Discussion: *Where do we go from here?*

1. **Major science questions still remaining in the field**

C. Russell. The fundamental question of atmospheric evolution of Mars and Venus is not yet solved.

L. Zeleny. Earth should be added to this list.

S. Bougher. We need (1) to carefully identify where our knowledge is week or incomplete and (2) weight what we assume vs what we know.

S. Barabash. Below is the table with suggested key science questions and corresponding instrumentation and missions required to address them.

Science questions	Required instrumentation and mission
Extreme conditions What is the total instantaneous escape rate for the extreme conditions? What is the global magnetospheric response to the SW disturbances (space weather at Mars)?	Global imaging techniques and upstream monitoring - ENA - EUV - Soft CX X-ray Solar maximum (around 2025)
Acceleration processes How are ions extracted from the ionosphere? ("The first 2-eV problem")	Low altitude orbits Low energy ion and electron detectors Spacecraft potential control
Mass composition What is the nitrogen escape rate?	CNO mass resolution

B. Jakosky. One can also consider measurements of carbon escape as one of the key specific questions in the field. However, the biggest concern is how to convince the planetary community and especially space agencies to put money into a mission. This required putting forward a really fundamental question that would address a "big picture" in the planetary physics.

A. Nagy. Indeed, the planetary community is dominated by geologists and surface scientists, that make very difficult to sell an aeronomy mission. We need to carefully select a theme. For instance, this could be "escape on magnetised vs unmagnetised planets".

I. Dandouras. The plasma community was very disappointed by ESA non-selecting any of plasma or aeronomy missions in M4 and M5 Calls.

D. Brain. We should make the best science case to convince the planetary community that aeronomy studies are of key importance for understanding of the Solar System as a whole as well as individual bodies and their evolution. A "whole system" multi-disciplinary approach should unify the community.

O. Vaisberg. A concept of Roscosmos-NASA mission to Venus (Venera-D) is currently under development. The mission will potentially have an aeronomy payload.

R. Lillis. Small satellites concept are being developed by both ESA and NASA. NASA looks for science questions that can be addressed by this type of missions. Specifically there are three different proposal teams for the upcoming NASA SIMPLEX-II call for interplanetary small satellites, who are planning to make multipoint measurements of the Martian plasma environment.

F. Gonzalez-Galindo. Modelling of escape processes is very complex. Knowledge of the thermospheric parameters should be improved. Also communication between escape and paleoclimate studies and communities should be strengthened.

M. Chaffin. Two outstanding questions: (1) coupling between the lower and the upper atmosphere that can be addressed either by combination of small and medium missions operating simultaneously, or by a single complex mission; (2) aeronomy of ice giants that is virtually unexplored field.

S. Brecht. (1) It would be important to study the flow of solar wind energy through the shock into the "magnetospheres" of Mars and Venus as compared to the Earth. Those shocks and the plasma behind them serve as a lens that can focus or defocus energy. Certainly, in the Earth system there is focusing going on in the cusps and the tail structures. Earth 3D MHD modelling suggested reconnection of the magnetic field lines where the Poynting flux focused.

(2) We should address the processes involved in energy transport between different regions of the "magnetosphere"/atmosphere/surface. Study of the couplings is extremely important for understanding of how the entire system works. While some of these issues are under investigation in MAVEN, MEX and such many are not.

(3) The discussion centered on determining past conditions on the various planets and even the sun. I would argue we should be focusing on the future and where these systems are going. That is of crucial importance to human beings. The models, the understanding, and the knowledge are not in place to provide accurate projections of an uncertain future.

Ch. Dong. The effects of exoplanetary space weather and stellar wind-induced atmospheric loss on planetary habitability deserve further investigation.

A. Ocampo. (1). Important is that we are a science family working together for the exploration of the Solar System. And multilateral dialogue should be encouraged by all the Agencies. (2). It would be interesting to discuss the possible triggering mechanism for the Martian dust storms and if there any influence or connections to the solar wind.

2. **How the key science questions should be addressed? (missing measurements? Space missions? models?)**

C. Russell. A breakthrough can be achieved by bringing back samples of rocks and atmospheres from Venus and Mars. Also essential would be magnetic field measurements on the surface of these planets.

Y. Ma. Multipoint measurements would be very desirable to study transient phenomena and to constrain models.

S. Barabash. Various imaging techniques could make a good job in continuous monitoring of interaction with the solar wind and escape processes on the planets.

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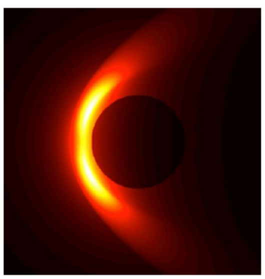
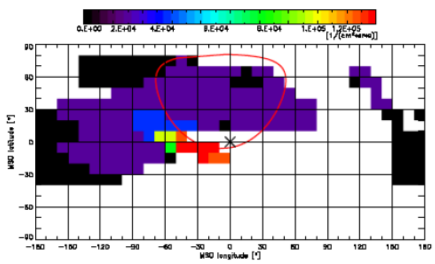
Introducing global imaging techniques at Mars. Efter MAVEN

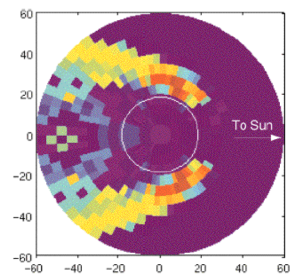
- ENA imaging of the magnetospheath plasma (hydrogen) and planetary ions (oxygen) to instantaneously define the escape region.
- X-ray imaging (charge - exchange x-rays) of the induced magnetosphere shape
- EUV imaging (30.2 nm, HeII) of the escaping plasma (He^+ and possibly CO_2^+)
- UV auroral imaging of the plasma entry into the atmosphere



CX X-ray image (simulations, Mats Holmström)



Hydrogen ENA image (MEX, Galli et al., 2008)



Oxygen ENA image (simulations, Barabash et al., 1996)

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S. Brecht. It would seem that the Swarm mission can in fact measure Poynting flux as well as neutral atmospheric heating from ionospheric flows. Similar mission should go to Venus or Mars as there is certainly numerical evidence that making small changes in the shock location can change what happens around the planet. Further as a "sales point" with the Earth's dipole indicating a significant reduction in magnitude and eventual flip, it is likely that Earth will resemble either Venus with no field or Mars with just quadrupole moments left. These two planets and the ionosphere/atmospheres will provide us a glimpse of the future.

J. Luhmann.

(1). No planetary aeronomy or aeronomy effects timeline can be reconstructed without the history of the Sun and of the planets' solid bodies and main atmospheres. Even though we compete with other missions investigating these matters we need them to make progress.

(2). Revisiting aeronomy impacts on 'Earth as a Planet' is a theme ripe for a mission. In particular, making a mission that can sample truly escaping ions far down-tail could be compelling and upstream solar wind monitors and solar observations are regularly available for Earth. (Orbits within the magnetosphere and upper atmosphere are good for ion energization process studies but are always ambiguous regarding escape fluxes).

R. Boumghar.

(1). One might think about possibilities offered by the Frontier Development Lab (http://frontierdevelopmentlab.org/) that gather researchers in AI and in science to join forces and tackle space challenges solving them with AI solutions. I will be co-mentoring the space weather challenge there and I hope to come back with interesting insights to share with you all.

(2). Observations of plasma phenomena would need a fleet of flying payloads not just one spacecraft. Multipoint quasi-simultaneous measurement is essential to build models. And once data is acquired, machine learning can be of great help.

(3). The issue of communication between scientists definitely requires attention. Research gate project, open access journal, open data, slack channels, dedicated ESA (or any other space agency) webpages – all these are the tools enabling interaction with communities.

3. Are current models in sync and agreement with available measurements?

R. Modolo. Current models provide good and consistent results in agreement with measurements. Modelling of transient events would require definition of more realistic conditions based on multi-spacecraft measurements. There is a need in extensive databases of plasma environments at various conditions.

R. Lillis. (1) Laboratory measurements should provide input parameters for the modelling (reactions cross-sections, for instance). (2) Solar evolution and history is quite uncertain. It can be improved by measuring isotopes in lunar samples (as once suggested by J. Luhmann).

S. Brecht. The need for far more information is developing as computers and our models become more sophisticated. The overall science questions about "energy and mass flow" have been a motivator in the past. But, the ability of spacecraft have improved greatly and the need for detail has exploded. It is no longer acceptable to simply draw a Dungey picture of the Earth's magnetosphere and claim we know what is necessary for understanding of our planet. Similarly, it is no longer good enough to use Larry Brace's cartoon of tail rays and say we have Venus understood.

J. Luhmann. Almost all of our models of plasma interactions and aeronomical processes are carried out for steady state or quasi-steady conditions. Time dependent phenomena are ubiquitous in nature and we have not yet done a good job at investigating the importance of processes and process responses to transients e.g. solar wind current sheet and shock passages, solar flares of all sizes, storms, lightning discharges, dust impacts, tectonic activity, etc. Such processes do not always fall in what we would call the 'extreme' category, instead making ongoing contributions we have not yet evaluated.

4. **Relation of the aeronomy/ plasma investigations at Mars, Venus and Earth**

A. Nagy. On Pioneer-Venus both some instruments and teams had connections to Earth aeronomy investigations.

R. Floberghagen. The SWARM mission has loose connections to the Venus / Mars missions and communities.

S. Barabash. Isn't it strange that the Earth community seems to care little about escape at Earth, despite of that the loss rates are by order of magnitude larger than those at Mars and Venus?

B. Jakosky. The likely reason is that escape does not significantly affect Earth total volatile inventory.

I. Dandouras. Originally the Earth community was mainly interested in sources of material in the Earth magnetosphere. Now the focus shifts to the study of escape processes, as a series of recent publications and the ESCAPE mission proposal show.

D. Brain. Even if escape on Earth has little effect on volatiles and climate on our planet, its study is important for understanding of escape processes on other planets. Thus, the planetary community should tighten contacts with the colleagues in Earth aeronomy. Also one could think about re-using instruments from the Earth aeronomy satellites.

S. Barabash. It is very efficient to use the same instruments at different planets. A serious worry, however, is that ESA planetary missions are not sufficiently frequent to ensure sustainability of aeronomy research.

S. Bougher. Models of the couplings between lower and upper atmospheres could be a good area for collaboration between Mars/Venus and Earth aeronomy research.

5. Do we know our Sun and solar wind well enough?

J. Luhmann. Two possible observation strategies could improve our knowledge of the present sun and solar wind: (1) spatially distributed "heliospheric observatory" for continuous monitoring of the solar wind and (2) space environment monitors at several planets.

6. Future meetings and conferences

S. Barabash. It's time to have a workshop focused on the role of intrinsic magnetic field in the planetary evolution.

A. Nagy. Future meetings on planetary aeronomy should include stronger participation of the terrestrial community. A possibility of using ISSI workshops should be also investigated.

L. Zeleny. Cometary type of interactions should be also included in the programme of future meetings.

H. Opgenoorth. MUAN offers a good platform for informal meetings on at least upper atmosphere and aeronomy of Mars. The 10th meeting of MUAN is tentatively scheduled on Cyprus in October 2018.

A. Burrell. It may be a good idea to have a summer school for planetary aeronomy, like, for instance, a NSF Pan-American Advanced Studies Institute program summer school on the dynamics and chemistry of the upper atmosphere. A similar summer school could do a lot to engage researchers from many different career stages.