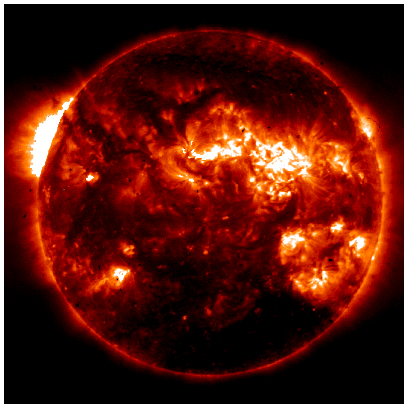
TRACE:http://vestige.lmsal.com

Coronal Science from TRACE

Leon Golub, SAO



ITP – 4 March 2002

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http://hea-www.harvard.edu/SSXG/

The SAO Solar-Stellar X-ray Group

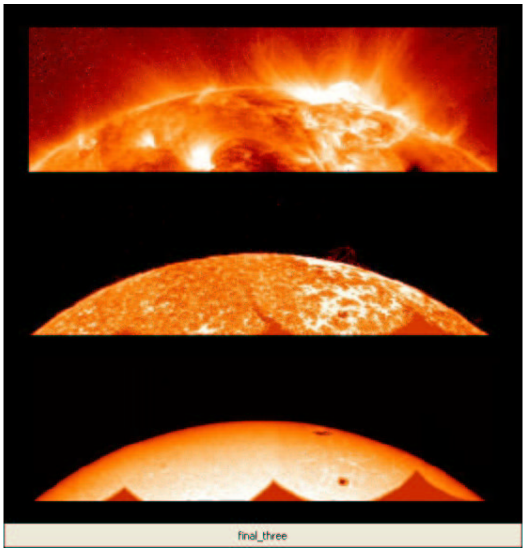
- Leon Golub
- Jay Bookbinder
- Ed DeLuca
- Kathy Reeves
- Steve Saar
- Harry Warren
- Amy Winebarger (now at NRL)
- Joe Boyd, Paul Hamilton, Dan Seaton

The Major Coronal Physics Problems

1. Why is the corona hot?
2. Why is the corona structured?
3. Why is the corona dynamic & unstable?

→*Emergence of* ***B*** *into the atmosphere,*
and response to ***B.***

Why Use X-rays to Observe Corona?

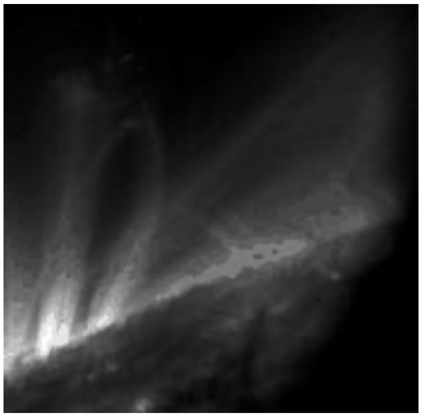


Response to flux emergence

1. Vigorous EFR Dynamics.

2. Large-scale B adjustment.

3. Strong local heating.



Outline of Talk

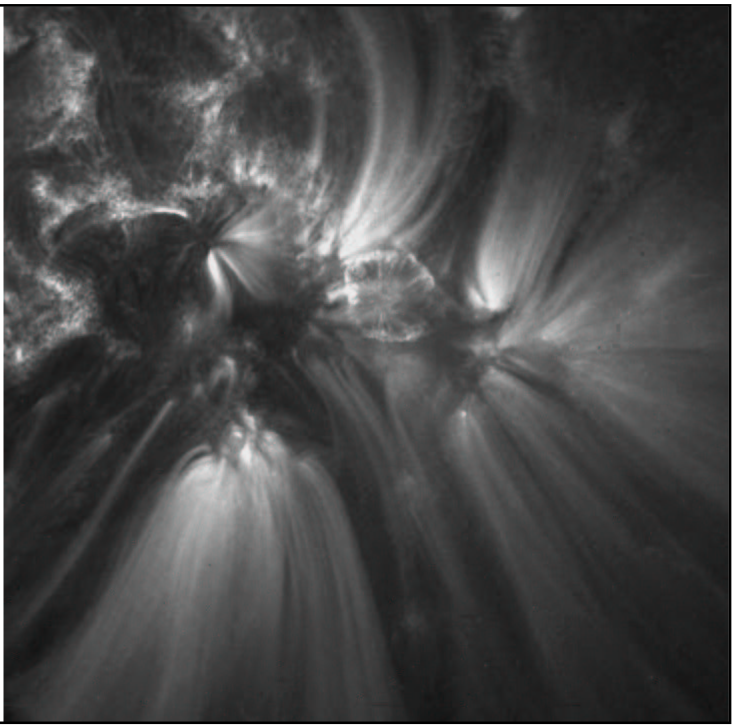
1. Coronal Heating: The New View From TRACE
2. Coronal Structure: Relation of **B** to X-ray Corona
3. Flares: What TRACE Has Added
4. CMEs
5. What Next?

Heating & Dynamics in ARs

TRACE sees at least *four* distinct processes in active regions:

1. Steady heating of hot loops (moss).
2. Transient loop brightenings in emerging flux areas.
3. Flare-like events at QSLs.
4. Steady outflows in long, cool structures.

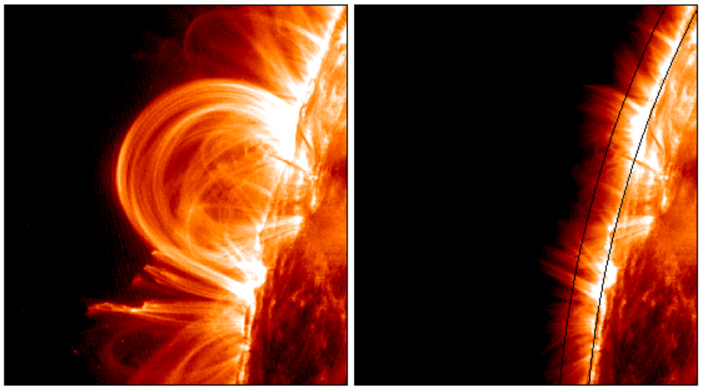
Examples of all four pheno-mena



TRACE Active Region Observations are ***not*** Consistent With Hydrostatic Model

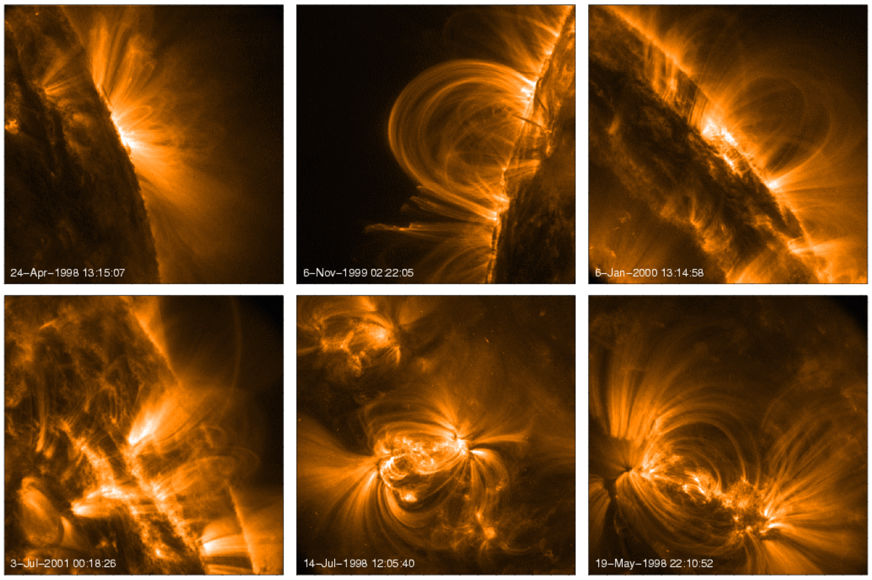
The Real Sun
observed by TRACE in 171 A
1999 Nov 6, 22:05 UT

The Theoretical Sun
How the Sun would look like if
it were in hydrostatic equilibrium

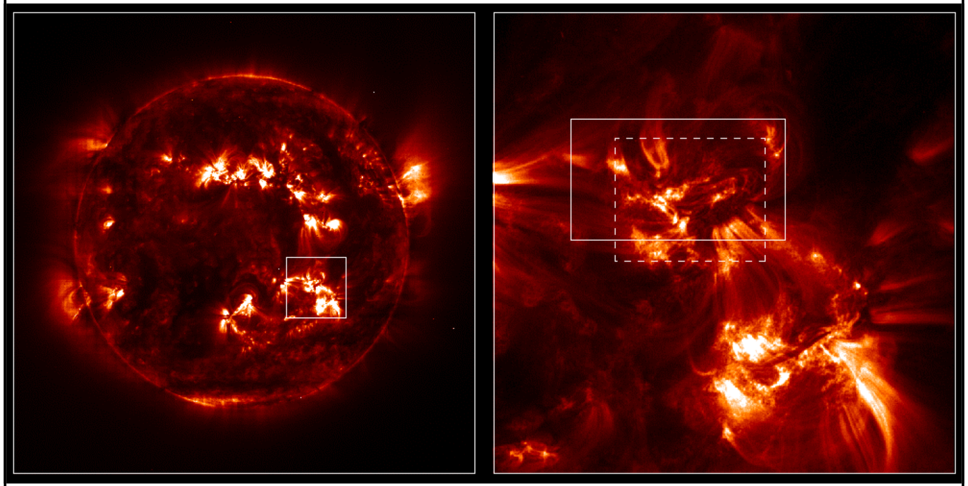


Density scale height $\lambda(T= \ MK)=47{,}000$ km
Flux or EM scale height $\lambda_{EM}=\lambda/2=23{,}000$ km

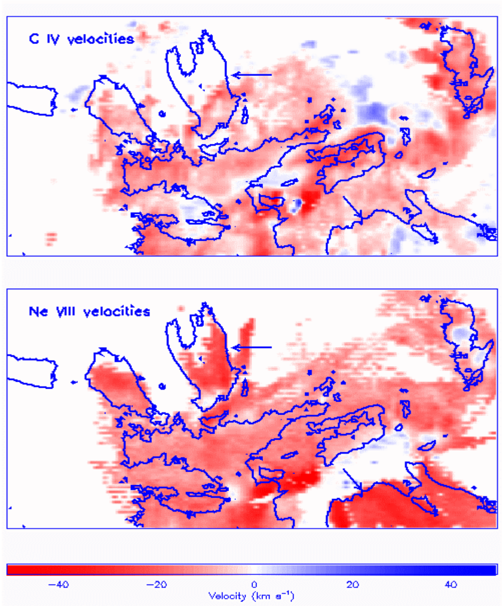
Loops are ubiquitous



Active Region 8536

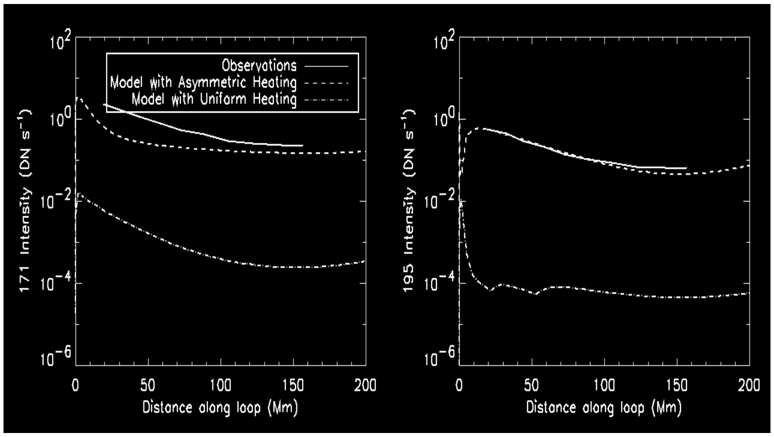


SUMER Velocities

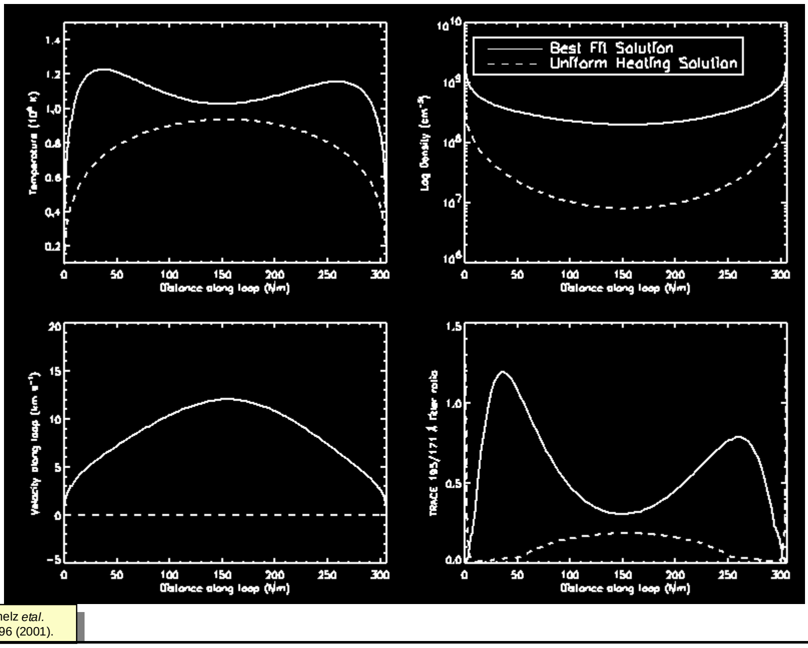


Winebarger ***etal*** ApJL (2001)

Static vs. Flow Model

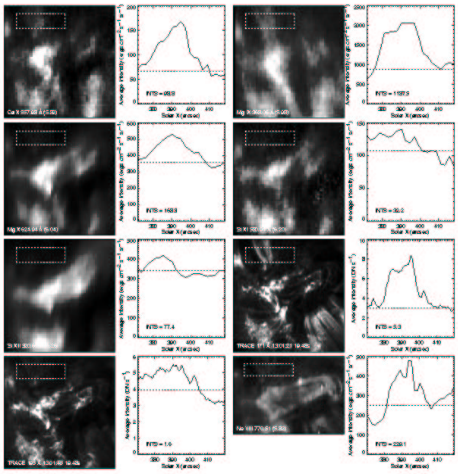


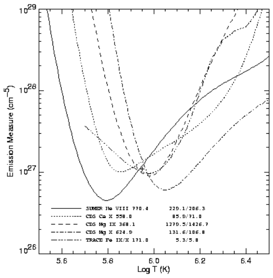
Best fit vs. Uniform heating



But cf. Schmelz *etal.*
Ap.J. **556**, 896 (2001).

How monochromatic are these loops?



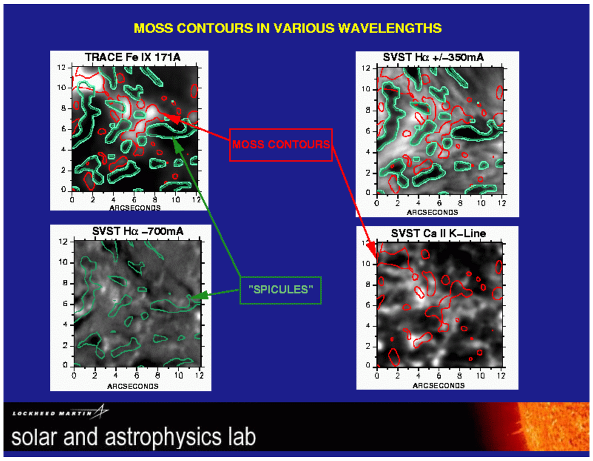


Microscale B vs. X

1. Complex relation between photosphere and corona.

2. Very rapid dynamics.

3. Large T-range to be observed.



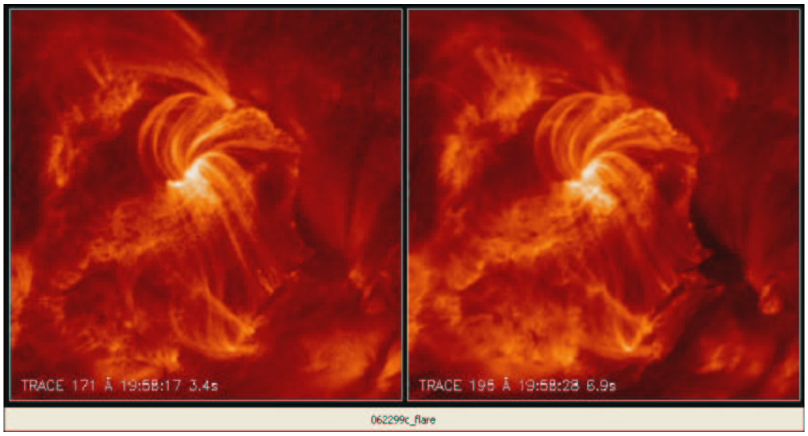
MOSS CONTOURS IN VARIOUS WAVELENGTHS

Resolution requires Solar-B observations!

TRACE Flare Results

- TRACE observes Fe XXIV 192 Å – *highest resolution images ever of hot flare plasma*
- Qualitatively consistent with flare models – *hot loops form first, cool post-flare loops form later*
- Evidence for “hot” regions – *20 MK plasma is found above 10 MK flare arcades*
- Fine structure in flares – *simulations with many small loops are needed to reproduce the observations*
- Pre-Flare observations – *evolution of ribbon brightenings is complex*

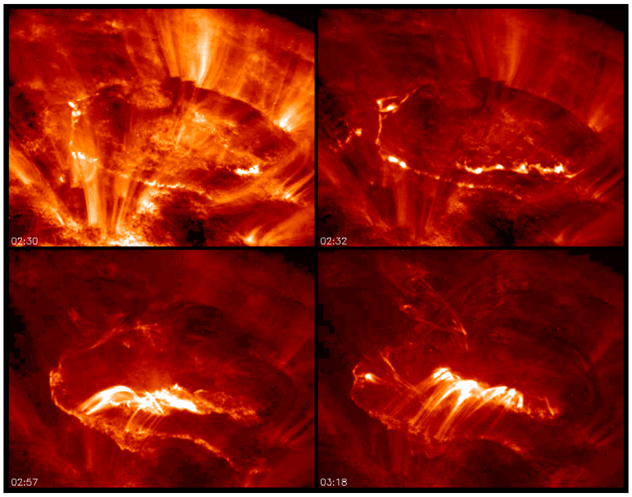
A Typical Event



Flares & CMEs

1. Initial energy release along current sheet ("spotty")

2. Spreading of ribbons vs. height of high-T (see next slide).



A Model for Flare Transition Region Evolution

[Antiochos *et al.* 2000, *Ap. J. Lett.* **542**, L151]

Flare loop evolution has three phases: heating, conduction-dominated cooling, and radiation-dominated cooling. Model of TRACE Emission:

- Standard 1D loop.
- Undergoing heating and/or conduction-driven evaporative cooling
- Assume radiative losses and gravity are negligible, motions are slow (compared to sound speed), and
- heating is spatially uniform ($\epsilon = \epsilon(t)$).

The DEM is given by:

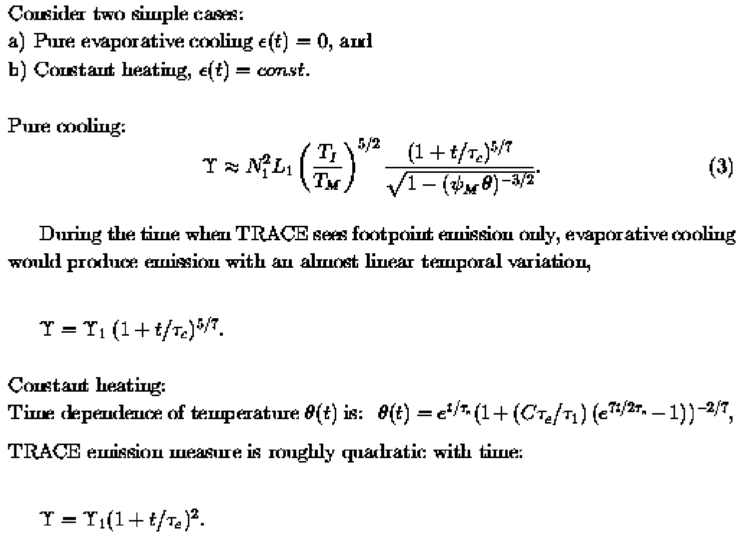
$$\Upsilon(t) = \frac{N_1^2 L_1}{2}\sqrt{\frac{3}{C}}\,\frac{p^2}{\theta^{5/2}\,\sqrt{\psi_M^{3/2} - \theta^{-3/2}}}, \tag{1}$$

where

$$\theta(\tau) = e^{p(\tau)}\left(\epsilon^{7/2} + \frac{7}{2}C\int_0^\tau e^{7p(u)/2}\,du\right)^{-2/7}, \tag{2}$$

and $p(\tau) = p(0) + \frac{2}{3}\int_0^\tau \epsilon(u)\,du$.

Given any assumed form for the heating $\epsilon(t)$, we determine the time dependence of the DEM. *We can, in principle, infer* $\epsilon(t)$ *from the observed form of* $\Upsilon(t)$.



Consider two simple cases:
a) Pure evaporative cooling $\epsilon(t) = 0$, and
b) Constant heating, $\epsilon(t) = const.$

Pure cooling:

$$\Upsilon \approx N_1^2 L_1 \left(\frac{T_I}{T_M}\right)^{5/2} \frac{(1+t/\tau_c)^{5/7}}{\sqrt{1-(\psi_M\theta)^{-3/2}}}. \qquad (3)$$

During the time when TRACE sees footpoint emission only, evaporative cooling would produce emission with an almost linear temporal variation,

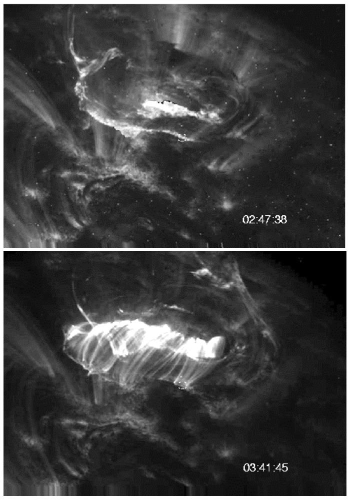
$$\Upsilon = \Upsilon_1\,(1+t/\tau_c)^{5/7}.$$

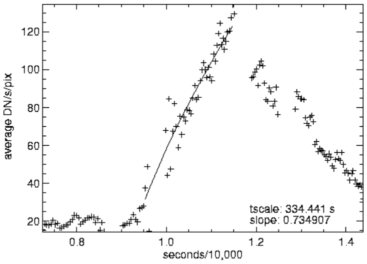
Constant heating:
Time dependence of temperature $\theta(t)$ is: $\theta(t) = \epsilon^{t/\tau_e}(1+(C\tau_e/\tau_1)\,(\epsilon^{7t/2\tau_e}-1))^{-2/7}$,

TRACE emission measure is roughly quadratic with time:

$$\Upsilon = \Upsilon_1(1+t/\tau_e)^2.$$

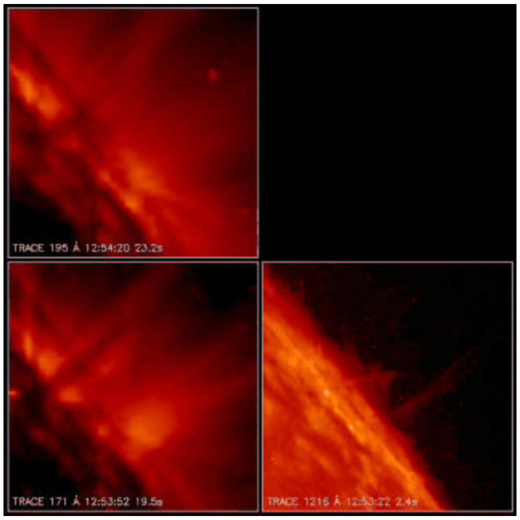
Comparison: Evaporative Model *vs.*TRACE Obs.



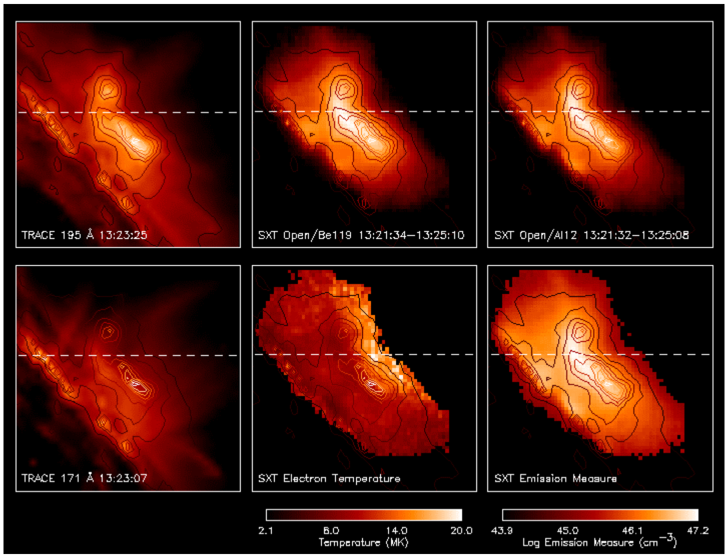


Warren *etal.*, ApJLett, 1999.

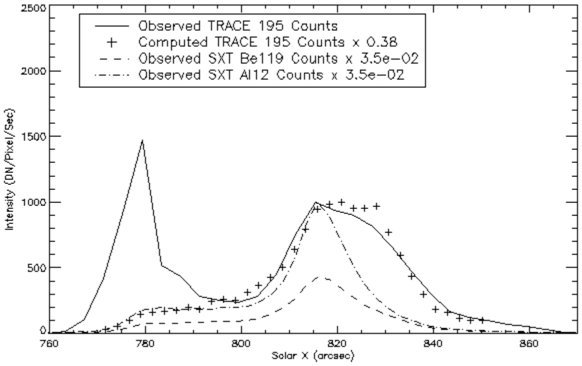
July 25, 1999 M2.4 Limb Flare



Most of the Flare Emission is Near 10 MK: June 25, 1999 M2.4

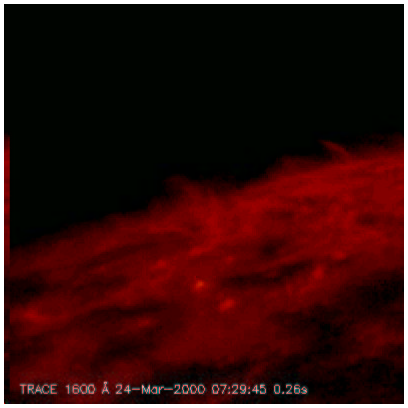


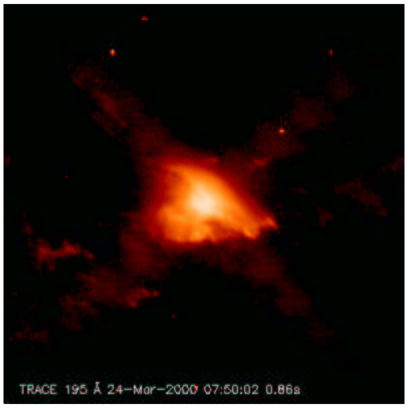
SXT and TRACE Show 15-20 MK Loop-Top Plasma



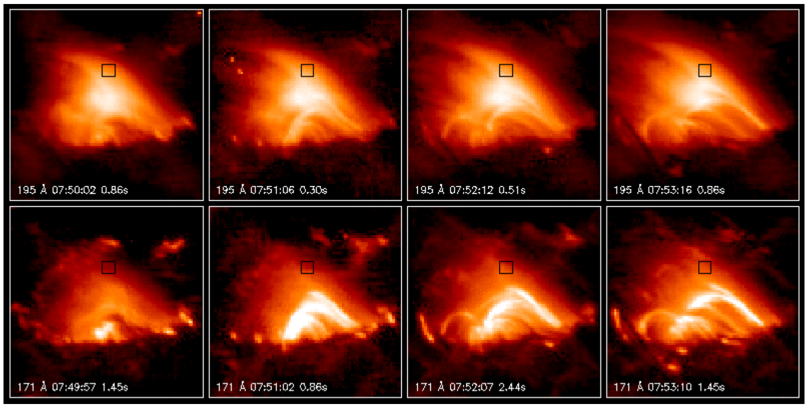
Warren & Reeves, ApJLett (2000).

March 24, 2000 X1.8 Flare: 1600 Å and 195 Å Movies

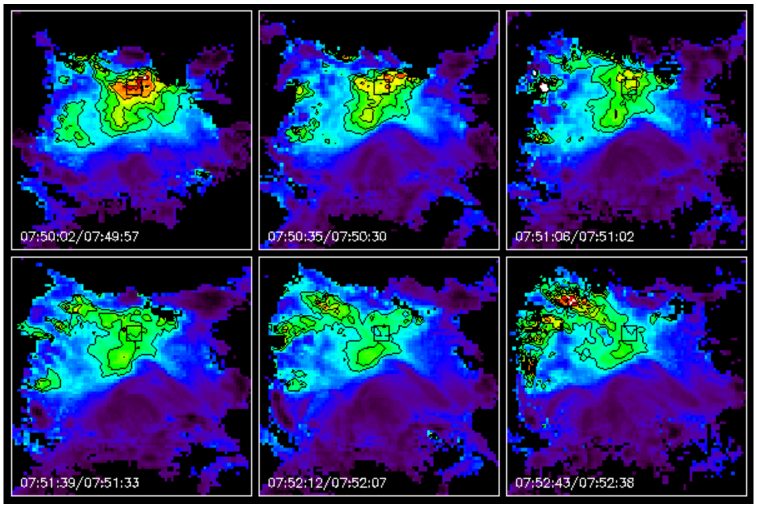




March 24, 2000 X1.8 Flare:
195 Å Near SXR Peak



March 24, 2000 X1.8 Flare:
195/171 Filter Ratios



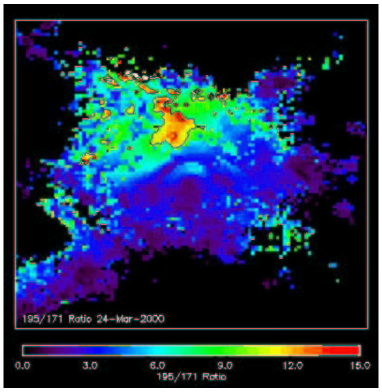
Reconnection at top of flares

1. Flare heating is preceded by expansion of high loops.

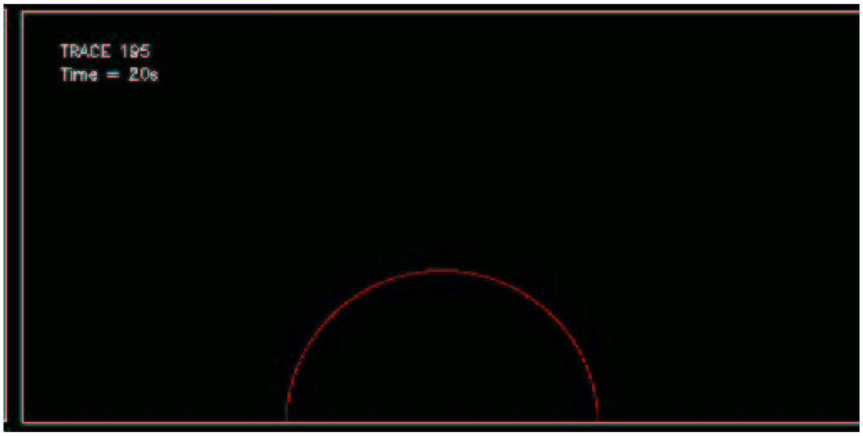
2. Hi-T source *above* postflare loops. ☜

3. Hi-T coincident with footpoint ribbon heating.

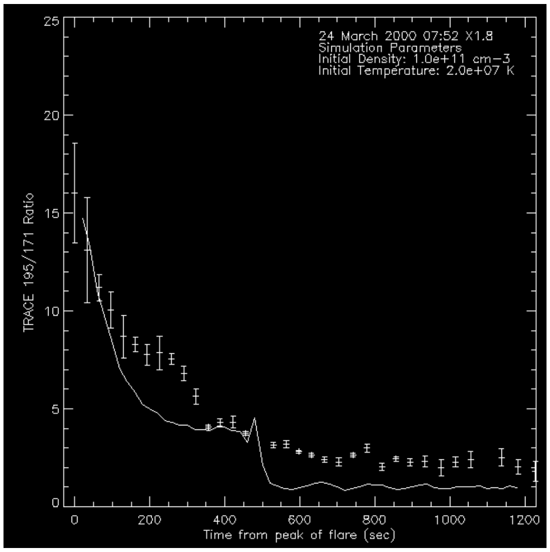
4. Source moves upward during course of flare. ☜



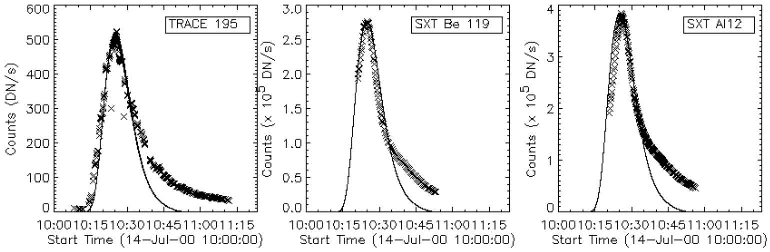
Modeling the Evolution of the Flare Arcade (2D)



Comparisons With Simulation: TRACE 195/171 Filter Ratios

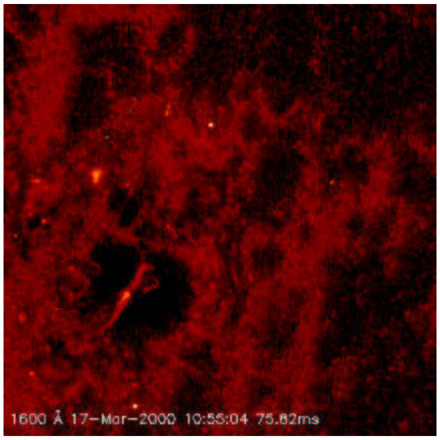


Improved Fit with Taller Loops

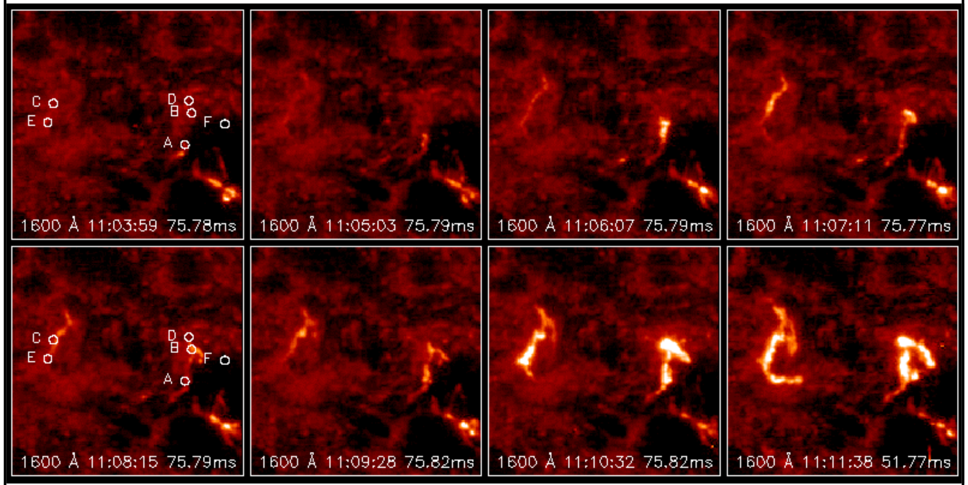


Warren & Warshall,ApJL (2001)

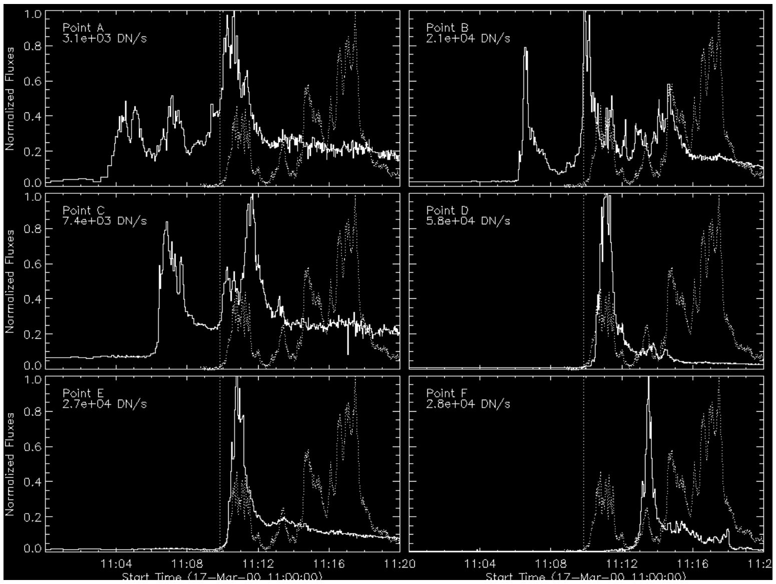
March 17, 2000 M1.1: TRACE 1600 Å Movie



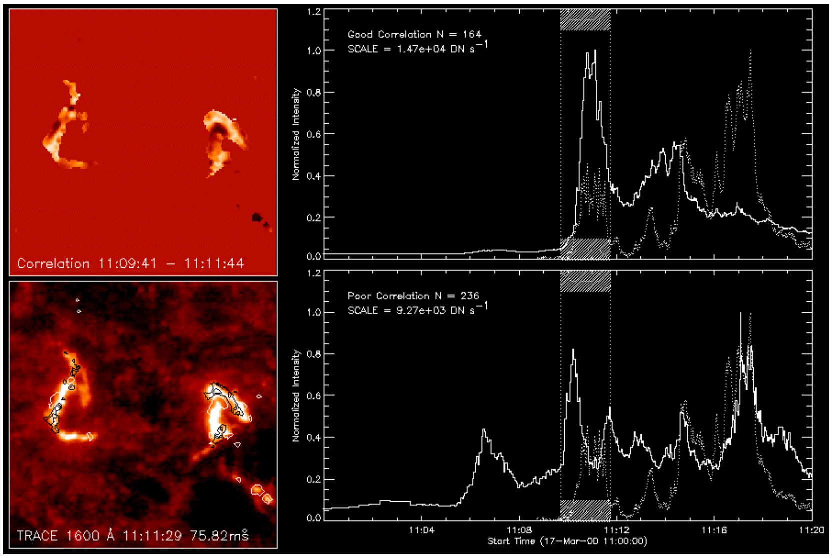
March 17, 2000 M1.1: TRACE 1600 Å Images



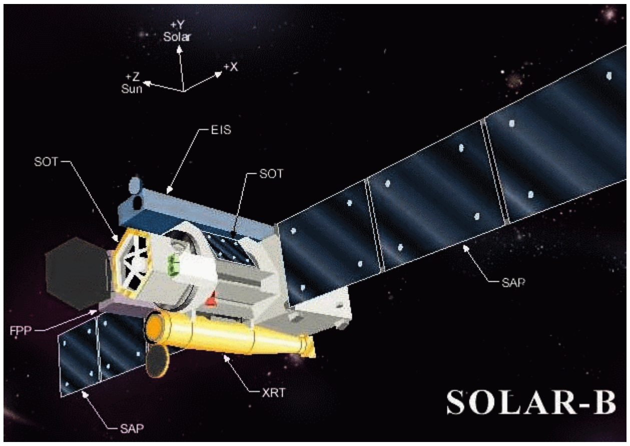
March 17, 2000 M1.1: TRACE 1600 Å Light Curves



TRACE Footpoint *vs.* BATSE HXR



The Solar-B Mission



The Solar-B Instrument Complement

1. Solar Optical Telescope with Focal Plane Package (FPP)
- 0.5m Cassegrain, 480-650nm
- VMG, Spectrograph
- FOV 164X164 arcsec

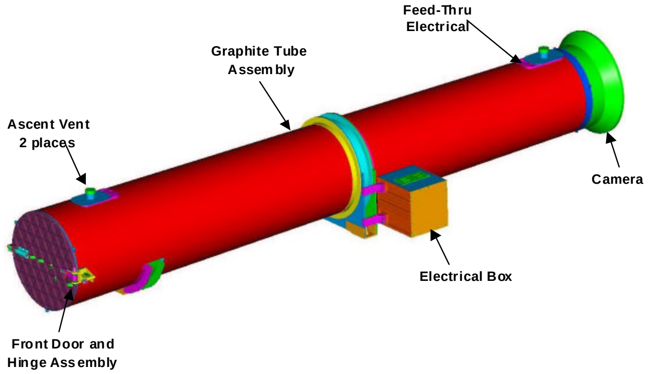
2. EUV Imaging Spectrograph (EIS)
- Stigmatic, 180-204, 240-290Å
- FOV 6.0X8.5 arcmin

3. X-ray Telescope (XRT)
- 2-60Å
- 1 arcsec pixel
- FOV 34X34 arcmin

XRT vs. SXT Comparison

1. Higher spatial resolution: 1.0” vs. 2.5”
2. Higher data rate: 512kB *continuous.*
3. Ten focal plane analysis filters.
4. Extended low-T *and* high-T response.
5. FIFO buffer for flare-mode obs.

Solar-B XRT Flight Design



October 24, 2001 XRT CDR Overview/Systems* P. Cheimets-1

Response to flux emergence

The observational problem:

1. Vigorous EFR Dynamics.
2. Large-scale B adjustment.
3. Strong local heating.

→ How are Solar-B Instruments to be Targeted?

Solar-B Observations

Full Sun or AR-belt X-ray obs, high cadence for extended time period.

Ground-based full Sun coordinated obs.

Q: How do we target FPIP and EIS to the regions of interest?

From Photosphere to Corona

1. Choose target of interest.

2. Surface **B** from FPIP.

3. Photospheric and chromospheric structure at high spatial and temporal resolution (FPIP/EIS).

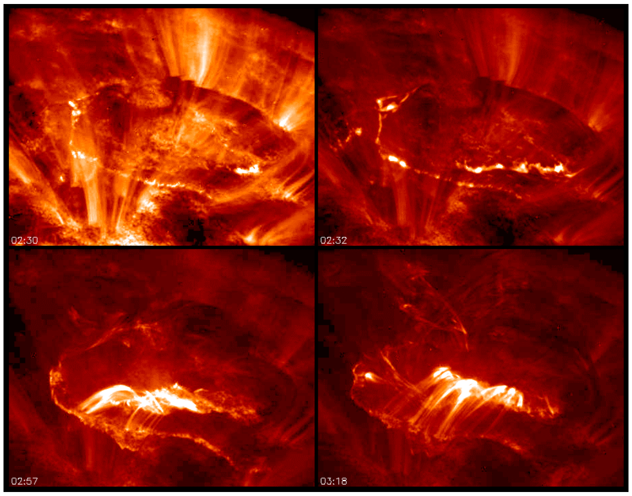
4. Chromosphere-TR-corona topology and dynamics (EIS/XRT).

5. Coronal structure and dynamics (XRT).

Flares & CMEs

1. Initial energy release along current sheet ("spotty")

2. Spreading of ribbons vs. height of high-T (see next slide).



Solar-B Flare Obs

Solar-B is launched near minimum of cycle.

Flare observations require difficult coordinated observations: FPP for **B**, EIS for T, XRT for geometry and context.

Recommendation: Do not attempt flare program at start of mission. (But be prepared to deal with flares when they occur.)

XRT Observing Wish List

Question: What observations would you forever regret not having done?

(Note: We ignore for a moment whether or not there practical difficulties in doing these observing programs.)

Full Corona Survey

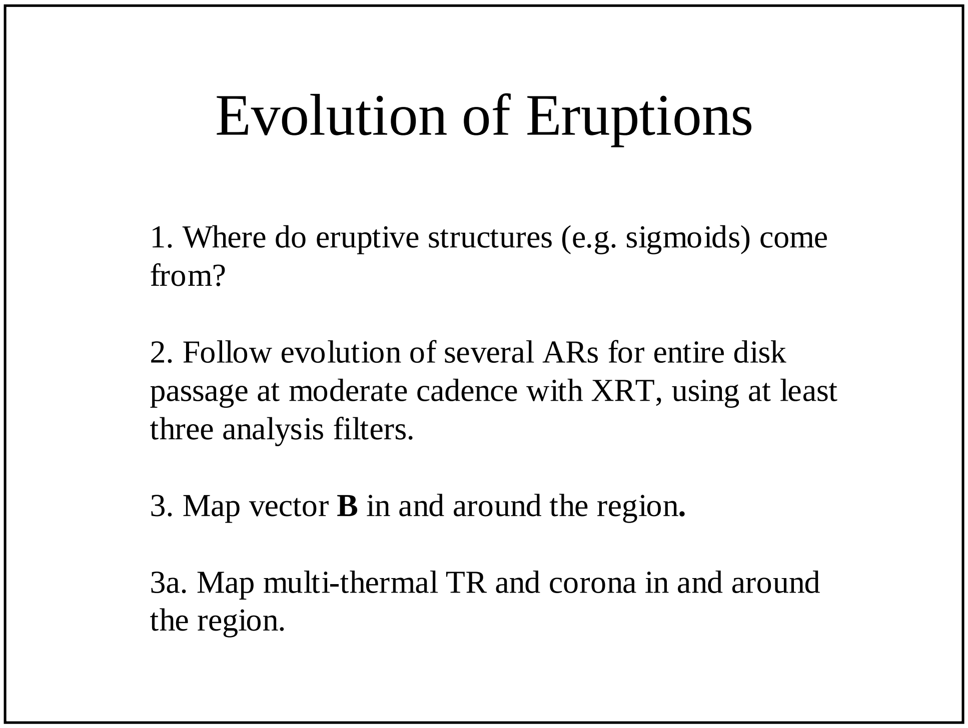
One full Solar rotation:

1. Full Sun, full resolution.
2. Cadence at least twice per orbit.
3. Two or more filters for analysis.

Coronal dynamics survey

One day of high time resolution, large-field coronal observation.

1. Image cadence at least every 20 seconds.
2. F.O.V. at least 512x512 arcsec, centered on chosen target.
3. At least two analysis filters, for disk passage.



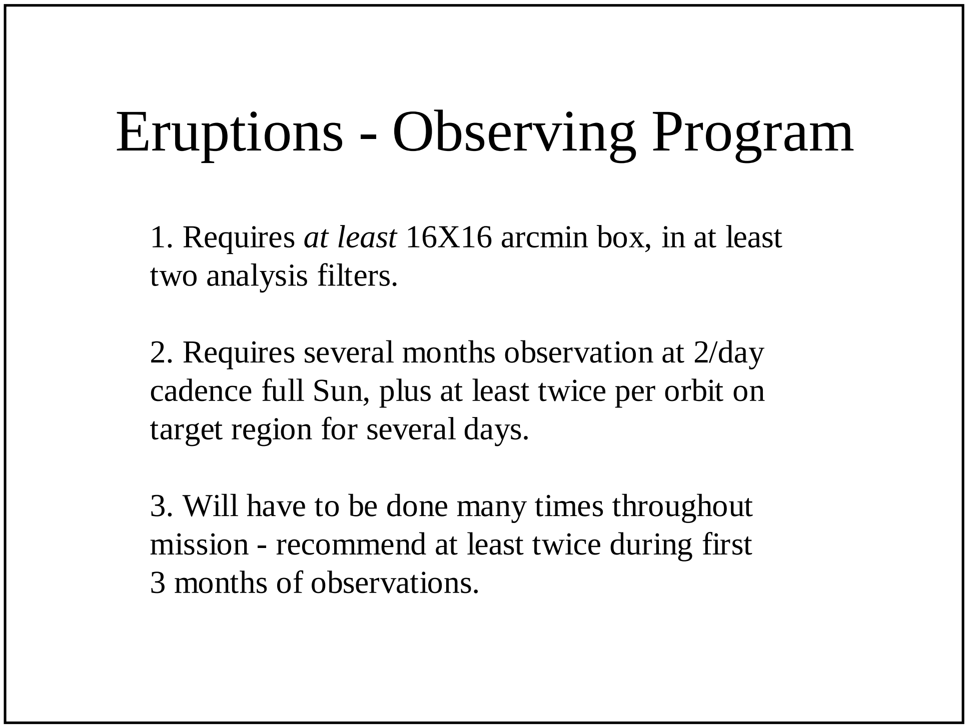
Evolution of Eruptions

1. Where do eruptive structures (e.g. sigmoids) come from?

2. Follow evolution of several ARs for entire disk passage at moderate cadence with XRT, using at least three analysis filters.

3. Map vector **B** in and around the region**.**

3a. Map multi-thermal TR and corona in and around the region.



Eruptions - Observing Program

1. Requires *at least* 16X16 arcmin box, in at least two analysis filters.

2. Requires several months observation at 2/day cadence full Sun, plus at least twice per orbit on target region for several days.

3. Will have to be done many times throughout mission - recommend at least twice during first 3 months of observations.

Requirements Flowdown

Primary Requirements	Definition	Value	Primary Hardware
Exposure Time	Shutter open/close	4ms (min) 10 sec (max)	Shutter, Filters, GI mirror effective area
Cadence	Time between exp.	2 sec	Shutter, Filter wheels
Temp. Range	Temp. range	6.1 < log T < 7.5	GI Coatings, Filters
Temp. Resolution	Temp. discrimination	Log T = 0.2	Filter selection
Image Resolution	50% encircled energy	2” at 0.5 keV on axis	GI Mirror Prescription
Field of View	Angular coverage	>30 arcmin	GI Mirror Prescription
GI to VLI alignment	Align X-ray to WL images	10 arcsec	Mirror Assembly
GI to [EIS,SOT] alignment	Align XRT to other instruments	1 arcmin	XRT structure
Derived Requirements			
Visible Light Rejection	Reduction of solar visible light at focal plane	>10**11	Prefilters, FP filters, structures

What Next?

RAM: A Solar Microscopy Mission

(Reconnection And Microscale Probe)

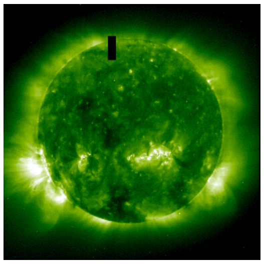
Science Objectives

- **Understand the dynamics of solar & astrophysical plasmas**
  - **image the structures of unstable plasma configurations**
  - **image the onset & evolution of plasma instabilities**
- **Understand the energetics of magnetically heated plasmas**
- **Understand the fine-scale structure of astrophysical objects from planets to quasars.**

  ***RAM* uses the Sun, solar system objects and galactic X-ray sources as laboratories for testing and extending our knowledge of astrophysical plasmas.**

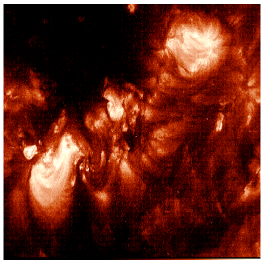
Comparative Resolutions

EIT/SXT image



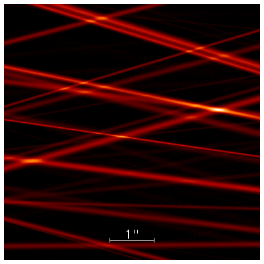
Global dynamics

TRACE resolution



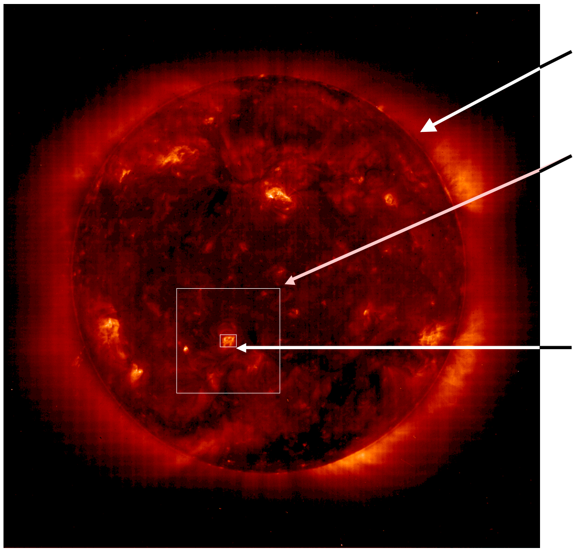
Coronal/Photospheric connections

RAM simulation



Microstructure
Dynamical processes
Plasma physics

Comparative Fields of View

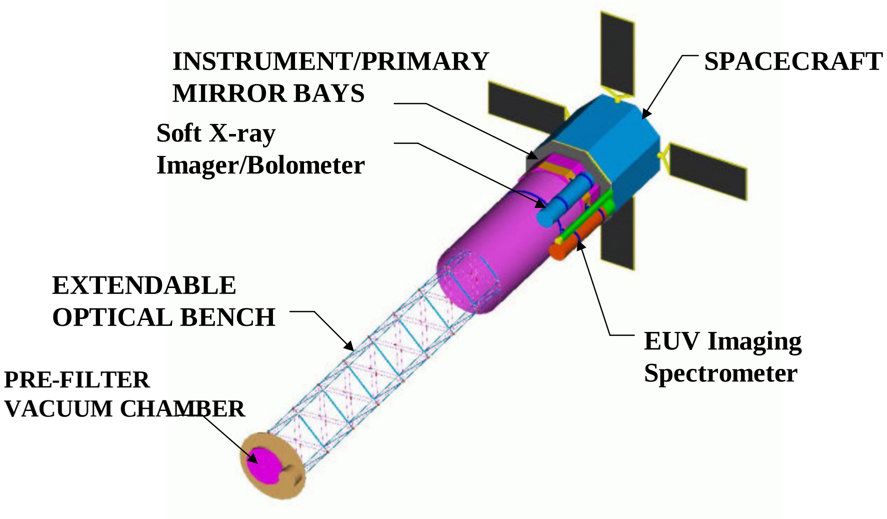


EIT/SXT F.O.V.
Solar-B F.O.V.

TRACE F.O.V.

RAM HIRES F.O.V.

Deployed RAM Configuration



INSTRUMENT/PRIMARY MIRROR BAYS

Soft X-ray Imager/Bolometer

EXTENDABLE OPTICAL BENCH

PRE-FILTER VACUUM CHAMBER

SPACECRAFT

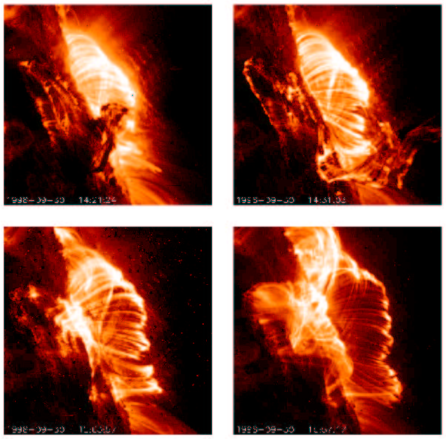
EUV Imaging Spectrometer

Science Themes

- Plasma Dynamics
- Thermal Structure and Stability
- The Onset of Large Scale Instabilities
- Non-Solar Objects

Plasma Dynamics

- Reconnection
  - – loop-loop interaction
  - – flux emergence
  - – nano-flares
  - – AR jets
  - – macro-spicular jets
  - – filament eruption



Plasma Dynamics

- Waves
  - **origin of high speed wind**
  - **tube waves**
  - **coronal seismology**

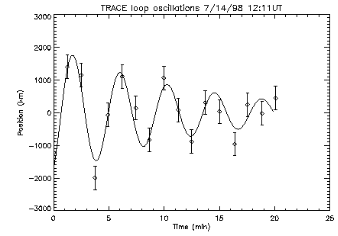


Figure 2: The temporal evolution of the loop displacement calculated as an average co-ordinate of the loop position for 4 neighboring perpendicular cuts through the loop apex (diamonds), with error bars (± 0.5 pixel). The solid line is the best-fit of equation 1. The effect of the image motion through the field of view were subtracted in the above analysis.

Global mode oscillations

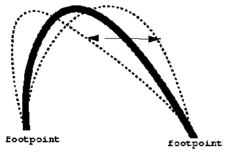


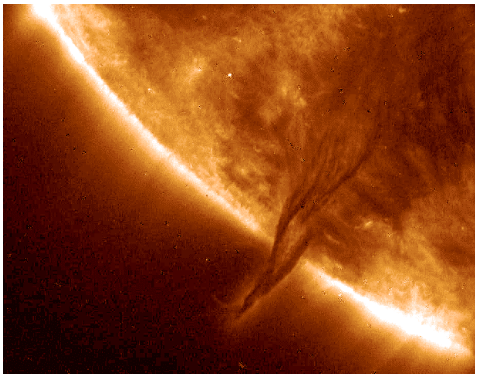
Figure 3: A sketch of a coronal loop that undergoes global mode oscillations. The dominant magnetic filed component is along the loop axis. The oscillations are transverse to the direction of the magnetic field.

Figures from Nakariakov et al. (1999): decaying loop oscillations seen in TRACE can be used to estimate the coronal dissipation coefficient.

R_e ~ 6 x 10^5 or R_m ~ 3 x 10^5 , about 8 orders of magnitude less than classical values.

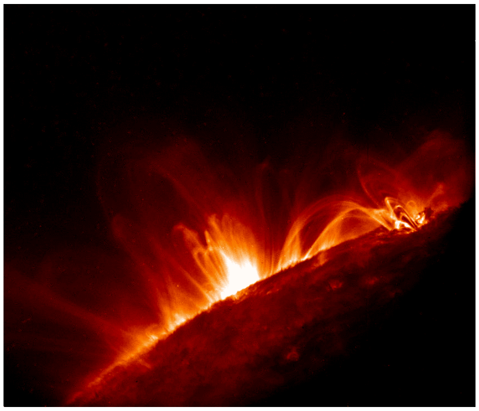
Thermal Structure/Stability

- Physical Properties
  - **Te, ne, EM**
  - **energetics**
  - **variability timescales**
- Multithermal Structure
  - **steady loops**
  - **filaments**



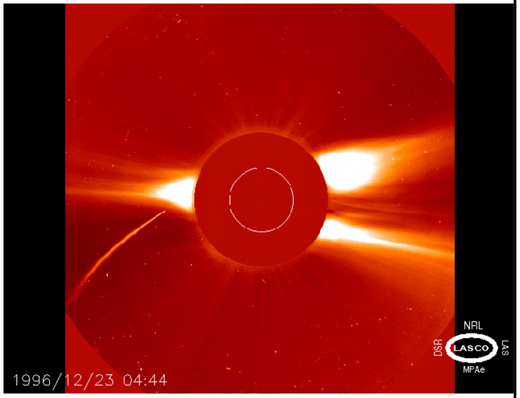
Onset of Large Scale Instabilities

- Emerging Flux Region
  - **twisting/untwisting**
  - **reconnection**
- delta Spots
  - **current sheets**
  - **topology changes**
- Active Filaments
  - **Te, ne**
  - **local heating**



Non-Solar Objects

- **Jupiter**
  - **S VII @ 198**
- **Nearby RS Cvns**
- **Galaxy Cluster Halos**
- **Comets**
- **Any EUVE source within 1 deg of Sun**



Science Drivers I: Spatial Scales

- **“Global” MHD Scales**
  - **Active Regions;**
  - **granulation scales**
- **Transverse scales**
  - **δT, δn**
  - **$\delta B_\perp$ and j**
- **Reconnection sites**
  - **location**
  - **size**
  - **dynamics**

10^5 km

10^3 km

10^1 - 10^3 km

<10 km

<10 km

RAM discovery space

Science Drivers II: Time Scales

Loop Alfven time	**~10 sec**
Sound speed vs. loop length	**~100 sec**
Ion formation times	**~1 - 10 sec**
Plasma instability times	**~10 - 100 sec**
Transverse motions	**1 - 100 sec**
Surface B evolution times	**minutes - months**

Current Instrument Complement

- **RAM has an EUV imaging instrument:**
  - **A High Resolution Telescope - 0.01 arcsecond pixels, >arcminute FOV.**
- **RAM has an EUV spectrograph:**
  - **SERTS- or SUMER-like spectrograph, w/improved optics and gratings for 0.5” performance**
- **RAM has an X-ray calorimeter, for imaging spectroscopy at X-ray wavelengths.**
- **RAM has a TRACE-like EUV context imager.**

Instrument Sensitivity I

Relative Throughput

Item	TRACE (195A)	HIRES (193A)	
Geometric Area (cm^2):	162	3,850	
Reflectivity (2 bounces)	0.12	0.25	
CCD QE	0.08	0.8	
Throughput Ratio (HIRES/TRACE)		480	
Pixel Size	0.5”	0.02”	0.01”
Pixel Area ratio:	1	1.6×10^{-3}	4×10^{-4}

Instrument Sensitivity II

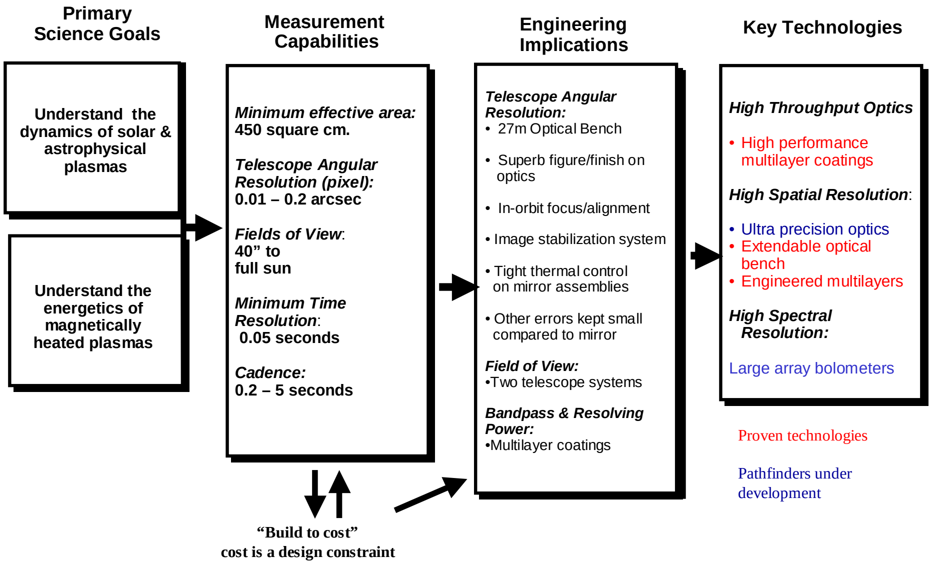
EXPOSURE TIMES

Item	**TRACE (195A)**	**HIRES (193A)**	
		(0.02”)	**(0.01”)**
Worst Case: **(no substructure)**	**10sec**	**10 sec**	**40 sec**
Best Case: **(all flux in one pixel)**	**10sec**	**0.005 sec**	**0.02 sec**
Nominal Case: **(flux “thread”)**	**10sec**	**0.5 sec**	**1 sec**

Instrument Details

	High-Resolution Imager	**Context Imager**
Mirror Diameter	**0.75m**	**0.3m**
Eff. Focal Length	**240m**	**5m**
Pixel Size	**0.01”**	**0.25”**
CCD Format	**6k x 8k**	**4k x 4k**
F.O.V	**60”x80”**	**16’ x 16’**

Requirements Flow Down



Primary Science Goals

- Understand the dynamics of solar & astrophysical plasmas
- Understand the energetics of magnetically heated plasmas

Measurement Capabilities

Minimum effective area: 450 square cm.

Telescope Angular Resolution (pixel): 0.01 – 0.2 arcsec

Fields of View: 40” to full sun

Minimum Time Resolution: 0.05 seconds

Cadence: 0.2 – 5 seconds

Engineering Implications

Telescope Angular Resolution:

- 27m Optical Bench
- Superb figure/finish on optics
- In-orbit focus/alignment
- Image stabilization system
- Tight thermal control on mirror assemblies
- Other errors kept small compared to mirror

Field of View:

- Two telescope systems

Bandpass & Resolving Power:

- Multilayer coatings

Key Technologies

High Throughput Optics

- High performance multilayer coatings

High Spatial Resolution:

- Ultra precision optics
- Extendable optical bench
- Engineered multilayers

High Spectral Resolution:

Large array bolometers

Proven technologies

Pathfinders under development

“Build to cost”
cost is a design constraint

Key Technologies

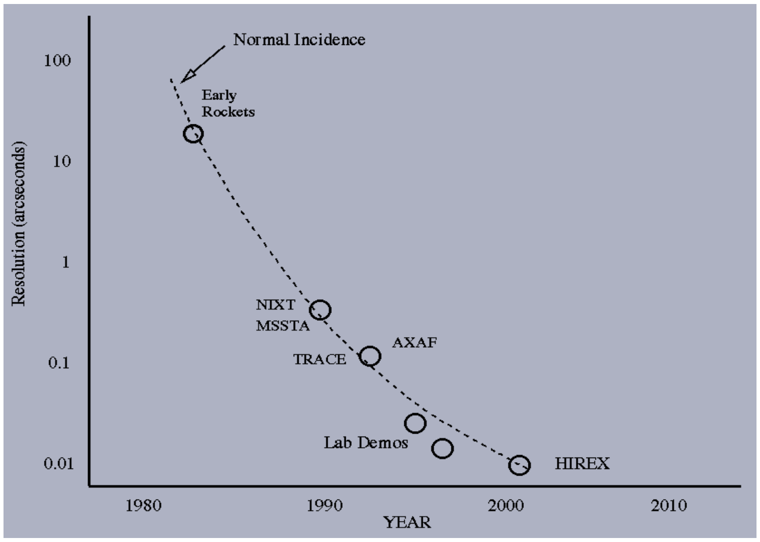
RAM uses a combination of innovative and proven technologies to yield exciting new science:

- **New Technologies**:
  - **Ultra-high precision optics (0.25m pathfinder mirror under development with partners ROSI and Bauer, Assoc.).**
  - **Cryogenic bolometers for soft x-ray spectroscopy.**
- **Heritage technologies:**
  - **Extendable Optical Bench: RAM re-uses the SRTM deployable mast to reduce cost, reduce risk, & improve reliability.**
  - **Image stabilization techniques: RAM extends techniques from TRACE and SOHO/MDI missions.**
  - **Multilayers based on TRACE heritage**

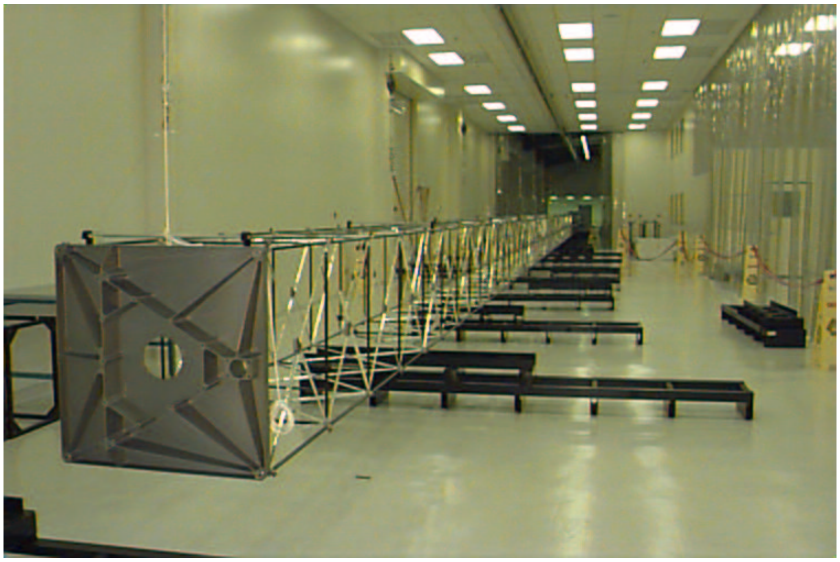
Ultra-Precision Optics

	HIRES Requirements	Commercial Goals
Figure error	**<0.4 nm rms**	**0.25 nm rms**
Mid-frequency Error	**<0.5 nm rms**	**0.2 nm rms**
Microroughness	**<0.3 nm rms**	**0.1 nm rms**

Optics Metric



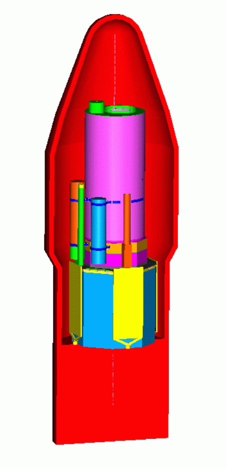
Extendable Optical Bench Prototype



Mission Summary

	Current Baseline
Class	ST Probe
Orbit:	L1
Mission Duration	3 year/5 year
Launch Date	>2007
Data Downlink	>1500 images/day
Launch Vehicle	Delta-III medium
Ground Station	continuous
Instrument Complement	HRI/CT/SoCCS/XRB

Launch Configuration



Mass (S/C):	446 kg (with reserve)
Mass (total):	1452 kg
Mass Margin:	23%
Power:	1410 watt EOL
Power Margin:	24.2%
Telemetry:	50Mbps (X-band)
On-board Storage:	40 Gbyte
Attitude:	3-axis stabilized
Stability:	20”, 3-σ, t<100s

Study Team Members

- SAO

- Lockheed-Martin
- NASA/GSFC
- NSO
- Univ. of Chicago
- ROSI
- Bauer Assoc.
- University of Tokyo
- Obs. de Paris, Meudon
- MPIAe
- Osserv. Astron. di Palermo
- Univ. of St. Andrews

End

Historical Context

Instrument	Resolution	F.O.V	Wavelength Coverage
NIXT	0.6”	full Sun	one line
YOHKOH	2.5”	full Sun	filters
SoHO	2.5”	full Sun	four lines
TRACE	0.5”	8.5’	three lines
Solar-B	1.0”	full Sun	Filters
Solar Probe	0.03”*	30”*	one line
HIREX	0.01,0.25	40”, 16’	One line

Solar-B Observations

Full Sun or AR-belt X-ray obs, high cadence for extended time period.

Ground-based full Sun coordinated obs.

Q: How do we target FPIP and EIS to the regions of interest?

Solar-B Flare Obs

Solar-B is launched near minimum of cycle.

Flare observations require difficult coordinated observations.

Recommendation: Do not attempt flare program at start of mission. (But be prepared to deal with flares when they occur.)

XRT Observing Wish List

Question: What observations would you forever regret not having done?

(Note: We ignore for a moment whether or not there practical difficulties in doing these observing programs.)

Full Corona Survey

One full Solar rotation:

1. Full Sun, full resolution.

2. Cadence at least twice per orbit.

3. Two or more filters for analysis.

Coronal dynamics survey

One day of high time resolution, large-field coronal observation.

1. Image cadence at least every 20 seconds.

2. F.O.V. at least 512x512 arcsec, centered on chosen target.

3. At least two analysis filters, for disk passage.

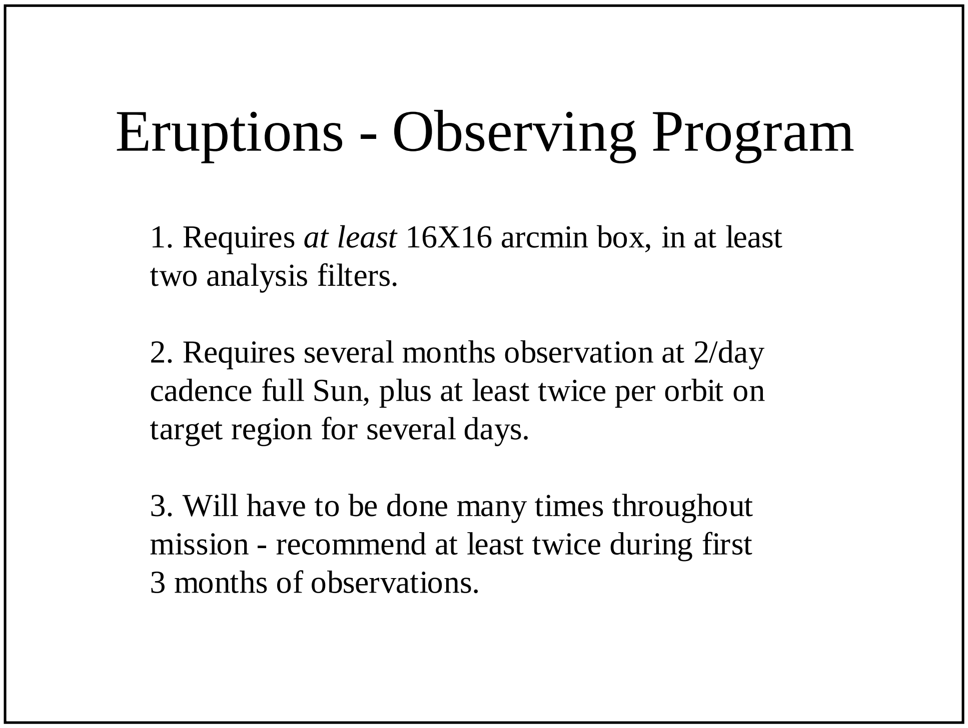
Evolution of Eruptions

1. Where do eruptive structures (e.g. sigmoids) come from?

2. Follow evolution of several ARs for entire disk passage at moderate cadence with XRT, using at least three analysis filters.

3. Map vector **B** in and around the region**.**

3a. Map multi-thermal TR and corona in and around the region.



Eruptions - Observing Program

1. Requires *at least* 16X16 arcmin box, in at least two analysis filters.

2. Requires several months observation at 2/day cadence full Sun, plus at least twice per orbit on target region for several days.

3. Will have to be done many times throughout mission - recommend at least twice during first 3 months of observations.