

ELECTRIC FIELD DIAGNOSTICS IN THE JOVIAN SYSTEM: BRIEF SCIENTIFIC CASE AND INSTRUMENTATION OVERVIEW

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ABSTRACT

The Jovian plasma environment exhibits a variety of plasma flow interactions with magnetised as well as unmagnetised bodies, making it a good venue for furthering our understanding of solar wind - magnetosphere / ionosphere interactions.

On an overall scale the solar wind interacts with the Jovian magnetosphere, much like at Earth but with vastly different temporal and spatial scales. Inside the Jovian magnetosphere the co-rotating plasma interacts with the inner moons. The latter interaction is slower and more stable than the corresponding interaction between the solar wind and the planets, and can thus provide additional information on the principles of the interaction mechanisms.

Because of the wealth of expected low-frequency waves, as well as the predicted quasi-static electric fields and plasma drifts in the interaction regions between different parts of the Jovian system, a most valuable component in future payloads would be a double-probe electric field instrument. Recent developments in low-mass instrumentation facilitate electric field measurements on spinning planetary spacecraft, which we here exemplify.

1. INTRODUCTION AND SCIENTIFIC CASE IN BRIEF

The Jovian environment contains two distinct types of plasma flow – (magnetised) solid body interactions. First, the solar wind obviously interacts with the giant magnetosphere of Jupiter. In many ways this interaction is similar to the solar wind’s interaction with Earth’s magnetosphere, although with vastly different temporal as well as spatial scales, because of both the size of Jupiter’s magnetosphere and the tenuous solar wind at 5 AU. Another characteristic difference is that at Jupiter the solar wind flow and the planetary rotation

contribute to the powering of the magnetosphere in roughly equal parts whereas at Earth the solar wind by far dominates as the energy source for the magnetospheric dynamics.

The other distinct interaction is that between the partially co-rotating planetary magnetosphere of Jupiter and the inner moons. Callisto, Ganymede, and Europa, icy Galilean moons of Jupiter, all orbit the planet well inside the Jovian magnetopause and, thus, interact primarily with Jupiter’s co-rotating magnetosphere rather than directly with the solar wind. The icy moons all have atmospheres [e.g., 1,2]. Europa’s atmosphere is believed to consist mainly of oxygen sputtered from the moons water ice surface [e.g, 3]. Ganymede’s atmosphere is thought to also mainly consist of oxygen [e.g., 4].

Io’s exosphere arises mainly from volcanic activity on the moon and from surface sputtering caused by impacting charged particles. The volcanoes release sulphur dioxide into the atmosphere, which is subsequently transformed into O, SO, and S₂ [5,6,7]. The atoms are at some point ionised and accelerated by the corotation electric field, moving outward until released into the Jovian magnetotail by reconnection [e.g., 8].

At higher altitudes the Ganymede ionosphere is dominated by molecular oxygen ions at polar latitudes and by atomic oxygen ions at low latitudes, whereas protons are not believed to exist in appreciable amounts [4]. The polar wind plasma outflow along polar cap field lines likely consists of atomic oxygen ions, due to their greater mobility. Polar cap here refers to the region where the magnetic field lines do not return immediately to the moon but instead connect to the Jovian main field. Thus, the configuration is similar to that at a planet interacting with the solar wind, but with a steady orientation of the “external” magnetic field and

Body	Io	Europa	Ganymede	Callisto	Unit
Radius	1815	1565	2640	2420	km
Distance from Jupiter	5.9	9.4	15.0	26.4	R_J
Orbital period	1.769	3.551	7.155	16.689	days
Co-rotation velocity	75	119	180	334	km/s
Observed plasma velocity	62-74	98	138	236	km/s
Orbital velocity	17.3	13.7	10.9	8.2	km/s
Relative co-rotation velocity	45-57	84	127	228	km/s
Density, Jovian magnetosphere	4000	50	4	0.2	cm^{-3}
Co-rotational dynamic pressure	400	12	2	0.4	nPa
Electron temperature	4	43	130	130	eV
Ion temperature	43	52	60	86	eV
Thermal pressure	30	0.8	0.1	0.01	nPa
Jovian magnetic field	1800	450	100	10	nT
Intrinsic B field (eq. surface)	1300?	small	700	small	nT
Alfvén velocity	130	300	250	300	km/s
Acoustic velocity	19	26	37	40	km/s
Magnetosonic velocity	133	310	250	300	km/s
Beta	0.02	0.01	0.03	0.2	

Table 1. The Galilean moons of Jupiter – properties of the moons and their plasma environment. Adapted after [8].

a relatively stable plasma flow. The interaction at the Galilean moons is sub-magnetosonic or possibly trans-magnetosonic, in contrast to the solar wind flow that interacts with Jupiter. All four of the moons have orbital velocities that are lower than the co-rotation velocity of Jupiter's magnetosphere and, thus, interact with the Jovian magnetospheric plasma as it overtakes the moons from behind. Because of the sub- or trans-magnetosonic nature of the plasma flow, no shock fronts form. Rather, the flow is diverted gradually. At Callisto, the Mach number may at times exceed unity [9].

Similar to the interaction between the solar wind and a planet, the interaction of the Jovian magnetospheric plasma with the icy moons acts as a dynamo, driving field-aligned currents along Jupiter's magnetic field that close in the Jovian ionosphere. The effect is clearly observed in HST images of UV emissions from Jupiter's ionosphere at the foot points of the Galilean moons [10]. The strongest emissions are seen at the foot point of Io, not unexpectedly because of the significant plasma production at Io.

The Jovian magnetospheric plasma is dense at low altitude and close to the equatorial plane but quite tenuous elsewhere, due to gravity and centrifugal acceleration. Thus, the parallel conductivity along the flux tubes connecting the moons with the Jovian ionosphere is low and parallel electric fields may need to develop to sustain the current flow. Also, the Alfvén velocity in this region is high, possibly with steep

gradients close to the planet as well as close to the equatorial plane. Strong gradients are also expected in the Io plasma torus, leading to generation of Alfvén waves, subsequently dumping energy at the magnetic foot point in the Jovian ionosphere.

Ganymede has an intrinsic magnetic dipole moment corresponding to an equatorial surface field of about 700 nT. The dipole moment is aligned with the Jovian magnetic field. Thus, the interaction at Ganymede's magnetopause is favourable to reconnection at all times, in contrast to the interaction between a planet and the solar wind which has a strong dependence on the instantaneous orientation of the interplanetary magnetic field.

Callisto and Europa do not have significant permanent magnetisation. Consequently, an induced magnetic field is set up through the interaction with Jupiter's planetary field. Because of the Jovian dipole tilt the induced fields at the moons vary at the synodic period of Jupiter, with a dominant field variation in the radial component. Table 1 summarizes key properties of the Galilean moons and their ionised environments. For a more thorough overview of the moons and their interaction with the Jovian magnetospheres see, for example, [9].

1.1 DC Electric Fields

The plasma in the Jovian magnetosphere co-rotates with the planet to first order. The co-rotation is not perfect,

but rather the plasma lags behind co-rotation by a rate that increases with distance from the planet (see Table 1). The co-rotation velocity exceeds the orbital velocity of each of the Galilean moons and thus the moons interact with plasma catching up from the trailing side. At Ganymede, which is magnetised, the interaction is similar to the interaction of the solar wind with a magnetised planet with three significant exceptions: 1) the flow is sub-magnetosonic, and thus no shock front is formed; 2) the flow velocity is relatively stable, in contrast to the fluctuating solar wind flow, and 3) the body is embedded in the inner parts of Jupiter's magnetic field rather than in the rapidly changing interplanetary magnetic field. Because of the tilt of the Jovian magnetic axis with respect to its rotation axis (10 deg) there is a diurnal variation of the field at Ganymede, but overall the field remains at all times in an orientation favourable to reconnection.

The reconnection flow resulting from the solar wind's interaction with Jupiter as well as the large-scale convective plasma flow in the Jovian magnetosphere are highly interesting to study and can be readily measured with a double-probe instrument. The deviation of the flow from nominal co-rotation and the plasma flow associated with the quasi-steady reconnection at Ganymede are of particular interest. The partial breakdown of co-rotation is believed to be related to parallel electric fields, in turn related to auroral emissions in the Jovian ionosphere [11,12].

Current circuits are set up along the flux tubes linking the Galilean moons to Jupiter. As they move through the Jovian magnetic field the moons act as dynamos dissipating power into the Jovian ionosphere via field-aligned currents. These currents are likely associated with parallel electric fields because of the tenuous, poorly conducting, plasma away from the equatorial plane. Experimental evidence for the existence of such parallel electric fields is found in HST ultraviolet images showing auroral emissions around the magnetic foot points of the moons [10]. Although the parallel electric fields [13] are difficult to measure directly, particularly in dilute plasmas, the associated perpendicular "closure fields" should be detectable with a double-probe instrument.

1.2 ULF Pulsations

ULF waves have been observed at Jupiter [e.g., 14] with periods in the range 10-20 mins. The eigenperiods of field line oscillations are of the order of hours, mostly because of the size of the Jovian magnetosphere [e.g., 15]. Since this is comparable to the rotation period of Jupiter stable global oscillations are not likely to occur. Rather, the oscillations observed are probably local standing waves, reflected at steep gradients in the Alfvén velocity (density gradients).

Whatever the reflection mechanism, such waves can carry energy and momentum over large distances, unless the reflection is perfect. Thus, transverse Alfvén waves are likely to play a role in the energetics and dynamics of the Jovian magnetosphere as well as of the plasma environments of the Galilean moons. Measuring the electric field in these pulsations in addition to the magnetic field will provide new information on the nature of the pulsations as well as their possible role in the magnetospheric dynamics.

1.3 Ion Cyclotron Waves

The Jovian magnetosphere picks up ions when interacting with the Galilean moons. The neutral atoms surrounding the moons can be ionised through photo ionisation, electron impact ionisation, and charge exchange. The processes are characteristically different in that ionisation creates additional charges that are added to the plasma and, thus, increases the plasma density, whereas charge exchange does not affect the plasma density. Both processes, however, add charges to the flowing plasma in turn requiring that momentum be extracted from the flow and added to the "new" ions. Momentum transfer primarily takes place in the plane perpendicular to the magnetic field, resulting in an anisotropic particle distribution that may become unstable and result in wave generation. Ion cyclotron waves have been observed near, for example, Europa [e.g., 16,17]. Observed frequencies include the gyro frequencies of O_2^+ , Na^+ , Ca^+ , and Cl^+ , around 1 Hz. A wealth of low-frequency wave emissions is related to mass-loading of the Io plasma torus [e.g., 18,19,20,21]. Having an electric field instrument in addition to a magnetometer, it is possible to study the energy flow (Poynting vector) of the waves, and hence to investigate their role in energy transport [22].

2. INSTRUMENTATION OVERVIEW

For future exploration of the Jovian magnetosphere, for example within the framework of ESA's upcoming Cosmic Vision programme 2015-2025 [e.g., 23], a most valuable payload element would be a double-probe electric field sensor. A state-of-the-art example of such a sensor system is MEFISTO [24], currently being implemented on BepiColombo MMO. MEFISTO employs the "hockey puck" principle, first flown on Cluster, to ensure optimum measurements at low frequencies. At the same time the instrument will measure AC fields up to 3 MHz with good sensitivity. At regular intervals, the current-voltage characteristic of the probes can be determined by sweeping the bias current and registering the corresponding probe potential. From the characteristic the optimal bias current setting can be determined, ensuring good low-frequency measurements.

2.1 Principle of measurement

The basic principle of a double-probe electric field instrument is identical to that of a voltmeter: the potential difference between two terminals is measured. In the case of a laboratory measurement where highly conductive clamps are used, ensuring good electrical contact between the probe and the point whose potential we want to examine is trivial. However, in tenuous space plasmas the probe-plasma coupling is a delicate problem. We want the potentials of the respective probes to deviate from that of the local plasma surrounding by the same amount, so that the difference in probe potential is representative of the potential difference in the unperturbed plasma. If we succeed in this, the electric field component along the direction of the booms is readily obtained as the potential difference divided by the separation distance of the probes.

In order to bring the probes outside the region electrostatically perturbed by the spacecraft, it is desirable to have very long booms. For BepiColombo the planned tip-to-tip distance is 32 m. The length needed on a future Jupiter mission depends on the mission concept and the orbit design, but is likely also in the range several tens of meters.

For optimal measurements over a wide frequency range the pre-amplifiers need to be located as close as possible to the probe. Historically, the pre-amps have often been mounted inside the probe itself. This necessitates a multi-conductor boom cable extending from spacecraft to probe. A new design was flown for the first time on Cluster [25]. There, the pre-amps were located in a separate housing (called “hockey puck” because of its shape) at a distance of 1.5 m from the probe. The “puck” was extended from the spacecraft body by a multi-conductor boom cable, whereas the probe was separated from the “puck” by a thin single wire. The Cluster design has proved to yield measurements of very high quality, likely because of the thin single wire, minimising the perturbations of the probe potential caused by the boom cable.

A potential problem with locating the pre-amplifiers close to the probes on a Jupiter bound spacecraft is the radiation environment. Depending on the details of the spacecraft orbit in the Jovian system pre-amplifier boxes outside of the protective cover of the spacecraft platform may or may not be feasible. If external pre-amplifiers can not be included instrument performance will be reduced, in that sensitivity will be lost either at the low-frequency or the high-frequency end of the spectrum, depending on the chosen sensor design. But, at the same time the mass of the boom mechanism can be reduced, since the boom wire does not need to be a multi-conductor and, thus, can be made thinner. However, if at all possible, the pre-amplifiers should be located close to the probes since then good sensitivity

can be achieved over the entire frequency range from DC to several MHz.

To optimise the operating point of the probe potential with respect to the plasma, the probe can be fed with a bias current. If the bias current is chosen such that the probes are kept close to the local potential of the surrounding plasma, the spacecraft potential may be monitored by recording the average potential of the two probes. Since the average of the two probe potentials is representative of the unperturbed potential at the location of the spacecraft body, the negative of this average will be a measure of the spacecraft potential. The spacecraft potential is an estimate of the plasma density, particularly in tenuous plasmas where spacecraft charge to positive potential due to photoemission [26]. Other techniques to measure plasma density and electron temperature at Jupiter are discussed by [27,28].

2.2 Boom mechanics and extension mechanism

The boom unit provides storage and deployment of the wire boom, the puck, and the probe. Mechanically, the wire acts as a boom; electrically, it acts as a carrier of the electrical connections between the probe at the end of the wire and the experiment unit in the spacecraft body. The boom wire, stored between two concentric cylinders, is fed using a mechanism driven by an electrical motor located at the rear end of the boom unit. This mechanism lifts the wire from its storage between the cylinders and pushes it out along the centre axis of the two cylinders. The wire deployment speed can be up to approximately 25 mm/s.

For BepiColombo, the mass of each puck is 50 g, each of the two boom cables is 79 g, and the boom deployment units are 380 g each. Thus, excluding platform harness, the total mass of the boom system (incl. probe, 50 g) is 559 g per unit. This is approximately a factor 5 less than the mass of conventional mechanism for the same boom length. The mechanism is scaleable and can easily be adapted to other boom lengths. The mass scales, to first-order, roughly linearly with boom length.

2.3 Synergies with Langmuir probes

A possible synergy exists between electric field sensors and Langmuir probes [28]. Electric field sensors of the kind presented here can alternatively be operated in Langmuir mode, where they are driven to a fixed potential relative to the spacecraft and the resulting current-flow between probe and plasma is monitored. The current-voltage characteristics can be obtained by sweeping the voltage (or possibly the current). The disadvantage of this approach is that electric field and Langmuir mode measurements can not be made

simultaneously (on the same probe). However, the mass of such a shared system is obviously less than the combined mass of a dedicated electric field instrument and a dedicated Langmuir probe instrument. It also provides the advantage of a longer separation distance of the Langmuir probe from the spacecraft than using a rigid boom. Alternatively, by using two pairs of wire booms, the system can alternately provide two components of the electric field, one component of the field plus two Langmuir probes, or four Langmuir probes making possible advanced interferometric diagnostics of small-scale plasma structures.

3. SUMMARY

There are several strong scientific reasons in favour of including the ability to measure quasi-static and low-frequency electric fields on future missions to explore Jupiter's magnetosphere [e.g., 23]. A state-of-the-art example of an electric field sensor was described.

Although the quasi-static field may under certain circumstances be estimated from low-energy particle measurements, assuming an $\mathbf{E} \times \mathbf{B}$ drifting plasma, a double-probe instrument typically provides better sensitivity, and always provides better time resolution. For measuring low-frequency waves and fluctuations a double-probe instrument is essential. As seen in this paper several key processes in the Jovian magnetosphere involve low-frequency waves, which thus are an important means for diagnostics.

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