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Early Prediction of Geomagnetic Storms
(and Other Space Weather Hazards)

David Collins, Joan Feynman, et al.

Jet Propulsion Laboratory, California Institute of Technology
Pasadena, California 91109-8099

Early Prediction of Geomagnetic Storms (and Other Space Weather Hazards)

Abstract

Solar coronal mass ejections (CMEs) can cause hazardous high-energy particles and geomagnetic storms that, in the more serious instances, can disrupt Earth power grids, communications, and satellites. Early prediction of these events is important to have sufficient time to take actions to ameliorate problems. In situ measurements in the vicinity of the sun-Earth line can be highly important to the prediction process but, if made close to Earth (such as at the L1 point), provide little warning time.

Now, a mission and spacecraft concept have been developed that would enable measurements much farther inward toward the sun and enable much earlier warning. A single launch sends up to nine microspacecraft toward Venus for independently targeted custom gravity assists that will send each into a unique orbit around the sun. As the orbits develop, the microspacecraft spread throughout a continually changing band covering 0.5 AU to 0.8 AU from the sun. The net result is that the majority of the time at least one spacecraft is relatively near the sun-Earth line but from 0.2 to 0.5 AU closer to the sun than the Earth is. (If desired to improve coverage, a second launch of up to nine additional spacecraft can be used.)

The microspacecraft include basic magnetic, plasma, and energetic particle detectors, and, within tight limiting constraints, they can accommodate a selectable sensor as well. In addition to satisfying the technical needs of this mission, the microspacecraft are designed for low cost and to be able to be collectively launched by a low-cost vehicle. As a group, they would not only provide an early warning capability but also would contribute to substantially better understanding of CME large-scale structure and particle acceleration mechanisms. In turn, this would fold back into providing even better early warning.

Study Background

- **1993-1995 NASA/JPL Studies**
  - Developed a revolutionary vision and approach for a new generation of spacecraft with:

    Greatly reduced life-cycle costs
    Much more frequent flight
    Higher return on investment (including the enabling of new capabilities)
    Stimulation of broad technological innovation

  - One of four example system concepts developed was the Space Physics Fields and Particles (SPF&P) Second-Generation Microspacecraft (SGM)
    - It was designed to be capable of at least four mission types, but the focus was on a 1-spacecraft solar early warning precursor mission with in situ tests as close as 0.5 AU to the sun.

- **1998-1999 Internal JPL-AFRL Studies**
  - One of a number of very small studies started with the SPF&P SGM study, and it:

    Developed a trajectory concept for a multispacecraft operational early warning mission
    Reduced dependence on certain very long-range technology developments
    Incorporated updates based on recent work at JPL and AFRL

- **1999-2000 NASA/JPL Study**
  - This much larger study started with the previous work and focused on much deeper analysis of:

    What can be accomplished related to space weather
    Launch, injection, and deployment
    Trajectories and spread of spacecraft around the sun
    The payload and microspacecraft flight system

NASA/JPL Multimission Space and Solar Physics Microspacecraft (MSSPM)

Objectives For The Focus Mission

- Provide Better Understanding of the Physics of Hazardous Space Weather, Particularly:
  - Particle acceleration by shocks
  - Large-scale structure and radial evolution of CMEs
- Forecast Hazardous Space Weather With 4 - 45 Hours Warning of:
  - High energetic particle peak fluxes
  - The probability of “killer” electrons in the magnetosphere
  - Severe geomagnetic activity

Mission and Microspacecraft
(overview)

- **One small (Taurus or Athena II class) launch vehicle and Venus gravity assists spread nine 15 kg microspacecraft though a band around the sun**

- **Simultaneous in situ measurements are provided over a wide range of locations covering 0.53 - 0.85 AU distance from the sun and 0 - 360° of solar longitude**

- **Data are continuously collected and analyzed on each microspacecraft**
  - **Processed information is returned from each microspacecraft weekly**
  - **Also, the nearest microspacecraft to the sun-Earth line is monitored continuously for alerts (which are only issued for large disturbances)**

- **Microinstruments include:**

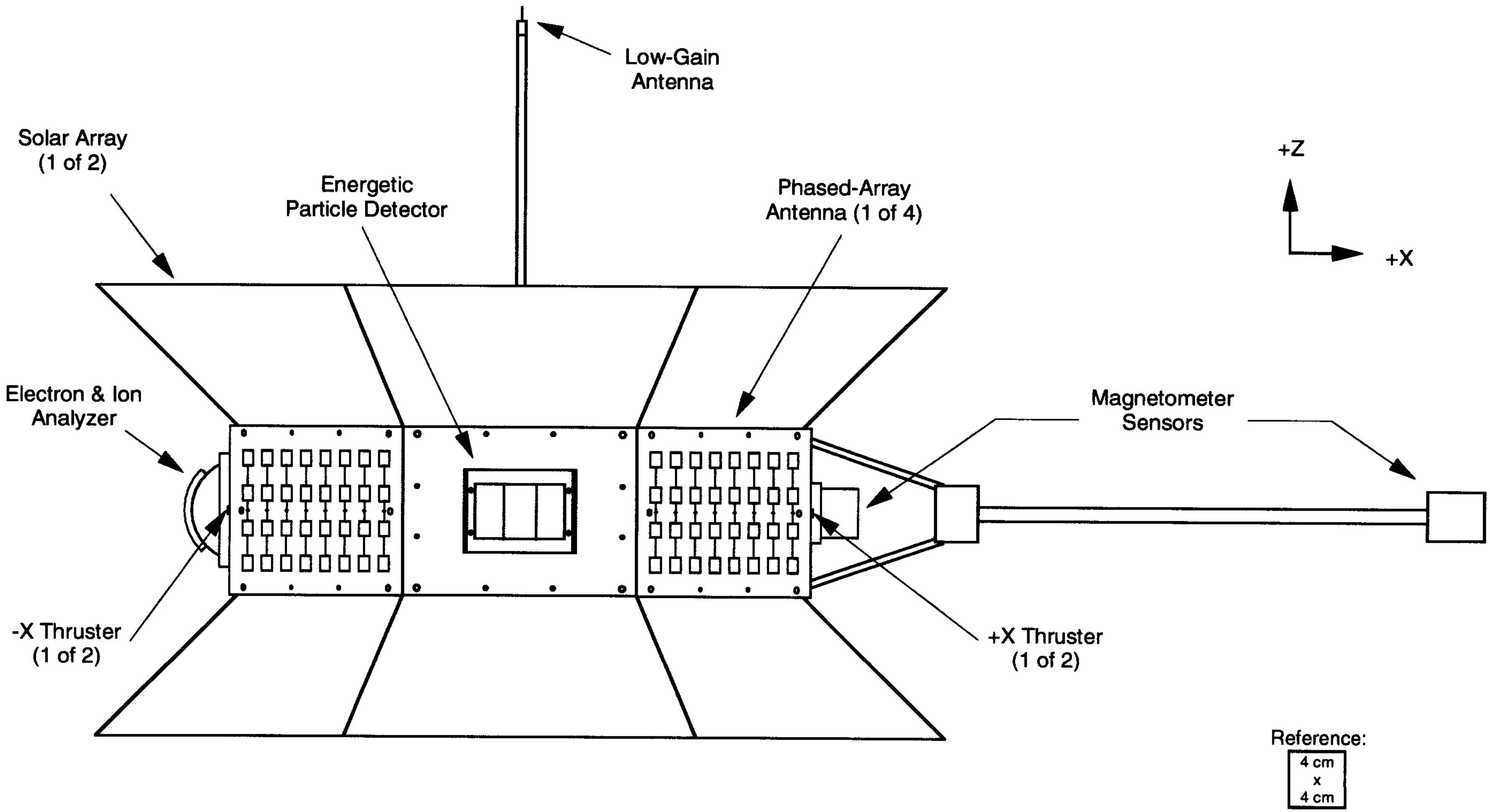
Electron and ion analyzer - for solar wind up to 2000 km/s

Energetic particle detector - for protons to 100 MeV (and other particles)

Magnetometer - for three vectors, ±200 nT each

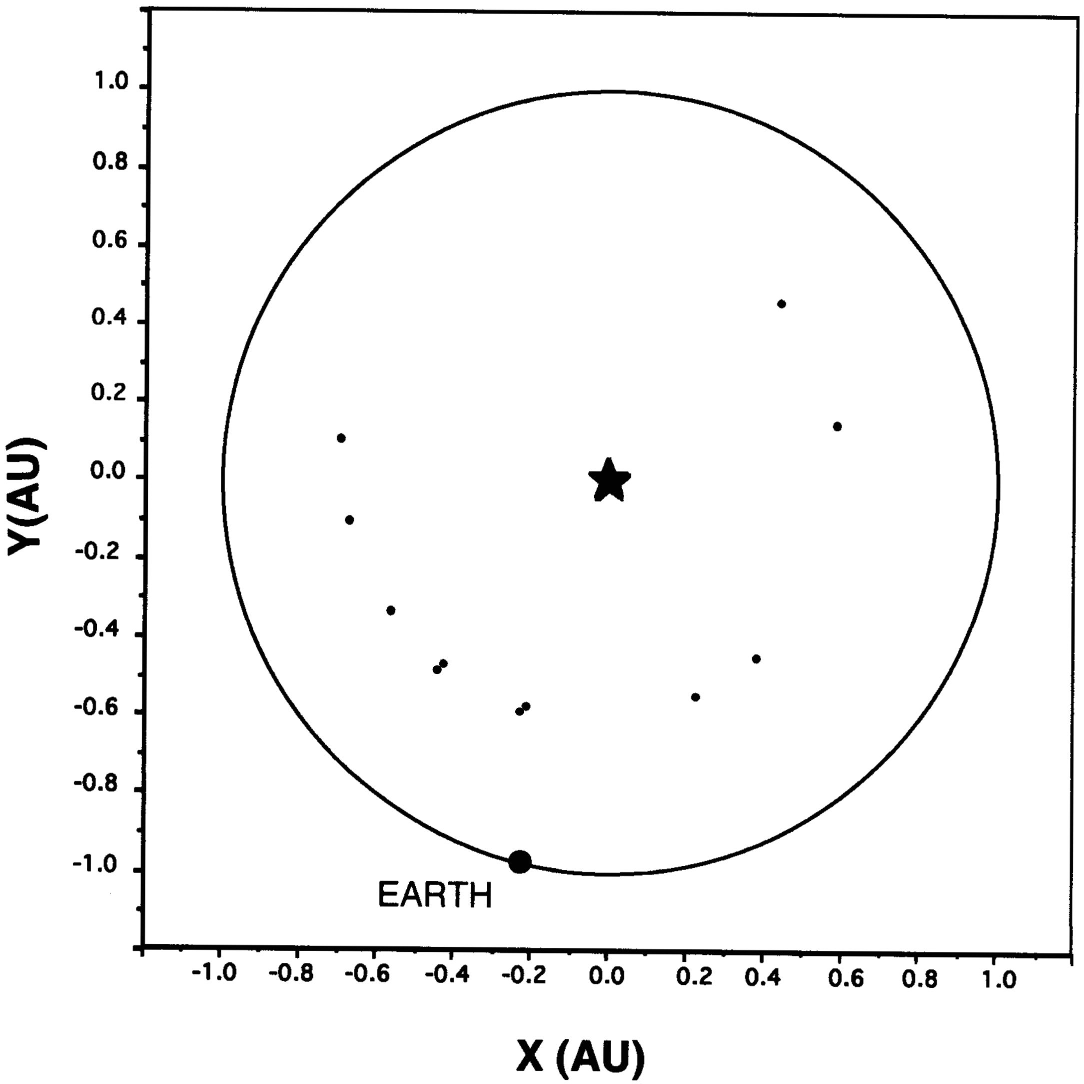
NASA/JPL Multimission Space and Solar Physics Microspacecraft

Flight Configuration Side View



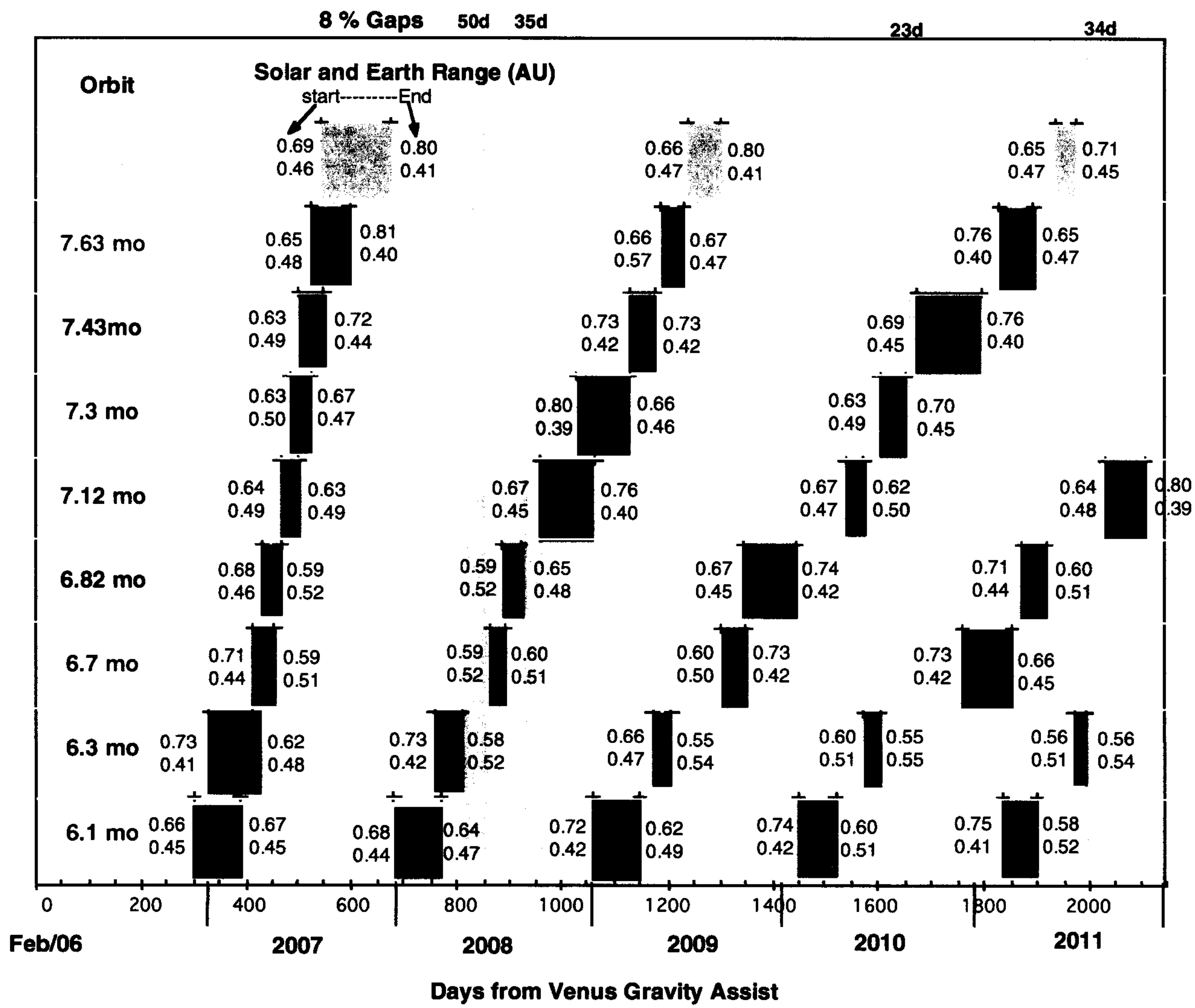
NASA/JPL Multimission Space and Solar Physics Microspacecraft

MSSPM Locations 480 Days After Venus Gravity Assist



NASA/JPL Multimission Space and Solar Physics Microspacecraft

MSSPM Near-Continuous Warning Coverage Within ±22.5° of Sun-Earth Line



What Particles Cause Hazardous Conditions in Space?

Parameter	Effects	Sources
Ionospheric currents	current surges on the ground (power outages, wear and tear of pipelines)	geomagnetic storms and aurora
Energetic electrons (10 - 100 keV)	spacecraft surface charging	magnetospheric substorms and trapped particles
Energetic electrons (>100 keV)	deep dielectric charging; background counting in sensors; solar cell damage	trapped magnetospheric particles
Energetic electrons (>1 MeV)	radiation damage (ionization)	primarily trapped and quasi-trapped magnetospheric particles
Protons (100 keV - 1 MeV)	surface damage to materials	primarily radiation belt particles
Protons (1 - 10 MeV)	displacement damage, particularly solar cell damage	radiation belts; shock acceleration in space
Protons (>10 MeV)	ionization and displacement damage, sensor background	radiation belts; solar energetic particle, galactic cosmic rays
Protons (>30 MeV)	damage to biological systems	radiation belts; solar energetic particle, galactic cosmic rays
Protons (>50 MeV)	single event effects	radiation belts; solar energetic particle, galactic cosmic rays
Energetic ions (>10 MeV/nuc)	single event effects	solar energetic particle, galactic cosmic rays
Very high energy (GeV) particles (ground level events)	single event effects; hazard to humans in planes in polar flights, astronauts	solar energetic particle, galactic cosmic rays

High-Velocity Coronal Mass Ejections (CMEs) are the most important cause of:

- The greatest geomagnetic storms
- The greatest solar energetic particle events
- And they may also play a role in producing the highly relativistic electrons that sporadically appear in the magnetosphere

High-Velocity Solar Wind Streams

- Geomagnetic storms caused by these are generally not as strong but are longer lasting than CME storms
- Some positively charged particles may also be accelerated by these streams, but they do not have high enough energies or large enough fluxes to constitute a space hazard
- The streams are implicated in the production of relativistic electrons in the magnetosphere

How Do CMEs Cause Solar Energetic Particle Events?

- Large hazardous particle events are caused by acceleration in space by shocks produced by high-speed CMEs

- Shock acceleration is currently an area of active research. Turbulence near the shock confines a particle to the vicinity of the shock long enough so that it is accelerated to high energy. Some particles leak away from the shock and propagate to Earth in a matter of minutes. Others remain trapped. The leaking particles are both controlled by the turbulence and cause the turbulence.

- The table shows that both the fluence and peak fluxes of these particles cause hazards. The fluences, mostly due to leaking particles, begin to appear within as little as 10's of minutes after initiation at the CME.

- The major peak flux events are associated with the arrival of the CME shock at Earth, long after CME initiation.

How Can MSSPM Contribute To New Science Needed To Enhance Our Solar Energetic Particle Forecast Capability?

- The mission will give the information on the turbulence in the solar wind in front of the shock at solar distances substantially less than 1 AU. This knowledge, obtainable only through in situ measurements, is necessary to test our present models for particle acceleration to energies > 15 MeV .

- The mission will also permit the radial dependence of the fluxes and fluences to be determined.

Can MSSPM Contribute To Solar Energetic Particle Forecasting?

- **High Fluence Onset - No:** The high fluxes arrive at Earth promptly from some CMEs (depending on position). This mission can not improve on the forecast of energetic particle event onset.

- **High Fluence Duration - Yes:** The length of time the fluxes will remain high depends on the shock speed and the particle release, which will be observed. Observations of the pre-shock interplanetary magnetic field will also permit better predictions of the propagation (using 3D MHD modeling).

- **Peak Flux - Yes:** By measuring the particle flux at the shock nearer the Sun (between 0.5 to 0.85 AU); these microspacecraft will, *for the first time*, give information that can be used to predict peak fluxes. The radial dependence of the flux will also be *measured for the first time*. Lack of this knowledge is currently a major deficiency in our prediction capability.

Can MSSPM Also Help Develop A Forecast Capability For Highly Energetic Electrons In The Magnetosphere?

- There is not as yet general agreement in the community as to the processes causing very high energy relativistic electrons in the magnetosphere, but they often appear in association with highly varying solar wind velocities and densities.

- These can be measured by MSSPM and propagated to Earth using existing or improved 3D MHD models to develop a forecast capability.

What Are The Most Important Parameters In CME Initiation Of Geomagnetic Storms?

- **Most important for geomagnetic activity is the rate at which the southward component of the interplanetary field is brought up to the magnetopause. The quantities needed for prediction are primarily the solar wind velocity, and the strength and direction of the magnetic field at the magnetopause.**

How Can MSSPM Contribute To New Science Needed To Enhance Our CME Geomagnetic Storm Forecast Capability?

- **The propagation of CMEs can be compared with that expected according to MHD propagation models, and the models can be validated or refined as necessary.**

- **Observation of the CMEs using many of the microspacecraft will lead to understanding the large-scale organization within CMEs.**

How MSSPM Contributes to CME Geomagnetic Storm Forecasts

- The mission will utilize its microspacecraft closest to the sun-Earth line to observe velocities and magnetic fields at distances that are substantially nearer the sun than 1 AU, and alerts will be issued when appropriate.

- The information acquired will be used as initial conditions in the propagation models to forecast the arrival and intensity of major storms at Earth. (The probability of substorms can also be evaluated but not the onset of individual substorms.)

- Much earlier prediction of hazardous storms will result.

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* The affiliations of non-JPL contributors are indicated as follows: AC, Aerospace Corporation; AFRL, Air Force Research Laboratory; CIT, California Institute of Technology; CWSA, C W Swift & Associates, Inc.; JT, James Trainor, Consultant; LASP, Laboratory for Atmospheric and Space Physics; MIT, Massachusetts Institute of Technology; OSC, Orbital Sciences Corporation; SWRI, Southwest Research Institute; TC, Thiokol Corporation; TUB, Technical University of Braunschweig, VTI, Valence Technology, Inc.