Reports

Jupiter's Decametric Radio Emission and the Radiation Belts of Its Galilean Satellites

Abstract. *Many of the observed properties of Jupiter's decametric radiation may be explained by postulation that the inner Galilean satellites of Jupiter have magnetic properties that strongly distort Jupiter's magnetic field in the region of each satellite. Charged particles from Jupiter's radiation belts are trapped by these distorted fields and emit synchrotron radiation.*

Burke and Franklin (*1*) in 1955 were the first to identify bursts of decametric radio noise as coming from Jupiter. Later it was shown (*2*, *3*) that the probability of these emissions depends strongly on the angular position of Io, the first Galilean satellite of Jupiter; this is true whether the angular position is measured from superior geocentric conjunction (SGC) or superior heliocentric conjunction (SHC)—a difference of only 11 deg (*4*). The two strongest correlations occur at 90 and 240 deg from SGC. The position of Io, relative to the plane that contains the rotation axis and the magnetic-dipole axis of Jupiter, also influences the probability of emission, which is greatest when Io lies above the magnetic-pole axis (*3*, *4*). These correlations are most strongly seen at frequencies higher than 30 Mhz but lower than 39.5 Mhz, the highest frequency recorded. In point of fact, the modulation due to Io has been shown to be very weak for frequencies lower than 20 Mhz (*5*, *6*).

More recently Tiainen (*7*) has shown that a weaker correlation exists between the probability of emission and the position of Europa, the second Galilean satellite, relative to SGC and SHC, for frequencies lower than 15 Mhz; he searched for a similar correlation with Ganymede, the third Galilean satellite. Since he gives no results for Ganymede, we may assume that either such correlation does not exist or it is very weak.

Tiainen (*7*) also looked in more detail at the events that are most highly correlated with the position of Europa and that occur when the angular departure of Europa from SHC is from 176 to 225 deg. In such cases, the probability of emission was most strongly enhanced when Io was 240 deg from SHC, or very close to Europa; this finding indicates that the emissions may come from the vicinity of the satellites.

Many mechanisms have been proposed for production of the radio emissions from Jupiter. It was realized early (*8*) that the steady decimeter radiation most likely reflects synchrotron or cyclotron radiation emitted by electrons in Jovian radiation belts resembling the Van Allen belts. However, the sporadic nature of the decametric radiation seemed to eliminate similar synchrotron radiation as a possible source, although many properties of the bursts of decametric radiation resemble those of cyclotron or synchrotron radiation.

After the correlation with the position of Io and the position of Jupiter's magnetic axis was discovered, many investigators described mechanisms in which plasma instabilities were driven by Io. Warwick (*6*) supposed that electrons are precipitated by Io from a radiation belt into Jupiter's ionosphere where they produce Cerenkov emission at nearly the cyclotron frequency. Recently Gledhill (*9*) proposed that the plasma in the Jovian magnetosphere is compressed into a discus-shaped region inclined to the equatorial plane; each time Io passes through this region, decametric radiation is produced by the oscillations of a plasma wave. All these theories must be modified to account for the correlation found (*7*) between the probability of emission and the angular position of Europa along with Io.

I suggest that the bursts of decametric radiation are synchrotron or cyclotron radiation; that the periodicity of the emissions reflects localized high densities of particles very nearly in a plane, and a beaming of the radiation that only periodically sweeps past Earth. The location of the high-density regions in this model is between the two inner Galilean satellites and Jupiter, but it is time-dependent; these regions may be considered as the radiation belts of the Galilean satellites. The high densities found there may be explained by the trapping of charged particles; this extraordinary trapping takes place in parts of the Jovian magnetic field that have been strongly distorted locally by the presence of the Galilean satellites. This distortion may be caused either by a satellite having a magnetic-dipole moment of its own (which is roughly parallel or antiparallel to that of Jupiter) or by the satellite being of a highly permeable material. The resultant magnetic fields and their trapping regions are sketched in Fig. 1.

The particles trapped in these regions come from, and are swept out of, the Jovian radiation belts; they remain longer in these regions because the distorted field lines are closed on the satellite, preventing escape once the particles are trapped. Because the densities of the trapped particles depend on the past history of the field, there may be great differences in the strength of the signals received. One would expect the injection of particles to be greatest when the magnetic pole of Jupiter points toward the particular satellite; thus would be explained the correlation of the probability of emission with the position of the magnetic pole.

If the trapping is confined to a set of field lines connected to Jupiter and to the satellite, and if we are observing synchrotron radiation, we should see polarized emissions when the satellites are about 90 and 270 deg from SGC. We do see the highest probability of Io-related emission at about 90 and 240 deg from SGC and for Europa-related emission at about 90 and 200 deg. These emissions are also known to be elliptically polarized (*6*).

Assuming that cyclotron emission is taking place, we can calculate the magnetic field in which the electrons are

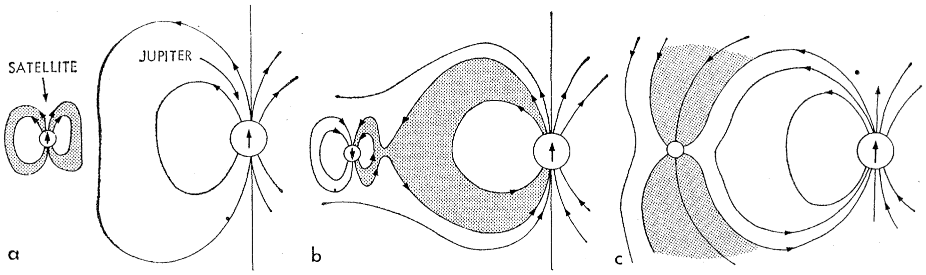

Fig. 1. Magnetic-field lines between Jupiter and a Galilean satellite for (a) parallel magnetic dipoles, (b) antiparallel magnetic dipoles, and (c) a high-permeability satellite. Possible trapping regions are stippled.

spiraling from the frequency of the radio emissions; that is, $\omega_c = eB/mc$, in which ω_c is the cyclotron frequency, e is the electron charge, m is the electron mass, B is the local magnetic field, and c is the speed of light. From this equation the sharp cutoff of the Io-related emission at 39.5 Mhz gives a maximum magnetic field of about 13 gauss, which is quite reasonable. A lower bound cannot be placed on the trapping field because the emission below 20 Mhz probably comes from several other sources as well (*5*). The required magnetic field would be lower for synchrotron radiation.

Both the injection of particles and their subsequent trapping should be less effective for Europa which is one and a half times farther from Jupiter than is Io. Thus the correlation of the probability of emission should be weaker for Europa than for Io. At the same time one might expect the trapping magnetic field to vary as that of Jupiter; if so, the frequency of the radiation emitted should be correspondingly lower, ranging around 10 Mhz, and the correlation would not be seen at the higher frequencies. Both these results agree with Tiainen's data (*7*). Moreover, the influence of Io on the Europa-enhanced events becomes more reasonable because in this model there is a temporary trapping of particles in a new magnetic field set up between the two satellites; this point would account for the unusual correlation mentioned by Tiainen (*7*).

Before discussing the possibility of these satellites strongly distorting the Jovian magnetic field, we should give some of their pertinent physical characteristics. Io and Europa are roughly the size of Moon and, along with the other Galilean satellites, have periods of rotation equal to their periods of revolution around Jupiter (1.8 and 3.6 days, respectively) (*10*); thus they rotate fairly rapidly as seen in an inertial frame of reference. They have similar densities of 3.76 and 3.66 g/cm^3, respectively, while Ganymede may be distinguished by its density of only 2.22 g/cm^3 (*11*).

The rapid rotation rates mentioned suggest the possibility of dipolar magnetic fields being generated in the satellites. However, this model is considered to be the less likely of the two suggested because the satellites are of fairly low density and have low surface temperatures; thus they are almost certainly solid bodies, not possessing a fluid inner core and not generating a magnetic field. However, until more is understood regarding the formation and structure of our Moon, this alternative cannot be entirely discounted.

The possibility that the inner Galilean satellites are comprised of highly permeable material seems likely; such material would draw in the Jovian magnetic-field lines until they were nearly normal to the entire surface of the satellite. This situation would grossly distort the Jovian magnetic field in the region of the satellite and permit trapping to take place in the region between the satellite and Jupiter.

Although most high-permeability materials have densities between 7 and 8 g/cm^3, a few magnetic materials (such as ferroxcube) and a few permanent magnetic alloys (such as vectolite) have densities between 3 and 5 g/cm^3 (*12*); it is interesting that both materials named are primarily iron oxides. If Io were composed of a similar material, one could speculate that such composition could account for the unusual redness of Io (*13*).

One should also mention that some of the particles that are injected into the satellite magnetic fields in this model should strike the satellite—more on the back or front surface of the satellite, depending upon whether the particles in the Jovian radiation belts are corotating with the Jovian magnetic field or are stationary in space. These collisions with the satellite surface might account for the large variation with rotational angle that is observed in the color and reflectivity of Io (*13*).

One might suggest that the high permeability would imply a high conductivity, and that the satellite's having high conductivity would permit an induction drag to act upon the satellites in their orbital motion and slow them down. However, using the results of Jefimenko (*14*) for artificial Earth satellites, one can show that the velocities of the Galilean satellites will be retarded only on the order of 1 percent in 10^9 years because of induction drag. But a similar effect will cause the rotational period to be the same as the revolutional period. It is gratifying that the Galilean satellites are known (*10*) to be so locked, even though they are more likely locked by tidal forces rather than by electromagnetic forces.

The ideas I have presented are unfortunately quite qualitative because of our lack of knowledge of the magnetic-field environment of Jupiter and because of conflicting information on the charged-particle properties (*6*). More accurate experimental location of the regions emitting decametric radiation from Jupiter would help to substantiate this model and to distinguish it from others presented.

J. A. Burns

Theoretical Studies Branch,
Goddard Space Flight Center,
Greenbelt, Maryland 20771

References and Notes

1. B. F. Burke and K. L. Franklin, *J. Geophys. Res.* **60**, 213 (1955).
2. E. K. Bigg, *Nature* **203**, 1008 (1964).
3. G. A. Dulk, *Science* **148**, 1585 (1965).
4. M. E. Tuiri, *Planetary Space Sci.* **15**, 1203 (1967).
5. R. A. Duncan, *ibid.* **14**, 173 (1966).
6. J. W. Warwick, *Space Sci. Rev.* **6**, 841 (1967).
7. P. O. Tiainen, *Nature* **215**, 1467 (1967).
8. F. D. Drake and H. Hvatum, *Astron. J.* **64**, 1163 (1959).
9. J. A. Gledhill, *Nature* **214**, 155 (1967).
10. A. Dollfus, in *The Solar System*, vol. 3, *Planets and Satellites*, G. P. Kuiper and B. M. Middlehurst, Eds. (Univ. of Chicago Press, Chicago, 1961).
11. C. W. Allen, *Astrophysical Quantities* (London, ed. 2, 1963).
12. *Handbook of Chemistry and Physics* (Chemical Rubber Co., Cleveland, Ohio, ed. 39, 1957).
13. D. L. Harris, *The Solar System*, vol. 3, *Planets and Satellites*, G. P. Kuiper and B. M. Middlehurst, Eds. (Univ. of Chicago Press, Chicago, 1961).
14. O. Jefimenko, *Amer. J. Phys.* **27**, 344 (1959).
15. I thank T. J. Birmingham, T. G. Northrop, and D. P. Stern for helpful discussions. Work completed while I was a NRC postdoctoral resident research associate with NASA's support.

30 November 1967