Potential Operational Uses for Directional Observations of Solar Proton Fluxes at Geostationary Orbit

Juan Rodriguez[1,2], Joseph Mazur[3], Janet Green[2], and Brian Kress[4]

[1]University of Colorado [2]National Oceanic and Atmospheric Administration

[3]The Aerospace Corporation [4]Dartmouth College

Tenth European Space Weather Week

November 21, 2013

This research is supported by National Science Foundation awards AGS-1024701 and AGS-1023339.

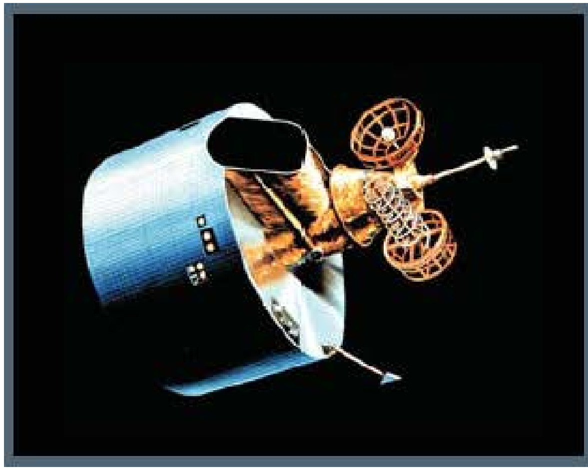
Potential Operational Uses for Directional Observations of Solar Proton Fluxes at Geostationary Orbit (GEO):

1. **Improved specification of the solar proton environment at GEO**
2. **Real-time, continuous estimate of the radial gradient of solar proton fluxes in the magnetosphere**

Outline

- Anisotropy in GOES Energetic Particle Sensor (EPS) Data
- Sources of Solar Proton Anisotropy Variability at GEO
- Cutoff Modeling of GEO Anisotropies
- GEO Anisotropies and Low-Altitude Gradients

Energetic Particle Sensors (EPS) on GOES 4-15



GOES 4-7

- GOES-4 launched 9 Sep 1980
- Spin-stabilized (0.6-sec period)
- First series of current EPS
- 3.0 sec accumulation period: EPS fluxes spin-averaged in the orbital plane

Anisotropy cannot be observed

GOES 8-12

- GOES-8 launched 13 April 1994
- Three-axis-stabilized
- Single EPS looked eastward on GOES 10, westward otherwise
- Dome D3 design modified to reduce aperture and provide two electron channels

Anisotropy observed thanks to GOES 10 orientation

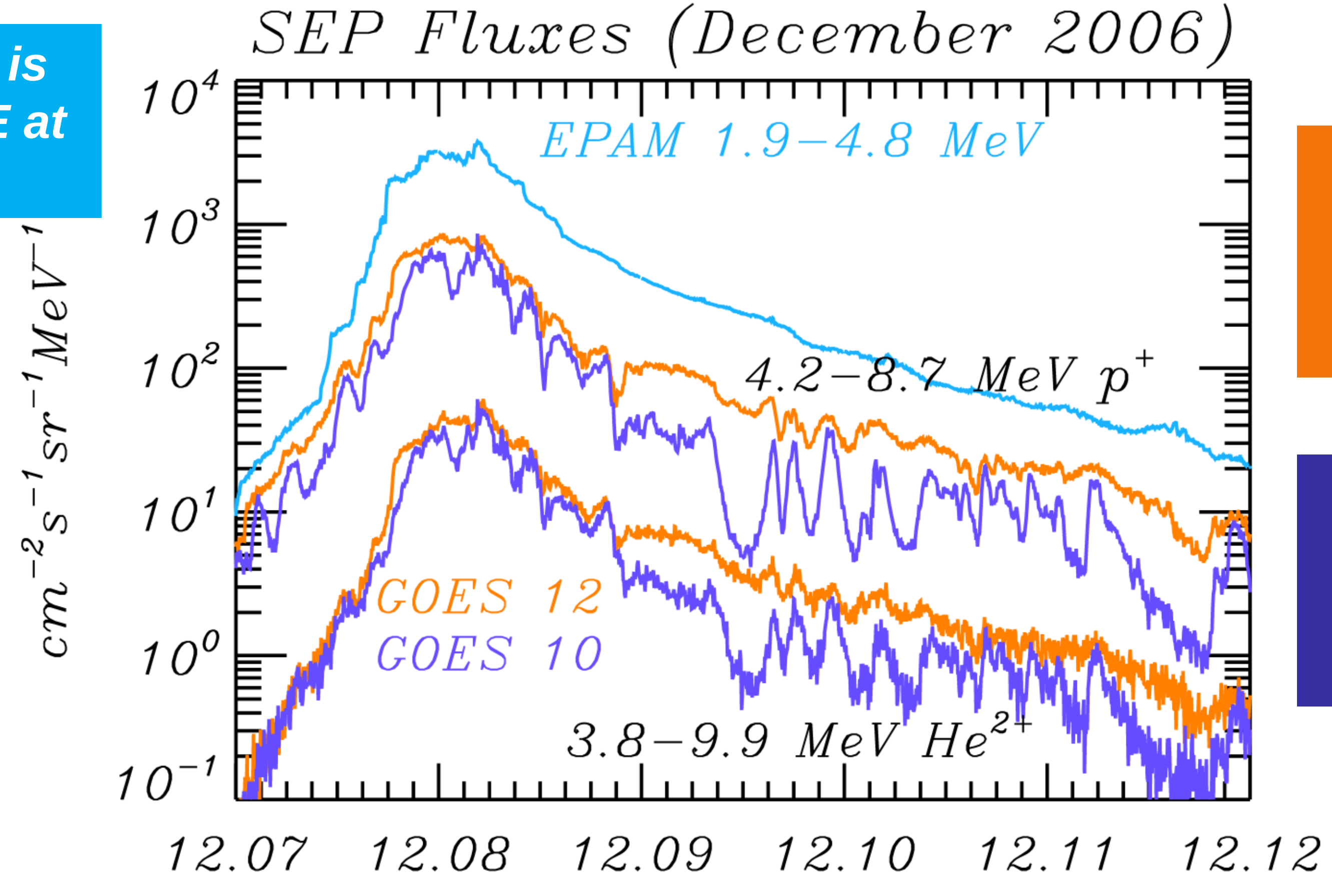
GOES 13-15

- GOES-13 launched 24 May 2006
- Three-axis-stabilized
- Two EPS, one westward and one eastward
- No detector design changes

Anisotropy observed by all satellites

GOES solar energetic particle (SEP) fluxes observed eastward are lower than those observed westward

EPAM is on ACE at L1



GOES 12 detector looks westward

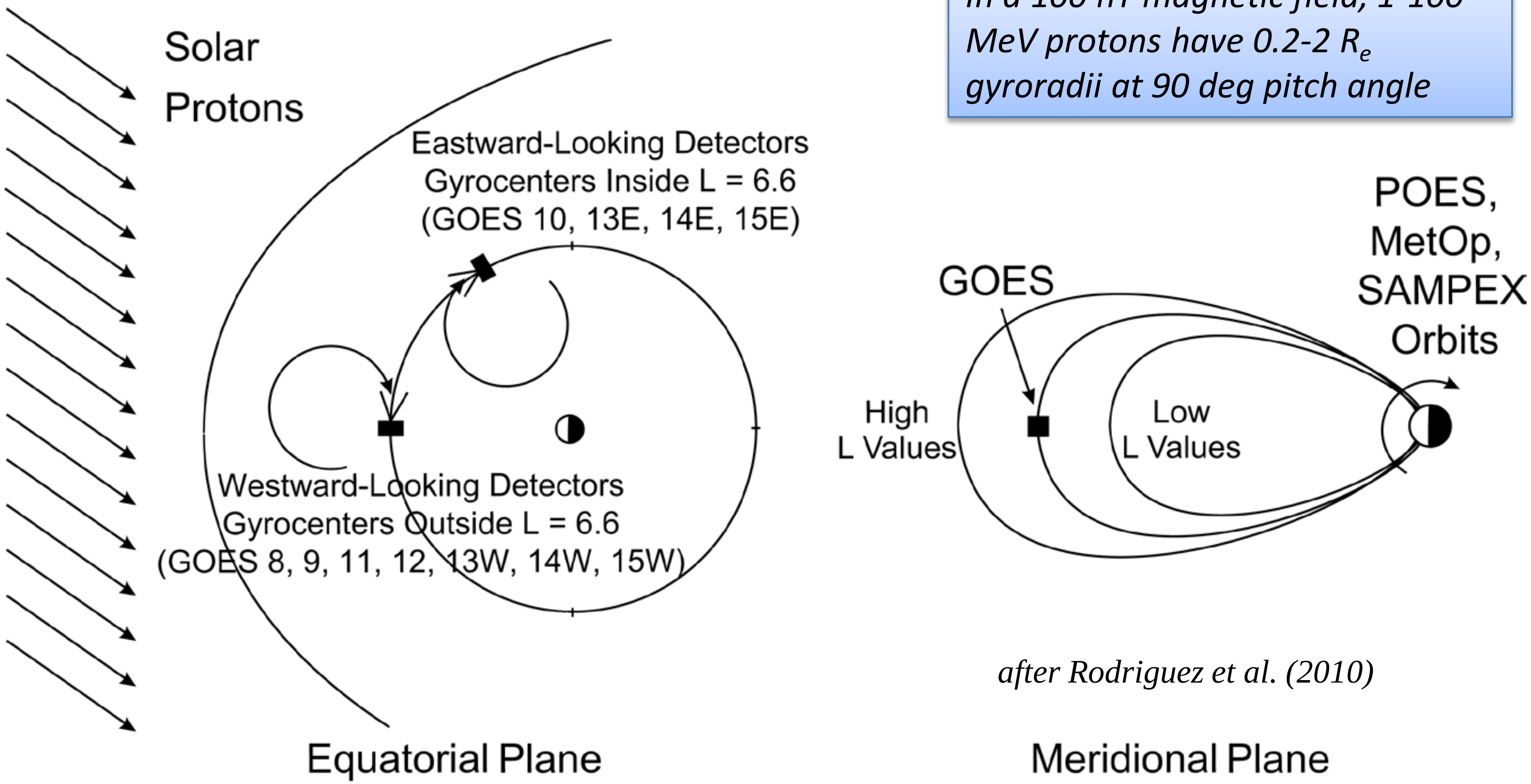
GOES 10 detector looks eastward

Rodriguez (2012)

Directional observations can be used to derive a more accurate specification of solar energetic particle fluxes at GEO

East-west differences are consequences of a large proton gyroradius and a *radial* flux gradient

In a 100 nT magnetic field, 1-100 MeV protons have 0.2-2 R_e gyroradii at 90 deg pitch angle

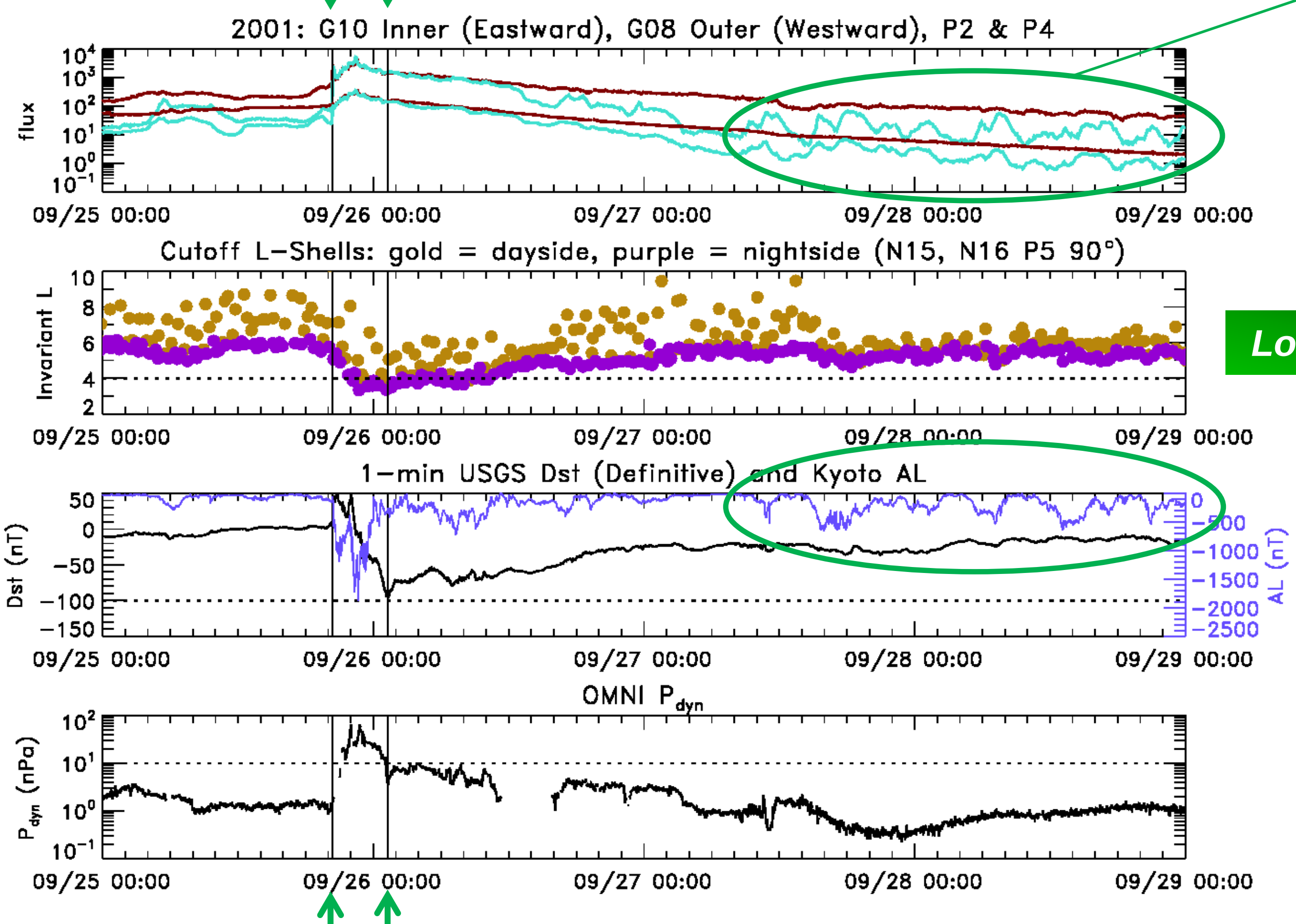


after Rodriguez et al. (2010)

GOES eastward (inner flux) and westward (outer flux) observations are equivalent to a 2-point measure of the SEP flux radial gradient

Effects of solar wind pressure, ring current and auroral activity on SEP anisotropies

SSC **min(Dst)** **undulations**



GOES 4.2-8.7 and 15-40 MeV fluxes

GEO

POES 2.5-7.0 MeV cutoffs

Low-Altitude

Dst and AL indices

OMNI Pdyn

Anisotropy reduced as Pdyn increases above 5 nPa, Dst approaches -100 nT

SEP flux undulations correlated with auroral activity (AL index), low Pdyn

Effects of pressure increases and substorms on SEP anisotropy: superposed epoch analysis

27 SSCs

85 dipolarizations at GOES

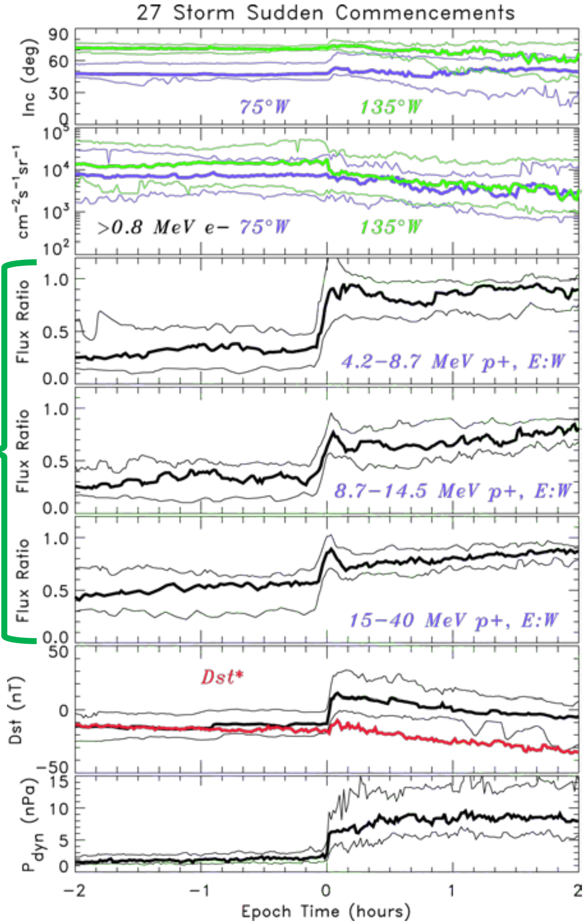
GOES B Inclination

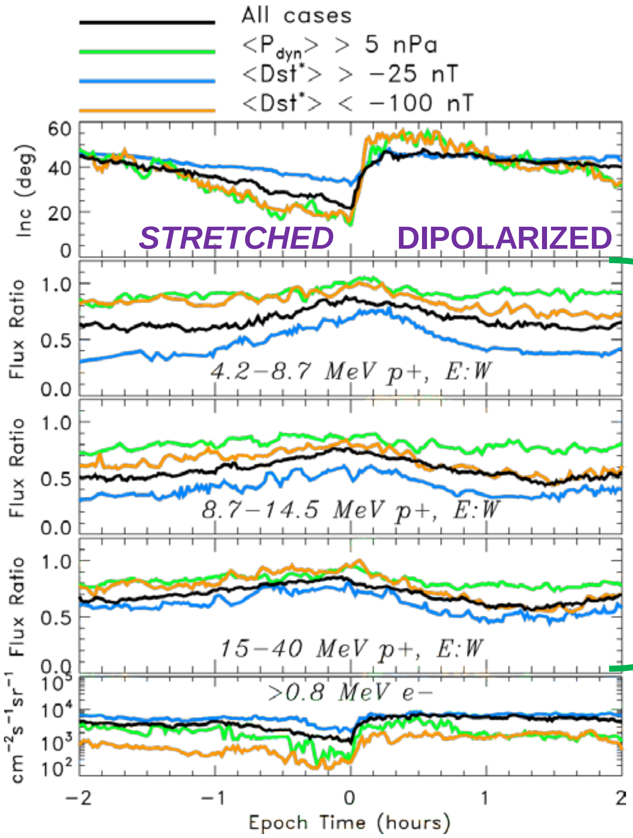
GOES >0.8 MeV e-

East-West Ratio, GOES 4-40 MeV p+

Dst and Dst*

Pdyn





GOES B Inclination

East-West Ratio, GOES 4-40 MeV p+

GOES >0.8 MeV e-

Zero epoch = start of SSC (IAGA Obs. de l’Ebre)

Zero epoch = time of minimum B inclination at GOES

Rodriguez (2012)

Liouville's Theorem applied to cosmic rays entering the Earth's magnetic field (1933-1934)

Enrico Fermi & Bruno Rossi

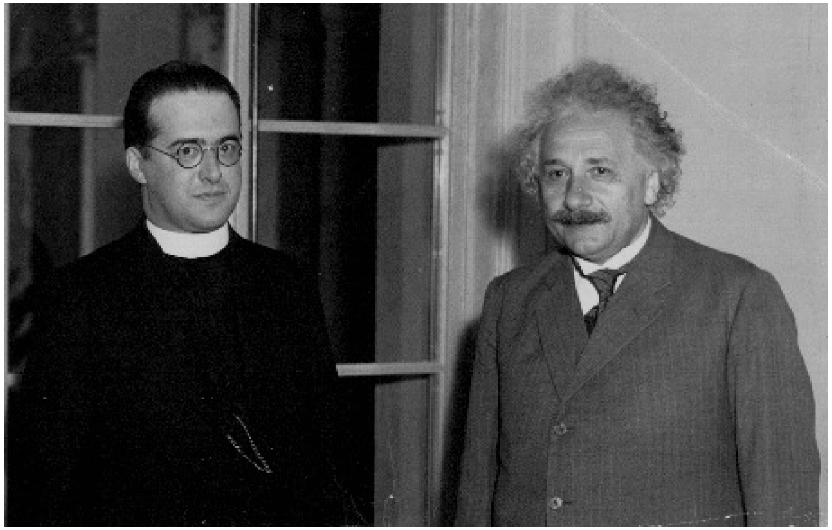
The differential flux of particles above the cutoff rigidity is the same as in interplanetary space.

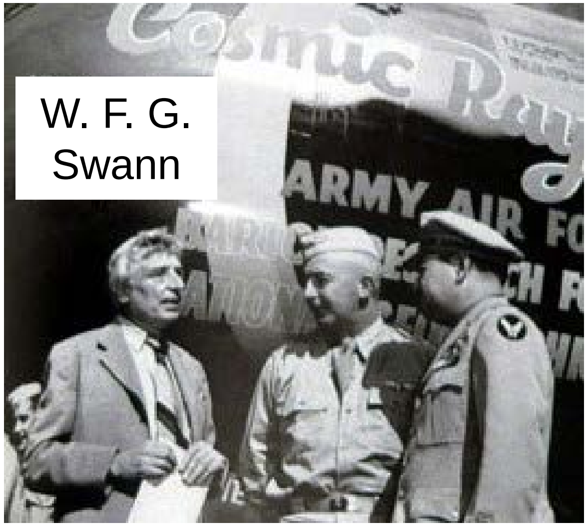
$$j^{\text{magnetosphere}}(E,\theta,\varphi)=\begin{cases}0, & E<E_C(\theta,\varphi)\\ j^{\text{interplanetary}}(E), & E>E_C(\theta,\varphi)\end{cases}$$

Photograph courtesy of the MIT Museum

Carl Størmer

Georges Lemaitre
(Catholic University of Leuven)

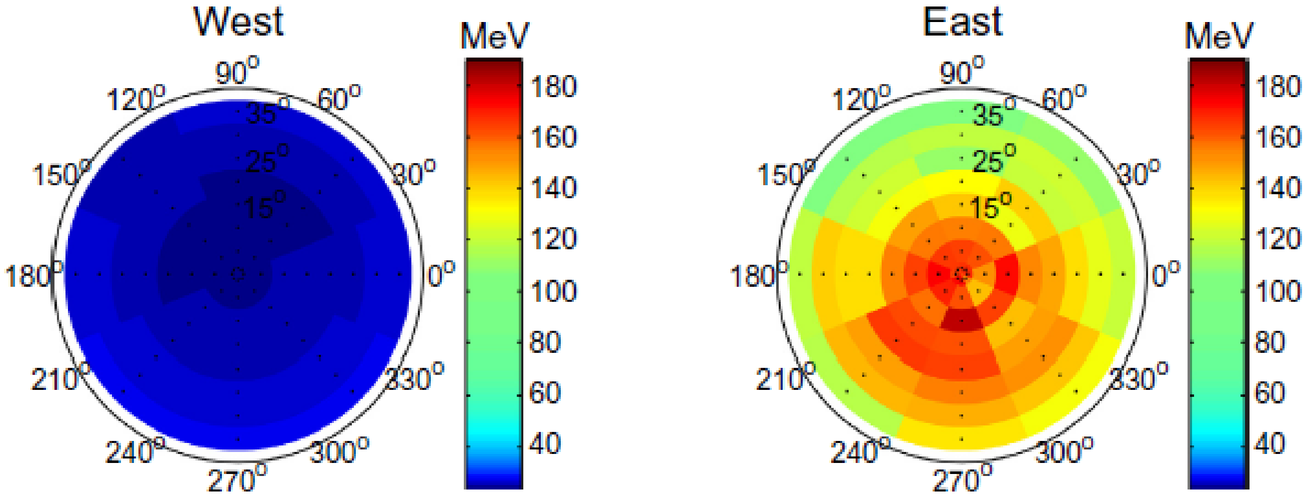




W. F. G. Swann

See Lemaitre et al. (1935) for a review of this work.

Effects of geomagnetic cutoffs need to be integrated over EPS fields-of-view



Kress et al. (2013)

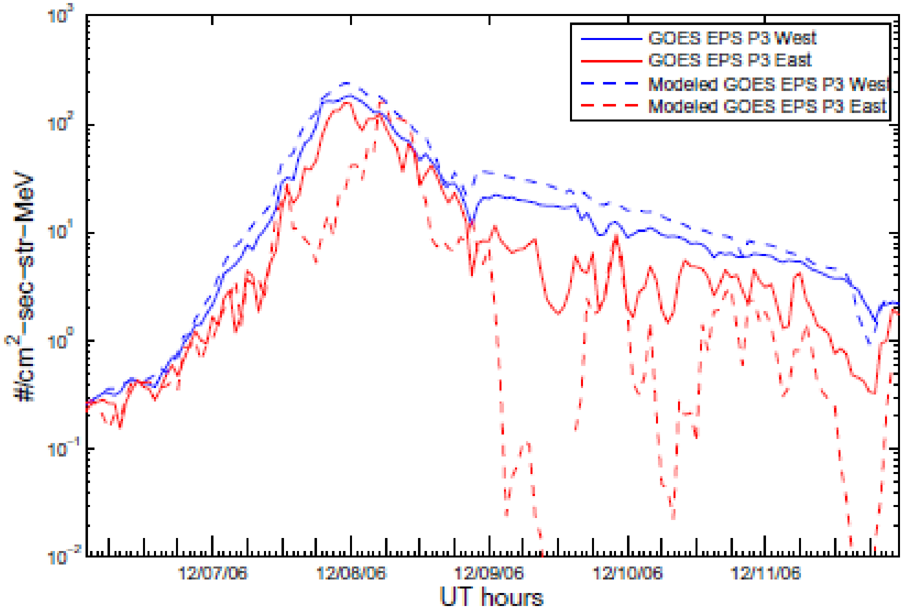
$$j^{\text{magnetosphere}}(E,\theta,\varphi)=\begin{cases}0, & E<E_C(\theta,\varphi)\\ j^{\text{interplanetary}}(E), & E>E_C(\theta,\varphi)\end{cases}$$

$$j_{\text{modeled}}(\#/\text{sec-cm}^2\text{-str-keV}) = \frac{\int_{FOV}\int_{E_C(\theta,\phi)}^{\infty} j_{\text{interplanetary}}(E)\,A(E,\theta,\phi)\,dE\,d\Omega}{G}$$

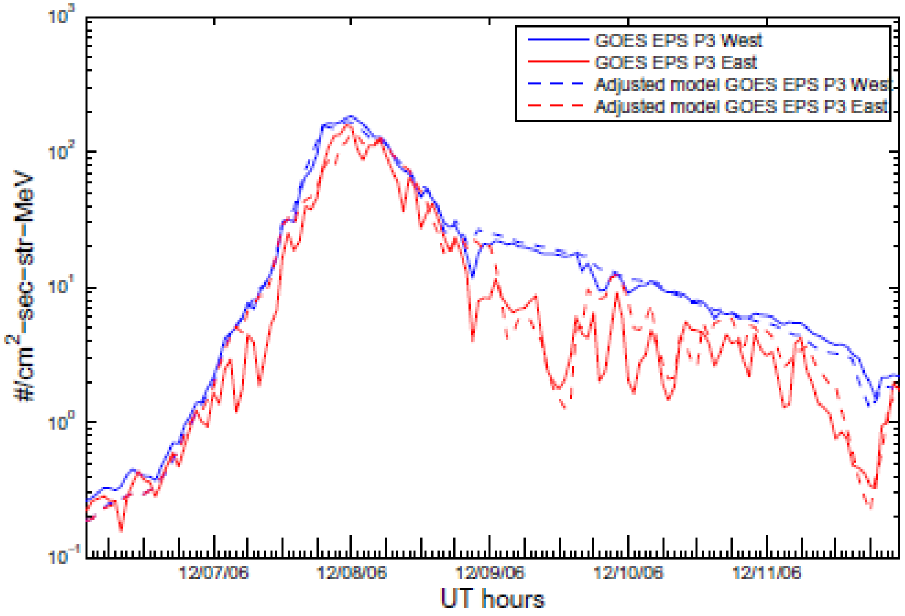
- Drive TS05 (*Tsyganenko and Sitnov,* 2005) magnetic field model with time-dependent solar wind density, speed and Bz and Dst* during events
- Following *Kress et al.* (2010), calculate cutoffs using time-reversed Lorentz trajectories in TS05 fields, integrate differential fluxes over broad angular and energy responses and compare to measurements

Time-varying cutoffs explain variations in December 2006 SEP fluxes observed by GOES-13

TS05 updated with OMNI solar wind data every 1 hour.
Cutoffs are suppressed and fluxes increase as driven current systems increase.



Cutoffs calculated in TS05 model



East and west FOV proton cutoffs reduced by 40% and 20% to minimize RMS error

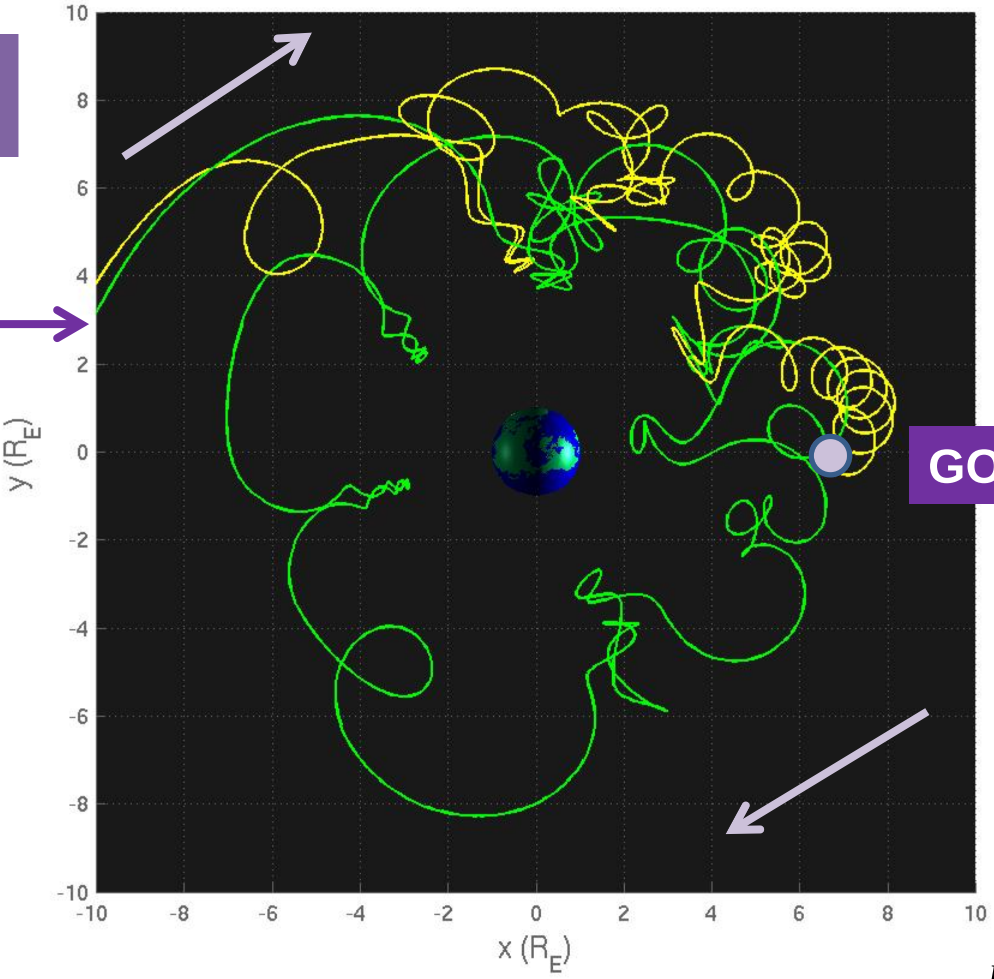
Kress et al. (2013)

Example of proton trajectories reaching the GOES East and West fields-of-view at noon

Lorentz trajectories in TS05 (quiet: Bz = +5 nT, Pdyn = 4 nPa, Dst = 0 nT) projected to XY plane

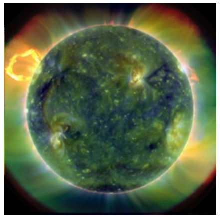
Protons drift westward

Protons near cutoff energies access inner magnetosphere from tail



GOES

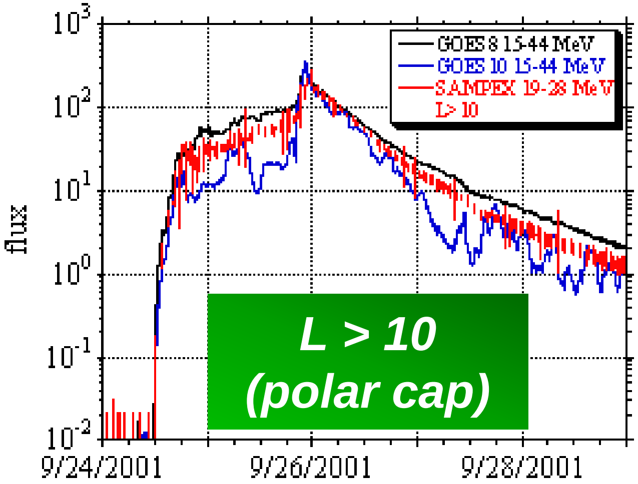
10 MeV proton reaches West FOV: outer trajectory

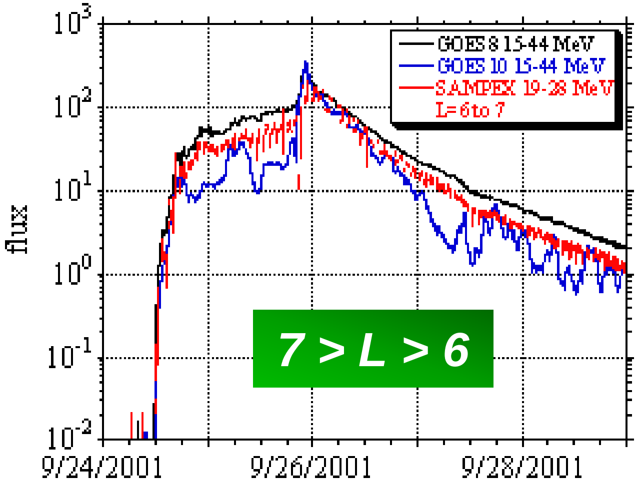


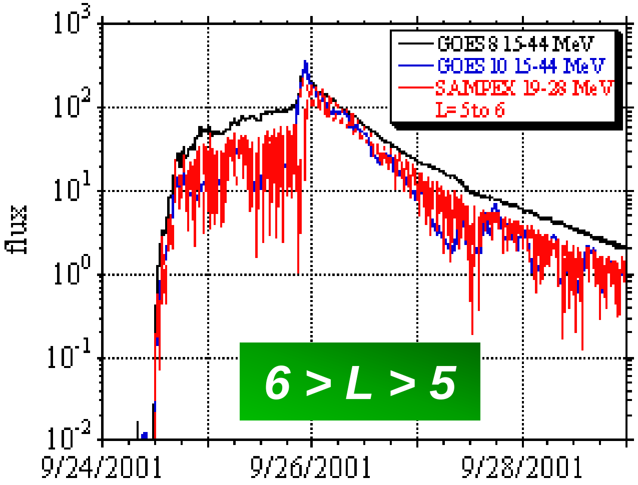
50 MeV proton reaches East FOV: inner trajectory

method of Kress et al. (2010)

GOES east-west anisotropy appears correlated with solar proton gradient between L = 5 and L = 7

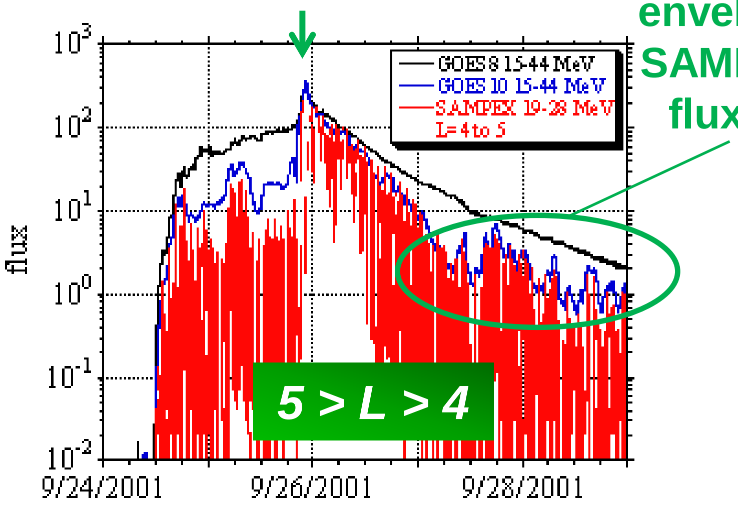






SSC

“undulations” envelope SAMPEX fluxes

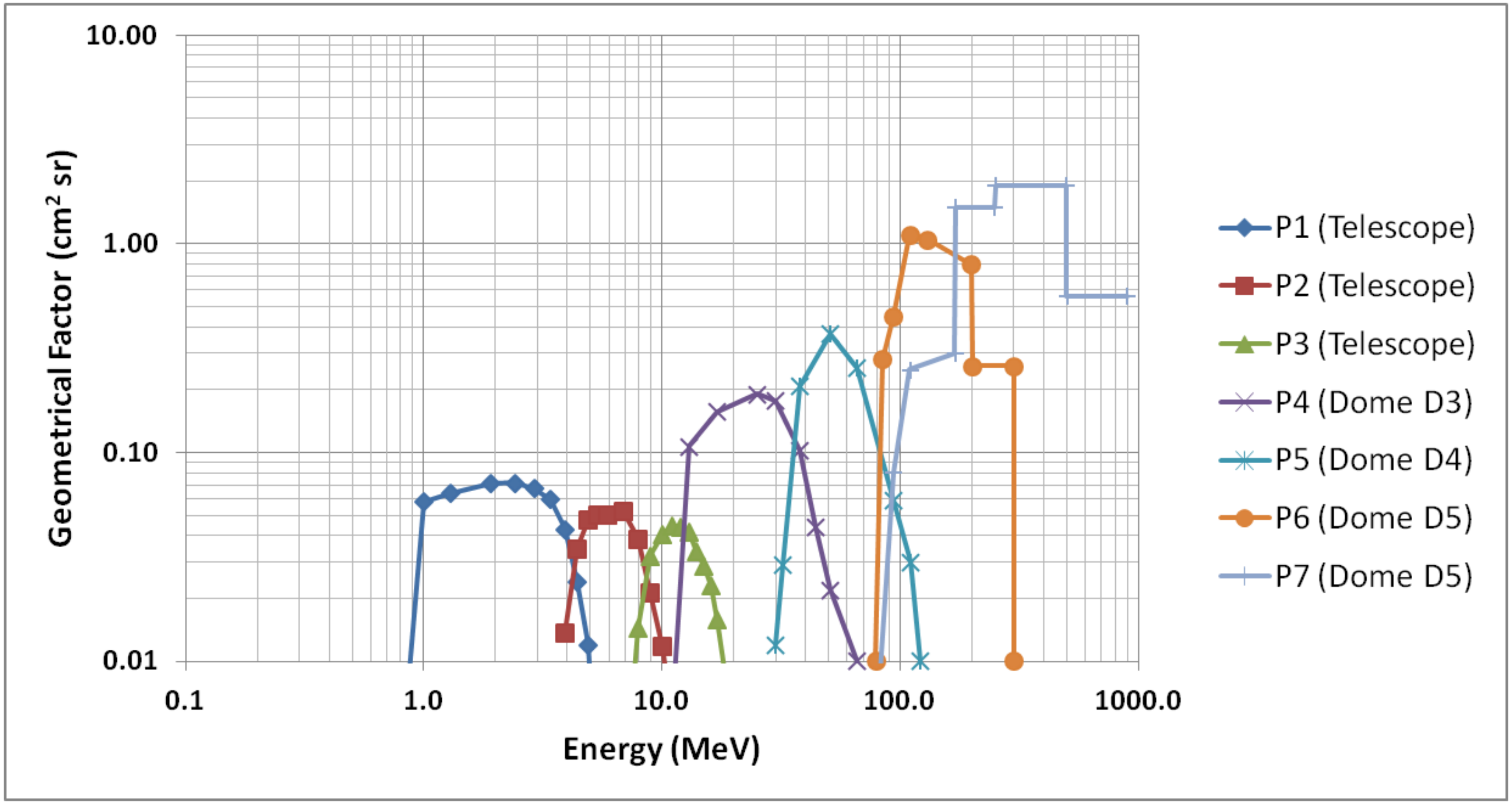


Summary

- GOES directional observations since 1994 may support more accurate specifications of solar proton fluxes in the magnetosphere
- Geomagnetic cutoffs at GEO are suppressed by auroral substorm activity, high solar wind pressure and increased ring current strength
- The anisotropy of GEO solar proton fluxes appears to be correlated with radial gradients at $L = 5$ to $L = 7$
- A successful 'nowcast' of solar proton fluxes in the inner magnetosphere will require real-time Dst and solar wind plasma data and will account for day-night asymmetries

Supporting Information

Responses of GOES EPS proton channels have been calibrated using proton beams



Geometrical factors are derived primarily from beam measurements of the GOES-4 engineering model and the GOES-8 and -9 flight models [Panametrics, 1979, 1980, 1995]

Intercalibrations show that GOES 8-15 responses agree to within 20% [Rodriguez et al., 2013]

References

- Kress, B.T., C. J. Mertens, and M. Wiltberger (2010), Solar energetic particle cutoff variations during the 29–31 October 2003 geomagnetic storm, *Space Weather, 8*, S05001, doi: 10.1029/2009SW000488. (also an invited talk at ESWW7, 2010)
- Kress, B. T., J. V. Rodriguez, J. E. Mazur, and M. Engel (2013), Modeling solar proton access to geostationary spacecraft with geomagnetic cutoffs, *Advances in Space Research,* doi:10.1016/j.asr.2013.08.019, in press.
- Lemaitre, G., M. S. Vallarta, and L. Bouckaert (1935), On the north-south asymmetry of cosmic radiation, *Phys. Rev., 47,* 434–436 [and references therein]
- Panametrics (1979), GOES D, E, F progress report, Energetic Particle Sensor Telescope calibration work, *Tech. Rep. PANA-GOESP-CR2,* Panametrics, Inc., Waltham, Mass.
- Panametrics (1980), GOES D, E, F progress report, Energetic Particle Sensor Dome calibration work, *Tech. Rep. PANA-GOESP-CR3,* Panametrics, Inc., Waltham, Mass.
- Panametrics (1995), Calibration report for the EPS Dome Sensor response to protons, *Tech. Rep. NXT-CAL-102,* Panametrics, Inc., Waltham, Mass.
- Rodriguez, J. V. (2012), Undulations in MeV solar energetic particle fluxes in Earths magnetosphere associated with substorm magnetic field reconfigurations, *J. Geophys. Res., 117,* A06229, doi:10.1029/2012JA017618.
- Rodriguez, J. V., T. G. Onsager, and J. E. Mazur (2010), The east-west effect in solar proton flux measurements in geostationary orbit: A new GOES capability, *Geophys. Res. Lett., 37,* L07109, doi:10.1029/2010GL042531.
- Rodriguez, J. V., J. C. Krosschell, and J. C. Green (2013), Intercalibration of GOES 8-15 solar proton detectors, submitted to *Space Weather*.
- Tsyganenko, N.A., and M. I. Sitnov (2005), Modeling the dynamics of the inner magnetosphere during strong geomagnetic storms, *J. Geophys. Res., 110*, A03208. http://dx.doi.org/10.1029/2004JA010798.