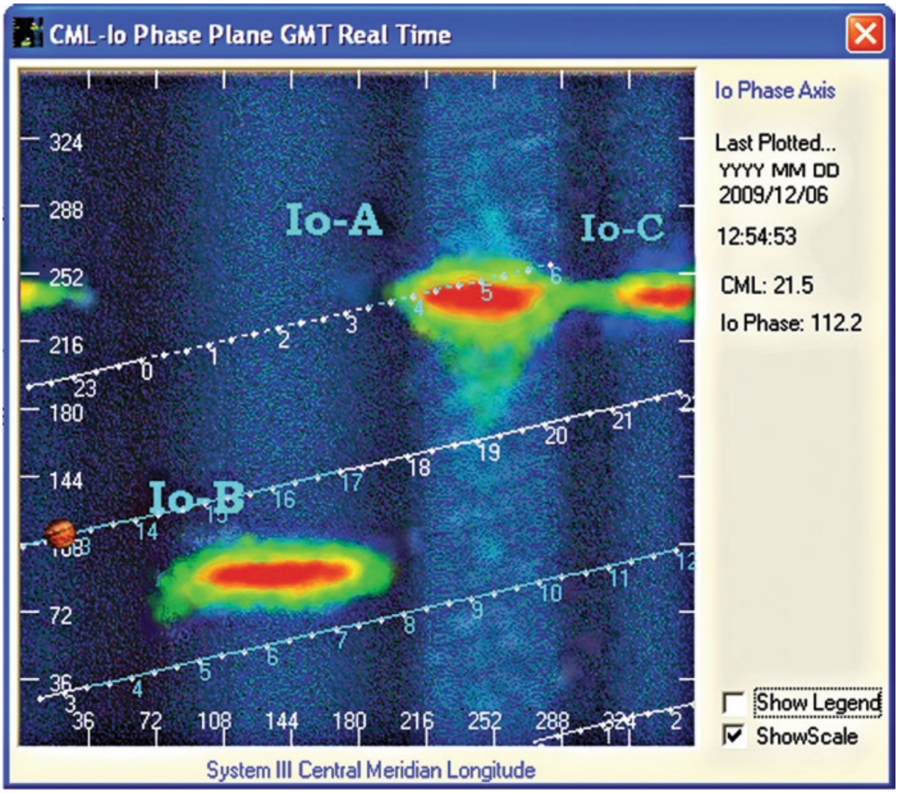


Fig. 2.4. Probability of the occurrence of decametric radio emission from Jupiter plotted against Jovian System III longitude.



Last Plotted...
YYYY MM DD
2009/12/06
12:54:53

CML: 21.5

Io Phase: 112.2

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Fig. 2.5. A plot of Jovian Central Meridian Longitude (System III) against Io phase angle. This image was captured from the software package Radio Jupiter Pro-3 published by Jim Sky of Radio Sky Publishing (http://www.radiosky.com). It shows the probability of receiving Jovian DAM for your observing site at a given time and date, a highly recommended piece of software for the regular radio observer. The *red areas* indicate the highest probability.

From this diagram the oval regions are referred to as Io sources, such as Io-A source. However, decametric emission can occur at any time, particularly when the Jovian CML is in the same range as the Io-A and Io-B sources. This emission is known as the non Io-A, and non Io-B source (Fig. 2.6).

The *Galileo* spacecraft showed there is also a much weaker modulation created by Callisto and to a lesser extent by Ganymede. Further evidence of interaction by other moons come from ultraviolet images from the Hubble Space Telescope and from infrared images from the NASA Infrared Telescope Facility on Mauna Kea. In these pictures, hot spots can be seen in the Jovian ionosphere at the footprint of the flux tubes emanating from the moons, including Europa.

Jovian decametric radio emission occurs in "storms" that can easily rival Type III solar outbursts for Earth-based observers. They can last for a few minutes to several hours. The storms consist of three types of features: L-bursts, standing for "long," which is a bit misleading, since they last from about 0.1 s to a few seconds; S-bursts have durations of from 1 to 200 ms. The final type is known as N-band.

Although *Pioneer 10* and *11* offered the first chance to observe Jupiter from close proximity, the first detailed in situ radio observations were carried out by the

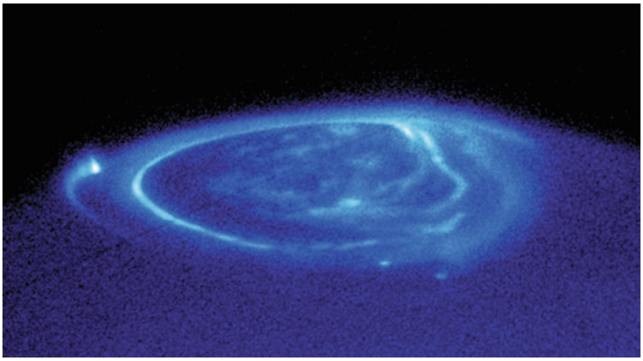

Fig. 2.6. Hubble photograph of the Jovian aurora showing the hot spot (*left side*) caused by the base of the Io flux tube, consisting of a current of charged particles in the order of one million amperes. A pair of weaker flux tubes from other Jovian moons appears in the lower foreground. (Image courtesy of NASA/ESA, John Clarke, University of Michigan).

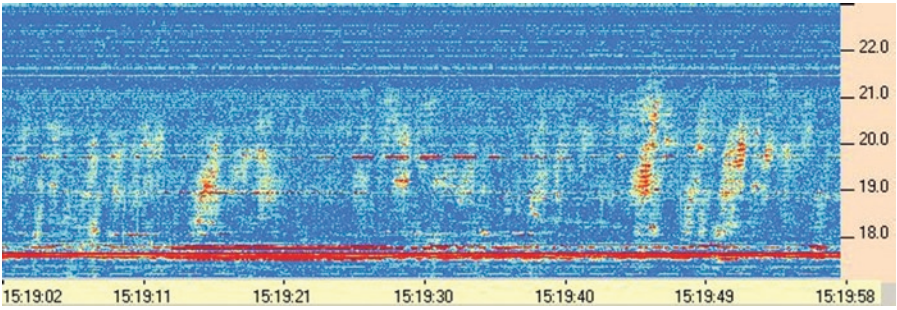

Fig. 2.7. Jovian decametric spectrum at 20.1 MHz, captured with a Radio Jove receiver by amateur astronomer Wesley Greenman on April 11, 2009. It shows L-burst activity from the Io-B source. Note the *horizontal lines* are noise or other radio activity. The *broad vertical patches* of the DAM are still clearly visible.

Voyager 1 and *2* spacecraft, which carried a plasma wave experiment for observation of low-frequency plasma waves up to 56 kHz and swept radio frequency receivers operating up to 40.5 MHz, slightly higher than the magnetic cutoff for decametric emission.

The resulting radio data was plotted on a waterfall spectrum, a type of spectral plot where one axis is frequency and the other is time. The density of the plotted results equates to relative signal strength. A modern example of a Jovian decametric spectrum taken by amateur astronomer Wesley Greenman is shown in Fig. 2.7.

The *Voyager* results showed what we now call spectral arcs – curved structures beginning with vertex early and followed later by vertex late arcs in the waterfall. The same structure can be observed by ground-based radio telescopes, but it is much more of a challenge due to the scintillating effects of the interplanetary medium (IPM), and Earth's ionosphere. The IPM and the ionosphere of Earth act on radio signals in a similar way to the way Earth's atmosphere acts on the optical image, creating a blurring effect. In addition, intervening magnetic fields, including Earth's, create Faraday rotation, which influences the polarization of the source radiation. The effect of this act is to disturb much of the spectral structure we would otherwise be able to see from an Earth-bound perspective.

Interpreting the Jovian Decametric Spectrum

The primary mechanism for decametric radio output is coherent maser emission by excited electrons. The radio frequency is close to the cyclotron rotation period of the electrons, as they revolve in spiral paths around magnetic field lines. This implies the particle velocities are much less than that of light. The emission is beamed perpendicularly to the magnetic field in a thin-walled hollow cone whose half angle is 70–80° and somewhat dependent on the radio frequency. Estimates obtained by simultaneous observation with *Cassini* and the WAVES spacecraft showed the thickness of the cone wall to be 1.5 ± 0.5°.

The Io sources are generated by the motion of Io through the inner magnetic field, which in turn induces instabilities in the plasma torus, generating Alfvén waves that propagate away from Io at an angle to the magnetic field. The exact angle varies with the local plasma conditions. Alfvén waves are a form of plasma wave. They are created when the local plasma is compressed, for example, by the motion of Io through the Io torus. The compression of the plasma induces electrical forces between the particles, which oppose and push back the plasma, which then overshoots their equilibrium position. The result is a back and forth longitudinal oscillation in the charged particles that propagates outward, similar to sound waves. Ultimately the longitudinal plasma wave can be converted into transverse radio emission by its encounter with large-scale inhomogeneities or more likely by scattering processes from small-scale local clumps of matter. The radio frequency emitted by scattering from ion concentrations is the same as the plasma frequency. If, however, the scattering is from a clump of electrons, the emitted frequency is double the plasma frequency. The conversion process to radio energy is very inefficient, however.

Theories proposed by Gurnett and Goertz suggest that the Alfvén waves undergo multiple reflections from magnetic pole regions, possibly as many as 9 times, creating a standing wave moving with Io. On each reflection the waves induce bursts of radio emission from high-latitude regions near the north and south poles. The bursts each generate an arc structure in the spectral waterfall as the cone beams sweep past the observer. The bursts are typically separated by 10° of longitude, or approximately 35 min in time in agreement with observation.

In a counter theory proposed by Smith and Wright, they believe the Alfvén wave speed would hugely increase while passing through the Io torus, thereby creating significant reflections. This would mean only about 30% of the waves would actually reach the poles. They proposed that the motion of Io creates a large magnetic disturbance in the wake of the moon, exhibiting large-scale structures around 60° wide and fine scale structures in the order of 6°. Their theory also predicts burst emissions that match observation.

Evidence that the burst emissions come from high latitudes include the greater degree of polarization for Io sources above 15 MHz. (The polarization below this level is more random.) Io-A and Io-B sources provide a significant level of right hand polarization, which is consistent with a northern hemisphere origin. Io-C and D sources give a left hand polarization, which is consistent with a southern hemisphere origin. Further studies by Queinnec and Zarka using data from the WIND spacecraft and the Nancay decametric array telescope showed that Io-B and D occur when Io is near to the Jovian dawn limb, while Io-A and C occurred near the Jovian dusk limb.

The non-Io sources have no connection with the phase of Io, or any other moon for that matter. Evidence obtained from the *Cassini* and *Galileo* spacecraft suggests that the non-Io sources occur at extremely high latitudes, well above the Io flux tube footprint in the ionosphere. These are believed to occur in a region of the outer magnetosphere in a zone closely tied to the magnetotail. The triggering mechanism is thought to be interplanetary shock waves propagated by the solar wind. The shock waves trigger the sudden release of magnetospheric energy, creating decametric and hectometric burst emissions.

Further evidence of the solar influence on non-Io sources comes from the correlation with the 11-year solar cycle. The occurrence of non-Io DAM varies linearly with the size of the Sun's polar coronal hole.