1) Moderate-to-extreme space weather has substantial impacts on society.

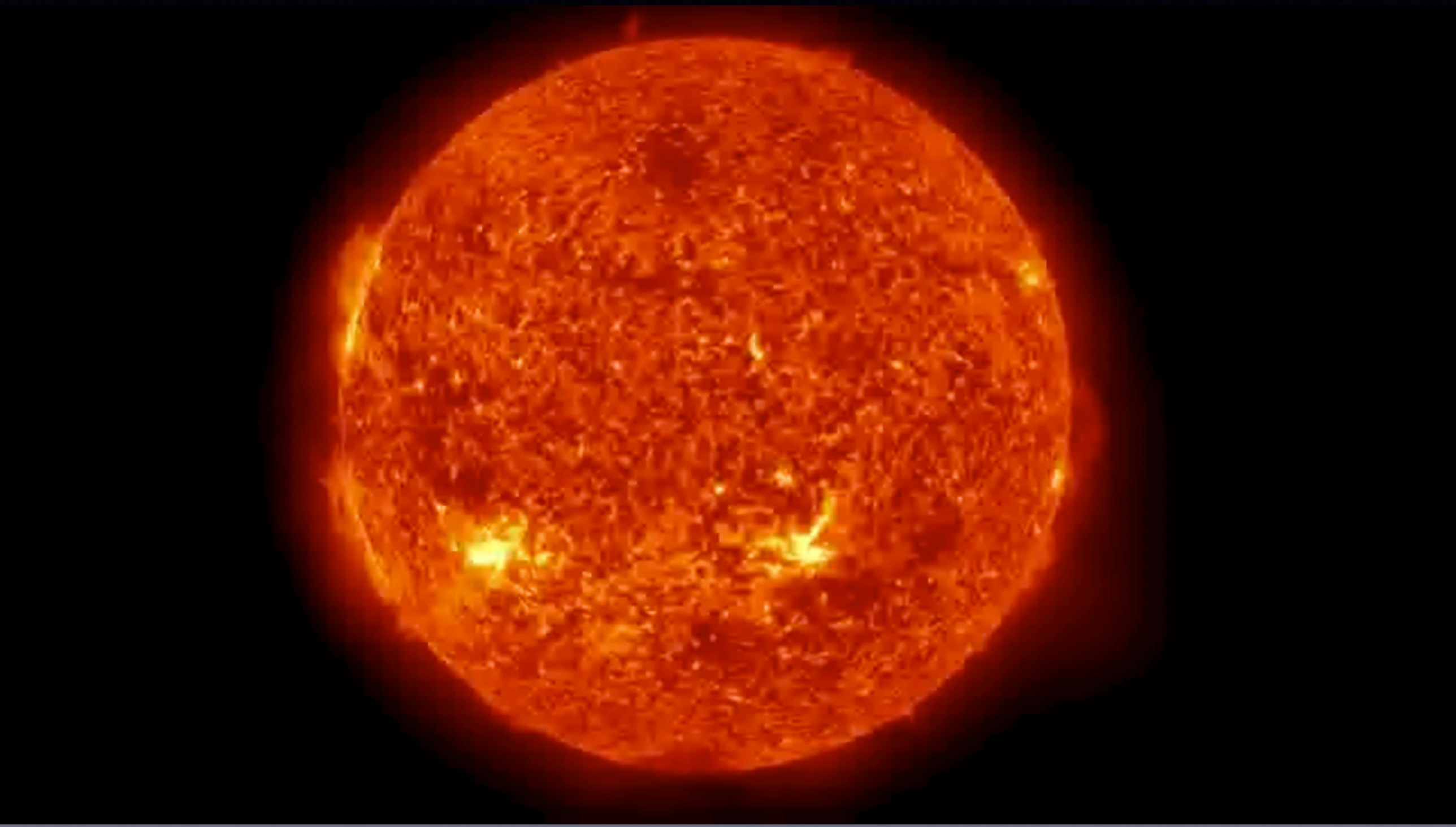
2) SWx situational awareness is operationally mature, and valued.

3) Reliable, actionable forecasts require significant advances in science.

4) “Sun-Earth Connections” = “Space weather science” = “Heliophysics”

Weather: all around us, all the time

Space weather: all around us, all the time



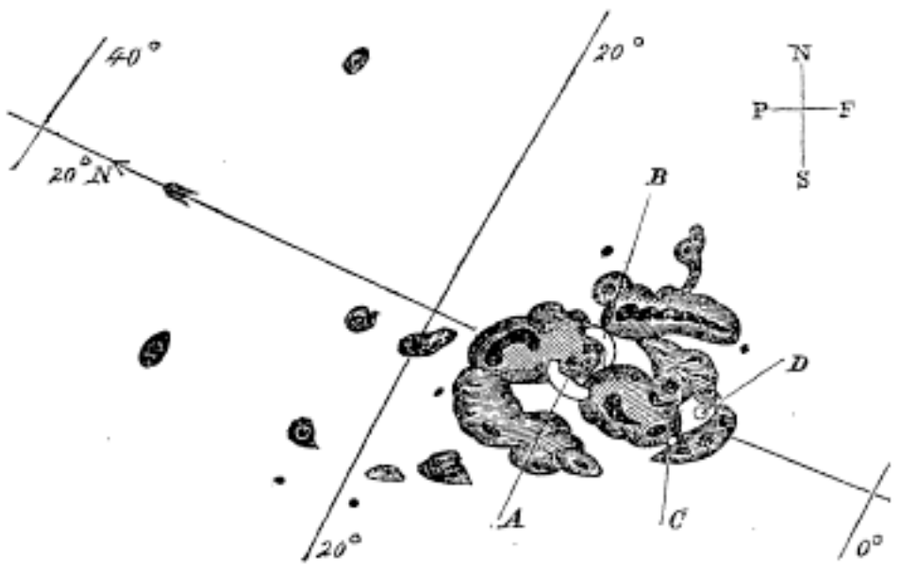
Solar flaring and the connection to geospace: discovered in 1859

On a curious Appearance seen in the Sun.
By R. Hodgson, Esq.

"While observing a group of solar spots on the 1st September, I was suddenly surprised at the appearance of a very brilliant star of light, much brighter than the sun's surface, most dazzling to the protected eye, illuminating the upper edges of the adjacent spots and streaks, not unlike in effect the edging of the clouds at sunset; the rays extended in all directions; and ng brilliancy of the ge telescope with s, and disappeared pe used, an equa-

Description of a Singular Appearance seen in the Sun on September 1, 1859. By R. C. Carrington, Esq.

While engaged in the forenoon of Thursday, Sept. 1, in taking my customary observation of the forms and positions of the solar spots, an appearance was witnessed which I believe to be exceedingly rare. The image of the sun's disk was, as usual with me, projected on to a plate of glass coated with distemper of a pale straw colour, and at a distance and under a power which presented a picture of about 11 inches diameter. I had secured diagrams of all the groups and detached spots, and was engaged at the time in counting from a chronometer and recording the contacts of the spots with the cross-wires used in the observation, when within the area of the great north group (the size of which had previously excited general remark), two patches of intensely bright and white light broke out, in the positions indicated in the appended diagram by the letters A and B, and of the forms of the spaces left white. My



first impression was that by some chance a ray of light had penetrated a hole in the screen attached to the object-glass, by

Advancing space weather science to protect society's technological infrastructure: a COSPAR/ILWS roadmap

chaired by

Karel Schrijver and Kirsti Kauristie

Lockheed Martin Adv. Techn. Lab, Palo Alto, CA

Finnish Meteorological Institute, Helsinki Finland

COSPAR site: *http://tinyurl.com/swxrm*

Advances in Space Research 55, 2745 (2015)

- Alan Aylward; University College London, UK
- Sarah Gibson; UCAR High Altitude Observatory, Boulder, CO, USA
- Alexi Glover; ESA-Rhea System, Germany
- Nat Gopalswamy; NASA/GSFC, Greenbelt, MD, USA
- Manuel Grande; Univ. Aberystwyth, UK
- Mike Hapgood; RAL Space, and STFC Rutherford, Appleton Lab., UK
- Daniel Heynderickx; DHConsultancy, Belgium
- Norbert Jakowski; Deutsches Zentrum für Luft und Raumfahrt, Germany
- Vladimir Kalegaev; Skobeltsyn Inst. of Nucl. Phys., Moscow, Russia
- Kirsti Kauristie, co-chair; Finnish Meteorological Institute, Finland
- Giovanni Lapenta; KU Leuven, Belgium
- Jon Linker; Predictive Science Inc., San Diego, CA, USA
- Liu Siqing; Nat'l Space Science Center, Chinese Acad. of Sciences, China
- Cristina Mandrini; Inst. de Astr. y Fis. del Espacio, Buenos Aires, Argentina
- Ian Mann; Univ. Alberta, Canada
- Tsutomu Nagatsuma; Space Weather and Env. Inf. Lab., NICT, Japan
- Dibyendu Nandi; Indian Inst. of Science, Ed. and Res., Kolkata, India
- Clezio De Nardin; INPE, Brazil
- Takahiro Obara; Tohoku University, Japan
- Paul O'Brien; Aerospace Corporation, USA
- Terry Onsager; NOAA Space Weather Prediction Centre, USA
- Hermann Opgenoorth; Swedish Institute of Space Physics, Sweden
- Karel Schrijver, chair; Lockheed Martin ATC, USA
- Michael Terkildsen; IPS Radio and Space Services, Australia
- Cesar Valladares; Boston College, USA
- Nicole Vilmer; LESIA Observatoire de Paris, France

science.nasa.gov

COSPAR/ILWS Charge

The RoadMap

I. focuses on high-priority challenges in key areas of research
II. leading to a better understanding of the space environment and
III. a demonstrable improvement in the provision of timely, reliable information
IV. pertinent to effects on civilian space- and ground-based systems,
V. for all stakeholders around the world.

The RoadMap prioritizes those advances that can be made on short, intermediate and decadal time scales, identifying gaps and opportunities from a predominantly, but not exclusively, geocentric perspective.

"Space weather refers to the variable state of the coupled space environment related to changing conditions on the Sun and in the terrestrial atmosphere."

e-Home: https://cosparhq.cnes.fr/scientific-structure/cospar-scientific-roadmaps

Fundamental questions

What will leave the Sun?
How will things evolve en-route to geospace?
What will it cause to happen in geospace?
How will that affect technology?
How can that affect society?
How can society respond to the threat?
How does any of these steps depend on what came before?
[Hysteresis, pre-conditioning, … "event studies" should become "interval studies of the system"]

Highest-priority recommendations in brief

In a collaborative international effort:

Research: observational, computational, and theoretical needs

1. **"Augment the system observatory"**
2. **"Initial focus: Know what $\vec{B}$ is coming"**
3. **"Initial focus: Establish the GDM-GIC response"**
4. **"Quantify conditions to expect"**

Teaming: coordinated collaborative research environment

I. **"Uncover susceptibility"**
II. **"Focus resources"**
III. **"Ease access to data"**
IV. **"Grow coverage affordably"**

Bridging communities: collaboration between agencies and communities

A. **"Trust partners"**
B. **"Learn about SWx and its impacts"**
C. **"Evolve priorities and coordinate"**
D. **"Make use of advancing knowledge"**
E. **"Avoid duplication and mistakes"**

Recommendations by pathway

on observational, computational, and theoretical needs

Pathway I: ... for impacts of GMD/GIC on electrical systems

to obtain >1d forecasts of incoming CME field, and anticipated geomagnetic response, and ionospheric disturbances.

Pathway II: ... for the particle environment of (aero)space assets

to improve environmental specification and near-real-time conditions

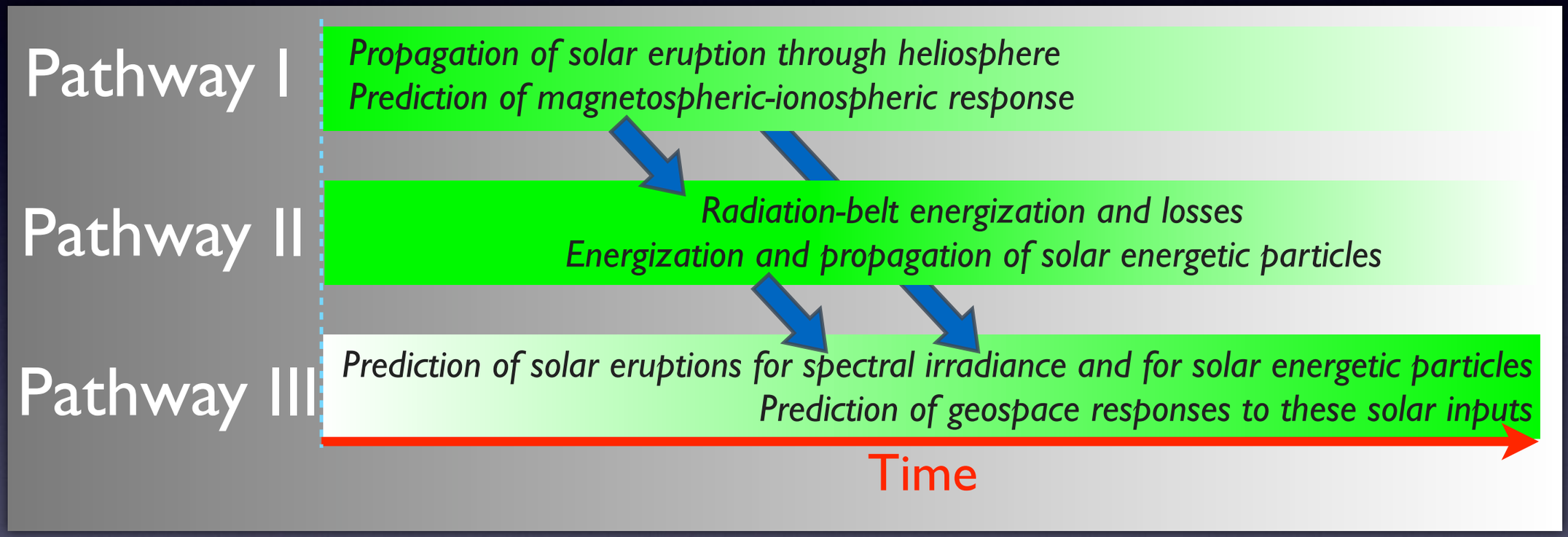
Pathway III: ... to enable pre-event forecasts of flares and SEPs

to enable short-term forecasts, including all-clear conditions, for particles and ionospheric conditions

N.B. Pathways reflect a merged weighting based on assessed societal impact, scientific need, estimated feasibility, likelihood of near-term success, and sequencing in a logical order of progression.

Recommendations by pathway

on observational, computational, and theoretical needs



N.B. Pathways reflect a merged weighting based on assessed societal impact, scientific need, estimated feasibility, likelihood of near-term success, and sequencing in a logical order of progression.

Differential needs and feasibilities

Recommendation for next steps towards meeting user needs, grouped to enable advances on phased paths.

Character of requirements

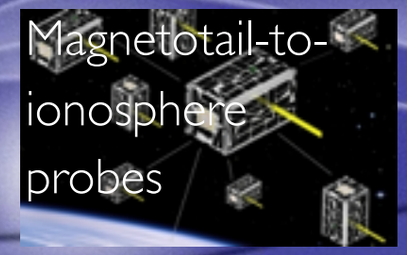
Most significant use: / *Needed product:*	Electrical systems *Geomagnetic variability* *protection of electrical & electronic systems*	Navigation/Comm. *Ionospheric variability* *reliability of navigation and communication*	(Aero)Space assets *Space particle environment* *anomaly resolution, and design specification*
Knowledge of environment for system design	***Pathway I***	***Pathway I***	***Pathway II***
Near-real time info and short-term forecasts	***Pathway I***	***Pathway III***	***Pathways II & III***
1-2 day forecasts	***Pathway I***	***Pathway III***	***Pathway II***

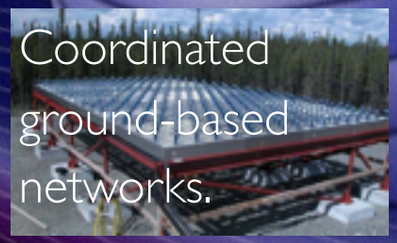
Pathway I: observational, computational, and theoretical needs to forecast GIC effects more than 12hrs ahead

Deployment of new/additional instrumentation:

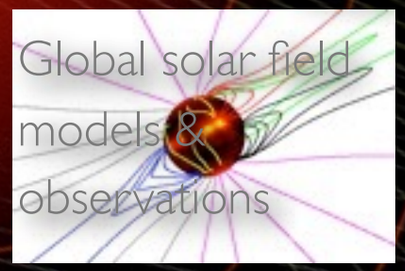
I-1: Quantify active-region magnetic structure for nascent coronal ejections

I-2: Solar wind-magnetosphere-ionosphere coupling inducing strong GICs

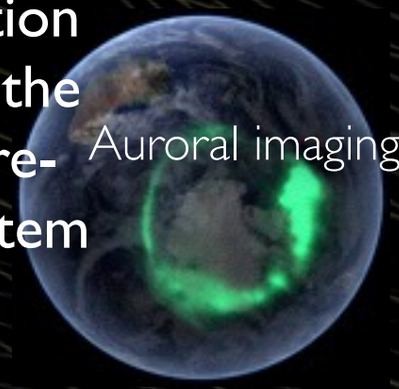




I-3: Global corona to drive models for the solar-wind plasma and field



I-4: Quantification of the state of the magnetosphere-ionosphere system

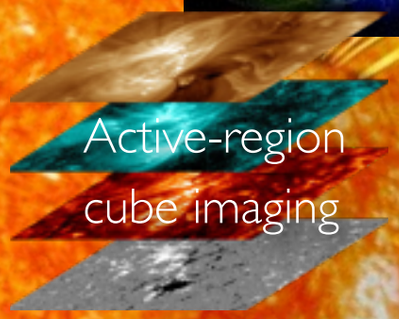


Pathway II: observational, computational, and theoretical needs for the radiation-belt environment

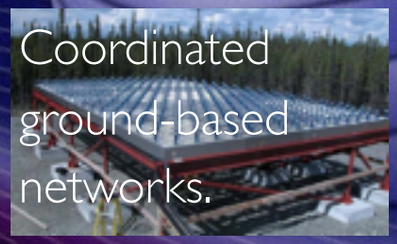
Deployment of new/additional instrumentation:

I-1: Quantify active-region magnetic structure for nascent coronal ejections

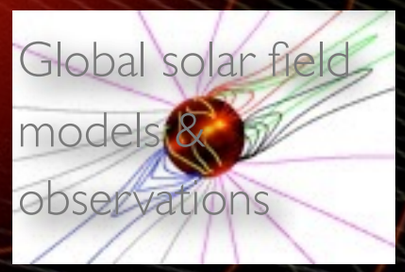
II: Data-driven dynamic radiation-belt modeling



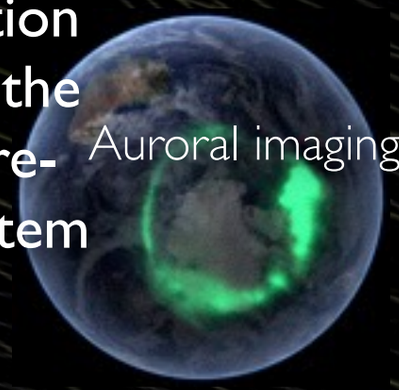
I-2: Solar wind-magnetosphere-ionosphere coupling inducing strong GICs



I-3: Global corona to drive models for the solar-wind plasma and field



I-4: Quantification of the state of the magnetosphere-ionosphere system

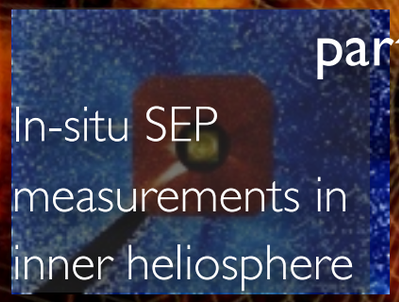


Pathway III: observational, computational, and theoretical needs to enable pre-event forecasts of flares and SEPs

Deployment of new/additional instrumentation:

II: Data-driven dynamic radiation-belt modeling

III: Solar energetic particles in the Sun-Earth system

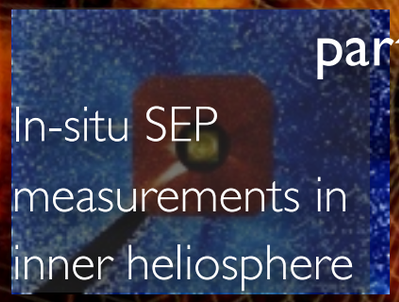


Deployment of new/additional instrumentation, to add to existing observational resources and to modeling capabilities to be developed soon:

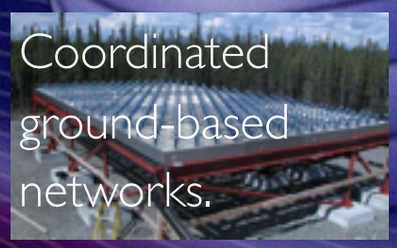
I-1: Quantify active-region magnetic structure for nascent coronal ejections

II: Data-driven dynamic radiation-belt modeling

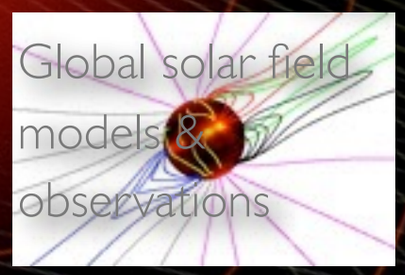
III: Solar energetic particles in the Sun-Earth system



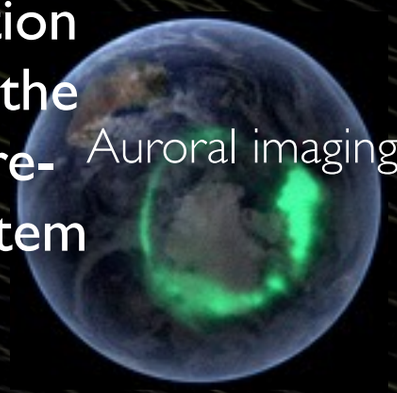
I-2: Solar wind-magnetosphere-ionosphere coupling inducing strong GICs



I-3: Global corona to drive models for the solar-wind plasma and field



I-4: Quantification of the state of the magnetosphere-ionosphere system



We live in the changing atmosphere of a powerful neighbor: space weather and its impacts are there all the time!

Domain volume, non-linearities, multi-process and cross-scale couplings, and hystereses require focused study before we can claim understanding and before we can expect to reliably forecast.

Major advances are possible with moderate investments in critical, state-of-the-art observations and models, through inter-agency, inter-national coordination, strengthening the existing Sun-Earth system observatory and the modeling capabilities that it enables.