Forward-Modeling for 3D Reconstruction from STEREO Observations

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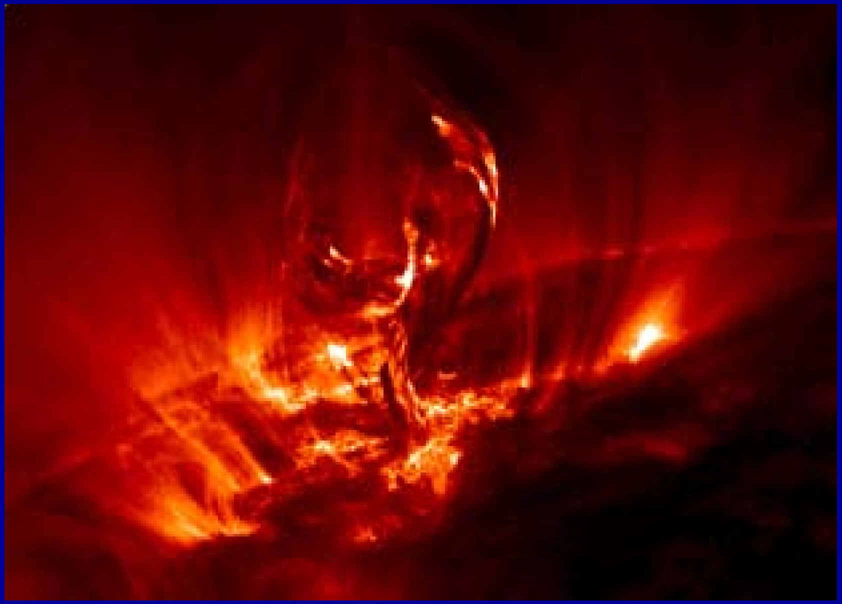
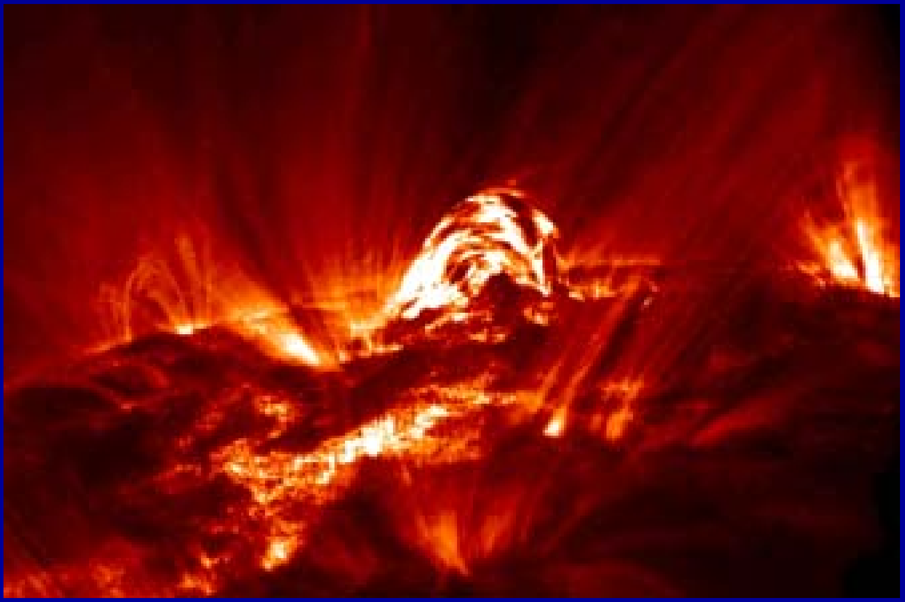
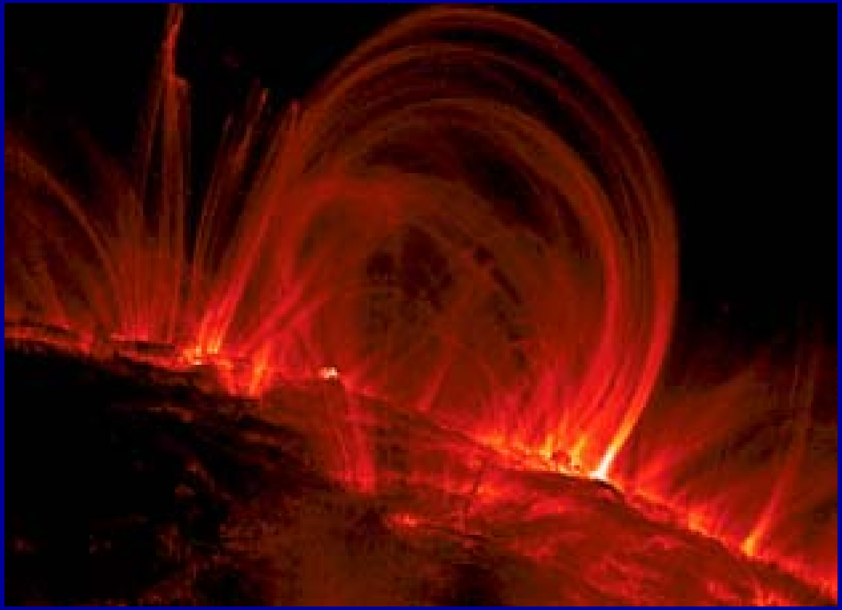
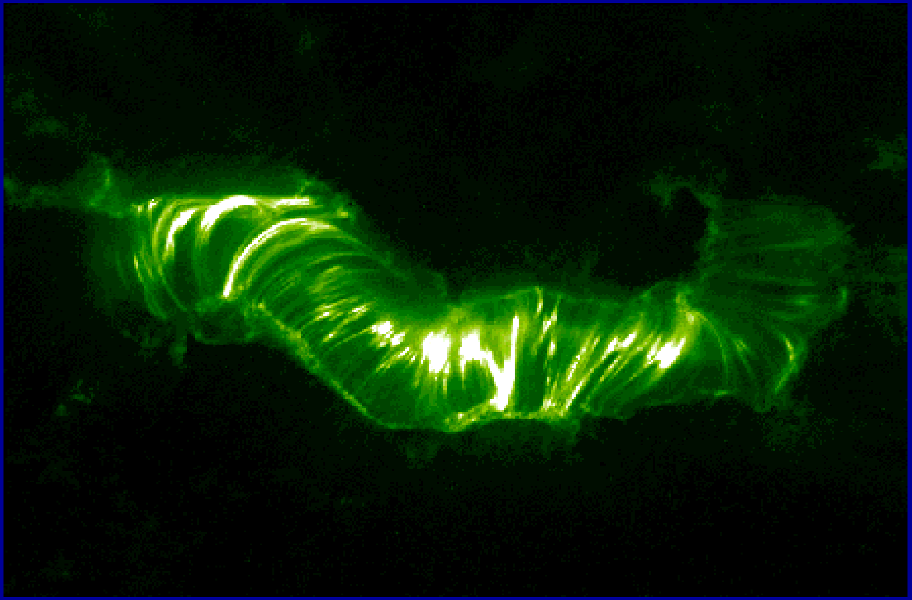
& LMSAL team

FIRST STEREO WORKSHOP, Carre de Sciences, March 18-20, 2002, Paris, France

Observations with TRACE, 171 A: Filaments, Loops, Flares

Scientific Problems for Forward-Fitting to STEREO Data :

* 3D Geometry [x(s),y(s),z(s)]
of coronal coronal structures, such as
filaments, loops, arcades, flares, CMEs, …

* 4D Modeling EM(x,y,z,t)
of temporal evolution of coronal structures

* 5D Modeling dEM/dT(x,y,z,t,T)
of differential emission measure of coronal structures

* <u>3D Geometry</u> [x(s),y(s),z(s)]
of coronal coronal structures, such as filaments, loops, arcades, flares, CMEs, …

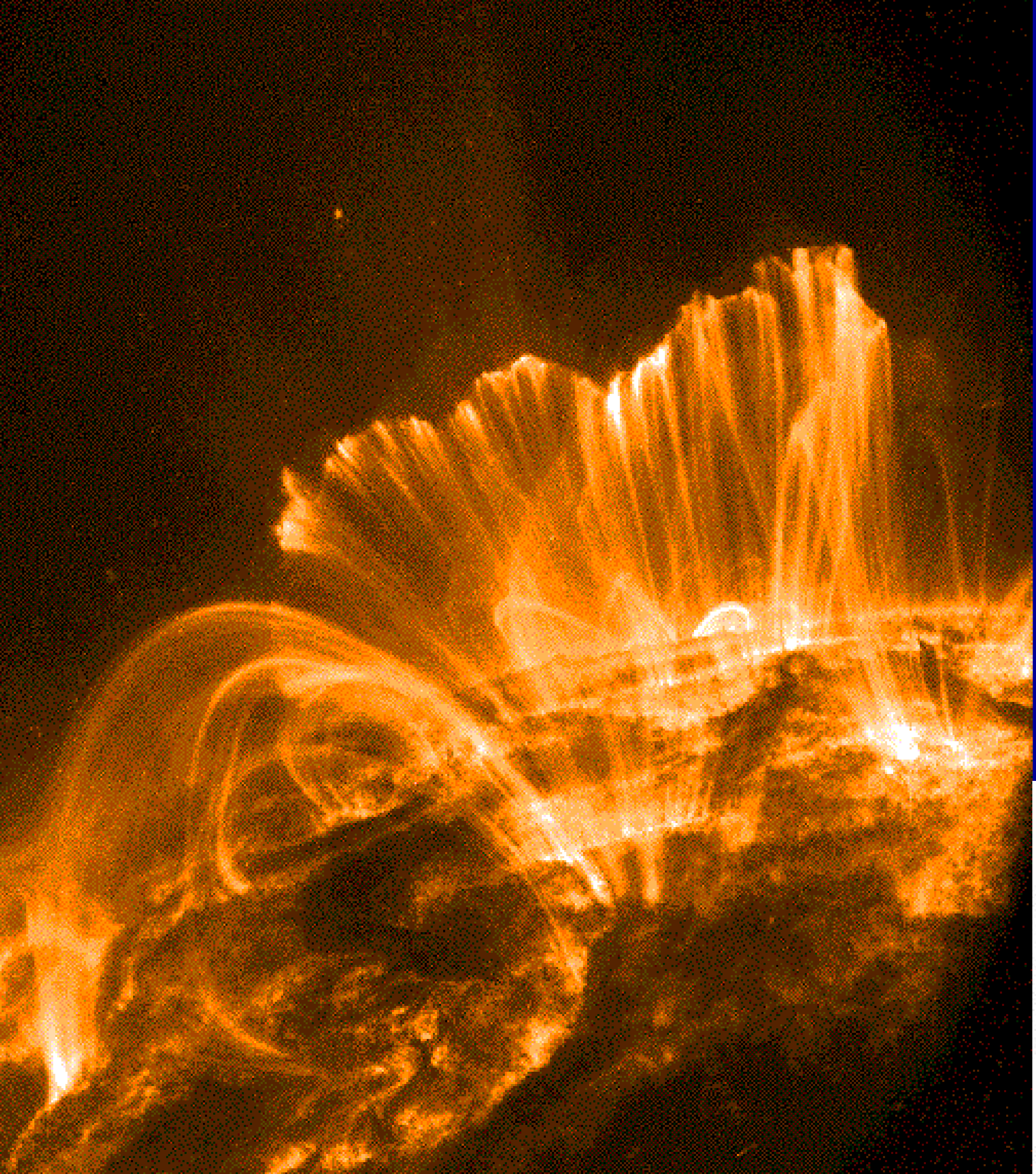
- Geometric definitions :
  1-dim parametrization along magnetic field lines
  is in low-beta plasma justified --> [x(s),y(s),z(s)]

- Cross-sectional variation for loops, --> A(s)

- Start with tracing in 2D in first STEREO image --> [x(s),y(s)]

- Model for 3D inflation z(s),
  e.g. semi-circular loops with vertical stretching factor
  z(s)=sqrt[(x(s)^2 + y(s)^2]*q_stretch

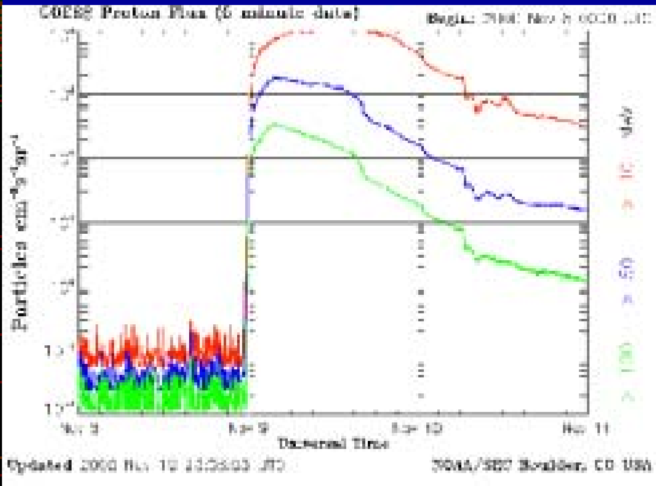
- Forward-fitting to second STEREO image to determine q_stretch

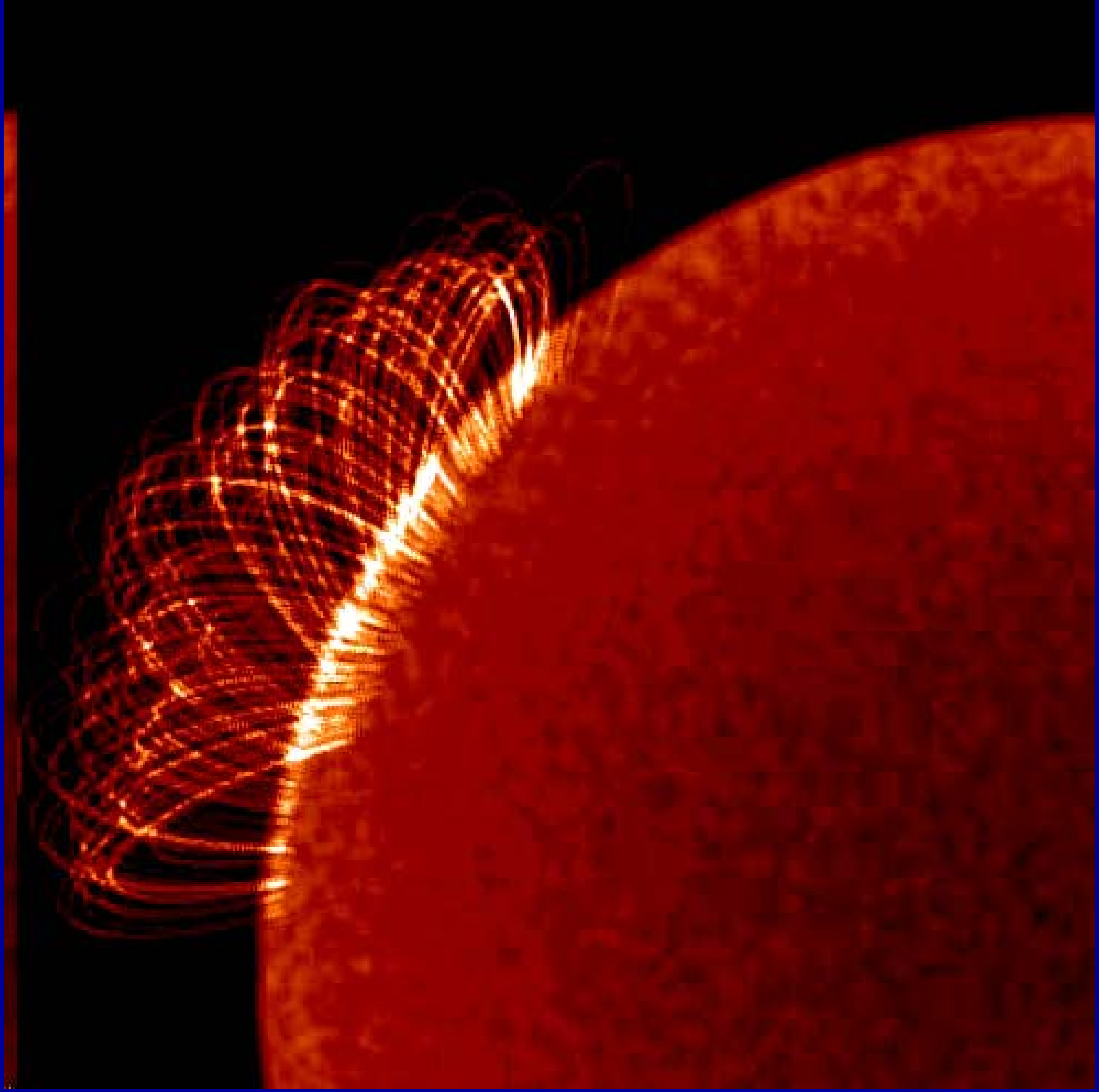


Flare 2000-Nov-8

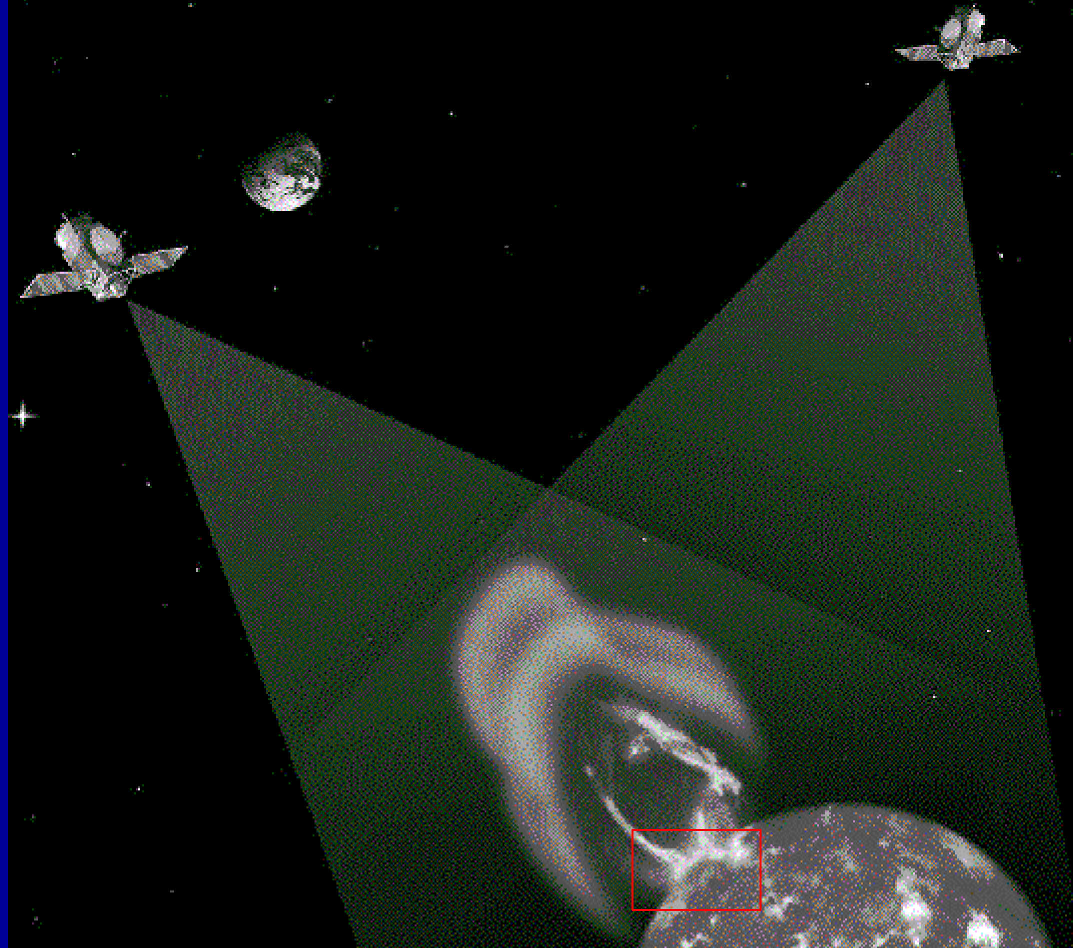
TRACE 171 A
2000-Nov-9, 00:05 UT

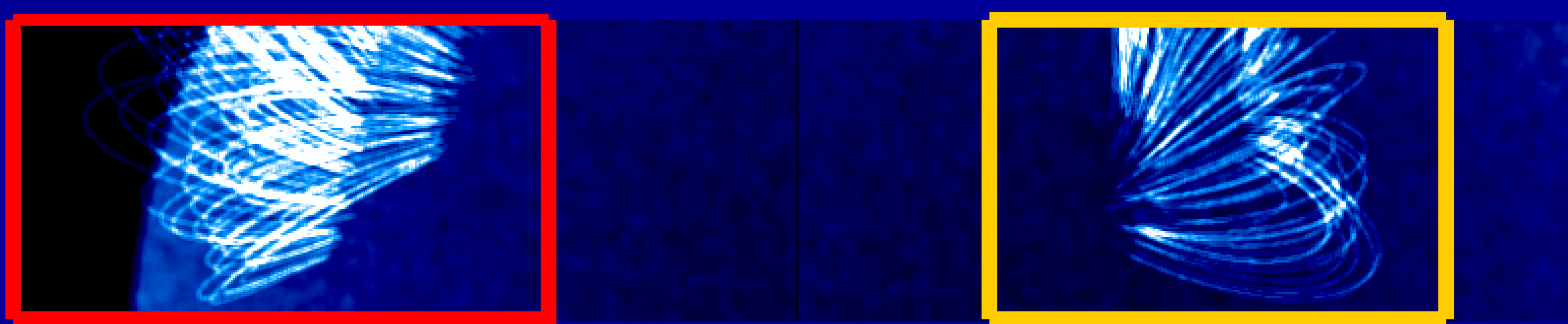
Flare start: Nov 8, 22:42 UT
GOES class: M7.4
NOAA AR 9213
Associated with CME





ANIMATION : 2D projections for varying stereo angle





STEREO - A

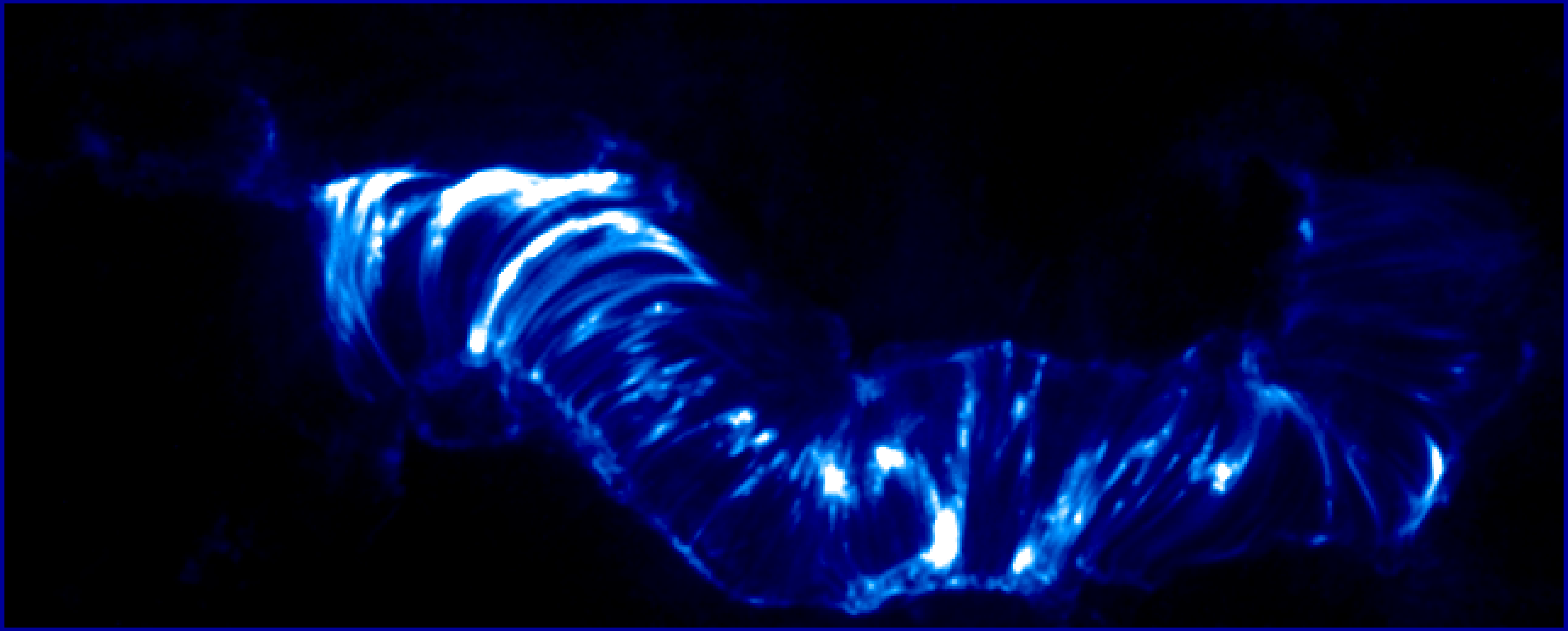
STEREO - B

The following 5D model dEM/dT(x,y,z,t,T) is constrained by data analyzed in the publication:

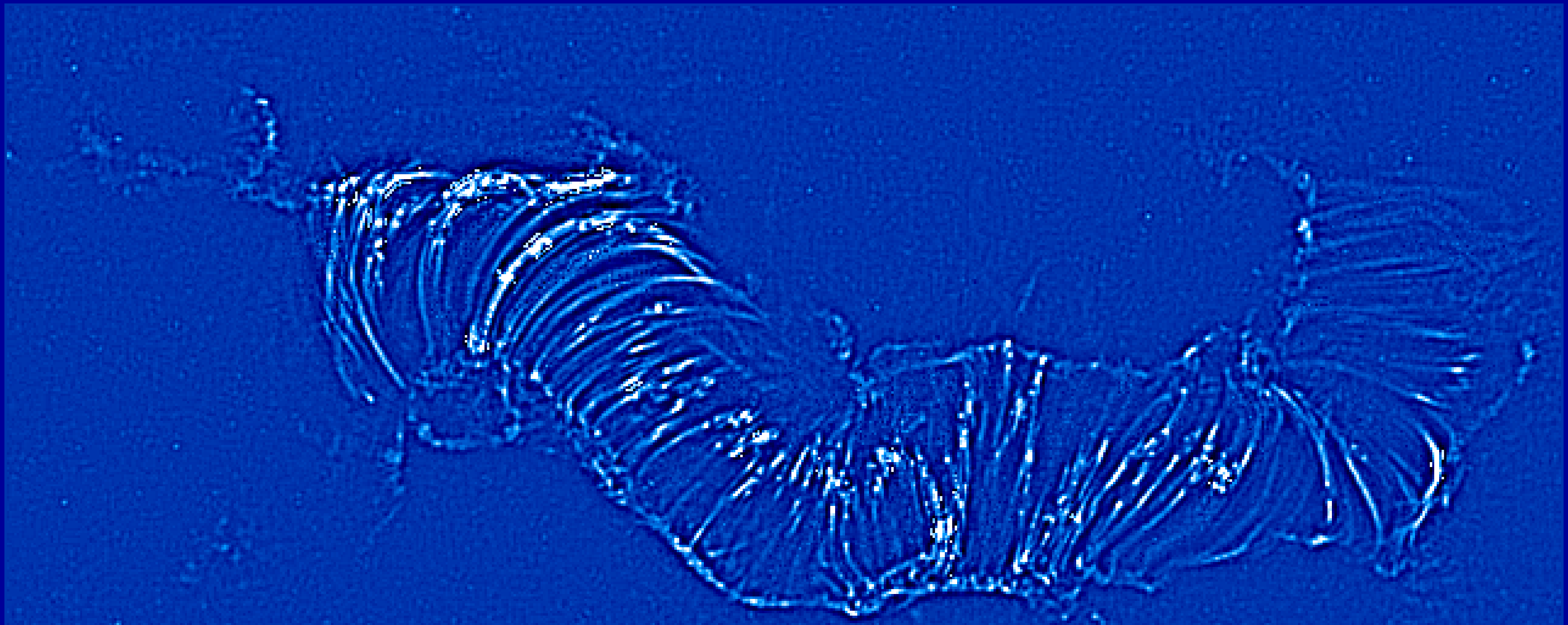
Aschwanden M.J. & Alexander,D. 2001, Solar Physics (Dec. issue) Vol.204, p.91-129

Energetics and Flare Plasma Cooling from 30 MK down to 1 MK modeled from Yohkoh, GOES, and TRACE Observations during the Bastille-Day Event (14 July 2000)

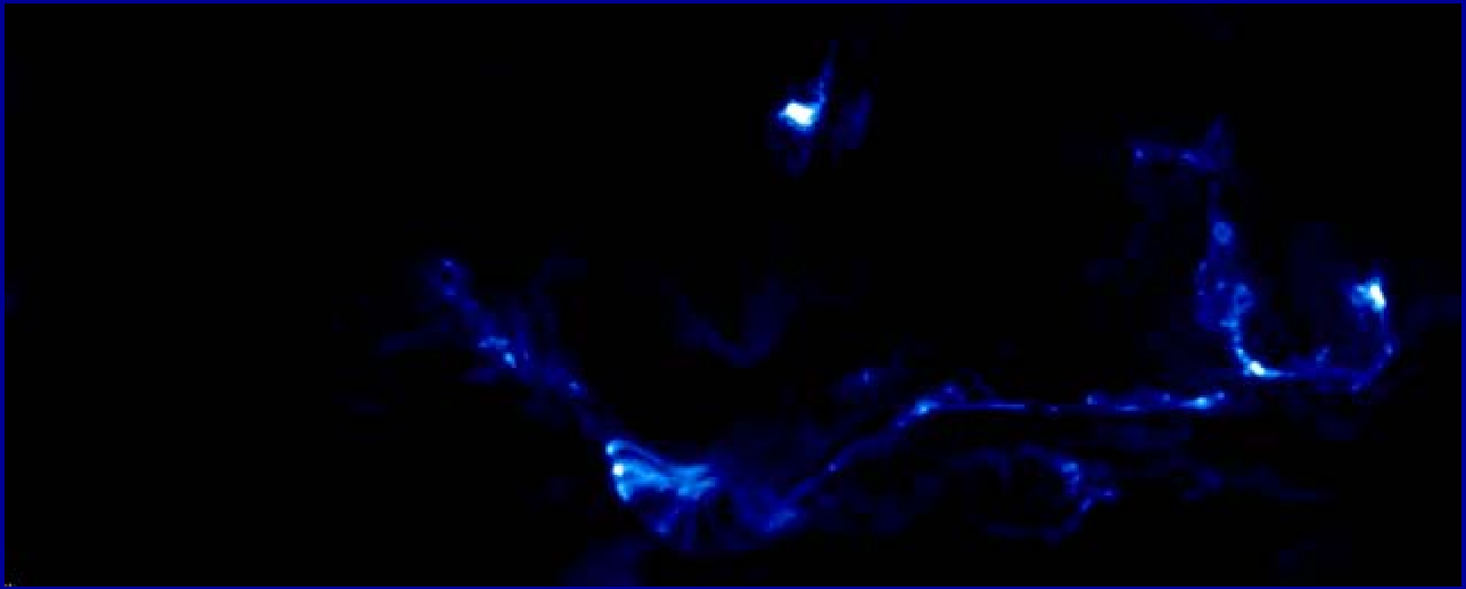
TRACE, 171 A, 2000-Jul-14, 10:59:32 UT



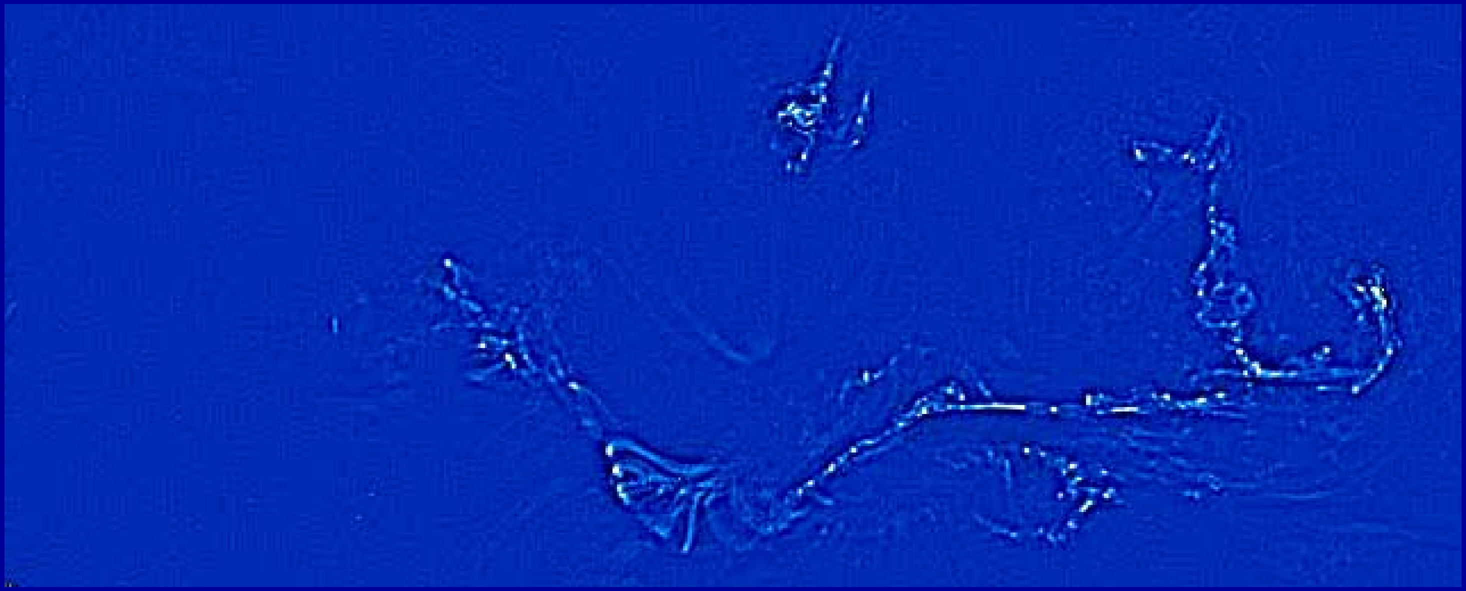
Highpass-filtered image



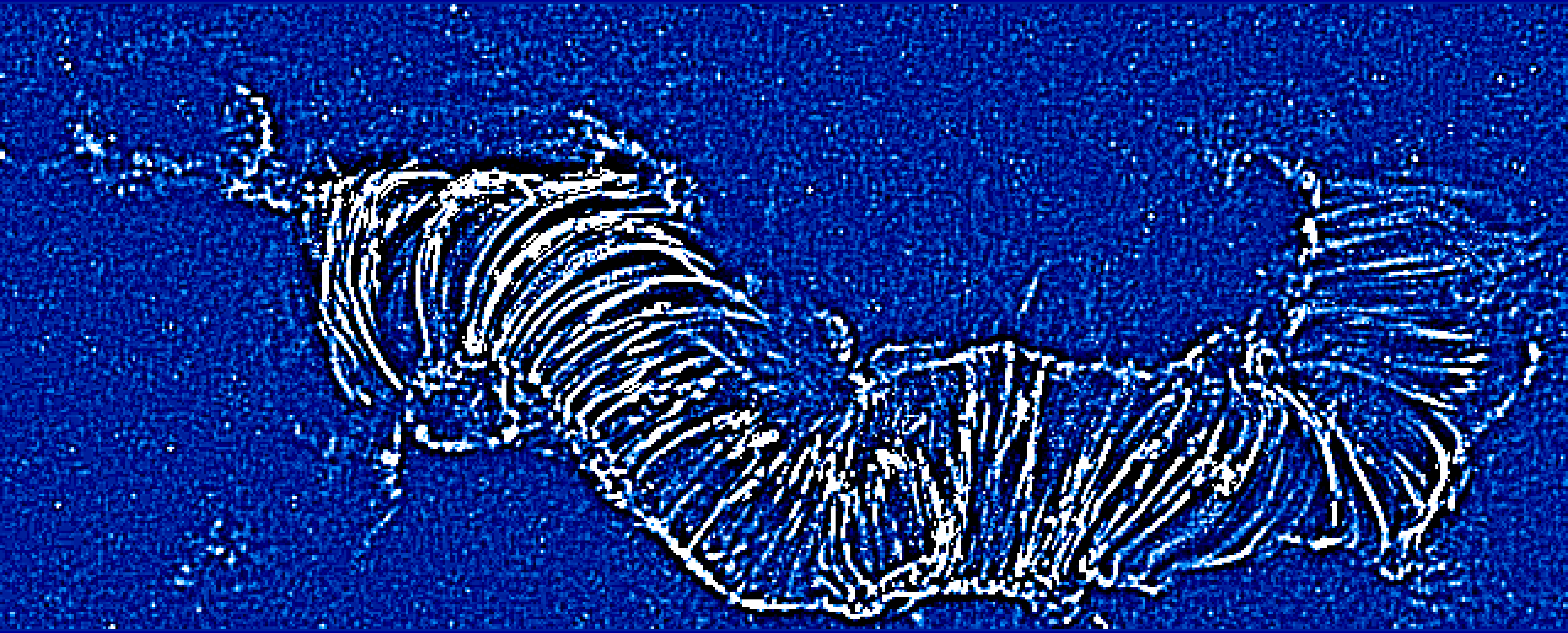
TRACE, 171 A, 2000-Jul-14, 10:11-10:59 UT, cadence=42 s



Highpass-filtered movie



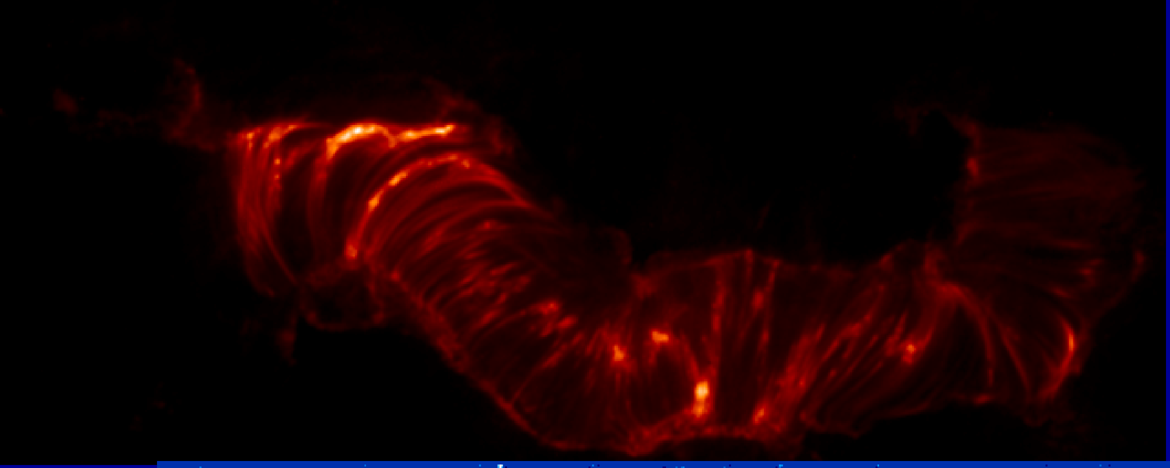
Highpass-filtered image, TRACE, 171 A, 2000-Jul-14, 10:59:32 UT

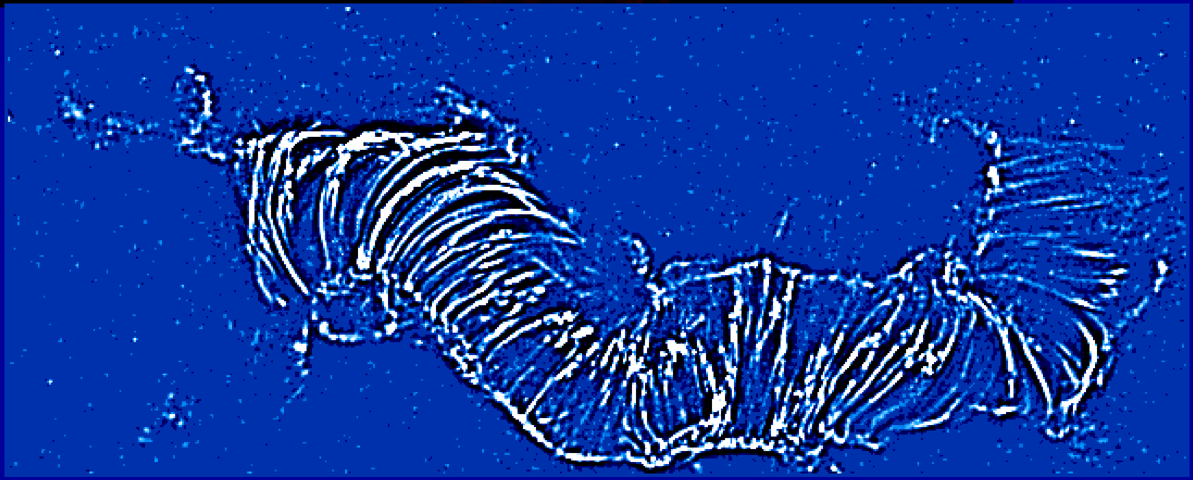


Number of postflare loop structures :	*N ~ 100*
Length of arcade :	*L ~ 180,000 km*
Average loop separation:	*L/N=1800 km*
Minimum loop separation (3 pixels) :	*ΔL=1100 km*

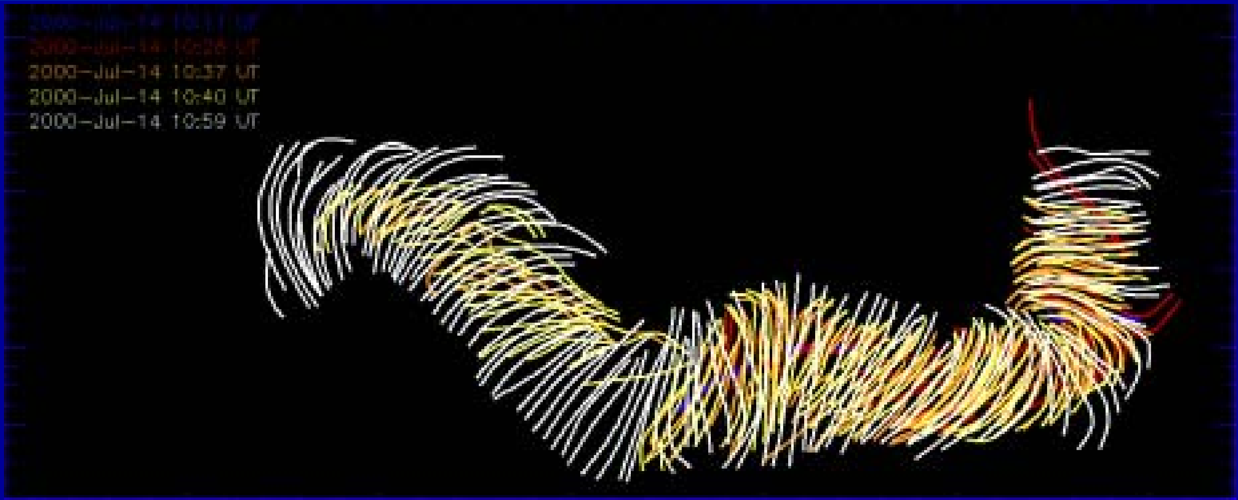
→ *The separation of arcade loops is observed down to the instrumental resolution !*

Tracing linear features :
--> [x(s),y(s)]

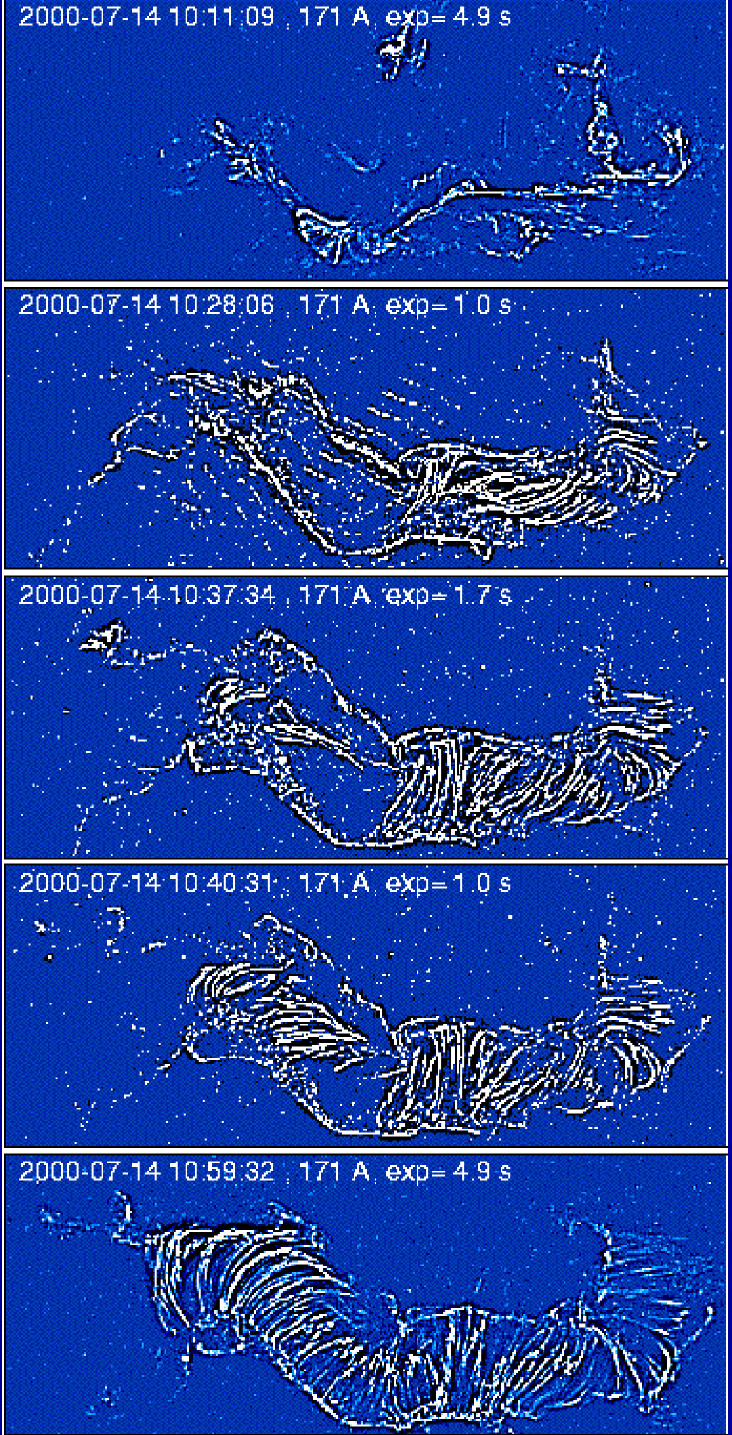




High-pass filtering

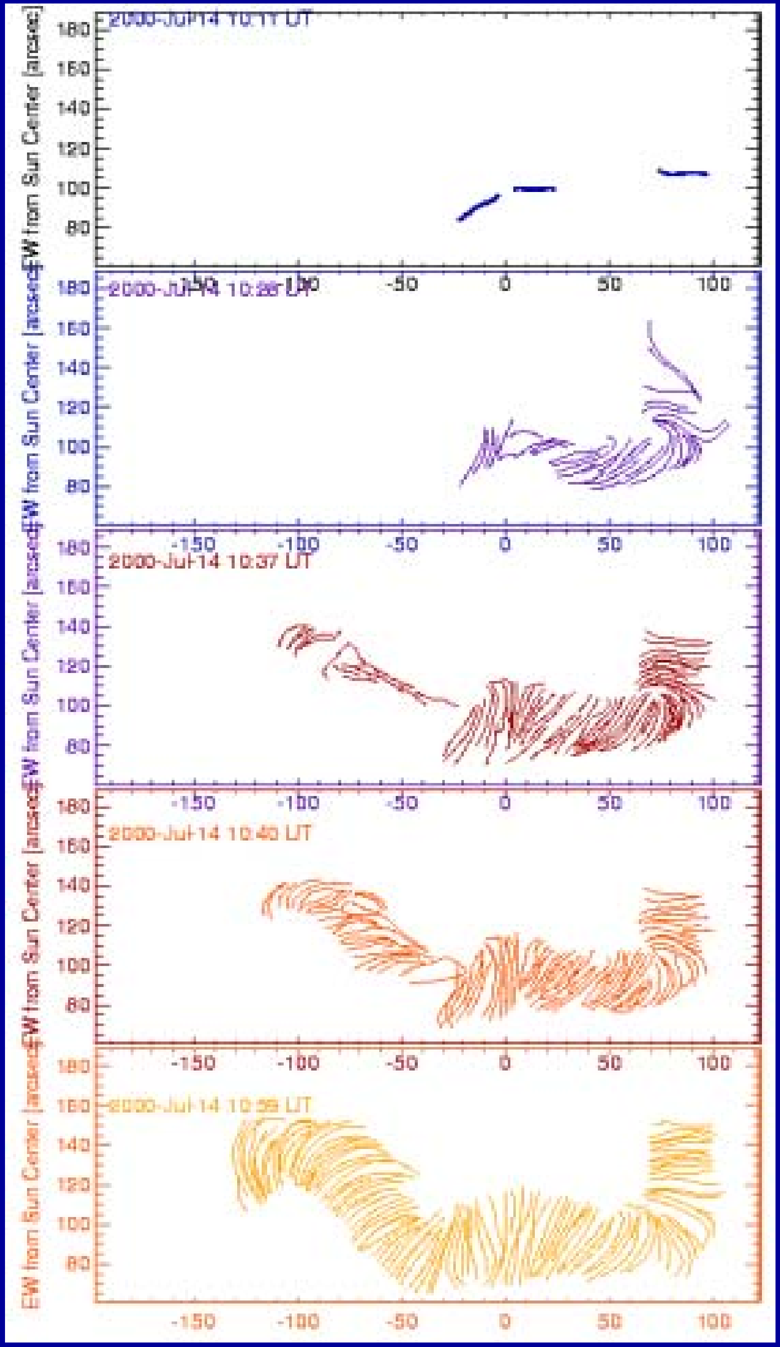


Feature tracing, reading coordinates, spline interpolation



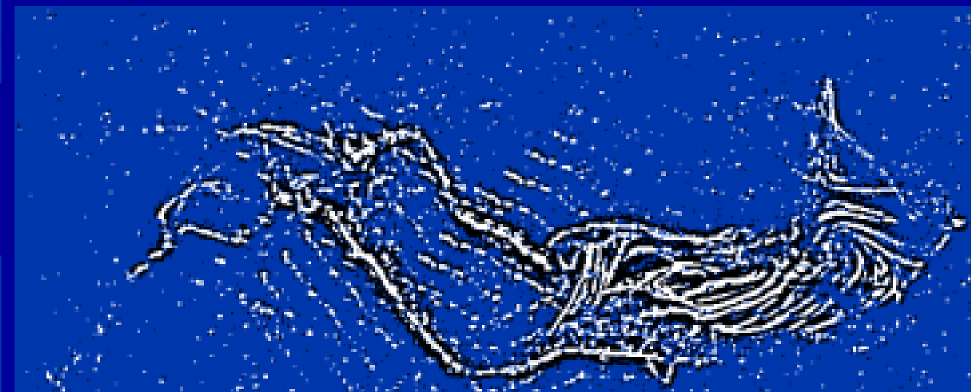
This sequence has time intervals of ~10 minutes, which equals about the cooling time of each loop

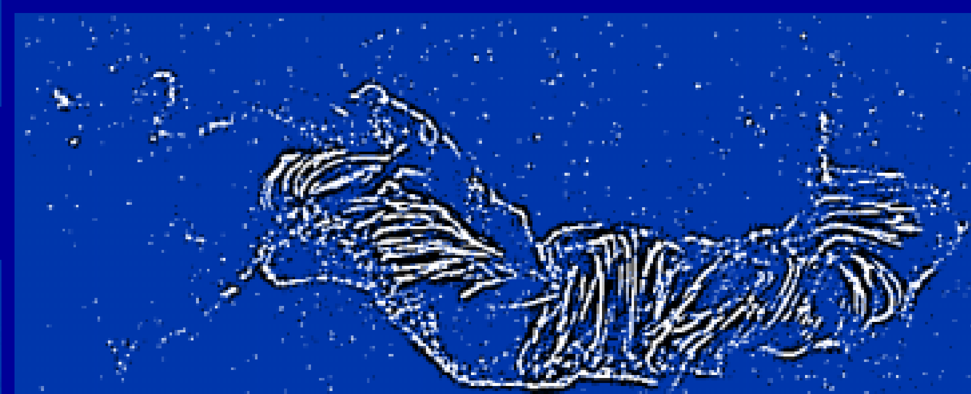
Thus each frame shows a new set of loops, while the old ones cooled down and become invisible in next frame.



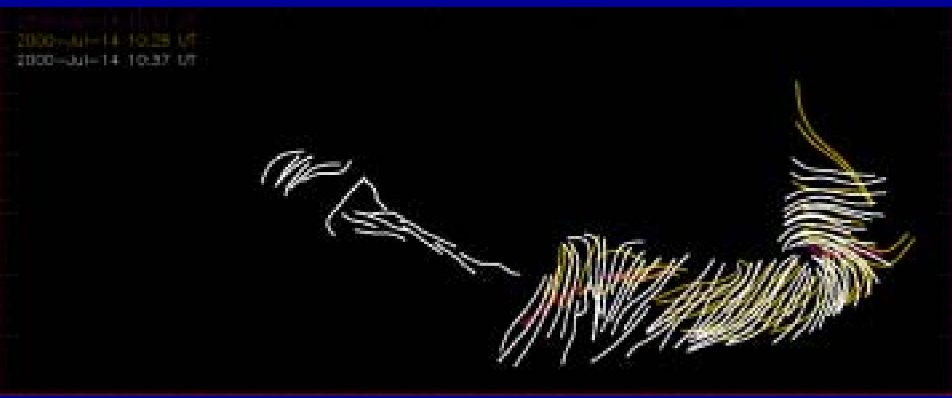
Temporal evolution
of EUV-bright flare loops

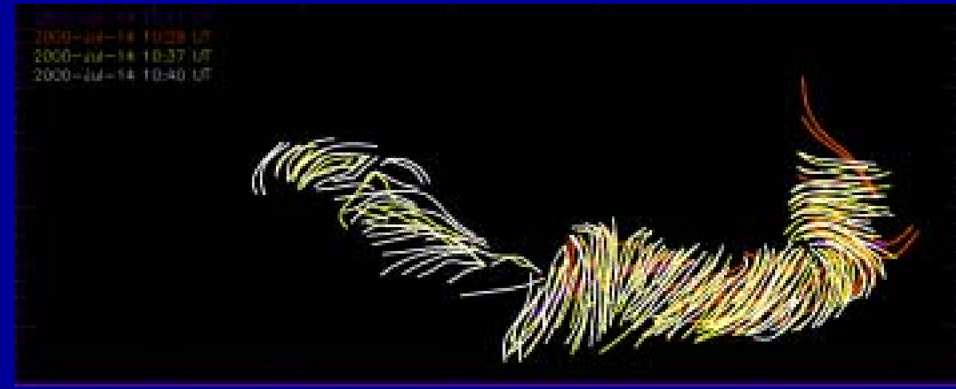
In this time sequence, postflare loops are illuminated progressively with higher altitudes, outlining the full 3D structure

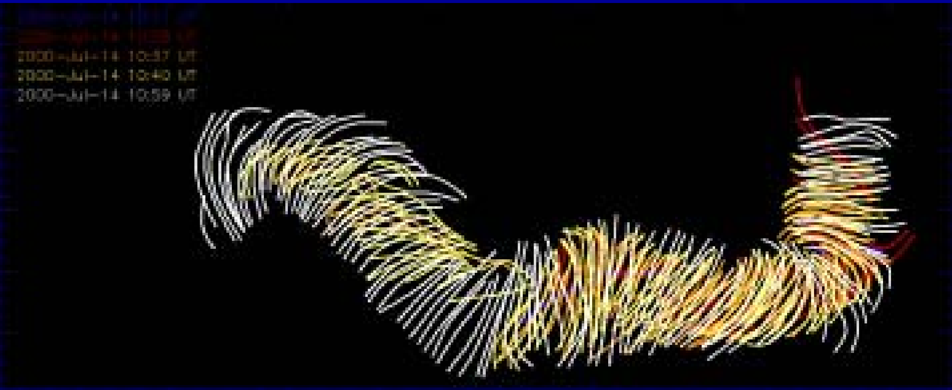


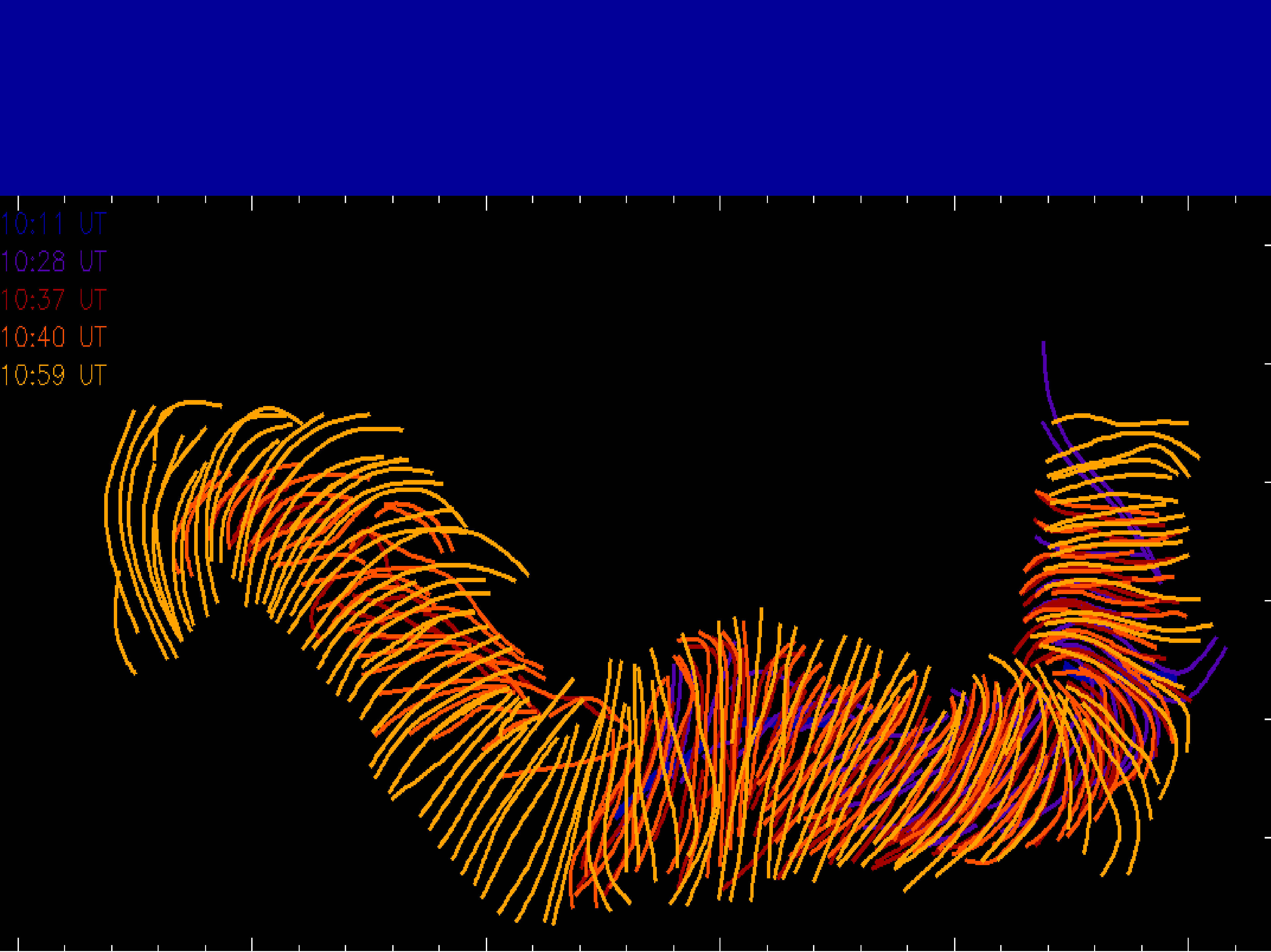


Tracing … progressing in time



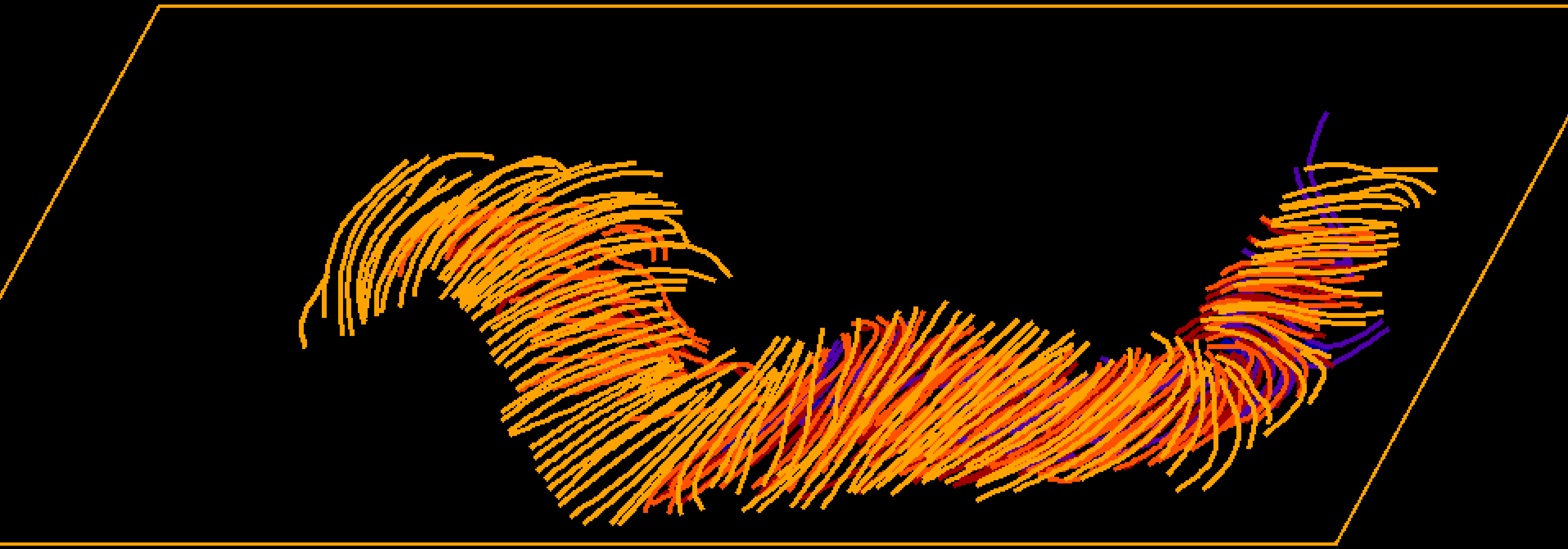




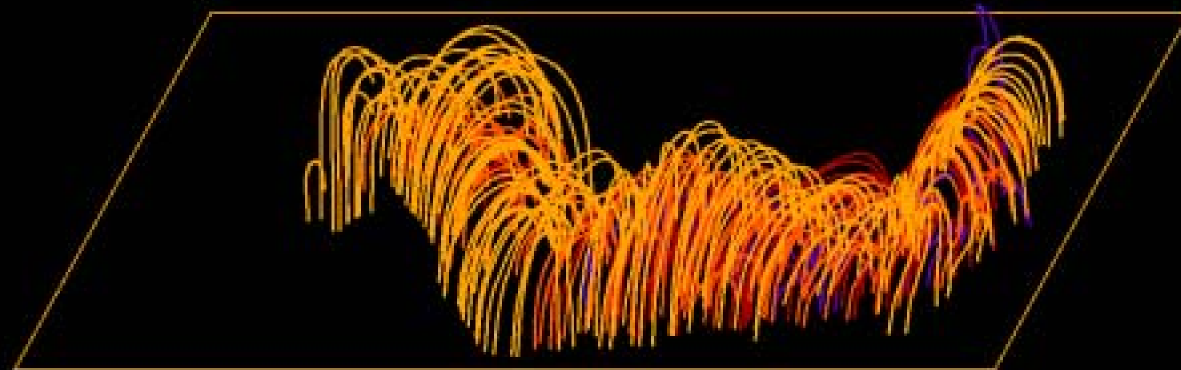


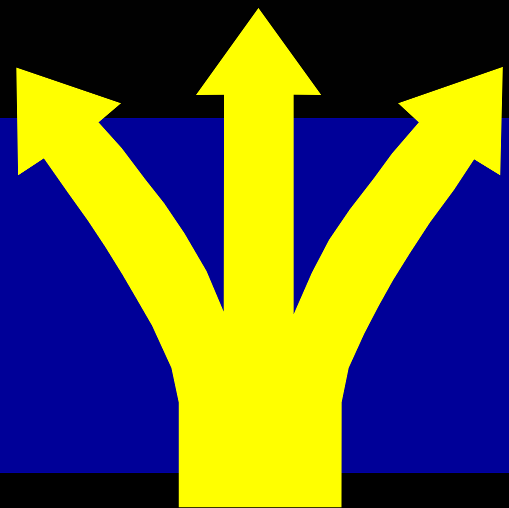
10:11 UT
10:28 UT
10:37 UT
10:40 UT
10:59 UT

Coordinates or linear structures: s(x,y,z=0)



s(x,y,z)

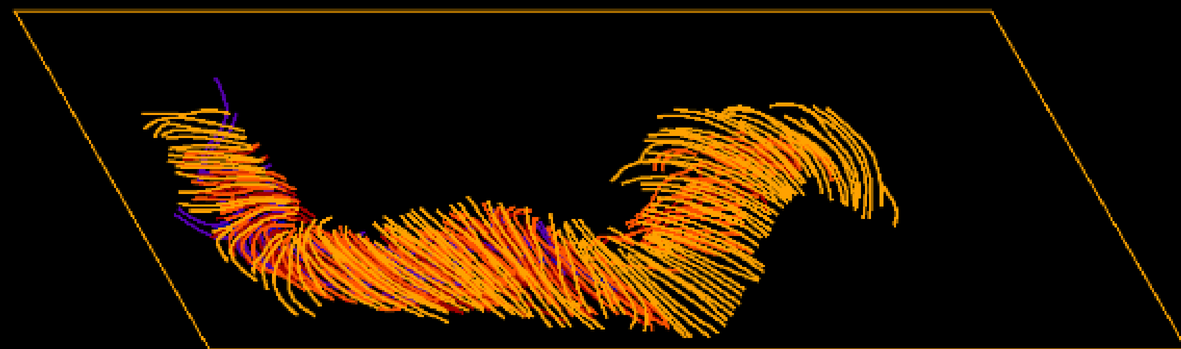




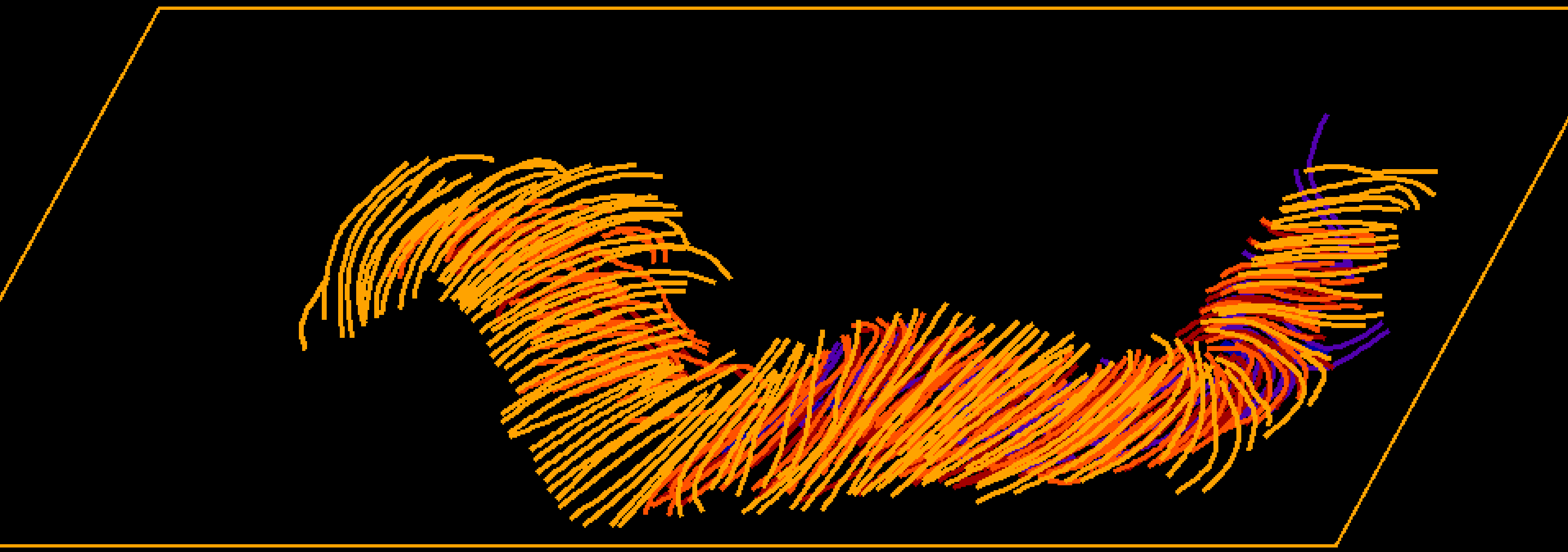
Step 3:

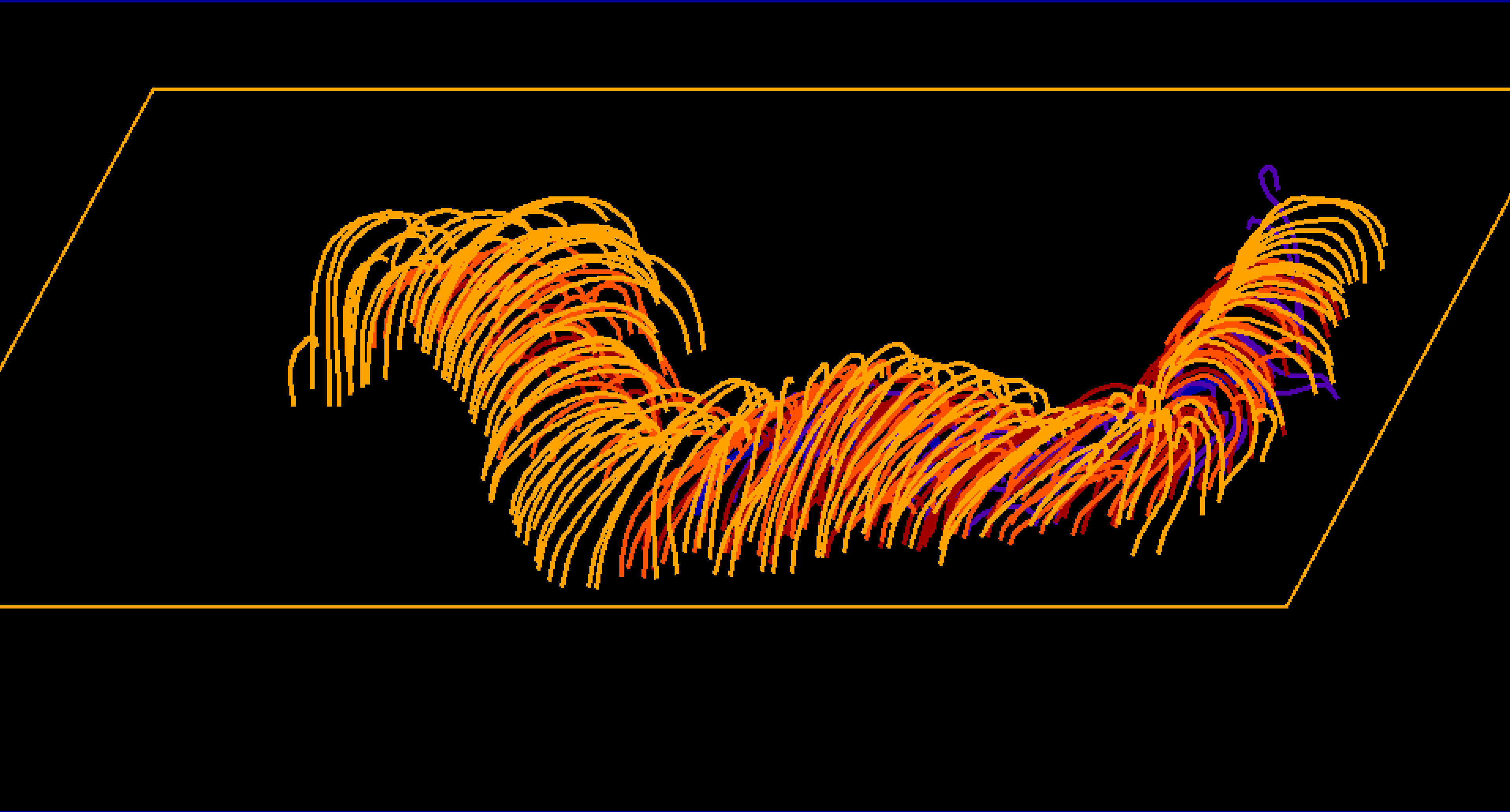
3D Inflation: z=0 -> z(x,y)

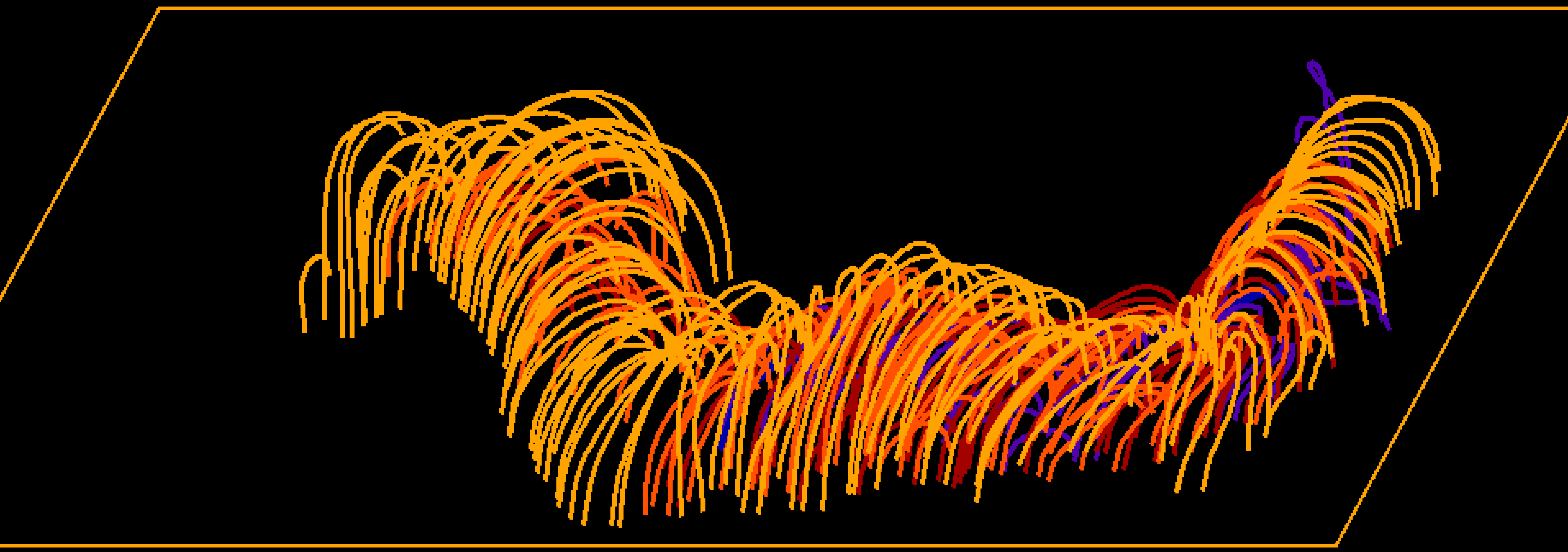
- model (e.g. semi-circular loops)
- magnetic field extrapolation
- curvature minimization in 3D

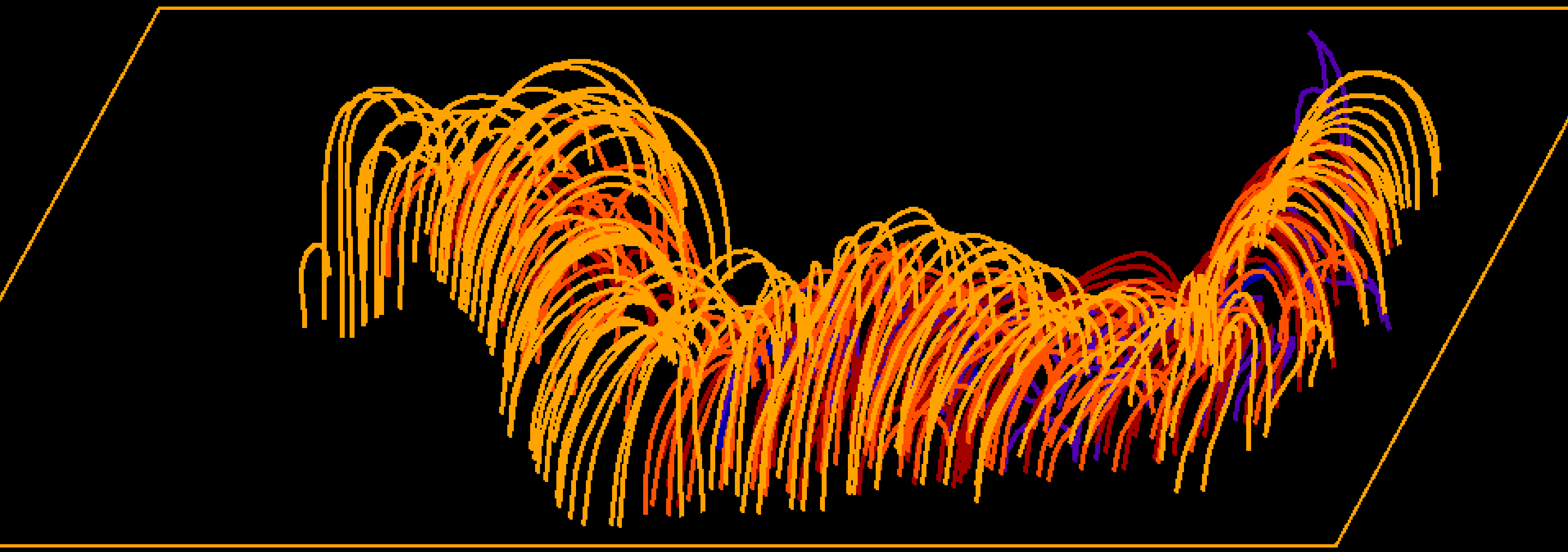


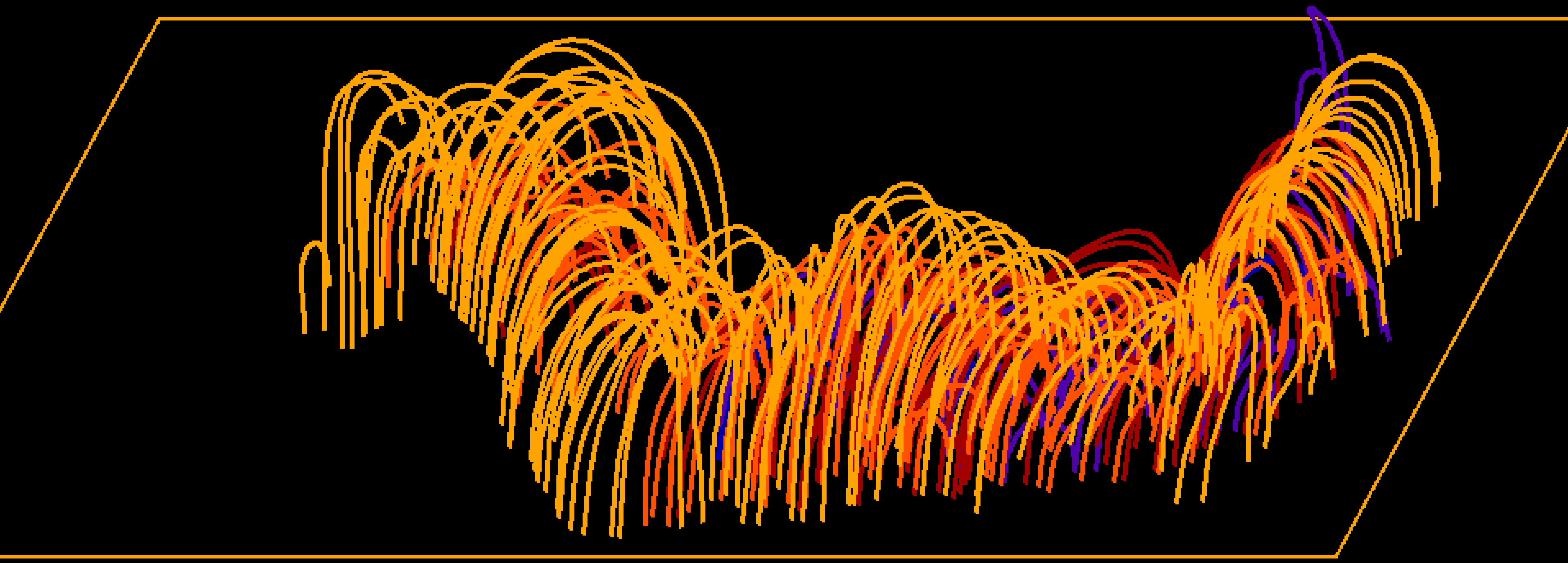
s(x,y)











* <u>3D Fitting:</u> F[x(s),y(s),z(s)]

Volume rendering of coronal structures

- Flux fitting in STEREO image :

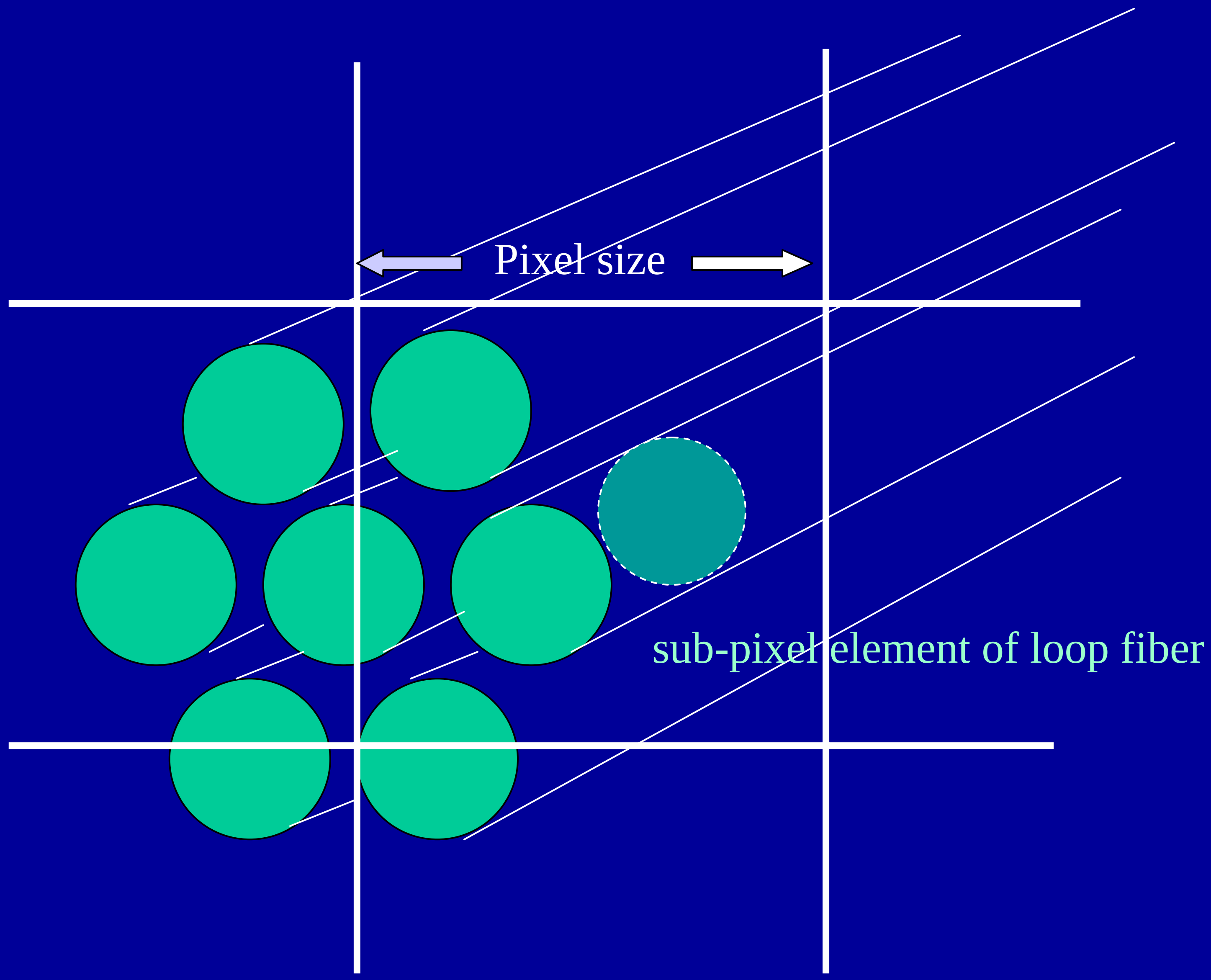
- Volume filling of flux tube with sub-pixel sampling

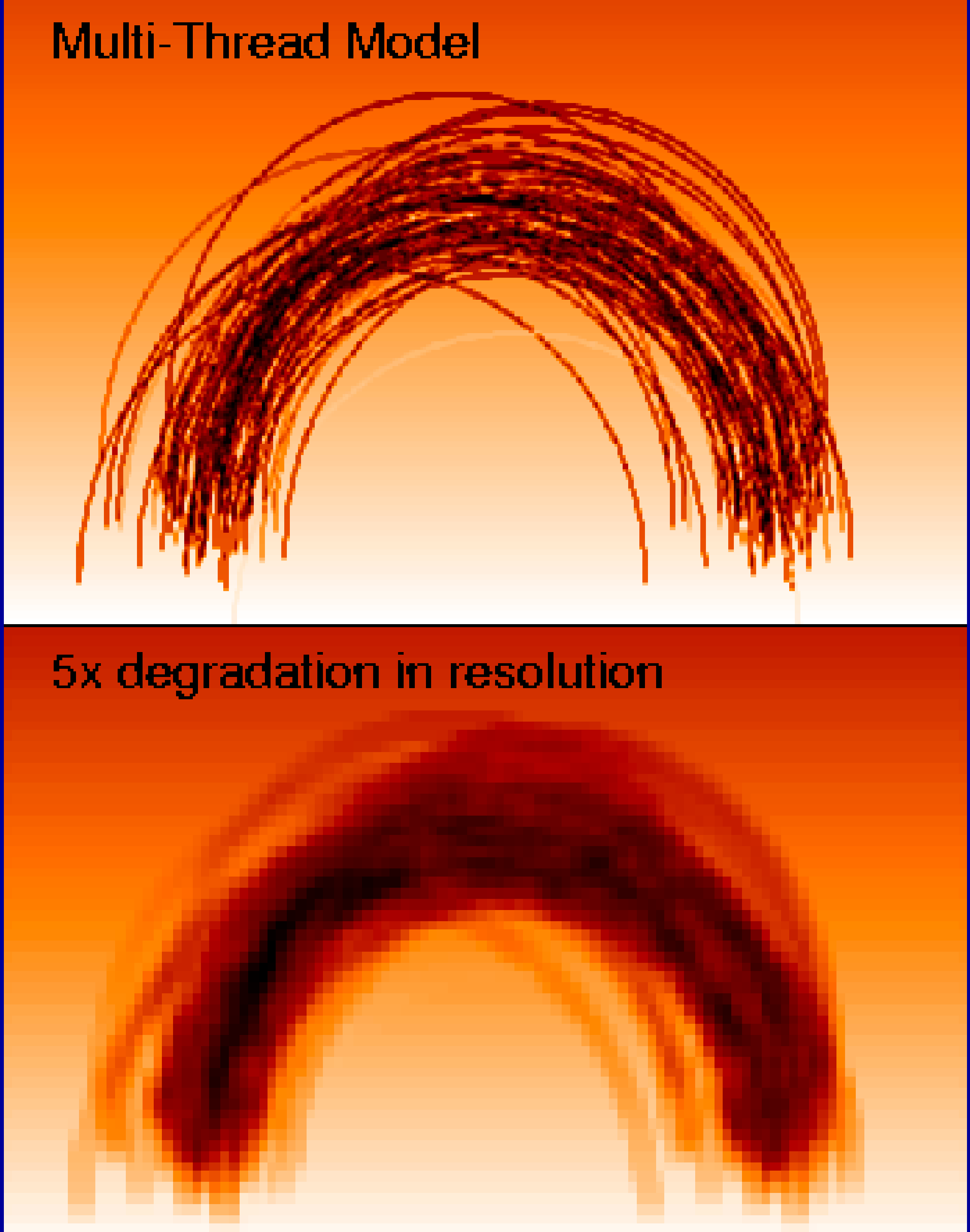
- Render cross-sections by superposition of loop fibers with sub-pixel cross-sections: A=Sum(A_fiber), with w_fiber<pixel

- Loop length parametrization with sub-pixel steps ds<pixel

- Flux per pixel sampled from sub-pixel voxels of loop fibers

Volume rendering of a loop with sub-pixel fibers:

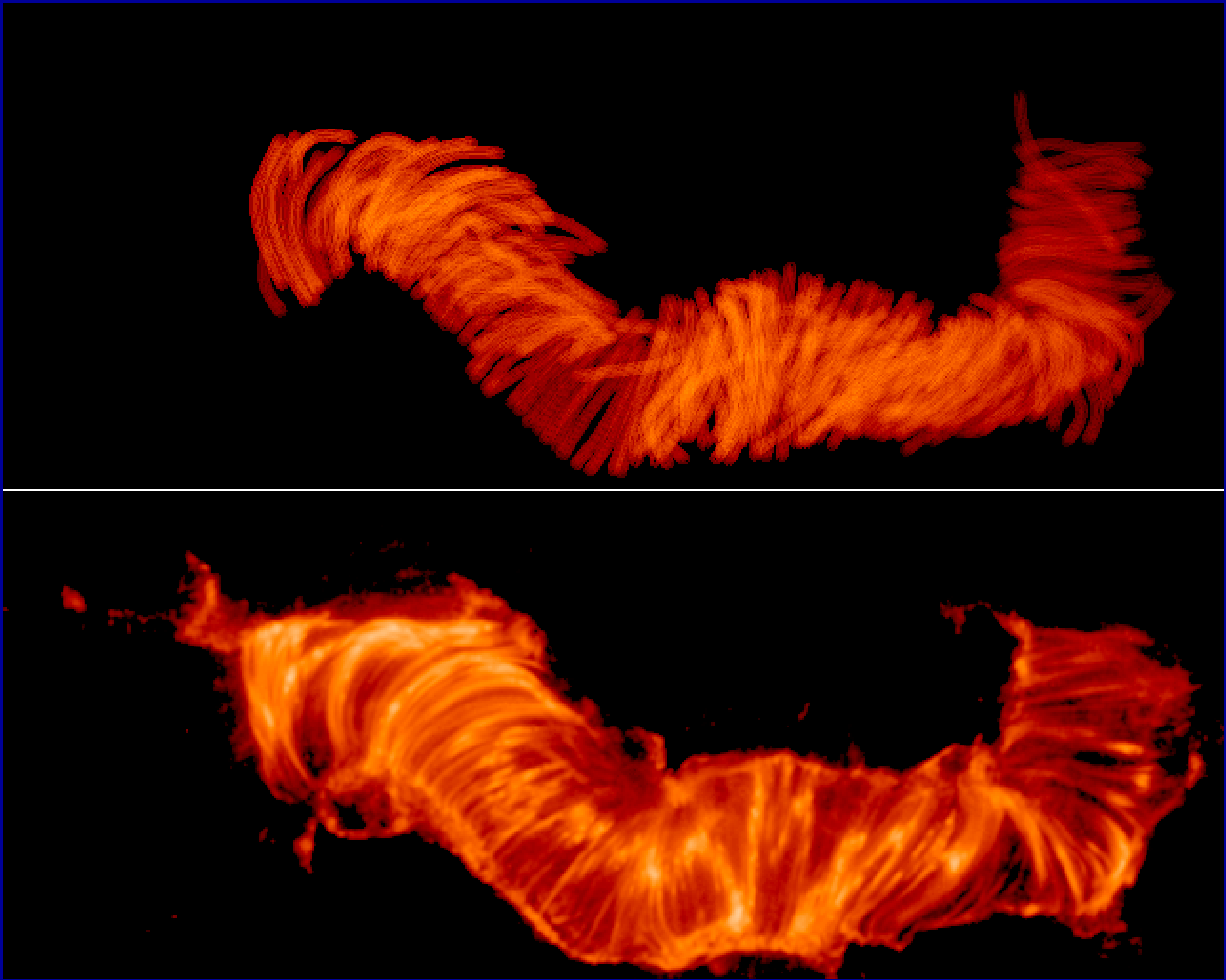




Voluminous structures are rendered by superposition of linear segments

Physical principle: optically thin emission in EUV and soft X-rays is additive

Forward-Fitting of Arcade Model with 200 Dynamic Loops



Observations from TRACE 171 A : Bastille-Day flare 2000-July-14

* 4D Fitting: F[x(s),y(s),z(s),t] of coronal coronal structures

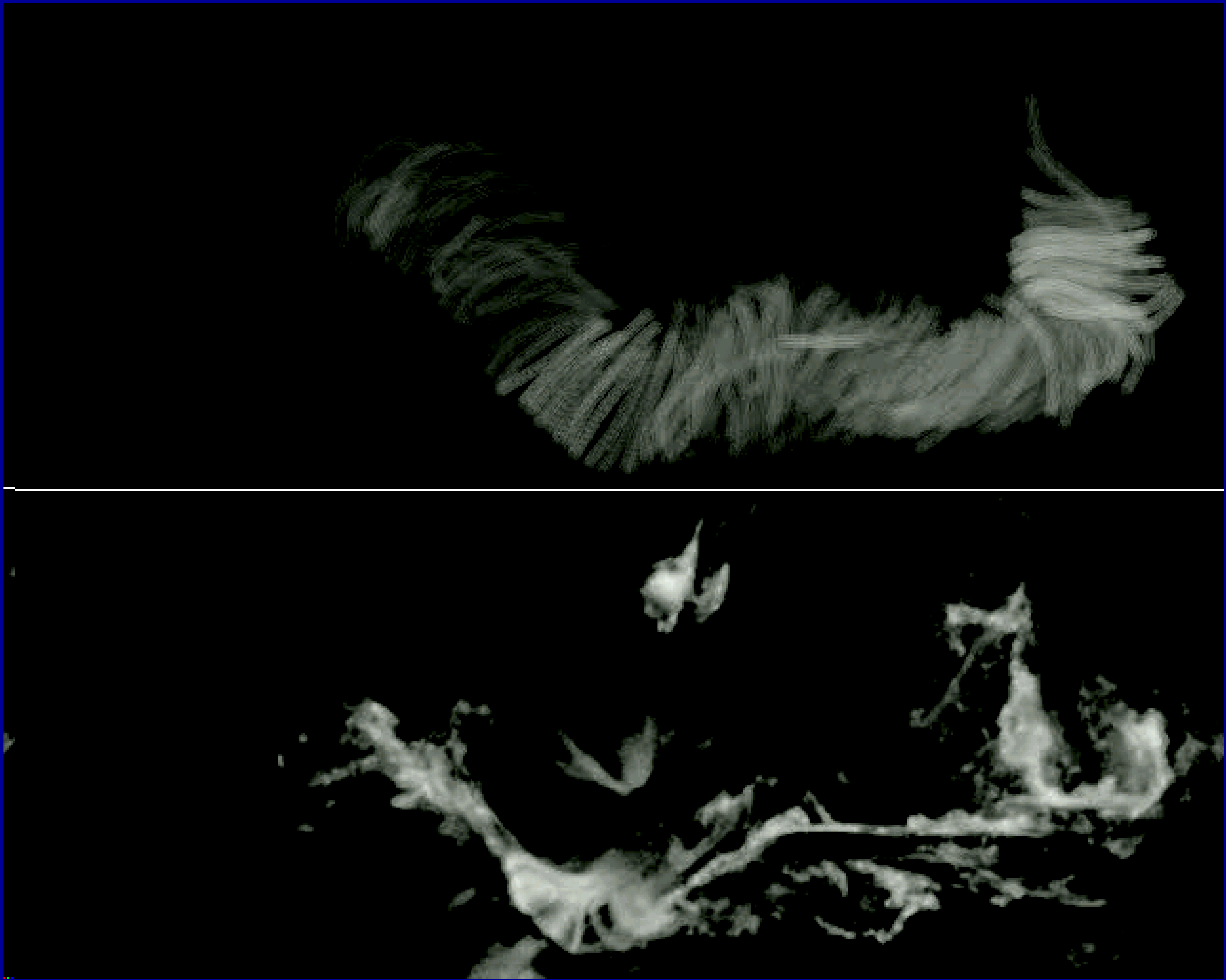
- Flux fitting in STEREO image #1 at time t1 :

$$F(x,y,t=t_1)_{obs} \Rightarrow F[x(s),y(s),z(s),t=t_1]_{model}$$

- Flux fitting in STEREO image #2 at time t1

- Sequential fitting of images #1,2 at times t = t2, t3, …. , tn

Forward-Fitting of Arcade Model with 200 Dynamic Loops

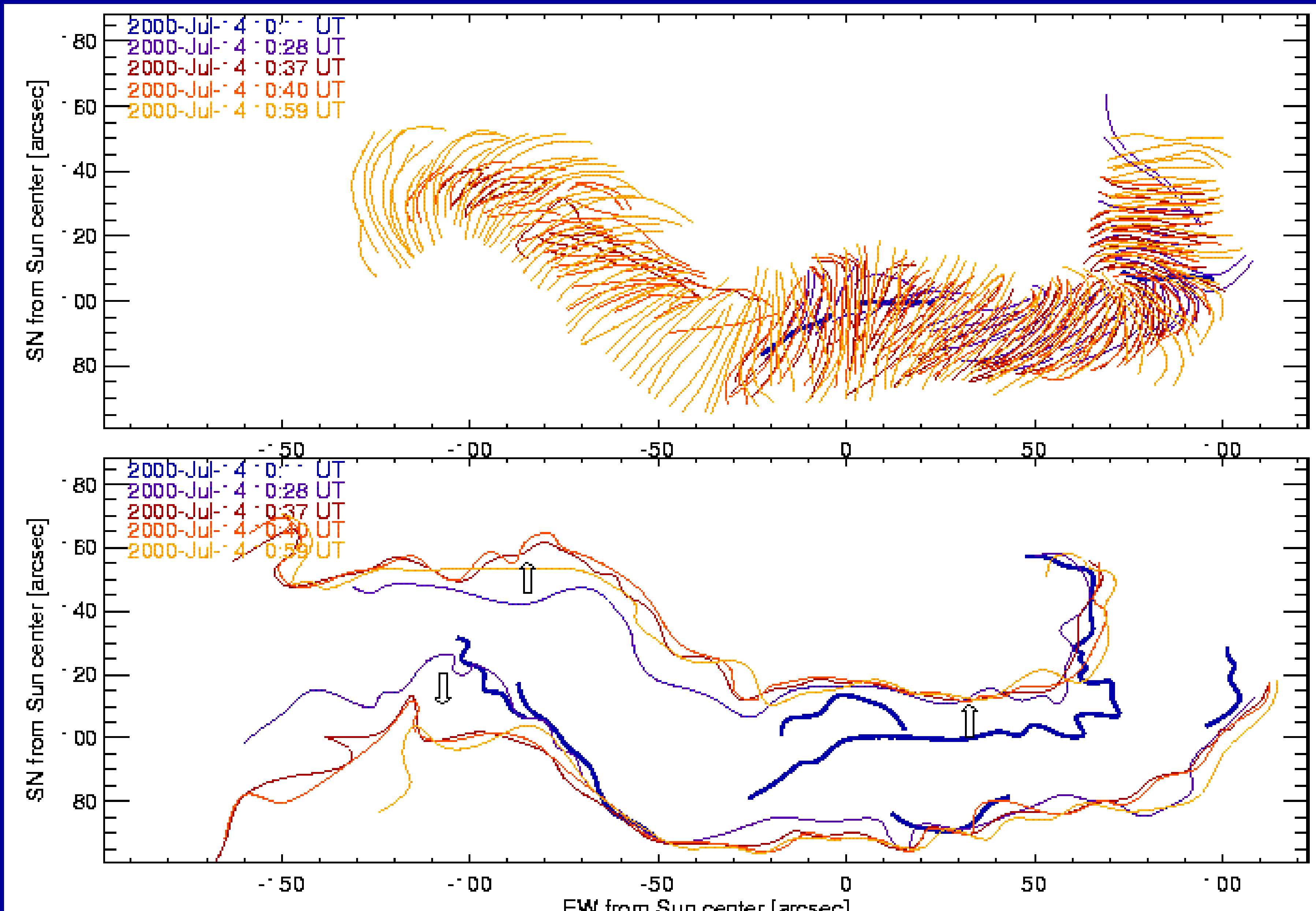


Observations from TRACE 171 A : Bastille-Day Flare 2000-July-14

* <u>4D Fitting:</u> F[x(s,t),y(s,t),z(s,t)] with dynamic model

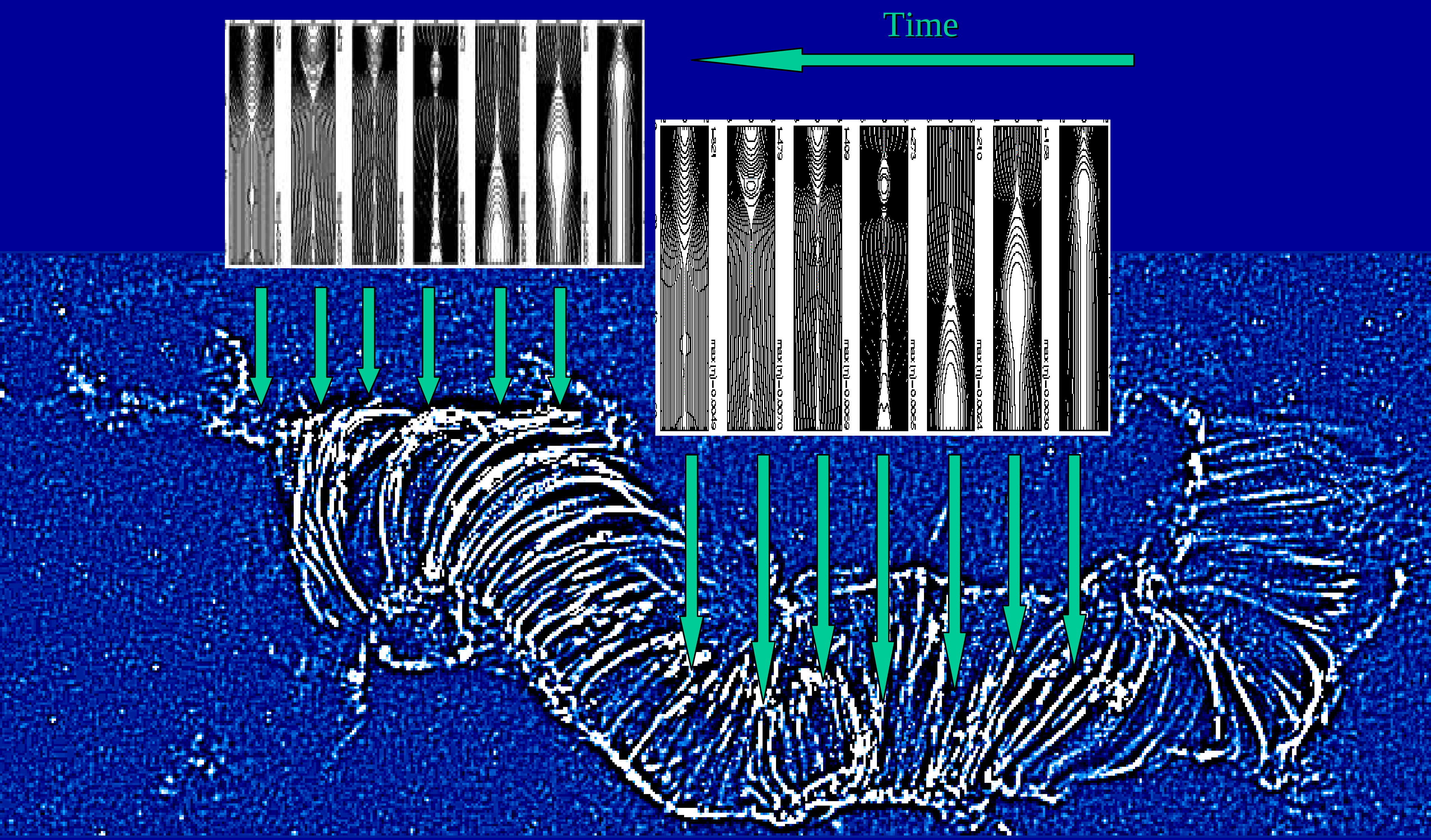
Observations that can constrain dynamic models:

- loop shear increase
- twisting of flux rope
- filament eruption
- loop expansion
- height increase of reconnection X-point
- loop relaxation from cusp-shaped loop into dipolar loop after reconnection



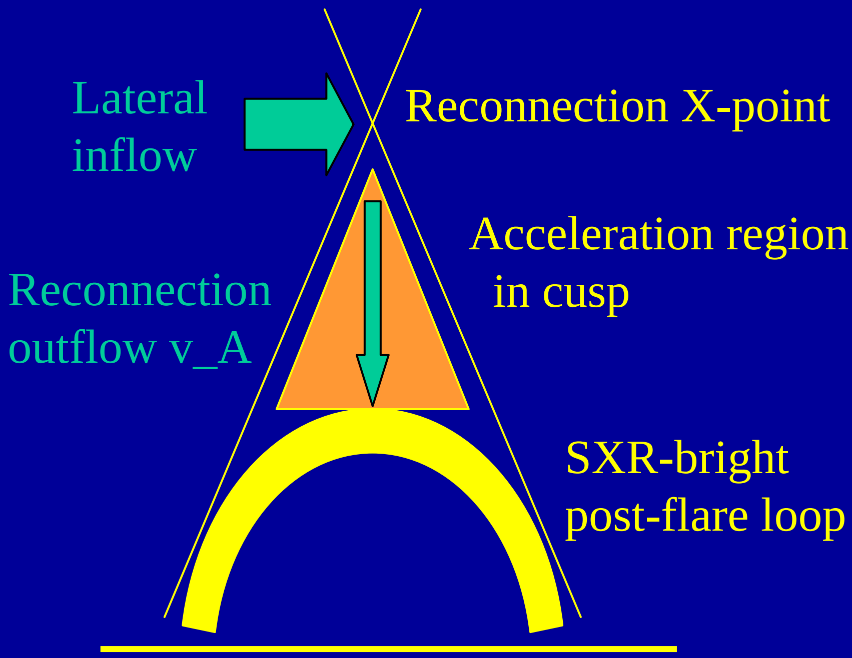
Evolution from high-sheared (blue) to unsheared (yellow) arcade loops

Spatial Mapping of Magnetic Islands to Arcade Loops



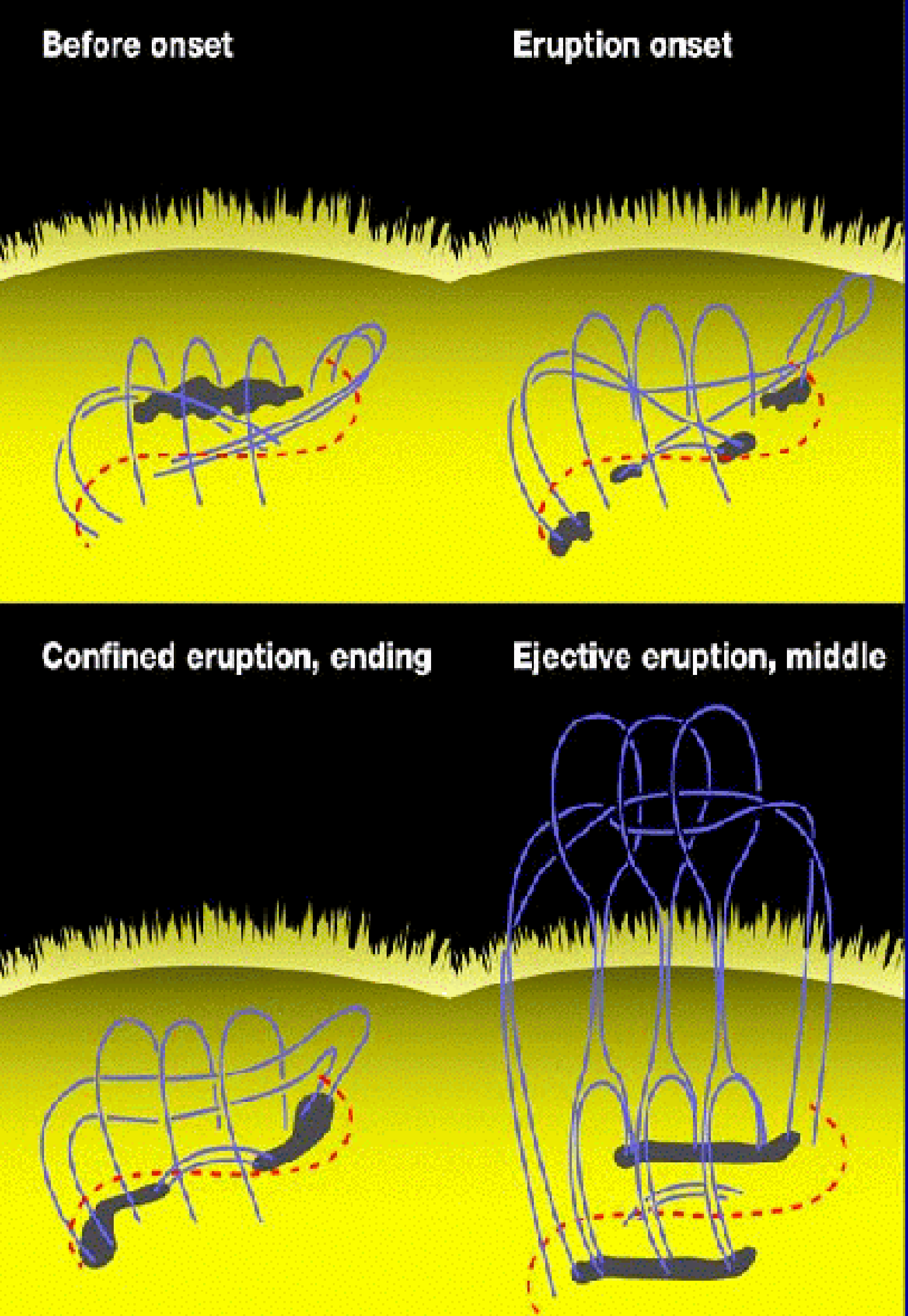
Each arcade loop is interpreted as a magnetic field line connected with a magnetic island generated in the (intermittent)"bursty regime" of the tearing mode instability.

X-type (Petschek) magnetic reconnection :



$N_{loop} = 100$
$E_{loop} = 5 * 10^{29}$ erg
$R_{loop} = 17.5$ Mm
$n_{cusp} = 10^{9}$ cm-3
$B_{cusp} = 30$ G
$h_{cusp} = 17.5$ Mm
$V_{cusp} = 1.5 * 10^{26}$ cm^3
$E_{HXR} = 25$ keV $= 4*10^{-8}$ erg

- Alfvenic outflow speed in cusp $v_A = 2.2 * 10^{11}\ B/\mathrm{sqrt}(n) = 2000$ km/s
- Replenishment time of cusp $t_{cusp} = h_{cusp}/v_A = 8$ s



Eruptive Flare Model (Moore et al. 2000, ApJ)

- *Initial bipoles with sigmoidally sheared and twisted core fields*
- *accomodates confined as well as eruptive explosion*
- *Ejective eruption is unleashed by internal tether-cutting reconnection*
- *Arcade of postflare loops is formed after eruption of the filament and magnetic reconnection underneath*

* 4D Fitting: F[x(s,t),y(s,t),z(s,t)] with dynamic model

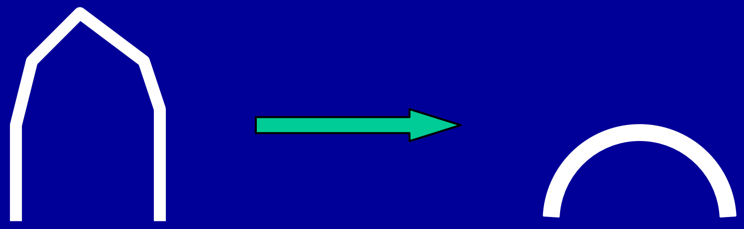
Example:

- relaxation of cusp-shaped loop after reconnection into dipolar loop

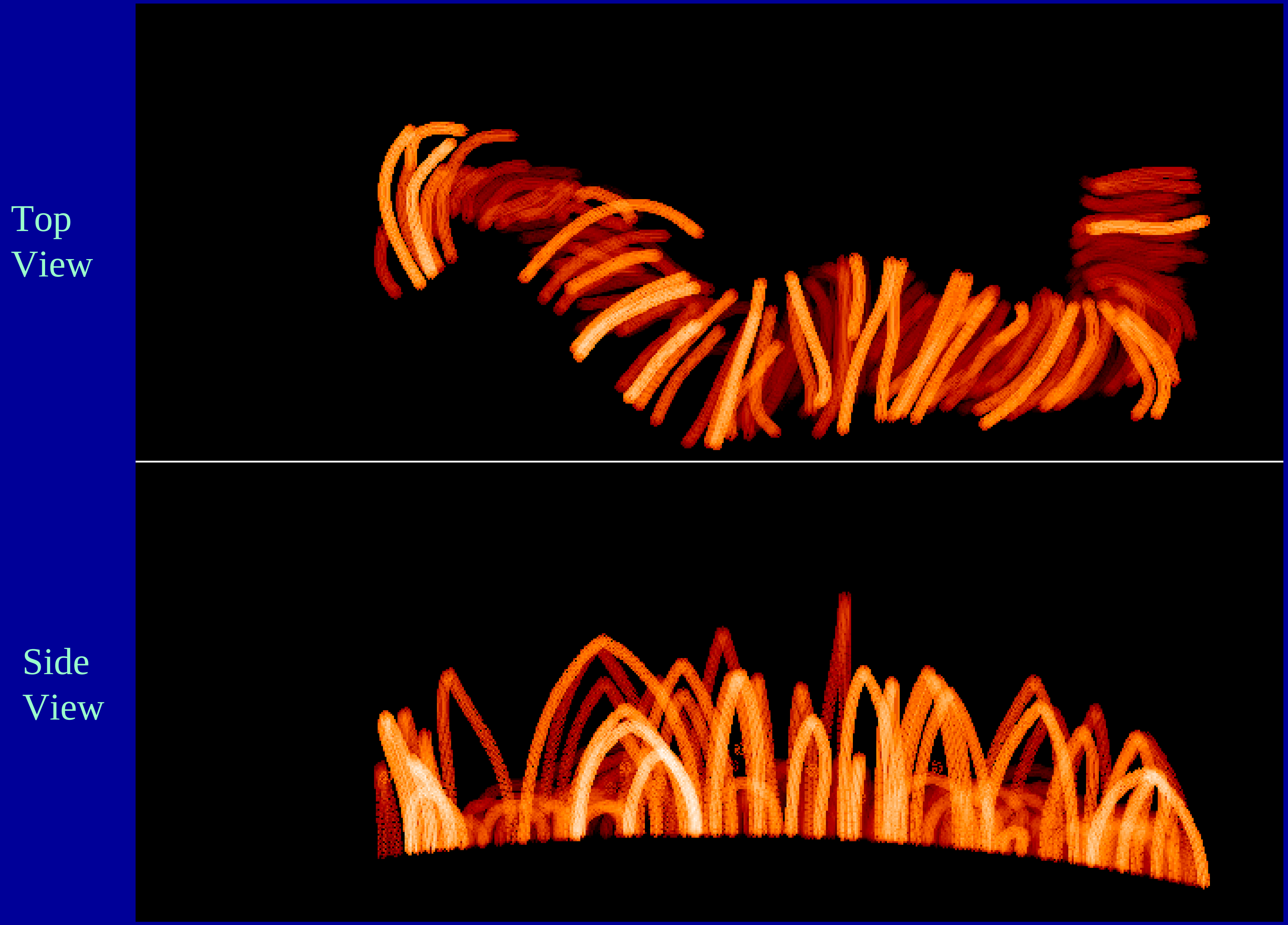
  z(s,t) = sqrt[x(s)^2 + y(s)^2] * (h_cusp-r_loop) * exp(-t/t_relax)

  t_relax = v_A(B,n) / [h_cusp- r_loop]

- could constrain cusp height h_cusp and magnetic field from v_A(B,n)



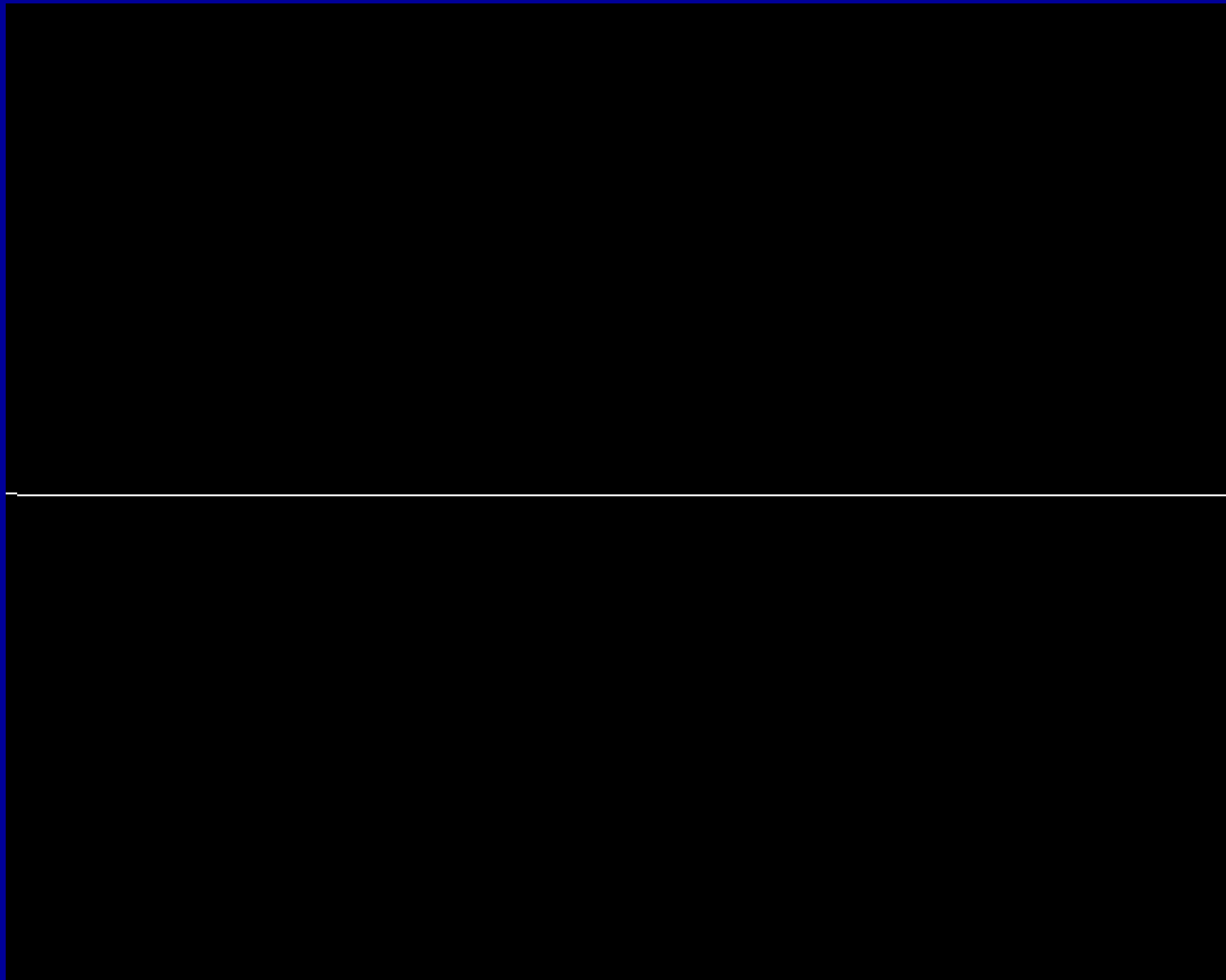
Dynamic Model of Arcade with 200 Reconnecting Loops



Dynamic Model of Arcade with 200 Reconnecting Loops

Top
View

Side
View



* 5D Model: DEM [x(s),y(s),z(s),T(s),t] with dynamic physical model

Ingredients for flare loop model :

- 3D Geometry [x(s), y(s), z(s)]
- Dynamic evolution [x(s), y(s), z(s), t]
- Heating function E_heat(s)
- Thermal conduction $-\nabla F\_cond(s)$
- Radiative loss E_rad(s) = -n_e(s)^2 Λ[T(s)]

-> Differential emission measure distribution dEM(T,t)/dT

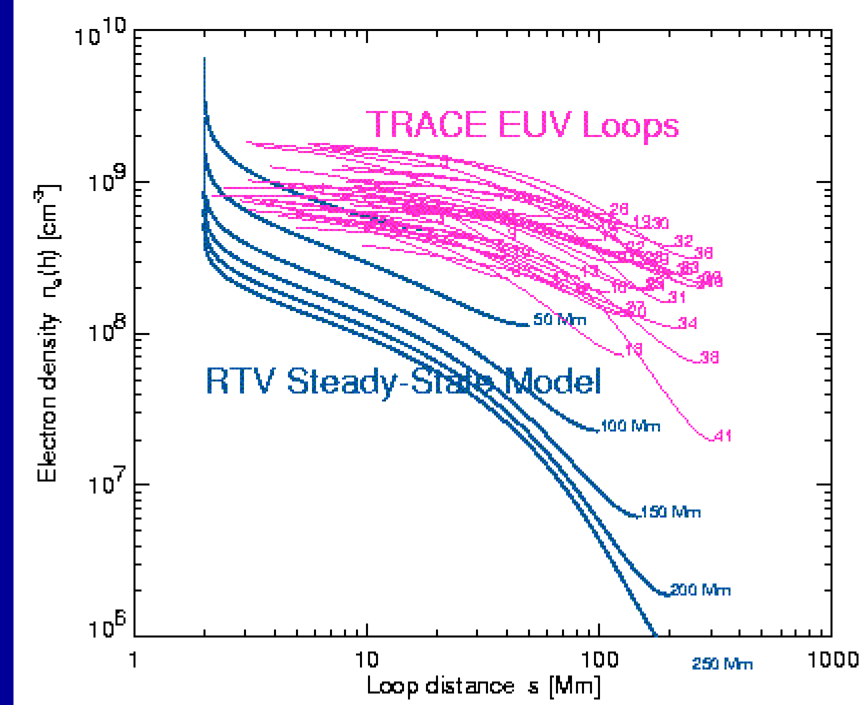
-> Line-of-sight integration EM(T)=∫ n_e(z,T,t)^2 dz (STEREO angle)

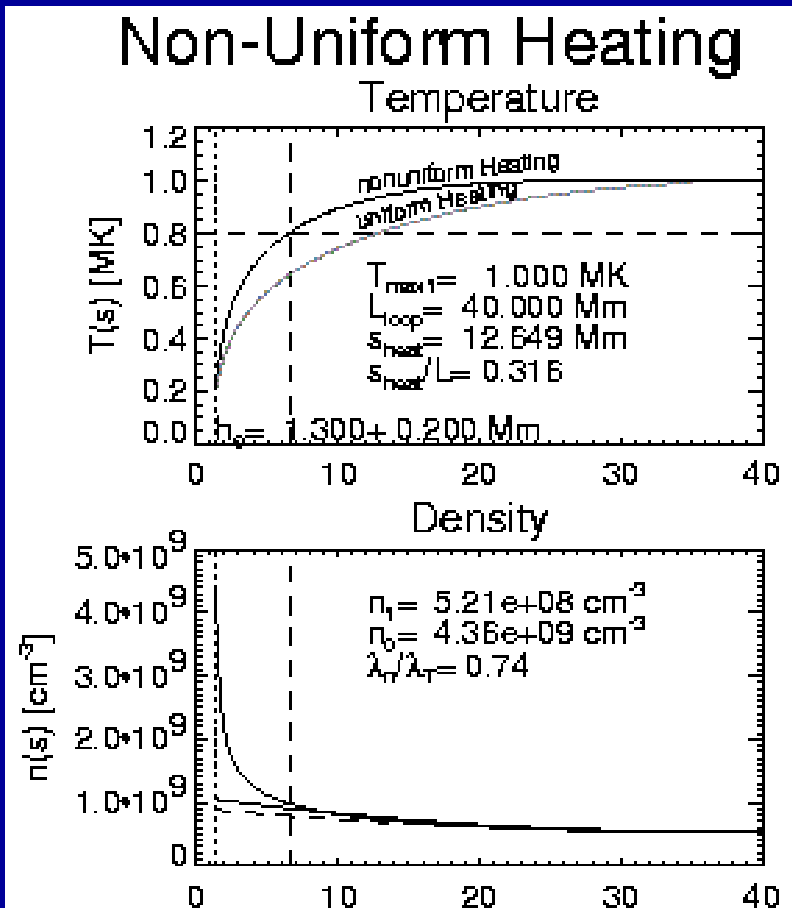
-> Instrumental response function R(T)

-> Observed flux F(x,y,t)= ∫ EM(T,t) * R(T) dT

-> Flux fitting of 5D-model onto 3D flux F(x,y,t)
for two stereo angles (4D) and multiple temperature filters (5D)

Step 4: Use physical hydrostatic models of temperature T(s), density n(s), and pressure p(s), to fill geometric structures with plasma





HYDRODYNAMIC EQUATIONS

Mass Conservation,

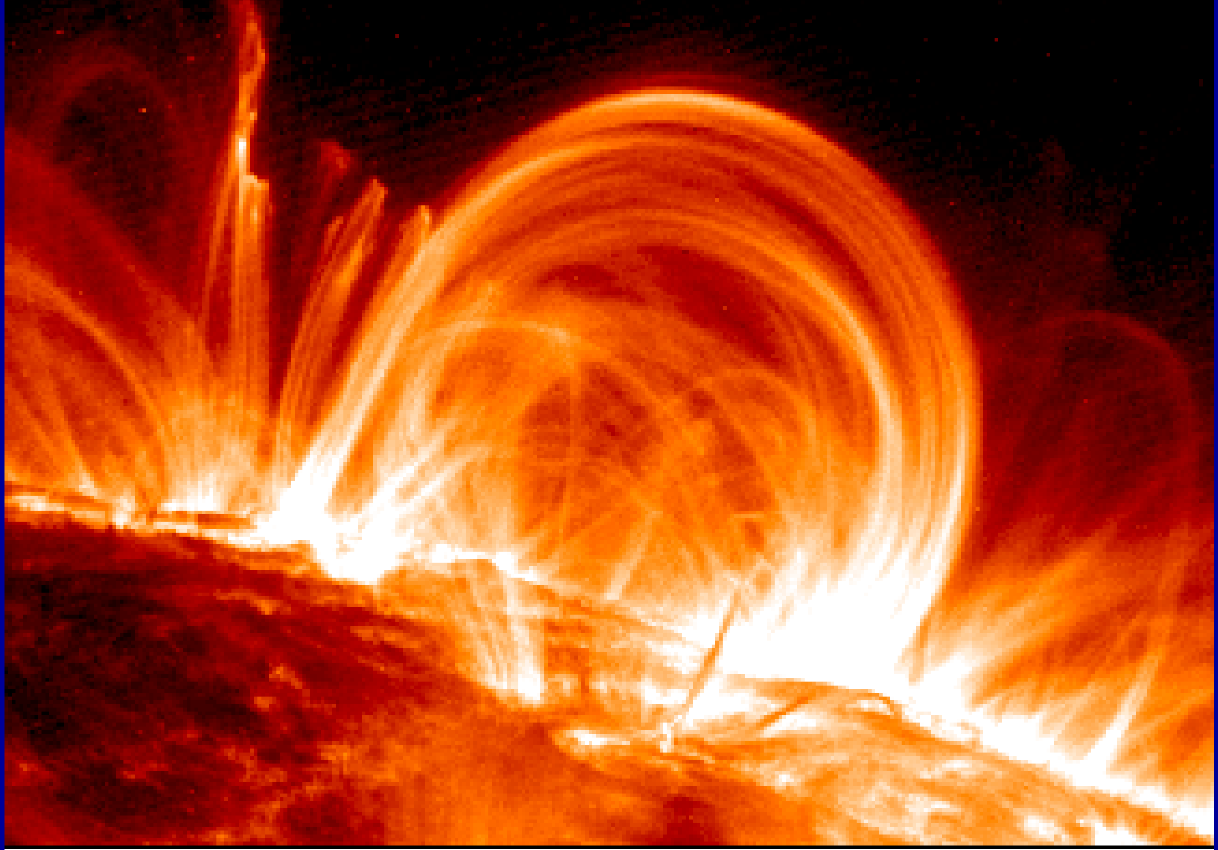
$$\frac{dn}{dt} + \frac{1}{A}\frac{d}{ds}(nvA) = 0$$

Momentum equation,

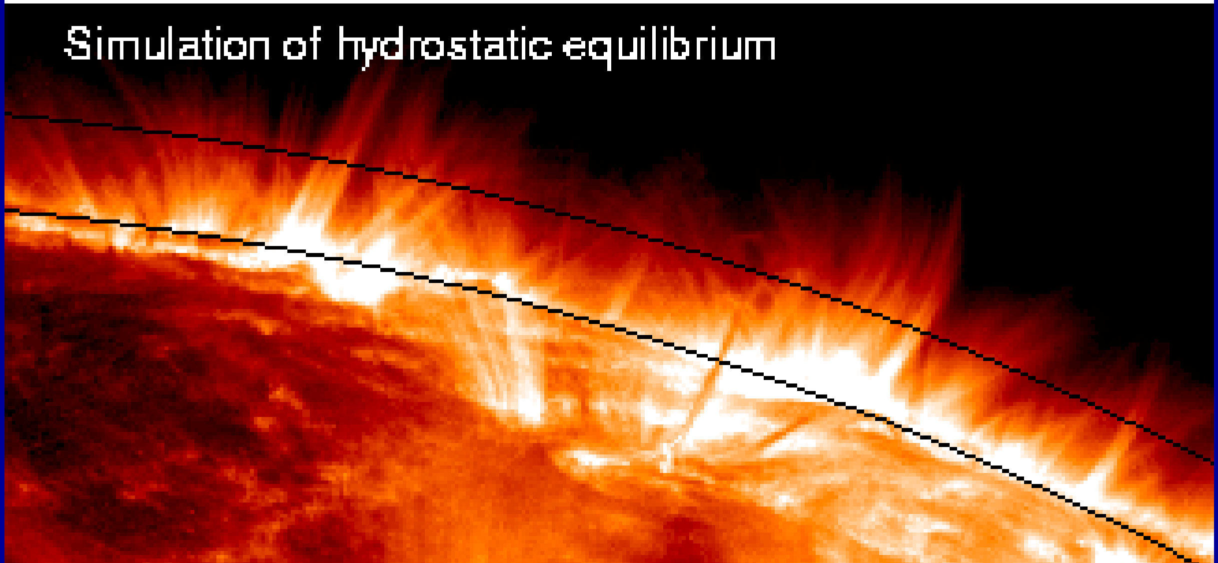
$$mn\frac{dv}{dt} + mnv\frac{dv}{ds} = -\frac{dp}{ds} + \frac{dp_{grav}}{dr}\left(\frac{dr}{ds}\right)$$

Energy equation (in conservative form),

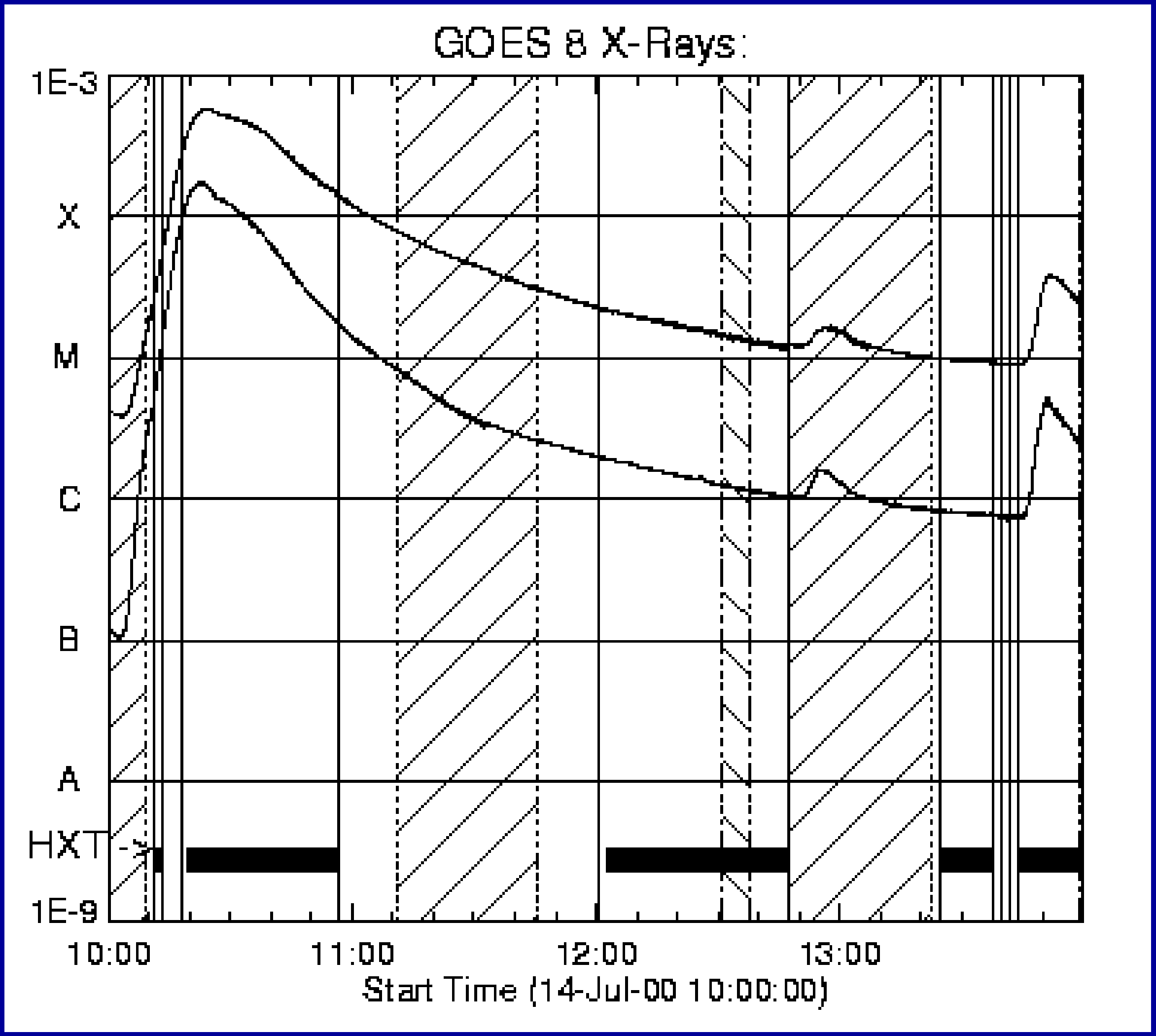
$$\frac{1}{A}\frac{d}{ds}\left(nvA[\epsilon_{enth} + \epsilon_{kin} + \epsilon_{grav}] + AF_{cond}\right) = E_{heat} + E_{rad}$$



Observed dynamic loops

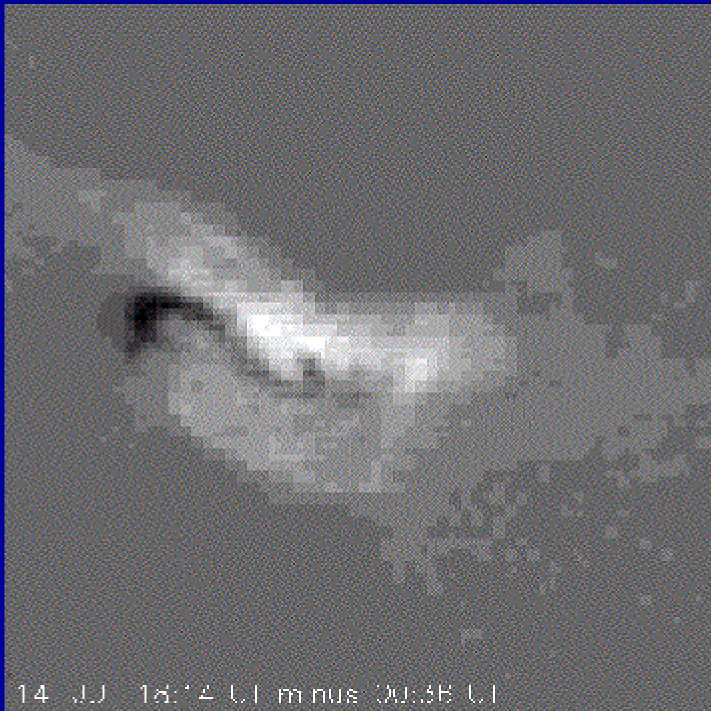


The same loops
how they would look like
in hydrostatic equilibrium



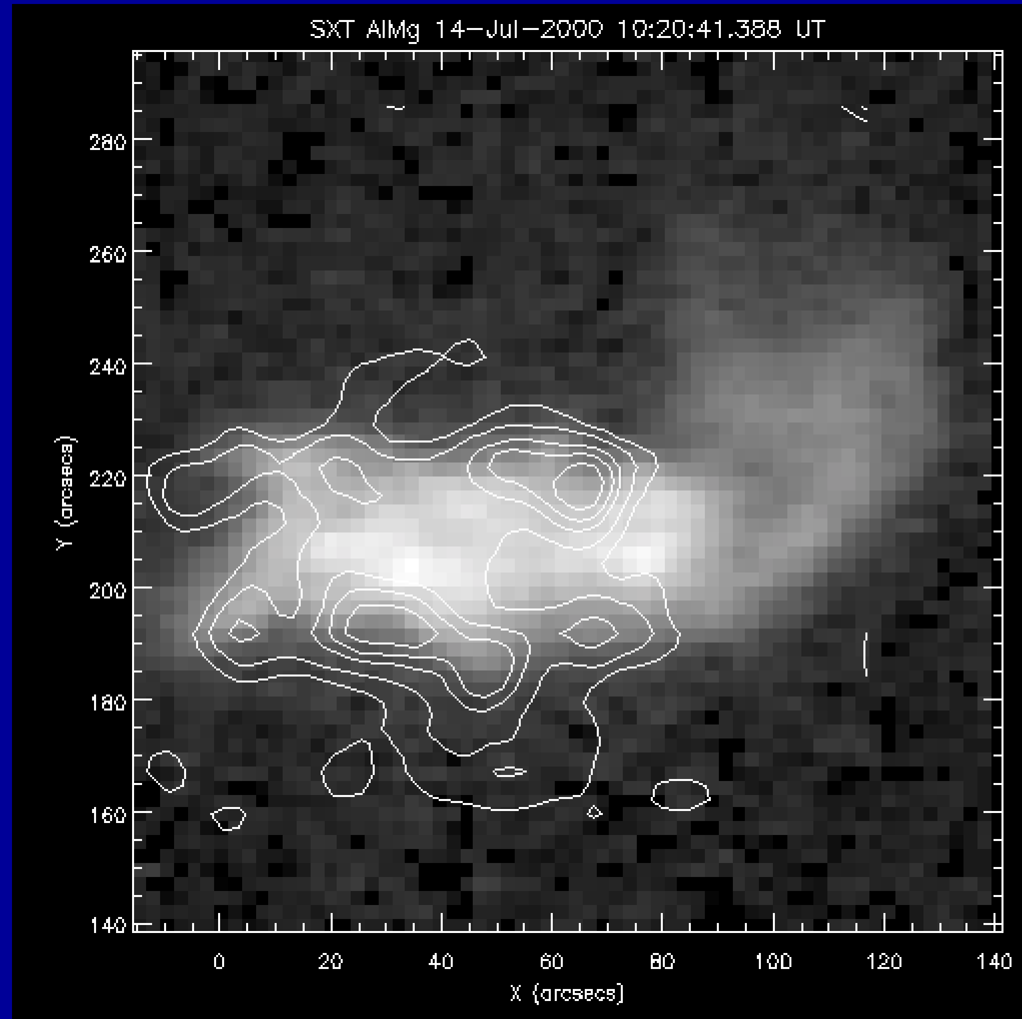
GOES light curves in 1-8 A and 0.5-4 A channel

Double-Ribbon Hard X-Ray Emission

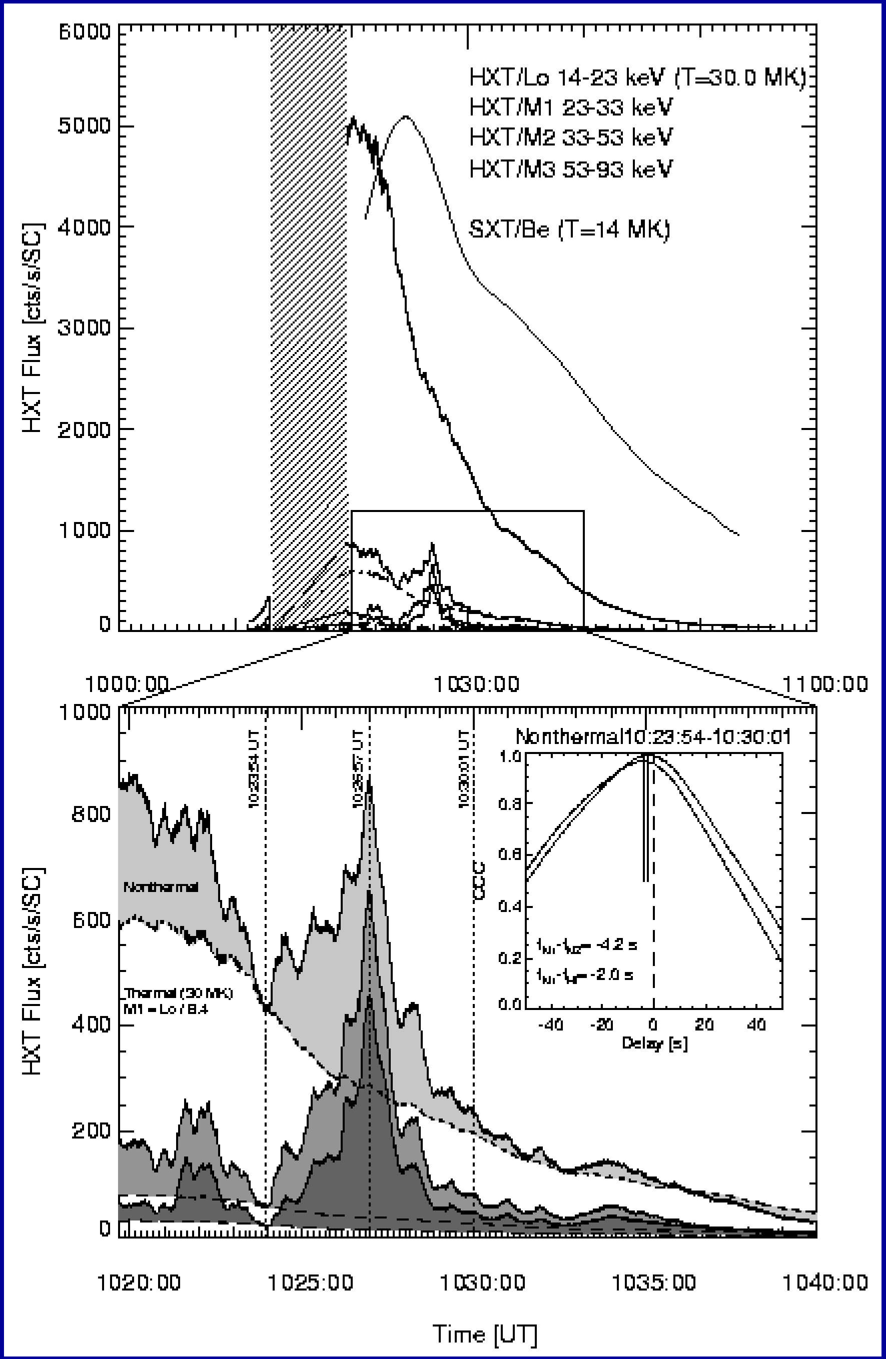


Yohkoh SXT: A difference image showing (bright) the extended arcade as seen in soft X-rays. This is a top-down view, so that the basically circular loops that form the cylinder look more or less like straight lines, some tilted (sheared) relative to others. The dark S-shaped feature is the pre-flare sigmoid structure that disappeared as the flare developed.

Courtesy of Hugh Hudson,
Yohkoh Science Nuggets, Sept 15, 2000



Yohkoh HXT and SXT overlay: The SXT image is taken on 2000-Jul-14 at 10:20:41 UT: The HXT image is in the high-energy band, 53-93 keV, integrated during 10:19:40-10:20:50 UT. The HXT shows clearly two ribbons ar the footpoints of the arcade lined out in soft X-rays. This is the first detection of hard X-ray double ribbons (see AGU poster by Masuda). [Courtesy of Nariaki Nitta].

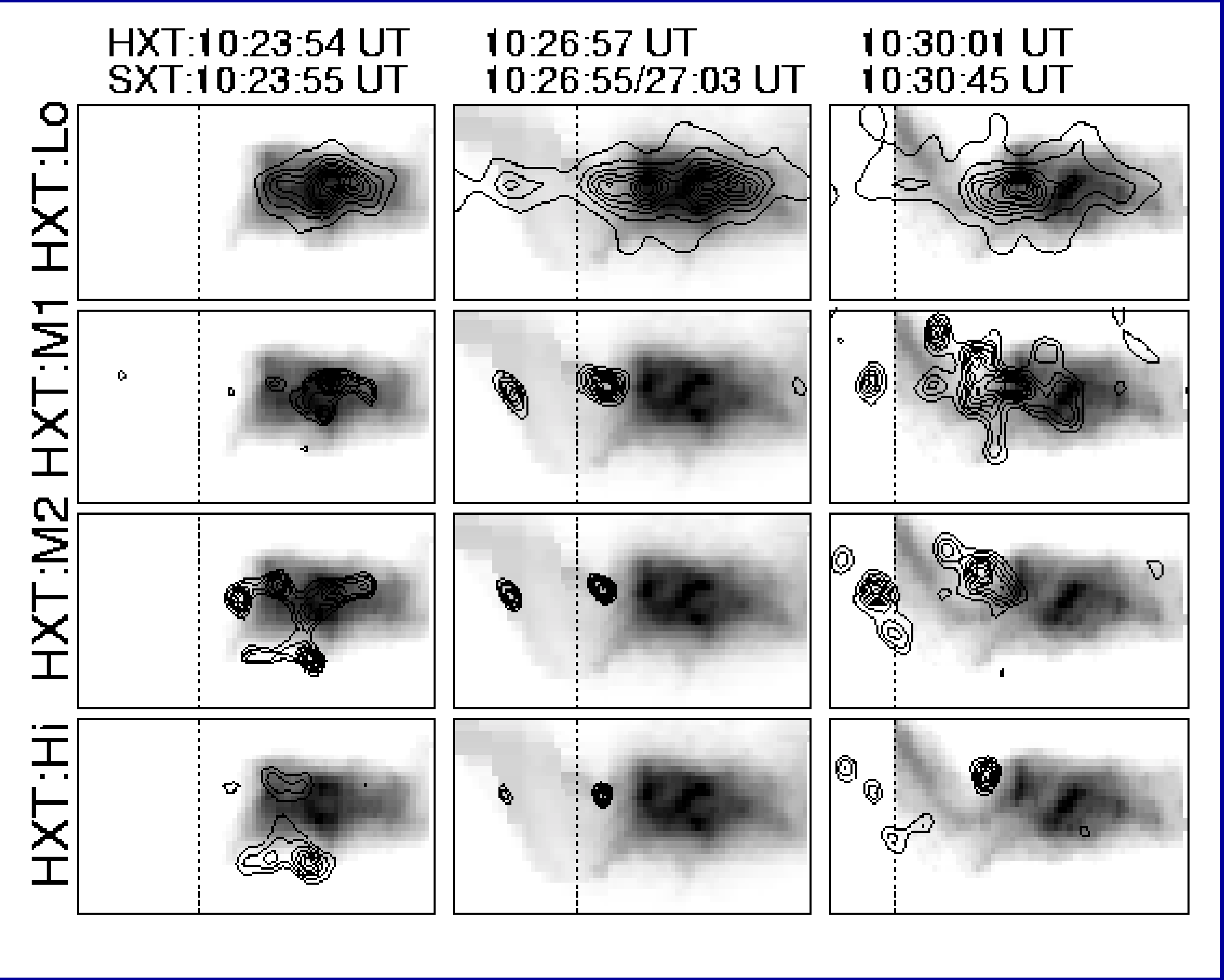


- Hard X-ray emission observed with Yohkoh HXT, 14-93 keV

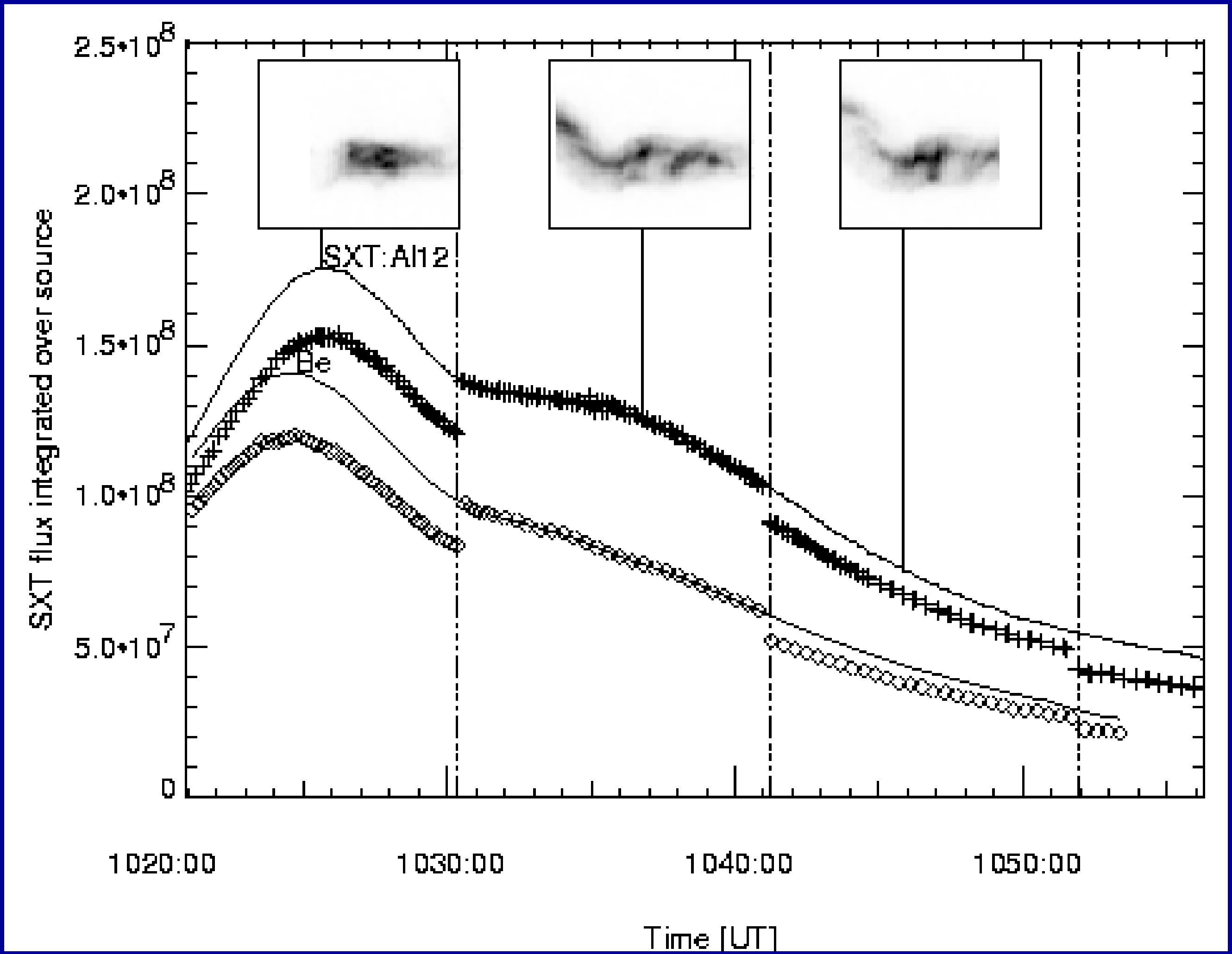
- Hard X-ray time profiles consist of thermal emission (dominant in 14-23 keV, Lo channel), which mimics a lower envelope in higher channels

- Nonthermal HXR emission is dominant at >23 keV energies, manifested by rapidly-varying spiky components

- High-energy channels (33-93 keV) are delayed by 2-4 s with respect to low-energy channel (23-33 keV) probably due to partial electron trapping

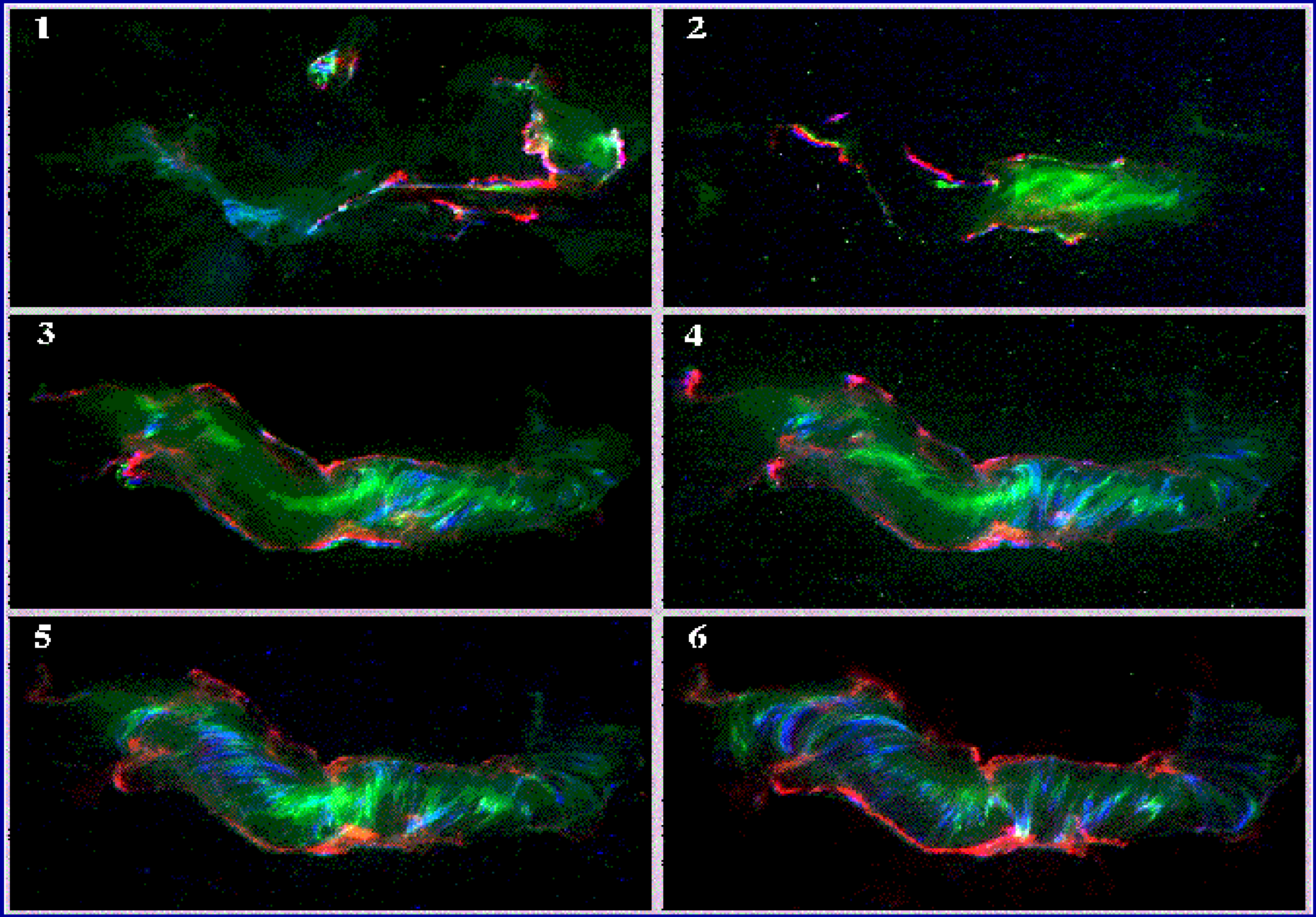


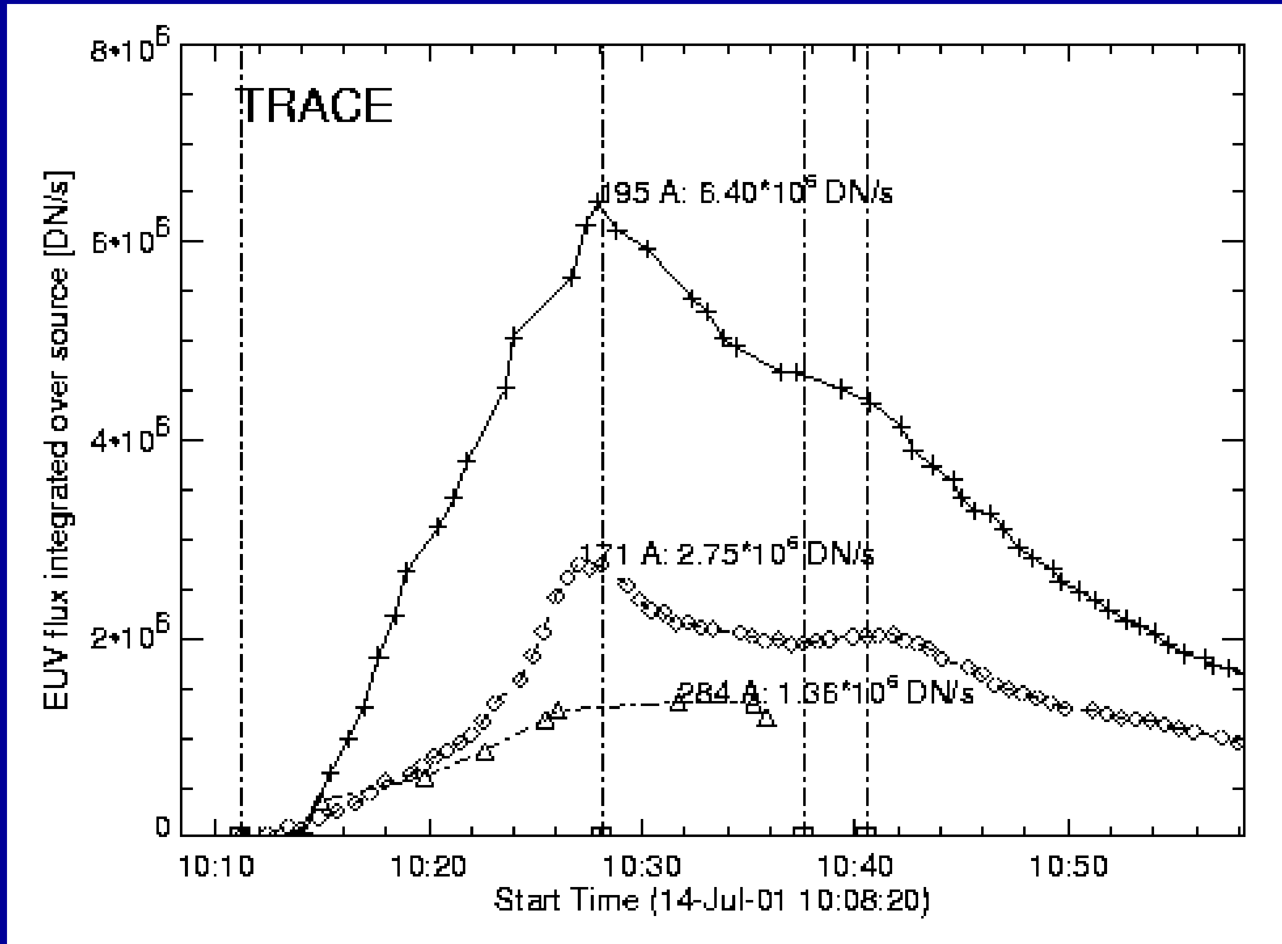
- Thermal emission is centered at top of arcade on HXT:Lo channel
- Nonthermal HXR emission is concentrated at footpoints of arcade



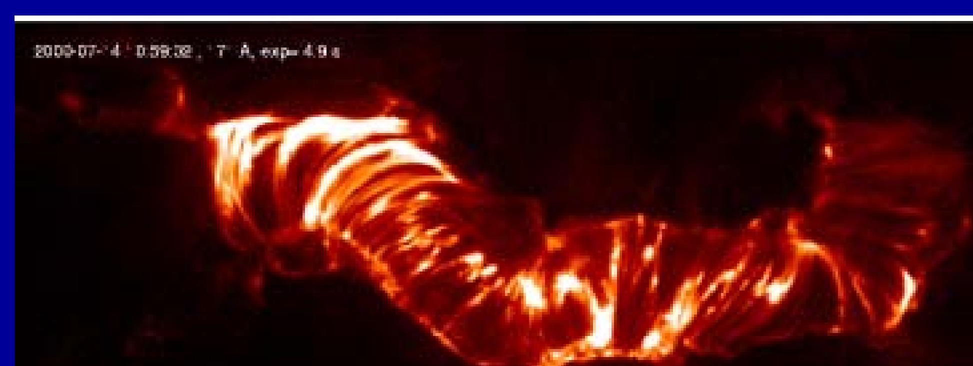
Yohkoh SXT Al12 and Be light curves
of total emission from flare arcade (within the partial frame FOV)

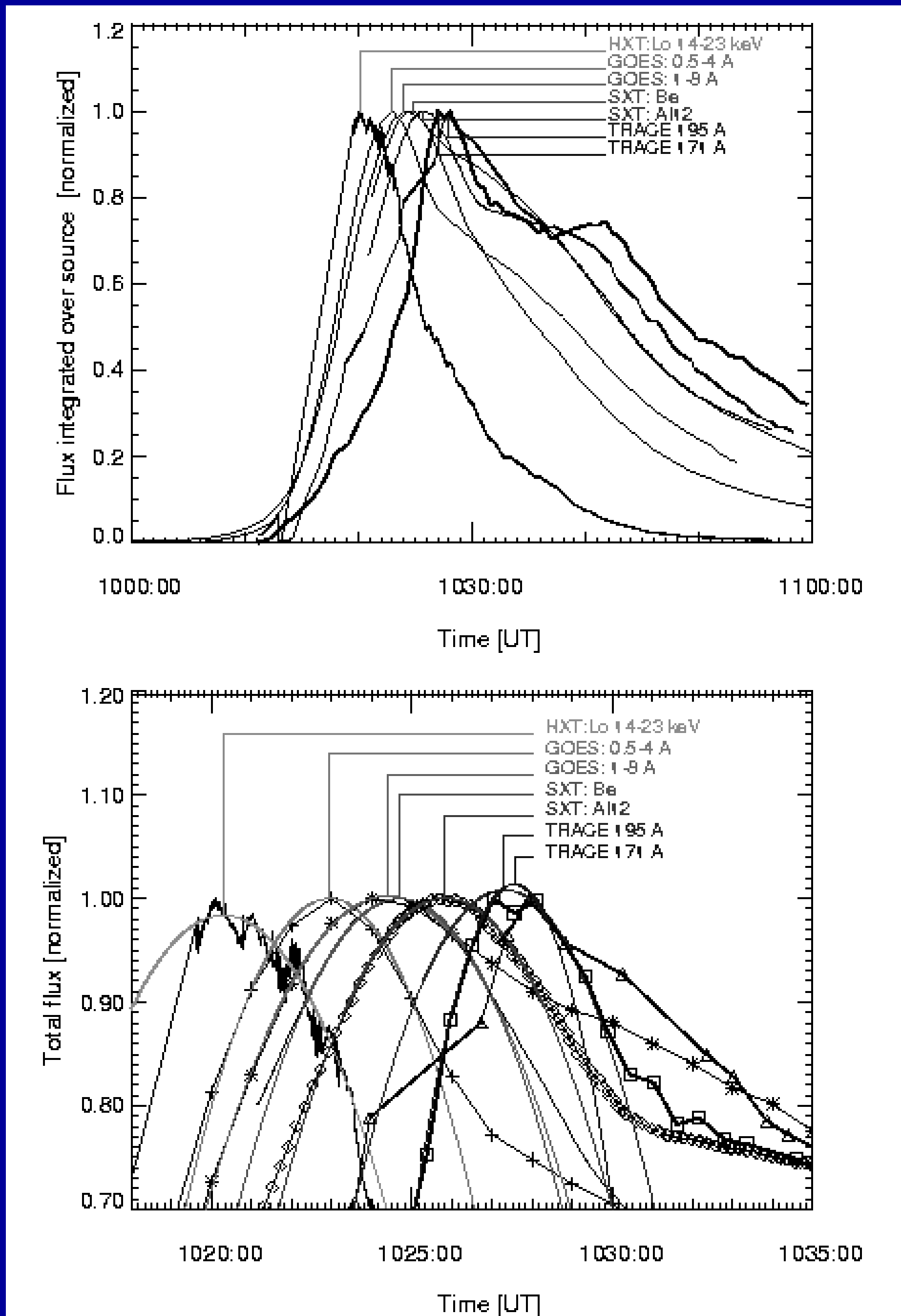
TRACE Observations: 2000-July-14, 10:03 UT,   (UV=red, 171 A=blue, 195 A=green)





TRACE 171 A, 195 A, and 284 A light curves of total EUV emission from flare arcade





- Composite of HXR, SXR, and EUV light curves

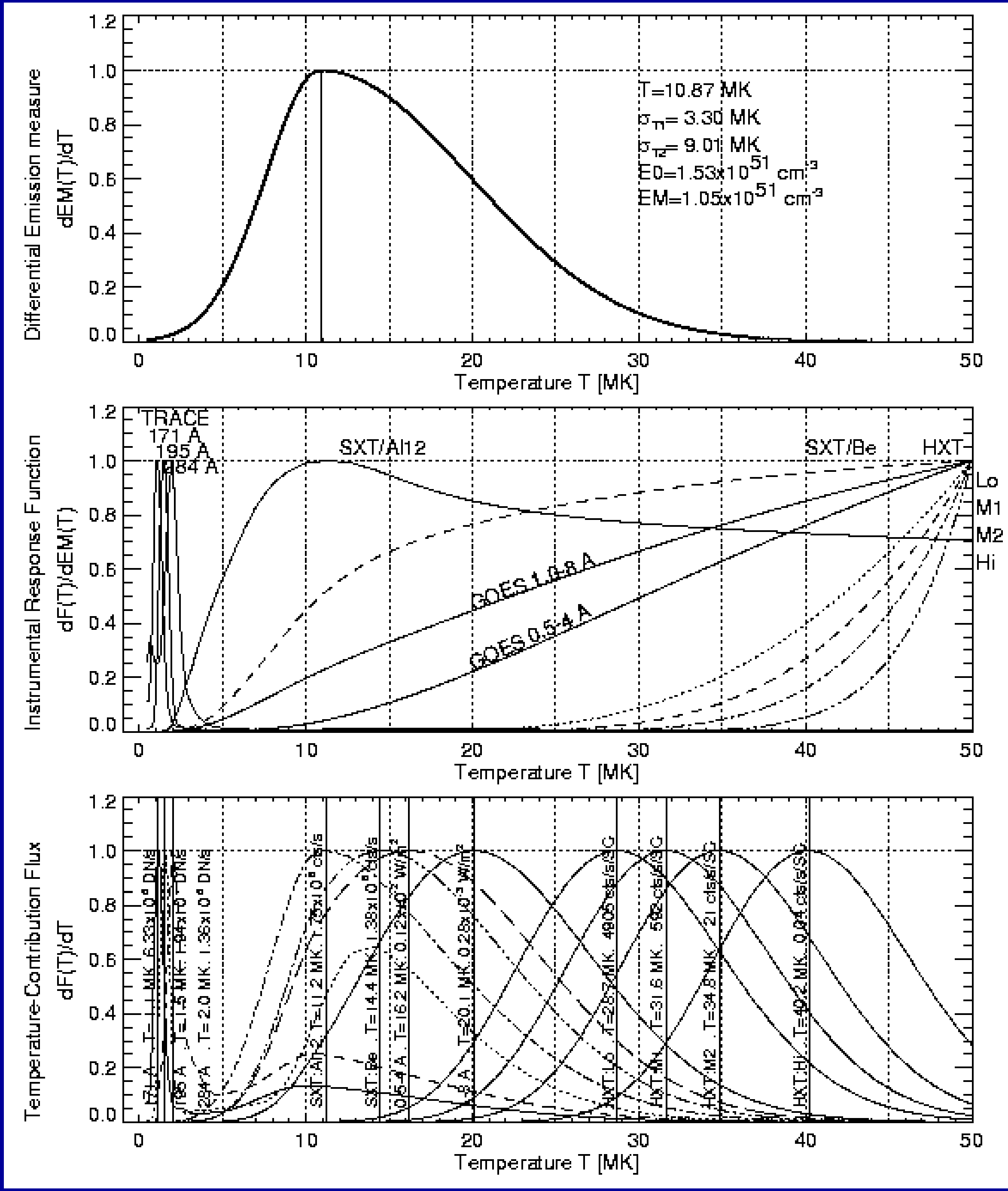
- HXT 14-23 keV peaks first

- GOES peaks second

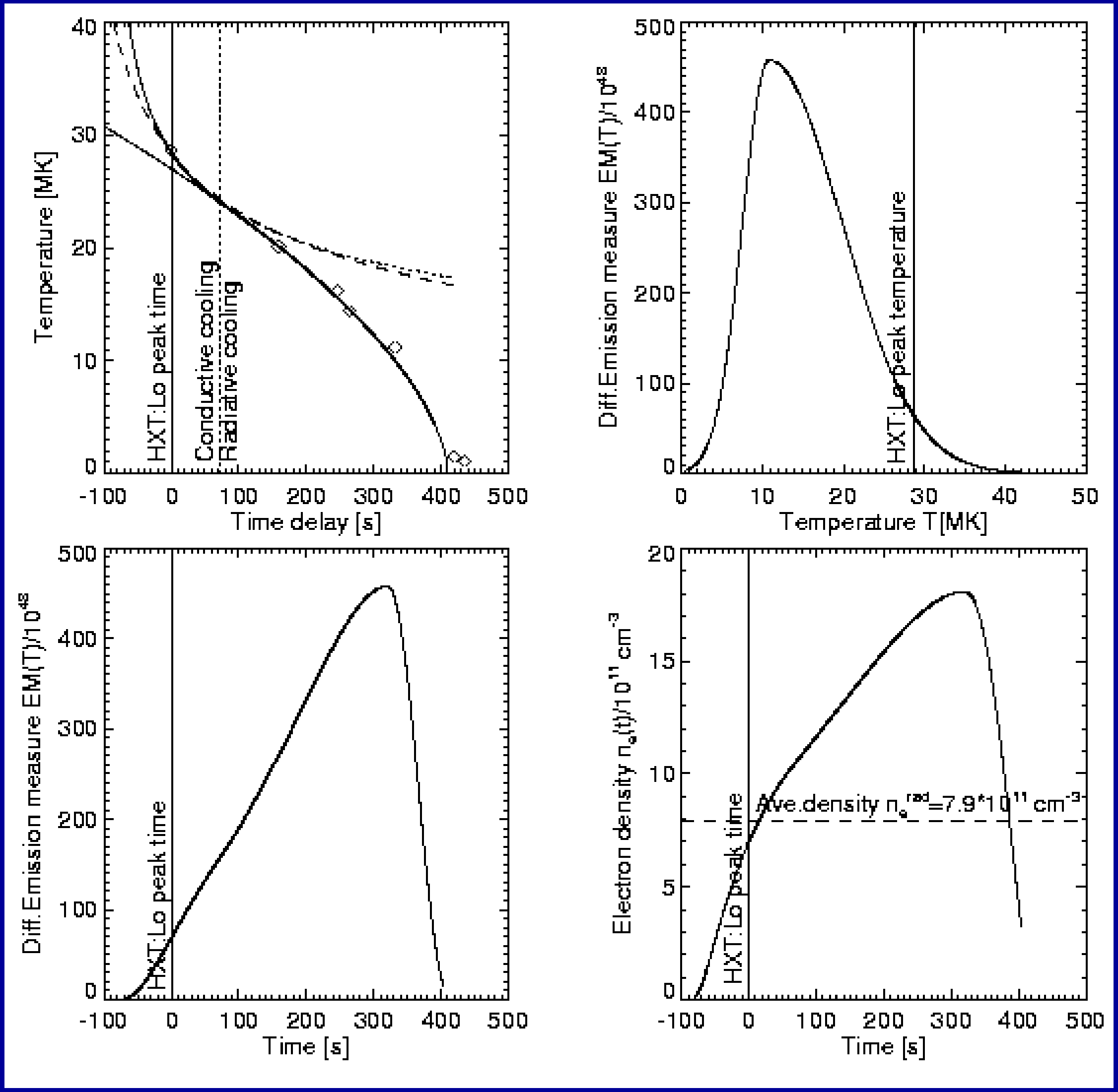
- SXT peaks third

- TRACE peaks last

- Time delays are consistent with flare plasma cooling from high (30 MK) to low (1 MK) temperatures within ~ 10 minutes.



- The observed peak fluxes in all instruments (TRACE, SXT, GOES, HXT) constrain the differential emission measure distribution dEM(T)/dT of the flare plasma



- The peak delays constrain a cooling time of t_cool ~ 400 s (~7 min)
- Evolution with initial conductive cooling (<1 min) and then radiative cooling (>1 min)
- The DEM(T) distribution and cooling curve T(t) can be converted into evolution of emission measure EM(t) and density n_e(t)

A) Conductive cooling phase

$$\frac{d}{dt}E_{enthalpy}(t)=\frac{d}{dt}[3n_e(t)k_BT(t)]=\frac{d}{ds}[\kappa T^{5/2}\frac{dT(t)}{ds}]$$

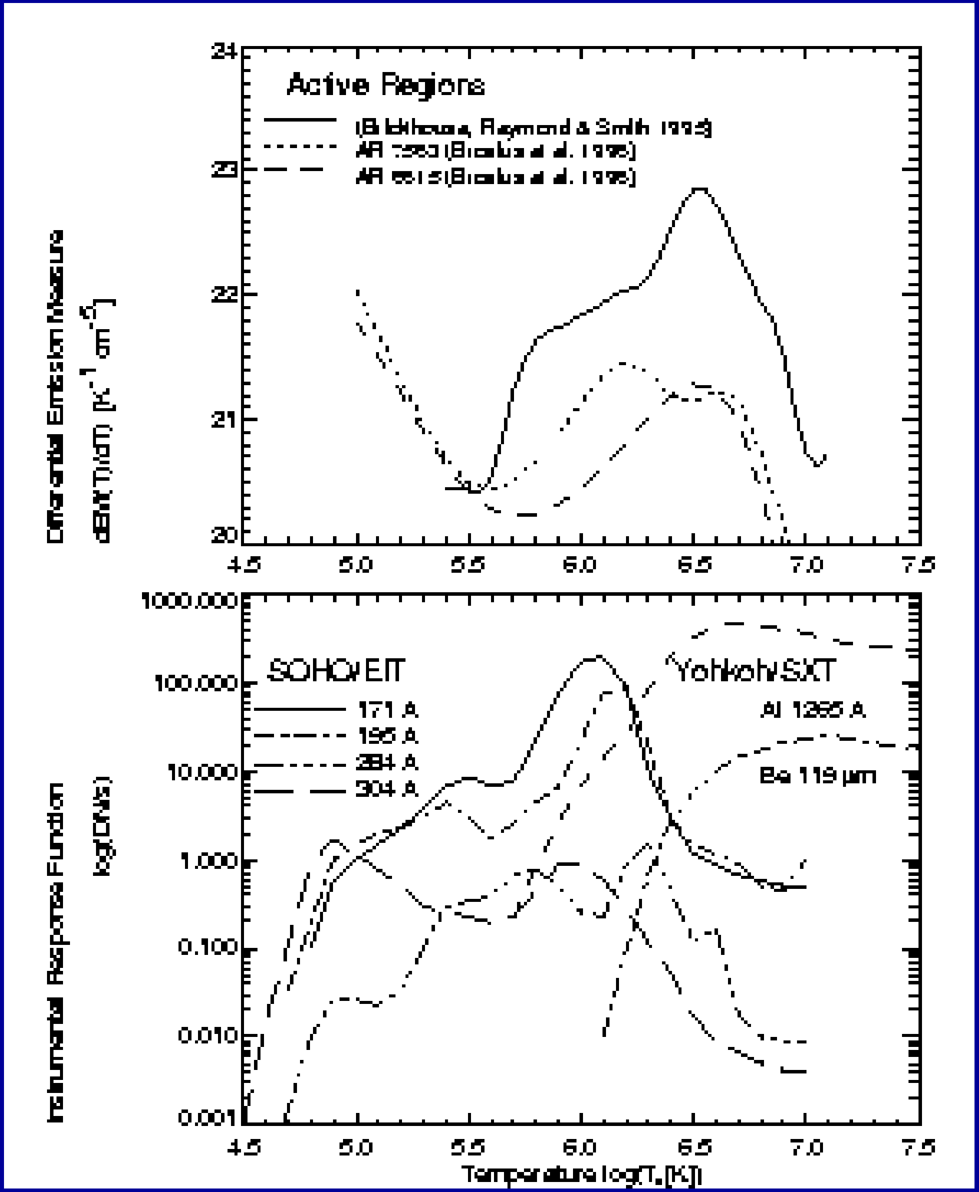
$$T(t)=T_1(1+\frac{(t-t_1)}{\tau_{cond}})^{-2/5},\tau_{cond}=71s,T_1=28.4MK$$

B) Radiative cooling phase

$$\frac{d}{dt}[3n_e(t)k_BT(t)]=-n_e(t)^2\Lambda_0T(t)^{-2/3}$$

$$T(t)=T_2(1-\frac{(t-t_1)}{\tau_{rad}})^{3/5},\tau_{rad}=420s,T_2=24.1MK$$

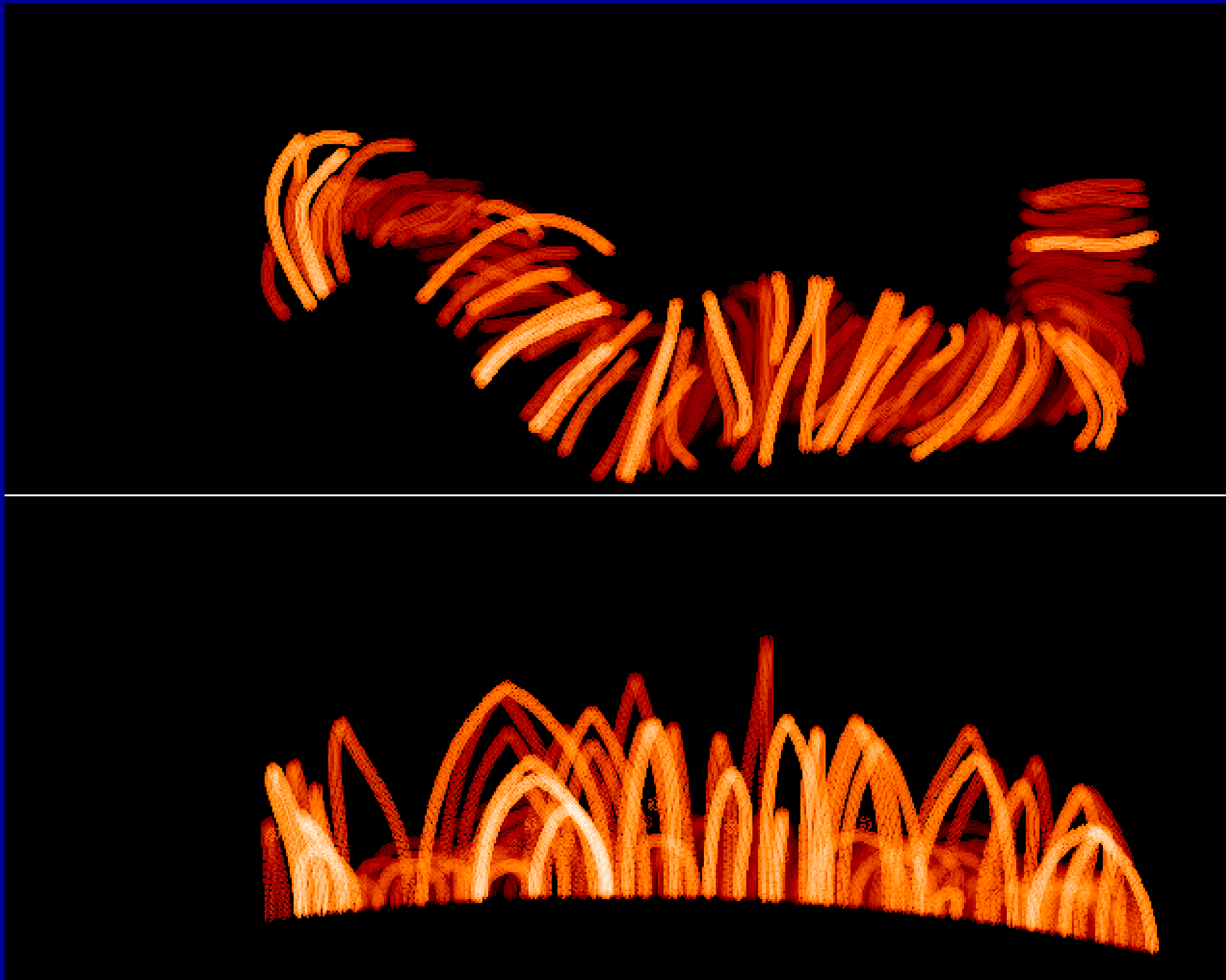
Step 6: Integration along line-of-sight
and convolution with instrumental response function



Dynamic Model of Arcade with 200 Reconnecting Loops

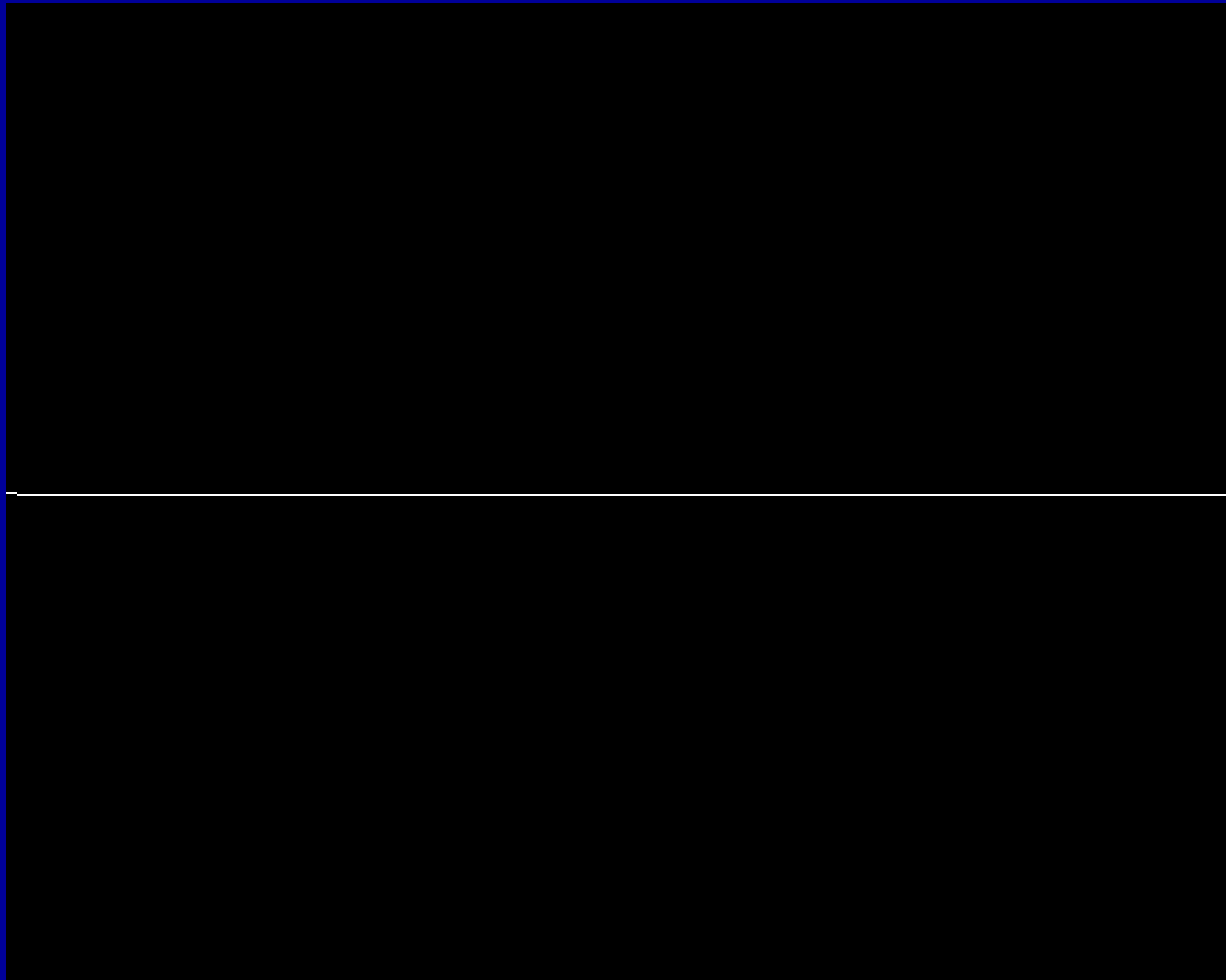
Top View

Side View



Dynamic Model of Arcade with 200 Reconnecting Loops

Top
View



Side
View

CONCLUSIONS :

Forward modeling for STEREO data at 3 levels of sophistication:

- 3D geometry [x(s), y(s), z(s)]
- 4D dynamics [x(s), y(s), z(s), t]
- 5D temperature evolution DEM[x(s),y(s),z(s),T(s),t]

What STEREO can provide uniquely :

- 3D geometry of sheared, twisted loops
- non-potentiality of magnetic field lines
- geometry of current-carrying loops --> currents
- 4D reconstruction of loop dynamics
- true (unprojected) speeds, acceleration, and deceleration
- dynamic forces with 3 vector components
- motion of reconnection points, Alfven speed, B-field
- 5D models: localization of heating sources
- temperature gradients, thermal flows, thermal conduction
- unambiguous reconstruction of differential emission distribution along two different line-of-sights

Plan for near future :

- The LMSAL group produces a package of EUVI stereo pair images :
  - containing different phenomena (flare, CMEs, filaments)
  - in different wavelengths (171, 195, 284, 211 A)
  - from different stereo angles (0, 5, 10, 30, 60, 90 deg)
  - based on self-consistent hydrostatic/dynamic models
  - FITS format with header info on spacecraft stereo angle

to be distributed to STEREO team members.

LMSAL STEREO Science website :

http://secchi.lmsal.com/Science/

* Simulations of STEREO data
* STEREO software development in IDL/SSW
* powerpoint and html presentations
* bibliography on 3D geometry, stereoscopy, tomography