Part 8

Sun and Planetary Systems

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Low Frequency Planetary Radio Astronomy

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Abstract. This paper reviews planetary radio astronomy at low frequencies. At least at frequencies observable from the Earth's surface, this field has been almost solely the study of Jovian magnetospheric emissions. With the discovery of extra-solar planets, and the potential for new telescopes with large collecting areas, we may well see more objects and emission mechanisms becoming detectable.

1. Introduction

Although the planets have been know since antiquity, it remains surprising the number of significant advances that have been made in planetary astronomy in the last 50 years. Yet the formation processes of the planets and the solar system in general remain poorly understood. Recent detections of large, extra-solar, planets (Marcy 1998) place many of them unexpectedly close to their stars. These detections further challenge current ideas of cosmogony. The understanding of our neighbouring planets is an important part of understanding the formation of our solar system and, indeed, our own planet.

Planetary astronomy is quite different to other astronomies. Whereas the foundation for other astronomies is passive observation, planetary science can use more "active" techniques: we can send space probes to the planets, and we can study them using radar (e.g. Ostro 1993). Although an in-situ probe clearly has a number of advantages over Earth-based passive astronomy, space-based approaches do have their limitations. Not the least of these is the expense of the space missions and their necessarily limited objectives. Additionally, some environments in the solar system are sufficiently hostile that in-situ investigation continues to remain infeasible. Passive observation of the planets is not outdated even in the "space age".

In this paper, I will review Earth-based planetary radio astronomy at frequencies from the Earth's ionospheric cut-off to about 1 GHz. This restricts attention to non-thermal processes; I ignore thermal emission, spectral lines and the atmospheric science that these tell us about. Although it is an important field, space-based observations at frequencies below the ionospheric cut-off are also excluded.

2. Jovian Cyclotron-Maser Radiation

Low frequency planetary radio astronomy had an unlikely start. With a fixed antenna operating at 22.2 MHz, Burke & Franklin (1956) noted interference-like emission at the same time each day. Like Jansky 25 years before them, they then noted that it was keeping track with the sidereal rather than solar day. But unlike Jansky, they then noted that it was moving slightly with sidereal day as well – they had discovered the decametric emission from Jupiter. The emission is intense and sporadic, with rich detail in its dynamic spectra. It is also highly elliptically polarized, and shows a pronounced cut-off above 40 MHz. Intriguingly, the decametric emission is strongly modulated by the rotational phases of Jupiter and the moon Io (Bigg 1964; Dulk 1965). Dulk (1970) also found that the emission was localized to regions smaller than 400 km. This implied brightness temperatures up to 10^{19} K. See Carr & Desch (1976) and Carr et al. (1983) for comprehensive reviews.

All these strongly argued against a thermal process. Indeed the extreme brightness temperature rules out incoherent processes, and the polarized nature of the emission implies a magnetic field. The sharp cut-off at 40 MHz suggests that the electrons are not relativistic (or at least only mildly so), for otherwise the electrons would emit at a series of harmonics and a sharp frequency cut-off would not be expected.

Although the processes responsible for the decametric emission are not completely understood, a good broad description is accepted. The emission is from magnetically trapped electrons within Jupiter's magnetosphere. Normally these electrons gyrate up and down magnetic field lines. The emission process, cyclotron-maser instability, was first well described by Melrose (1973), and refined by Wu & Lee (1979). The emission occurs in the auroral regions of Jupiter from mildly relativistic electrons ($\sim$ 10 keV). The emission occurs at just above the local cyclotron frequency. As such, the 40 MHz cut-off in emission is a direct measure of the maximum magnetic field in the auroral region. The basic requirements for cyclotron-maser emission is a mechanism to form a population inversion of the electron distribution (i.e. a maser pump), and a low-density plasma or strong magnetic field, so that the cyclotron frequency exceeds the plasma frequency (i.e. the emission can escape). In the case of Jupiter, the population inversion is the loss-cone distribution which is produced when the mirror points of the gyrating electrons are in the high atmosphere of the planet. The emission is strongly beamed, being emitted in a cone with an opening angle of 70° around the local field line. This beaming, and an electrodynamical interaction between Jupiter and Io are responsible for the observed dependence on rotation phases.

It is interesting to remember the standard view of the solar system at the time of Burke & Franklin's discovery. The solar wind was theorized through the relationship between solar storms and aurora. But the solar wind was not believed to be a continuous flow, and was thought to strike the Earth's upper atmosphere. The giant planets were thought to be nothing more than large balls of gas – a Jovian magnetic field, and the internal structure and dynamo that that implies, was not expected. The discovery of the Earth's radiation belts (van Allen 1959), and the subsequent realization of the existence of magnetospheres around magnetized bodies, was still some years away.

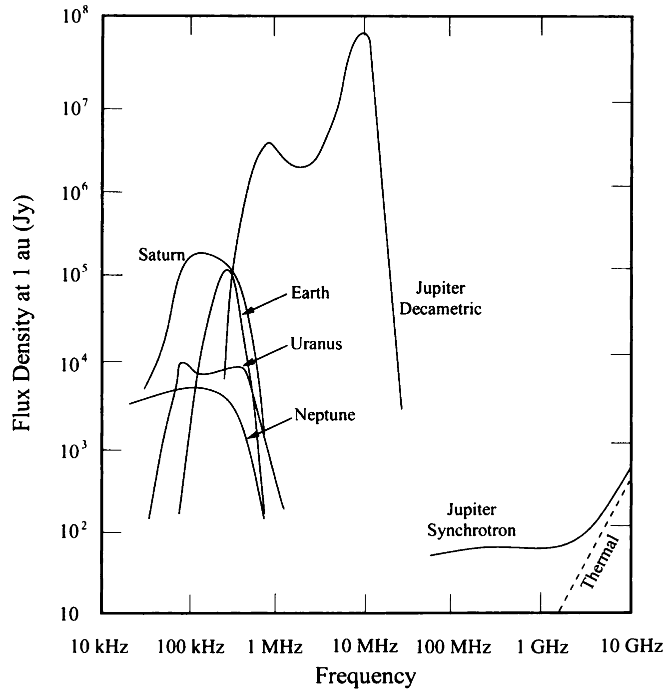

Figure 1. Integrated flux densities of planetary radio emission. The measurements are normalized to a distance of 1 AU.

3. Other Cyclotron-Maser Emitters

Cyclotron-maser emission is by now means a rare form of emission. In the late 1960s, satellites detected the Earth's cyclotron-maser emission (Benediktov et al. 1965) which radiates up to 10^9 W of energy. It had remained undetected because it lies completely below the ionospheric cut-off. Spacecraft later showed that all the magnetized planets with atmospheres emit cyclotron-maser radiation. Figure 1 gives a spectrum of the radio emissions of the magnetized planets.

Because of the Earth's ionospheric cut-off, only Jupiter's cyclotron-maser emission is detectable from the Earth's surface. This is because the maximum frequency of the emission is directly proportional to the local magnetic field, and Jupiter's field far exceeds that of the other planets.

With the discovery of large extra-solar planets (Marcy 1998), is it realistic to attempt to detect cyclotron-maser emission from these? Observations of this kind could potentially measure magnetic field strengths and rotation periods of the planets. One really does appreciate the $1/r^2$ dependence on emission when one does the calculation using various models for for large planets at a parsec or so, but the numbers do come out to be challenging, not hopeless. Flux densities of milliJanskys to Janskys at low frequency are plausible. Additionally, there are large uncertainties in the models. Winglee et al. (1986), Burke (1991) and Farrell et al. (1999a) all do these calculations for various candidates. Observations to date (e.g. Winglee et al. 1986; Bastian et al. 1999) have failed to make detections.

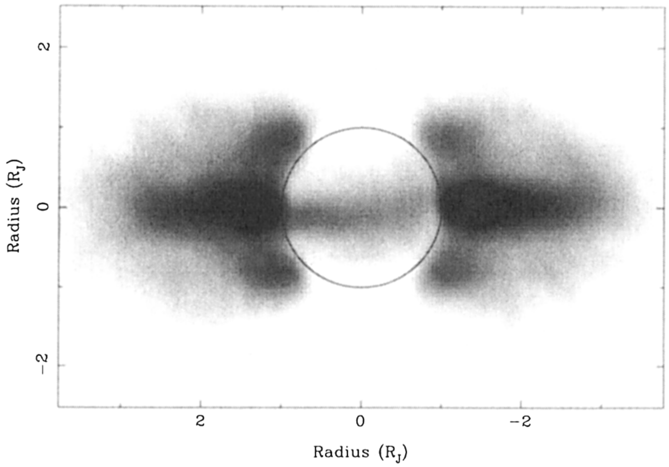

Figure 2. A radio image of Jupiter at 20cm. The equatorial and high latitude electron populations are plainly visible. The central meridian longitude is $\lambda_{\mathrm{III}} = 140°$. The position of the planet is given by the circle.

4. Jovian Synchrotron Emission

Apart from the cyclotron-maser emission, Jupiter is also an emitter of synchrotron radiation (a few Janskys at the Earth's distance), with this showing a flat spectrum from metric to decimetric wavelengths. The electrons producing this emission are a relativistic ($E \sim 1 - 20$ MeV), magnetically trapped population. The emission shows both a maximum, and a sharp cut-off to smaller radii, at about 1.4 Jovian radii. This cut-off is presumed to result from loss of the electrons to the planet, caused by pitch-angle scattering by plasma waves. The emission is strongly beamed, and with the magnetic field being (approximately) a dipole tilted by 10°, the emission as see from the Earth wobbles and varies with Jupiter's rotation. The first detailed modelling of the synchrotron in the Jovian environment was performed by Pater (1981a, 1981b). Since then it has been found that the pitch angle distribution of the synchrotron electrons is bimodal, with a 'pancake' distribution of electrons which are confined to the magnetic equator ($\alpha_{\mathrm{E}} \approx 90°$), and a population which mirrors at high latitudes. These two populations are clearly seen in Figure 2 (the planets thermal emission has been subtracted off). The high latitude population is caused by an interaction with the moon Amalthea (Dulk et al. 1997; de Pater et al. 1997). However it is unclear whether this results from a pure loss of electrons to the moon (S.J.Bolton, private communication) or whether pitch-angle scattering by the moon is also involved (de Pater et al. 1997).

Apart from information on the high energy electrons themselves, and their interaction with moons and rings, study of the synchrotron emission is a means of studying the magnetic field (e.g. Dulk et al. 1997). Surprisingly the synchrotron emission is one of the few available probes of the inner magnetosphere of Jupiter. Because of the high energies of the particles and potential radiation damage, only two spacecraft have visited the synchrotron region, with both of these visits being brief.

In studying the synchrotron emission, it is interesting to note the progression in imaging techniques. The first observations were made with single dishes. Even with no resolution, by studying the variation of flux density as Jupiter rotated (the so-called 'beaming curve') smart single-dish astronomers were very successful at deducing the magnetic field geometry and some simple measures of the pitch-angle distribution (e.g. Roberts & Komesaroff 1965). Interferometry cannot be used on Jupiter without using a few tricks. The wobbling of the emission with rotation (caused by the tilt of the magnetic dipole) causes Jupiter to vary with time, which breaks an important assumption in rotation synthesis. However de Pater (1980) circumvented this by patching together visibilities at the same Jovian central meridian longitude from several days of observing. In this way, she was able to well sample the Fourier plane at many rotational phases of Jupiter. An alternative technique is to assume that the synchrotron emission is rotationally symmetric about the magnetic axis, and to manipulate the visibility data before imaging to take out the wobble of the magnetic axis. A more novel approach, however, is possible. As the synchrotron plasma is optically thin, and because it is frozen to Jupiter's rotation, it is possible to perform a three-dimensional tomographic reconstruction of the synchrotron plasma (Sault et al. 1997). Indeed, the visibility measured by an interferometer is related to the the plasma volume emissivity, I_0, by a three-dimensional Fourier transform relationship

$$V = \left(\frac{R_0}{R}\right)^2 \int I_0(x,y,z) \exp\left(-i2\pi(xu+yv+zw)/(\lambda R) \right) dx\,dy\,dz.$$

Here R is the distance to Jupiter, R_0 is 'standard distance' that the observation is normalized to, (x,y,z) are jovicentric spatial coordinates, and (u,v,w) are coordinates in a three-dimensional Fourier space. These (u,v,w) coordinates depend on the interferometer baseline geometry and the rotational phases of the Earth and Jupiter, and can be derived from the conventional (u,v) coordinates of interferometry. Figure 3 gives a visualization from such a three-dimensional reconstruction. The thermal emission from the planet is subtracted off before these reconstructions. See `http://www.atnf.csiro.au/~rsault/Jupiter/movies` for animations of reconstructions.

Interest in Jupiter has substantially increased in recent years because of two events: the orbit of of the Galileo spacecraft around Jupiter since December 1995, and the collision between Jupiter and the fragments of Comet Shoemaker-Levy 9 (SL9) during the week 16-22 June 1994. The collision was of particular interest to the synchrotron community. Pre-impact predictions were predominantly "no effect" or a reduction in the synchrotron emission resulting from quenching of electrons by cometary dust. The actual effect, however, was a significant increase in the emission (de Pater et al. 1995) of typically 30%. This occurred during the course of the impact week, and then the emission decayed back towards its quiescent state with a time scale of a few months. The actual mechanism for the increase remains incompletely understood. Different comet fragments had different effects. However it is clear that the different locations of the impacts, in magnetic coordinates, plays an important part. Bolton & Thorne

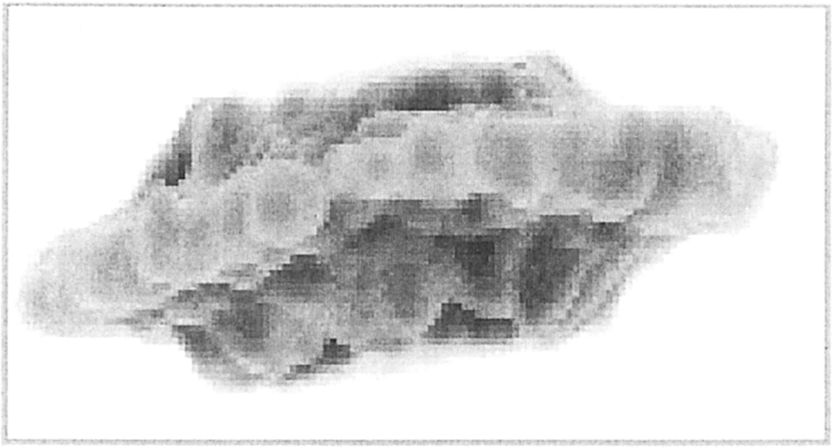

Figure 3. A three-dimensional visualization of Jupiter's synchrotron emission at 20cm wavelength. The central meridian longitude is $\lambda_{\rm III} = 90°$.

(1995) note that the field lines that thread the impact sites are, by chance, bimodal. There are those that thread the very inner magnetosphere, near the peaks of synchrotron emission, and those that thread further out. The impacts whose field lines thread the inner magnetosphere brightened substantially more. Sault et al. (1997) were able to perform a three-dimensional tomography reconstruction of the brightening, with modest temporal and spatial resolution. They noted that the brightenings were localized and could be associated with impact events. However the brightenings took about two days after an impact to build up, and that they remained longitudinally fixed. That they remained longitudinally fixed is a hard constraint on the mechanism responsible for the brightening. This is as the synchrotron electrons tend to drift around the planet with a period of a few days (the so-called "grad B" drift). That the brightenings remained fixed implies a persistent mechanism. The mechanism favoured by them was that disturbances at the impact sites to the ionosphere disrupts the coupling between the ionosphere and magnetosphere, which in turn potentially causes pitch-angle scattering and inward diffusion of the synchrotron electrons.

The decametric emission was not statistically unusual around the time of the impacts. The field lines threading the impacts did not pass through the decametric auroral region, so the disturbance probably did not propogate to this part of the magnetosphere.

5. Other Synchrotron Emitters

It is perhaps surprising that Jupiter is the only one of our planets to emit synchrotron radiation. The difference between Jupiter and the others is the magnetic field strength – Jupiter's is 20-30 times stronger than any other planet. Additionally in Saturn's case, collisions with the ring will quickly eliminate any electrons.

6. Probes of Atmospheres and Ionosphere

Apart from magnetospheric physics, low frequency observations can provide information about processes closer to the planet. One way to do this is through occultation experiments, where properties of the planet are deduced from the light curve as it occults a background source. Spacecraft missions have often used this technique, with the spacecraft being used as an artificial "background source". The greater source number density at low frequencies makes it the more attractive part of the spectrum for natural sources. To achieve the required combination of sensitivity and time resolution to probe atmospheres and ionospheres will require very large collecting areas for natural sources – occultation events last no more than tens of seconds. To date, G.J. Black and collaborators (private communication) have used occultation experiments to study Saturn's ring, where the time resolution required is less stringent.

Another potential low frequency probe of atmospheres is sferic ('lightning') emission. Indeed one of the early theories about Jupiter's decametric radiation was that it was emission from thunderstorms. Sferic emissions of some form are expected from any atmosphere where there is some form of differentiation between the constituents. To date, no planetary sferic emission has been detected from Earth observatories. The Voyager spacecraft detected lightning-like phenomena at all the giant planets (e.g. Zarka 1985; Desch 1991), and both the Galileo orbiter and probe confirmed lightning at Jupiter (e.g. Farrell et al. 1999b). However calculations suggest radio emission from Jovian sferics is at a sufficiently low frequency that it will not penetrate the Jovian ionosphere. The situation with Saturn looks more promising. The Voyager observations suggested that Saturnian sferics can escape through the ionosphere in the region shadowed by the ring. With a duration of 50 ms, and a radio power density of order 100 W/Hz in the decametric band, a Saturnian lightning bolt should be detectable on Earth using current antennas and a high time resolution recorder. Such emission may potentially tell us about the ring, as well as atmosphere and ionosphere. The challenge might be to differentiate between instrumental glitches, interference and signal.

7. Conclusion

Although the planets are close and, therefore "strong", at low frequencies the future lies with detections of extra-solar planets, occultation events and sferic emissions. All these require, of would greatly benefit, from new telescopes with enhanced sensitivity and good time resolution (perhaps to milliseconds). However it might be the technical challenges of such telescopes, such as interference rejection and high dynamic range imaging, will ultimately determine what science we can do.

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