Towards realistic models of interplanetary transport of solar energetic particles

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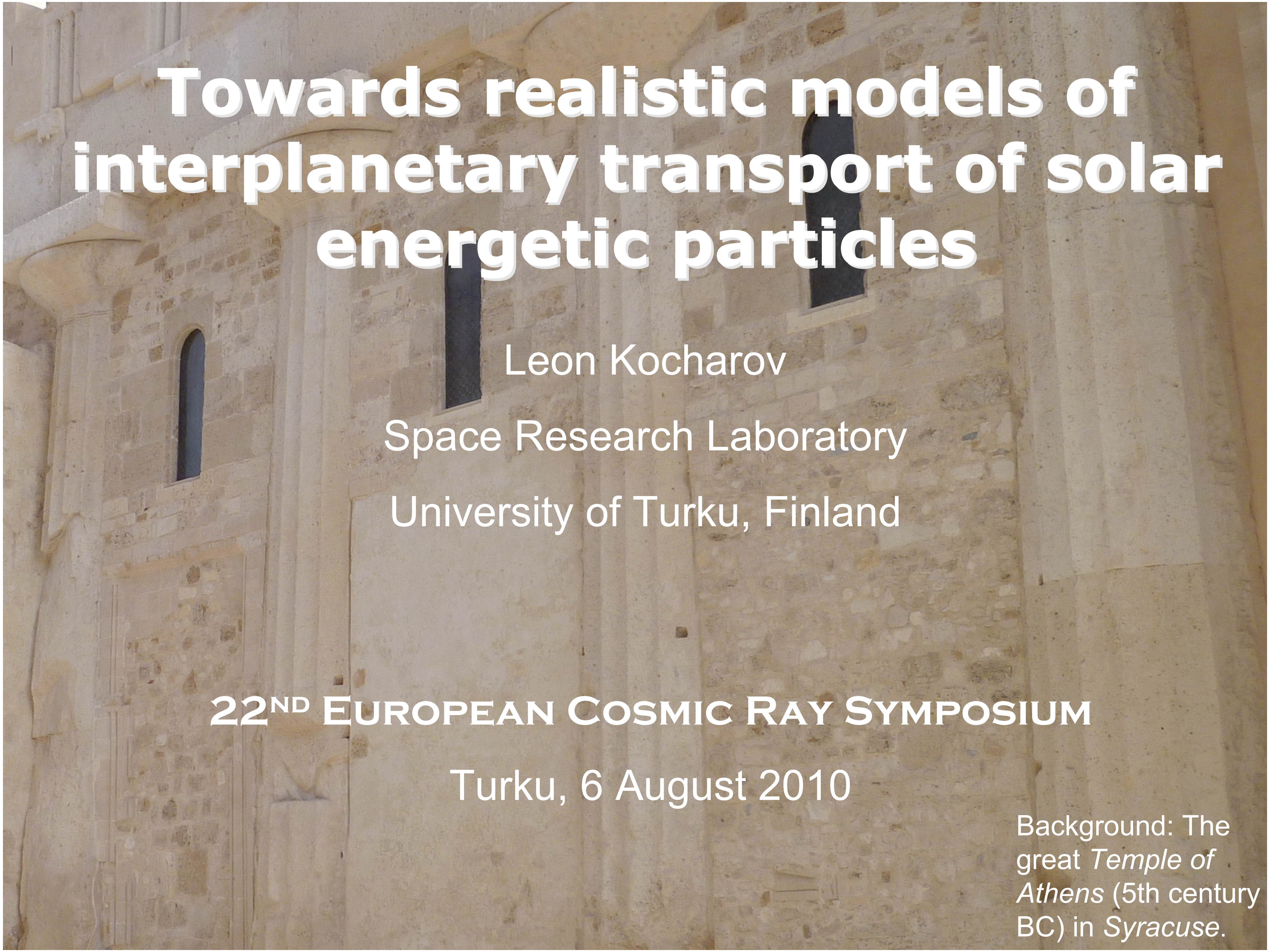
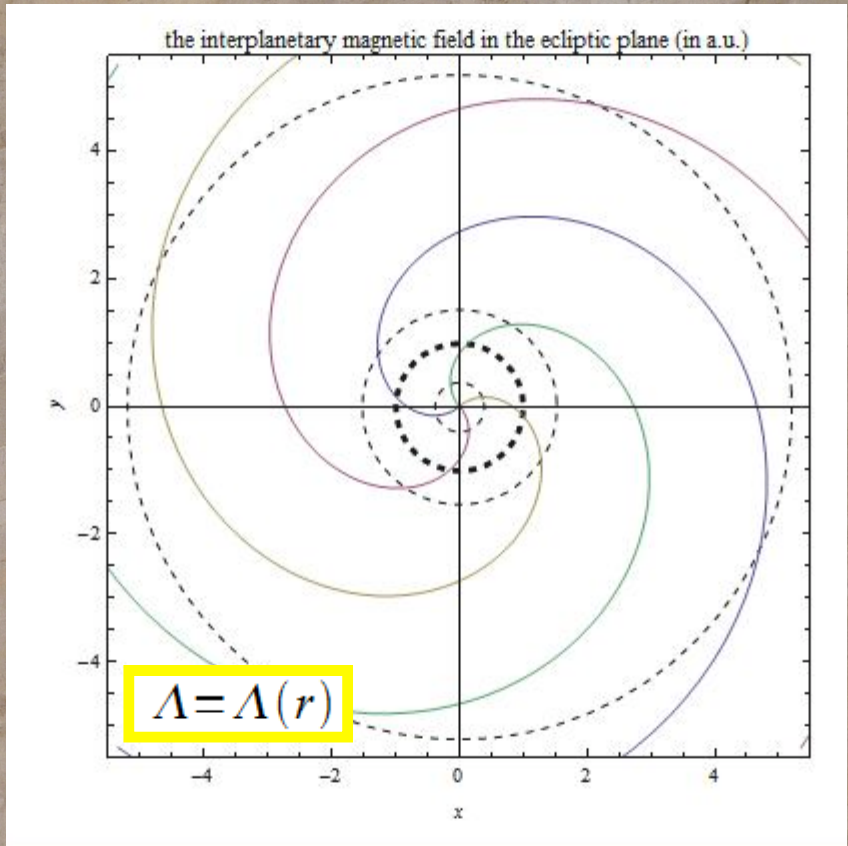
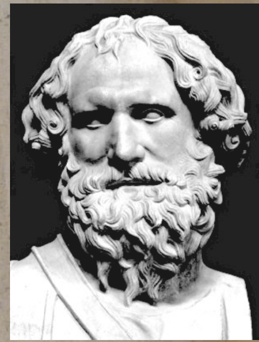


Background: The great *Temple of Athens* (5th century BC) in *Syracuse*.

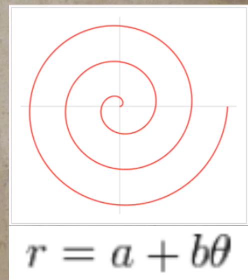
Standard SEP transport model



Classic model of the interplanetary magnetic field (E. N. PARKER, 1958): IMF lines of *Archimedean spiral* shape.



Archimedes of Syracuse (287-212 BC)



Background: The great *Temple of Athens* (5th century BC) in Syracuse.

SEP transport in impulsive events

THE ASTROPHYSICAL JOURNAL, **225**:281–303, 1978 October 1

Z-RICH SOLAR PARTICLE EVENT CHARACTERISTICS 1972–1976

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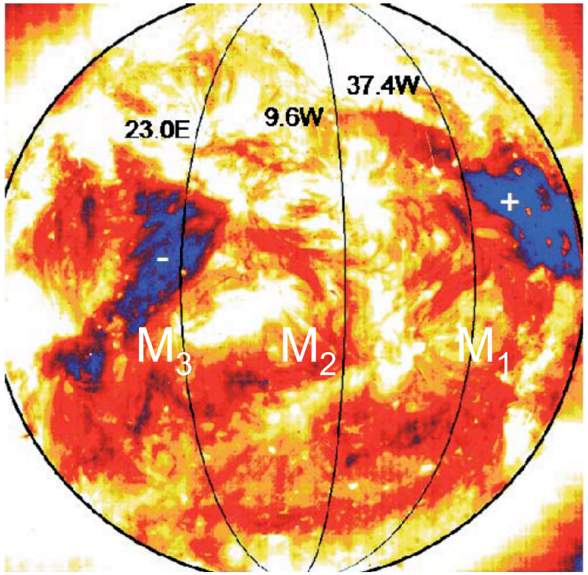
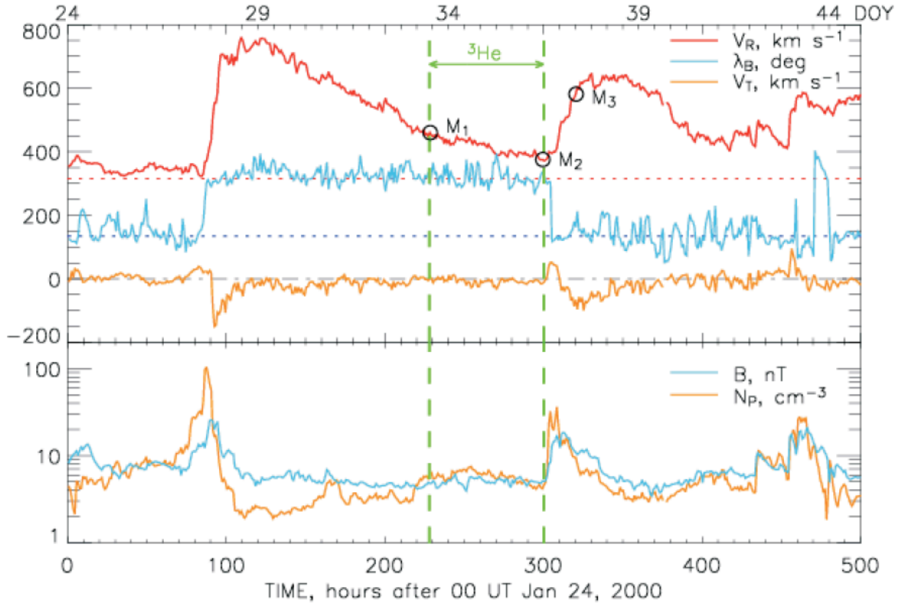
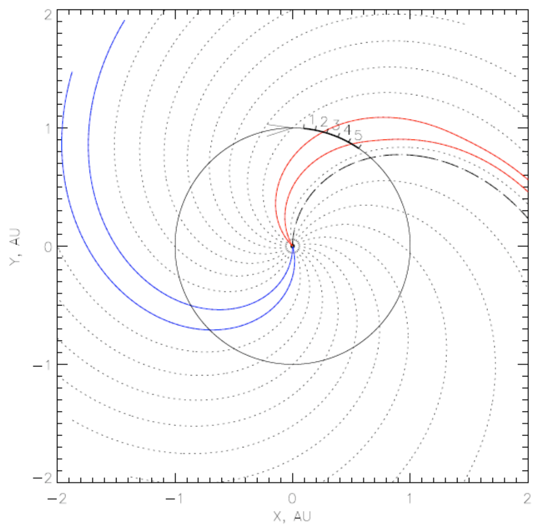
ABSTRACT

A systematic analysis of the hourly average $Z \geq 3$ rate data (1972 September–1976 December) measured with the JHU/APL *IMP 7* and *IMP 8* detectors has revealed 13 short-lived events that have greatly enhanced $Z \geq 3$ fluxes. In addition to confirming the results of earlier studies that all ^{3}He-rich events are Fe-rich but not vice versa, we find that these 13 enriched events have several remarkable characteristics: (1) they are generally not associated with *major* solar flares but appear to be associated with low levels of activity (subflares) in western-hemisphere solar active regions that are located very close to the spacecraft's high coronal interplanetary magnetic field connection longitude; (2) they have very large and prolonged outward streaming anisotropies, sometimes persisting ~1 day; (3) the spectral indices measured for p, α, and $Z \geq 3$ particles during the times of maximum flux for the *Z*-rich events are identical within errors to those measured in large flare events, while small impulsive and corotating events generally show a softer spectrum; and (4) *Z*-rich events appear to be associated with the low-speed wind that precedes the onset of solar wind streams. We conclude from this study that the same type of acceleration process that is responsible for the large proton events is responsible for the small *Z*-rich events, and therefore that the $Z \geq 3$ and ^{3}He enrichments are more likely due to enhanced abundances in the preaccelerated plasma than to preferential enrichment during the acceleration

Coronal and solar wind structures associated with ^{3}He-rich SEP events



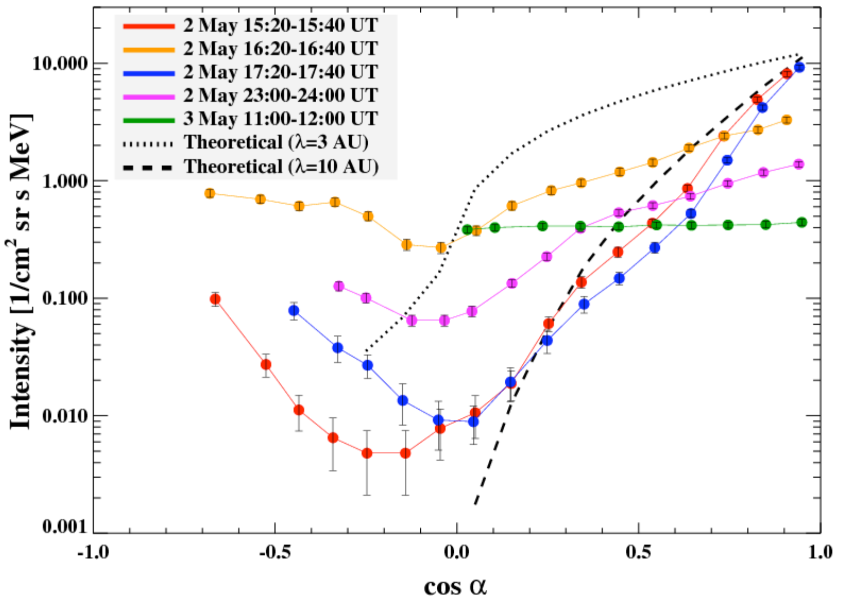


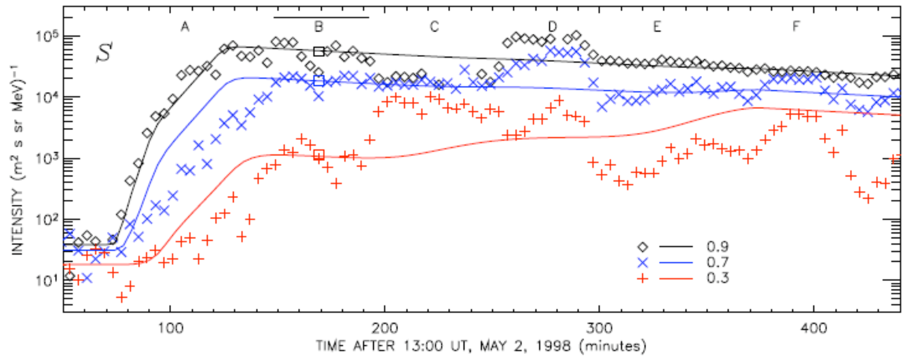


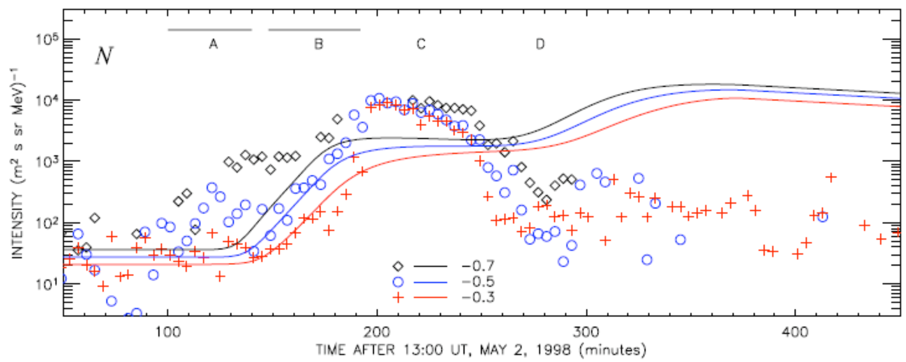
Kocharov, L., Laivola, J., Mason, G. M., Didkovsky, L., and Judge, D. L.: 2008, Extended ^{3}He-rich periods of solar energetic particles in structured solar wind.- *Astrophys. J. Suppl.*, **176**, 497-510.

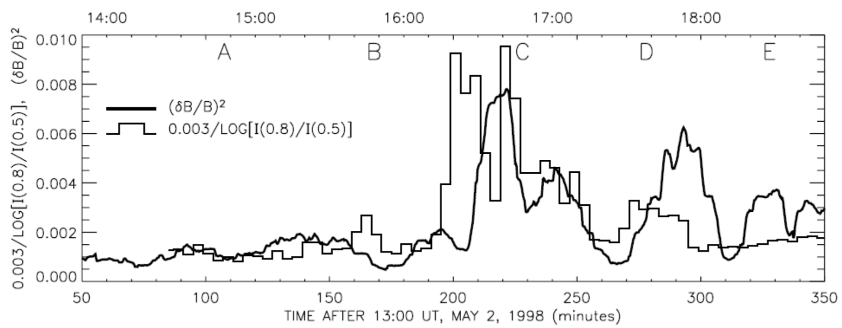
SEP transport in gradual events

SEPs inside magnetic cloud of a previous ICME: The 1998 May 2 event







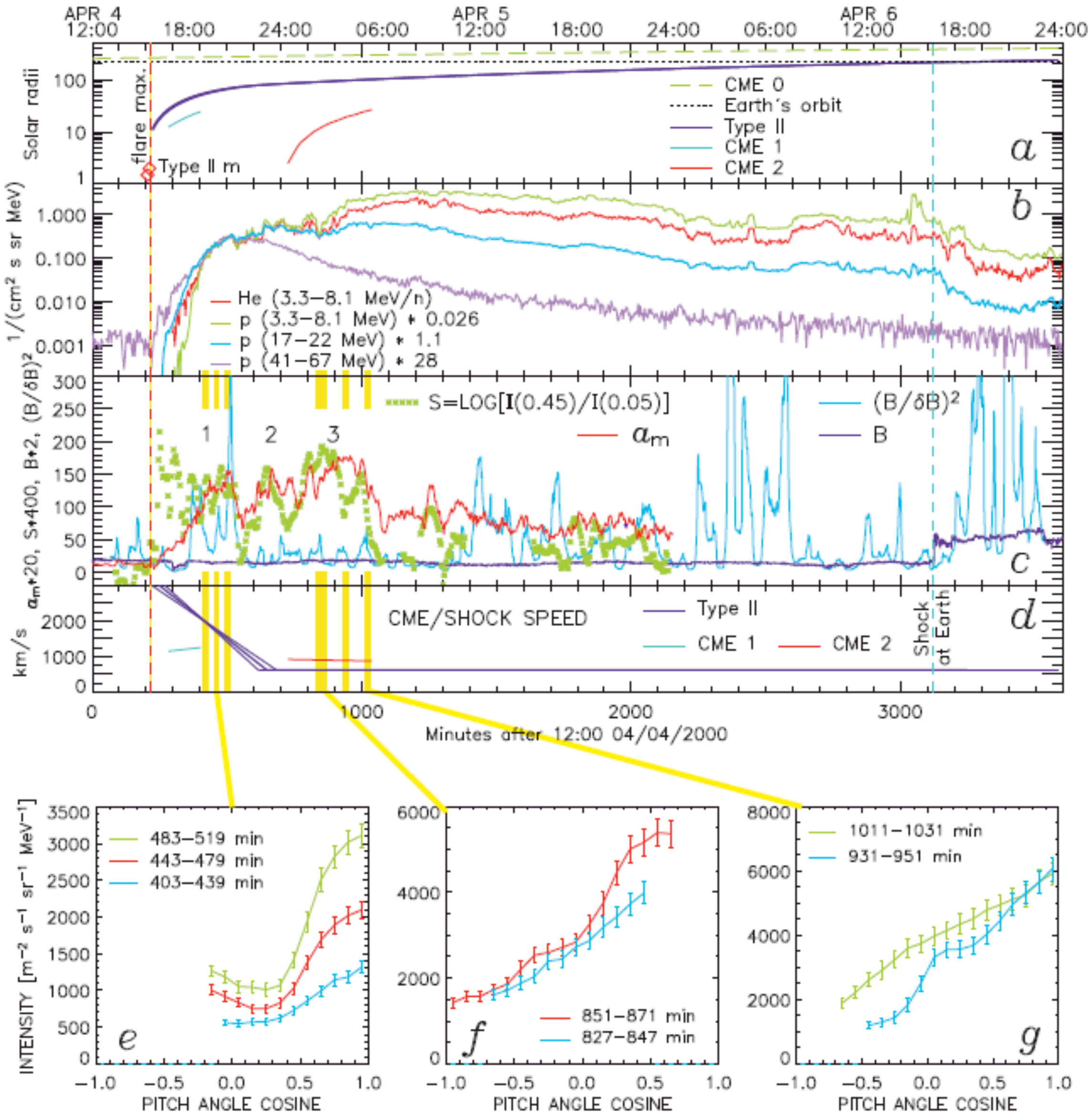


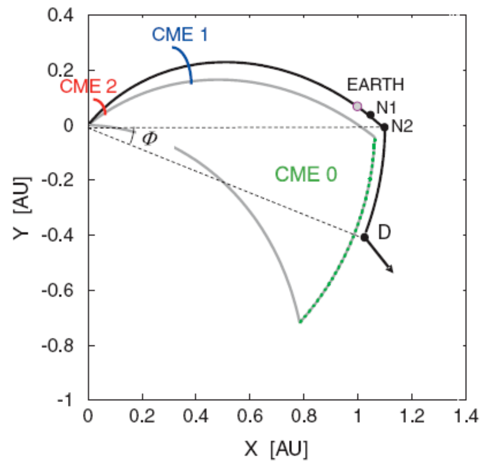
Torsti, J., Riihonen, E., and Kocharov, L.: 2004, The May 2-3, 1998 magnetic cloud: An interplanetary “highway” for solar energetic particles observed with SOHO/ERNE.- *Astrophys. J. Letters*, 600, L83.

Kocharov, L., Saloniemi, O., Torsti, J., Kovaltsov, G., and Riihonen, E.: 2007, Scanning an interplanetary magnetic cloud using high-energy protons.- *Astrophys. J.*, 654, 1121.

SEP transport in gradual events

SEPs in vicinity of a previous ICME: The 2000 Apr 4 event

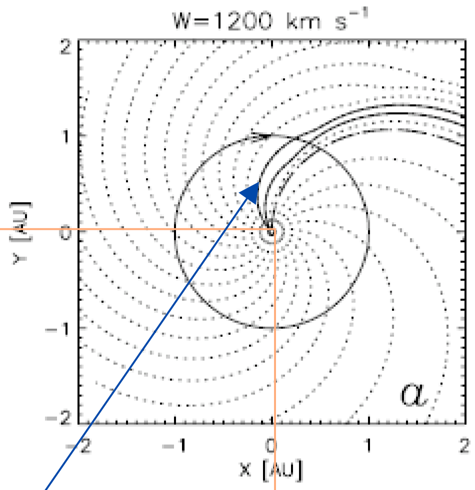




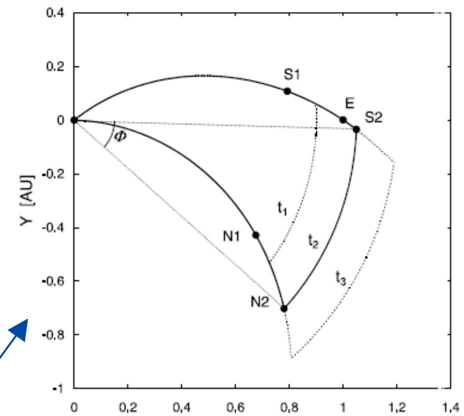
Kocharov, L., Laitinen, T, Al-Sawad, A., Saloniemi, O., Valtonen, E., and Reiner, M. J.: 2009, Gradual solar energetic particle event associated with a decelerating shock wave.- *Astrophys. J. Letters*, 700, L51.

Practical transport models for analysis of *SOHO*/ERNE data

J. Torsti, E. Valtonen, et al. 1995, Sol. Phys., **162**, 505

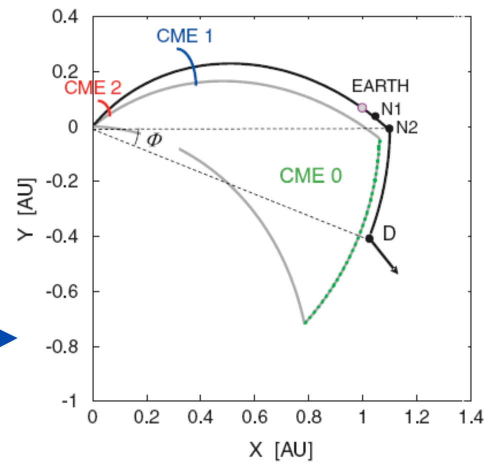


Kocharov, L., Vainio, R., Torsti, J., Kovaltsov, G. A.: 1998, Adiabatic deceleration of solar energetic particles as deduced from Monte Carlo simulations of interplanetary transport.- *Solar Physics*, **182**, 195-215.



Kocharov, L., Kovaltsov, G. A., Torsti, J., Anttila, A., and Sahla, T.: 2003, Modeling the propagation of solar energetic particles in corotating compression regions of solar wind.- *J. Geophys. Res. - Space Physics*, **108**, No. A11, 1404 [the analytical MHD model by J. Giacalone, J. R. Jokipii, and J. Kóta: 2002.- *Astrophys. J.*, **573**, 845]

Kocharov, L., Kovaltsov, G. A., Torsti, J., and Huttunen-Heikinmaa, K.: 2005, Modeling the solar energetic particle events in closed structures of interplanetary magnetic field.- *J. Geophys. Res. - Space Physics*, **110**, No. A12, A12S03.



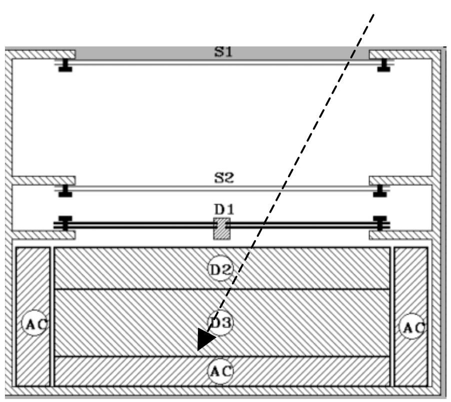
L. Kocharov, T. Laitinen, A. Al-Sawad, O. Saloniemi, E. Valtonen, and M. J. Reiner: 2009, *ApJL*, **700**, *L51.*

ERNE
University of Turku

A realistic model intends to meet the following **requirements**:

- Allow observers to fit intensity-time profiles and pitch angle distributions of high-energy particles and to understand what is observed in different events.
- Allow the energetic particle modeling in realistic interplanetary magnetic field structures.
- Be ready to accommodate the numerical MHD input.
- Account for (highly) variable scattering conditions.
- Provide extensibility for more sophisticated event scenarios.

J. Torsti, E. Valtonen, et al. 1995, Sol. Phys., **162**, 505



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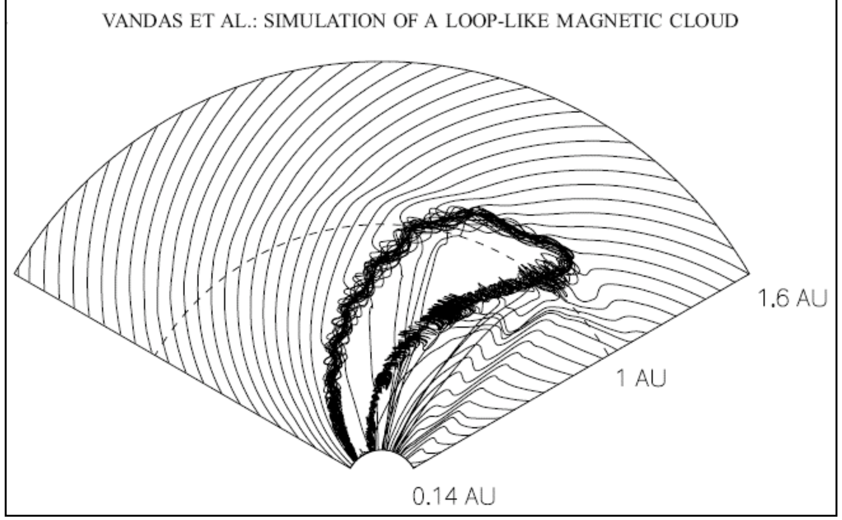


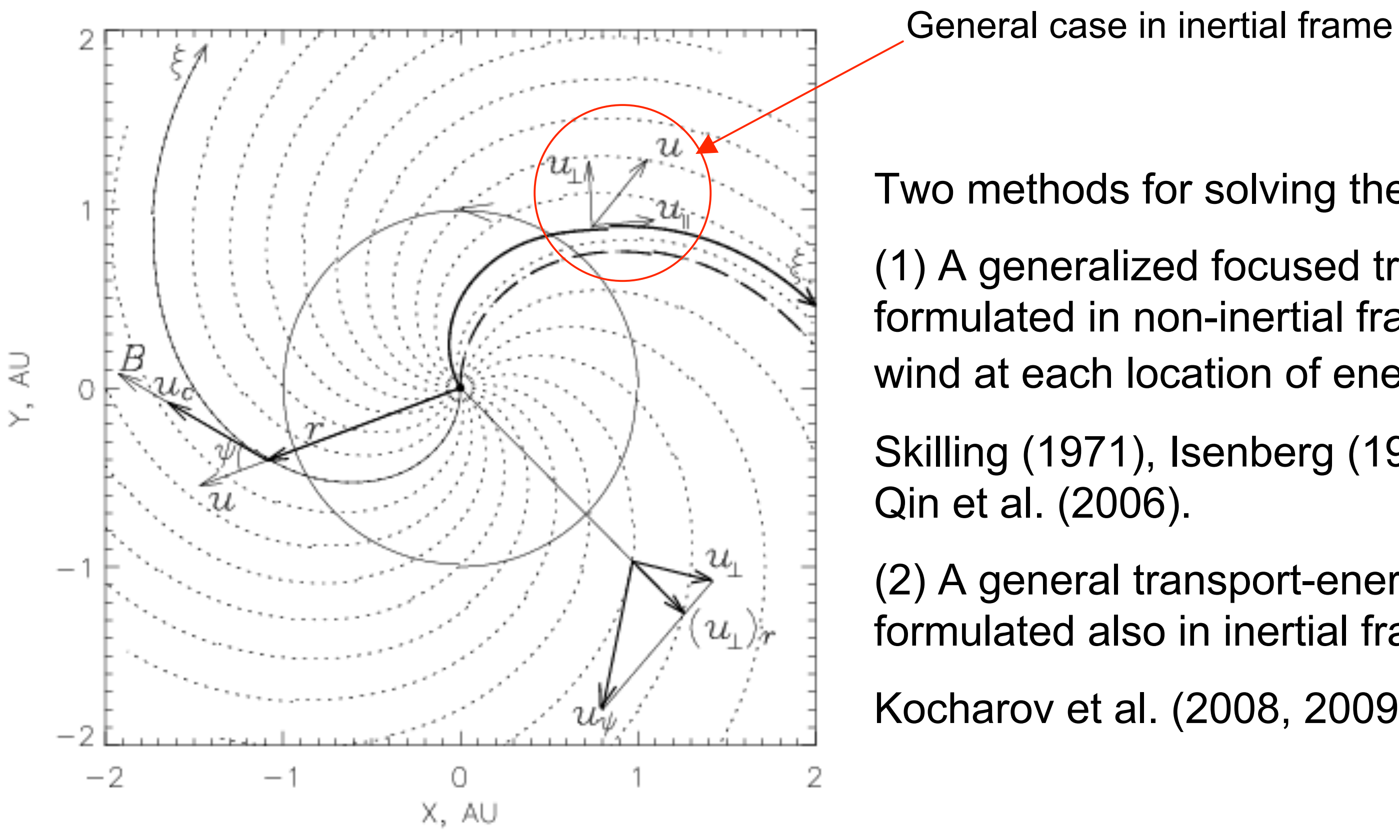
Stochastic simulations of energetic particles in coronal / interplanetary magnetic field structures

Two kinds of stochastic simulations:

First approach is based on the fact that the Fokker-Planck equation can be expressed as a set of stochastic differential equations with random scattering terms. The set can be solved by time stepping the progress of individual (quasi-) particles, and the results (e.g., particles with a particular energy at a particular position) are binned to give a final distribution. The formal solving of transport equation with Monte Carlo method may simulate not real physical processes with real particles but imaginary particles in imaginary processes [e.g., Qin et al., 2006].

Second approach: start with a microscopic description of physical processes, to develop a numerical code, and afterward if possible to link the code to a Fokker-Planck equation. The stochastic simulations method was applied in particular to modeling of nuclear interactions of high-energy particles in solar flares [e.g., Hua and Lingenfelter, 1987; Mandzhavidze and Ramaty, 1992] and to SEP transport in nterplanetary space [e.g., Toptygin, 1985; Kocharov et al., 1998]. The Monte Carlo method can also incorporate ionization and recombination of accelerated ions, the generation of plasma waves by energetic protons and electrons, and any other elementary processes in question [e.g., recent Kartavykh et al., 2007; Vainio and Laitinen, 2007].

Solving the focused transport problem of SEPs in general case



Two methods for solving the general case:

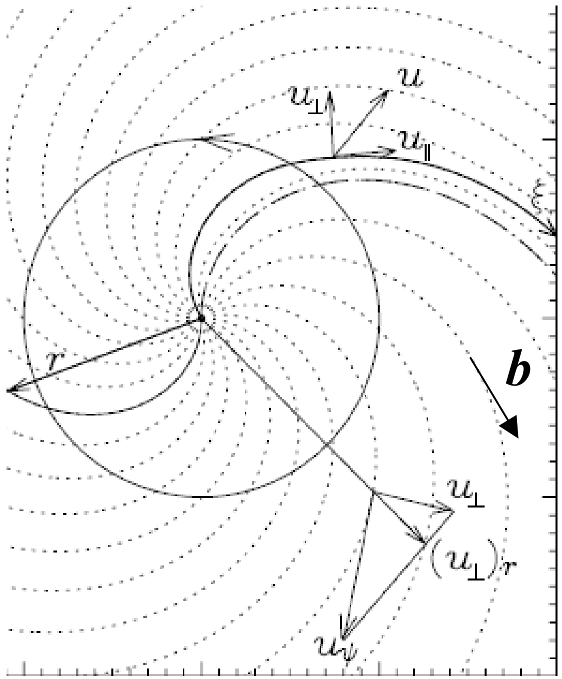
(1) A generalized focused transport model may be formulated in non-inertial frame co-moving with solar wind at each location of energetic particle:

Skilling (1971), Isenberg (1997), Kóta et al. (2005), Qin et al. (2006).

(2) A general transport-energy-change model can be formulated also in inertial frame terms:

Kocharov et al. (2008, 2009).

Stochastic simulations of SEP transport in evolving solar wind



Streaming and explicit parallel convection	$\delta\xi = v\mu\delta t + u_\psi\delta t$
Focusing and scattering	$\delta\mu = (1-\mu^2)v\delta t/(2L) + \delta\mu_{sc}$
Explicit betatron effect	$\delta v_\perp^2 = v_\perp^2 \frac{1}{B}\frac{d_\perp B}{dt}\delta t$
Explicit first order Fermi effect	$\delta v_\parallel = v_\parallel \boldsymbol{u}_\perp \cdot \frac{\partial \boldsymbol{b}}{\partial \xi}\delta t$

$$\frac{d_\perp}{dt} = \frac{\partial}{\partial t} + \boldsymbol{u}_\perp \cdot \nabla$$

$$\delta\xi_{pc} = \frac{(\boldsymbol{u}_\perp)_r \delta t}{\cos\Psi}$$

u_ψ

$$\delta v_\parallel = v_\parallel \boldsymbol{u}_\perp \cdot \frac{\partial \boldsymbol{b}}{\partial \xi}\delta t + \frac{\mu}{|\mu|}\boldsymbol{u}_\perp \cdot \frac{\partial \boldsymbol{b}}{\partial t}\delta t$$

Kocharov, L., Pizzo, V. J., Odstrcil, D., and Zwickl R. D.: 2009, A unified model of solar energetic particle transport in structured solar wind.- *J. Geophys. Res.*, 114, A05102.

Link to Diffusion-Convection Equation of cosmic ray transport

$$\frac{\partial f}{\partial t} = \nabla_i \kappa_{ij} \nabla_j f - \boldsymbol{u} \cdot \nabla f + \frac{p}{3} \frac{\partial f}{\partial p} \nabla \cdot \boldsymbol{u}$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{u} \times \boldsymbol{B})$$

$$\nabla \cdot \boldsymbol{u} = (\boldsymbol{b} \cdot \nabla)\, u_{\parallel} - \frac{1}{B} \left(\boldsymbol{u}_{\parallel} \cdot \nabla\right) B - \frac{1}{B} \frac{d_{\perp} B}{dt} - \boldsymbol{u}_{\perp} \cdot \frac{\partial \boldsymbol{b}}{\partial \xi}$$

Implicit first order Fermi effect

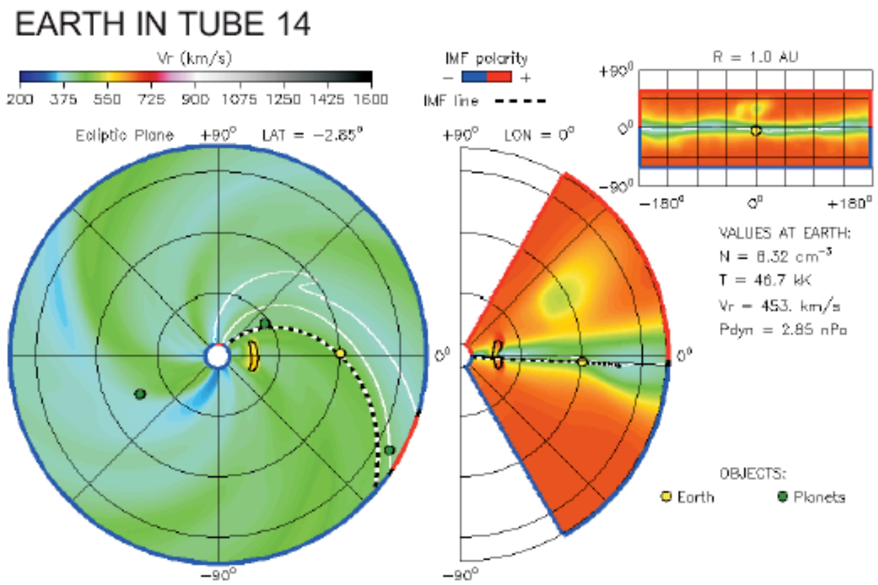
Implicit betatron effect

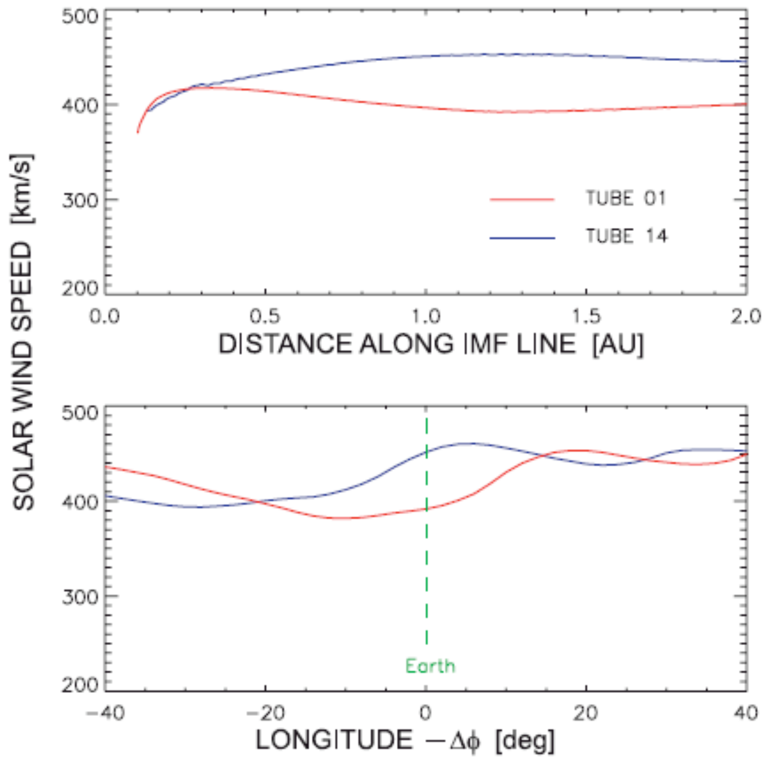
Explicit betatron effect

Explicit first order Fermi effect

$$\frac{d_{\perp}}{dt} = \frac{\partial}{\partial t} + \boldsymbol{u}_{\perp} \cdot \nabla$$

Accommodating the numerical 3-D MHD input





Odstrcil, D., P. Riley, and X. P. Zhao (2004), Numerical simulations of the 12 May 1997 interplanetary CME event, *J. Geophys. Res., 109*, A02116.

Odstrcil, D., V. J. Pizzo, and C. N. Arge (2005), Propagation of the 12 May 1997 interplanetary coronal mass ejection in evolving solar wind structures, *J. Geophys. Res.,* 514 *110*, A02106.

First results of the SEP transport modeling with numerical 3-D MHD input.

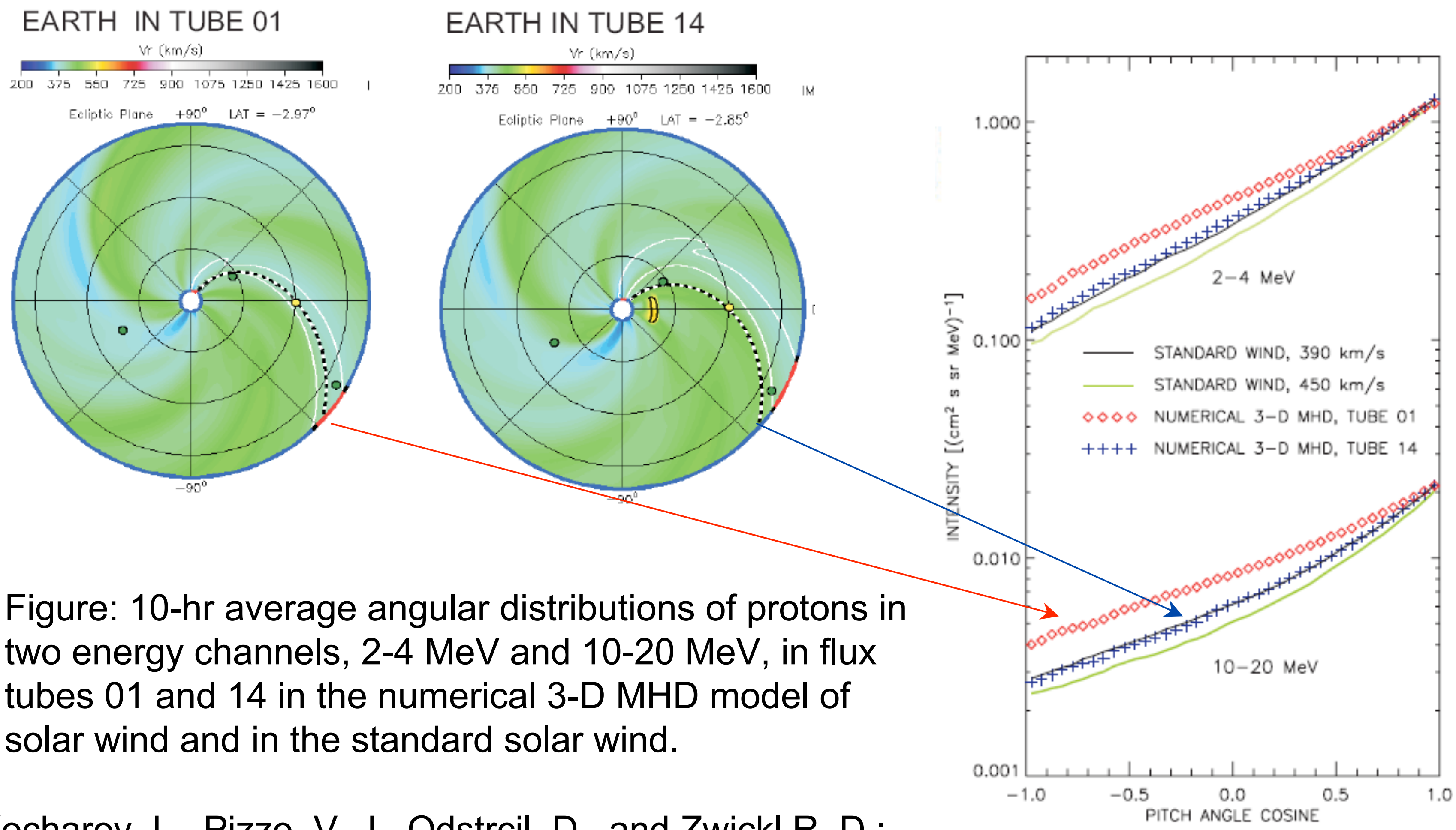


Figure: 10-hr average angular distributions of protons in two energy channels, 2-4 MeV and 10-20 MeV, in flux tubes 01 and 14 in the numerical 3-D MHD model of solar wind and in the standard solar wind.

Kocharov, L., Pizzo, V. J., Odstrcil, D., and Zwickl R. D.: 2009, A unified model of solar energetic particle transport in structured solar wind.- *J. Geophys. Res.*, 114, A05102.

Discussions underway

- Solar wind structures to be accounted for.
- Variability of mean free path in different interplanetary structures.
- Regions of enhanced cross-field transport.
- Particle transport in the CME-shock complex in solar wind.
- Coronal acceleration in major SEP events and coronal transport.

“Dispute” between
a Centaur and a Lapith.
5th century BC, British
Museum, London