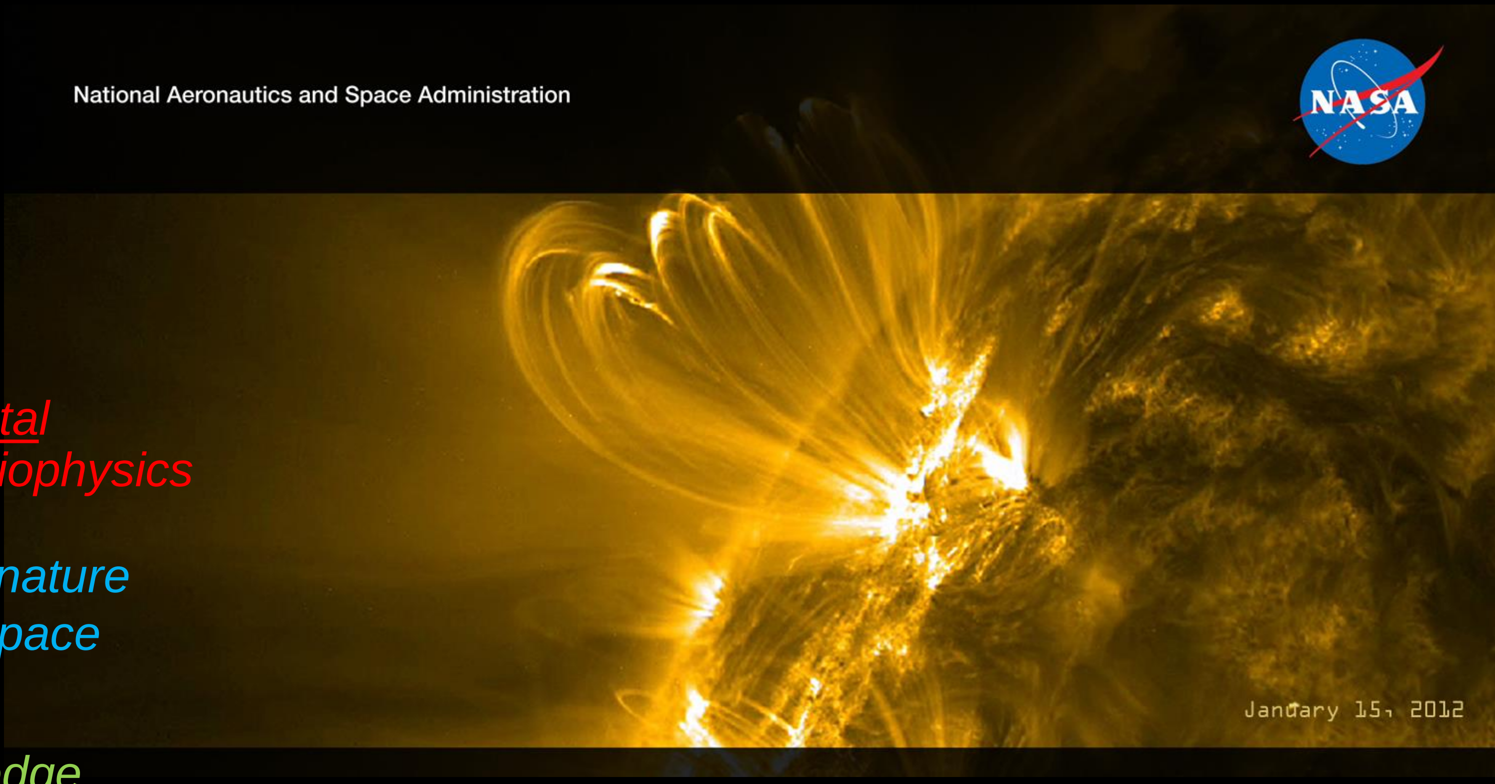
Living with a Star: Science That Matters to People

Living with a Star: Past Accomplishments and Future Promise
(CSSP, Washington DC, October 7th , 2014)

Understanding the Sun and its interactions with the Earth and the Solar System.



Solve <u>fundamental</u> mysteries of Heliophysics

Understand the nature of our <u>home</u> in space

Build the knowledge to forecast space <u>weather</u> throughout the heliosphere

Madhulika Guhathakurta
LWS Lead Program Scientist, Heliophysics
NASA Headquarters

Why Do Science?

For Utility

		No	*Yes*
For Understanding	*Yes*	**Bohr**	**Pasteur**
	No		**Edison**

From Donald Stokes (Woodrow Wilson School for Public and International Affairs, Princeton University)

The Sun-Earth Connection -- Science in the Pasteur Mode

- *How a star works*
- *How it affects humanity's home*
- *How to live with a star*

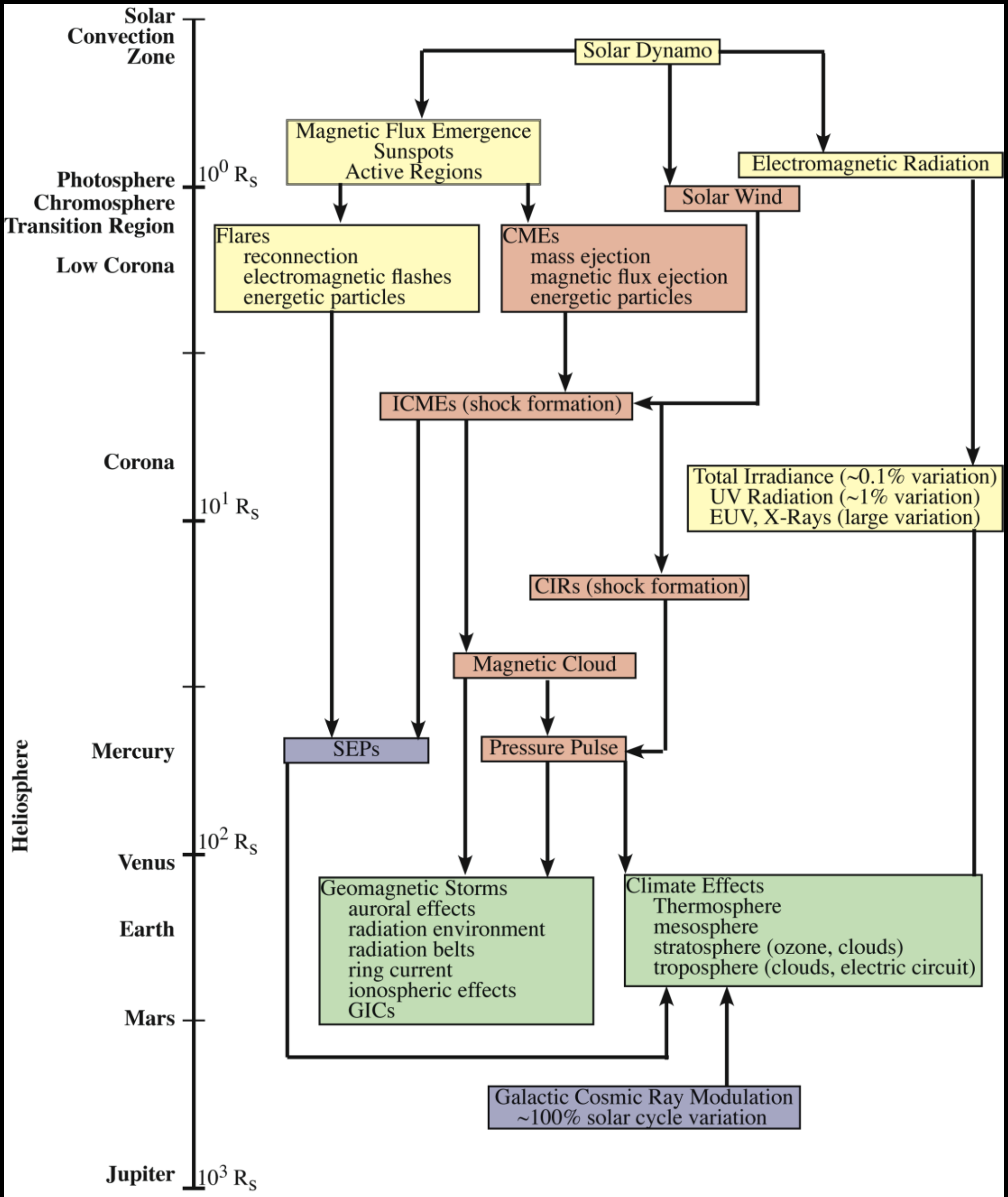
SOCIETAL CONSEQUENCES OF SOLAR VARIABILITY

- **Human Radiation Exposure**
  - Space Station
  - Space Exploration and Utilization
  - High Altitude Flight

- **Impacts on Technology**
  - Space Systems
  - Communications, Navigation
  - Terrestrial Systems

- **Terrestrial Climate**
  - Short Term
  - Long Term

Key Elements of the Strategic Plan



Drivers of Space Weather

Coronal Mass Ejections (CMEs):
- Arrive 1- 4 Days later
- Last a day or two
- Produce Geomagnetic Storms at Earth
- Systems Affected
  - Radio Communications
  - Navigations
  - Electric Power Grids
  - Pipelines

Solar X-Rays:
- Arrive in 8 Minutes
- Last minutes to hours
- Increases ionosphere density
- Systems Affected:

  Radio Communications

  Navigation

High-Speed Solar Wind:
- Common During Solar Minimum
- Enhances Radiation Belts
- Systems Affected
  - Satellite Charging
  - Astronauts

Solar Energetic Particles:
- Arrive in 30 Minutes to 24 hours
- Last several days
- Systems Affected:
  - Astronauts
  - Spacecraft
  - Airlines
  - Radio Communications

SCIENCE FLOWDOWN

Measurement Definition Issues

• What are the required predictive capabilities?

• What parameters should be measured?

• Where is the best place to measure them?

• What models and theory are needed?

• What long-term studies of sources of energy from the Sun should be undertaken to advance understanding of solar effects on climate change?

• What long-term studies are needed to understand the role of the intermediate regions such as the heliosphere, magnetosphere and the upper atmosphere/ionosphere on climate?

• How should development of quantitative models proceed?

LWS TR&T Science Definition Team Report, November 2003

- LWS is a systematic, goal-oriented research program targeting those aspects of the Sun-Earth system that affect society.
- The TR&T component of LWS provides the theory, modeling, and data analysis necessary to enable an integrated, system-wide picture of Sun-Earth connection science with societal relevance.
- The successful implementation of TR&T depends on the adoption of the following principles:
  - ✓ Support data analysis and the development of theories and models that directly address TR&T priority targets, and that have potential societal benefits;
  - ✓ Require all TR&T-supported activities to identify deliverables with clear relevance to the program's goals and establish schedules and milestones for delivery;
  - ✓ Give particular emphasis to cross-disciplinary research;
  - ✓ Support synergistic activities such as workshops and summer schools to facilitate cross-disciplinary activities and to foster the development of a personnel infrastructure for Sun-Earth connection science;
  - ✓ Support the development of certain strategic capabilities that have broad potential use for science and application;
  - ✓ Support model testing and validation;
  - ✓ Support technology and data environment development relevant to LWS goals and objectives;
  - ✓ Support both small and large research proposals.

LWS TR&T Strategic Plan

based on the LWS TR&T Science Definition Team report of November 2003

- LWS is a systematic, goal-oriented research program targeting those aspects of the Sun-Earth system that affect life and society.
- The TR&T component of LWS is to provide the theory, modeling, and data analysis necessary to enable an integrated, system-wide approach to LWS science.

TR&T Supports:

Focused Science Teams
Strategic Capabilities
Cross-cutting Workshops
Summer Schools

The LWS Targeted Research and Technology (TR&T) Program

GOAL OF LWS:

- Develop the science understanding necessary to enable the US to address those aspects of the connected Sun-Earth System that directly affect life and society.

CHALLENGES:

Science: Must achieve system science
- Integrate knowledge across LWS missions
- NEW concept for existing science community
- Demands new methodology

Relevance: Must deliver concrete benefits to life and society
- Again NEW to existing science community

Personnel: Must develop cross-disciplinary scientists
- LWS demands Heliophysicists, not solar or magneto or …
- But universities geared toward discipline science
- LWS Program required to define the field and the practice of Heliophysics

TR&T CHALLENGEs:

- Implement revolutionary programs with disparate disciplines
- Continuously evolve TR&T as LWS missions, science, user community needs and community progress

SOLUTION:

TR&T Steering Committee

- Community committee selected annually by NASA HQ
- Provides monitoring and guidance
- "Learn as you go" adjustments to program

THE TR&T – SOLUTION TO LWS CHALLENGES:

Focused Science Topic (FST) Program

- Transformational methodology for achieving system science, but with existing community
  - Delivers most relevant cutting-edge science
  - Develops a cross-disciplinary science field

Strategic Capability (SC) Program

- Delivers models and tools necessary for LWS Goal
  - Also prototypes for eventual operational capability

Infrastructure Building Program

- Foster next-generation Heliophysics science community
  - Develop Heliophysics educational resources for whole community

TR&T GOALS: (from Steering Committees)

- Deliver the understanding and modeling required for useful prediction of SEP variability and GCR modulation at the Earth, Moon, Mars and throughout the solar system.
- Deliver the understanding of how variations in solar radiation, particles and magnetic fields contribute to global and regional climate change.
- Deliver the understanding and modeling required for effective forecasting/specification of inner magnetospheric radiation and plasma.
- Deliver understanding and predictive models of upper atmospheric and ionospheric coupling above and below.

The TR&T Focused Science Topic (FST) Program

TR&T Solution to SCIENCE Challenge:

- Implement FST Program – **transformational** approach to achieving system science

FST Methodology:

1. Steering Committee identifies major Science Topics impeding progress on LWS objective; NASA HQ selects subset for NRA
2. Community proposes individual investigations that attack most promising aspects of major Topics
3. Selected individual investigations coordinated into Focused Science Team to make progress on whole Topic

Benefits to LWS:

- Directs resources at science problems most critical to LWS – higher payoff for investment
- Attacks major cross-disciplinary science problems, not possible with usual R&A programs
- Obtains system-science while retaining effectiveness of individual investigations with specialized expertise
- Affords complete flexibility in type and scope of Topic (basic science, applied oriented, …); selected Topics updated annually
- Allows new missions and knowledge gained from previous FSTs to be incorporated into new Topics

Benefits to Science:

- Builds cross-disciplinary science community that can attack large-scale problems – critically important for establishing the field of Heliophysics
- Allows science community to give NASA input on science directions for LWS – unique and effective partnership
- Allows individual investigators to propose studies that they can do best, while still advancing system science
- Forms new science collaborations; investigators team with best individuals, as selected by peer-review process, across whole Heliophysics discipline

Progress:

- 40 FST Teams over 9 years, most cross-disciplinary
- Topics included theory, data analysis, and modeling
- Delivered both new understanding and new models on all four TR&T objectives
- Fostered system science and forged Heliophysics community

Plans:

- Science and community advanced to point where self-selected Team proposals now possible
- FSTs with direct relevance now possible e.g., mitigating SEPs effects, predicting GICs, etc

The TR&T Strategic Capability (SC) Program

TR&T Solution to RELEVANCE Challenge:

- Implement SC Program – new paradigm for LWS model development
- Effective partnership between NASA and the NSF

SC Methodology:

1. Steering Committee identifies large-scale models; both LWS critical and ripe for development
2. Steering Committee defines detailed properties of models and schedule for delivery to CCMC
   - All models reviewed after 3 years for continuation to final 2 years
3. Community assembles proposing development Teams

Benefits to LWS:

- Delivers models/capabilities that have clear relevance
  - Direct path for transitioning to operations
- Develops capabilities for transitioning mission data to operations
  - e.g., SDO magnetic field for solar wind models
- Delivers models to CCMC that are most critical to science community for further studies
- Transitions knowledge gained from FSTs into useful capabilities
- Modular, flexible approach allows for continuous updating of capabilities as knowledge base increases

Benefits to Science:

- Provides the whole Heliophysics science community with access to the best state-of-art models
  - Especially useful for small university groups and for the training of new researchers
  - Greatly facilitates system science studies
- Provides opportunity to science community to develop advanced computational models
  - Not possible with usual R&A programs
- Critical support for LWS missions
  - Pathway for incorporating LWS mission data into useful models

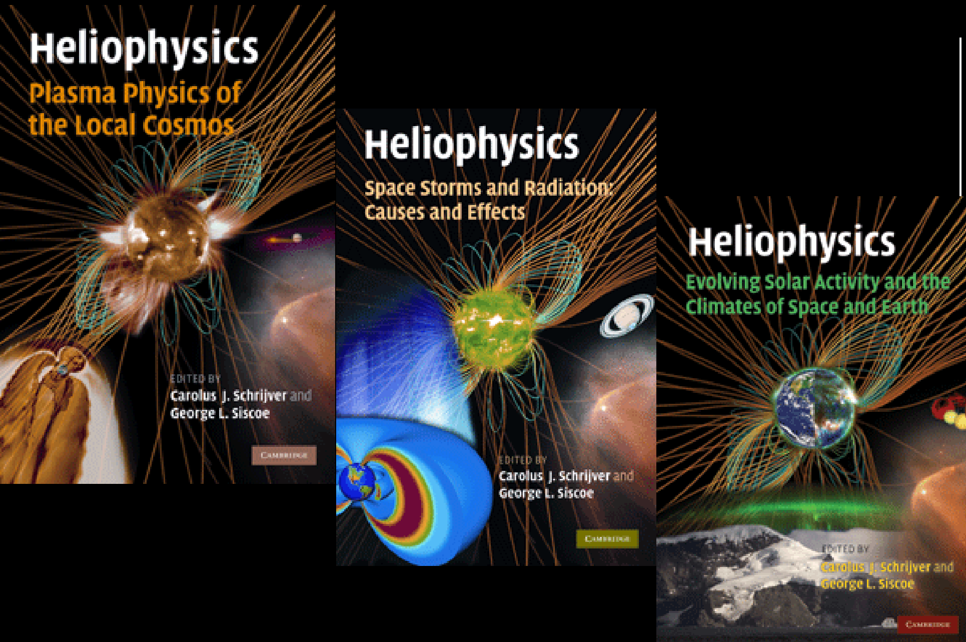
Progress:

- 16 Strategic Capabilities over 9 years
  - 8 selected in 2012
- Cover complete Sun-Earth system, all 4 TR&T Goals
- All SCs to date delivered specified objectives, or better
  - All passed third year review
- Widespread and increasing use by community through CCMC.

Plans:

- Extend programs to allow proposing Teams more flexibility in defining detailed properties of SCs
- Extend toward predictive models with direct utility

The TR&T Infrastructure Building (IB) Program



Benefits to Science:

- Provides effective mechanism for dissemination of Heliophysics science to new researchers
  - Especially important to small single-discipline university groups
- Instructs new researchers on using LWS Strategic Capabilities and on analyzing LWS mission data
  - Greatly enhances quality of early-career research
- Exposes new researchers to operations and to methods for transitioning science to capabilities
- Supports exchange of new science knowledge and science tools

TR&T Solution to PERSONNEL Challenge:

- Implement new opportunities for early-career researchers, with system science as focus
- Develop teaching tools that define field of Heliophysics

Methodology:

1. Offer Postdoctoral Fellowships requiring cross-disciplinary research topics
   - Encourage cross-institution fertilization
2. Establish permanent summer school with Heliophysics system science as curriculum
   - Develop textbooks for widespread use
3. Encourage cross-disciplinary workshops

Benefits to LWS:

- Helps define the field of Heliophysics and grows system science community
- Fosters science community with interest in relevance, critical for progress on LWS Goal
- Establishes Heliophysics as attractive field for new science talent
- Promotes use of LWS mission data and tools by early-career scientists
- Breaks down communication barriers dividing usual disciplines
- Establishes new cross-disciplinary collaborations

Societal Needs

- Power Grid
- Energetic Particles
- Particle Precipitation
- HF Communication
- Single-Frequency Navigation
- Dual-Frequency Navigation
- Safety of Human and Robotic Explorers in Space

Current Physics Understanding

- Climatology (background state) has the measurements available for characterization
  – Research into mechanisms continues
- Weather (disturbed state) includes solar and geospace storms, plasma structures, wave activity, and plasma instabilities
  – Weather characterization and mechanism is main research focus of community

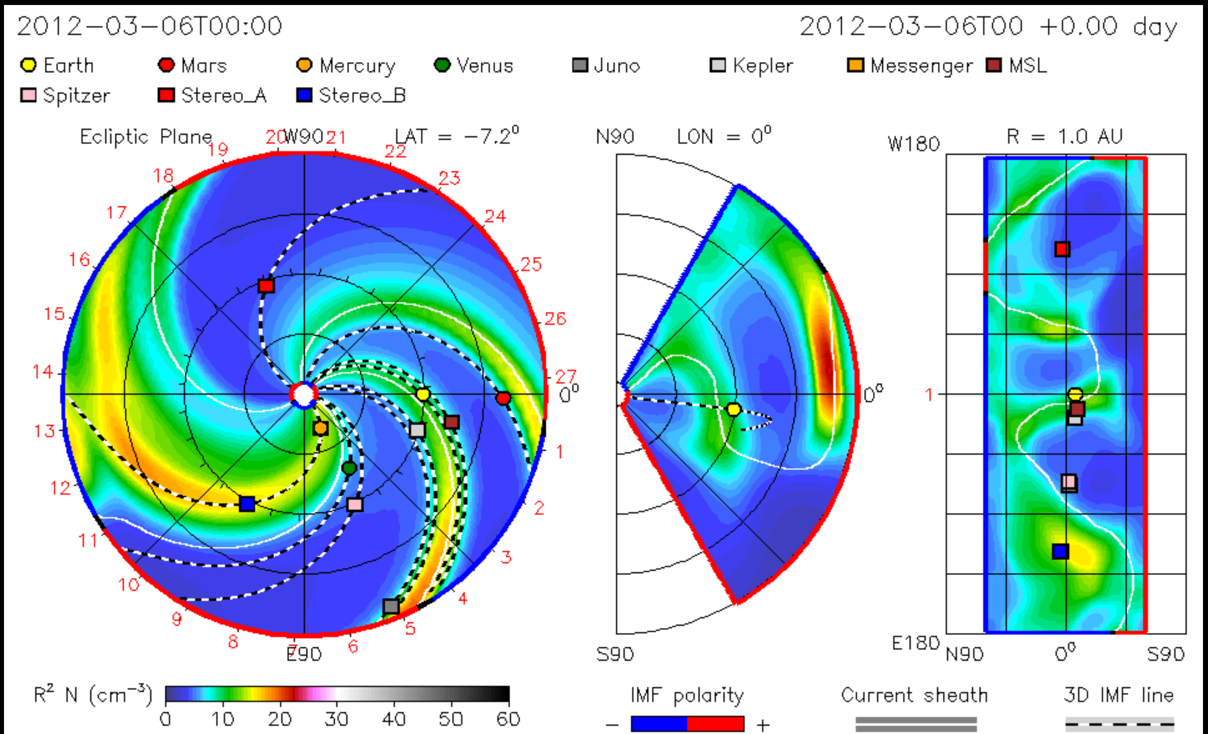
Modeling status

- Models now can simulate the progress of a disturbance from the Sun to the Earth
- Have we captured the physics?
- How well are subgridscale and boundary conditions parameterized?
- How accurate are the models?
- How acccurate and robust are predictions?

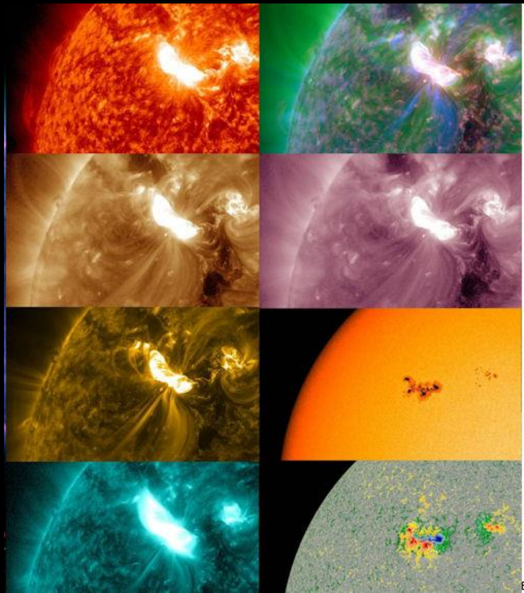
Interplanetary Space Weather & Climate: A New Paradigm

NASA and other space agencies have begun to expand their research into the solar system. **Probes are now orbiting or en route to Mercury, Venus, the Moon, Mars, Ceres, Saturn, and Pluto—and it is only a matter of time before astronauts are out there too.** Each mission has a unique need to know when a solar storm will pass through its corner of space.

An intense episode of solar activity **in March 2012 drove this point home. It began on 2 March with the emergence of sunspot AR1429. For the next 2 weeks, this active region rotated across the solar disk and fired off more than 50 flares, 3 of which were X-class flares, the most powerful type of flare.** By the time the sunspot finally decayed in April 2012, it had done a 360-degree pirouette in heliographic longitude, hitting every spacecraft and planet in the solar system at least once with either a coronal mass ejection or a burst of radiation. **This extraordinary series of solar storms, referred to as the "St. Patrick's Day storms" caused reboots and data outages on as many as 15 NASA spacecraft.**



This highlights NASA's need for interplanetary space weather forecasting.



Reasons for developing this capability may be divided into three pressing areas:

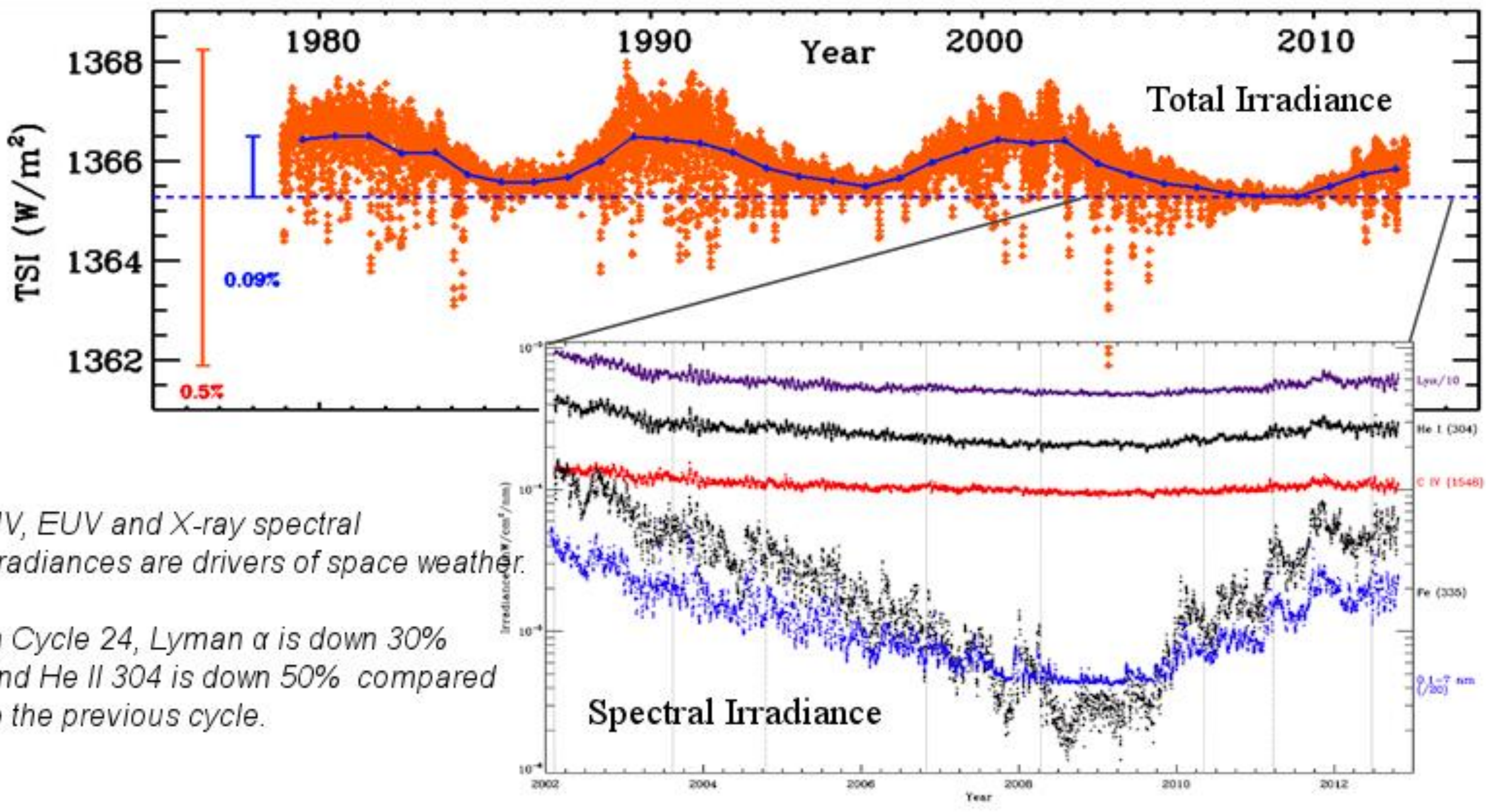
Human safety is of paramount concern. At the moment, humans are confined to low-Earth orbit where the planetary magnetic field and the body of Earth itself provide substantial protection against solar storms. Eventually, though, astronauts will travel to the Moon, Mars and beyond where natural shielding is considerably less.

Spacecraft operations are also key. Energetic particles accelerated by solar storms can cause onboard computers to reboot, introduce confusing noise in cameras and other digital sensors, or simply accumulate on the surface of a spacecraft until a discharge causes serious problems.

Scientific research could be the greatest beneficiary of interplanetary space weather forecasting. What happens to asteroids, comets, planetary rings and planets themselves when they are hit by solar storms? Finding out often requires looking at precisely the right moment.

Signs of a Weakening Cycle: Total and Spectral Solar Irradiance

Total Solar Irradiance is up only half of its rise in the last three cycles.



UV, EUV and X-ray spectral irradiances are drivers of space weather.

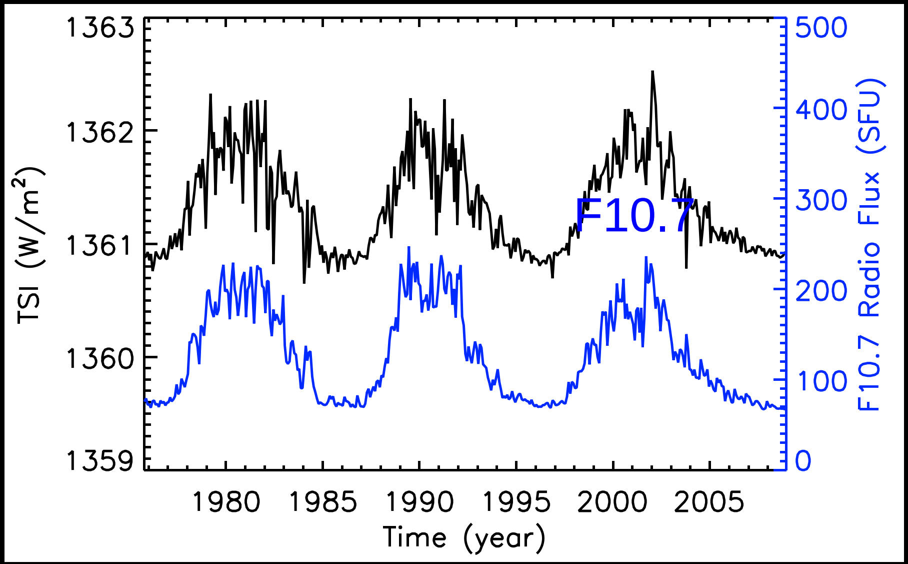
In Cycle 24, Lyman α is down 30% and He II 304 is down 50% compared to the previous cycle.

Sun Climate Connection

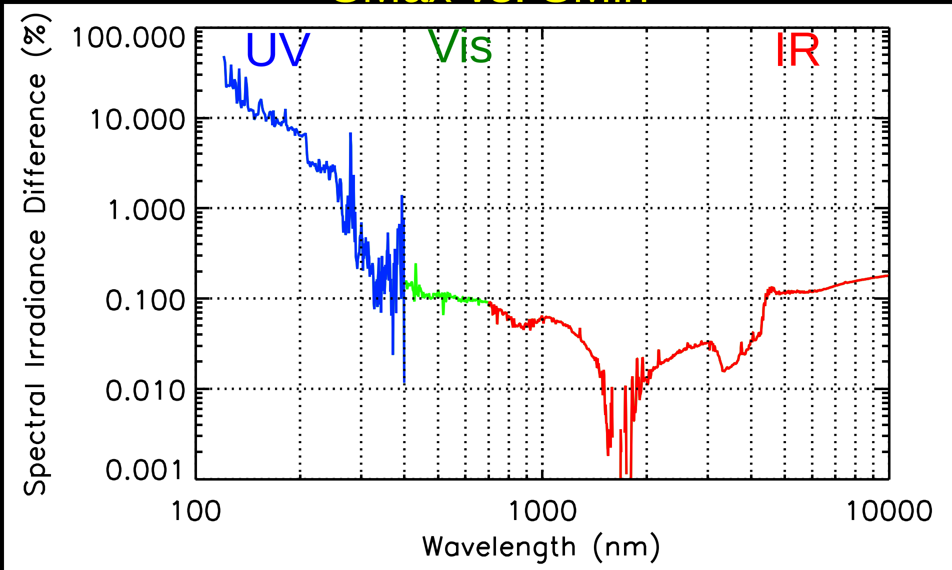
As the scope of space weather forecasting expands to other planets, it is also expanding in directions traditionally connected to climate research. Climate refers to changes in planetary atmospheres and surfaces that unfold much more slowly than individual storms. There is no question that solar activity is pertinent to climate time scales.

The radiative output of the Sun, the size and polarity of the Sun's magnetic field, the number of sunspots, and the shielding power of the Sun's magnetosphere against cosmic rays all change over decades, centuries, and millennia.

Total Solar Irradiance (TSI)



Spectral Solar Irradiance (SSI): SMax vs. SMin



Small variations in the visible (0.1%), but big changes in the UV.

As the solar cycle unfolds in an unexpected way, it is important to remember that

Space Weather Swings Between Extreme Effects & Occurs at All Phases of the Solar Cycle

Solar La Niña
(low sunspot number)

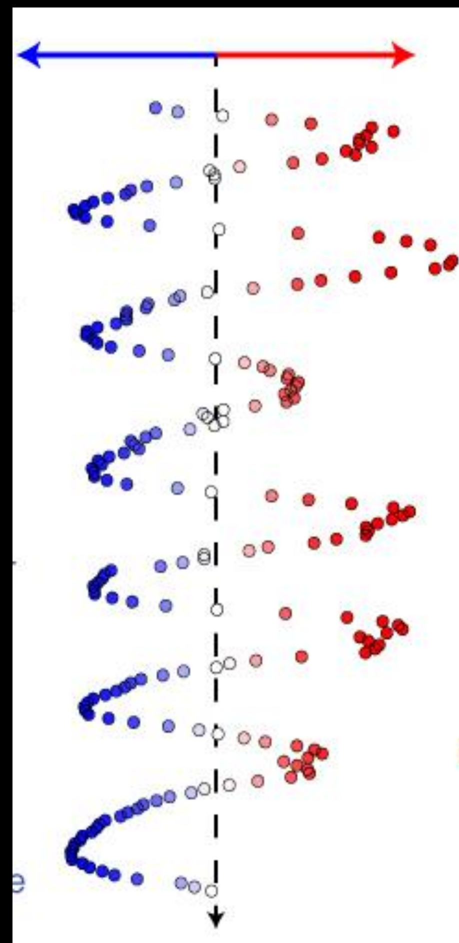
extreme galactic cosmic rays

rapid accumulation of space junk

sharp contraction of the heliosphere

collapse of the upper atmosphere

total solar irradiance changes



Solar El Niño
(high sunspot number)

super solar flares

extreme solar "cosmic rays" (energetic particles)

radio blackouts

extreme geomagnetic storms

power grid impacts – power blackouts

solar wind streams hit Earth

Illustration shows smoothed monthly sunspot counts from the past six solar cycles plotted horizontally instead of vertically. High sunspot numbers are in red and on the right, low sunspot numbers are in blue and on the left. Associated with each high and low sunspot numbers are different space weather impacts experienced at Earth (*Image: Guhathakurta, M. et al, "The Solar Cycle Turned Sideways," Space Weather, Wiley, doi: 10.1002/swe.20039*
)

Looking Forward

Ultimately, expanding the reach of space weather & climate forecasts throughout the solar system will require advances in theory, observations, and computing power.

Recently published series of three volumes entitled the "Heliophysics Lecture Series that deal with this subject matter and the facility called the Community Coordinated Modeling Center (CCMC) are laying the groundwork for the accurate interplanetary forecasts using physics-based models.

The combination of two can really help in a big way to move this interdisciplinary field forward.

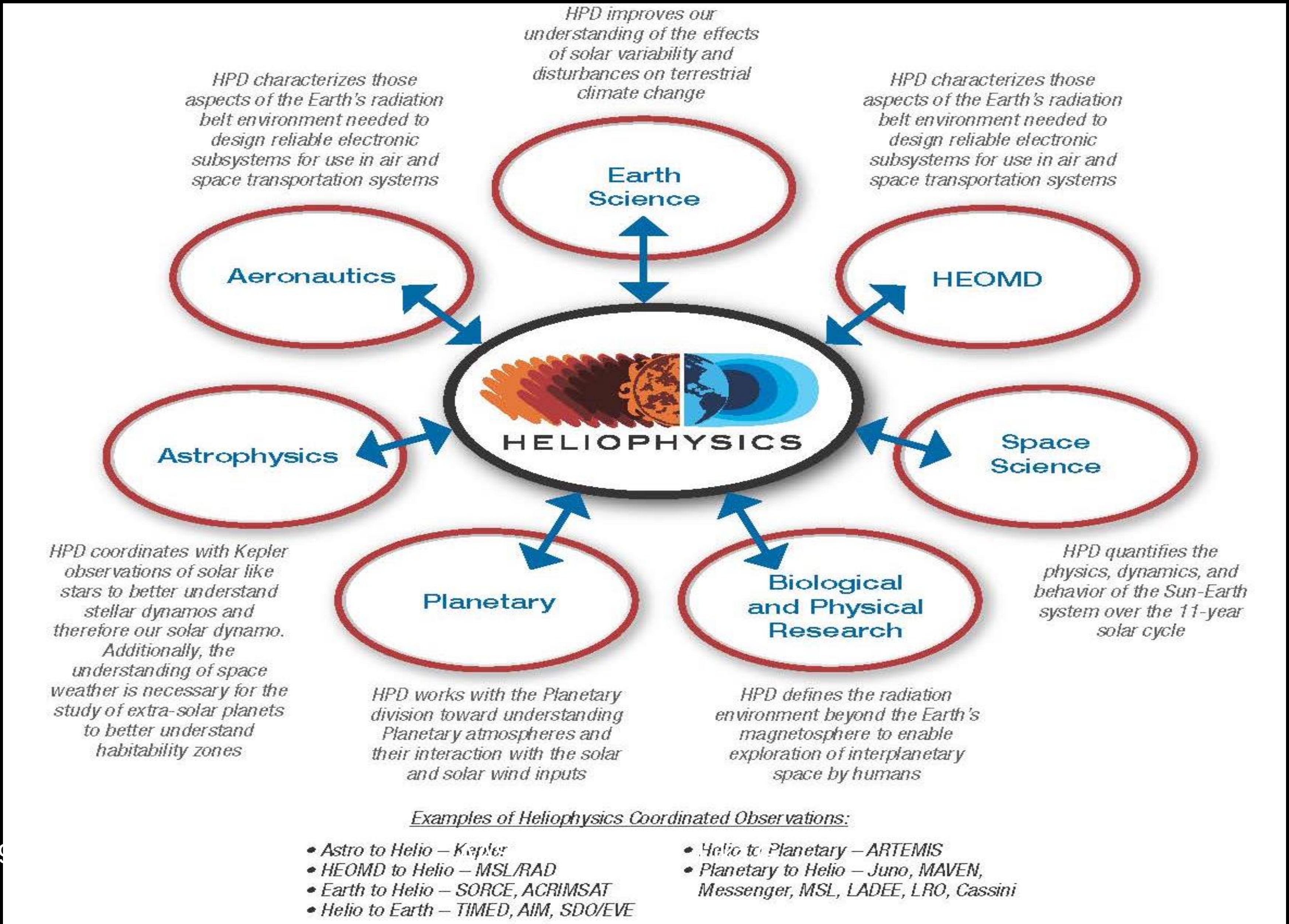
LWS future viewed in the context of the past (one solar cycle…or so)

- TR&T SDT, 2003 and on-going
- Launched SDO, 2/2010
- Launched RBSP, 8/2012
- Developed curriculum and Heliophysics Text Books
- Established Eddy Fellowship for early career scientists
- Established Heliophysics Summer School
- Started ILWS as an inter agency cooperation in 2003
- Started Space Weather as a regular agenda item at UNCOPUOS

LWS Future: Short term

- Increasing emphasis on future FSTs on science focused on societal impacts including sun-climate.
- 4.2 M/year effort of strategic capability (with NSF) to fill gaps and develop end to end space weather models.
- Maximize scientific return from SDO & Van Allen Probes.
- Lead the UN effort on Space Weather
- Initiate more inter-agency and international partnership.
- Develop more cross-directorate partnership within NASA.
- Establish COSPAR/ILWS Space Weather Roadmap Study.

Heliophysics/LWS Coordination with HEOMD, Earth, Planetary, and Astrophysics



Future: Medium Term

- Solar Probe Plus
- Solar Orbiter Collaboration
- Utilize other ILWS missions such as Aditya from India, Inter-Helio Probe Russia.
- In light of constrained budgetary environment develop appropriate small mission concepts to satisfy space weather model/observational needs.
- Implement a robust sun-climate program utilizing feedback from the NRC report and in partnership with NSF and ESD.
- Invest in Strategic Capability emphasizing more societal impacts.
- Next text book from the summer school on Comparative Heliophysics.
- Develop curriculum for 4 year degree colleges
- Continue developing the interdisciplinary science of "Interplanetary Space Weather"

Looking Forward: O2R: High Priority Goals for Space Weather Research

From Rodney Veireck

- Forecasts of solar flares (timing and magnitude)
- Forecasts of Solar Energetic Particle (SEP) events and radiation storms at Earth
- Specification and forecasts of the radiation levels at LEO and aircraft altitudes
- Forecasts of Bz (z component of the magnetic field) with a CME when it arrives at Earth
- Spatially resolved forecasts of geomagnetic storm impacts
- Forecasts of the location and intensity of the Aurora
- Forecasts of ionospheric scintillations and TEC gradients

Looking Forward: New HSO Components

Addition of new HSO component where each component need not carry a comprehensive payload

- The network can grow serendipitously, with key measurements made on distributed platforms
- Single instrument Missions Of Opportunity (MOOs)
- Cubesats dedicated to one or two instruments
- Individual measurement sets add value by complementing the existing network

In addition, we need techniques to assess the value of additional components to the HSO as a whole

- Models of data assimilation effectiveness
- What is the minimum infrastructure?
- How can we assess and maintain system reliability

“Nature, at its most fantastic…”