Modeling of the Mercury Environment: Where are we before BepiColombo?

9-10 August 2004,
Swedish Institute of Space Physics
Kiruna, Sweden

A European Science Foundation Exploratory Workshop

1. Executive Summary

Mercury is a different planet in many ways. All components of the Hermean environment, its magnetosphere, atmosphere and surface, are coupled. In the past most research has treated these components separately, but to accurately model and understand the environment of Mercury, we have to consider the whole system at once. For this, an interdisciplinary approach is necessary, since it requires expertise in solar wind, magnetosphere, exosphere, and surface modeling, e.g., the modeling of surface sputtering requires material science knowledge.

Due to the tenuous atmosphere and ionosphere of Mercury, we can consider the neutral and ion populations as collisionless. There is however couplings between neutrals and ions through charge-exchange, photoionization and sputtering. Sputtering from the planetary surface takes place when a particle (ion or neutral) precipitates, and results in the production of sputtered particles. The exact details of this particle-surface interaction process are difficult to model, and even if the results from laboratory experiments can be used for guidance, the existing models are just rough estimates. In parts, that is because the regolith composition and roughness are not well known. The small magnetosphere of Mercury is highly variable, and simulations of the interaction with the solar wind suggest that large parts of the planetary surface is directly exposed to the solar wind for long times. This results in the sputtering of neutral atoms from the surface, and due to the collisionless environment, these neutrals can be detected at a distance, the more energetic ones even by instrumentation on an orbiting spacecraft. The measurements of these neutral atoms could give information about the location of areas exposed to the solar wind, and information on the regolith composition. One can view these neutral atom emissions as an aurora on Mercury, but with neutrals instead of photons, and taking place on the surface, instead of in the atmosphere. Imaging of these neutral atom emissions can provide a global, instantaneous, pictures of the planetary surface.

The only in situ measurements made at Mercury was by the Mariner 10 spacecraft during three flybys in 1974 and 75. In addition to that there are ground based observations by radar and telescopes. The lack of observational data has made numerical simulations an important tool to investigate the exosphere and ionosphere. That the environment can be considered collisionless simplifies numerical modeling, since it is possible to compute trajectories of individual neutrals and ions, without regard to the local particle populations. However, the coupling between ions and neutrals of the same specie through photoionization and charge-exchange, and the coupling between different species through surface sputtering, makes self consistent simulations a demanding task in terms of computational resources, especially considering that ideally also the electric and magnetic fields should be self consistently computed. Up until now the approach taken has been to focus on one specie, and one process at a time, but future work lies in the direction of coupling as large parts of this complex system as possible, to make the models more accurate and self consistent. The final verification of the models and numerical simulations of Mercury's environment will only be possible when there is real data returned from the European BepiColombo mission (launch 2011, arrival 2014), and NASA's Messenger mission (launch 2004, arrival 2009).

In view of the upcoming European BepiColombo mission to Mercury, it is important that the modeling of Mercury's environment is mature enough to accurately interpret the returned data, a goal that this workshop hopefully has furthered.

There are at the moment many groups in Europe that have initiated work on Mercury modeling, as seen by the many presentations on the subject at recent meetings of EGU, AGU and COSPAR. Due to the complexity of the topic, it is however difficult to have in-depth discussions at such general meetings, and it is especially important for numerical simulations to understand all details and assumptions of a model. A short focused workshop provided a better forum for scientists to present their work, and strengthen the European efforts in Mercury modeling.

The workshop also initialized efforts to view the Hermean environment as a coupled system that must be modeled self consistently.

2. Scientific Content of the Event – Minutes of the Meeting

Here follows a summary of the presentations and discussions.

Jim Slavin
2:15 August 3 Messenger launch
Understanding of the end points – Agency's interests
Surface started developing rather early.
Messennger is a non-strategic mission (Discovery).
Laser altimeter accuracy 20 cm to define flatness (expected 3 m if the core is solid).
Potter and Morgan, 2002 Image of Na D2 emisison of Mercury.
<u>S/C design</u>
One can add up to 18 Sun intensities.
SA: 230° - 240° operation temperatures.
<u>Magnetometer</u>
Mag. Boom – 3.6 m, 0.05 nT
Magnetic cleanliness: <0.1 nT, shield of momentum wheels
<u>Particles</u>
Solar direction is not visible (thermal shield)! There is no solar wind monitor.
FIPS: 0 – 15 keV/ q, composition, innovative ESA, scans full ranhe in 60s., mass vs, E/q
EPS: 10 keV – 5 MeV (i), 10 keV – 400 kev (e)
FIPS + EPS = 2kg.
No electrons below 10 keV.
<u>Mission scenario</u>
(!) Intercalibration with Venus Express (Messenger Nov. 2006, June 2007)
Earth fly –by July 2005
Venus Fly – by Nov. 2006
Venus Fly – by June 2007
Mercury Fly-by Jan. 2008 200 km, close terminator, tail crossing
Mercury Fly-by Oct. 2008 (all three are in the same geometry inc. Mercury season)
Mercury Fly-by Sept. 2009
MOI March 2011

Orbit: 200 km x 15193 km, T = 12 h, Pericenenter = 60° North, I = 80°

No nadir pointings, S/C is rotating around solar direction. Ceramic shield gets charged limit low energy ion measurements,

Mukai, MMO
MMO: launch 2012, arrival 2016, 400 km x 12000 km, T = 9.3h
Cruise: electrical propulsion, orbit insertion –chemical
MMO PI – instrument 23.9 kg (without margin)
P/L review committee (6 Japan, 3 from Europe)
S/C size: ø180cm x 90 cm, 200 kg inc. margin (230 kg inc. separation mechanism).
Spin axis titled 2° (wave instrument requirement), Spin period 4s.
Time resolutin of 3D measurements – 2s
Orbit in SW: 7.4MB / 9.4h -> 17MB / day

Orbit in tail: 56 MB/ 9.4h -> 140 MB / day
Insertion on Mercury is done at the same time for MMO and MPO. MPO continues with the transport module and reduce pericenter.
No science for MMO until insertion.
Boom deplaylent and spin up after separtion.
Only instrument check – up during cruise later
Souyz Fregat 2B launch from Kouru
Problem with MMO – MPO separtion: compensation for MPO wobbling and risks MMO will get in the MPO thruster plumes.

Mukai, Empirical model
Based on analogy with the Earth and scaling of the solar wind parameters.
Scale: >> ion inertia length (Earth) ~ion inertial length (Mercury)
(!) Contribution of the ionospheric / exospheric particles is very difficult to include,
The model was needed to get extreme conditions for the instrument design.
No comparision was made with existing models. MHD does not provide Temperatures.
One needs comparison with hybrid models.

Slavin, Review of observations and simulations
Magnetosphre structure: boundaries and regions
Dynamics: re-configuration and particle acceleration and heating
Elect. Dyn. Coupling: FAC and induction currents
Neutral and charged particles: sputtering, precipitation

Mercury 10
3 fly-byes: each 15 minutes
- mag.field
- plas,a electrons
- energetic electrons

What is missing
- plasma ions
- comprehensive energetic particles
- E-fields
- Waves

Theory and simulations
Analitical models
- night side reconnections and substroms, Siscoe et al., 1975
- Day side reconnection and erosin, Slavin et al., 1979
- Interior induction currents, Hood and Schubert (1979), Glassmeier (2000)
- Mag. Ions, Lykyanov et al. (2001), Delcourt et al., (2002), Mukai et al. (2004)
- Neutral and charged particles, Cheng et al (1987), Ip (1987), Killen et al. (2001)

Global simulations
- global MHD, Kabin et al (2000), Ip and Kopp (2002)
- global hybrid, kallio and Janhunen (2003), Kallio (2004)

Very few global models vs. analytical (back-of-envelope types)
Discussion: Applicability of MHD for Mercury (Stas, Jim, Jabin, Yamau): Mercury is an ideal place for MHD. Gyrorad. 1% of the plan. Radius. High density and high B-field are important (wave – particle interaction importance). MHD reproduces all regions very well.

Strong Bx => very strong asymmetry in the solar wind precipitation between North and South (reconnection and typology).
Event D (energetic particles) is the main indication of the substorms.
Small time scale makes possible to study clearly particle acceleration no mixing up between different acceleration events (Comments to Lykyanov et al. (2000)).

Pedersen conductivy is about 0.1 mho 10 times less than the earth's ionosphere (conductivity of the salt water..) FAC dissipare their energy very fast.

(Question) No knowledge of the surface conductivity
(Question) What does varying conductivity on the magnetospheric dynamics.
Close FAC

- regolith Hill et al., 1976
- Pick-up ions, Cheng et al., 1987
- photo-emission sheath Grard et al , 1998
- Alven waves Glossmier et al.

(Question) Very little known about closure
(Question) Self-consistance ions, precipitation, and dynamics

Future directions

1. Structure – Self-consistent incorporation of induction currents
2. Dynamics – Effects of time – variable dayside – nightside reconnection on coupled system
3. Coupling – Sources of FAC and effects on coupled currents
4. Neutral and charged particle coupling – self – consistent incorporation of sputtering, pickup, and precipitation.

Point 4 is related to Dynamics
Existance of ionosphere: no importance of collision

Kabin, MHD model
Obstacle is a superconductive (sphere + cylinder), existence of two shock conviguartion
Possibilities to include heavy ions (quasi – MHD, multi fluid MHD, clamping ions)
Limitations og MHD

- no gyro effects
- no kinetic effects
- no multifluid or charge – separtion
- resisttivity and viscosity are numerical

Reconnection is pure numerical effects.

Advantages of MHD
- operation level of development
- GD and electro-magnetic effects are combined in a self-consisttent way
- Based on the conservation laws it must be correct

Assymetry in the subsolar density distribution.
Current system is similar to the earth. The intensity is even higher that at the earth. That is possible because of hogher dynamic pressure.

One can get from MHD
- reasonmabe first order description of the enviroment
- basis for the other models
- separte effects of external and internal mag. Field sources
- improve understanding of the magnetospheric responces – triggering of substrorms.

Mercury is a unique place to observed “unsual” shocj structures.
(Mats) Improving resolution: better cusp structure and current calculations, region structure does not change.
(Jim) MHD is very matured. MHD is approaching its physical assumption limits.
(Kabin) Resolution is an issue for turbulence studies. Next step is hybrid and kinetic. The real problem is analysis.

Kallio, Hybrid model
QNH model questions
- kinetic effects
    - large loss cone, non-Mxwellian distribution
    - finite gyroradius effects
- role of planetry ions
- particle – surface interaction

Problem is there is no the conservation of the energy and momentum. There is no theoretical background in comparison with MHD. An exploratory approach.

The grid is not adaptive.
Boundary conditions
- ions are away at he simulation box and Mercury surface (absorbing boundary)
- Ue = 0 at r < Rm
- No boundary conditions for B goes from faraday law

Source terms
- 3D neutral density
- Ionization: photo, CX
- emissions from the surface: Fully 2D

Reproduced good enough BS and MP position.
(Stas) Assymetries of the na+ distribution wrt Esw – similar to Mars
(Jim) Effect of the heavy ions on the magnetic field configuration. It is not clear.

(Mukai) The reason for the plasmasheet Na+ ions. E x B drift from the lobes.
(Kabin) The simulation box is limited for ONH wrt MHD. It may have an effect on the tail field configuration. Yes, correct (Esa)
(Kabin) It is time to compare two models, QNH and MHD.
Precipitation maps (only Bz): sw particles get inside magnetopause on open field lines, due to finite gyroradius get on the closed lines and start drifting and precipitate on the day side.
(Question) Where those particles come from? Need test particle approach.
Precipitation map (Parker): direct sw impact and closed line particles
(Jim) Importance of the inductive currents for the very high dyn. Pressure conditions. How the planet react? One should run the models for different conditions on the surface.
(Yamau) Impact of high energy particle on the surface? MeV particles hardly see the magnetosphere.
Development
Numerics:
3D – spherical, Liner for the plasma sheet
Minimum grid size: 0.05 (10^5 cells)
Time step: 0.01 – 0.001 s
Number of particles in a cell (30 ions)
Simulation box : +/- 4R)

Physics

- SW parameters eccentricity of orbit

Future plans

- multiple charged ions
- heavy ions (dust)
- neutral particles: ENAs
- exosphere

QNH summary

- global plasma parameters
- gives kinetics
- computationally expensive
- many unknown free parameters

(Rual) What guarantee energy conservations?
(Esa) Nothing. QNH may work or may not depending on the planet.

Lykyanov, Dynamical issues of ion dynamics
Substorm – a resistive tearing mode instability of the tail region. Magnetic field perturbations.
Dispersive kinetic Alfven waves propogation, dB ~10 nT, wave length 500 km, period ~2s
(Stas) Any wave generation in kinetic models?
(Jim) Large flux of protons precipitate already – one does not need wave to get even more. We know too little about Mercury to start to apply our magnetosphere knowledge on waves. The wave generation is very sensitive to the condictions which we do not

know.

Terada, Test particles in MHD fields
Modified MHD by Ogino et al. (1992, 1994), Very high Reynold numbers
Problem with interpolation (linera interpolation does not conserve adiabatic invariants) -> flux interpolation.

Mercury neutral line is located at –2Rm when Bz < 0 and moves to –5Rm depending on clock angle.

E = 30 mV / m near polar cap region, V ~Ve ^2, energy of the order of magntitude higher then DeCourt.

Ions emitted from the surface do not convect sunward and do no re-impact the surface.
The difference (MHD filed vs. analytical filed) is the field structure in the plasma sheet
(Jim) Analitical model corresponds Bz > 0 conditions (neutral line is far away from the planet). Should not be compared with Bz < 0 for MHD fields.

Bz > 0, reconnection occurs in the cusp region.

All exospheric ions are converted tailward.

Mercury magnetosphere shape is different from the earth

Mura, Proton circulations
(Question) Can Tsyganenko model be used for mercury simulation?
(Jim) For most of the time when the neutral line in the tail does not exist.

Jan Grosser, Induced magnetic fields
Glassmeier, 2000 first estimations of induction currents.
Magnetospheric current

- only magnetopause currents
- no tail current
- no ring current

(Jim)Tail current may approach the surface closely giving rise to an increase of 50 nT at the equator

mean surface intensity of the induced field of 4-8% of Bint.
Importance of the magnetic field distributions separations.

Manuel Grande, X-ray measurements at mercury
Origin and evalution of mercury, 3 models

- selective accretion
- post accretion vaporization
- giant impact

Lammer, Exosphere
P_exo = 10^-10 mbar

Surface release processes

- regolith diffusion, all
- solar wind H, he
- sputtering, Na, K, Ca, O
- photon stimulated desorption
- micrometeoroids

<u>Diffusion</u>
Thermal component
Gradient in mineral

Uncertanties related with sputtered yield

- surface binding energy
- composition
- porosity

(Peter) Importance of the Moon observations and research. Simpler and easier to reach

Need for more accurate magnetospheric models

Cremonese, Flux of meteoroid impact
First ground mercury observations in Europe
The model is for r > 1 cm
There is an asymmetry in the meteor flux distribution.

Wurz, Simulations of particle release
Thermal release

- only volatile: one needs a reservoir, diffusion, highly specific species
- dawn / dusk asymmetry
- stong function of surface temp.
- characteristic energy of release particle is low: low scale height

Micrometeor vaporization

- themp. 2500 – 5000 K
- acts on all elements: independent on diffusion, crater diamter 10 times impactor size, large par of ejects is gas
- operates everywhere: may be the only one on night –side
- time dependent process

PSD / electron SD

- acts only on specific spieces: Na, K, H2O, Sdiffusion to the surface
- dawn / dusk asymmetry
- function of UV flux: subsolar point
- characteristics energy of released particles is low: low scale height

Sputtering

- acts on all elements / species
- sputtered flux has the same composition as surface
- sputtered yields for H 0.1
- operates on day and night sides

Raul, Sputtering
Do ions alter the surface composition by inducing migration of Na?
Role of charge deposition
Is sputtering by H_2^+ the same as by $2H^+$
Is chemical sputtering important at high fluences?
Is the sputtered flux stoichiometric?
Why are protons more important than He?
What fraction of atoms are sputtered as ions?
What is the effect of the surface temperature?

3. Assessment of the Results

The aim of the workshop was to further the efforts of modeling Mercury's environment. Probably the most important contribution of this workshop toward this goal was to bring together scientists from three different fields: Mercury Magnetospheric-, Exospheric-, and Surface modeling. None of the scientists had detailed knowledge of all three of these fields, but the workshop provided an oppurtunity to learn about and meet scientists from these fields. The atmosphere of a small workshop at a remote location enables very open discussions and exchanges. For the future, I think all participants left the meeting with a better overview of the Mercury environment as a coupled system, and with good contacts with scientists from all the relevant diciplines. A continuation of this effort might be in the form of additional workshops in a couple of years, or a more formal network of scientists.

Ultimately, the success of the workshop depends on the knowledge, contacts, and impressions gained by the participants. Therefore we below present some comments made after the workshop by the participants:

Kiruna always seems to produce open and constructive dialog, and I learned a lot.

– Manuel Grande

The best thing about the workshop was the flexibility with complete freedom for questions. This served to bring up the essential unsolved questions.

– Raul A. Baragiola

The Mercury Workshop was extremely valuable to me because of the extremely interdisciplinary nature of the environmental science at this innermost planet. Real progress in the understanding of the surface, atmosphere and magnetosphere appear to be linked with advances in each. As with most participants, I am an expert in one of the three areas, somewhat knowledgeable in a second, and woefully uninformed (I realized as a result of the workshop) in the third.

To arrive at an optimum set of instruments on BepiColombo, as well as prepare for the scientific "harvest" once new measurements become available, my recommendation would be to hold additional workshops perhaps on an every second or third year basis to provide a forum of the exchange of ideas and the marking of progress in Mercury surface - atmosphere - magnetosphere science.

If this idea were widely supported, then I would be pleased to offer to host the next meeting here in the US -- much in the vein of the US-Finland Auroral Workshops in the late 1980's and 90's.

Again, thanks for the extremely useful and productive Mercury Workshop.

– Jim Slavin

I think that the workshop has been very interesting and stimulating on the works regarding the exosphere and magnetosphere of Mercury. It is very difficult to have meeting on specific subject and with a small number of partecipants because very often thay are representd on short section in wider conferences. Specific meetings allows to discuss, and maybe to understand better, in details the models avoiding to dilute too much the subject. Then they should stimulate the collaborations between people interested on the same specific subject, maybe that they have never met before. The small number of partecipants allows to have better discussion on every presentation without having big problems of time. The subject is very interesting considering the strong efforts of the major space agencies devoted to space missions to explore Mercury, according to specific requests of the scientific community. The modelling have to be considered well in advance with respect the to timing of the space exploration, in order to be ready to intepret the data will come.

I think it would have been interesting to include in the discussions and the presentations something regarding the exosphere and magnetosphere observations to be correlated to the models.

I like to say that was a pity not having time for a general discussion at the end of the meeting, it *would have been useful as startup for collaborations and for any further actions toward the EU. I mean further workshops or specific proposal to be submitted to the EU for funding in order to develope a new environment of scientists on Mercury.*

– Gabriele Cremonese

Program of the ESF Workshop in Kiruna, August 9-10, 2004

Monday

8:30	Bus leaves Kiruna from the hotels Vinterpalatset and Ferrum	
9:00	Registration	
9:15	Welcome and presentation of ESF	M. Holmström
	Messenger: Mission overview	J. A. Slavin
10:00	Coffe	
10:30	*BepiColombo MMO and empirical model of the magnetosphere*	T. Mukai
	Review of recent magnetospheric simulations	J. A. Slavin
12:00	Lunch	
13:00	*MHD modeling of the magnetosphere*	K. Kabin
	Hybrid modeling of the magnetosphere	E. Kallio
15:00	Coffe	
15:30	*MHD simulation and dynamics of single-particle trajectories in the Hermean magnetosphere: A comparison with analytical models*	N. Terada
	Simulations of proton dynamics	A. Mura
	A model of the Mercury environment	A. Lukyanov
18:00	Dinner at the Institute	
20:00	Bus to Kiruna	

Tuesday

8:30	Bus leaves Kiruna from the hotels Vinterpalatset and Ferrum	
9:00	*Induced Magnetic Field Effects at Planet Mercury*	J. Grosser
10:00	Coffe	
10:30	*X-ray science at Mercury*	M. Grande
	Flux of meteoroid impacts on Mercury	G. Cremonese
	Meteoroid-induced vaporization on Mercury	G. Cremonese
12:00	Lunch	
13:00	*The production of Mercury's exosphere environment*	H. Lammer
	Simulations of surface gas release processes	P. Wurz
14:30	Coffe	
15:00	*Sputtering Contribution to the Exosphere*	R.A. Baragiola
	Final discussions and conclusions	
17:00	Bus to activities in Jukkasjärvi	
19:00	Dinner	
22:00	Bus to Kiruna	

5. Final List of Participants

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6. Statistical information on participants

Age brackets
PhD and Post Docs: 4
Senior scientists: 18

Countries
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United Kingdom: 2
USA: 2
Switzerland: 2
Ireland: 1
Canada: 1
Germany: 1
Austria: 1
France: 1
Finland: 1