

Jupiter's and Saturn's fine-scale magnetic fields

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Jupiter's field is strongly dipolar but with relatively large high order moments compared to the Earth's. *In situ* magnetic field data allow us to interpret most of the Earth-based microwave observations of Jupiter, with the exception of Branson's hot spot. Decametric emissions have a complex rotational pattern which has been stable since 1950; their agreement with the spacecraft magnetic fields is much less satisfactory than that of the microwaves. We conclude that the extrapolation of magnetic fields from the spacecraft to the surface of Jupiter is in error by 40% in the Southern Hemisphere.

Saturn's radio emissions show complexities similar to Jupiter's. They are strongly asymmetric about the rotational axis, although Saturn's Field is nearly axisymmetric. Their strong asymmetry suggests strong longitudinal variations in the magnetic field a few thousand kilometers from the cloud tops, in conflict with the field measured aboard Pioneer 11.

The magnetic fields within a few thousand kilometers of either Jupiter's or Saturn's cloud tops are probably unknown. It is discouraging that more is not known about the fields after a total of 7 encounters. Perhaps the Galileo probe can test usefully models of the Jupiter field, even if its measurements refer to just one trajectory through the clouds. An arguable case can be made that the giant planets exhibit complexity of magnetic structure similar to the Sun.

1. Introduction

Radio emission from Jupiter was discovered in 1955, but first recorded in 1950, in a curious sequence of events documented by Franklin (1964). This was not thermal emission in the decametric range of frequencies. Non-thermal emission at decimetric, and shorter, wavelengths was discovered shortly afterwards, and almost immediately interpreted in terms of synchrotron emission from Jupiter's magnetosphere. In addition, almost simultaneously, the decametric emission was recognized as a product of the interaction of low-energy electrons with the upper ionosphere of Jupiter. Therefore there are 2 data bases in existence that

can help us to define properties of Jupiter's magnetic field over some 30 y. The data at low frequencies represent relatively highly structured field components close to Jupiter; at high frequencies, they represent the dipole component of the field at and beyond several tenths of a Jupiter radius above the surface of the planet.

2. Radio data and their implications for planetary magnetic fields

The first property of Jupiter's field that can be recognized in these data is its rotation. Both at low and high radio frequencies, the emission is varia-

ble in intensity, with the same period, 9h 55 min 29.71 s. This is the rotation period of the field's sources which lie deep in the interior of the planet. Earlier reports of variability in the period or differences between the values in the 2 frequency ranges are now considered to be produced largely by other features of the emission, for example, the subtle effect of the small tilt of Jupiter's rotation axis with respect to the plane of its orbit on the statistics of the low frequency emissions. The error bars on this period are of the order of a few hundredths of one second. Substantial changes on a time scale of tens of thousands of years might therefore exist presently without our knowledge. The Earth's poloidal field has often reversed in the last 10 Ma; it is scarcely more stable than Jupiter's field.

At high frequencies the emission is from MeV electrons spiraling in Jupiter's magnetospheric magnetic field. This emission varies strongly with field strength, the orientation of the field with respect to the line of sight, and electron energy. The field strength and the particle energy both increase rapidly towards the planet's surface. The synchrotron emission comes mainly from close-in portions of the magnetosphere, within less than 1 planet radius above the surface. Smith and Gulkis (1979) have combined *in situ* field measures and details of the energetic electron distribution to infer what maps of the synchrotron emission should look like. They could understand several previously puzzling aspects of the total emission, particularly its polarization angle as a function of central meridian longitude. De Pater (1980, 1981a, b) discussed the detailed brightness distribution of the synchrotron emission observed with the Westerbork array in 1973, 1977, and 1978. She compared her results with the data of Branson (1968) who had demonstrated the existence of a "hot spot" at radio longitude 200° in 1967. This hot spot moved $\sim 60^\circ$ westward on Jupiter's surface sometime between 1967 and 1973, but appears not to have moved since then. De Pater stated that the hot spot can be explained only partly by the *known* [our modifier] multipole terms of the magnetic field. Its movement signals a possible change in the magnetic field in those years. For the Earth, localized changes in field intensity and direction

take place over intervals as short as 1 or 2 decades and over less than half the Earth's surface (Chapman and Bartels, 1940). These are regional rather than planetary scale variations and resemble in linear size and time scale the variations occurring presumably on Jupiter. Their magnitude is of the order of 0.1%, however, and their precise similarity to eventual Jupiter anomalies might well be argued.

At decametric wavelengths, corresponding to frequencies in the range from a few megahertz to an upper limit a few tenths of a megahertz < 40 MHz, the emission depends upon the details of magnetic field strength and orientation very close to the surface of Jupiter. Its complicated distribution in frequency as a function of radio longitude remained virtually unchanged for 2 decades of observation, including the epoch during which the Branson hot spot was observed to wander through 60° . This Jupiter emission depends upon the detailed orientation of the satellite Io as well as the orientation of the planetary magnetic field. Io, at 5.9 Jupiter radii from the center of the planet, moves in a virtually circular orbit in Jupiter's equatorial plane.

One of us (Warwick, 1981) emphasized the importance of the observed latitudinal and longitudinal asymmetries in decametric emission, especially since they are known to be under the control of Io, a virtually symmetric orbiter. This fact sets very strong constraints on possible emission mechanisms. The presence of a sharp upper bound of decametric frequency, ~ 39.5 MHz, within the longitude range of the early source, leads to the inference that the emission occurs in the Northern Hemisphere. Extrapolation of the multipole fields, determined by the Pioneer magnetometer experiments, suggests a surface field of 14.4 Gs at the pole. The northern and southern poles are very close to the corresponding trace of the footprint of the Io flux tube (Acuna and Ness, 1976). The extrapolation suggests a field of ~ 10.4 Gs near the southern footprint in the vicinity of the South pole. If right-hand emission associates with the North pole and left-hand emission with the South pole, we should expect to see right-hand emission when the North pole presents itself to our receiver and left-hand emission when the South pole does. Their maximum frequencies should be ~ 40 MHz

and 29 MHz, respectively. The agreement of the observed decametric frequency observed in the range from 100 to 200° central meridian longitude with the extrapolated Pioneer observations (multiplied by the conversion factor 2.80 MHz Gs^{-1}) is impressive in the Northern Hemisphere. The polarization of the emission is consistent also with the assignment of this emission to the North pole in the vicinity of the Io footprint. But there is no left-handed emission anywhere above 20 MHz (with the exception of polarization diversity events (see Gordon and Warwick, 1967)); central meridian longitudes near 20°, directly opposite the North pole, contain no emission above 20 MHz that can be identified as South pole emission. Below ~16 MHz, left-hand polarized emission appears more frequently in a broad longitude range around this longitude. These facts argue that the widely-held view that decametric emission uniquely occurs on the Io flux tube (Goldreich and Lynden-Bell, 1969) is probably oversimplified.

A similar conclusion was reached recently by Riddle (1983). He noted that decametric arcs, which dominate the emission associated with Io, last for many (that is, tens of) minutes, even though Io crosses a given flux tube in < 1 min. If, as many interpreters have insisted, a given arc represents emission from a single flux tube, this flux tube contains Io for only 10% or less of the time during which the flux tube creates the radio emission that characterizes the arc. Riddle identified, by certain well-defined spectral features, emission occurring on the flux tube which at that moment threads through Io. Nevertheless, the vast bulk of the emission, which is known to be closely associated with Io in particular ranges of early or main source emission, does not originate on the instantaneous Io flux tube at all.

We are aware that many workers understand that Jupiter's magnetic field is complicated, especially so at the planet's surface. For example, we note that Vasyliunas and Dessler (1981) spoke of the "well-established" extensive region of unusually weak magnetic field centered ~30° west of the northern tip of the dipole, and in the Northern Hemisphere. In their view, this structure, which extends over ~120°, may account for inconsistencies between Pioneer and Voyager observa-

tions of the current sheet and, as well, of a clustering of magnetopause crossings near the "active sector". These workers do not, in this recent study, attempt to explain the asymmetries of decametric emission in terms of the active sector. It is clearly also far from the bright region identified on microwave maps by Branson (1968) and by de Pater (1980, 1981a, b).

We wish to distinguish the "well-established" structure of Jupiter's magnetic field, defined essentially only by magnetometers aboard the 4 fly-by spacecraft, from the hypothetical close-in field structures required to explain decametric emissions, or perhaps even the decimetric hot spot. The close-in structures are constrained by the fly-by data, which define both an upper bound to the magnetic flux that can be assigned to such hypothetical structures and a lower bound to their total number over the planet's surface. The radio data give every indication that the close-in structure necessary for their proper interpretation is not even suggestively present in the known, that is, the "well-established" structure. Although only a very schematic description of some of these data was presented above, many other similar details could be added. Despite the wide understanding among the space physics community that Jupiter's surface field as defined by the fly-by spacecraft is very complicated, the actual field is, we believe, even more complicated than that.

The 3 spacecraft to have encountered Saturn, returned data that bear on this interpretation of the Jupiter data almost as strongly as they relate specifically to Saturn itself. All these spacecraft carried magnetometers, and one, Pioneer 11, flew within 1 planetary radius of the planet's surface. But the 2 Voyagers also carried radio receivers that discovered strong kilometric radiation from Saturn's poles (see Kaiser et al., 1980). It was immediately obvious that Saturn's radiation occurred in a strongly-modulated pattern that defines a rotation period of 10h 39.4 min, as accurately as the period one would determine for Jupiter's rotation based similarly on a few months of decametric data. But this was puzzling, since the magnetometers aboard Pioneer 11 (Acuna and Ness, 1980; Smith et al., 1980) had established just as definitively that Saturn's field was virtually

perfectly symmetrical, in the rotational sense (and as well in the N–S sense). In fact, the former authors stated, only a few days before the initial Voyager radio astronomy observations of the rotation of Saturn, “that... (strong longitudinal control... of... radio bursts)... will not be the case for Saturn... Determining Saturn’s rotation period with an accuracy comparable to that of Jupiter may be extremely difficult.”

The Voyager radio data on Saturn’s kilometric radiation suggest strongly a N–S asymmetry in the occurrence of SKR (Warwick et al., 1982). It may be argued that this radiation, fixed under the noon meridian of Saturn, responds to N–S asymmetry of the magnetosphere of Saturn, whose Northern or Southern hemispheres will be favored at different positions of Saturn in its orbit around the Sun. The Voyager 1 encounter, which showed these asymmetries as strongly as did Voyager 2, occurred when Saturn’s ring system, and its presumed rotational equator, defined a plane virtually containing the Sun. No magnetometer data suggest a field sufficiently asymmetric in the N–S sense to allow us to interpret the radio emissions.

It has become evident further that Saturn’s spokes, in the rings at a mean distance of 1.80 planetary radii from the center of the planet, show a modulation consistent with the period and phase of Saturn kilometric radiation (Porco and Danielson, 1982). The obvious conclusion is that the spokes, often interpreted as electrostatic in origin, relate to the same non-axisymmetric field components as does the kilometric radiation. This correlation bolsters further our inference that extrapolation of fly-by magnetometer data to the surface regions of a giant planet may not predict accurately, or even to good approximation, the actual fields that are involved with kilometric radiation or the sources of spokes.

3. Conclusions

It is a curious feature of these 2 planets that both may have highly non-dipolar fields on their surfaces, but that one, Jupiter, is known to be to a certain degree non-poloidal, while the other, Saturn, is believed to be axisymmetric. In the

latter case, first the kilometric radiation and then the spoke phenomenology have shown, by the fact of their strong non-symmetric character, the danger in the extrapolation. In the former case, because the field was, as extrapolated, already very non-symmetric, workers have often, even in the great majority of cases, been content to assume that all the structure they need to understand Jupiter’s complicated particles, fields, and wave radiations has been revealed by the magnetometers, even though they never flew within 50 000 km of Jupiter’s surface. Our object has been to show that the following case is strong: whatever is known about the surface fields of Jupiter and of Saturn (where there has never been a serious case made to the contrary) is known in detail only on the basis of low-frequency radio data. To a much lesser extent, Jupiter’s decimetric and centimetric synchrotron emissions within a few tenths of a planetary radius of the surface also contribute to the solution.

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