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FORCE BALANCE IN THE MAGNETOSPHERES OF JUPITER AND SATURN

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ABSTRACT

Spacecraft measurements of the plasma populations and magnetic fields near Jupiter and Saturn have revealed that large magnetospheres surround both planets. Magnetic field measurements have indicated closed field line topologies in the dayside magnetospheres of both planets while plasma instruments have shown these regions to be populated by both hot and cold plasma components convected azimuthally in the sense of planetary rotation. By using published data from the Voyager Plasma Science (PLS), Low Energy Charged Particle (LECP), and Magnetometer (MAG) instruments, it is possible to investigate the validity of the time stationary MHD momentum equation in the middle magnetospheres of Jupiter and Saturn. At Saturn, the hot plasma population is negligible in the dynamic sense and the centrifugal force of the cold rotating plasma appears to balance the Lorentz force. At Jupiter, the centrifugal force balances $\sim$25% of the Lorentz force. The remaining inward Lorentz force is balanced by pressure gradients in the hot, high-β plasma of the Jovian magnetodisk.

INTRODUCTION

During the 1970's, close encounters of the planets Jupiter and Saturn by Pioneer and Voyager spacecraft have revealed extensive magnetospheres influenced by the rapid rotation rates of these planets.

Before direct observations were available, Dungey [1] and Gold [2] noted that the magnetic fields of rotating celestial bodies impart an angular speed to local plasma which results in a centrifugal force, stressing the field. As a result, the field lines are stretched out, or, equivalently, a current sheet is formed such that the Lorentz $\vec{J} \times \vec{B}$ force in the sheet balances the centrifugal force of the rotating plasma. Piddington [3] discussed the formation of such a current sheet at Jupiter. When the Pioneer 10 probe revealed a much larger magnetosphere than had been expected, Smith et al. [4] suggested that this radial distention resulted from the presence of an unseen, corotating low energy plasma. However, Walker et al. [5] found that magnetic field and high energy particle data implied a high temperature for the plasma population.

Before the Pioneer 11 encounter with Saturn, Scarf [6] and Siscoe [7] noted that a Saturnian magnetosphere should be similar to the Jovian one. Data taken by experiments on Pioneer 11 revealed an essentially dipolar field, compressed on the dayside by the solar wind [8]. Substantial amounts of low energy plasma were detected on the dayside in the radial range of 4 R_S to 16 R_S [9].

VOYAGER OBSERVATIONS

The more detailed observations of the Jovian and Saturnian magnetospheres made by instruments on the Voyager spacecraft permit a quantitative assessment of the balance of radial forces. To obtain a zeroth order estimate of the force balance, it is convenient to consider those regions in which the magnetospheres are reasonably axisymmetric. At Jupiter, this includes both the "inner" and "middle" magnetospheres which lie within $\sim$40 R_J of the planet. At Saturn we consider the region within $\sim$15 R_S. The flow of the plasma in these regions is primarily azimuthal [10], [11], [12]. Consider the standard MHD force balance equation:

$$\rho(\vec{v} \cdot \vec{\nabla})\, \vec{v} = -\vec{\nabla}p + \frac{1}{4\pi} (\vec{\nabla} \times \vec{B}) \times \vec{B} \tag{1}$$

In cylindrical coordinates $(\tilde{\omega}, \phi, z)$ we neglect terms of order $z^2/\tilde{\omega}^2$ in the components of (1). Define the plasma β by $\beta \equiv 8\pi p/B^2$ and the Alfvén Mach number by $M_A{}^2 \equiv 4\pi\rho v^2/B^2$. If we assume that the current density falls off as the inverse power of the radial distance[13], then the radial component of equation (1) in the z = 0 plane becomes

$$M_A{}^2 = \frac{1}{2}\,\beta\,\frac{\partial \ln p}{\partial \ln \tilde{\omega}} + \frac{4\pi}{c}\,\frac{I_o}{B} \tag{2}$$

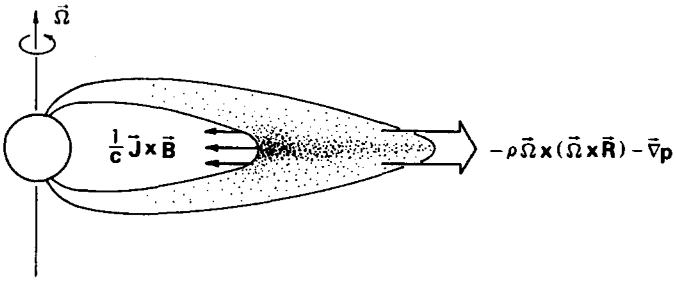

Fig. 1. Force balance in a rotating plasma. The outward centrifugal and pressure gradient forces are balanced by an inward Lorentz force.

Jupiter

Figure 2 shows the Alfvèn Mach number of the cold (<100 eV) plasma in the Jovian magnetosphere during the Voyager 1 encounter derived from PLS and MAG measurements [10], [11] [acknowledgements at end of paper]. The local maxima all have about the same value in the middle magnetosphere and roughly coincide with the crossings of the magnetic equatorial plane (MEP). The super-Alfvènic region reaches from $\sim$17 R_J outward to $\sim$42 R_J. The plotted values of M_A are lower limits because both the plasma bulk velocity and mass density have probably been underestimated [10].

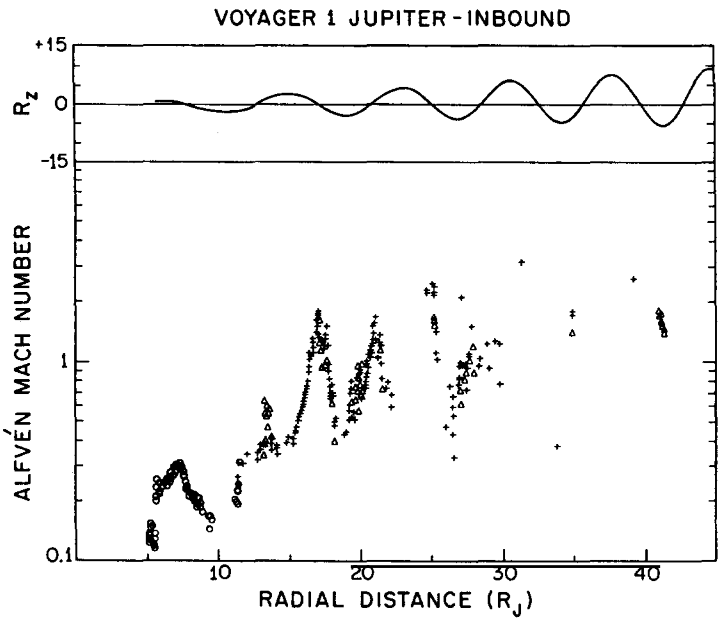

Fig. 2 The bottom panel shows Alfvèn Mach numbers derived from MAG and PLS data (Δ high resolution, + low resolution PLS spectra from [10], O high resolution from [11]). The top panel shows vertical distance from the MEP. Both panels are plotted versus radial distance.

The Voyager 1 LECP measurements indicate the presence of a significant amount of hot ($\gtrsim$25 keV) plasma which carries relatively little bulk kinetic energy but a great deal of thermal energy [14]. The data shown in Figure 24 of [14] for Voyager 1 inbound, as well as the analysis of Barbosa et al. [15], are consistent with $p \sim \tilde{\omega}^{-3.6}$, hence, we can take $\partial \ln p/\partial \ln \tilde{\omega} \simeq -3.6$ in the region of interest. The plasma β is almost entirely due to the hot plasma component. Lanzerotti et al. [16] studied data taken by LECP on Voyager 2 outbound and found that protons contribute $\sim$75% to the energy density and O^+ ions contribute $\sim$25%. Assuming these values to be typical of the region considered in this paper and using the data in Figure 24 of [14], the values of β can be computed.

The force contributions by the current sheet can be estimated by using the model of Connerney et al. [13]. They find for Jupiter that during the Voyager 1 encounter $4\pi I_o/c \simeq 451\gamma$, and, for the Voyager 2 encounter, $4\pi I_o/c \simeq 301\gamma$, two-thirds of the Voyager 1 value.

In Table 1 we list the various contributions to force balance as measured in the MEP as a function of radial distance (see Eq. 2). The initial increase of the Lorentz force with $\tilde{\omega}$ followed by a decrease is indicative of the finite radial extent of the current sheet. Recent modeling has shown that a better fit to the magnetic field data can be obtained if the model current sheet is tilted toward the centrifugal equatorial plane (CEP) [17]. Such a tilt is expected if the cold component plays a significant dynamical role [18]. The weaker current sheet observed by Voyager 2 is consistent with the lack of a super-Alfvènic cold component of the plasma during that encounter [10]. The current sheet observed at that time should have been more closely aligned with the MEP than with the CEP.

TABLE 1 - Force Balance at Jupiter

$\tilde{\omega}$	M_A	β	$M_A^2 + 1.8\beta$	$\frac{4\pi}{c} \cdot \frac{I_o}{B}$
17	1.7	2.4	7.2	9.0
21	1.6	5.7	13	17
25	1.6	7.4	16	20
28	1.2	4.5	9.5	24
35	1.5	3.8	9.1	28
42	1.8	1.0	5.0	25

Saturn

Observations by LECP on Voyagers 1 and 2 at Saturn indicated a very tenuous hot plasma component [19], [20]. During the Voyager 2 flyby, the LECP observations implied values of β only as large as $\sim$0.02 [21].

Cold plasma data from the PLS experiment on Voyager 1 show that a significant amount of plasma is concentrated near the equatorial plane [12]. Proceeding in a fashion analogous to that followed in [10] we have produced Figure 3 in the same manner as Figure 2. The flow is super-Alfvènic in the region of $\sim$9 R_S to $\sim$17 R_S and sub-Alfvènic at smaller distances.

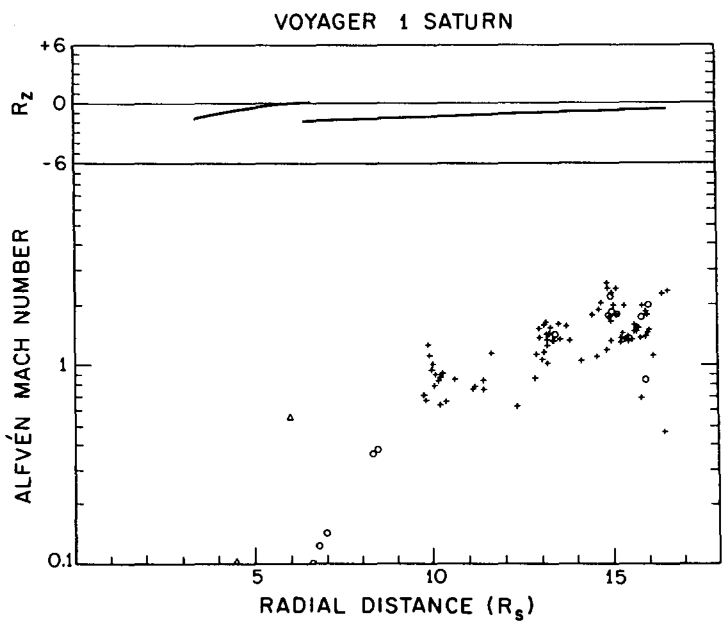

Fig. 3 The bottom panel shows Alfvèn Mach numbers derived from MAG and PLS data (O inbound high resolution, + inbound low resolution, Δ outbound high resolution PLS spectra). The top panel shows vertical distance from the MEP. Both panels are plotted versus radial distance.

Results from the magnetometer experiment indicate the presence of a ring current in the range of $\sim 8.5\ R_S$ to $\sim 15.5\ R_S$ [22] with a current density of about one-tenth that carried by the current sheet at Jupiter. Using equation 2 with $\beta = 0$, the data from Figure 3, and the fact that in this region B varies from $\sim 10\gamma$ to $\sim 20\gamma$ [22], it is apparent that the Saturnian current system is also in rough force balance with the plasma distribution. Hence, the Saturnian current system is due primarily to the centrifugal force resulting from cold rotating plasma, the scenario originally postulated for Jupiter [3] but not the case there.

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