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The Integrated Science Investigation of the Sun (ISIS): Energetic Particle Measurements for the Solar Probe Plus Mission

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Abstract: One of the major goals of NASA's Solar Probe Plus (SPP) mission is to determine the mechanisms that accelerate and transport high-energy particles from the solar atmosphere out into the heliosphere. Processes such as coronal mass ejections and solar flares, which peak roughly every 11 years around solar maximum, release huge quantities of energized matter, magnetic fields and electromagnetic radiation into space. The high-energy particles, known as solar energetic particles or SEPs, present a serious radiation threat to human explorers living and working outside low-Earth orbit and to technological assets such as communications and scientific satellites in space. This talk describes the Integrated Science Investigation of the Sun (ISIS) - Energetic Particle Instrument suite. ISIS measures key properties such as intensities, energy spectra, composition, and angular distributions of the low-energy suprathermal source populations, as well as the more hazardous, higher energy particles ejected from the Sun. By making the first-ever direct measurements of the near-Sun regions where the acceleration takes place, ISIS will provide the critical measurements that, when integrated with other SPP instruments and with solar and interplanetary observations, will lead to a revolutionary new understanding of the Sun and major drivers of solar system space weather.

Keywords: instrumentation, solar energetic particles, suprathermal particles.

1 Introduction

NASA's Solar Probe Plus (SPP) mission has a planned launch date in 2018 and will be the first "mission to a star". Over more than six years, using seven Venus flybys, SPP will orbit closer and closer to the Sun, getting to within 5.9 million km (10 solar radii) of the Sun's surface in 2024, more than eight times closer than any previous spacecraft. Solar Probe Plus' main three scientific goals are to 1) trace the flow of energy that heats the solar corona and accelerates the solar wind; 2) Determine the structure and dynamics of the plasma and magnetic fields at the sources of the solar wind; and 3) Explore mechanisms that accelerate and transport energetic particles [1].

In September 2010, NASA announced the selection of four SPP instrument investigations and an SPP Observatory Scientist investigation. This paper describes the selected portion of one of the SPP instrument investigations, the Integrated Science Investigations of the Sun (ISIS), which consists of a suite of two energetic particle instruments. The primary science of ISIS is the origin and transport of solar energetic particles (SPP Goal 3). Testing, discriminating, and refining SEP acceleration models is difficult at 1 AU due to separation from the sources and associated mixing during transport. The Helios mission demonstrated the advantages of venturing closer to the Sun to investigate SEP processes near their origin. For example, what appeared to be a single SEP event at 1 AU on IMP 8 turned out to be at least five separate injections when observed at 0.3 AU by Helios [2].

The SPP scientific goal 3 has been divided into three questions. The first is "What are the roles of shocks, reconnection, waves, and turbulence in accelerating particles?" ISIS helps answer this question by measuring composition and spectra for 1 <= Z <= 28 ions from 0.02 to >100 MeV/nuc which enables accurate identification of SEP seed-particle populations, fractionation patterns, spectral breaks, and other features. ISIS also resolves ^{22}Ne/^{20}Ne, which enables ionic charge states of major shock and flare-accelerated species to be estimated using observed Q/M-dependent fractionation patterns [3,4].

The second goal 3 question is "What are the seed populations and physical conditions necessary for energetic particle acceleration?" ISIS identifies the seed population of individual SEP events by measuring the elemental and isotopic composition, and angular and velocity distributions of the suprathermal and energetic particles. By simultaneously observing the spatial and temporal variations of the seed particles and accelerated energetic ions, ISIS will reveal the energies, conditions, and processes that inject particles into shock acceleration.

Question 3 is "How are energetic particles transported from the corona to the heliosphere?" Processes such as scattering by waves, cross-field diffusion and adiabatic deceleration modify SEP properties during transport to 1 AU. ISIS resolves the origin of temporal variations in SEP events by untangling transport-related effects on spectra, intensities, and abundances.

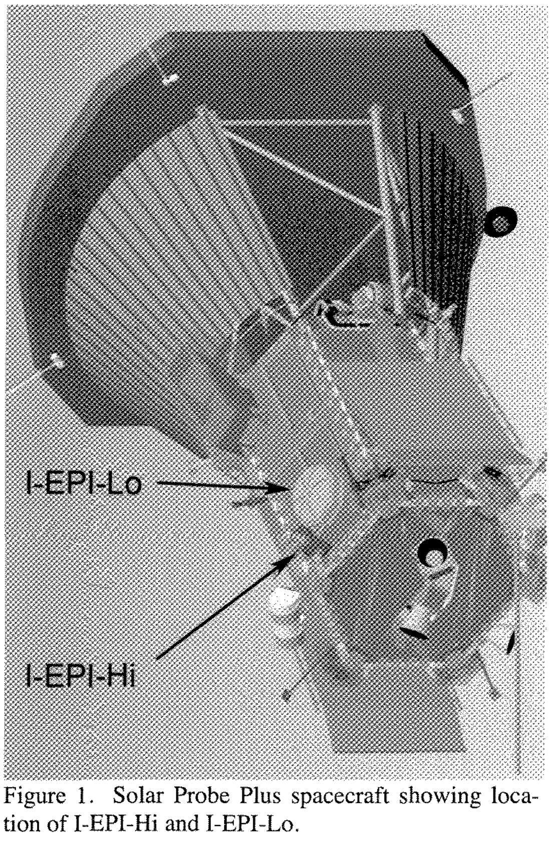

Figure 1. Solar Probe Plus spacecraft showing location of I-EPI-Hi and I-EPI-Lo.

2 ISIS Instruments

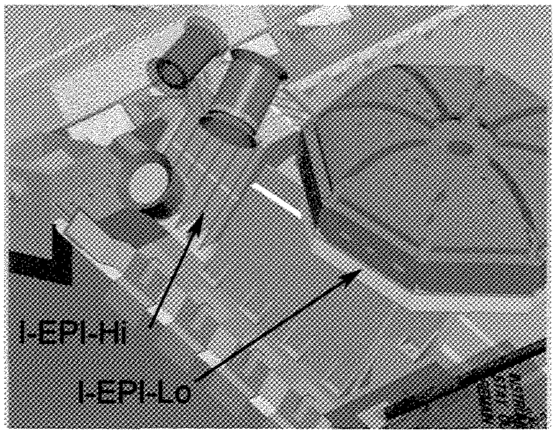

Figure 2. Close up of SPP spacecraft showing the I-EPI-Hi telescopes (HET on top, double-ended LET1 to right, and single-ended LET2 below) and the eight I-EPI-Log wedges.

2.1 I-EPI-Hi

The ISIS Energetic Particle Instrument – High (I-EPI-Hi) measures energetic particle spectra, composition, and angular distributions using the dE/dx vs. E technique (e.g., [5]). The sensor system consists of a double-ended High Energy Telescope (HET) and two Low Energy Telescopes (LETs), one of which is double-ended (LET1) and one of which is single-ended (LET2). Together they cover ~ 1 to > 100 MeV/nucleon for protons and heavy elements and ~ 0.5 to 6 MeV for electrons. The three telescopes are mounted on an electronics box, enabling view directions covering ~50% of the sky (Figure 3).

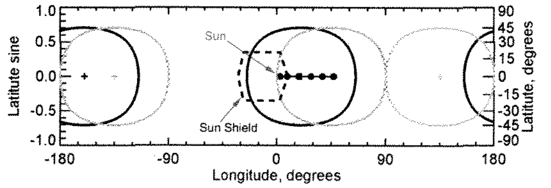

Figure 3. FOV of the I-EPI-Hi telescopes: HET (dark), LET (light). Black points show (from left to right) the average direction of the Parker spiral magnetic field for 400 km/s solar wind velocity at heliocentric distances of 9.5 R_S, 30 R_S, 0.3 AU, 0.5 AU, 0.72 AU, and 1 AU.

HET has a stack of 16 silicon Solid State Detectors (SSDs), LET1 has 9, and LET2 has 7. The LETs achieve a threshold of ~1 MeV/nucleon for ion identification by using new thin front detectors (L0, ~10 micron) and multiple thin windows (~3 micron Si-equivalent total thickness) to protect against UV and dust. The front detectors at both ends of each telescope are segmented into five individually-analyzed active regions (Figure 4) to measure particle arrival directions (~20 x 20 degree sectors) which provide corrections to dE/dx to improve species resolution, and enable accumulation of angular distributions. Most of the detectors have an annular "guard" segment to reject particles that enter or exit through the side of the stack. Segmentation also reduces electronic noise and susceptibility to saturation at high rates and provides redundancy. Each detector stack is contained in a relatively thick-walled collimator to reduce background from out-of-geometry particles.

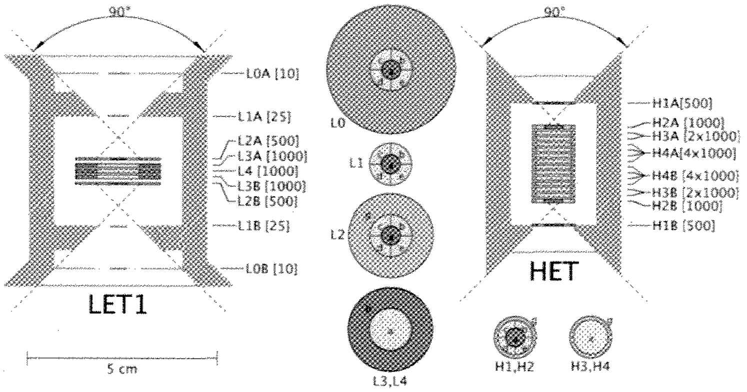

Figure 4. Schematic cross sections of the I-EPI-Hi telescope designs. Detector thicknesses in microns are shown in square brackets. The outer ring on L0 is inactive silicon with the same thickness as the L0 active region, all other detector regions are active silicon. Thick, inactive peripheries and detector mounts are omitted. LET2 is single-ended, closed off below L2B.

For ions, the energy responses of LET and HET overlap, facilitating intercalibration. The HET upper limits for ions are > 100 MeV/nucleon.

Electrons incident from one end of a LET telescope produce no measurable signals in the thin L0 and L1 detectors, but do in the central regions of the thicker detectors. LET1 provides front/back anisotropy measurements for electrons, supplemented by LET2 at 90 degrees.

The geometry factor of I-EPI-Hi is energy dependent and varies from 0.6 cm^2 sr at 1 MeV/nuc to 2.6 cm^2 sr at 10 MeV/nuc to 0.12 cm^2 sr for >100 MeV/nuc. The instrument covers a dynamic range in proton flux from ~ 10^{-4} to 10^6 /cm^2sr-s (1 – 15 MeV). The high end is achieved by using a "dynamic threshold" technique, successfully employed in the STEREO/LET and HET instruments [6], in which the geometrical acceptance for H, He, and electrons is reduced by progressive increases of selected trigger thresholds to reduce dead time while maintaining full geometry for Z>2 ions.

2.2 I-EPI-Lo

I-EPI-Lo is a novel, light-weight, high-heritage Time-of-Flight (TOF) based mass spectrometer that measures energetic electrons (25 – 500 keV) and ion spectra (~ 0.02 – 7 MeV for protons and 0.02 – 2 MeV for heavier ions) and resolves all major heavy ion species and ^{3}He and ^{4}He over much of this energy range and with a large field-of-view (FOV).

I-EPI-Lo consists of eight sensor wedges mounted above an electronics box. It has 80 separate entrances (10 per wedge) spread nearly continuously over 2 pi steradians. This configuration permits full angular distributions without articulation or duty cycle, and maximizes the probability, regardless of the vector direction of the local magnetic field, of measuring the first-arriving, field-aligned ions at the spacecraft.

Over 2 pi steradians, ions generate start-position electrons as they transit thin foils in the entrance apertures, and then strike a stop foil and SSD, yielding angle and E X TOF. Energetic electrons enter the same apertures as the ions, and are detected in a second set of SSDs located behind light- and ion-rejecting cover foils. Incoming ion velocities are determined by measuring the TOF between two thin (100 nm Start, 65 nm Stop) carbon-polyimide-aluminum foils. An ion passing through each of the foils, it produces secondary electrons, which are deflected

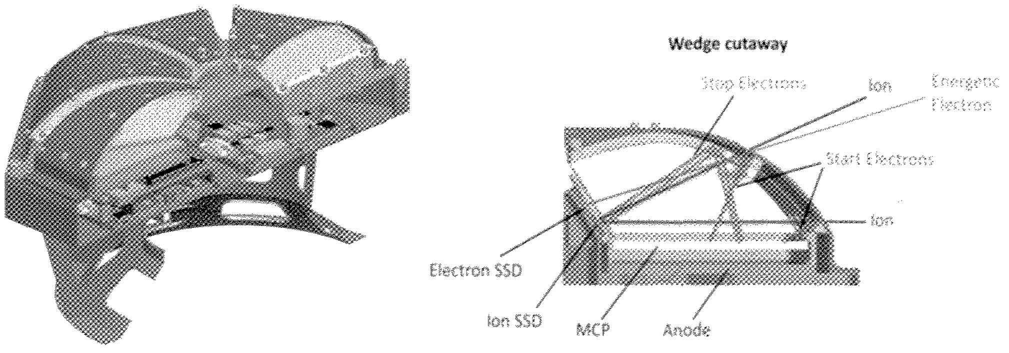

Figure 5. I-EPI-Lo comprises 8 ion-composition wedges mounted on a common electronics box.

toward a microchannel plate (MCP) producing "Start" and "Stop" pulses. The ion entrance angles are determined from the position where the Start electrons strike the MCP and are unique for each entrance foil location. Species determination is done onboard with the ion energy deposited in the SSD, together with velocity from the TOF.

I-EPI-Lo rejects background by requiring coincidence between the start and stop pulses from the TOF, in addition to an energy measurement within appropriate TOF time gates. This rejection is non-linear, and is very effective for background counting rates in individual detectors below ~ 10^6/s; projected singles rates are <= 3 x 10^5/s.

3 Data Products

ISIS will fully cover the energy range from 0.02 to >100 MeV/nuc for all the major ion species and 0.03 to 3 MeV for electrons. Because of power and telemetry constraints, most of the data will be collected during the prime data phase of the SPP orbit, when the spacecraft is less than 0.25 AU from the Sun.

I-EPI-Hi will generate differential energy spectra (>= 6 bins/decade) for H, ^{3}He, ^{4}He, C, O, Ne, Mg, Si, Fe and e^-. Cadence will depend upon species and will vary from 1 second for protons and electrons to 60 seconds for most other ions. The ^{3}He will be well resolved when it is more than 1% of the ^{4}He flux. In addition, important isotope ratios such as ^{22}Ne/^{20}Ne will be determined and less abundant elements including those heavier than iron will be measured. Angular distributions for ions with a resolution of ~20 degrees are determined over the I-EPI-Hi FOV, and coarse anisotropy (front/back) is measured for the electrons. I-EPI-Hi is also sensitive to high energy (>1 MeV) Energetic Neutral Atoms (ENAs) from solar flares [7], and the HET telescope will make observations of neutrons and gamma-rays.

I-EPI-Lo also generates differential energy spectra (>= 6 bins/decade) for H, ^{3}He, ^{4}He, C, O, Ne, Mg, Si, Fe and e^- with a cadence as fast as 1 second. It also resolves ^{3}He . The angular resolution varies over the 2 pi FOV of the instrument from ~ 4 x 7 degrees to 8 x 19 degrees, yielding accurate pitch angle distributions.

All of the ISIS data will be made publically available on the web as soon as the ISIS science team validates the data.

4 Conclusion

The Solar Probe Plus mission will illuminate the origin of the hot corona, the solar wind, and solar energetic particles in ways that simply are not achievable without flying to within ~10 solar radii of the Sun. On SPP, ISIS will explore the inner heliosphere with state-of-the-art energetic-particle sensors and revolutionize our understanding of acceleration, seed particles and particle transport in the heliosphere. This will improve current models and enable the community to advance new models. Almost certainly, we will be surprised by some of the new phenomena observed. Solar Probe Plus will be one of the most exciting and scientifically important missions of our time.

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