- Science
- Mission
- Technology, TRL

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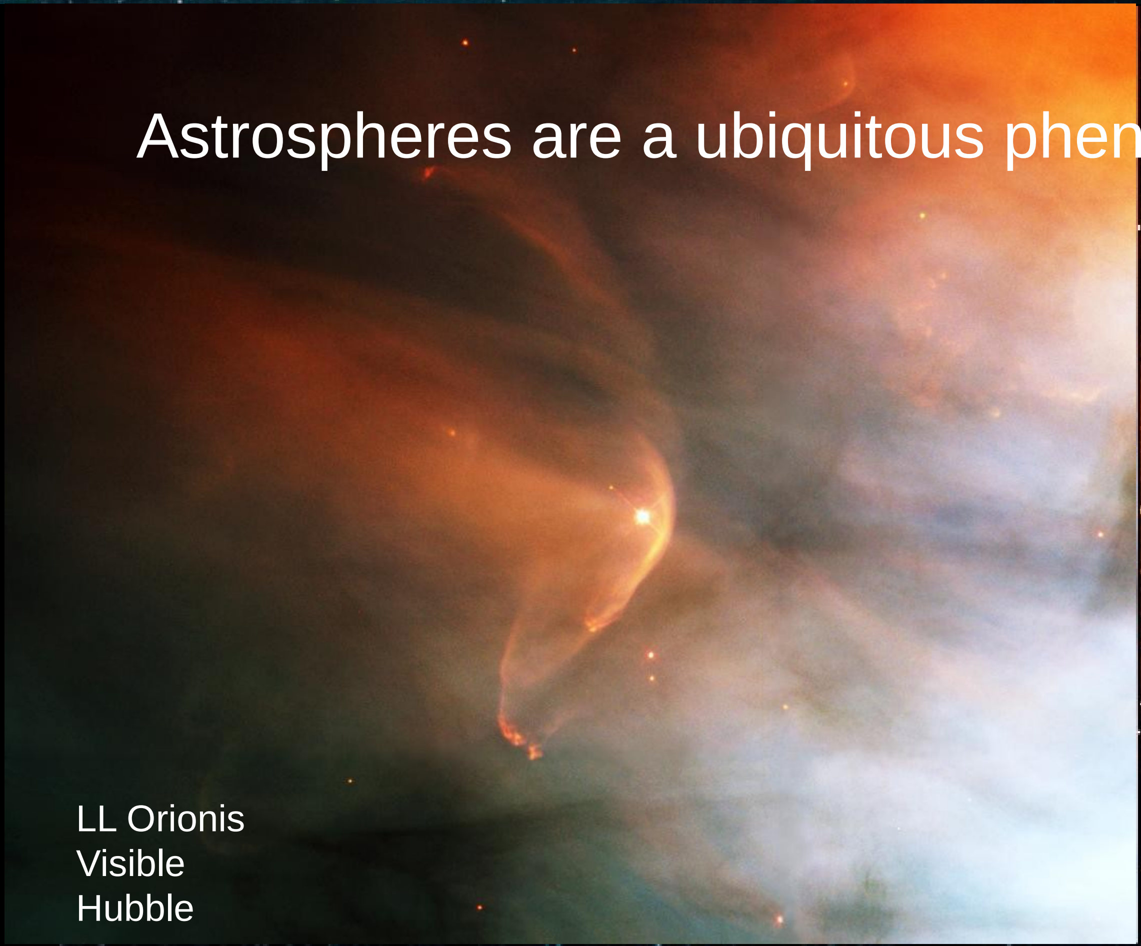
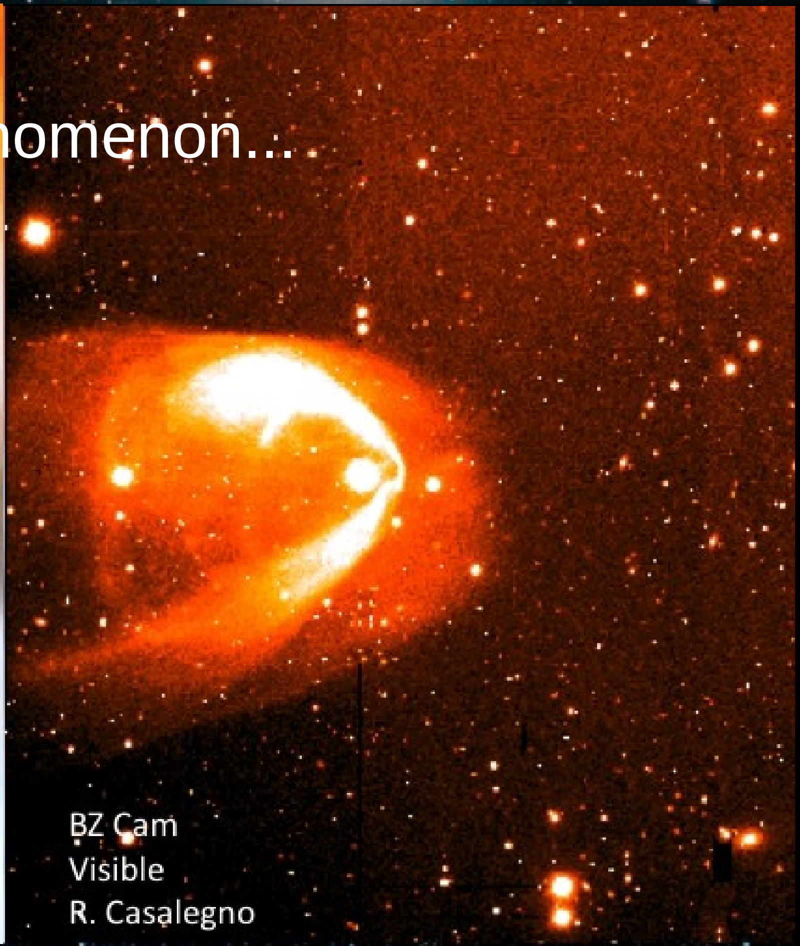
Astrospheres are a ubiquitous phenomenon...

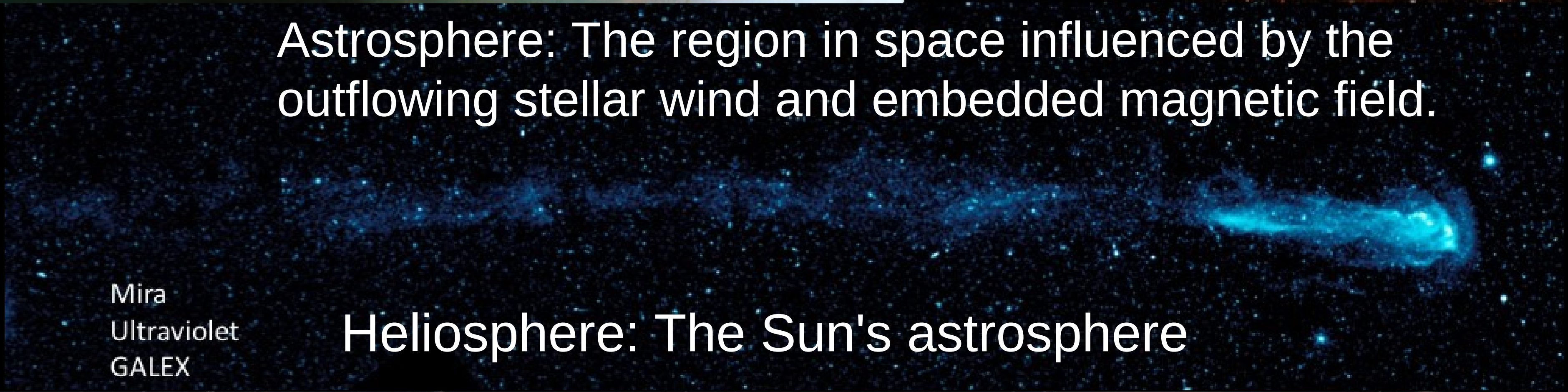


LL Orionis
Visible
Hubble



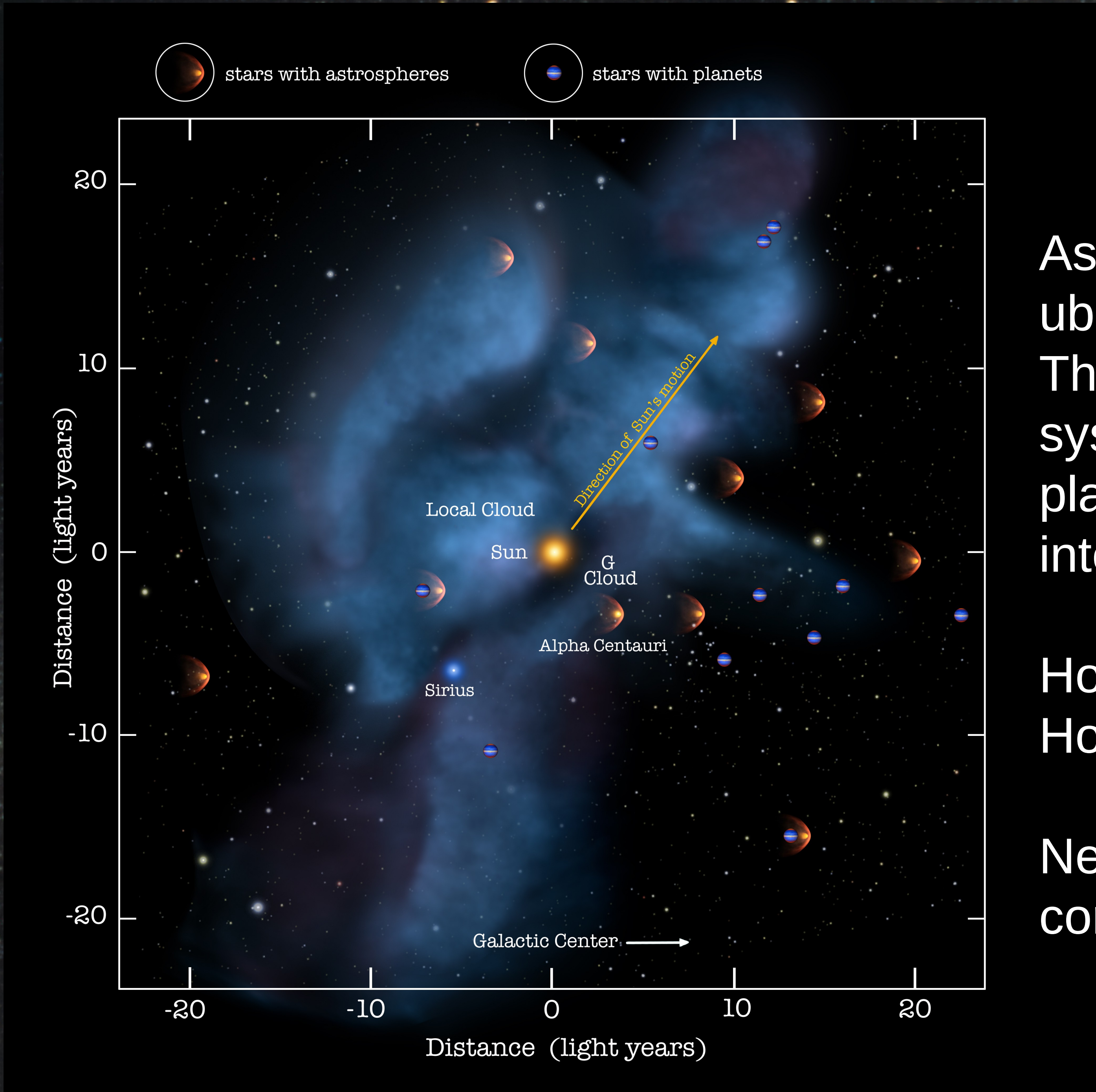
BZ Cam
Visible
R. Casalegno

Astrosphere: The region in space influenced by the outflowing stellar wind and embedded magnetic field.



Mira
Ultraviolet
GALEX

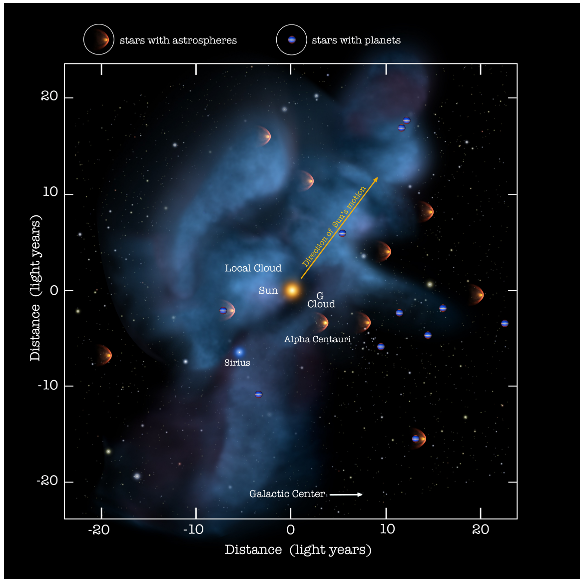
Heliosphere: The Sun's astrosphere



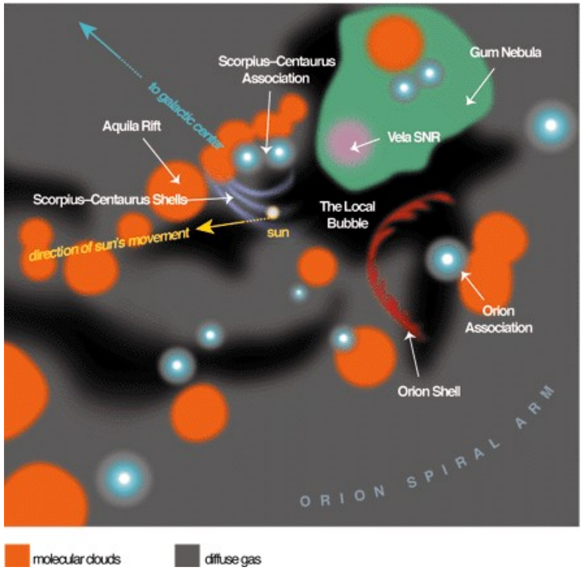
Astrospheres are a ubiquitous phenomenon. They protect their stellar systems, some with planets, from the interstellar medium.

How do they form?
How do they work?

Need to address three complexes of questions:



40 light years



1000 pc

How do they form & work?

Heliophysics: How do stellar wind and interstellar medium interact to form the astrosphere and how variable is the universal phenomenon of the formation of astrospheres?

Astrophysics: What are the properties of the surrounding ISM and how do they relate to the typical ISM?

Fundamental Physics: How do plasma, neutral gas, dust, waves, particles, fields, and radiation interact in extremely rarefied, turbulent and incompletely ionized plasmas?

Heliosphere is the only accessible astrosphere

What do we know?

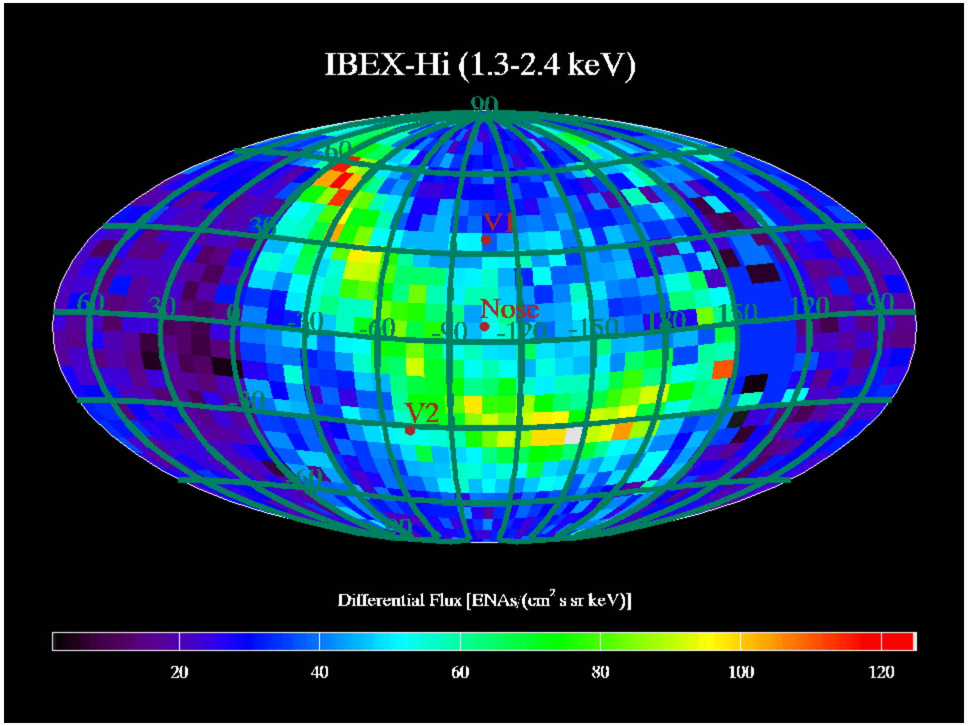
The heliosphere is much more complicated than we ever believed:

Shaped by

- interstellar magnetic field,
- ISM gas/plasma/dust,
- suprathermal particles,
- solar wind, magnetic field

Very complex interaction between ISM and solar wind

Our understanding is severely hampered by insufficient knowledge of the ISM boundary conditions.



IBEX Ribbon in ENAs

The ribbon appears to be organized by the BLISM as inferred from other measurements.

As BLISM is draped around the heliosphere,

$$\mathbf{B} \cdot \mathbf{r} = 0$$

is believed to organize the ribbon.

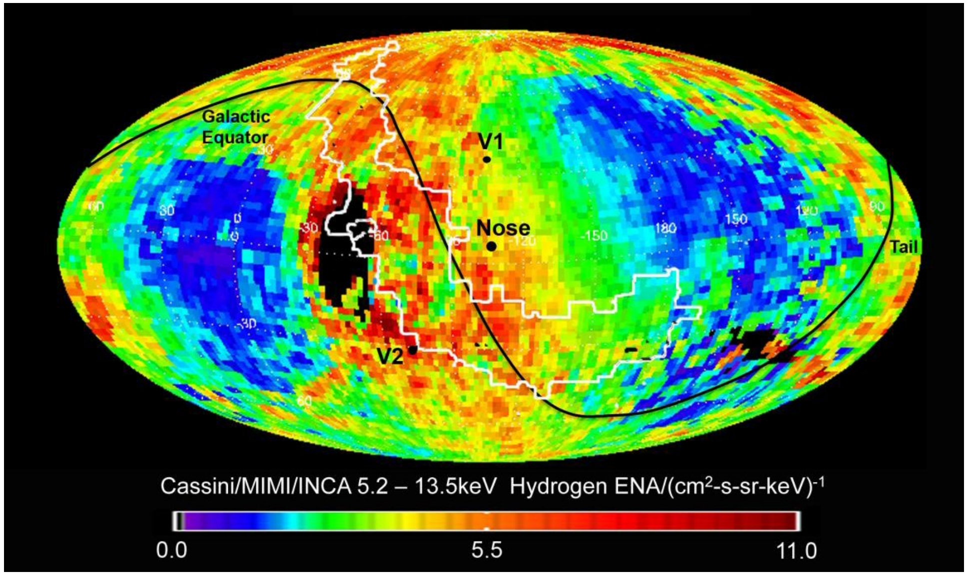
Inferred BLISM-strength implies that heliosphere has no bow shock.
Heliosphere is 'squashed' by BLISM.

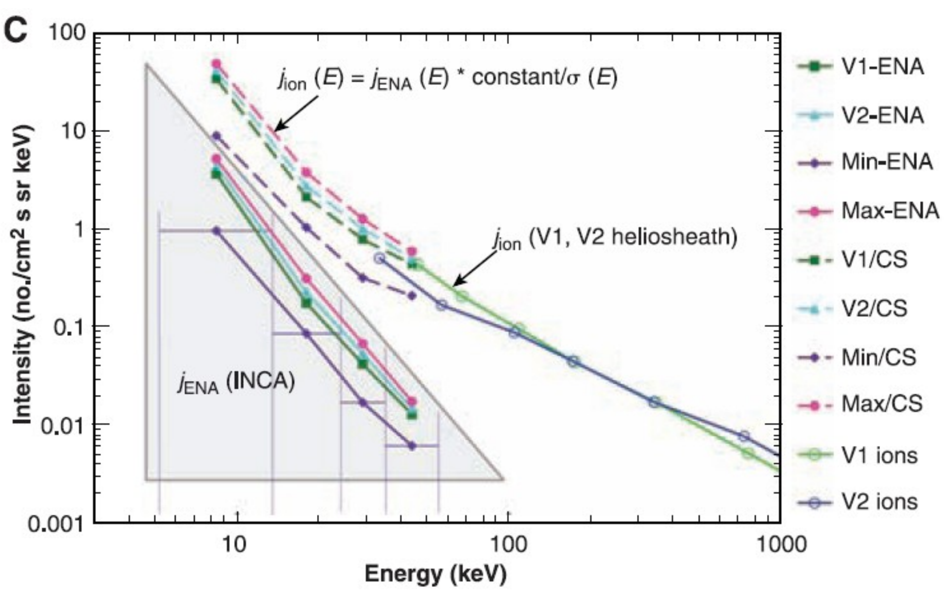
Voyagers don't measure ENA source population

We have no measurements of BLISM

IMAP highest-ranked mission in US NRC's 2010 decadal review.

(ENA: Energetic Neutral Atom, BLISM: Local interstellar magnetic field)





Cassini/INCA Ribbon

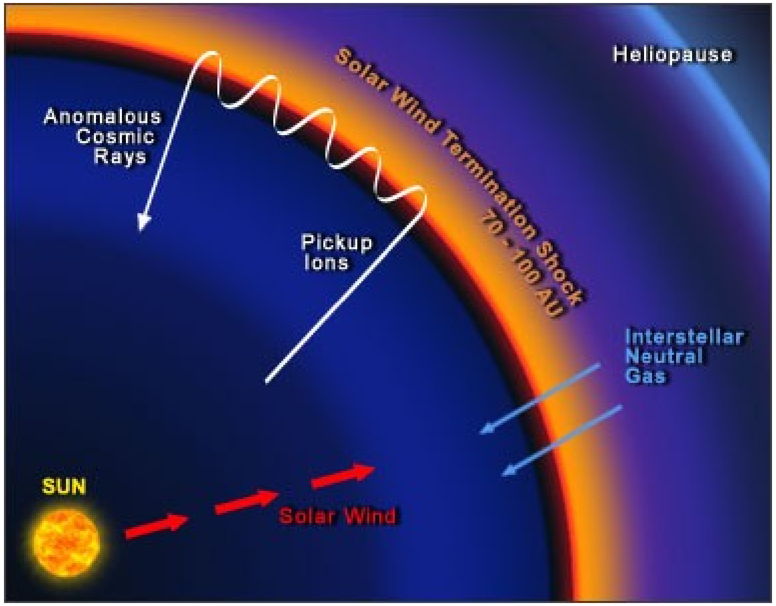
Cassini/INCA ENAs are in a higher energy range.

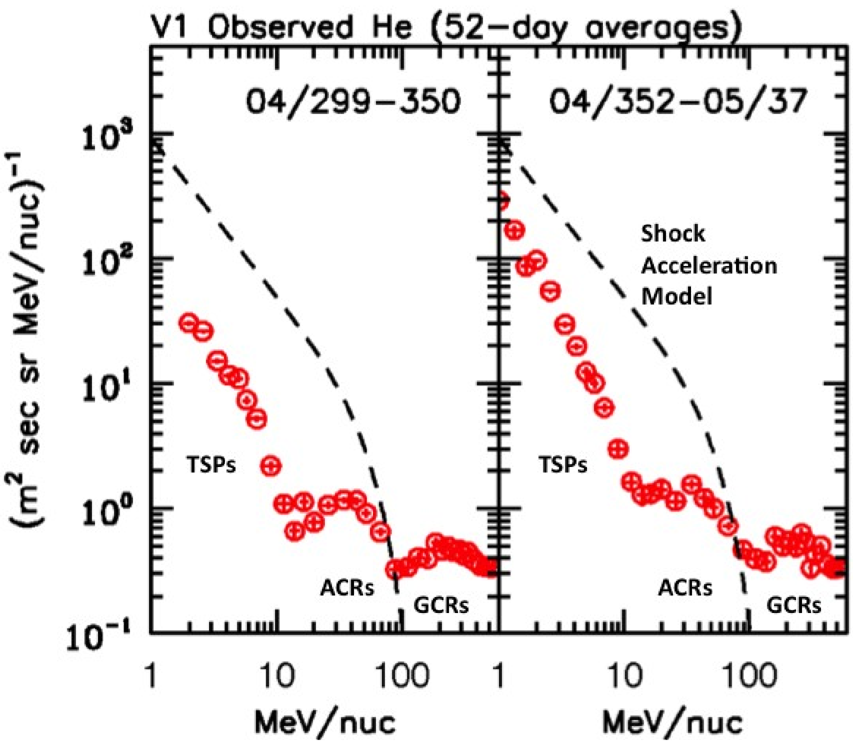
- Ribbon is tilted w.r.t. IBEX ribbon
- Voyager measurements of low-energy ions appear to extend modeled energy spectrum of ENAs at V1, V2

Pressure out there is dominated by suprathermal particles!

New regime, only occasionally seen in magnetospheres during highly disturbed time periods.

Need measurements!



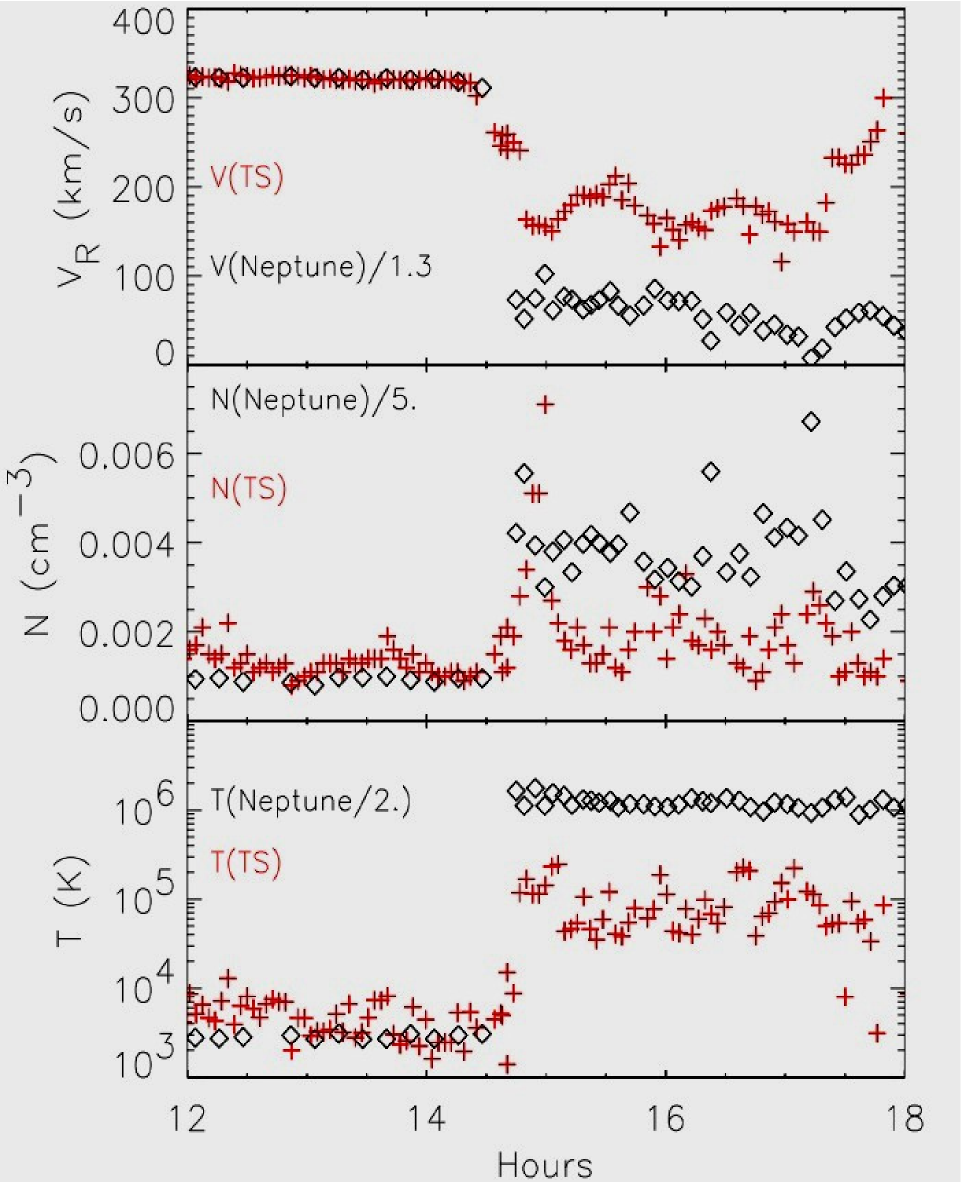


The Termination Shock

Anomalous Cosmic Rays (ACR) believed to peak at termination shock.

- 'recycled' pickup ions
- no substantial enhancement of ACRs seen at termination shock

Termination shock is quite different from all expectations



The Termination Shock

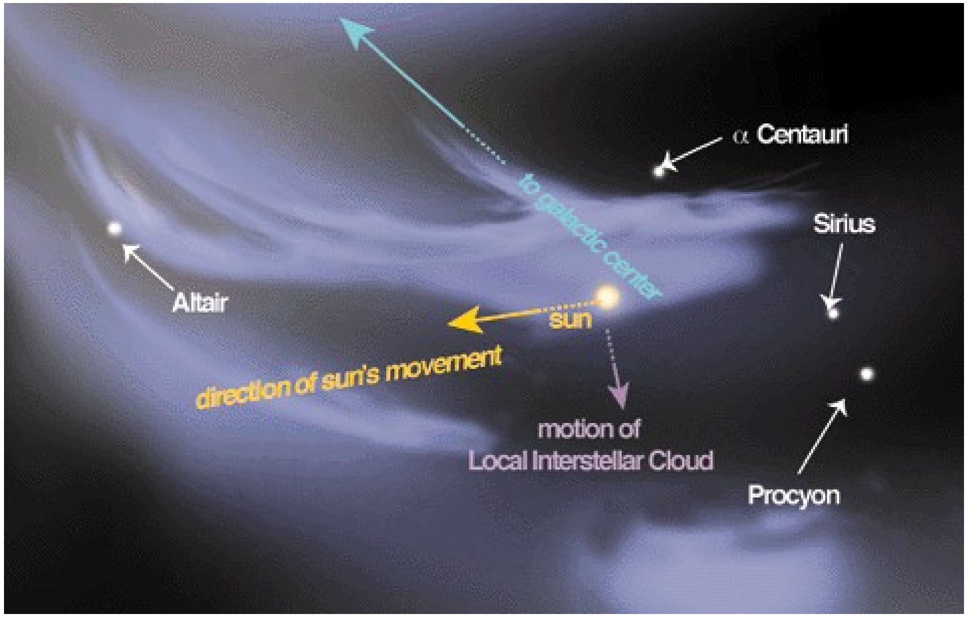
Anomalous Cosmic Rays (ACR) believed to peak at termination shock.

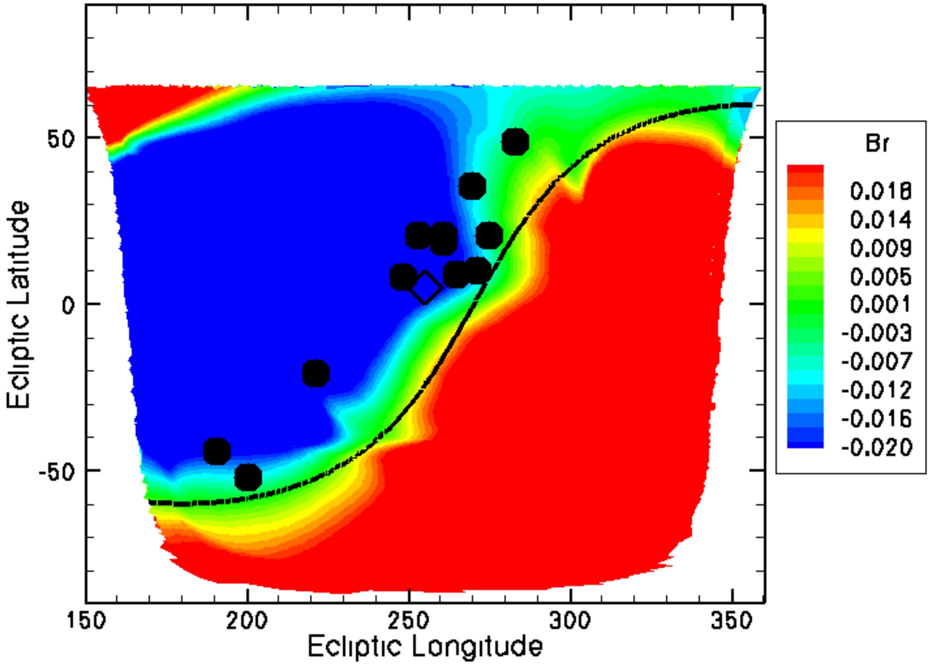
- 'recycled' pickup ions
- no substantial enhancement of ACRs seen at termination shock

Termination shock is quite different from all expectations

Solar wind did not turn subsonic at the termination shock. But all other properties indicate it is a shock. Suprathermal particles mediate the shock.

V1, V2 not equipped to measure such particles and weak fields.





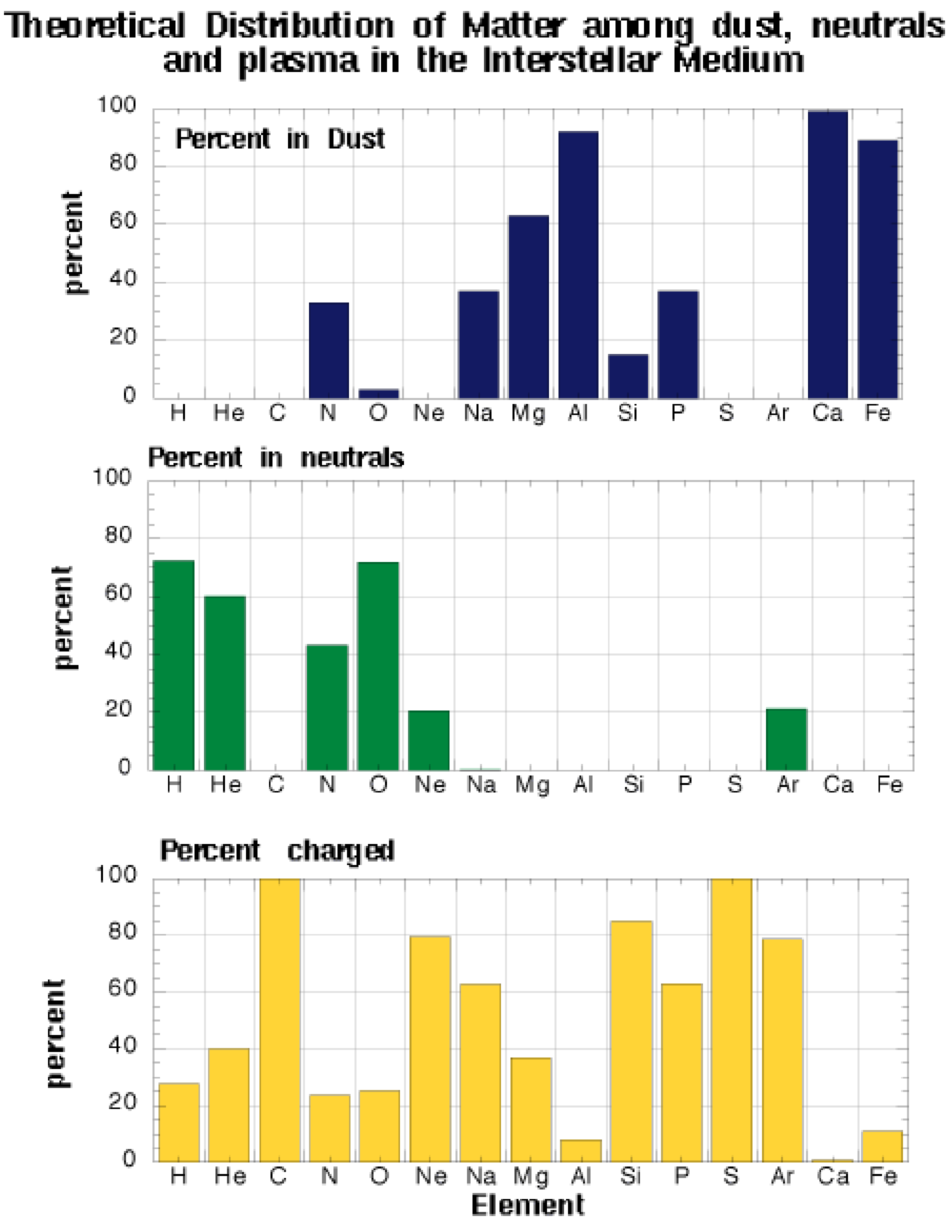
The Very Local ISM

Ulysses GAS experiment and studies of pickup ions show inflow direction of gas disagrees with relative flow direction between heliosphere and local cloud:

- Heliosphere close to edge of LIC
- VLISM may change 'soon'
- BLISM orientation not in galactic plane
- Interstellar flow highly turbulent
- Implications for GCR modulation
- Was GCR constant as assumed in climate studies?

Need to measure outer boundary conditions of the heliosphere!

VLISM: Very Local ISM, GCR: Galactic Cosmic Rays

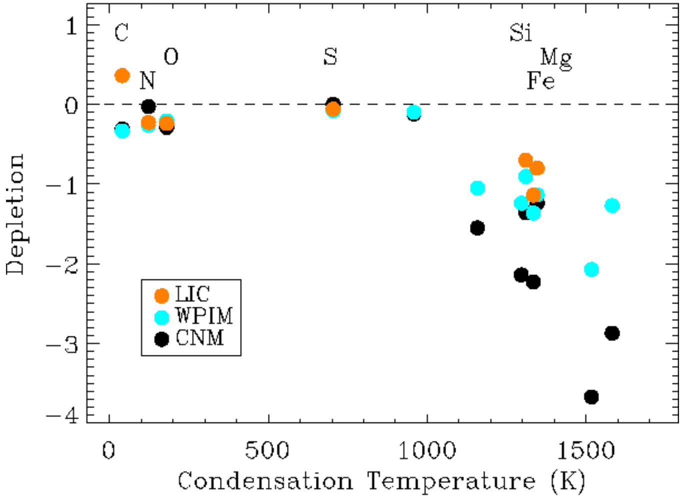


The Very Local ISM

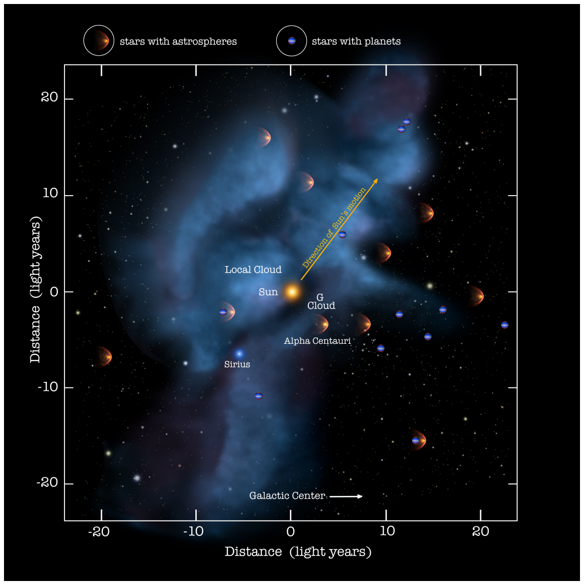
Compositional studies hampered by unknown dust/gas/ions ratio.

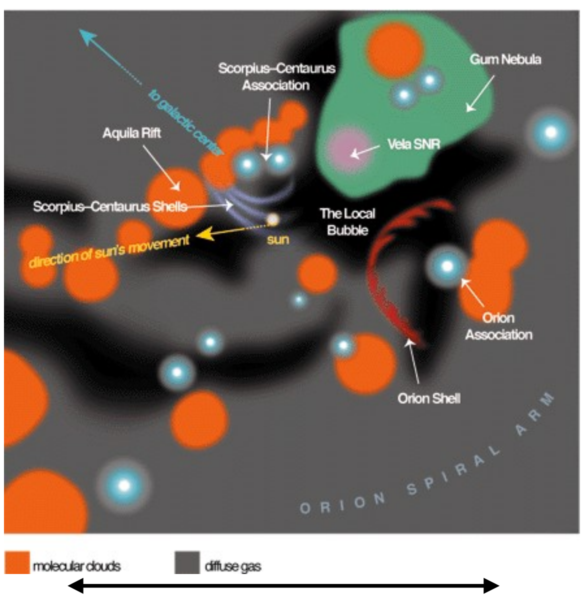
- Properties of small dust particles unknown
- Carbon abundance >2 times higher than solar
- Implications for galactic chemical evolution

Need measurements!



In situ Investigations of the Local Interstellar Medium





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Science Objectives:

Heliophysics: How do solar wind and interstellar medium interact to form the heliosphere and how does this relate to the universal phenomenon of the formation of astrospheres?

Astrophysics: What are the properties of the very local ISM and how do they relate to the typical ISM?

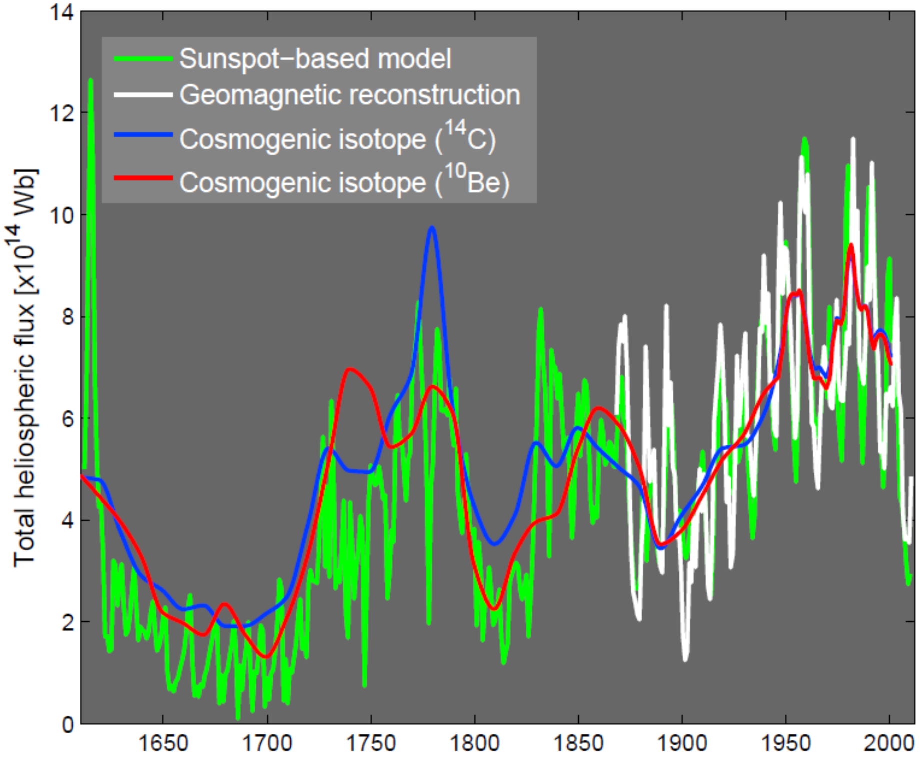
Fundamental Physics: How do plasma, neutral gas, dust, waves, particles, fields, and radiation interact in extremely rarefied, turbulent and incompletely ionized plasmas?

This requires an interstellar probe (IP)

Bonus Science: Extragalactic background light, soft-X-ray background, multi-spacecraft studies

Relation to Cosmic Vision 2015 – 2025 Themes

CV 2015-2025 Theme	Relevance
What are the conditions for planet formation and the emergence of life?	Shielding of GCR, dust, and neutrals: dust-plasma interactions
How does the solar system work?	Structure and dynamics of the heliosphere
What are the fundamental physical laws of the universe?	Fundamental plasma physics, extremely rarefied plasmas
How did the universe originate and what is it made of?	LISM composition and galactic chemical evolution

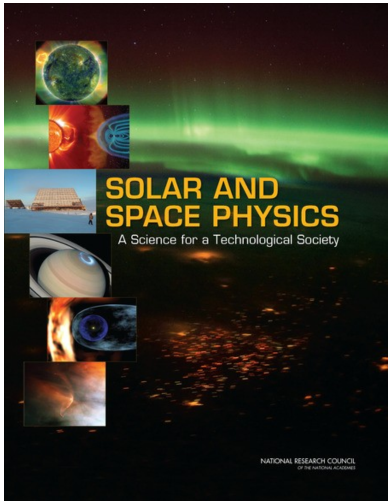


Why Now?

The Sun appears to be exiting its 'Grand Solar Maximum':

- Leads to a smaller heliosphere
- Leads to shorter travel time
- Catch dynamics 'in the act'

Voyagers are not likely to last beyond 2020 and don't measure relevant particle population.



Only new, innovative instruments on an interstellar probe will provide required measurements.

“That is the SHP panel’s final major science goal ..., **to discover how the Sun interacts with the local galactic medium and protects Earth.”**

Philosophical: Prepare interstellar exploration

Measurement Requirements

SCIENCE GOAL	SCIENCE QUESTION	REQUIRED MEASUREMENTS
	Heliospheric Science (H)	
How do solar wind and interstellar medium interact to form the heliosphere and how does this relate to the universal phenomenon of the formation of astrospheres?	**H1:** How does the heliosphere shield against cosmic rays and neutral particles and what role does it play in the interstellar–terrestrial relations?	GCR, energetic particles, ENAs, plasma, **B**-field, waves
	H2: How do the magnetic field and its dynamics evolve in the outer solar system?	energetic particles, ENAs, plasma, **B**-field, waves
	H3: How do heliospheric structures respond to varying boundary conditions?	Plasma, **B**-field, ENAs, Ly-alpha
	H4: How do the boundary regions in the heliosphere modify the intensities of the various particle populations?	GCR, energetic particles, ENAs, plasma, **B**-field, waves, dust
	H5: How does the interstellar medium affect the outer solar system?	GCR, energetic particles, ENAs, plasma, **B**-field, waves, dust

Measurement Requirements

SCIENCE GOAL	SCIENCE QUESTION	REQUIRED MEASUREMENTS
	Astronomy and Astrophysics (A)	
What are the properties of the very local interstellar medium and how do they relate to the typical ISM?	**A1:** What is state and origin of the local interstellar medium?	Charge-state and element composition, waves, **B**-field, Ly-alpha, ENAs
	A2: What is the composition of the local interstellar medium?	Composition
	A3: What is the interstellar spectrum of the GCR beyond the heliopause?	GCR
	A4: What are the properties of the interstellar magnetic field?	**B**-field, waves, plasma
	A5: What are the properties and dynamics of the interstellar neutral component?	ENAs, dust, plasma
	A6: What are the properties and dynamics of interstellar dust?	Dust, **B**-field, plasma

Measurement Requirements

SCIENCE GOAL	SCIENCE QUESTION	REQUIRED MEASUREMENTS
	Fundamental Physics (F)	
How do plasma, neutral gas, dust, waves, particles, fields, and radiation interact in extremely rarefied, turbulent, and incompletely ionized plasmas?	**F1:** What is the nature of wave–particle interaction in the extremely rarefied heliospheric plasma?	Distribution functions, energetic particles
	F2: How do the multiple components contribute to the definition of the local plasma properties within the heliospheric boundary regions?	Plasma, ENAs, energetic particles, composition, waves, **B**-field
	F3: What processes determine the transport of charged energetic particles across a turbulent magnetic field?	Plasma, ENAs, energetic particles, composition, waves, **B**-field
	Bonus (B)	
	- Extragalactic Background Light - Soft X-ray background - Multispacecraft studies	IR/Vis wide-field imaging soft X-ray measurement time series

Strawman Payload

Acronym	Instrument	Mass [kg]	Power [W]	Telemetry [bps]	Volume [cm^3]	Measurements
MAG	Magnetometer	2.0	1.5	50	500	1 Hz magnetic fields
PA	Plasma Analyzer	3.5 (2)	3.5 (2)	60 (20)	2 x 25x25x25	Plasma composition
NA	Neutral Analyzer	2.5	3.5	50	25x25x25	Neutrals, limited composition
PW	Plasma Waves	5	4	30	25x25x25	Radio and Plasma waves
DA	Dust Analyzer	1	1	10	25x25x30	Dust mass, velocity, composition
EP	Energetic Particles	4.5 (2)	5 (2)	60	2 x 25x25x25	H: 4 keV – 300 MeV ions: 5 keV/n – 400 Mev/n e-: 2keV – 20 MeV
ENA	Energetic Neutrals	5	5	50	60x60x20	Hydrogen ENAs: 0.05 – 5 keV Key elemental composition
LA	Ly-alpha	1.2	1.5	50	tbd	Ly-alpha broad-band photometry
IRV	IR/VIS imager	(5)	(5)	(50)	tbd	Wide-field infrared and visible imaging
SXR	Soft-X-Ray	(5)	(5)	(50)	tbd	Soft X-ray background, solar wind – planet interactions
Total		**24.7**	**25**	**360**		

Payload provided by member states.

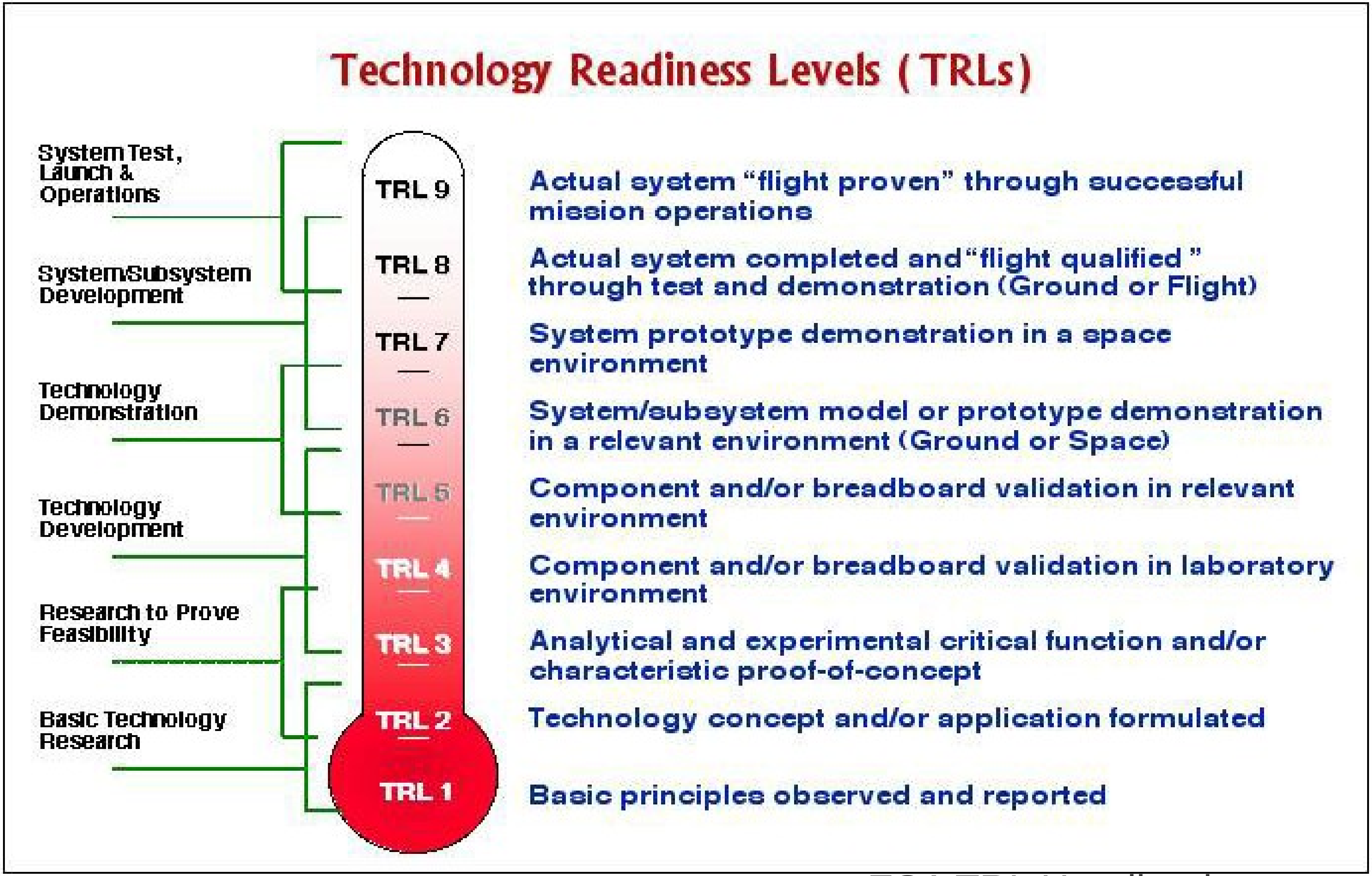
Mission Requirements

- **M1** spacecraft to arrive within a ~25° cone of the heliospheric 'nose' (+7°, 252° Earth ecliptic coordinates) or a similarly interesting region (based on IBEX results). This aims at the scientifically most compelling region and minimizes travel time.
- **M2** Provide data from ~5 AU out to at least 200 AU
- **M3** Arrive at 200 AU 'as fast as possible', ideally within 25-30 years

This is challenging in various aspects:

- Long duration, high reliability (done with Voyagers, Ulysses)
- Propulsion, mass, and power are all critical to mission success
- Near-term planned demonstrator missions, e.g., Sunjammer and ESTCube-1, will retire perceived risk.

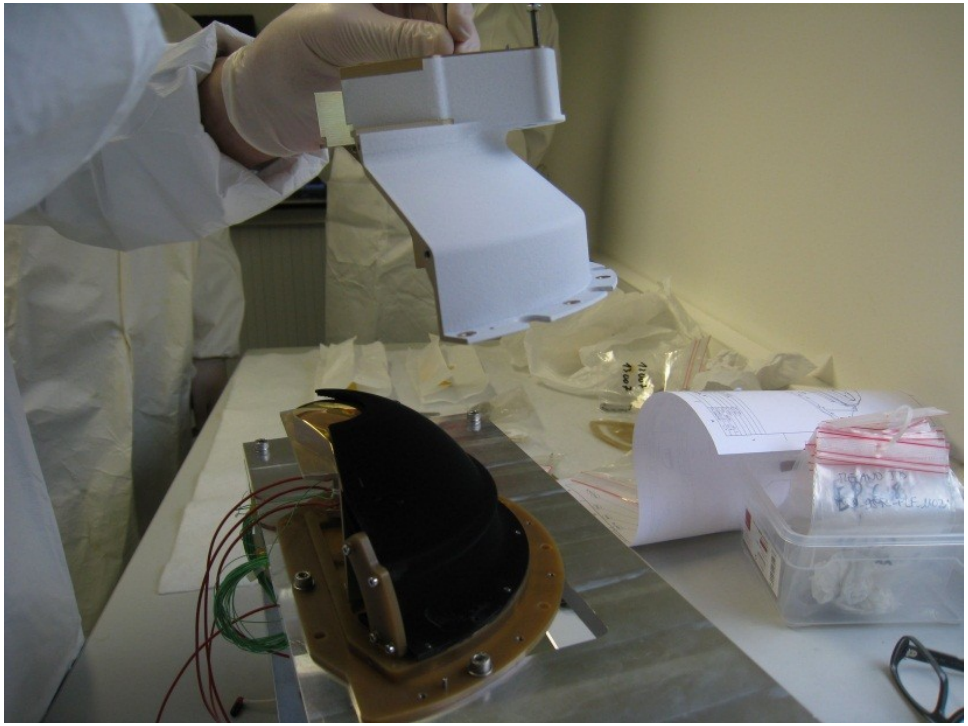
Critical Technology and TRL

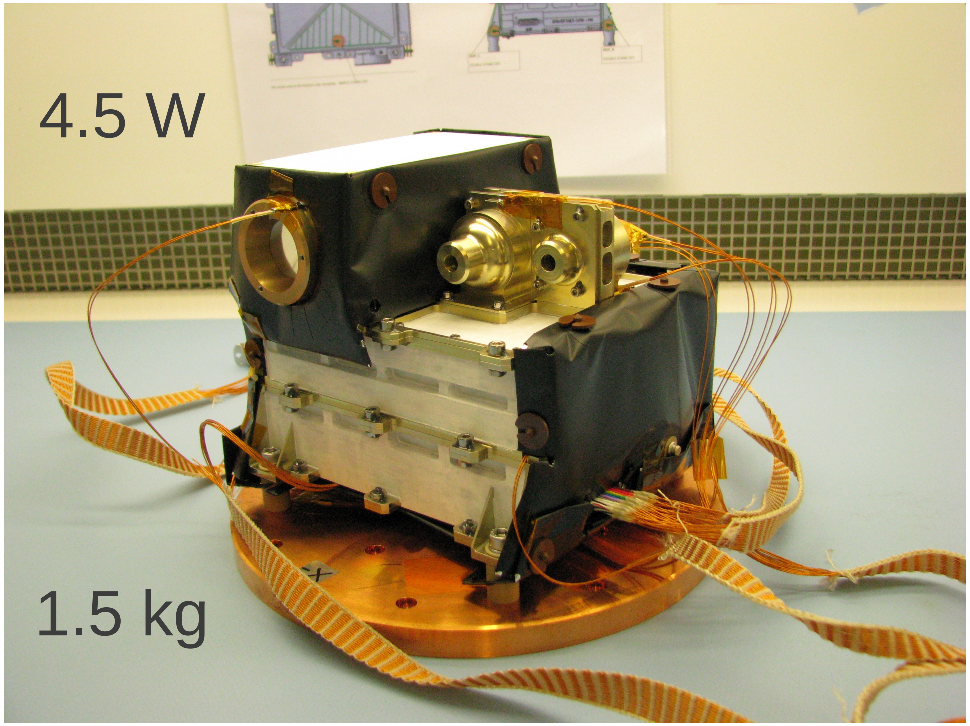


ESA TRL Handbook

Payload TRL

Examples for improvement in resource performance





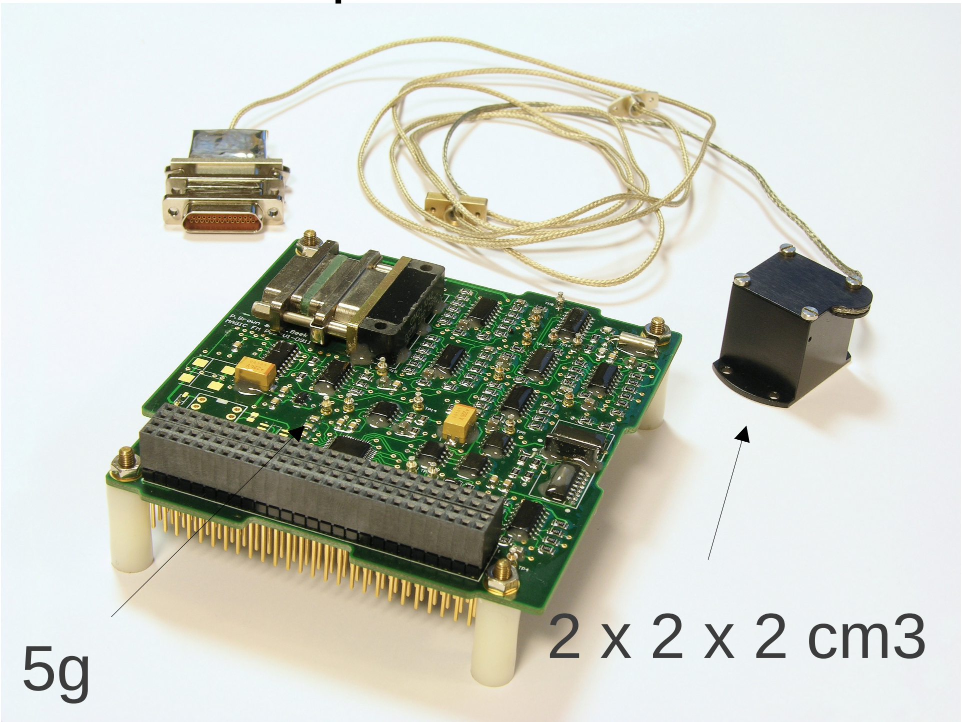
Solar Orbiter SWA/PAS covers protons/alphas from 0.2 to 20 keV/q, SWA/HIS ionic composition. SWA preparing for **CDR end 2013.**

Solar Orbiter EPT/HET covers electrons (protons) from 20 keV to 30 (100) MeV, also covering the crucial suprathermal part of energy spectrum. **CDR end 2013.**

Payload TRL

- Payload generally has high TRL (TRL ≥6)
- Miniaturization can achieve major mass and power savings
- Payload TRL is not a mission driver

Further example for improvement in resource performance

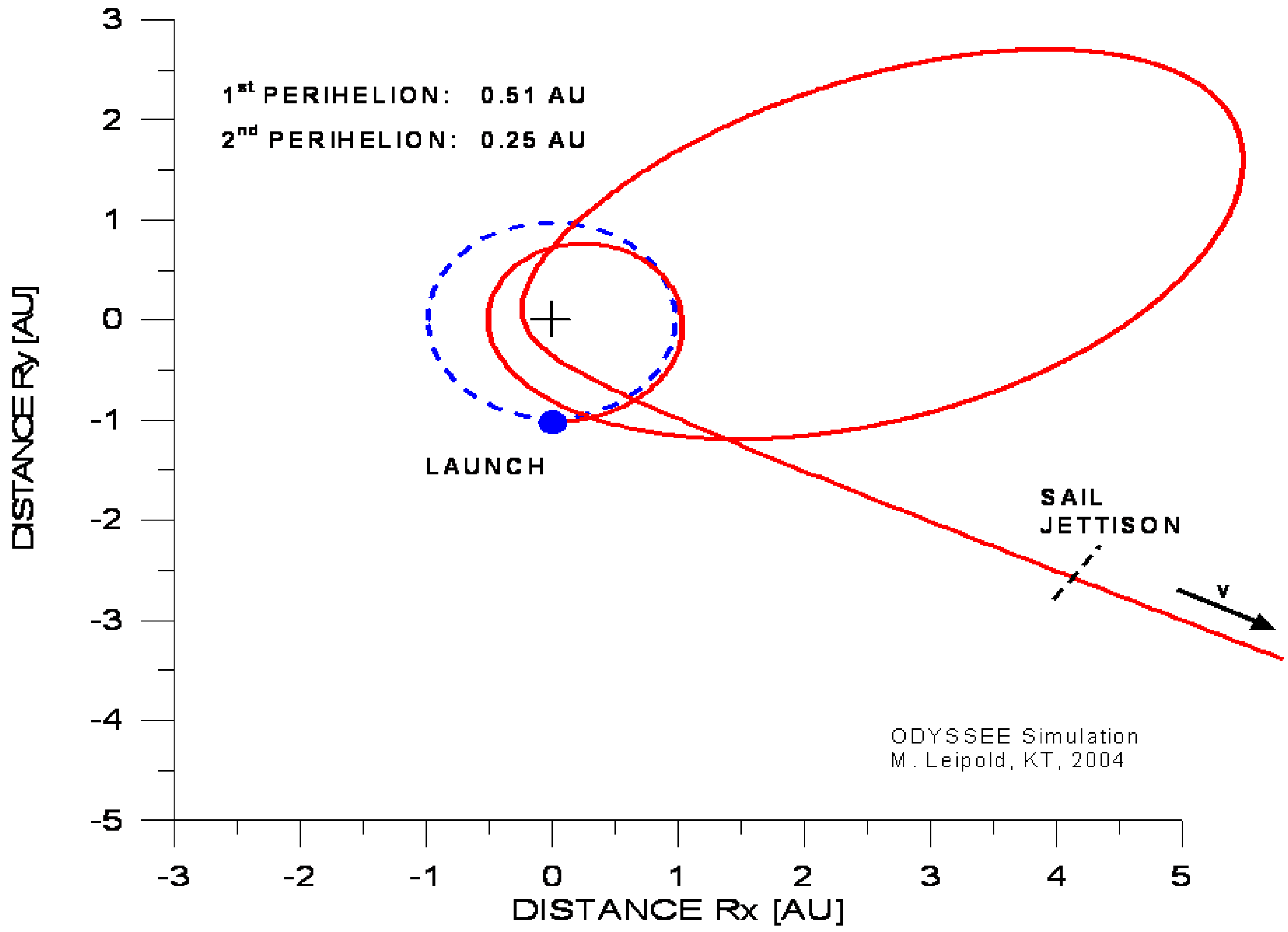


Miniaturized magnetometer:
MAGIC on CINEMA: 200 mW
TRL 9 (launched 2012)

TRL 6	System/subsystem model or prototype demonstration in a relevant environment (Ground or Space)

Propulsion

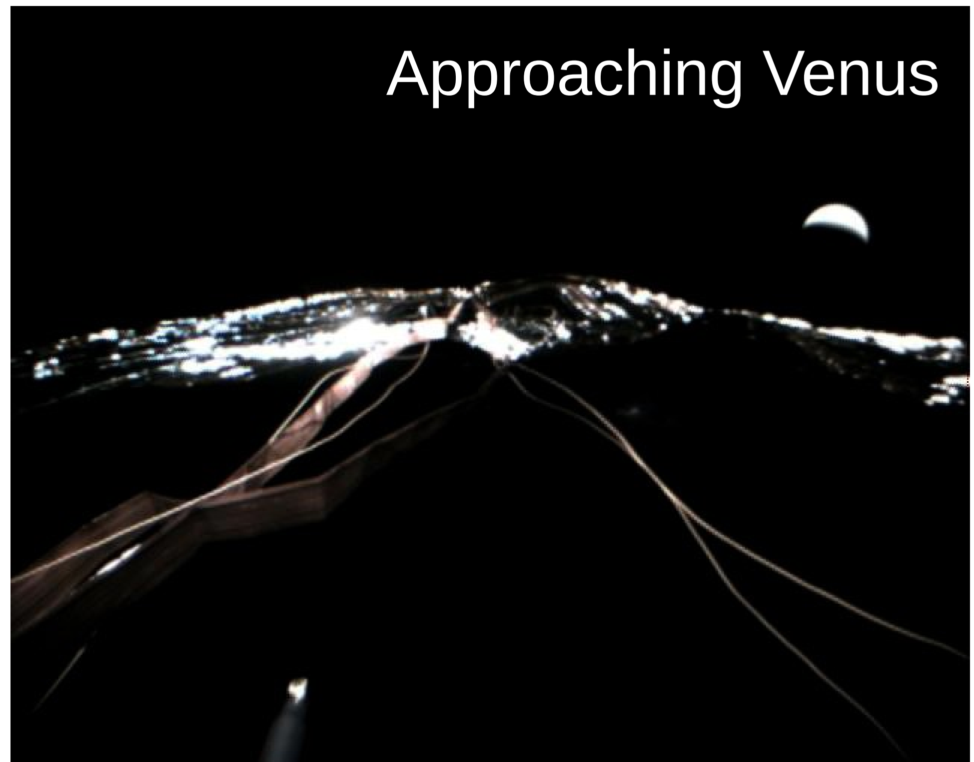
- Solar Sail
- Electric Sail
- Radioisotope Electric
- Heavy Launcher



Solar Sail

IKAROS was launched by the H-IIA F17 from the Tanegashima Space Center at 6:58:22AM (JST) on May 21 2010. After the initial operation check, IKAROS started the missions for the world's first demonstration of solar power sail.

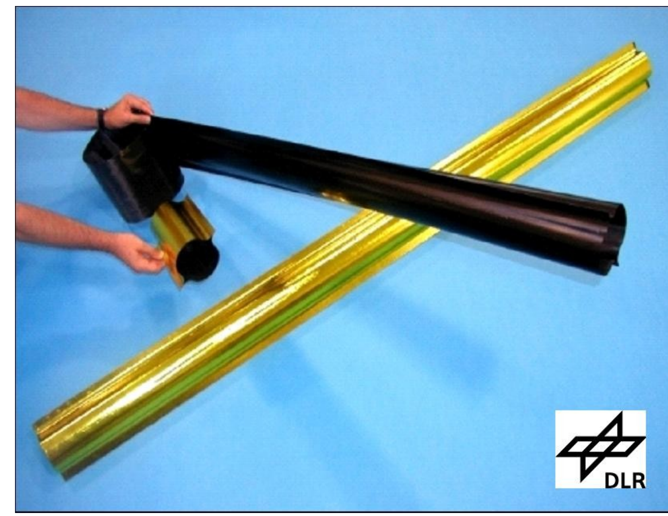
Initial separation



TRL 9 — Actual system "flight proven" through successful mission operations

Solar Sail

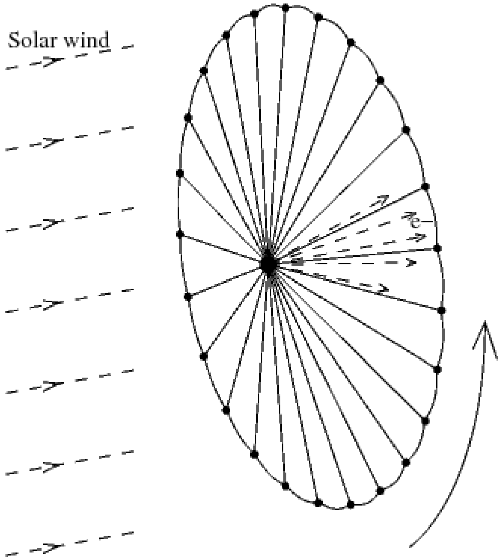
Sunjammer launch foreseen on Falcon 9 November 2014 (NASA, L'Garde). → TRL 6 now, TRL 7 by end of 2014



European commitment can readily be revived.

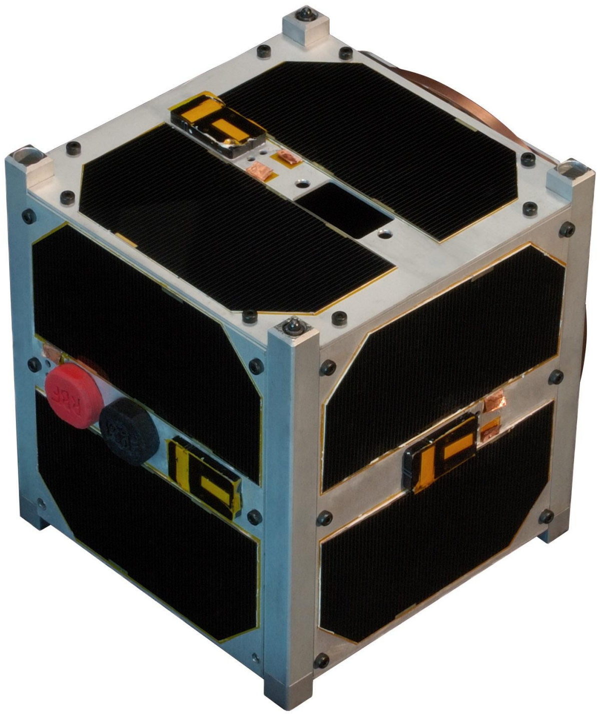
TRL 6	System/subsystem model or prototype demonstration in a relevant environment (Ground or Space)
TRL 7	System prototype demonstration in a space environment

Electric Sail



- Deflect solar wind protons with charged wires
- HV penetration depth ~ 10 r_{Debye}, i.e., ~100m @ 1 AU
- Requires HV (20-40 kV) and ~700 W
- ESTCube-1 launched May 2013
- Tether deployment Sept. 2013

TRL ~ 4-5



TRL 4	Component and/or breadboard validation in laboratory environment
TRL 5	Component and/or breadboard validation in relevant environment

Radioisotope Electric

- Radioisotope → See power
- Electric: ESA's Smart-1 used solar generator
- Requires large mass (~400 kg) of Xe-propellant
- Requires significant power (~900 W)
- Smart-1 → TRL 7 for electric propulsion

System TRL 5 (combination of nuclear & electric)

TRL 5	Component and/or breadboard validation in relevant environment

Propulsion TRL

- Solar Sail: currently TRL 5-6, TRL 7 by end of 2014
- Electric Sail: currently TRL 4, TRL 5 by end of Sept.
- Radioisotope electric: TRL 5
- Heavy Launcher: TRL 9

Rolled up TRL is 4-5

TRL 4	Component and/or breadboard validation in laboratory environment
TRL 5	Component and/or breadboard validation in relevant environment

Power

Mars Science Laboratory
MMRTG delivers 115 We
and weighs 45 kg: ~2.6 W/kg
Voyagers had ~4.2 W/kg

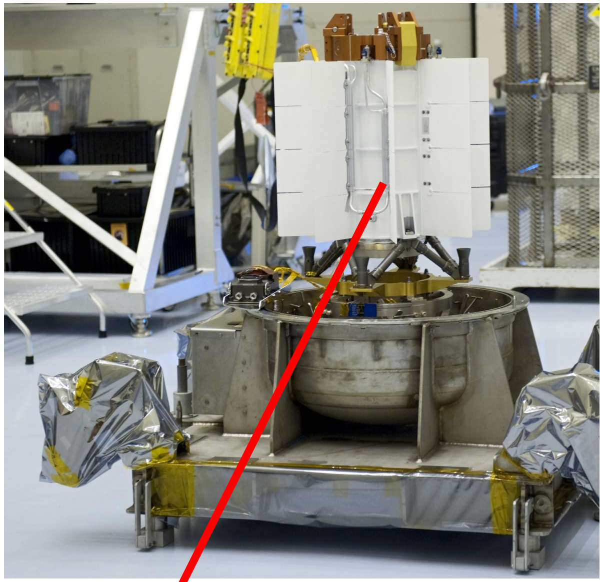
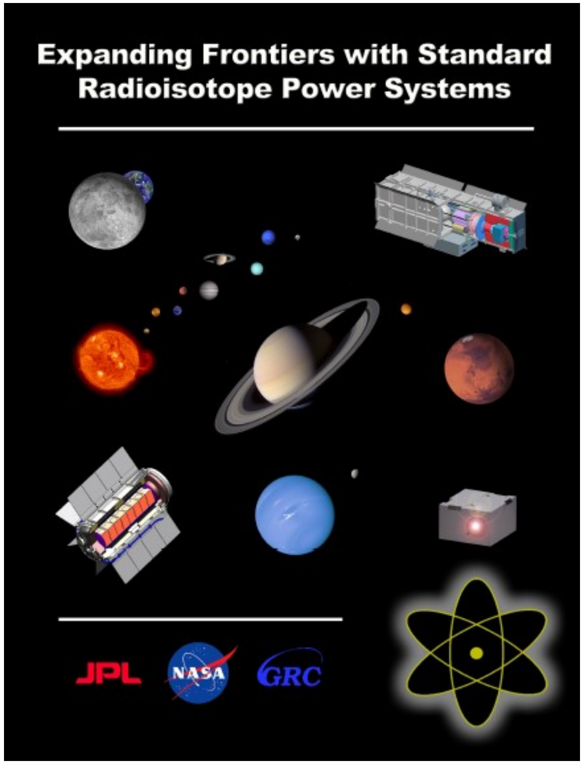


Table 3-8. Current Performance Parameters of the MMRTG and SRG [52, 59, 60]

RPS Parameters	MMRTG	SRG
General Characteristics		
Dimensions	66 cm (L) x 64 cm (W) x 64 cm (H)	104 cm (L) x 29 cm (W) x 38 cm (H)
Mass[1], kg	43	34
Number of GPHS Modules	8	2
Reference Thermal Inventory[2] at BOM, Wt	1984	496
T_{cold} at BOM, °C	208[3] / 189[4]	42[5] / 18[6]
Performance at BOM		
Deep Space		
Electrical power, We	125	116
Conversion Efficiency, (%)	6.3%	23.4%
Specific Power, We/kg	2.9	3.4
Mars Surface		
Electrical power, We	123	103
Conversion Efficiency, (%)	6.2%	20.7%
Specific Power, We/kg	2.9	3.0
Performance at 14 Years past BOM		
Deep Space		
Electrical power, We	100	101
Conversion Efficiency, (%)	5.5%[8]	22.8%[7]
Specific Power, We/kg	2.3	3.0
Mars Surface		
Electrical power, We	98	90
Conversion Efficiency, (%)	5.4%[8]	20.2%[7]
Specific Power, We/kg	2.3	2.6

Notes
1. Current estimates from Boeing and Lockheed Martin.
2. Reference thermal power numbers used to calculate system efficiencies for each RPS type.
3. Temperature at the MMRTG thermoelectric cold junction [52]
4. Temperature at the MMRTG fin root [52]
5. Temperature of the SRG SCA cold end [59]
6. Temperature of the SRG SCA alternator [59]
7. Data provided by [60]
8. Computed from MMRTG thermal inventory of 1805 Wt and indicated electrical output at 14 years.



Power: TRL 9 for low power-density RTGs, (4.2 W/kg on Voyagers!)

European technology being developed, TRL 3, and lower power density due to use of Am-241.

Summary & Conclusions

Science:

Interstellar Probe addresses key problems in three major fields:

Heliosphysics: Complex dynamics of the heliosphere

Astrophysics: In situ investigation of the local ISM

Fundamental Physics: Physics of truly complex plasmas

IP addresses all four CV 2015-2025 science themes.

Technology:

Propulsion:
- Solar or electric sails
- Nuclear electric
- Commercial launcher?

Power:
- European development
- Use US RTGs?

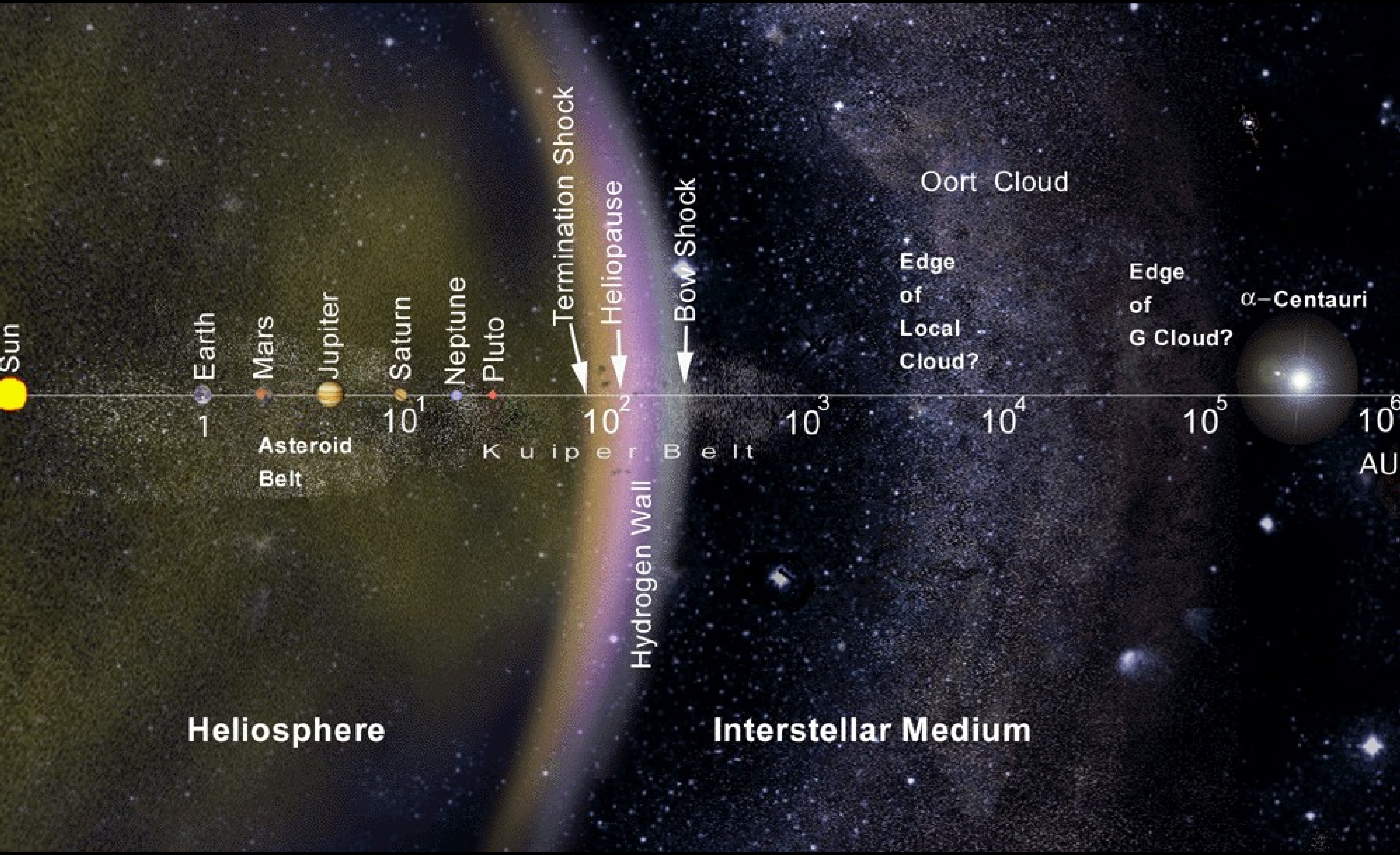
Whichever is chosen, it will be enabling technology for other missions.

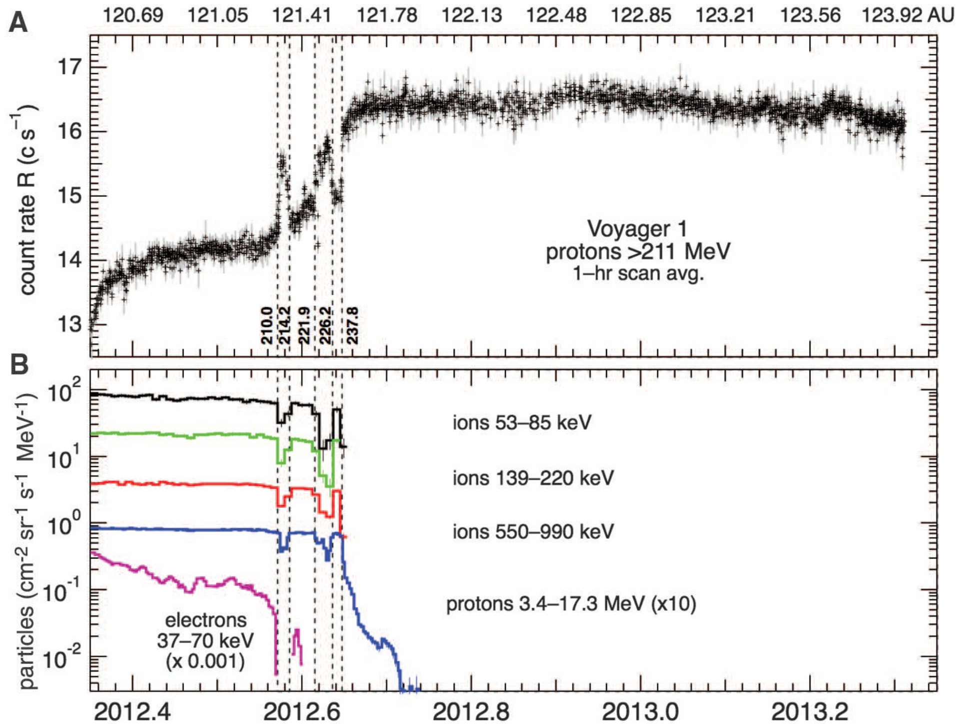
Interstellar Probe Team is ready to go!

Thanks to the IBEX, Voyager, Cassini & IP teams

Backup Slides

Science Objectives In situ Investigations of the Local Interstellar Medium



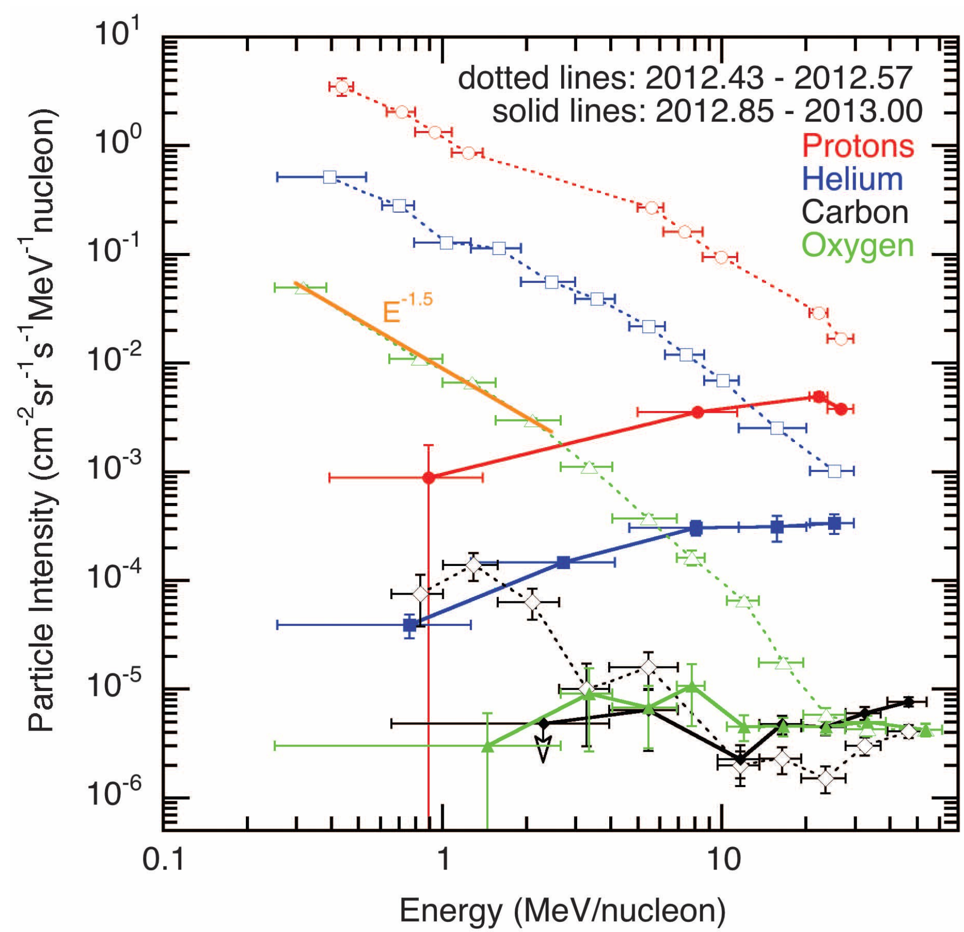


Substantial anisotropies seen, implying complex physics at this boundary region.

The heliosphere is much more complex than was ever believed!

The Heliopause?

V1 has entered a new region in space. Disappearance of low-energy 'solar' ions.



Telemetry

- Low bit rate is ok since changes are also slow
- 500 bps baseline
- 2x8 hours weekly passes
- 5.8 kbps also at 200 AU
- 35m antenna initially, but 70m antenna needed in later mission stages.
- Of course, the more the better...
- Has been done with Pioneers, Voyagers

Telemetry TRL is 9

TRL 9 Actual system "flight proven" through successful mission operations