form is in the interpretation of results: conclusions based on analysis of the logarithms are not necessarily valid for the values. Therefore, we tested both the values and the logarithms. Of the 12 sets of tests performed on both the BOE values and the logarithms of BOE values, in only one instance were the two results different at a 95 percent rejection level (see text).
9. J. V. Bradley, *Distribution-Free Statistical Tests* (Prentice-Hall, Englewood Cliffs, N.J., 1968).
10. Sale 31 contributed only two tracts to the analysis, neither of which was particularly unusual in the same sense as the 19 tracts from sale 30. We therefore caution the reader not to extrapolate our statements about the "transition period" to the entire suite of leases issued in sale 31.
11. We thank J. R. Pearcy, T. G. Crawford, B. S. Dickerson, and J. Hunter of the U.S. Geological Survey, Metairie, La., for their help in compiling data, and G. W. Horton, L. J. Drew, and R. Kasper for their critical comments. Supported in part by USGS contract 14-08-0001-17217.

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Magnetospheres of the Galilean Satellites

Abstract. *The plasma and field perturbations of magnetospheres that would surround magnetized galilean satellites embedded in the corotating jovian plasma differ from those produced by interaction with an unmagnetized conductor. If the intrinsic satellite dipole is antiparallel to that of Jupiter, the magnetosphere will be open. It is predicted that Io has an internal magnetic field with a dipole moment of 6.5 × 10*^{22} *gauss-cubic centimeters antiparallel to Jupiter's, and Io's special properties can be interpreted on the basis of a reconnecting magnetosphere.*

The intriguing speculation that the galilean satellites of Jupiter may possess intrinsic magnetic properties (*1, 2*) gains support from Voyager's photographic evidence of surface activity consistent with a molten interior for Io (*3*). If some or all of the galilean satellites are magnetized, the properties of the magnetospheres that will result from their interaction with the corotating jovian plasma can account for numerous puzzling features of the jovian system in a way that avoids inconsistencies inherent in earlier models of satellite-planet interactions.

In our initial arguments we assume the magnetic moments (M_s) proposed by Neubauer (*2*) on the basis of Busse's (*4*) scaling law. "Bode's law" estimates (*5*) differ by less than a factor of 2. Neubauer's magnetic moments and other parameters needed for the arguments presented here are listed in Table 1. Voyager measurements may change these estimates, but the burden of this report will be unaffected provided the ratio of the thermal plasma pressure to the magnetic pressure and the ratio of flow velocity to Alfvén velocity remain less than 1. Because Pioneer 10 and Pioneer 11 measurements show little departure from a dipole magnetic field in the vicinity of Io and Europa, we are confident that the required conditions are met, at least inside of 10 R_J [R_J (Jupiter radius) = 71,000 km].

Suppose that the dipole moment of the satellite is strictly aligned with that of Jupiter. The satellites are embedded in the jovian plasma. Relative to the more slowly moving satellites, the flow arrives from behind and is diverted by the satellite magnetic field. A closed magnetosphere should form around the satellite as the highly conducting corotating jovian plasma moves by. The total external pressure (P_{tot}) at the nose of the magnetosphere is the sum of the ram pressure, the thermal pressure, and the magnetic pressure (Table 2). The standoff distance, R_m, satisfies

$$R_m{}^6 = \kappa(M_s{}^2/P_{tot})$$

where $\kappa = 1.7$ for Earth's magnetosphere and M_s is the satellite's magnetic moment (*6*). The magnetic pressure dominates or equals the other contributions, at least for Io and Europa (Table 2). This means that the satellite magnetosphere would form a bubble with little asymmetry between upstream and downstream dimensions and with little disruption of jovian plasma in this aligned-moment configuration. We suggest that this occurs at Europa and possibly at Ganymede and Callisto.

The occurrence pattern of jovian decametric radiation (*7*) suggests that Io alone is strongly coupled to the jovian magnetosphere and ionosphere (*8–10*), and this can occur if its dipole is approximately antiparallel to that of Jupiter. As in the earlier case, we focus on an extreme by taking the dipoles to be exactly antiparallel. We now expect a Dungey-type (reconnected) magnetospheric configuration (*11*). This expectation is consistent with the results obtained for the lowest Alfvénic Mach number (M_A = 1.5) flow recently reported for terrella experiments (*12*).

The antiparallel jovian and ionian field lines will extend from Io's ionosphere to Jupiter's. Field lines will be dragged ahead of Io in its orbit and will skew toward Jupiter as their feet in the jovian ionosphere corotate. Stress is transmitted along this extended tail by field-aligned currents. The tail length can be readily estimated. If the electric field imposed across Io's magnetosphere is reduced by a factor ϵ from the corotation field upstream and A is the fractional area of Io with field lines connecting to Jupiter, a straightforward calculation (*13*) yields a length 5.6 A/ϵ in units of Io radii, ϵ measures the efficiency of reconnection and is about 0.1 at Earth. For $A/\epsilon \sim 10$, the tail is 56 r_{Io} long and subtends an angle of 14° ahead of Io. We picture the field moving through the ionian ionosphere and frozen to Jupiter, in contrast with some earlier accounts (*9*). The high conductance of Io's ionosphere (*10*) is not high enough for us to modify this view. The field-aligned current system connecting ionian and jovian ionospheres has an associated magnetic perturbation, δB, that, unlike the main field, is roughly independent of the distance from Jupiter. If δB is constant and azimuthal, we can give an expression for the equatorial trace of Io's flux tube. If χ is the angle between that trace and the radial direction, then tan χ is the ratio of δB to the radial component of the approximately dipolar jovian field and varies with radial distance r (in R_J) as

$$\tan \chi = (\delta B/2B_J)(1 - r/6)^{-1/2}(r/6)^3$$

The skewing of the field toward Jupiter increases rapidly as the flux tube moves inward from Io at r = 6.

The open ionian magnetosphere provides a model which can explain many Io-related phenomena, some of which have been hard to understand until now. First consider Io's ionosphere, whose density profile Kliore *et al.* (*14*) established with Pioneer 10 occultation data. Cloutier *et al.* (*15*) have pointed out the difficulty of understanding how Io's weak gravity (1.8 m/sec^2) can hold an ionosphere against the large electromagnetic ($\mathbf{j} \times \mathbf{B}$) forces produced by ionospheric currents and the ram pressure of the corotating jovian plasma (Table 2). In addition, both the strong day-night asymmetry of the measured ionosphere (Table 2) and the sharp cutoff of the "nightside" or upstream electron density at an altitude of 200 km have been hard to understand.

Our open magnetosphere model readily explains the retention of the ionosphere. The magnetic field of Io shields the ionosphere from the flowing jovian plasma and produces a strongly asymmetric cavity. On the upstream side, which is (fortuitously?) the nightside in the observations, the cutoff of ion density could be the magnetopause. Were this so, the magnetic moment would need to be half Neubauer's value. The observation is suggestive enough that we denote by M'_s this revised moment and use it in the remaining calculations of this report. This moment reduces our tail length estimate to 32 r_{Io} subtending 8°. The high electron density in the downstream ionosphere may be produced both by sunlight and by precipitation from a reconnecting tail, by analogy to the auroral electron precipitation phenomenon at Earth. Whether electromagnetic and gravitational forces are comparable cannot be firmly answered without a model of Io's atmosphere. The open magnetosphere model predicts ionospheric currents large enough to drive decametric radiation but smaller than those used in nonmagnetized models (10) and is compatible with the neutral atmosphere models reviewed by Brown and Yung (16).

Io's effect on jovian energetic charged particles can be explained in the framework of our model. In Thomsen's (17) summary of Pioneer 10 and Pioneer 11 observations, she notes that near Io's orbit all electrons (energies between 40 keV and 35 MeV) show strong absorption and energetic protons also show strong losses except in the > 80-MeV channel. Those energetic protons can "hop over" Io in their rapid drift and are not strongly affected by Io in any model. Losses in other energy channels result when particles moving along a jovian flux tube temporarily connected with Io's polar cap approach Io's surface or the level in Io's atmosphere where they can be scattered and lost. Only a fraction will come close enough to Io's polar cap to be lost. Others will mirror in Io's polar cap field and remain in the flux tube. We can estimate the fraction lost from an isotropic pitch angle distribution as $1 - \cos \alpha_c$, where α is the equatorial pitch angle in the ambient jovian field (B_J) and $\sin^2 \alpha_c = B_J/B_{pc}$, where B_{pc} is the polar cap field of Io. This figure is extremely sensitive to the assumed magnetic moment. For Neubauer's (2) moment, 24 percent of the particles are lost, those with equatorial pitch angles < 40°, but with our smaller magnetic moment M'_s 70 percent of the particles, all those with equatorial pitch angles < 72°, are lost. The 70 percent loss is qualitatively in agreement with the data and can also explain why pitch angle distributions peaked at 90° develop near Io's orbit (17). Further study could refine our estimate (M'_s) of the ionian magnetic moment.

Thomsen also reports that electrons with energy < 560 keV are injected near Io's orbit and that the magnitude of the injection varies from one pass to another. A reconnecting magnetosphere subject to substorm type instabilities as at Earth or Mercury produces bursts of energetic particles. Experience at Earth suggests that the substorm-accelerated particles may have energies greater by an order of magnitude or more than the total available potential energy across the magnetosphere (in electron volts) (18). At Io the voltage available from the corotation electric field is 680 kV, and accelerated particles up to this energy would be anticipated. The accelerated particles could be emitted in a range of directions centered in the plane of Io's orbit and the pitch angle distributions of the injected particles should peak near 90°, consistent with the observations.

At Europa, for which we suggested an approximately aligned dipole configuration, particle absorption should be weak. There should be no changes noted in the flux of particles whose gyroradii are small with respect to the radius of Europa. The 10° tilt (19) of the jovian dipole means that weak interaction with the particle environment can occur and some particle loss is anticipated and possibly observed. The losses should be weak enough that pitch angle distributions and injection would be little affected by Europa's magnetic properties. The gyroradius of 30-MeV protons is comparable with Europa's radius, and protons of some tens of millions of electron volts will be able to penetrate the satellite magnetosphere and be lost. Absorption seen near Europa is greatest for high-energy protons (17).

An additional Io-associated phenomenon which fits well into the open-magnetosphere model is the strangely skewed neutral sodium cloud (16, 20). The shape of the neutral sodium cloud has recently been described by Murcray and Goody, who noted (20, p. 327) that "the sodium is in a column extending forward from Io with the axis pointing slightly inside the orbit." Without invoking any strong anisotropy of emission regions, we account for the shape described by noting that the neutral sodium whose radiation is detected is lost when it becomes ionized by charge exchange and electron ionization through interaction with the jovian plasma. Within Io's magnetosphere, the flux of ionizing jovian plasma is significantly reduced relative to the ambient level because of the loss process described above. Consequently, the lifetime of sodium atoms shielded within the ionian magnetosphere is several times

Table 1. Physical properties of the galilean satellites and their environments.

Physical property, symbol, and unit	Io	Europa	Ganymede	Callisto	Reference
L_s = Jupiter-satellite distance (R_J)	6.0	9.5	15	27	(24)
r_s = Satellite radius (km)	1800	1500	2600	2500	(24)
ρ_s = Satellite density (g/cm^3)	3.5	3.4	2.0	1.6	(24)
T_s = Satellite period (hours)	42	85	170	400	(24)
B_{Js} = Local jovian field (γ)	2000	500	100	25	(2)
M_s = Magnetic moment from (2) (Γ-cm^3)	1.4×10^{23}	2.9×10^{22}	4.0×10^{22}	9.3×10^{21}	(2)
M'_s = Revised magnetic moment (Γ-cm^3)	6.5×10^{22}				
B_{eq} = Equatorial field from (2) (γ)	2400	860	230	60	
B'_s = Revised equatorial field (γ)	1100				
Δv = Relative plasma velocity (km/sec)	57	100	180	320	
E_{cr} = Corotation electric field (mV/m)	114	50	18	8	
n_e = Plasma number density (cm^{-3})	4000?	600?			
kT_p = Plasma temperature (eV)	10?	2.5?			(25)

Table 2. Properties of satellite magnetospheres and of Io's ionosphere. In the calculations we assume an average mass of 10 proton masses for plasma ions.

Property	Io	Europa	Ganymede	Callisto
External pressure (dynes)				
Ram pressure, ρv^2	2.1×10^{-6}	9.6×10^{-7}		
Thermal pressure, nkT	6.4×10^{-8}	2.4×10^{-9}		
Magnetic pressure, $B^2/8\pi$	1.6×10^{-5}	9.9×10^{-7}	4.0×10^{-8}	2.5×10^{-9}
Magnetopause standoff distance, R_m				
For M_s, from center of satellite (r_s)	1.4	1.5	< 1.8	< 1.8
For M_s, altitude above surface (km)	780	710	< 2100	< 2100
For M'_s, from center of satellite (r_s)	1.1			
For M'_s, altitude above surface (km)	200			
Ionospheric properties				
Upstream (night) peak density (cm^{-3})	1×10^4			
Upstream (night) peak altitude (km)	50			
Downstream (day) peak density (cm^{-3})	6×10^4			
Downstream (day) peak altitude (km)	100			

larger than in the adjacent regions outside. Because of magnetospheric asymmetry, the partially shielded region extends farther ahead of Io than behind and is also skewed toward Jupiter.

A similar argument can be applied to the interpretation of the Io-associated decametric radiation (*7*), whose source region is in the jovian ionosphere near the foot of Io's flux tube where strong field-aligned currents produce instabilities. Models of the emission mechanism have been reviewed by Smith (*21*). Decametric radiation is emitted most often when Io is at 90° and at 240° from the Earth-Jupiter line (0° is away from Earth). The strange asymmetry of these preferred positions relative to Earth has previously been accounted for by assuming that the foot of the flux tube leads Io by 15° in just the manner we have described (*22*). An 8° lead is predicted by the revised order of magnitude numbers which we have introduced. A more systematic selection of parameters and a treatment that properly accounts for the tilt of the jovian dipole would be needed to test whether the difference between 8° and 15° presents a problem to the open magnetosphere model.

If the Voyager or Galileo spacecraft confirm the existence of satellite magnetospheres, a radically different view of the inner jovian system will emerge. Moreover, the properties of a magnetosphere immersed in a sub-Alfvénic plasma flow would augment the developing general theory of magnetospheres (*23*).

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Solitons in a Reaction-Diffusion System

Abstract. *Solitary waves in reaction-diffusion systems usually annihilate on collision. A nonlinear system of reaction-diffusion equations has been constructed which has solitons: solitary waves whose interaction in a collision results in the emergence of two solitary waves identical to the colliding waves.*

Solitons may be defined as solitary waves which asymptotically maintain their shape and velocity after a collision with other solitary waves (*1*). They were demonstrated numerically (*2*) and analytically (*3*) for the Korteweg-deVries equation and have been found in a number of physical systems (*1*).

In this report evidence is presented that solitons may exist in a nonlinear system of reaction-diffusion equations. The system has solitary waves and when two solitary waves collide we find solitary waves identical to the original waves emerging from the collision. The methods employed consist of numerical integration of the reaction-diffusion equations.

Reaction-diffusion systems of equations arise in many models of biological

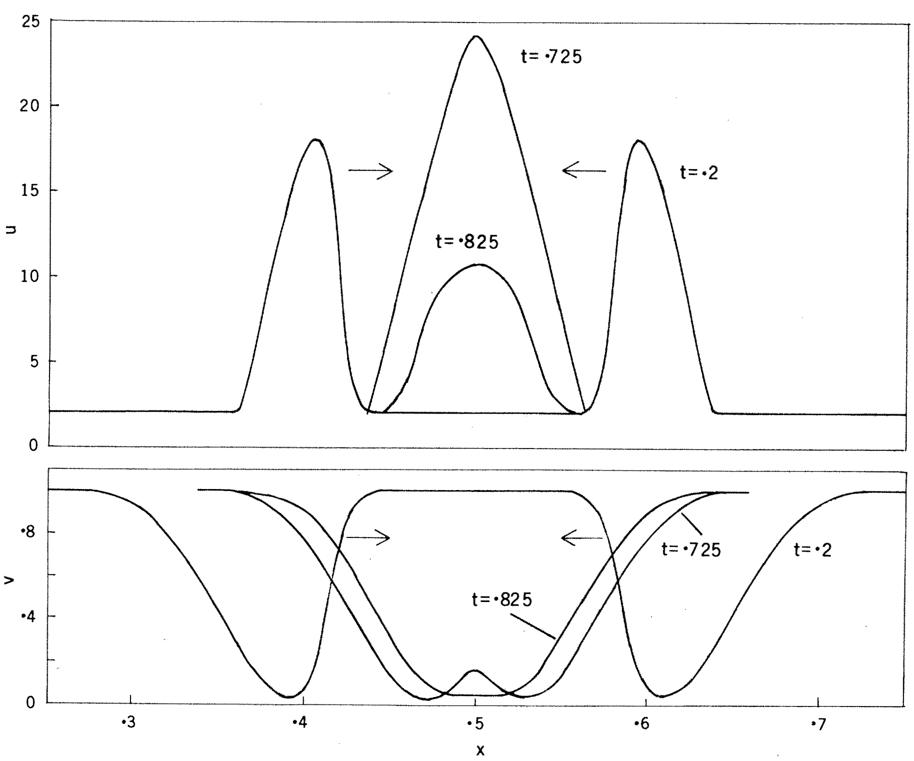

Fig. 1. Computed solutions of the reaction-diffusion equations which display solitons. At $t = 0.2$ two solitary waves with peaks for u at $x = 0.4$ and $x = 0.6$ are approaching the center of the figure. The collision takes place and the waves merge so that at $t = 0.725$ the u envelope has values which are larger than those in either solitary wave. This envelope drops to that shown for $t = 0.825$.

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