High energy particles at Mars and Venus: Phobos-2, Mars Express and Venus Express observations and their interpretation by hybrid model simulations

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⇒ (o HYB global kinetic planetary plasma simulation platform

Introduction

Mars and Venus can be reached by Solar Energetic Particles (SEPs). Such high energy particles (protons, multiply charged heavy ions, electrons) can penetrate the upper atmospheres of Mars and Venus because, in contrast to Earth, these bodies do not have a significant, global, intrinsic magnetic field to exclude them.

In the present work we present SEP events measured at Mars and Venus based on Phobos-2, 1989 data and on, more recent, MEx and VEx (particle background) observations. We further introduce numerical global SEP simulations of the measured events based on 3-D self-consistent hybrid models (HYB-Mars and HYB-Venus). Through comparing the in situ SEP observations with these simulations, new insights are provided into the properties of the measured SEPs as well as into how their individual planetary bow shocks and magnetospheres affect the characteristics of the ambient Martian and Venusian SEP environments.

Energetic Particle Model

Energetic particles are treated self-consistently within the particle-in-cell HYB model as macroparticles. Small timestep requirements by the fast particles are satisfied with substepping particle propagations where necessary, allowing for proton energies in the MeV range. The energetic particle distribution is characterized by an energy distribution (eg. a power law) and a pitch angle distribution (eg. Gaussian, isotropic), as displayed in Fig.1.

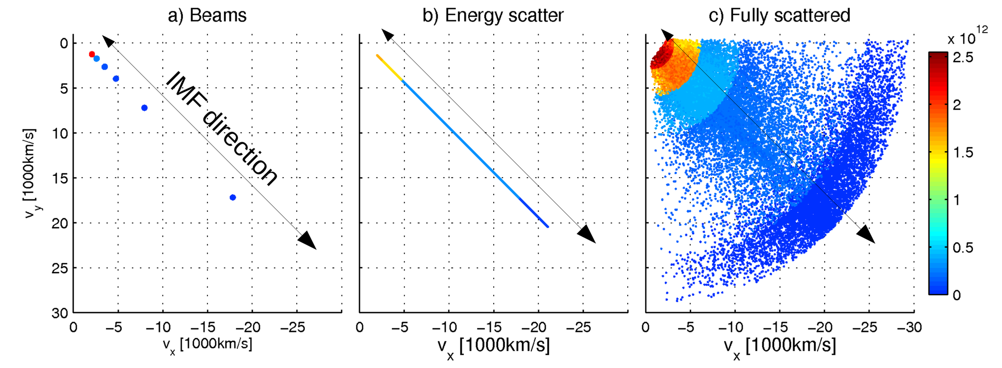


Fig.1: Energetic particle distribution examples in HYB. a) Beams in velocity space b) A unidirectional beam with a power law distribution c) Gaussian pitch angle distribution, including a power law E distribution

Phobos-2/SLED

One especially well documented, complex and prolonged SEP took in place in early 1989 (Solar Cycle 23) when the Phobos-2 spacecraft was orbiting Mars. This spacecraft had a dedicated high energy particle instrument onboard (SLED), which measured particles with energies in the keV range up to a few tens of MeV. There was in addition a magnetometer as well as solar wind plasma detectors on board which together provided complementary data to support contemporaneous studies of the background SEP environment. Fig.2 displays a case study on one orbit of this event.

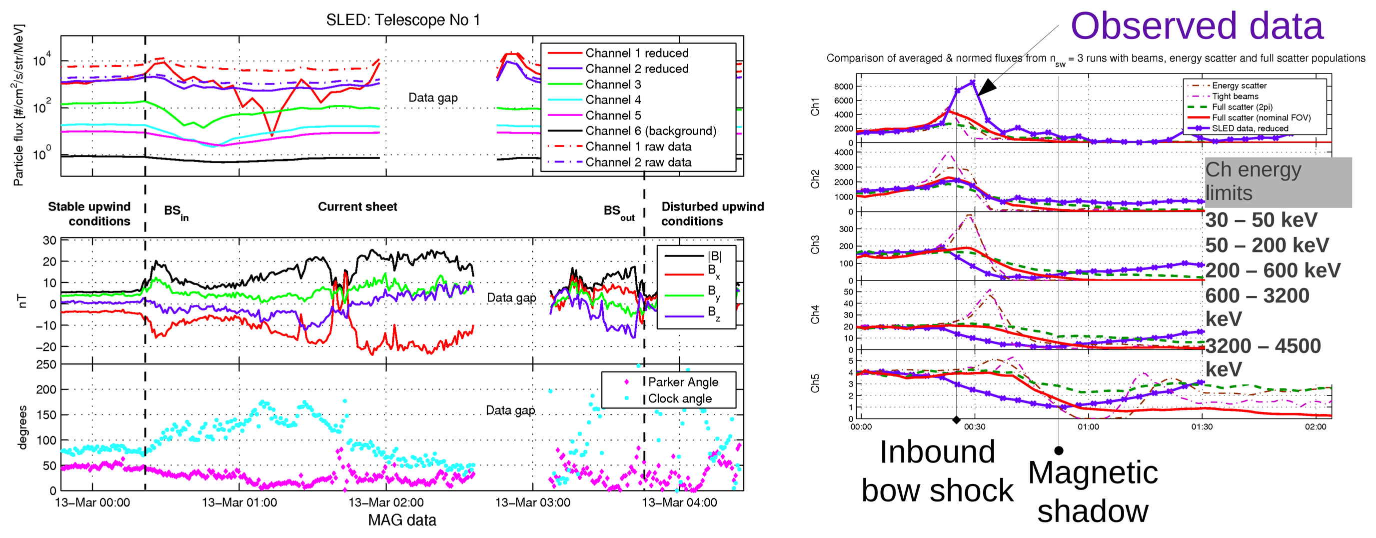


Fig.2: Phobos-2/SLED observations and simulated data with different distributions and simulated apertures, from [1].

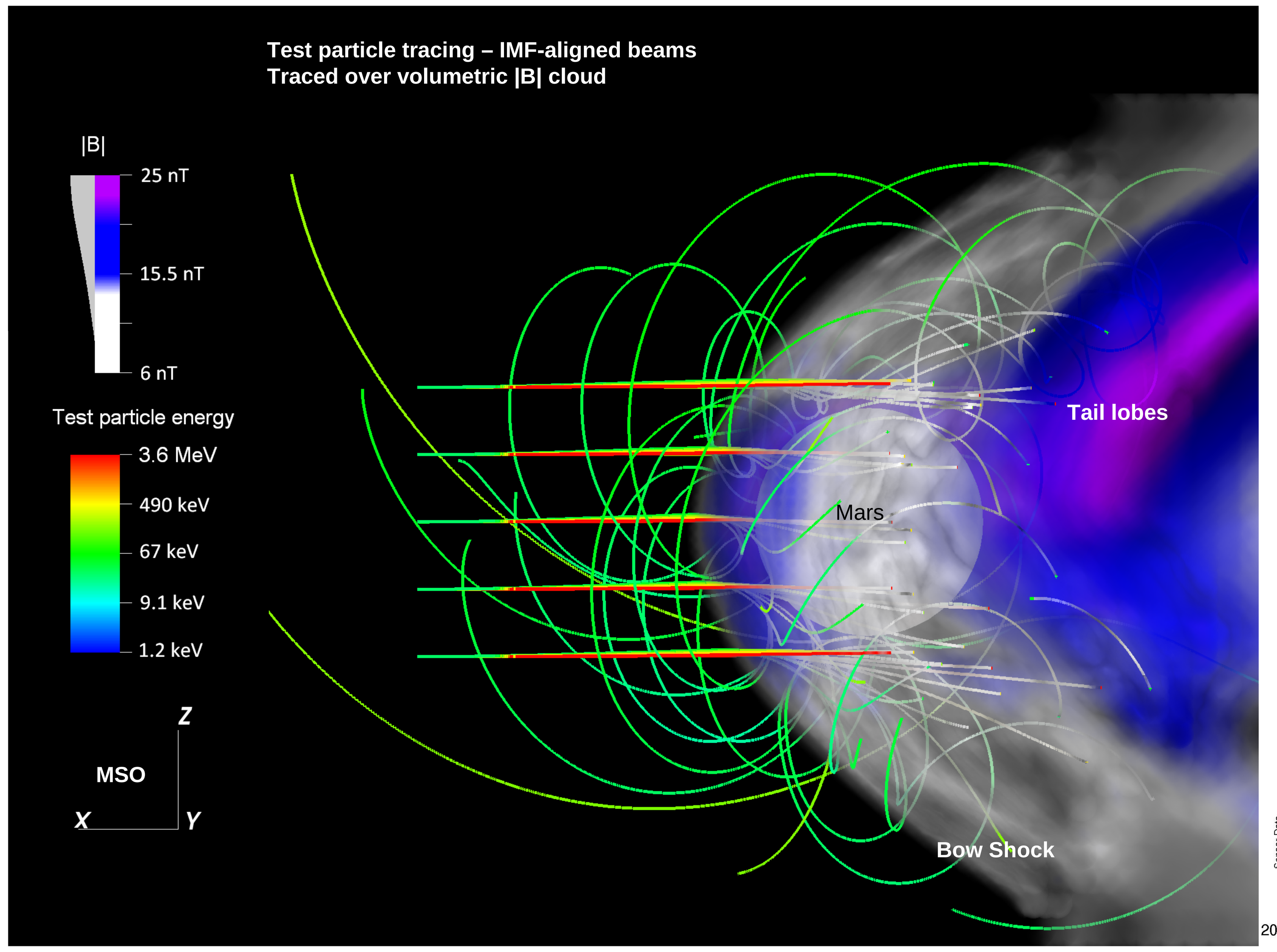


Fig.3: Test particle traces of 30keV (green) to 3.2 MeV (red) protons shot along the IMF (45deg Parker angle) in the Martian plasma environment. Notice the complex trajectories produced by the lowest end of the energy spectrum. High-energy ions are relatively unaffected by the induced magnetosphere.

Mars and Venus Express

Currently, while the Sun is displaying maximum activity (Solar Cycle 24), Mars and Venus are being individually monitored by instrumentation flown onboard the Mars Express (MEX) and Venus Express (VEX) spacecraft. Neither of these spacecraft carry a high energy particle instrument but their Analyzer of Space Plasmas and Energetic Atoms (ASPERA) experiments (ASPERA-3 on MEX and ASPERA-4 on VEX), can be used to study SEPs with E ≥ 30 MeV which penetrate the instrument hardware and form background counts in the plasma data.

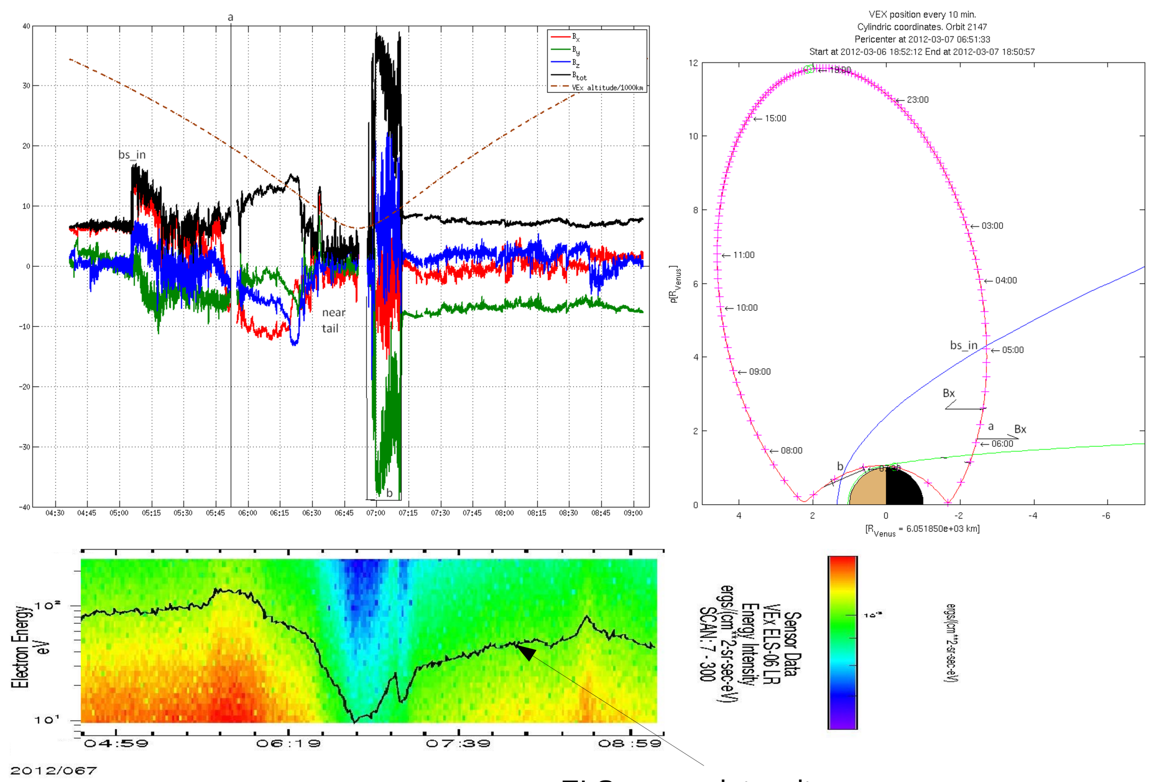
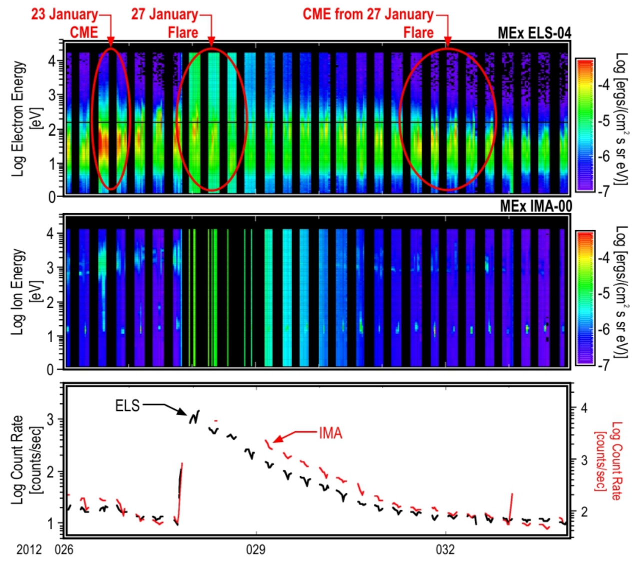


Fig.4: Venus Express observations on the 7.3.2012 energetic particle event (that blacked out eg. the VEx ASPERA/IMA instrument). The ELS signal contains an energy-independent signal due to penetrating radiation by solar energetic particles. Dynamic upwind conditions create a challenging modeling case – in particular in the outbound phase with a flow-aligned IMF.
SEP signal roughly corresponds to an isotropic SEP distribution.

Fig.5 (right)**:** MEx observations of the 27.1.2012 flare and gradual SEP event [2]. ELS and IMA instruments (top two panels) display significant background contamination (background counts on the lowest panel) by the gradual SEP event. The background counts are modulated along the orbit due to shadowing by the planetary environment.
The lack of a magnetometer aboard the spacecraft the direction of IMF, and thus the streaming direction of the energetic particles remains a free parameter in modeling.



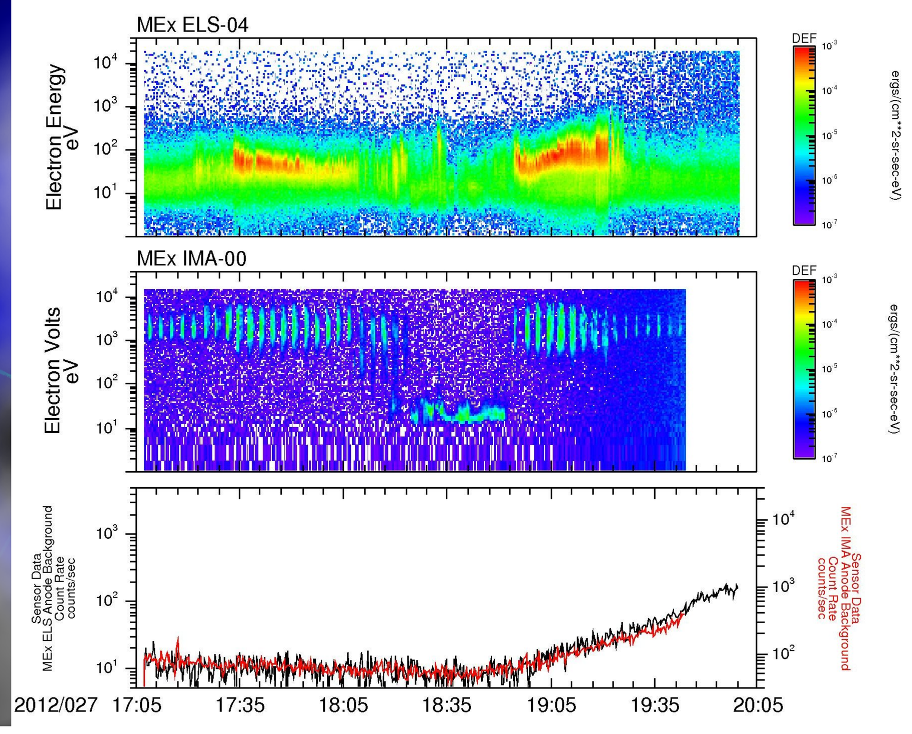


Fig.6 (left)**:** Mars Express observations on the onset of the 27.1.2012 flare and gradual SEP event (corresponding to the steepest rise in fig. 5). The spacecraft emerges from beyond the planetary shadow just before SEP arrival. SEP arrival is seen in both IMA and ELS instruments (two top panels) as an exponential rise in energy-independent background counts (lowest panel).
The gradual event dominates the background counts for most of the duration of the event, displaying a planetary shadow repeatedly (as seen in Fig. 5).

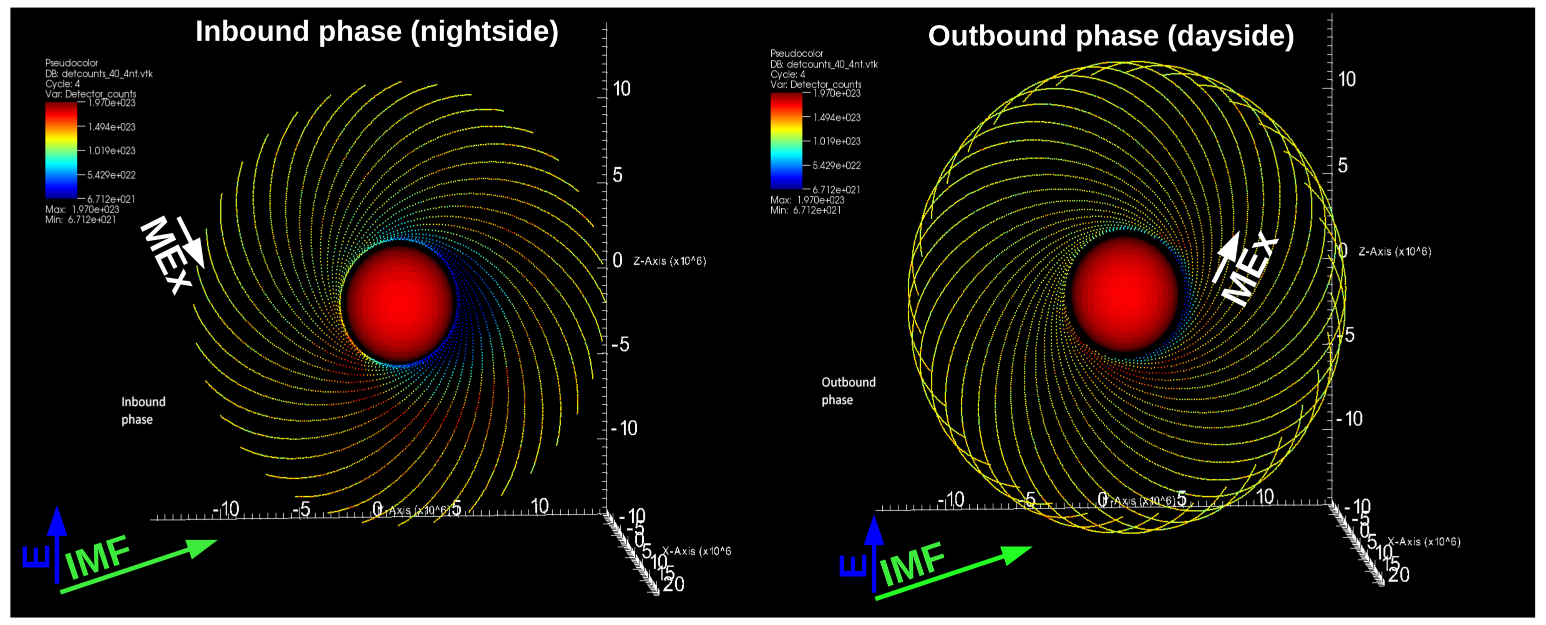


Fig.6: Simulated counts of energetic particles in the SLED energy range on Mars Express orbit corresponding to the 27.1. event orbit above, inbound and outbound phases separated. The actual orbit in MSO coordinates is annotated by the MEx arrows; other orbits correspond to rotations of the orbit around X axis in 10 degree intervals, giving, firstly, a better spatial sense of the SEP flux, and secondly, since the model is cylindrically symmetric around the X axis, a full sampling over IMF clock angles. Location of the SEP shadow (blue) is determined by the IMF direction. Flux enhancements (red) coincide with the bow shock, and are prominent on the lowest energy part of the distribution. An ad hoc Gaussian pitch angle distribution was used for the energetic particles, with a set of nominal solar wind parameters.

Conclusions

We have developed tools and methods for integrated SEP modeling and analysis within the HYB hybrid model. *Phobos-2*, *Venus* and *Mars Express* data has been used in conjunction with the model. The model will be well suited for interpretation of future SEP observations with eg. the *MAVEN* spacecraft.

References

[1] Kallio, E. et al, Energetic protons at Mars: interpretation of SLED/Phobos-2 observations by a kinetic model, Ann. Geophys., 30, 1595-1609, 2012, doi:10.5194/angeo-30-1595-2012
[2] Frahm, R. A. et al, Solar Energetic Particle Arrival At Mars Due To The 27 January 2012 Solar Storm, Solar Wind 13, AIP Conference Proceedings Series, 2013, accepted.

HYB model website: http://hwa.fmi.fi/hyb/ - including a more thorough model description

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