Space Instrumentation for Heliophysics

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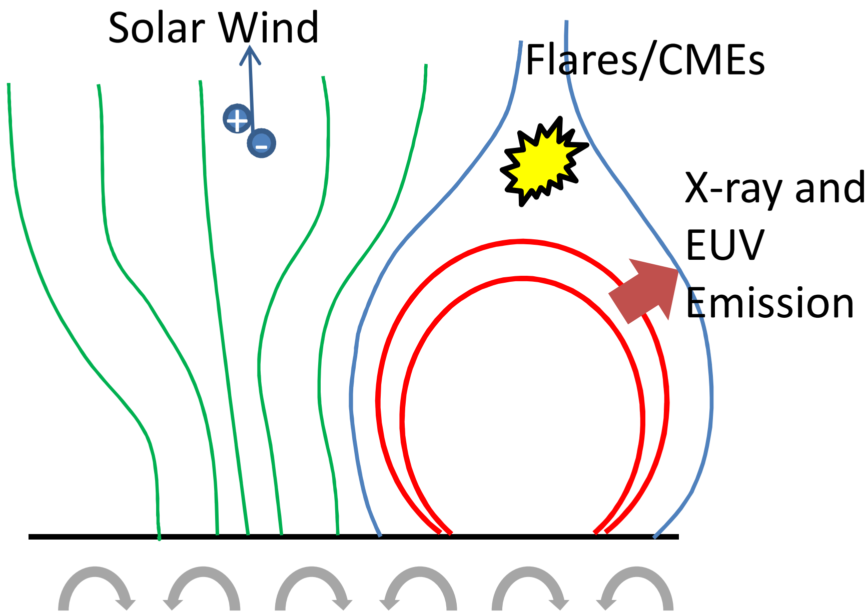
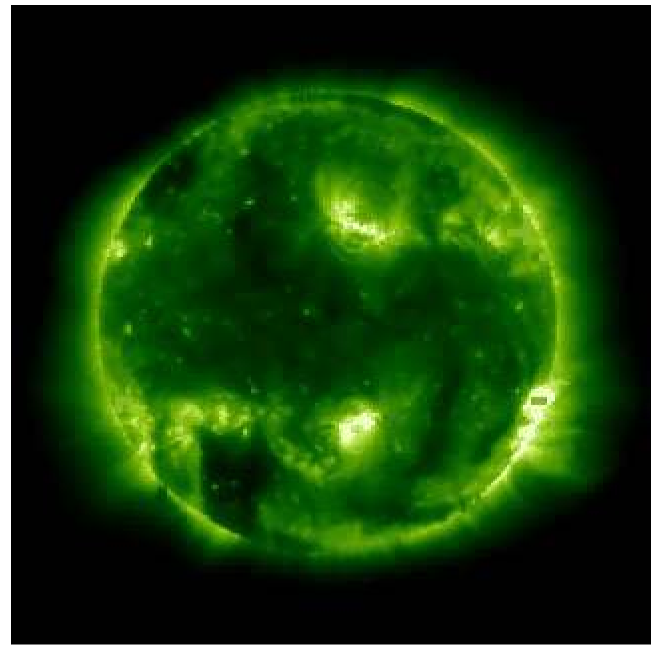
How Do Observations Contribute to Heliophysics?

- Heliophysics is a broadening of the concept "geophysics," extending the connections from the Earth to the Sun & interplanetary space.
- Advances in Heliophysics are made by the application of theoretical concepts, guided by observational reality.
- Neither theory or observational science can flourish alone.

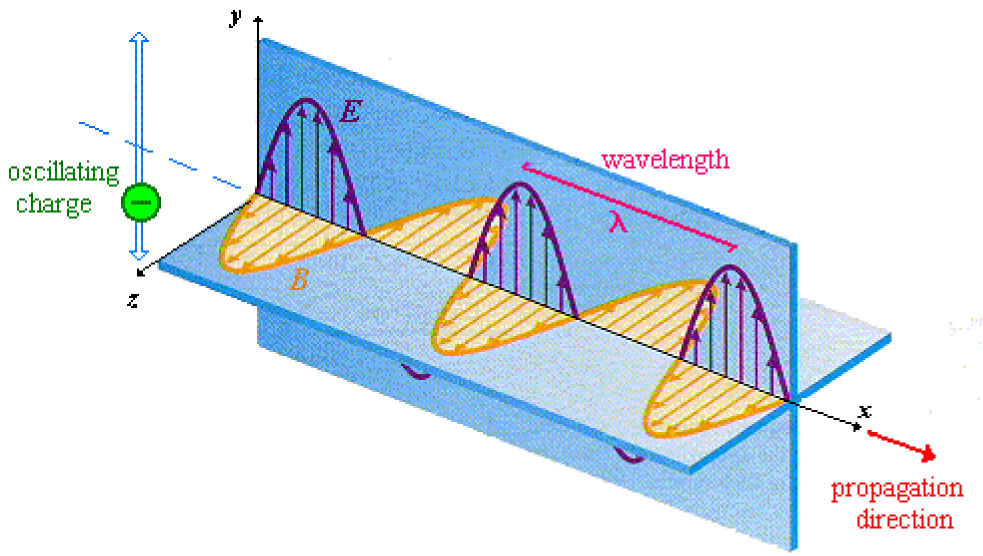
Remote Observation





- Spatial distribution
- Spectral distribution
- Polarization
- Time variation

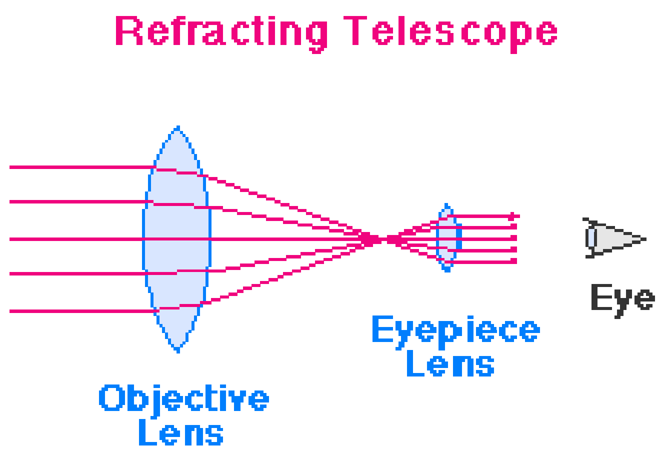
Electromagnetic Radiation



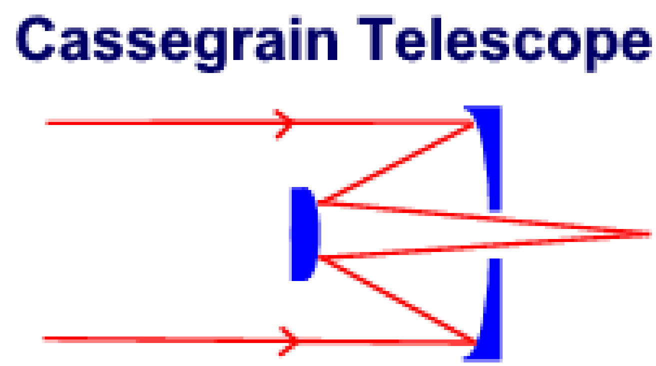
- Propagation direction
- Intensity ($|E|^2$)
- Wavelength (frequency)
- Polarization (direction of E)

Two Major Types of Optical Instrument

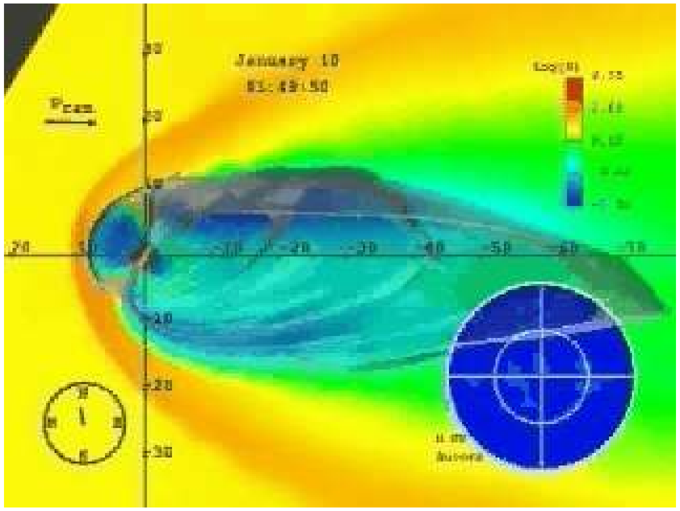
- Refraction
  - Refracting telescope was invented Hans Lippershey in 1608
  - Gallileo was the first to use it to study the heavens

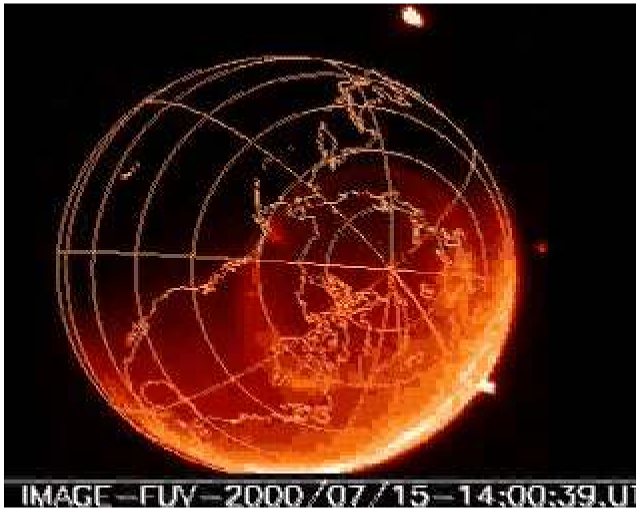


- Reflection
  - James Gregory, came up with the design for the reflecting telescope in 1663
  - Sir Isaac Newton built the first model in 1688



In-situ Observation

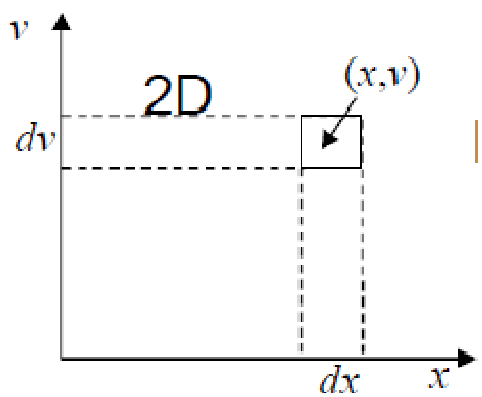




- Particle species
- Ionization distribution

- Velocity or energy distribution

Distribution Function



- f(**x**, **v**, t) gives the probability of finding a particle in d^3**x** d^3**v** dt

$$\int_V \int_{\mathbf{v}} f(\mathbf{r}, \mathbf{v}, t) d^3 r d^3 v = N$$

Moments of f(**x**,**v**,t)

$$\int f \; d^3v\,; \quad \int \mathbf{v} f \; d^3v\,; \quad \int \mathbf{v}\mathbf{v} f \; d^3v$$

$$n(\mathbf{r},t) = \int f(\mathbf{r},\mathbf{v},t) d^3v$$

Density is the zeroth moment; $[n] = \mathrm{m}^{-3}$

The first moment:

$$\boldsymbol{\Gamma}_\alpha(\mathbf{r},t) = \int \mathbf{v} f_\alpha(\mathbf{r},\mathbf{v},t) d^3v$$

Particle flux; $[\Gamma] = \mathrm{m}^{-2}\,\mathrm{s}^{-1}$

$$\mathbf{V}_\alpha(\mathbf{r},t) = \frac{\int \mathbf{v} f_\alpha(\mathbf{r},\mathbf{v},t) d^3v}{\int f_\alpha(\mathbf{r},\mathbf{v},t) d^3v}$$

Average velocity = flux/density, $[V] = \mathrm{m}\,\mathrm{s}^{-1}$

Pressure and temperature

from the second velocity moments

Pressure tensor
$$\mathcal{P}_\alpha(\mathbf{r},t) = m_\alpha \int \underbrace{(\mathbf{v}-\mathbf{V}_\alpha)(\mathbf{v}-\mathbf{V}_\alpha)}_{\text{dyadic product} \;\rightarrow\; \text{tensor}} f_\alpha(\mathbf{r},\mathbf{v},t)\,d^3v$$

If $\mathcal{P}_\alpha = p_\alpha \mathcal{I}$ where $\mathcal{I}$ is the unit tensor, we find the scalar pressure

$$p_\alpha = \frac{m_\alpha}{3}\int (\mathbf{v}-\mathbf{V}_\alpha)^2 f_\alpha(\mathbf{r},\mathbf{v},t)\,d^3v = n_\alpha k_B T_\alpha$$ introducing the temperature

Assume $\mathbf{V} = 0$:
$$\frac{3}{2}k_B T_\alpha(\mathbf{r},t) = \frac{m_\alpha}{2}\frac{\int v^2 f_\alpha(\mathbf{r},\mathbf{v},t)\,d^3v}{\int f_\alpha(\mathbf{r},\mathbf{v},t)\,d^3v}$$

$\boxed{T \;\; \mu \;\; \langle \text{K.E.} \rangle}$

Thus we can calculate a "temperature" also in non-Maxwellian plasma!

Magnetic pressure
(i.e. magnetic energy density) $B^2/2\mu_0$

Plasma beta
$$\beta = \frac{2\mu_0 \sum_\alpha n_\alpha k_B T_\alpha}{B^2}$$
thermal pressure / magnetic pressure

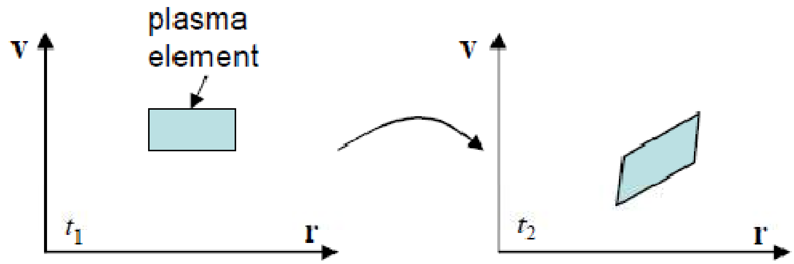
$\beta \ll 1$ $\mathbf{B}$ dominates over plasma

$\beta \gg 1$ plasma dominates over $\mathbf{B}$

3rd velocity moment → heat flux (temperature x velocity), etc. to higher orders…

Vlasov and Boltzmann equations

equation(s) of motion for f



Each point in the element moves according to

$$\frac{d\mathbf{r}}{dt} = \mathbf{v} \quad ; \quad \frac{d\mathbf{v}}{dt} = \frac{\mathbf{F}}{m}$$

Let V be some phase space volume (6D) containing

$$N = \int_V f(\mathbf{r}, \mathbf{v}, t) d^3r d^3v$$ particles

Conservation of particles in a volume moving with the particles gives

$$0 = \frac{dN}{dt} = \int_V \frac{\partial f}{\partial t} d^3r d^3v + \oint_{\partial V} f\mathbf{U} \cdot d\mathbf{S}$$

$\mathbf{U} = (\dot{\mathbf{x}}, \dot{\mathbf{v}}) = (\mathbf{v}, \mathbf{F}/m)$ in 6D space

$d\mathbf{S}$ 5D surface element in 6D space

Divergence theorem $\Rightarrow$

$$0 = \frac{dN}{dt} = \int \left(\frac{\partial f}{\partial t} + \underbrace{\nabla}_{(\partial/\partial\mathbf{r}, \partial/\partial\mathbf{v})} \cdot (f\mathbf{U}) \right) d^3r d^3v$$

The conservation law is independent of the phase space volume selected

$$\Rightarrow \boxed{\frac{\partial f}{\partial t} + \nabla \cdot (f\mathbf{U}) = 0}$$

If $\mathbf{F} \neq \mathbf{F}(\mathbf{v})$ $$\frac{\partial f}{\partial t} + \nabla \cdot (f\mathbf{U}) = 0 \quad \Rightarrow \quad \frac{\partial f}{\partial t} + \mathbf{v} \cdot \frac{\partial f}{\partial \mathbf{r}} + \frac{\mathbf{F}}{m} \cdot \frac{\partial f}{\partial \mathbf{v}} = 0$$

$$\Rightarrow \quad \boxed{\frac{\partial f}{\partial t} + \mathbf{v} \cdot \frac{\partial f}{\partial \mathbf{r}} + \frac{q}{m}(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \cdot \frac{\partial f}{\partial \mathbf{v}} = 0}$$

Vlasov equation (VE)

Compare with the Boltzmann equation in statistical physics (BE)

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \frac{\partial f}{\partial \mathbf{r}} + \frac{\mathbf{F}}{m} \cdot \frac{\partial f}{\partial \mathbf{v}} = \left(\frac{\partial f}{\partial t}\right)_c$$

Boltzmann derived $(\partial f/\partial t)_c$ for strong short-range collisions

Ludwig Boltzmann

In plasmas most collisions are long-range small-angle collisions.
They are taken care by the average Lorentz force term

$$\boxed{\frac{\partial f}{\partial t} + \mathbf{v} \cdot \frac{\partial f}{\partial \mathbf{r}} + \frac{q}{m}(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \cdot \frac{\partial f}{\partial \mathbf{v}} = \left(\frac{\partial f}{\partial t}\right)_c}$$

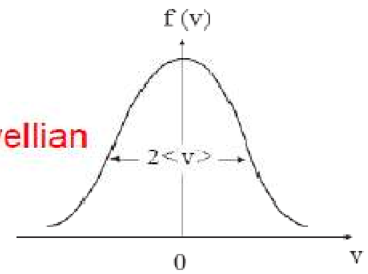
large-angle collisions only
e.g., charge vs. neutral

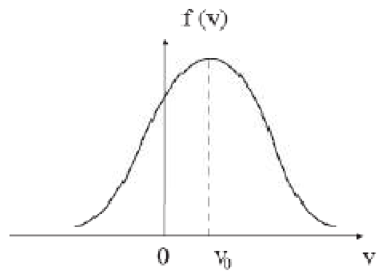
VE is often called collisionless Boltzmann equation

(M. Rosenbluth: actually a Bolzmann-less collision equation!)

Variations of the Distribution Function

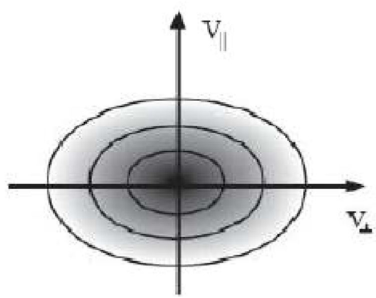
Maxwellian





$$f(v) = n\left(\frac{m}{2\pi k_B T}\right)^{3/2} \exp\left(-\frac{m(\mathbf{v}-\mathbf{V}_0)^2}{2k_B T}\right)$$

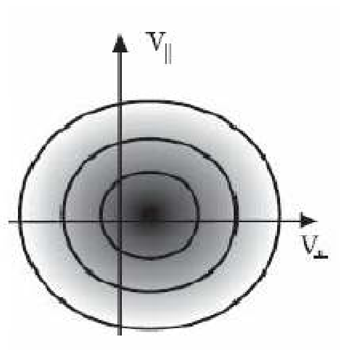
Maxwellian in a frame of reference that moves with velocity $\mathbf{V}_0$



Anisotropic (pancake) distribution ($\mathbf{v}_{\parallel} \parallel \mathbf{B}$)

$$f(v_\perp, v_\parallel) = \frac{n}{T_\perp T_\parallel^{1/2}}\left(\frac{m}{2\pi k_B}\right)^{3/2} \exp\left(-\frac{m v_\perp^2}{2k_B T_\perp} - \frac{m v_\parallel^2}{2k_B T_\parallel}\right)$$

Can also be cigar-shaped (elongated in the direction of $\mathbf{B}$)



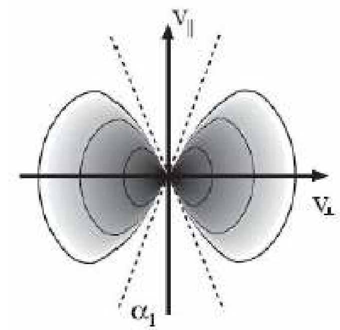
Drifting Maxwellian

$$f(v_\perp, v_\parallel) = \frac{n}{T_\perp T_\parallel^{1/2}}\left(\frac{m}{2\pi k_B}\right)^{3/2} \exp\left(-\frac{m(\mathbf{v}_\perp - \mathbf{v}_{0\perp})^2}{2k_B T_\perp} - \frac{m v_\parallel^2}{2k_B T_\parallel}\right)$$

Magnetic field-aligned beam (e.g., particles causing the aurora):

$$f(v_\perp, v_\parallel) = \frac{n}{T_\perp T_\parallel^{1/2}} \left(\frac{m}{2\pi k_B} \right)^{3/2} \exp\left(-\frac{m v_\perp^2}{2 k_B T_\perp} - \frac{m (v_\parallel - v_{0\parallel})^2}{2 k_B T_\parallel} \right)$$

Loss-cone distribution in a magnetic bottle:



Kappa distribution ~ Maxwellian with high-energy tail

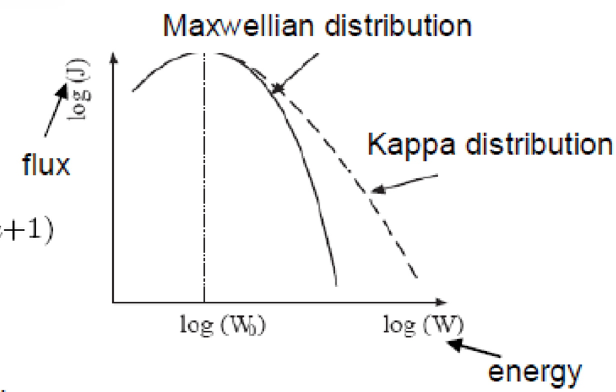
The tail follows a power law $f(W) \propto (W_0/W)^\kappa$

$$f_\kappa(W) = n \left(\frac{m}{2\pi\kappa W_0} \right)^{3/2} \frac{\Gamma(\kappa+1)}{\Gamma(\kappa - 1/2)} \left(1 + \frac{W}{\kappa W_0} \right)^{-(\kappa+1)}$$

$$[f_\kappa] = \mathrm{m}^{-6}\mathrm{s}^3$$

Γ-function

energy at the peak of the distribution



Observed particle distributions often resemble kappa distributions;
a signature that non-thermal acceleration has taken place somewhere

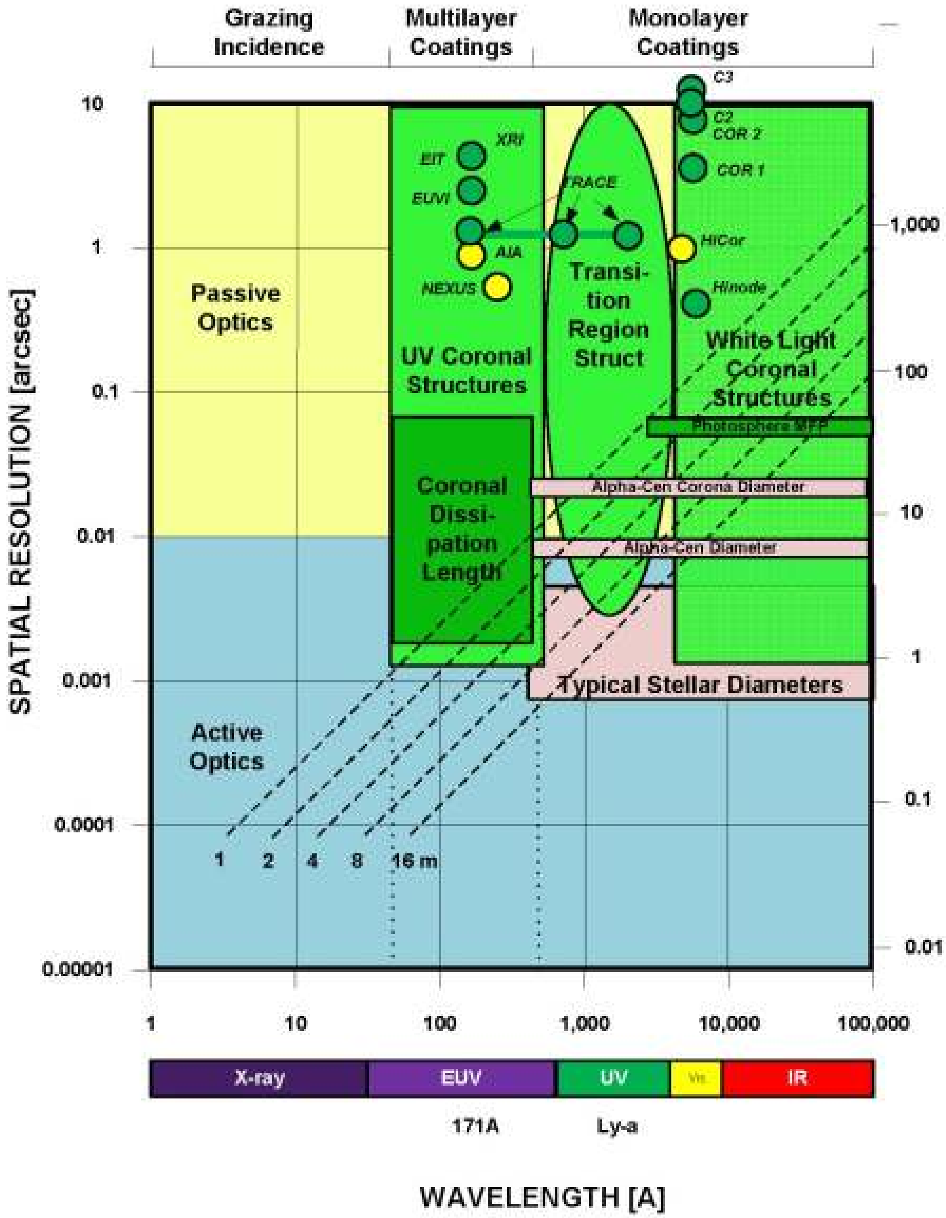
What Can We Typically Observe -> Learn

Remote Sensing

- **Electromagnetic Radiation**
  - Position -> Structure of the emitting region
  - Intensity -> Strength of heating
  - Variability -> Correlate with other phenomena
  - Frequency -> Can be radio, IR, visible, UV, EUV, …, Gamma-ray
  - Polarization -> Usually related to magnetic field, or other anisotropy

In-situ

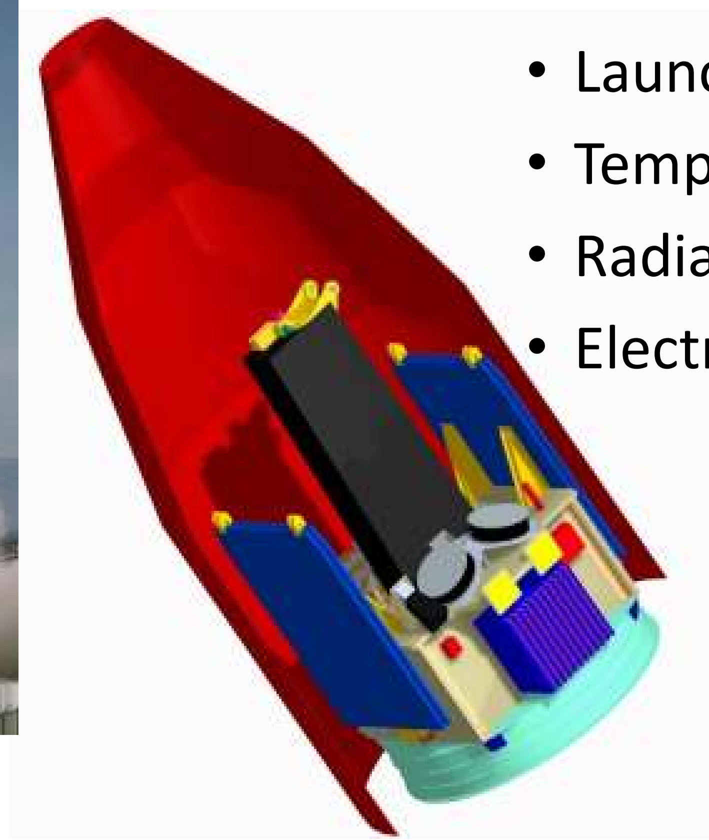
- **Particles**
  - Temperature -> Energy balance
  - Pressure -> Fluid forces
  - Velocity -> Kinetic energy of fluid
  - Energy flux -> Where is energy released?
- **Waves/Turbulent Motions**
  - Position -> Excitation mechanism
  - Intensity -> Strength of excitation mechanism
  - Variability -> Driver, or quenching of the instability
  - Frequency -> Information about excitation mechanism
  - Polarization -> Anisotropy in the emission region



Planning

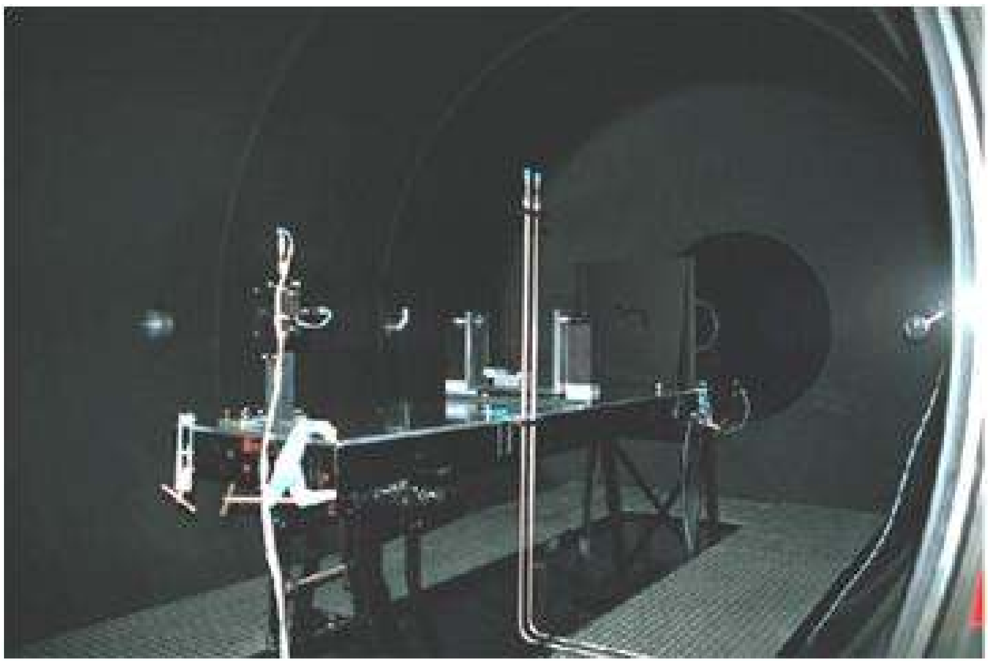
- Science
- Implementation

Surviving Launch



- All instruments must survive
  - Launch loads
  - Temperature environment
  - Radiation environment
  - Electromagnetic environment

PROTOTYPE UNDERGOES SCATTERED LIGHT TESTING



- Where possible instruments and instrument prototypes are tested on the ground

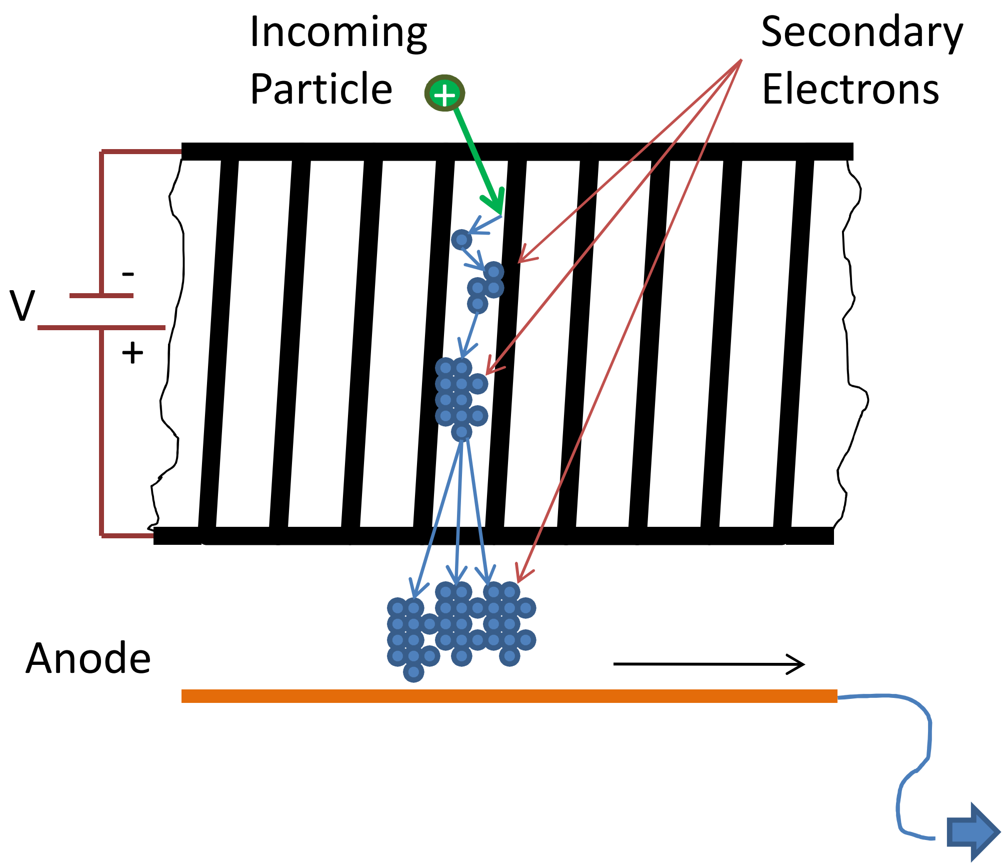
Telescope

- This is a small 15 cm telescope undergoing vibration testing

In situ Particle Measurements

What can we learn?

Microchannel (MCP) Plate Operation



A Simple Instrument to Measure Ion Energy Distribution

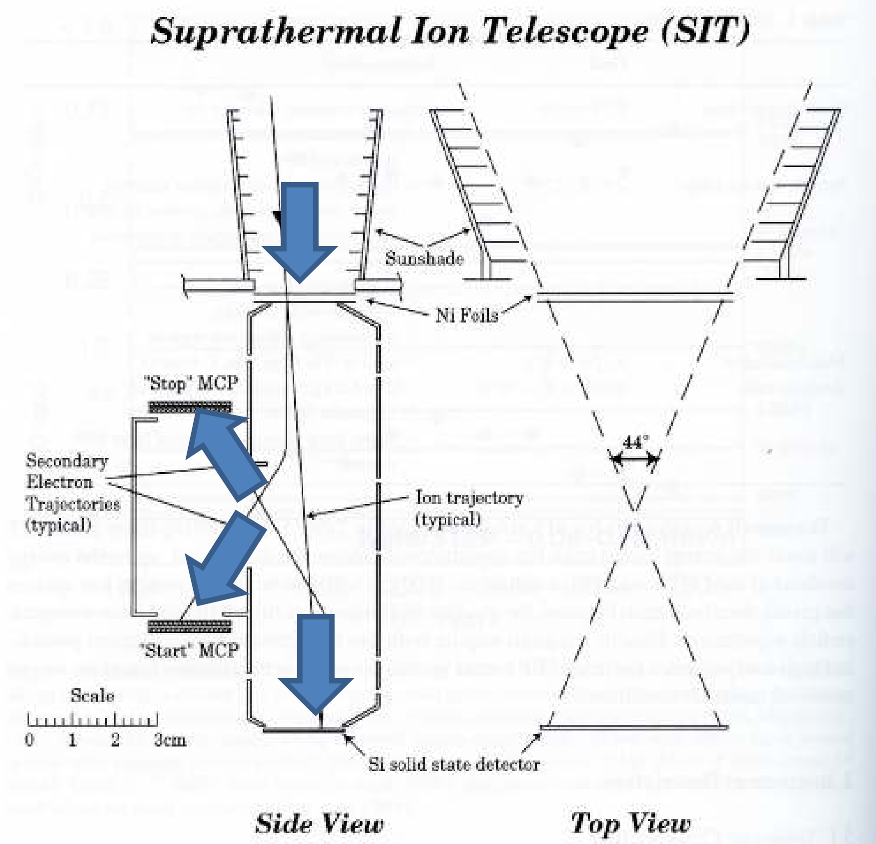


Fig. 11 Schematic cross sections of the Suprathermal Ion Telescope (SIT, see also von Rosenvinge *et al.*, 1995). Acceptance angle for *left* view is 17°. See text for a description of the operating principles

- Ions enter the aperture and strike thin foil
- Secondary electrons generated in the foil are deflected into START MCP
- Primary energetic particle continues down the tube and strike second thin foil
- Electrons from this collision are deflected into STOP MCP
- The time between these two events are used to determine the particle energy
- Rate determines the flux
- Instrument pointing gives direction of flux

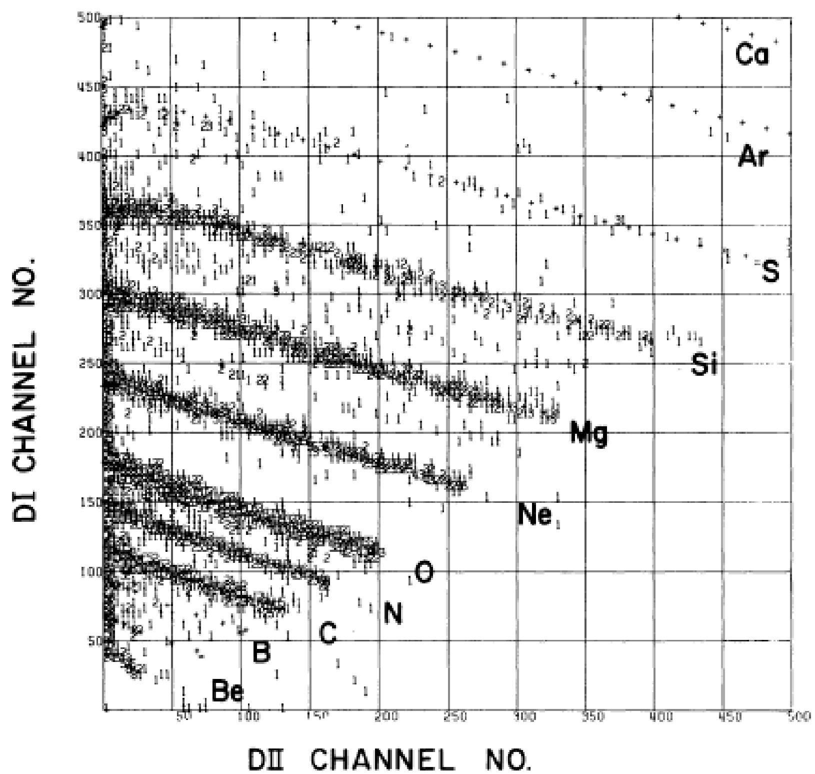
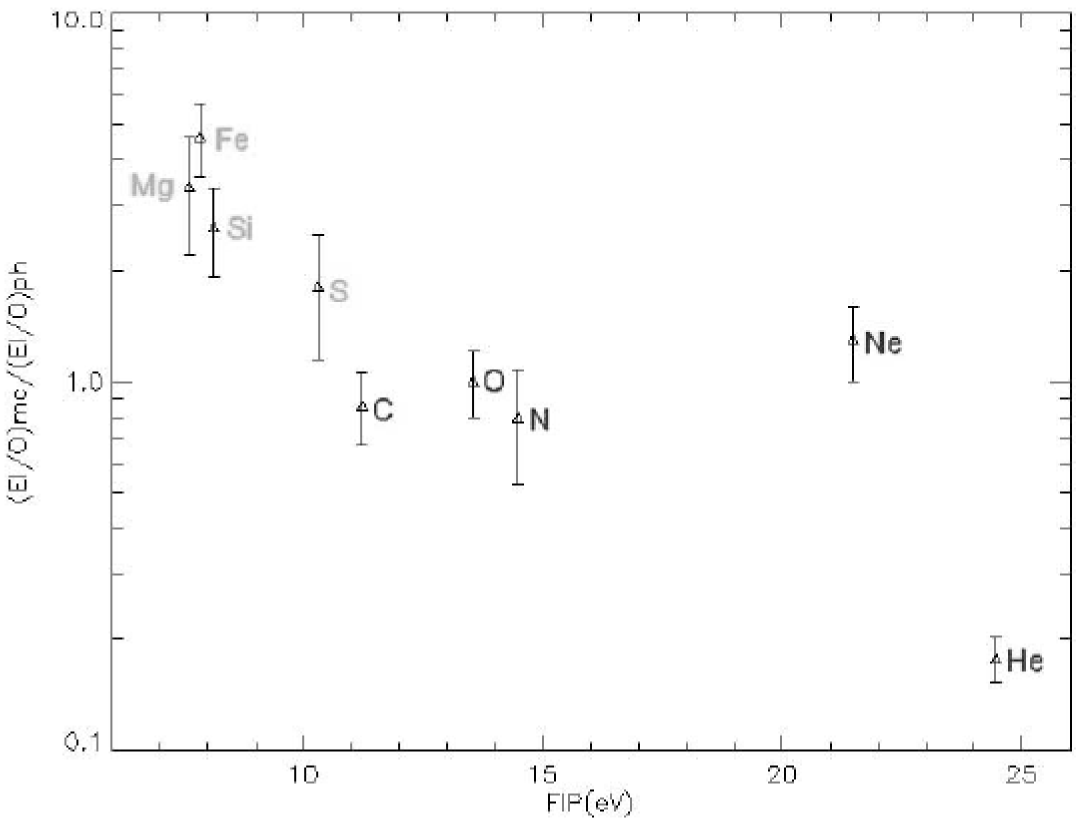


FIG. 2*a*

FIP Effect

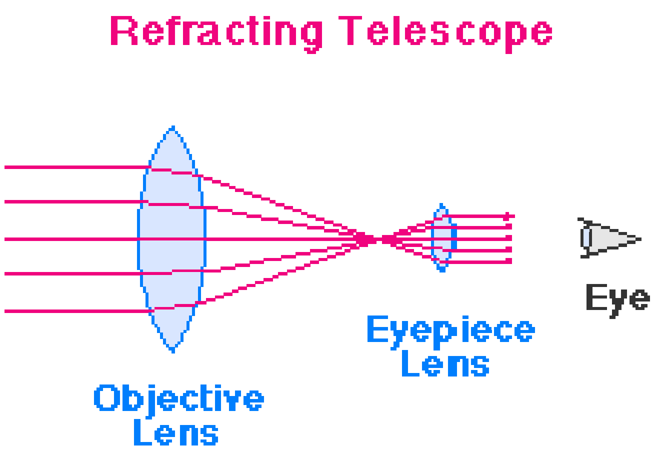


Remote Sensing Measurements

What can we learn?

Two Major Types of Optical Instrument

- Refraction
  - Refracting telescope was invented Hans Lippershey in 1608
  - Gallileo was the first to use it to study the heavens



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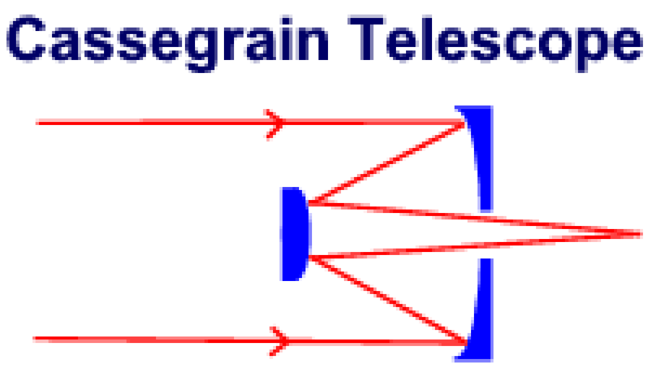
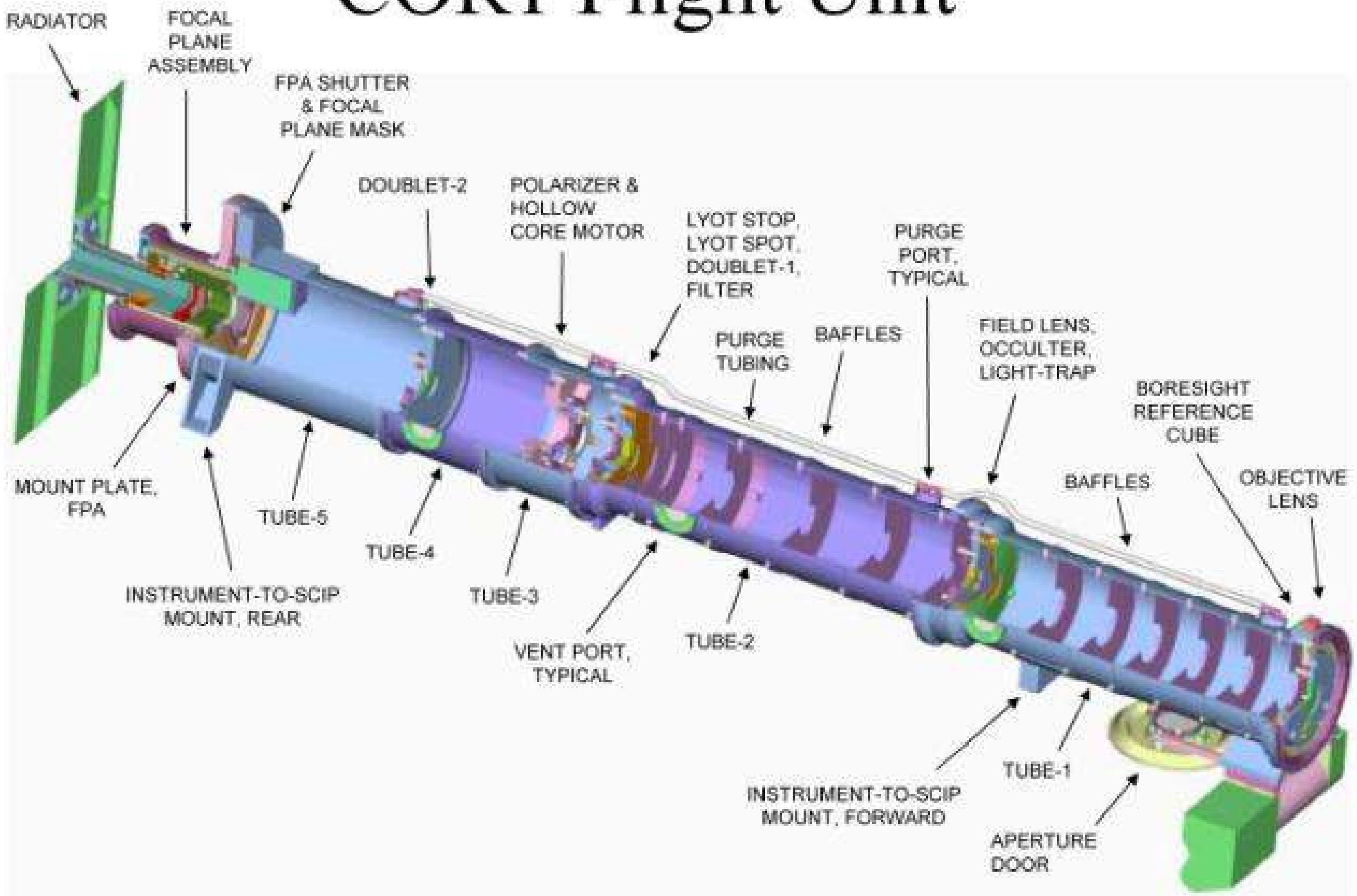
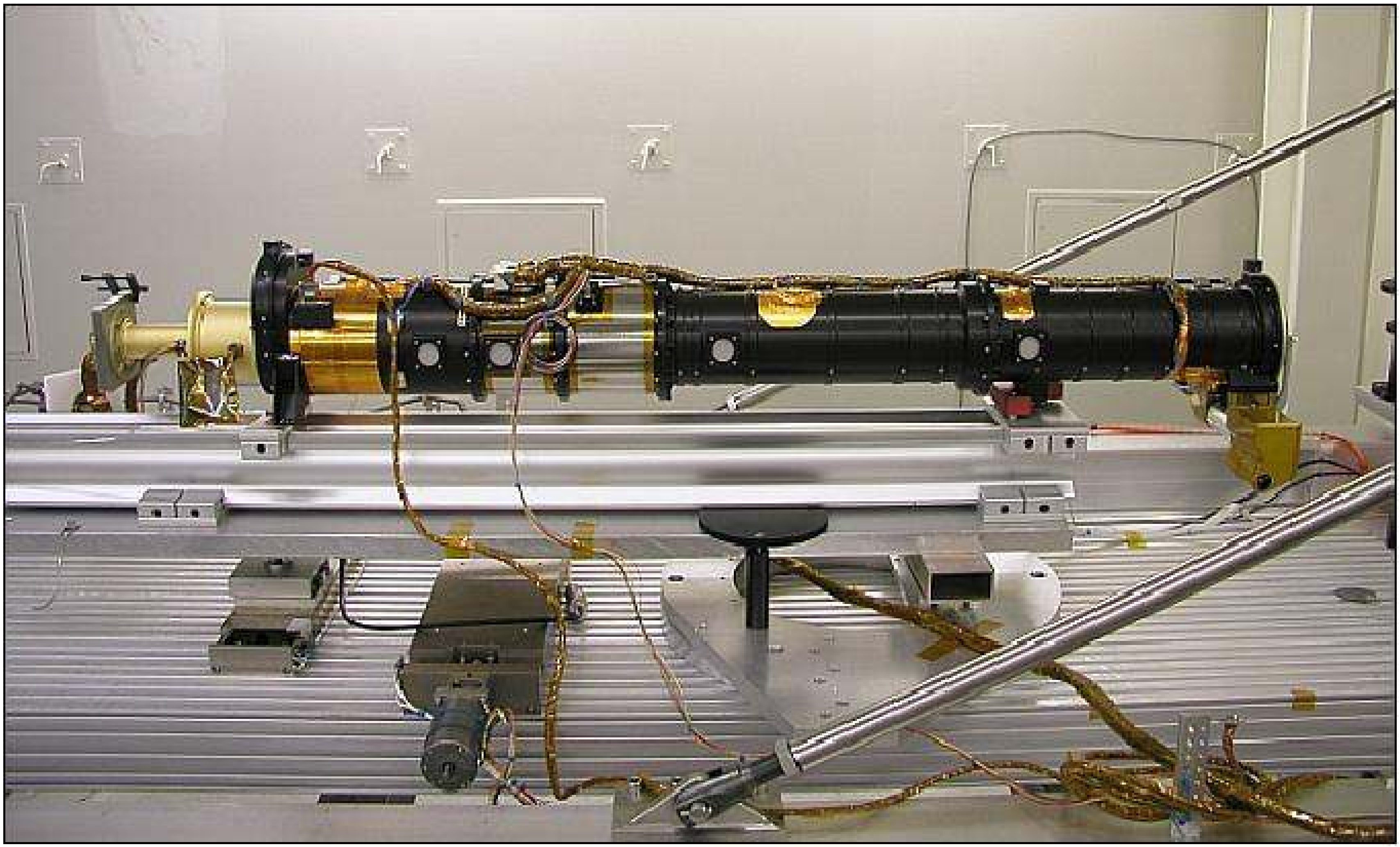
  - Sir Isaac Newton built the first model in 1688

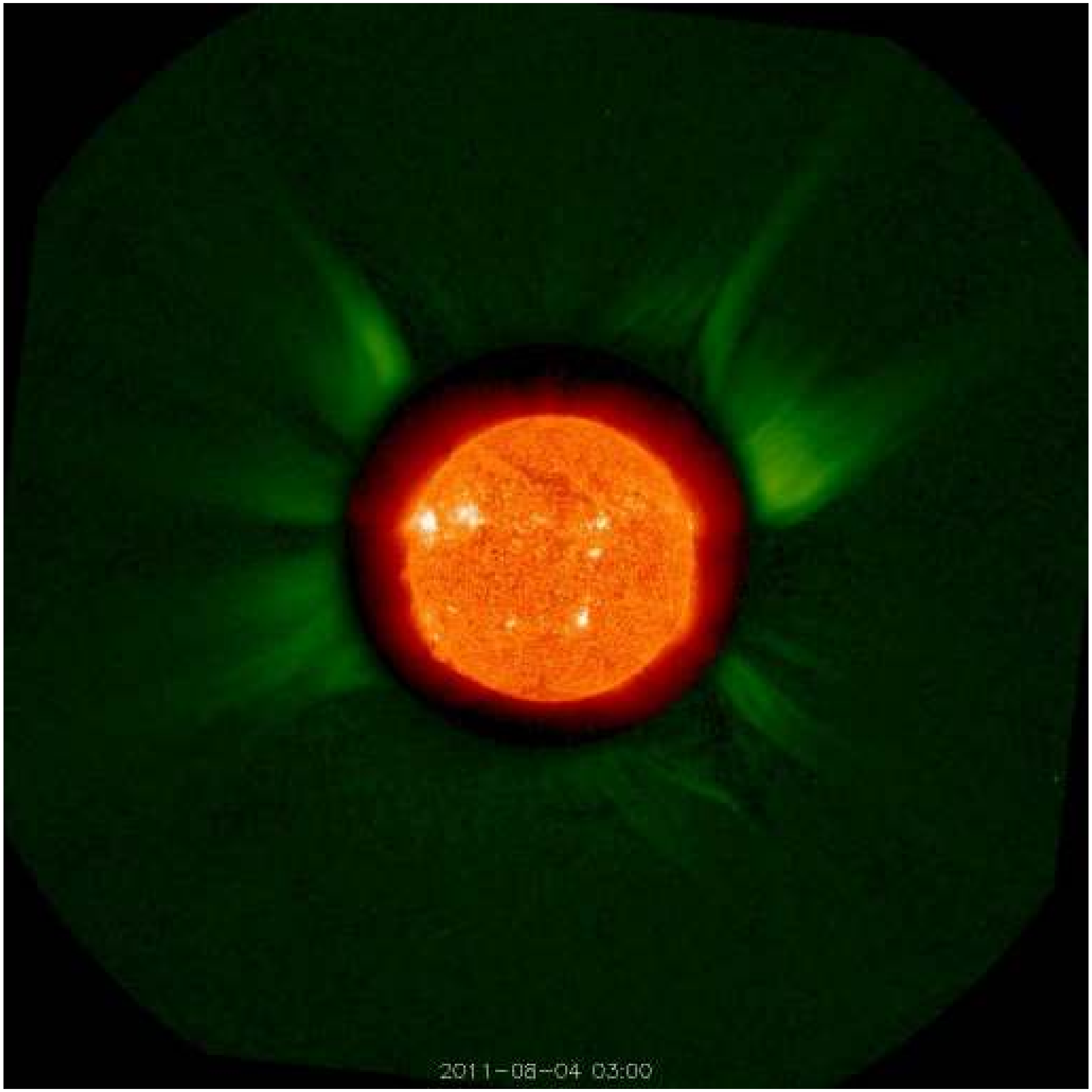


COR1 Flight Unit



Completed COR 1

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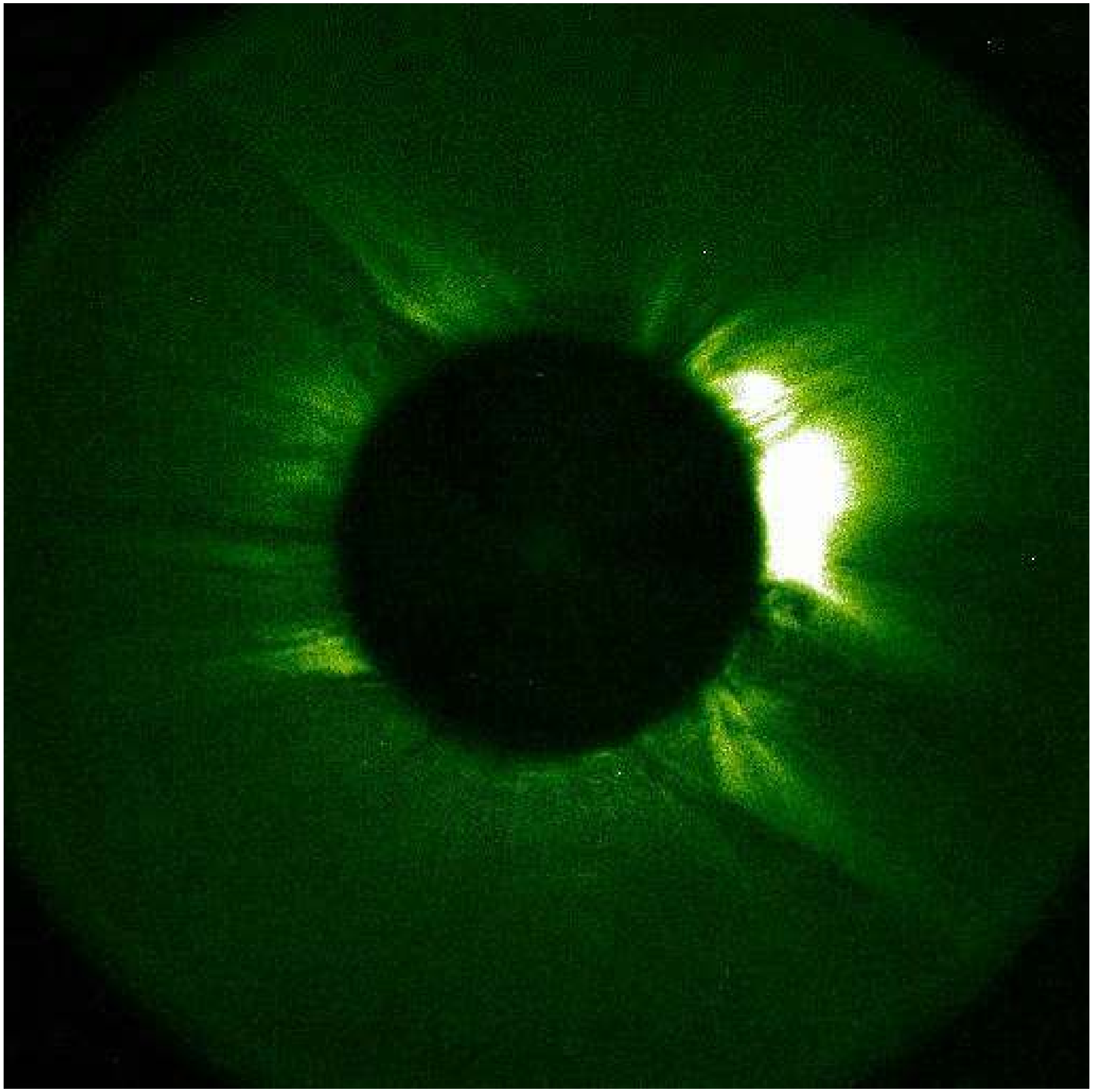
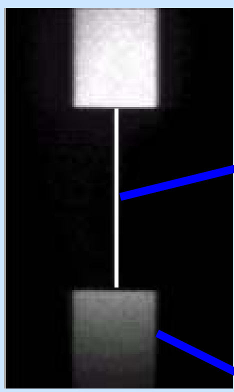


What Can we get from Spectra?

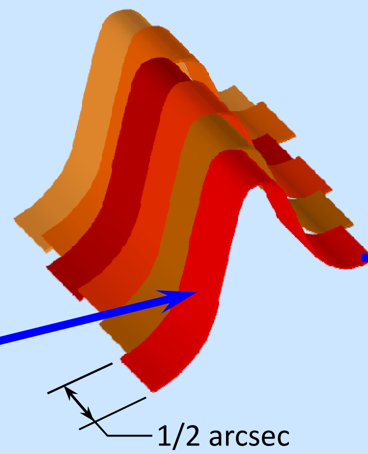
Observed Emission Line



Each emission line reproduces spectrograph aperture

Resolved Components

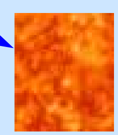
Each spatially resolved element is analyzed to obtain both intensity and velocity information



Spatially resolved line profiles are observed in narrow slit

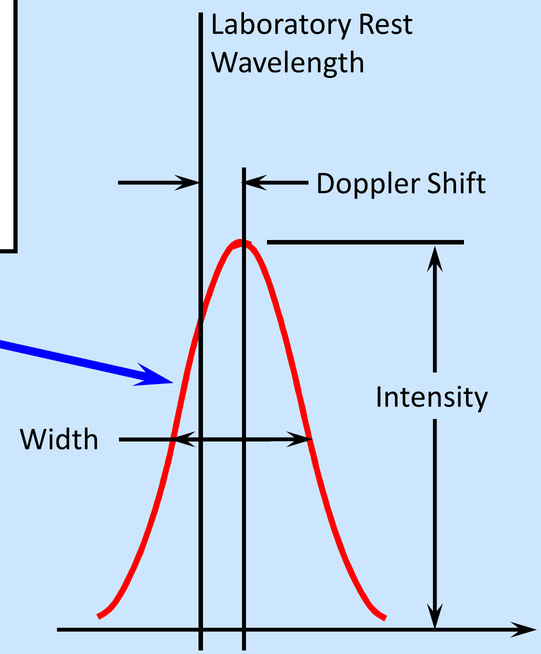
Line identification gives temperature

Ground Co-Alignment



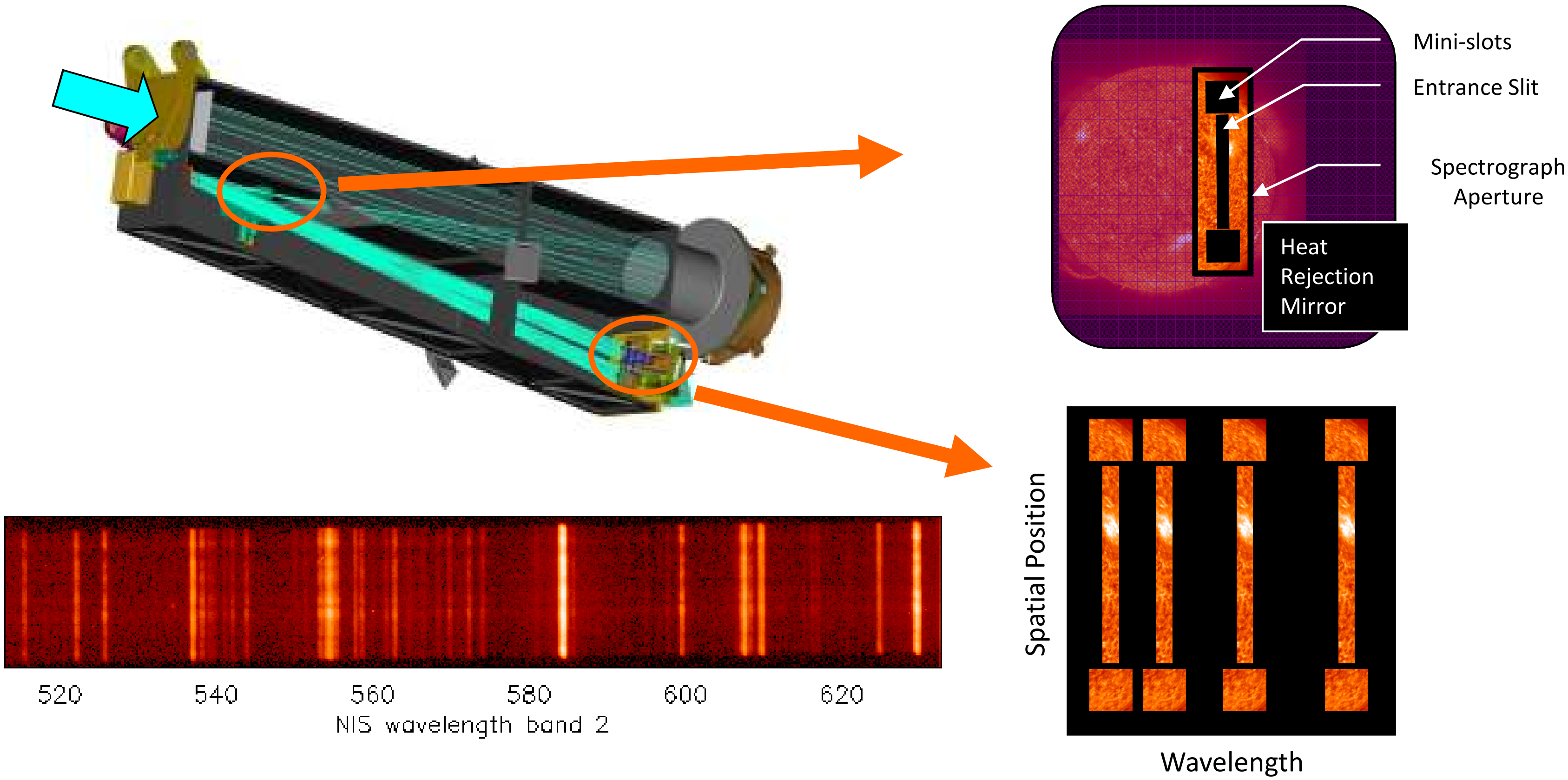
Wide slit provides 1’ x 1’ mini-images which allow coalignment on the ground

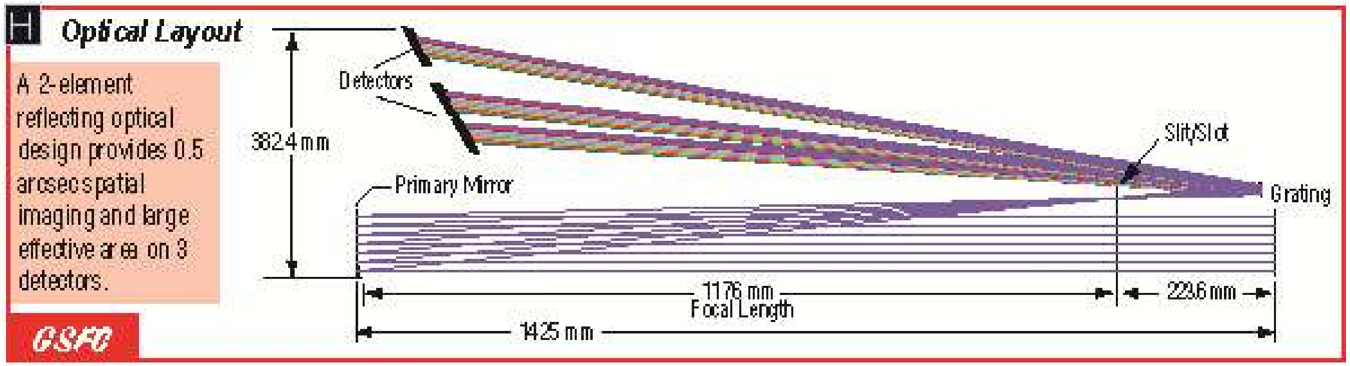
Physical Parameters



- **Intensity** – Measures plasma density, same as image
- **Doppler Shift** – Measures line-of-sight flow velocity
- **Width** – Measures unresolved turbulence in the plasma

How does a Imaging Spectrograph Work?

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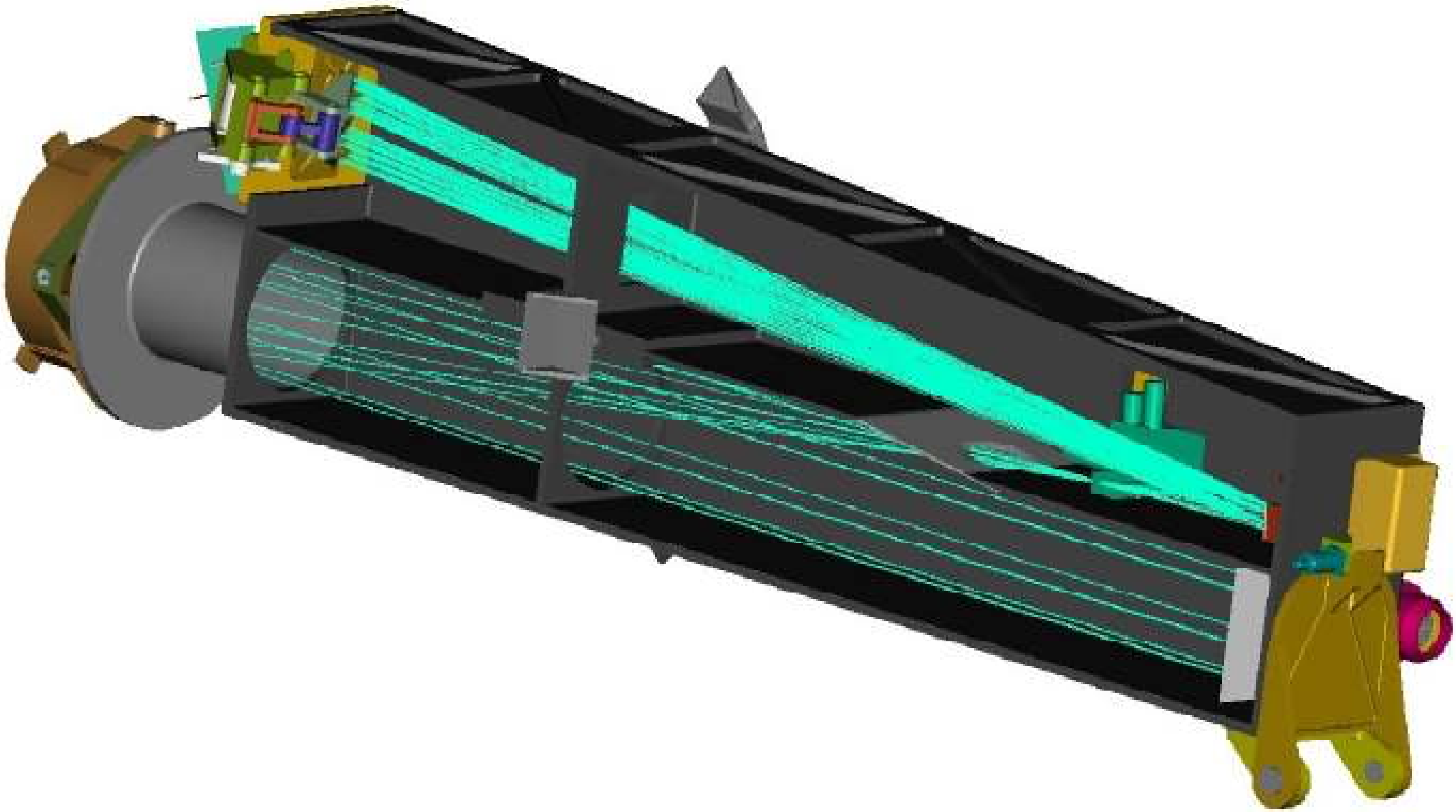
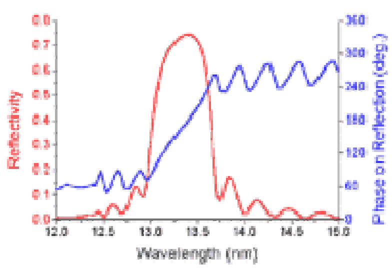
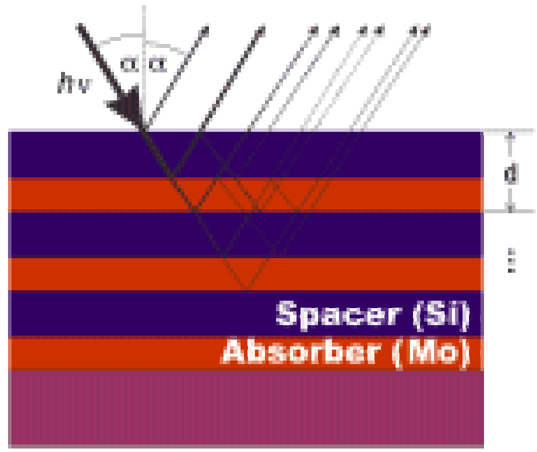
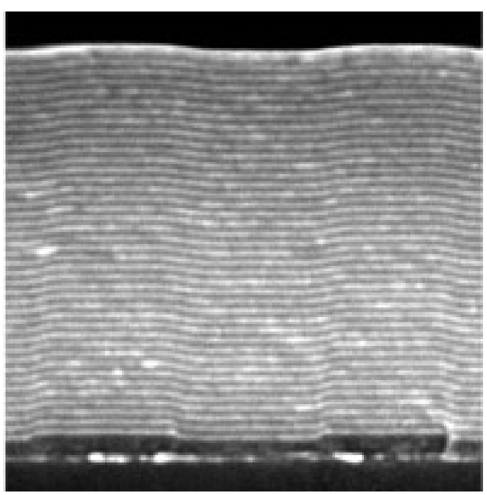
Optical Layout
A 2-element reflecting optical design provides 0.5 arcsec spatial imaging and large effective area on 3 detectors.
GSFC
Detectors
382.4 mm
Slit/Slot
Grating
Primary Mirror
1176 mm
Focal Length
223.6 mm
1425 mm



Multilayer Coatings







- Alternating stack of materials with different index of refraction
- Spacing chosen to provide constructive interference
- Lifetime is major concern

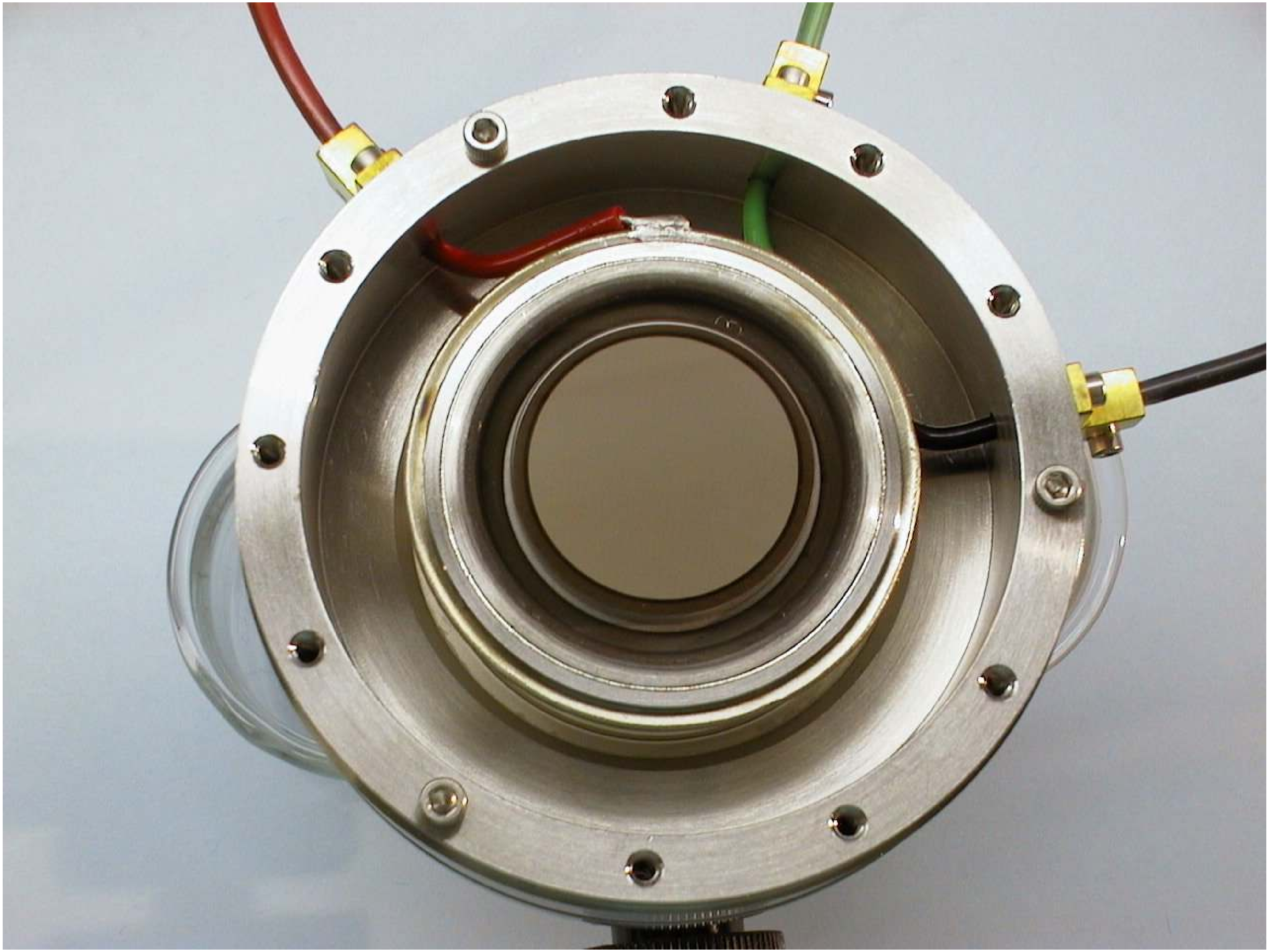
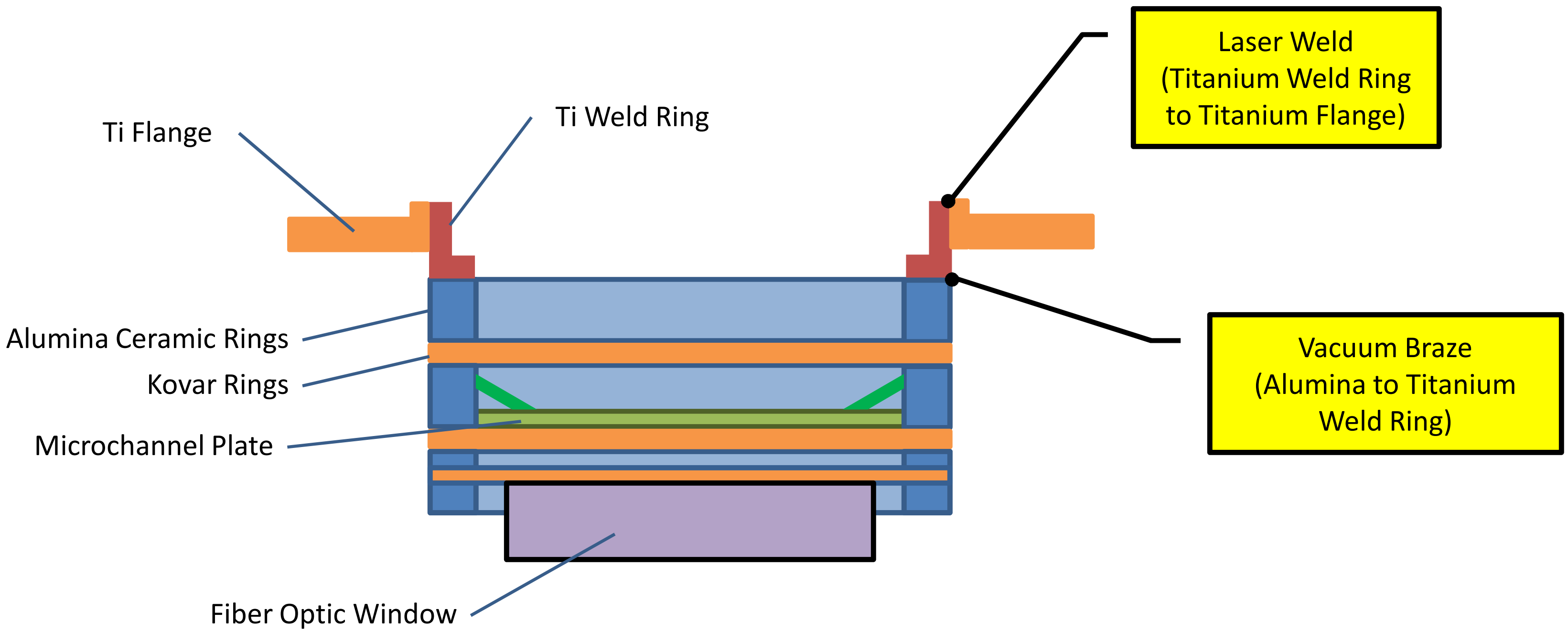
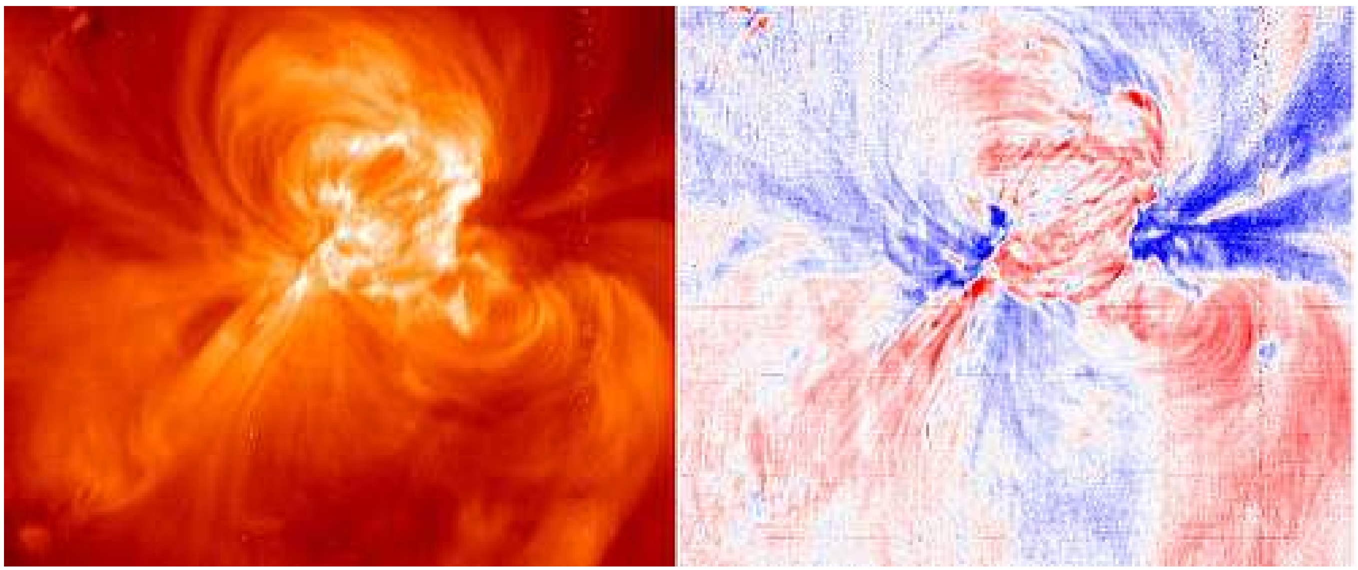


Image Intensifier



A Result from Hinode/EIS



Concluding Remarks

- I have tried to provide a broad overview of Heliophysics instrumentation in this talk
- However much has been glossed over, or left out entirely
- But I think that what we have done here gives you a foundation on which to think about heliophysics space instrumentation in your career.