

Three-Dimension Heliosphere in EUV

Mapping the Heliopause and 3-D Solar Wind

Mike Gruntman

Department of Aerospace Engineering

University of Southern California

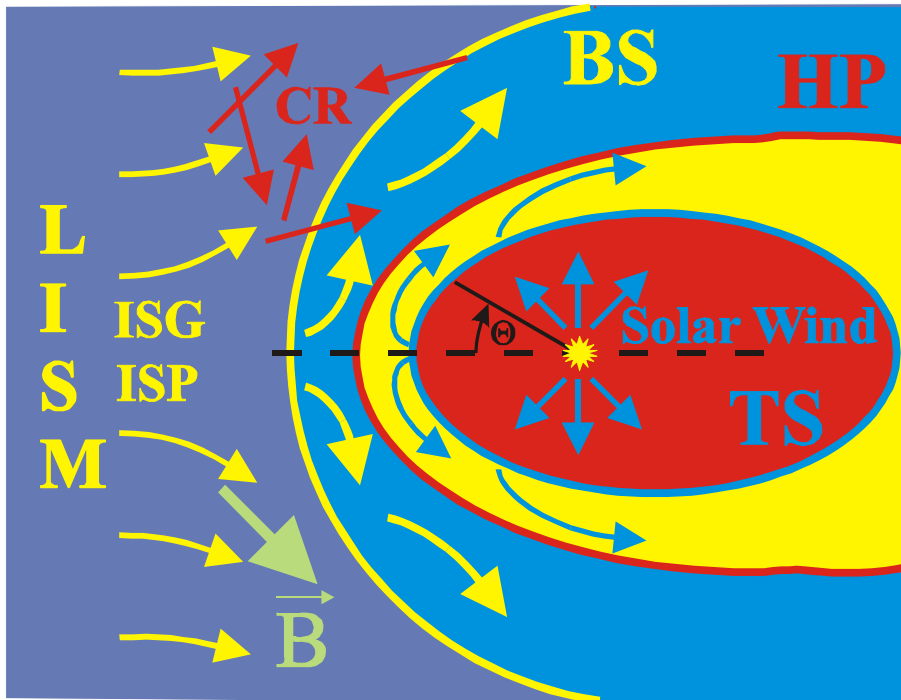
Los Angeles, California

mikeg@spock.usc.edu; tel. 213-740-5536

Solar System Frontier

- ⇒ **How does the Sun and Galaxy interact?**
- ⇒ **What is the nature of the surrounding local interstellar medium (LISM)?**
- ⇒ **What is the structure of the global heliosphere?**
- ⇒ **What is the nature of the interface between the solar wind and the interstellar medium?**
- ⇒ **What physical processes occur there?**

Outer Heliosphere



- Theoretical concept
- Scarce direct (unambiguous) experimental data
 - ⇒ most data indirect
- Uncertainties
 - ⇒ LISM properties
 - ⇒ 3-D solar wind
 - ⇒ physical processes of the interaction

Outer Heliosphere – In-situ Exploration

- **Pioneer 10/11**
 - Terminated
- **Voyager 1/2**
 - V1 at 90 AU (Fall 2003)
 - in subsonic SW flow - ?
 - Operate till 2020-2025
 - 120-140 AU
 - reach heliopause - ?
- **Interstellar Probe**
 - 15-20 years away
- **One (two) directions**
 - **Pioneer 10**
 - downwind (ISW)
 - reached ~half distance to TS
 - **Voyager 1**
 - upwind
 - **Interstellar Probe**
 - upwind
- **Heliosphere is 3-D**

Three-Dimensional Heliosphere

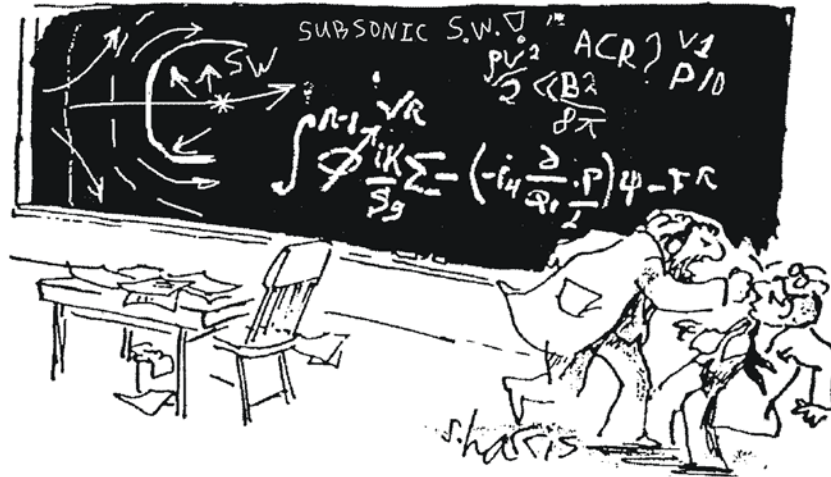
- **Essentially three-dimensional (3-D)**
 - Sun's motion with respect to LISM (*Interstellar Wind*)
 - Asymmetry (in heliolatitude) of the solar wind
 - Asymmetry of the interstellar magnetic field
- **Size of the heliosphere calls for remote techniques**
 - The most desirable remote observations are those when one measures particles that are minimally disturbed by propagation from the heliospheric interface
 - Complementary to in-situ (ground truth) measurements

Outer Heliosphere – Indirect Study

- a) **Interplanetary glow (58.4 and 121.6 nm)**
- b) **Pickup ions**
- c) **Anomalous Cosmic Rays (ACRs)**
Uncertainties of propagation and/or effect of the heliospheric interface
- d) **Direct interstellar He atom detection**
Insensitive to the interface structure
- e) **Spectroscopic observations of nearby stars & ISM**

- 1) weak dependence on the 3D structure of the heliosphere, or
- 2) sensitive to the structure in the upwind direction only.

Experiments/Observations Needed



**You want proof that the heliopause is stable, eh?
I will give you proof!**

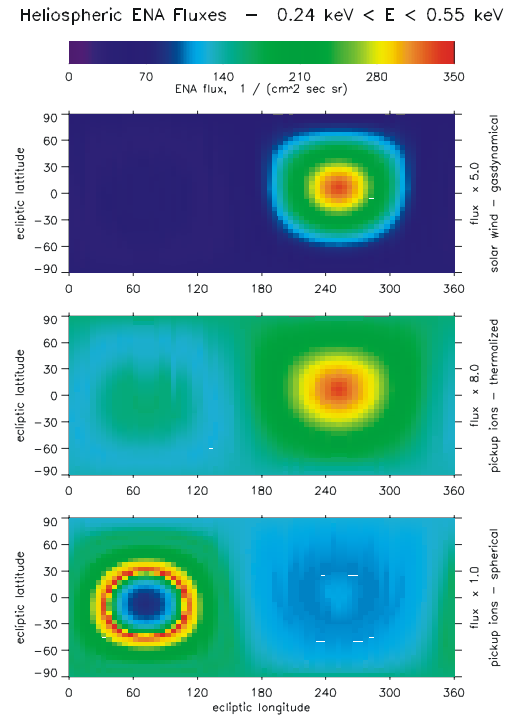
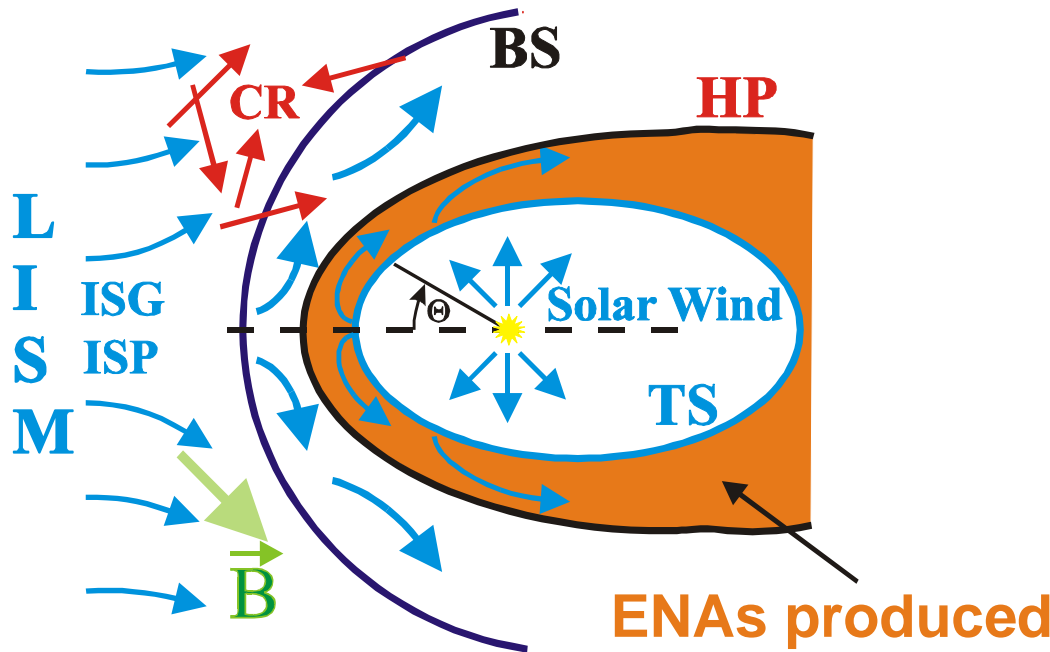
Based on cartoon by S. Harris in *Physics Today*, 1989

- **Fundamentals of our concepts of global heliospheric interactions must be established through complementary direct in-situ and remote observations**

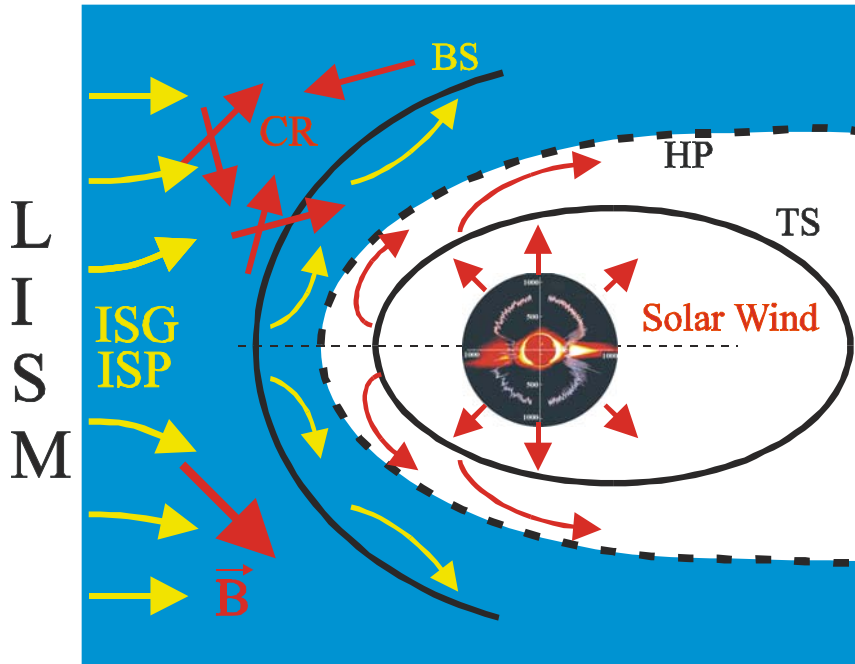
Remote Sensing of the Outer Heliosphere

- **Imaging in energetic neutral atoms (ENAs)**
 - Establish the nature of the termination shock and plasma properties in the heliosheath
 - Concept originated ~1980
 - Instrumentation developed
 - Experiment and mission concept well established
 - Has been and will be proposed as part of the Explorer program
- **Imaging in extreme ultraviolet (EUV)**
 - Establish the shape of the heliopause and probe LISM properties, including ionization state and magnetic field
 - Originated in mid-1990s
 - Concept understood
 - Enabling advancement (~100) of instrumentation required
 - early in development

Heliosphere ENA Imaging



Heliosphere EUV Imaging



- Interstellar plasma much denser than the solar wind
- Interstellar ions would scatter solar line emissions (“glow”) in EUV
- “**Next step**” in probing the heliospheric interface after ENA imaging
- Instrumentation must be advanced

Heliopause Moat

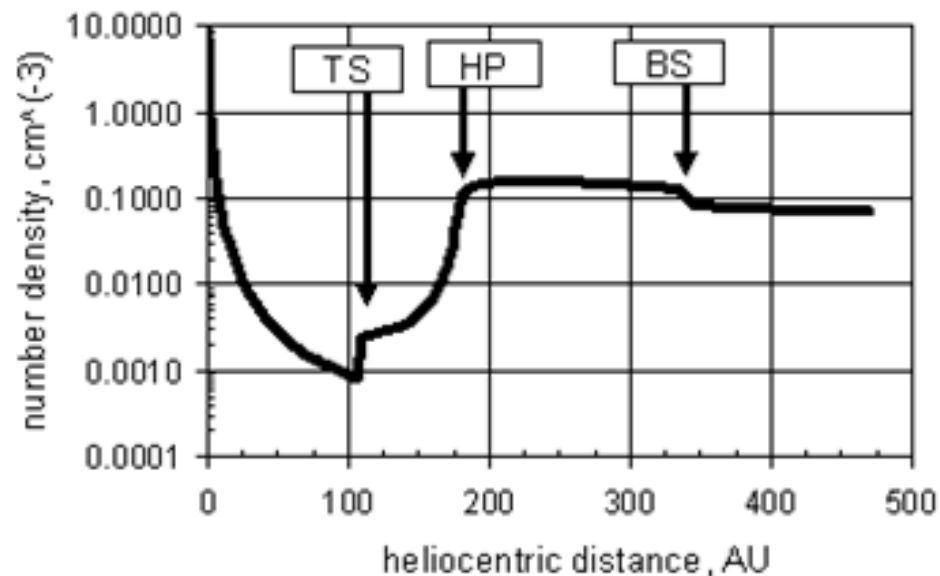
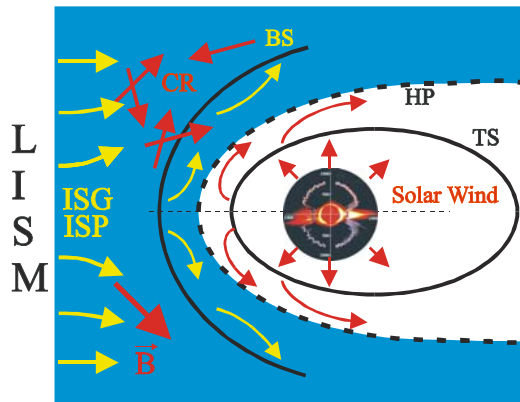


Fig. 4. Heliopause plasma “moat” surrounding the sun: a typical expected heliocentric dependence of the plasma number density in the upwind direction. The arrows indicate the positions of the termination shock (TS), heliopause (HP), and bow shock (BS).

Three Sources of EUV Radiation

1. **Glow of (a) interstellar plasma outside the heliopause and (b) solar wind pickup ions**
2. **Emissions of the solar wind plasma (Doppler-shifted emissions near 30.4 nm)**
3. **Galactic EUV background: line and continuum emissions of hot interstellar plasmas in the *Local Bubble***

1. EUV Glow of I.S. Plasma and P.U. Ions



Glow of (a) interstellar plasma outside the heliopause and (b) solar wind pickup ions

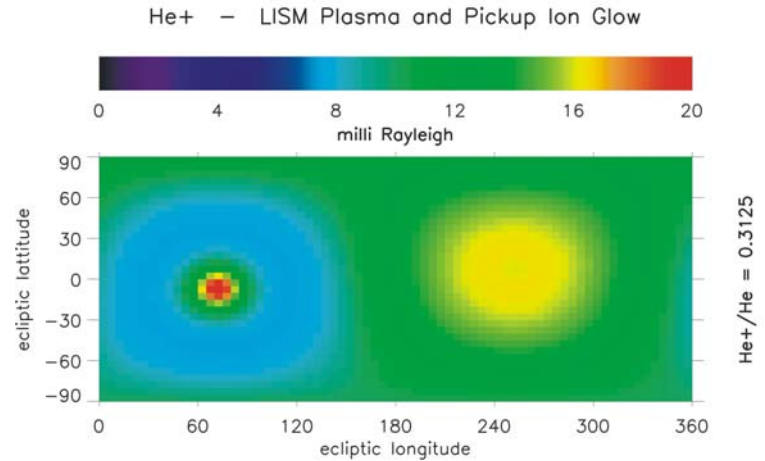
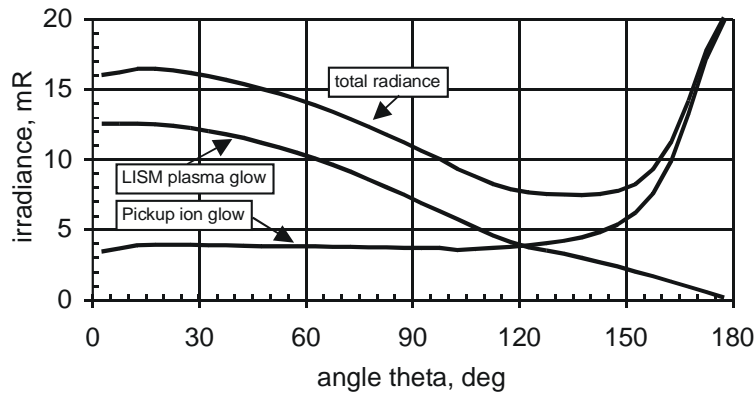
Glow

scattering of solar line emissions by interstellar He⁺ (30.4 nm) and O⁺ (83.4 nm) ions

Imaging

- will map the heliopause
- reveal asymmetry of the interstellar magnetic field

1. EUV Glow of I.S. Plasma and P.U. Ions



$(F_{upwind} / F_{downwind})$ depends on ionization state of He in LISM

Sky maps in O^+ line (83.4 nm): $F \approx 0.5-5$ micro-Rayleighs

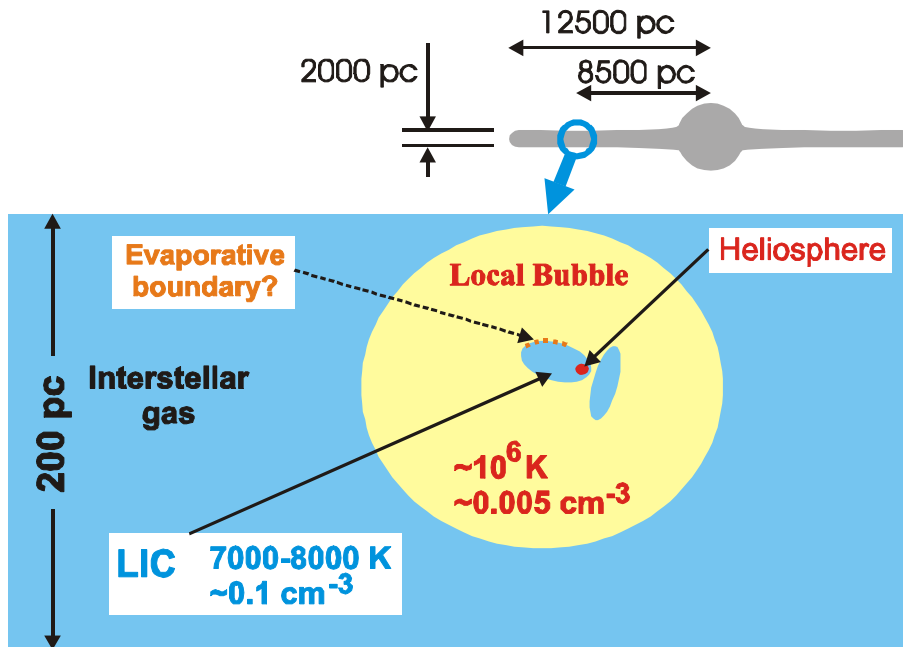
2. Solar Wind Emission

- Charge exchange collisions between the solar wind alpha particles (He^{2+}) and heliospheric atomic hydrogen
 - Unique emission in the 30.4-nm line
- $$\text{He}^{2+} + \text{H} \rightarrow (\text{He}^+)^* + \text{H}^+ \rightarrow \text{He}^+ + \text{H}^+ + h\nu \text{ (30.4 nm)}$$
- Cross section strongly depends on velocity
 - Doppler shifted emissions
 - 0.005 nm (0.05 Å) shift corresponds to 50 km/sec

2. Solar Wind Emission

- **All-sky images in solar wind emissions will reveal the global 3-D flow properties of the solar wind at the moment of observation, including the flow properties in the regions over the sun's poles and on the far side of the sun. (Also important for heliopause mapping.)**
- **The boundary separating the fast (high-latitude) and slow (low-latitude) solar wind can be established remotely, from 1 AU, everywhere in the heliosphere.**
- **Solar wind velocities can be obtained from both the radiance intensities and more precisely directly from Doppler shifts.**

3. Galactic EUV Background



Local Bubble EUV emissions: line and continuum

EUV stellar field

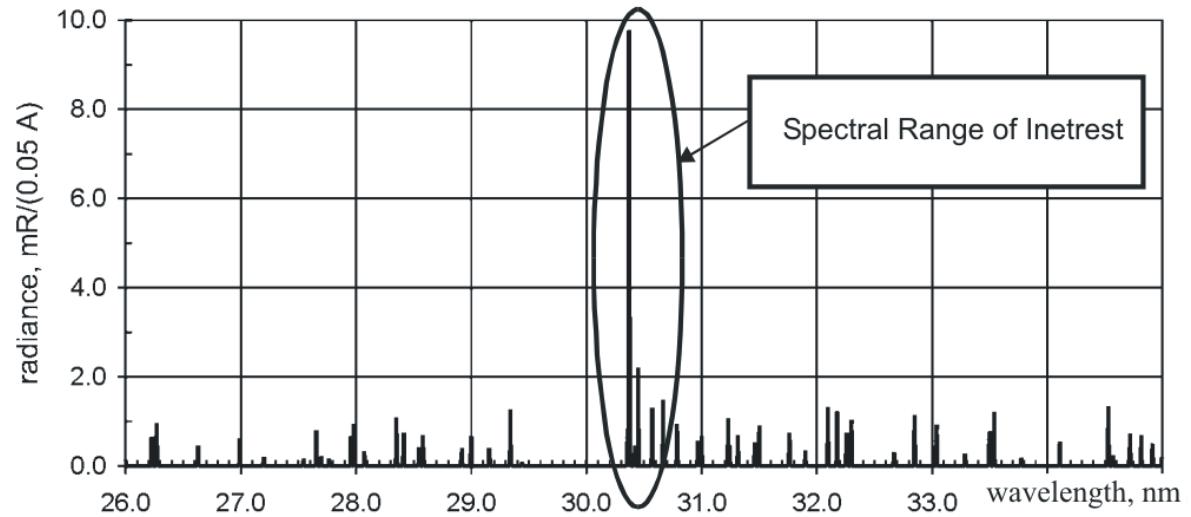
dominates continuum at $\lambda > 20 \text{ nm}$
a few hot white dwarfs [Vallergera, 1998]

Evaporative boundary

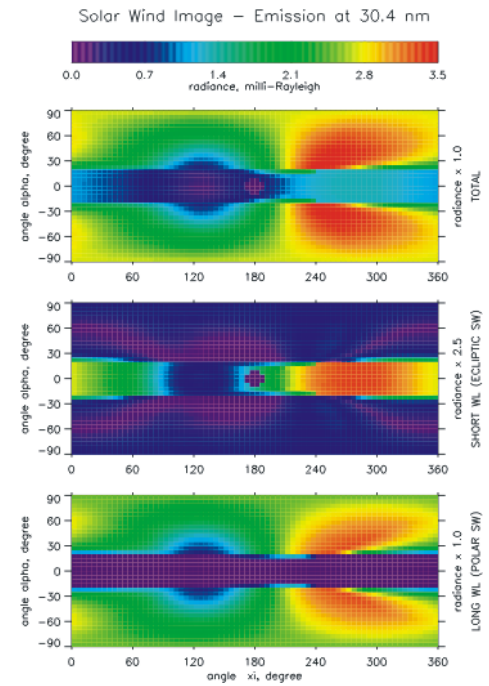
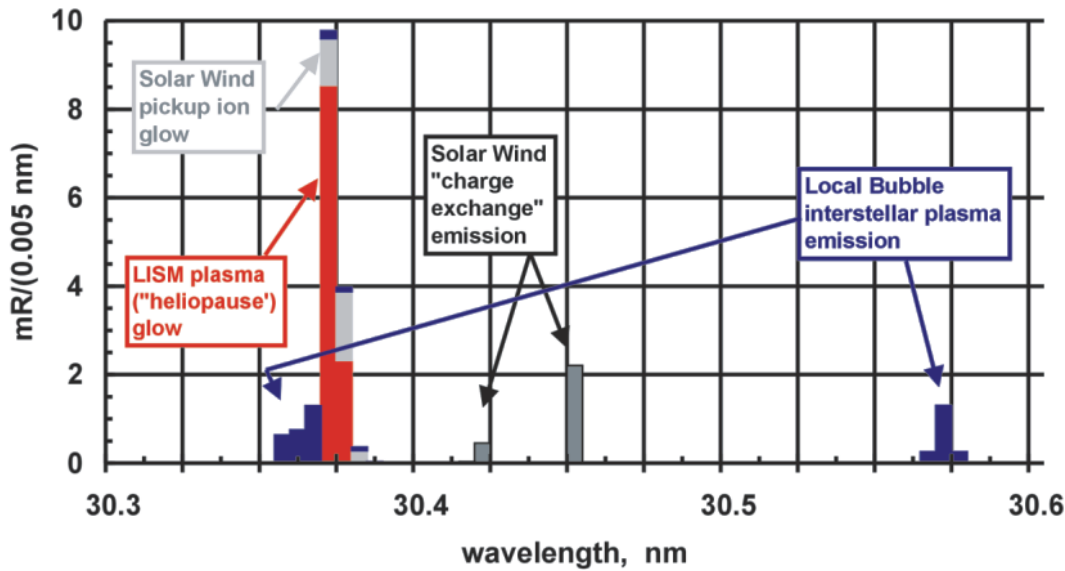
[Frisch and Slavin]
no experimental evidence yet

Spectral Distribution

Expected spectral radiance at 30.4 nm from the Local Buble plasma, solar wind emissions, and glow of the heliopause and solar wind pickup ions.



Spectral Distribution



Imaging Heliosphere in EUV

- **Heliopause mapping**
 - one full-sky image per year
 - heliopause asymmetry (insight to interstellar magnetic field)
 - interstellar plasma flow around the heliopause
 - ionization state of He in LISM
- **Monitoring global solar wind plasma flow**
 - one (almost) full-sky image per week
 - solar wind flow evolution during the solar cycle
 - fast/slow solar wind boundary evolution
 - 1-D North-South 100° swath every 6 hours

Imaging Heliosphere in EUV

- New instrument concept has been developed
 - spectral range: $30.4 \text{ nm} \pm 4 \text{ nm}$
 - can be implemented in other spectral bands
 - angular resolution: $5^\circ \times 5^\circ$
 - spectral resolution: 0.005 nm (0.05 \AA)
 - corresponds to $\sim 50 \text{ km/sec}$ velocity resolution
 - sensitivity: $0.1 \text{ (count/sec)/milli-Rayleigh}$
 - 1 milli-Rayleigh/bin (1σ) in 1000 sec
- Feasibility study has been started
- Will be a powerful tool for study of astrophysical emissions

Key References:

- **EUV Mapping and Imaging**

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- M. Gruntman and H. Fahr, Heliopause imaging in EUV: Oxygen O⁺ ion 83.4-nm resonance line emission, *J. Geophys. Res.*, 105, 5189-5200, 2000.
- M. Gruntman, Mapping the Heliopause in EUV, in *The Outer Heliosphere: The Next Frontiers*, pp.263-271, Pergamon, 2001.
- M. Gruntman, Imaging the three-dimensional solar wind, *J. Geophys. Res.*, 106, 8205-8216, 2001.

- **ENA Imaging**

- M. Gruntman, Energetic neutral atom imaging of space plasmas, *Rev. Sci. Instrum.*, 68, 3617-3656, 1997.
- M. Gruntman, E.C. Roelof, D.G. Mitchell, H.J. Fahr, H.O. Funsten, and D.J. McComas, Energetic neutral atom imaging of the heliospheric boundary region, *J. Geophys. Res.*, 106, 15767-15781, 2001.