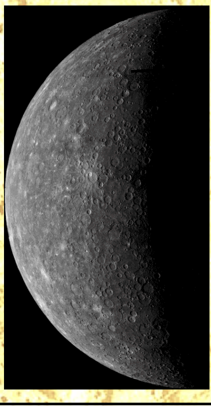
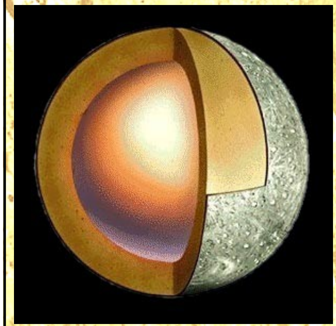
The Magnetosphere of Planet Mercury



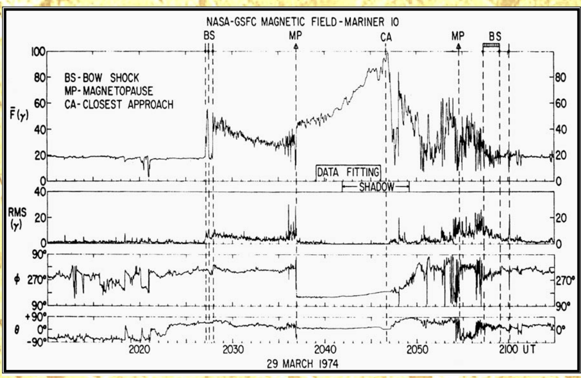
- The planet
- Shape and structure of the magnetosphere
- Current systems
- Dynamics
- Energy sources
- Eigen oscillations

Planet und Magnetfeld



Planetenradius:	2439 km
Kernradius:	~1829 km
Mittl. Dichte:	5.42 g/cm^3
Rotationsrate:	58.64 Tage
Dipolmoment:	5·10^{19} Am^2
Ober. Temp.:	-173° - 429°
Atmosphäre:	Nein
Exosphäre:	Ja
Plasmasphäre:	Nein
Magnetosphäre:	Ja

Das Magnetfeld des Planeten Merkur



Ness et al., 1978

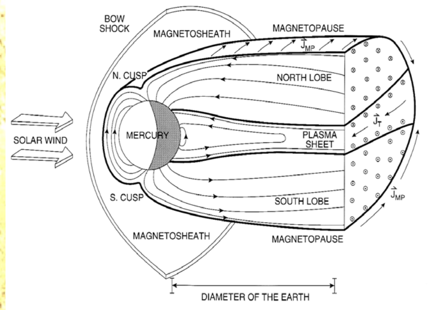
Planetary Magnetic Fields

Planet	Radius [km]	Rotationsperiode [Tage]	Äquatoriales Magnetfeld [nT]
Merkur	2439	58,6	340
Venus	6052	243	0.4
Erde	6371	1	31000
Mars	3397	1	< 0.5
Jupiter	71398	0.4	424000
Braille	0.8	3.6	92500
Saturn	60000	0.41	21500
Uranus	26200	0.72	22800
Neptun	24300	0.70	14400

Magnetospheric Plasma Sources

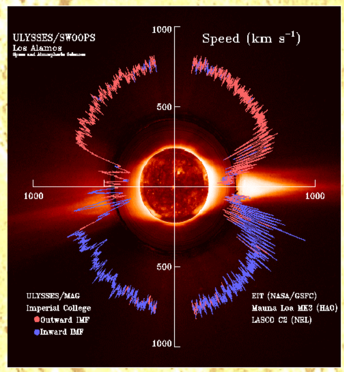
Mercury:	solar wind and sputtering of surface material, e.g. sodium
Earth:	solar wind and ionosphere
Jupiter:	solar wind and volcanic activity of the moon Io
Saturn:	solar wind, atmosphere of moon Titan, sputtering at surfaces of icy moons and rings
Uranus:	polar ionosphere, minor solar wind contribution
Neptun:	ionosphere, moon Triton

The Magnetosphere of Mercury



- No atmosphere
- thus no ionosphere
- but exosphere
- No plasmasphere
- Weak magnetic field
- Multi-ion plasma
- Small magnetosphere

Solar Wind: The Embedding Medium



Magnetic field and plasma density

Mercury:	46 - 21 nT	73 - 33 cm^{-1}
Earth:	8 nT	5 cm^{-1}
Jupiter:	1 nT	0.2 cm^{-1}
Saturn:	0.6 nT	0.06 cm^{-1}
Uranus:	0.3 nT	0.01 cm^{-1}
Neptun:	0.005 nT	0.005 cm^{-1}

The velocity is almost constant in the inner part of the heliosphere

Magnetopause Formation

The magnetopause is a surface where the dynamic pressure of the solar wind and the magnetic pressure of the magneto-spheric plasma are in equilibrium:

$$p_{dyn} = 2\, n_{sw} m_p v_{sw}^2 = \frac{B^2}{2\mu_0}$$

The dynamic pressure of solar wind particles is transferred to the magnetospheric plasma by specular reflection of the particles at the boundary.

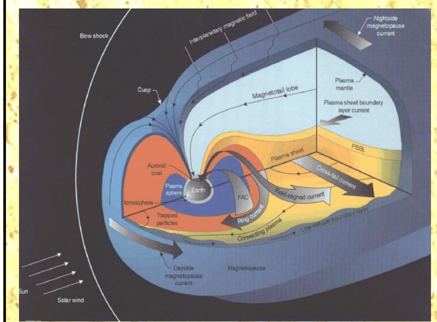
Magnetoapause Position

The magnetopause stand-off distance along the Sun-Earth line is given by

$$R_{MP} = \left(\frac{4B_{Surface}^2}{2\mu_0 k\, n_{sw} m_p v_{sw}^2}\right)^{1/6}$$

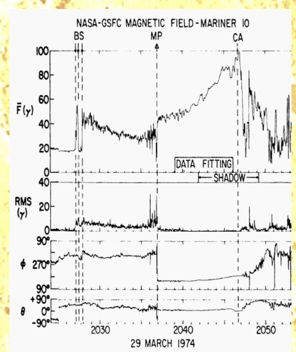
where k = 0.88 is a correction factor resulting from gasdynamic approximations to the magnetosheath flow: At Mercury $R_{MP} = 1.5\ R_P$

Electric Currents in the Magnetosphere



- Magnetopause currents
- No ring current
- Neutral sheet current
- Tail current
- Field-aligned currents
- No polar electrojet currents

Magnetopause Current - Chapman-Ferraro Current



At the mp jump in magnetic field by about 24 nT, a value typical also at the terrestrial mp.

From $\nabla \times \vec{B} = \mu_0 \vec{j}$ a current density of about $j_{MP} \approx 1.5 \cdot 10^{-7}$ A/m² results, assuming an mp thickness of 125 km.

Magnetopause Current – Ground Magnetic Effect

Chapman-Ferraro currents produce ground-magnetic effects, which at

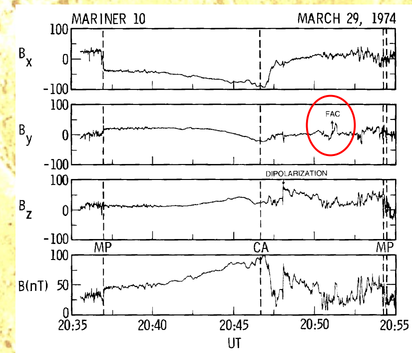
Earth are of the order of 10 nT added to a 30,000 nT background field

and at

Mercury are of the order of 70 nT added to a 340 nT background field

The external field matters at the surface !!!!

Field-Aligned Currents



Slavin et al., 1997

Field-aligned current density:

$\approx 7x10^{-7}$ A/m^2

Closure problem

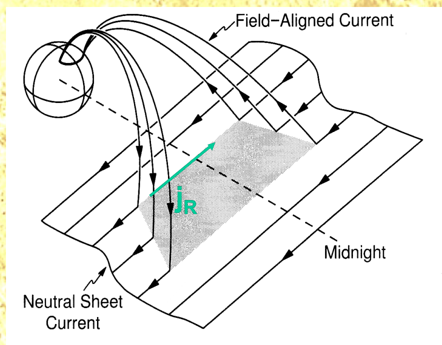
as at Earth FACs close in the ionosphere but Mercury has no ionosphere

Is there a substorm current wedge at Mercury ?

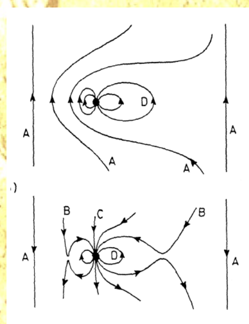
Enhanced westward electrojet in the Ionosphere

or

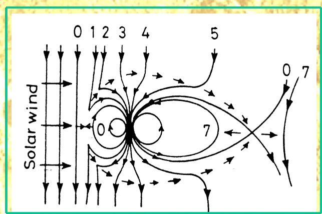
closure via diamagnetic currents in the plasma itself



Substorms and Flux Transport in the Open Magnetosphere

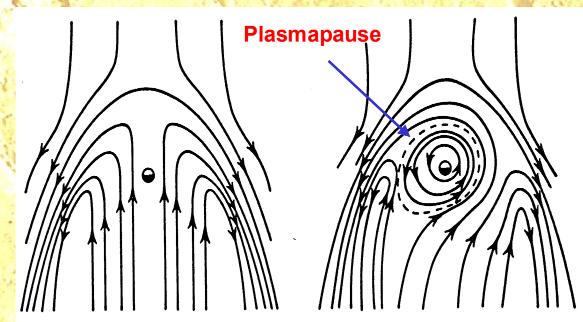


Dungey's model of the closed and open magnetosphere



Dayside reconnection transports plasma and magnetic flux towards the nightside tail where return flux is initiated by reconnection again.

Corotation, Reconnection Induced Convection, and the Plasmapause



Does Mercury have a plasmasphere ?

Magnetospheric Convection and Corotation

Corotation implies plasma motion and via the frozen-in theorem

$$\vec{E} + \vec{v} \times \vec{B} = 0$$

electric fields, that is the corotational electric field is given as

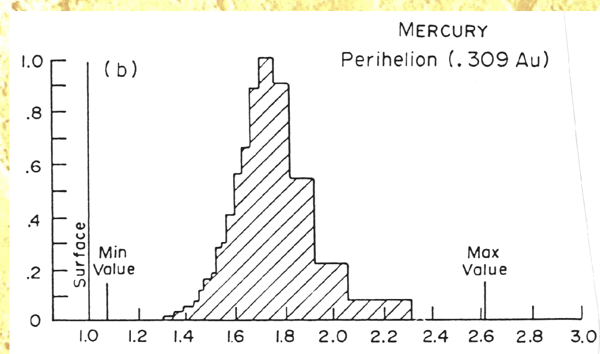
$$\vec{E}_{cor} = -\frac{\Omega_{Earth} B_{surface} R_E^3}{r^2} \vec{e}_r$$

and corotation driven plasma motion is ExB-drift convection

$$\vec{v}_{cor} = \frac{\vec{E}_{cor} \times \vec{B}}{B^2}$$

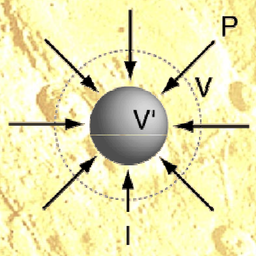
Mercury has no plasmasphere

External Forcing – Internal Reactions ?



Siscoe and Christopher, 1975

Bulk Modulus and Compressibility



$$K = V \cdot \frac{\Delta p}{\Delta V}$$

Modulus

$$\kappa = \frac{1}{V}\frac{dV}{dp}$$

Compressibility

The Magnetospheric Bulk Modulus

$$R_{MP} = \left(\frac{B_0^2}{\mu_0 p}\right)^{1/6} \; ; \quad p = n_{sw} m_p v_{sw}^2$$

Magnetopause position

$$K = R_{MP} \cdot \frac{dp}{dR_{MP}} \propto p_{MP} \; ; \; p_{MP}(r = R_{MP})$$

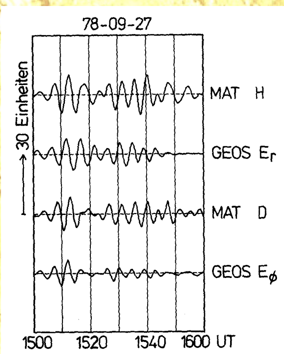
Bulk modulus

$$\kappa = 1/K \propto -1/p_{MP}$$

Compressibility

Mercury has a very stiff, but Jupiter a very fluffy magnetosphere; Mercury rings, Jupiter not !!!!!!

Ringing the Magnetospheric Bell

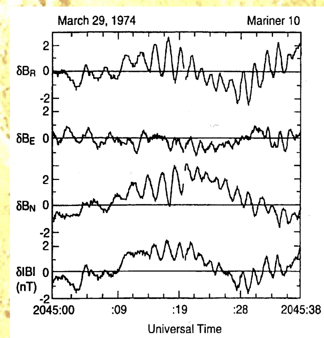


Units: 1 nT; 0.1 mV/m

Magnetospheric eigen-oscillations are MHD waves in the terretrial magnetosphere.

Their periods are much longer than proton gyroperiods !!!

ULF Waves at Mercury



(from Russell, 1989)

This is the only published evidence for ULF waves in the Hermean magnetosphere.

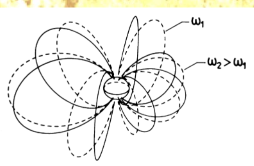
Amplitude: 2 nT

Period: 2 s, e.g.

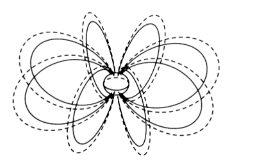
about twice $T_{G,Proton}$

this wave is not an MHD wave !!!!

Global oscillations: The Dungey Problem



Toroidale Mode



Poloidale Mode

Dipolemagnetosphere

MHD oscillations

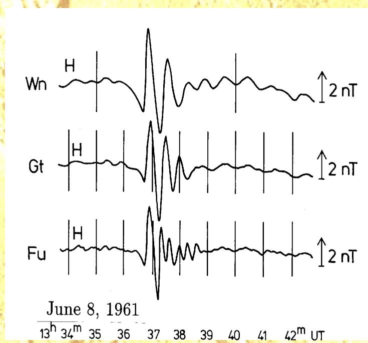
Axisymmetric perturbations

$$\left(\frac{\mu_0\rho}{B_0^2}\frac{\partial^2}{\partial t^2} - \frac{\partial^2}{\partial r^2} - \frac{\sin\theta}{r^2}\frac{\partial}{\partial\theta}\frac{1}{\sin\theta}\frac{\partial}{\partial\theta}\right) r\sin\theta\, E_\phi = 0$$

$$\left(\mu_0\rho\frac{\partial^2}{\partial t^2} - \frac{1}{r^2\sin^2\theta}\left((\vec{B}_o\cdot\nabla)(r^2\sin^2\theta)(\vec{B}_o\cdot\nabla)\right)\right)\frac{v_\phi}{r\sin\theta} = 0$$

Decoupled toroidal and poloidal oscillations

Global oscillations: Earth



Decoupled toroidal and poloidal eigen-oscillations for axi-symmetric (m=0) perturbations

Voelker,1963

Global oscillations: Mercury

To treat this question we need Dungey's equations for a non-MHD model of the Hermean magnetosphere as the anticipated eigenfrequencies are less, but comparable to the gyrofrequency

Mercury: A Two Component Cold Plasma Approach

$$\varepsilon = \begin{pmatrix} \varepsilon_1 & -i\varepsilon_2 & 0 \\ i\varepsilon_2 & \varepsilon_1 & 0 \\ 0 & 0 & \varepsilon_3 \end{pmatrix}$$

Dielectric Tensor;
0<< ❄ < ♦$_i$

$$\varepsilon_1 \cong \frac{c^2}{v_A^2} + \frac{c^2}{v_A^2}\frac{\omega^2}{\Omega_i^2}; \quad \varepsilon_2 \cong -\frac{c^2}{v_A^2}\frac{\omega}{\Omega_i}$$

$$\varepsilon_3 \cong -\frac{\omega_{pe}^2}{\omega^2}$$

Mercury: Global Oscillations
Axisymmetric Perturbations m=0

$$\vec{E} = -\nabla_\perp \Phi + \nabla_\perp \times \Psi \vec{e}_{||}$$

Scalar potentials

Toroidal operator using curvi-linear coordinates

$$\mathrm{T}(\omega) = \partial_3 \frac{g_2}{\sqrt{g}} \partial_3 + \frac{\sqrt{g}}{g_1}\frac{\omega^2}{v_A^2}$$

$$\partial_1 \mathrm{T}\, \partial_1 \Phi = i\partial_1 \varepsilon_2 \sqrt{g/g_1}\, \partial_1 \Psi$$

Toroidal oscillation coupled to poloidal though m=0, due to ⌨$_2$

=> Dmitri Klimushkin and Pavel Mager

Kinetic Alfvén Waves in the Hermean Magnetosphere

a) Solar wind buffeting causes ringing of the magneto-sphere

b) The scale of the magnetosphere is about 10 x the ion gyroradius

c) Waves generated by buffeting are kinetic Alfvén waves with $E_{||} \cong 0.2$ mV/m (Glassmeier, 2000)

d) Buffeting causes particle heating via kinetic Alfvén waves

Electromagnetic Induction at Mercury

We have a small magnetosphere

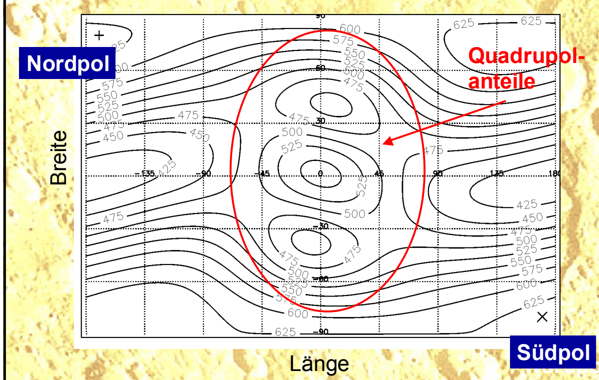
Magnetopause currents are close to the planet

Temporal variations of magnetopause currents may cause strong induction effects

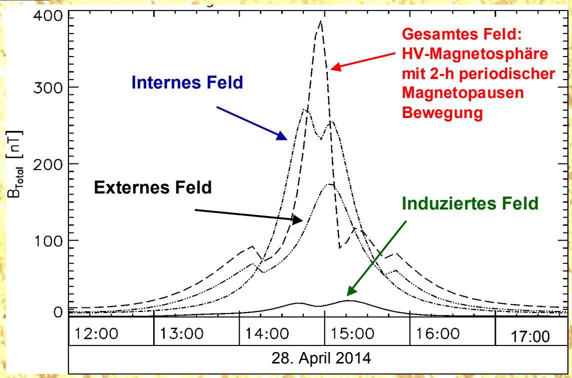
As the planet consists mainly out of a highly conducting core

How large are these induced fields ?

Isototalen an der Merkuroberfläche



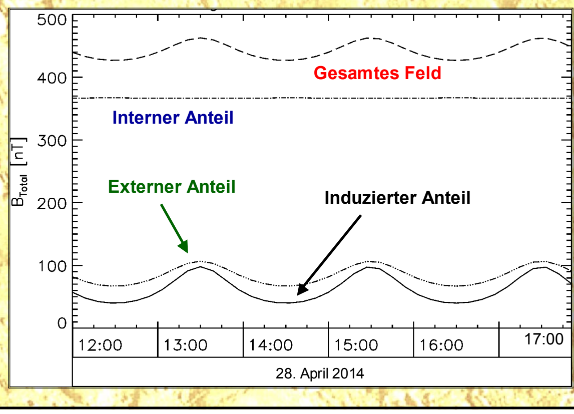
BepiColombo am 28. April 2014



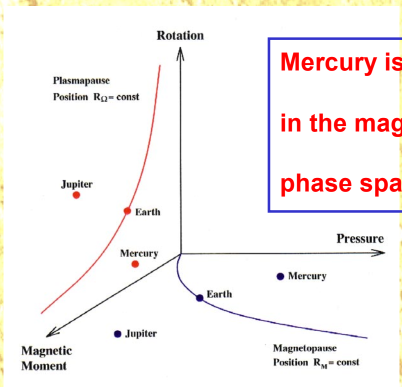
Jan Grosser, Diplomathesis

Das Humboldt Observatorium,

Merkuräquator, 28. April 2014, 18:00 Lokalzeit



Summary



Mercury is a new point in the magnetospheric phase space !!!!!!

Ein Dankeschön an...

Jan Grosser	Diplomand am IGM, TUBS
Anja Stadelmann	Doktorandin am IGM, TUBS
Dr. Ulrich Auster	IGM, TU Braunschweig
Prof. Dr. D. Klimushkin,	Irkutsk, Russia
Dr. P. Mager,	Irkutsk, Russia
Prof. Dr. J. Vogt	IUB, Bremen
Prof. Dr. G.-H. Voigt	FH Aachen