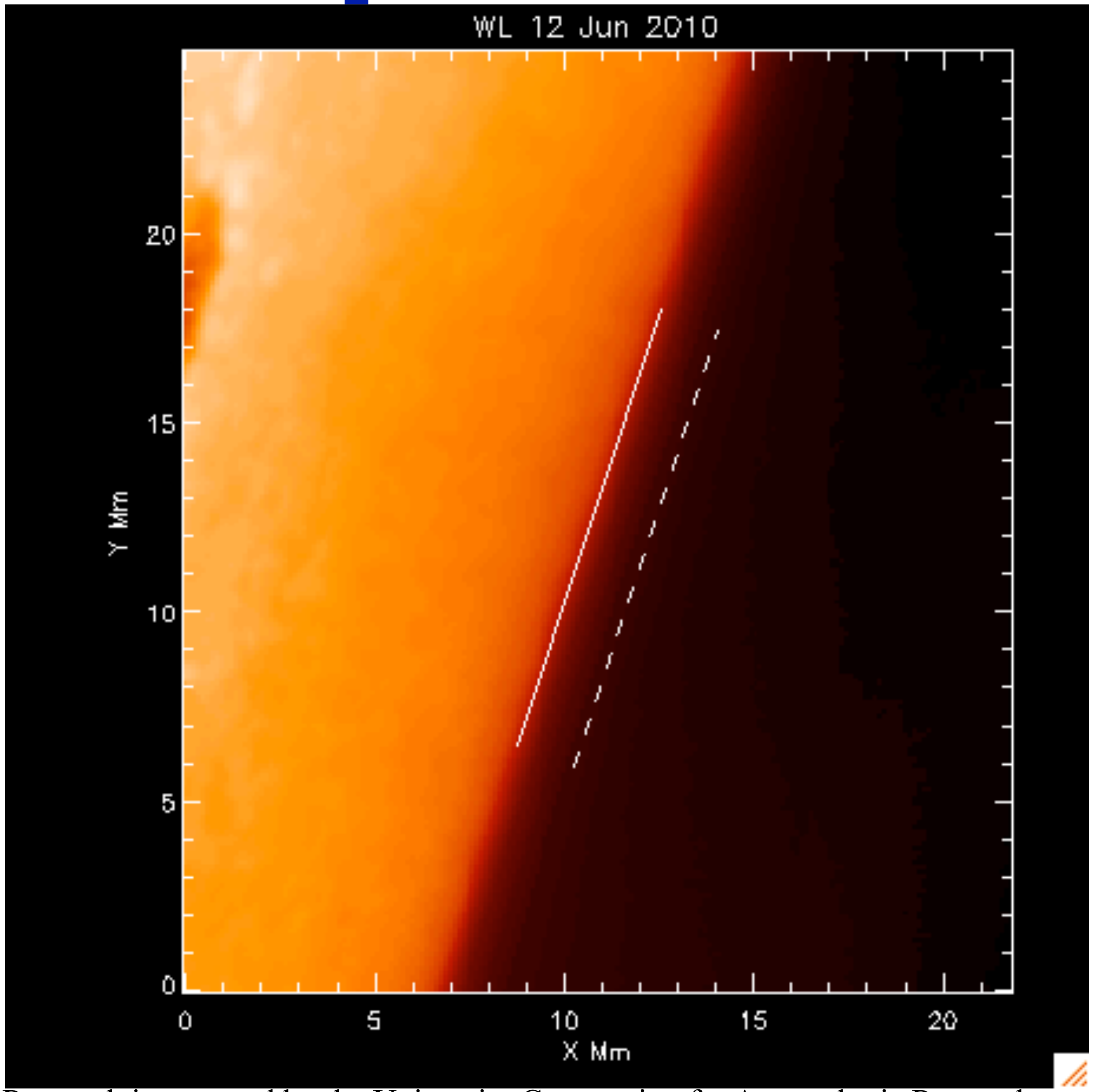
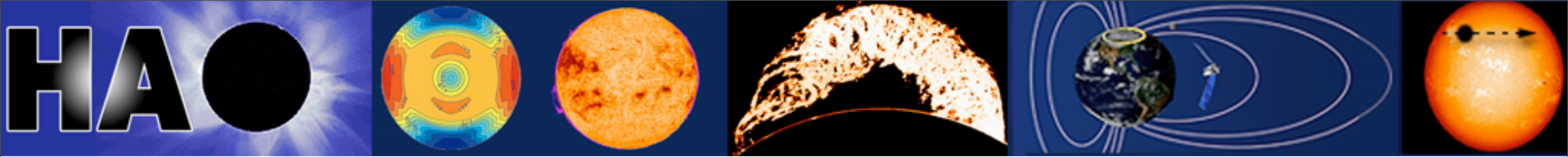
The Dawning of the Age of the Chromosphere

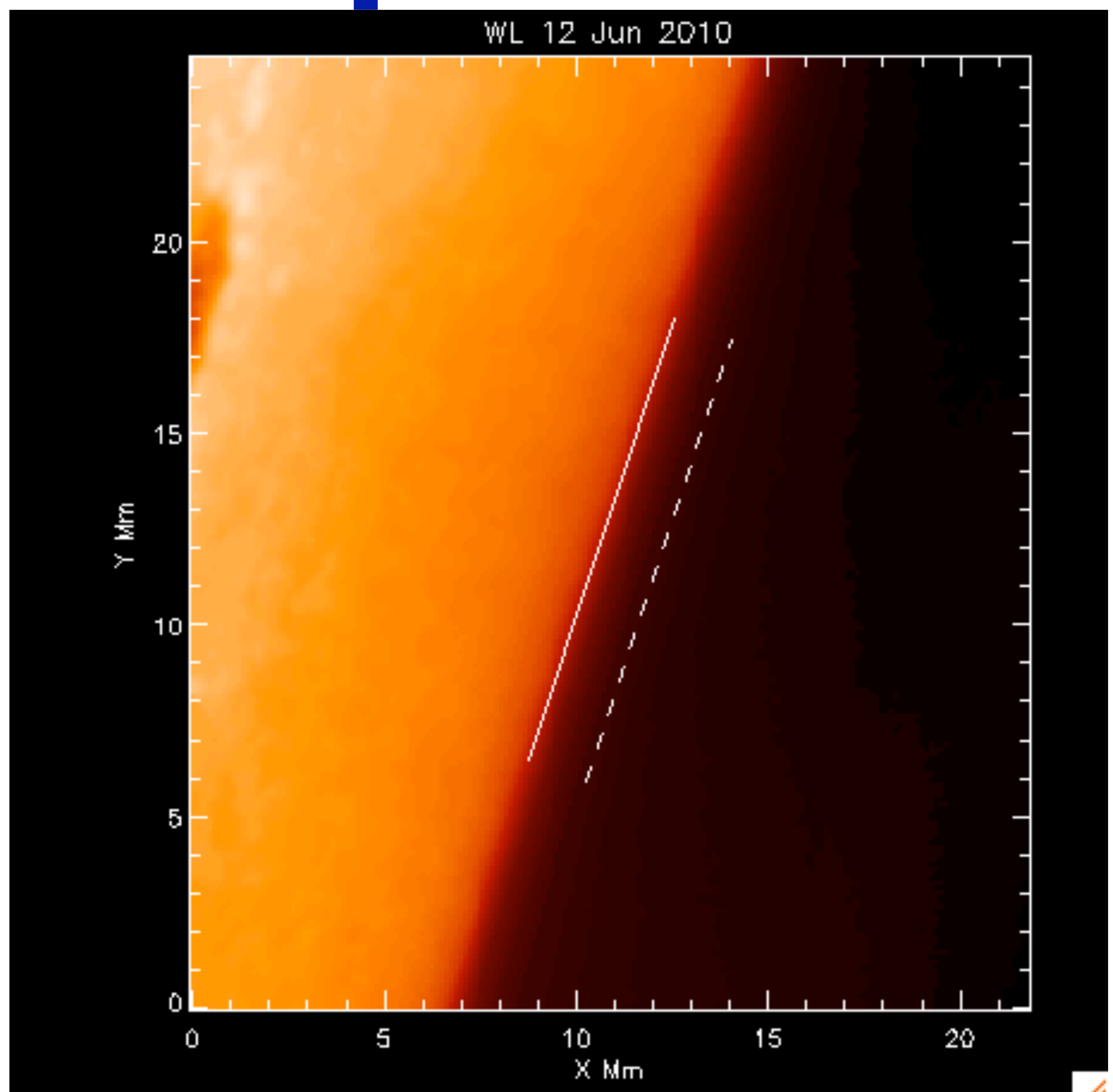


Philip Judge

HAO, NCAR



The Dawning of the Age of the Chromosphere

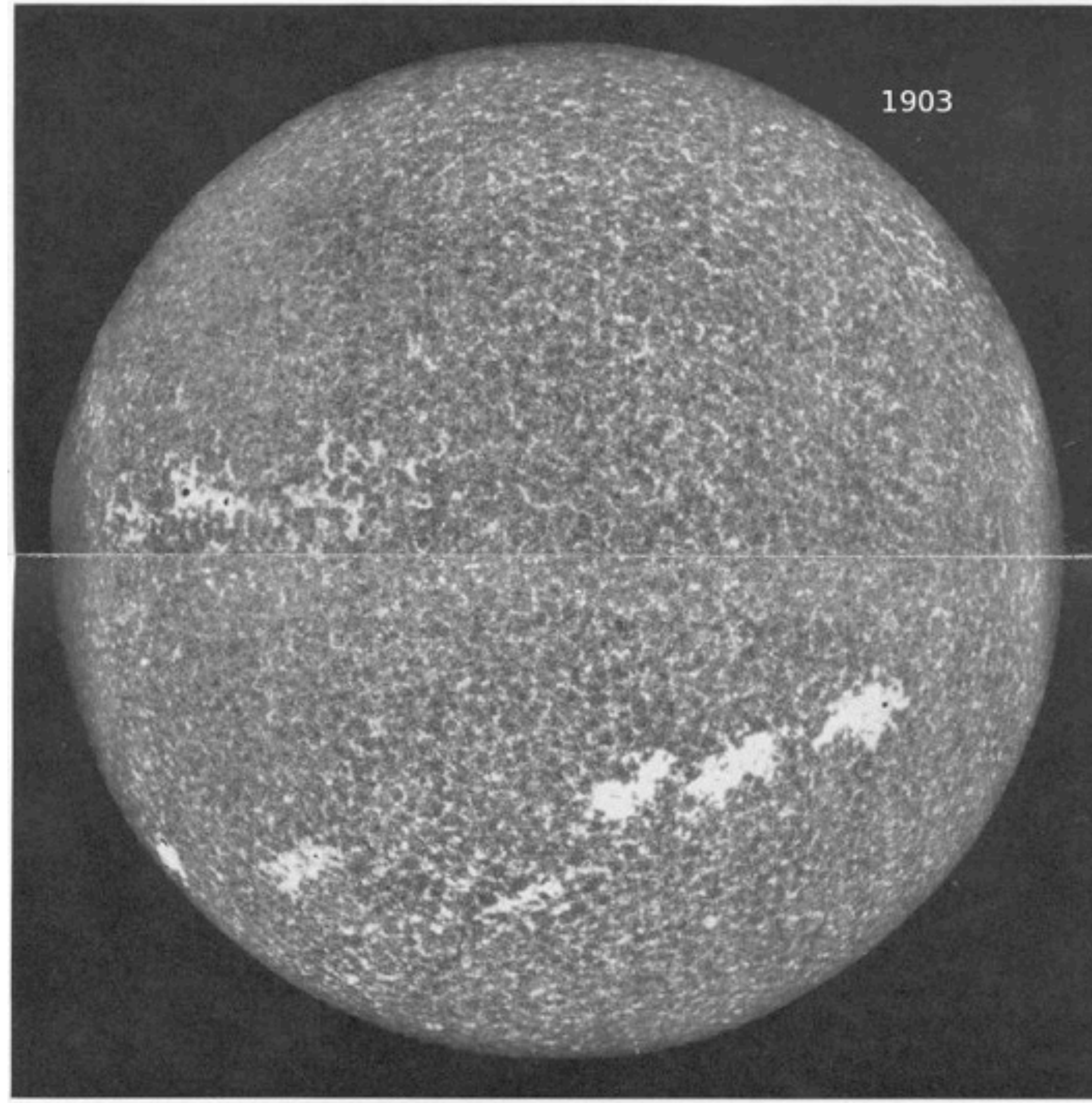


Philip Judge
HAO, NCAR

NCAR

chromosphere: main physical characteristics

- stratified: spans 9 pressure scale heights and high to low-β
- requires 30-100x as much power as the corona
- “thermostat”
- nLTE, partially ionized, (magnetized) plasma dynamics
- strongly influenced by surface magnetism



8

THE SUN, SHOWING THE CALCIUM FLOCCULI (H_2 LEVEL). 1903, AUGUST 12, $8^h 52^m$. C. S. T.

(Scale of Original Negative.)

(See p. 41.)

HAO

The awkward β≳1 transition occurs within the chromosphere

Gold (1964).

stratification makes this transition geometrically thin

that is not the whole story...

yet the chromosphere is often so-treated

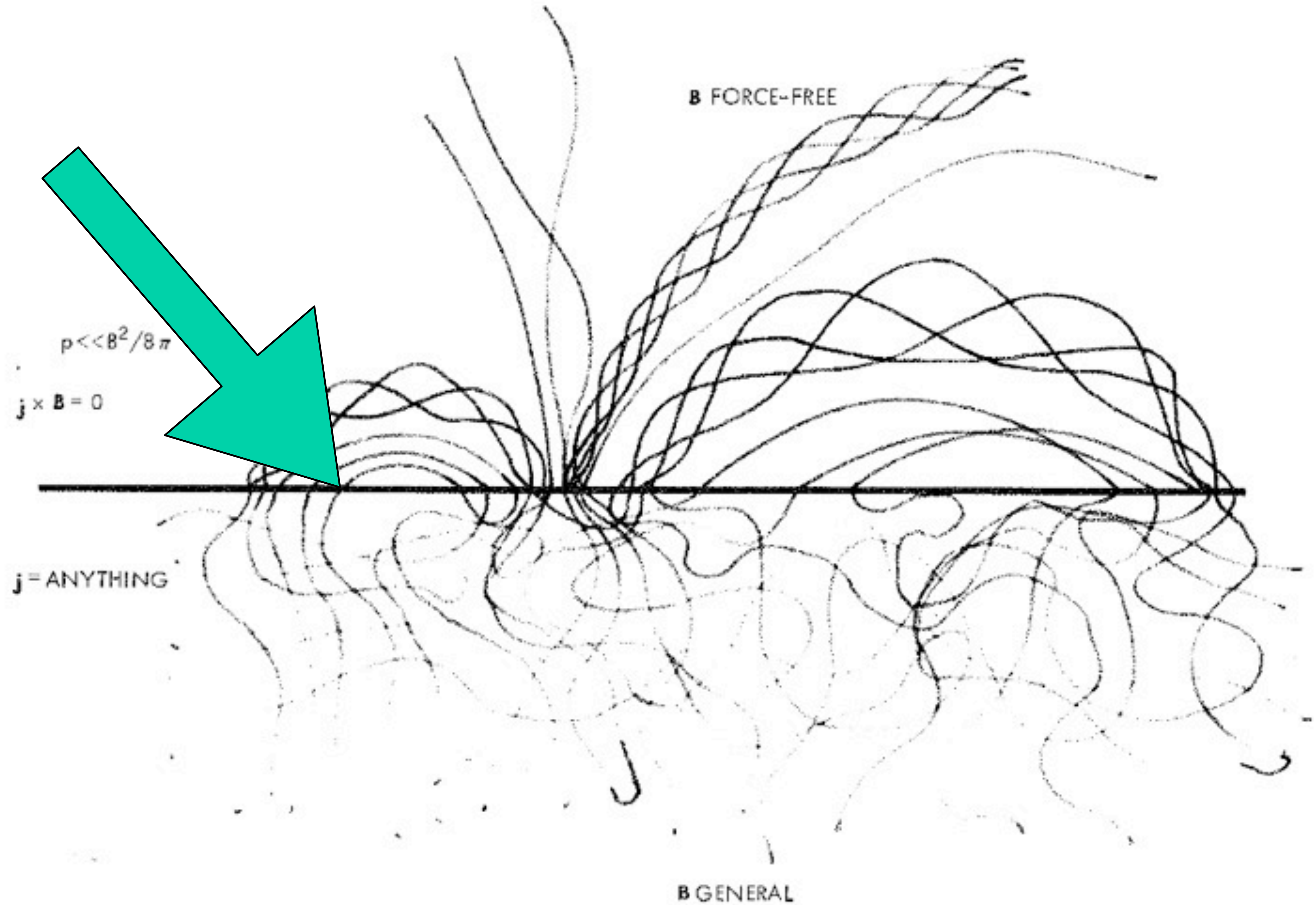


FIGURE 44–2. Magnetic field in a turbulent conducting medium. The fluid pressure is assumed large compared with magnetic forces below the dividing plane and small above it.

390

Manifestations of the storage and release of magnetic energy in the Sun’s atmosphere

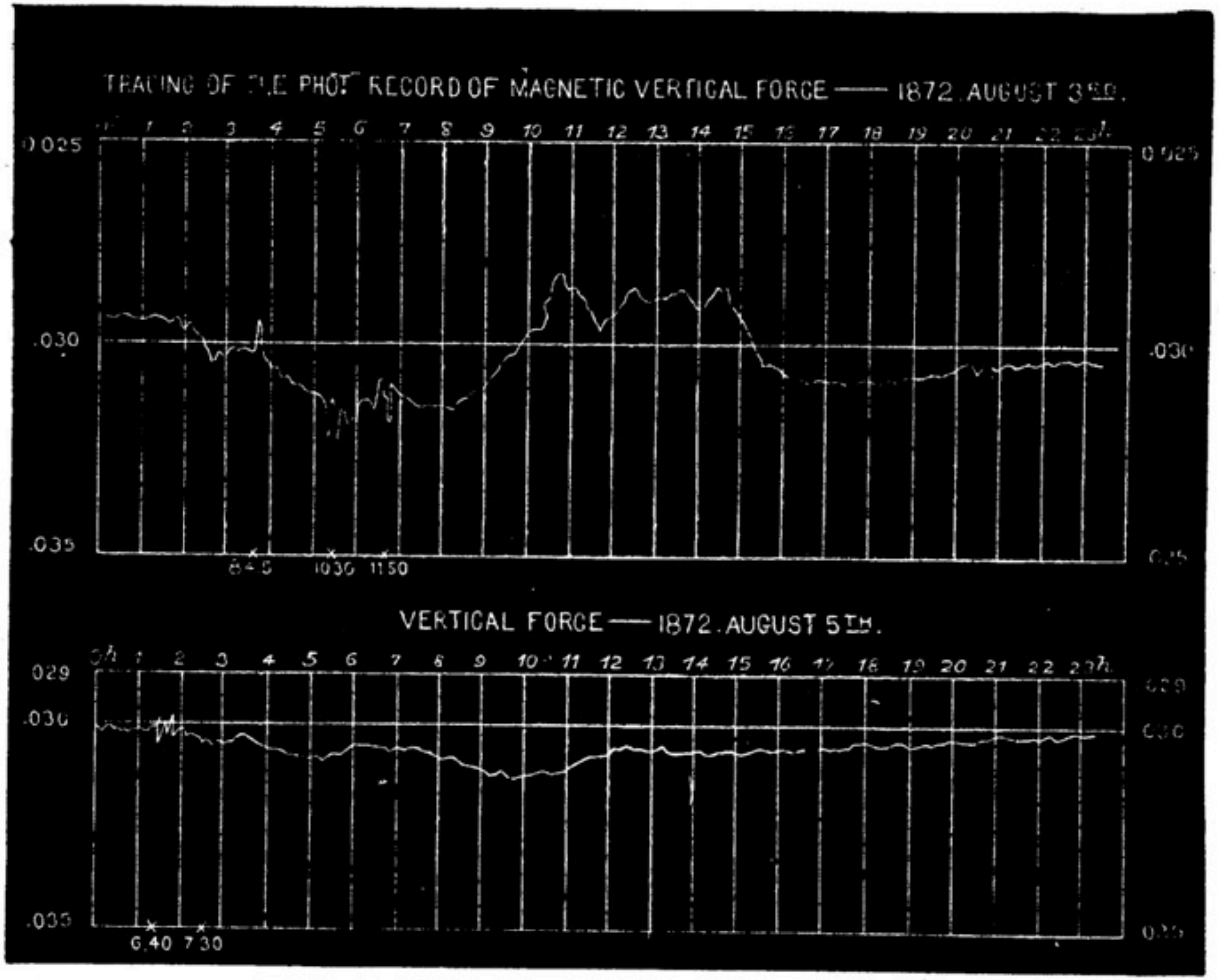
Young (1892)

MAGNETISM AND SUN-SPOTS. 159

The occurrence observed by Carrington and Hodgson (p. 119), on September 1, 1859, was immediately followed by a magnetic storm of unusual intensity, the auroral displays being most magnificent on both sides of the Atlantic, and even in Australia.

Young (1892)

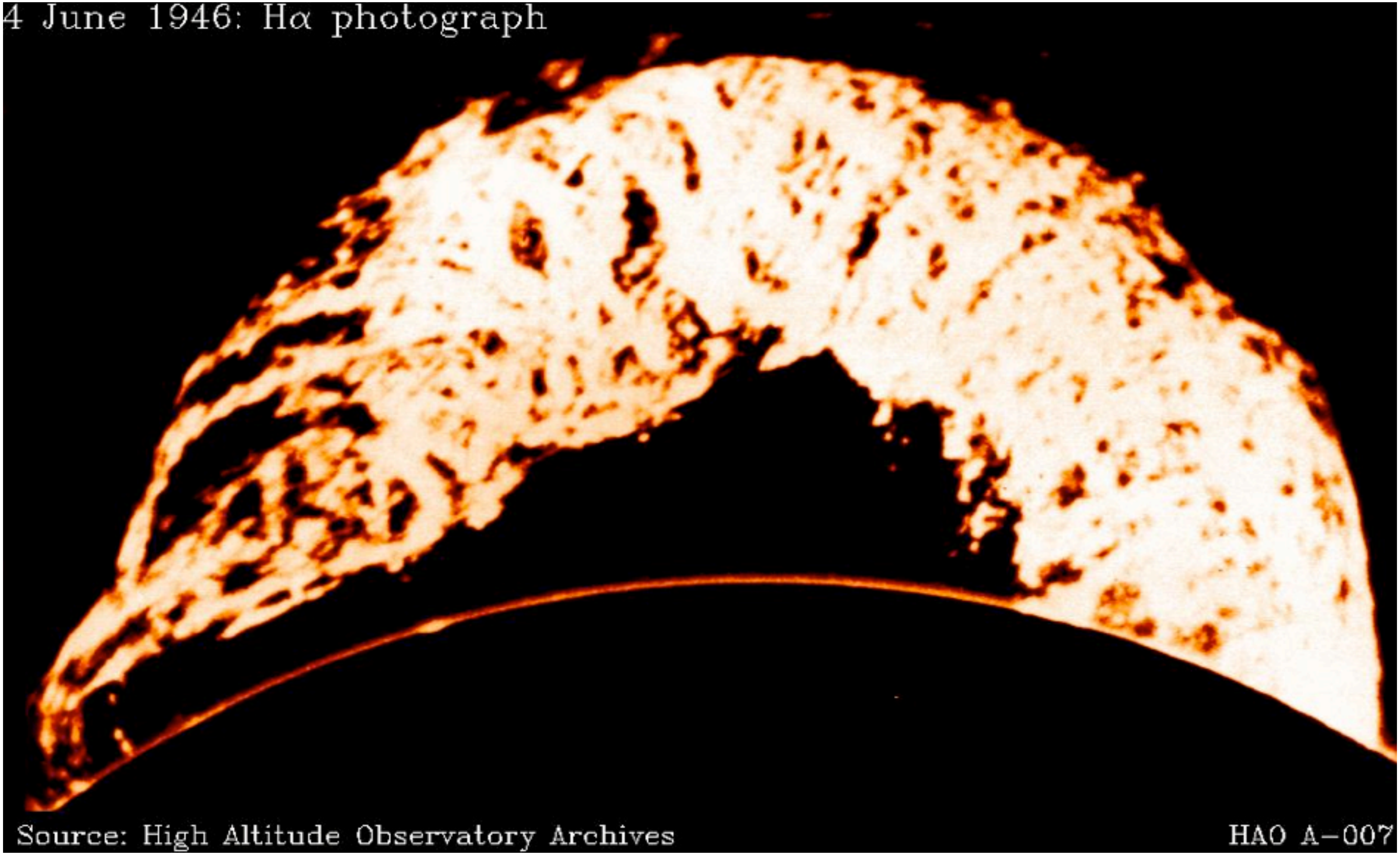
Fig. 36.



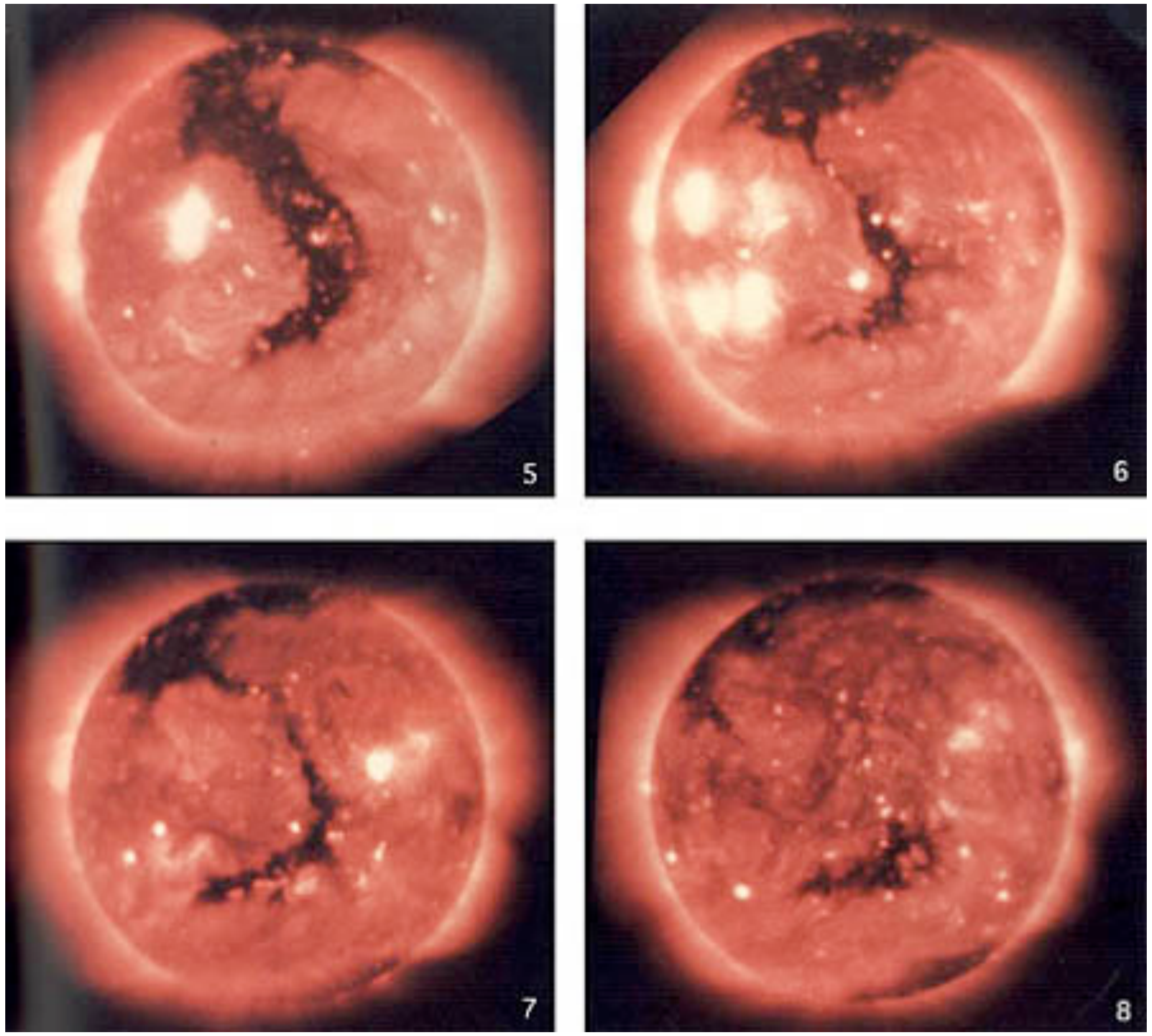
Magnetic Curves at Greenwich (August 3 and 5, 1872).

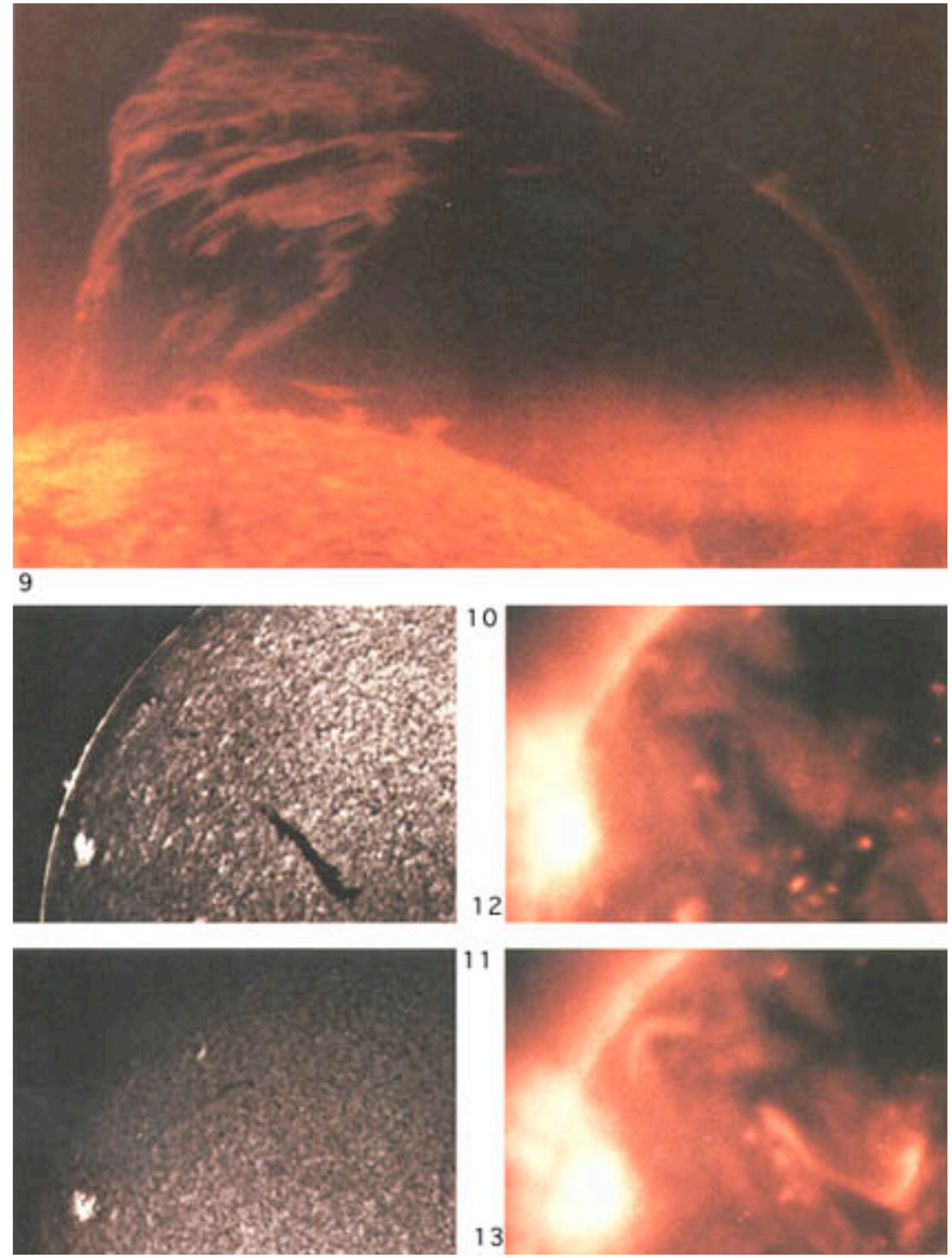
ser
ten
sto
mo
eve

HAO (Roberts)

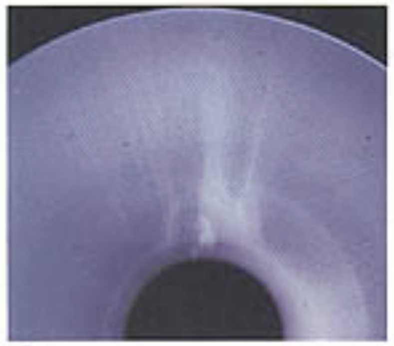

4 June 1946: Hα photograph
Source: High Altitude Observatory Archives
HAO A–007

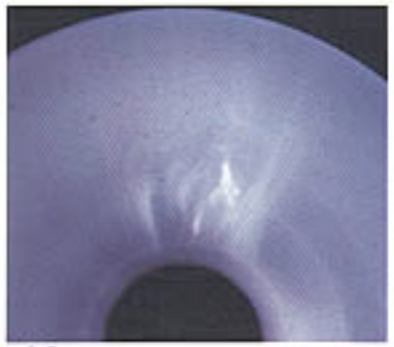
SKYLAB 1973



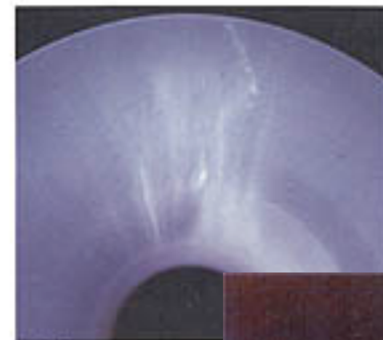


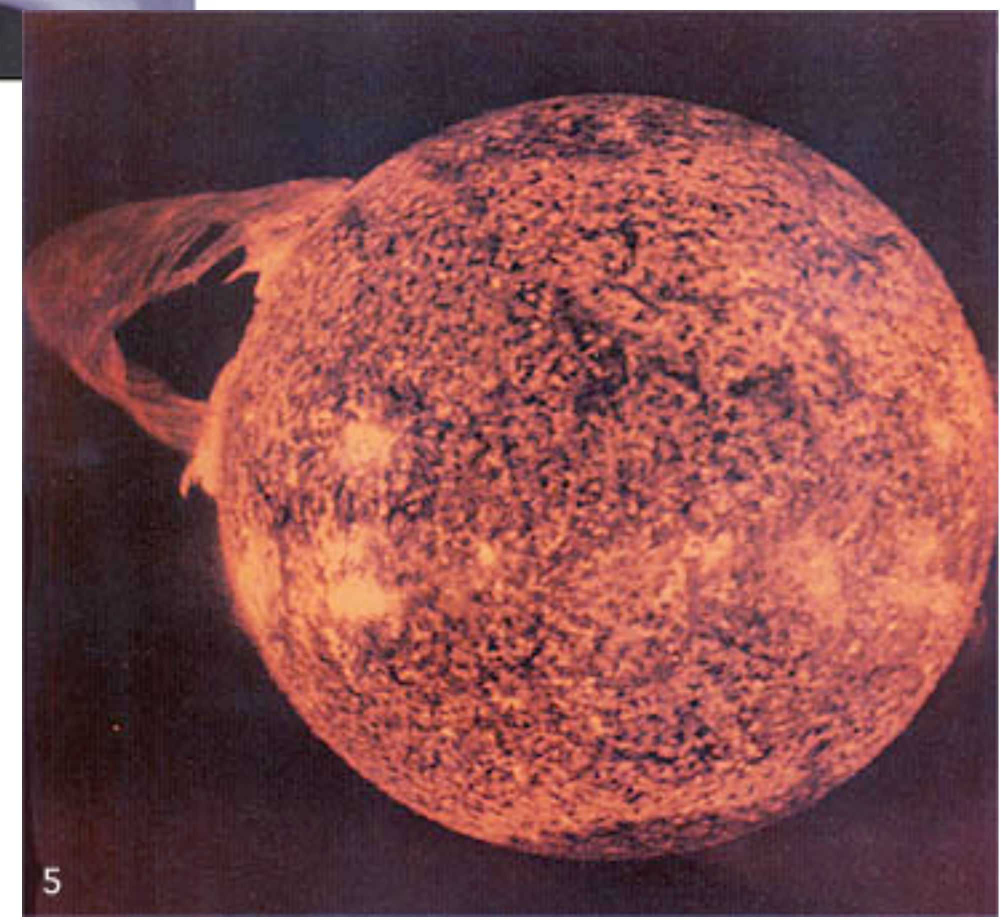
SKYLAB 1973

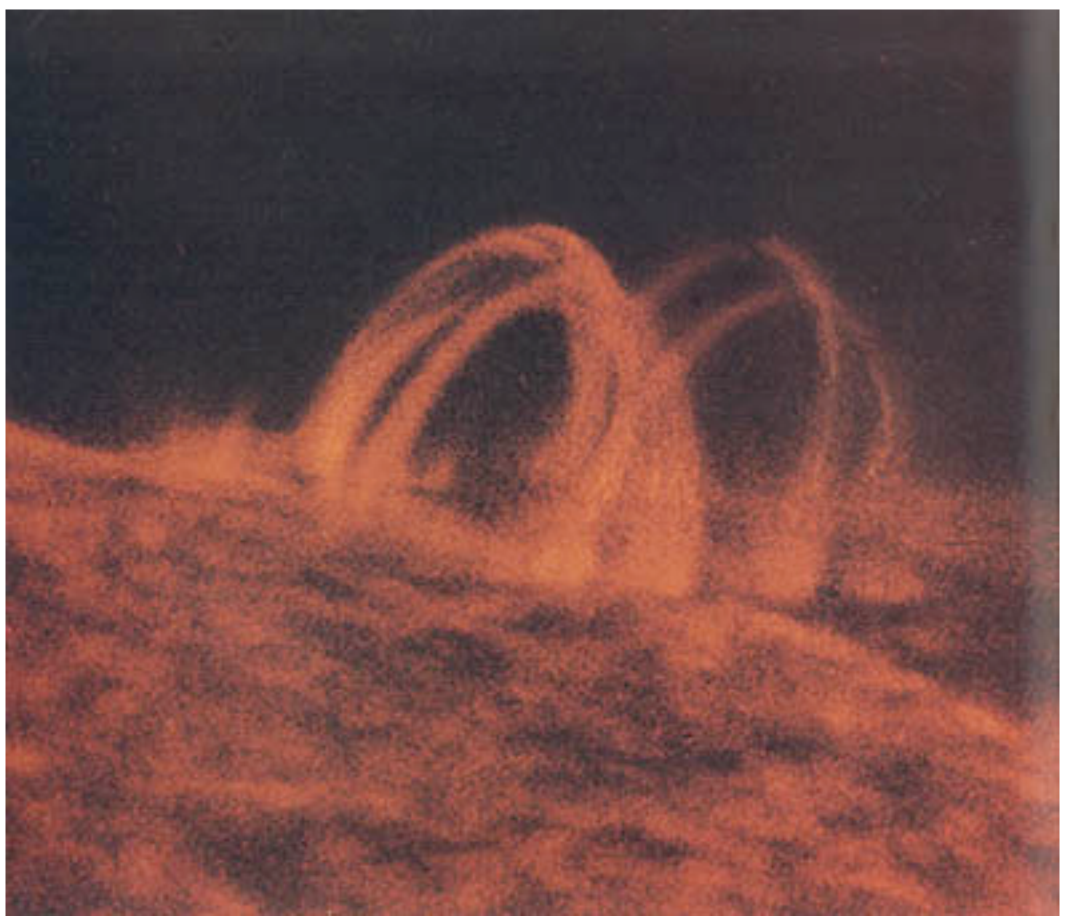

9


10

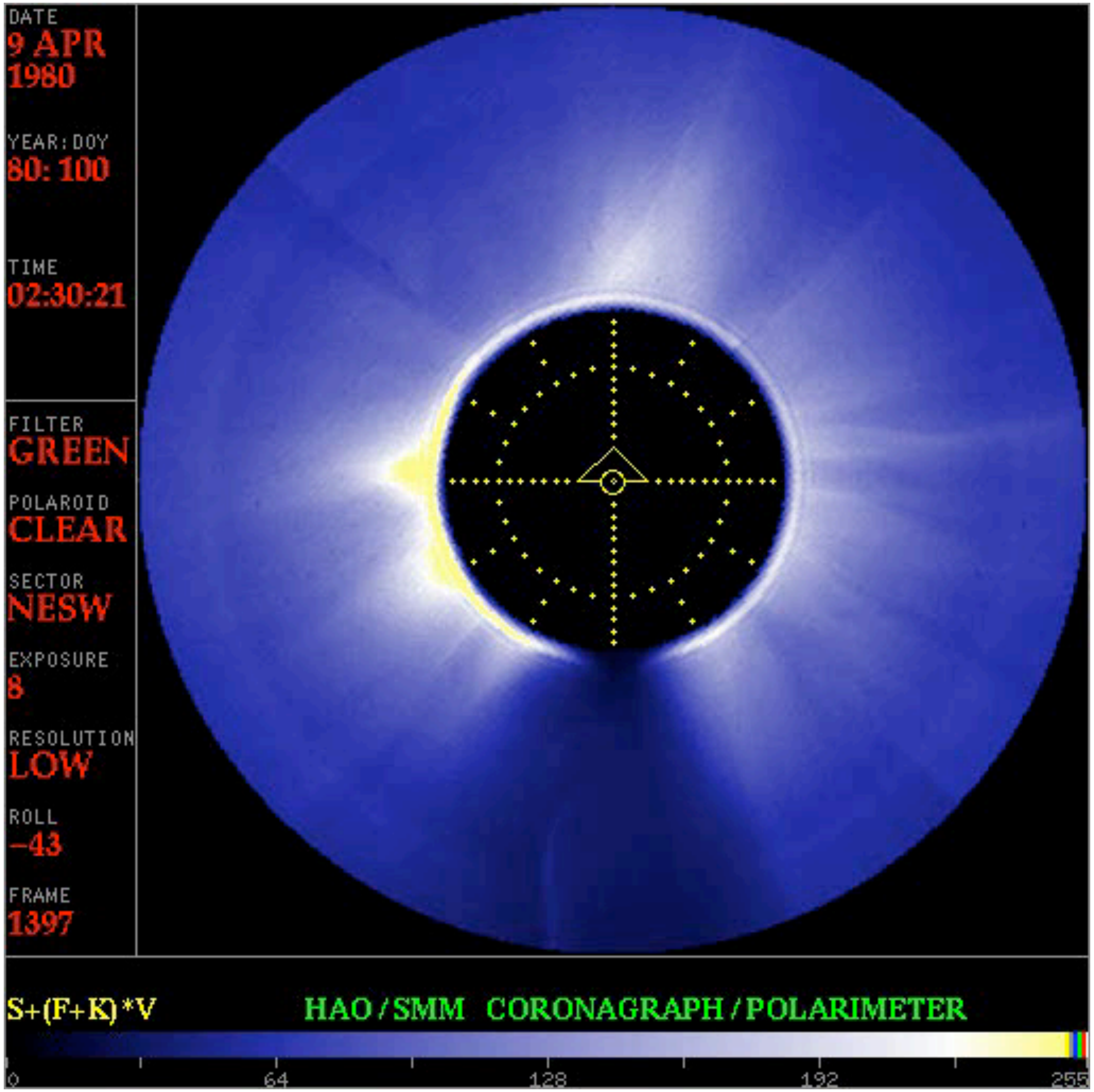

11


12



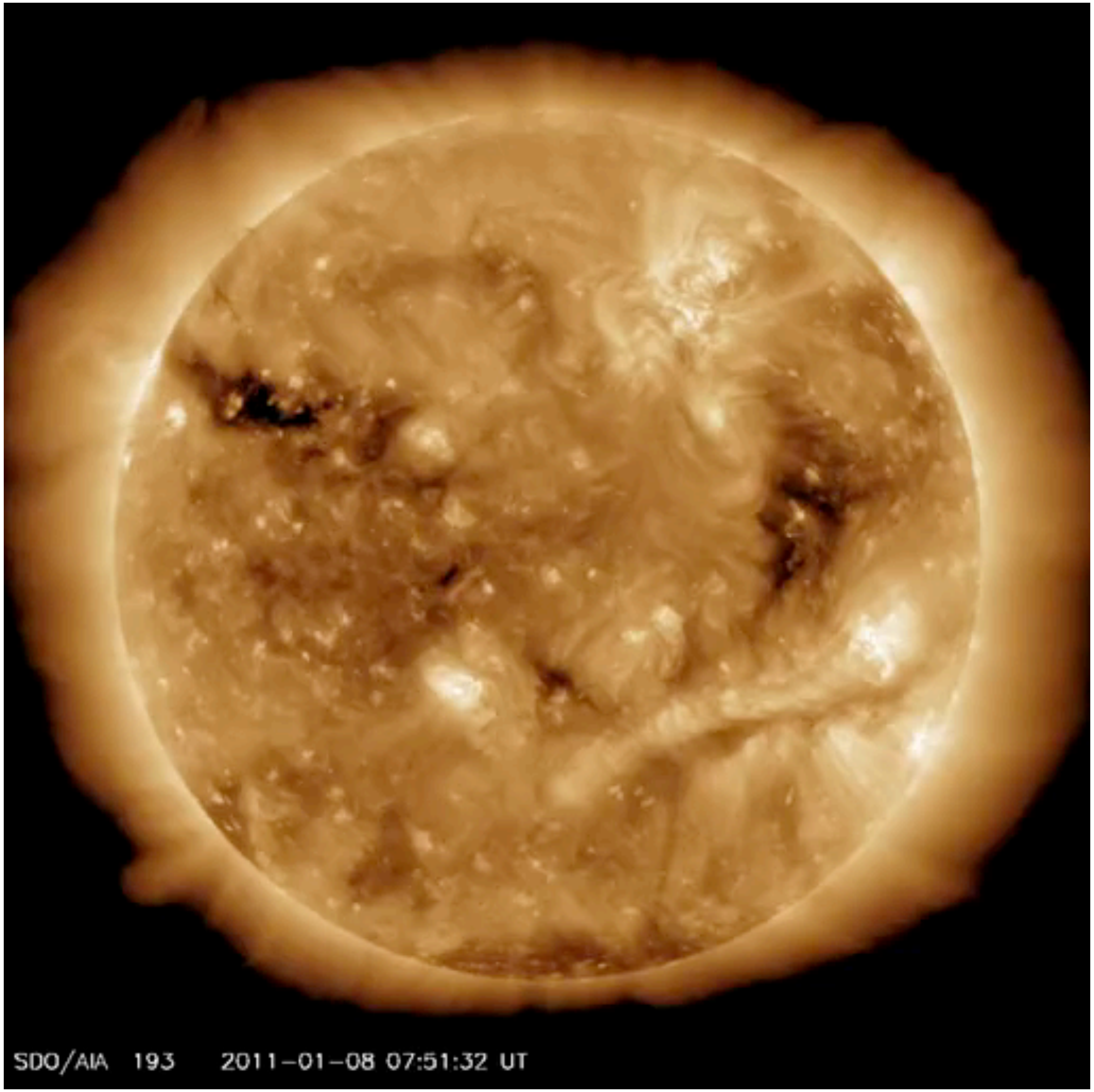


SMM April 1980

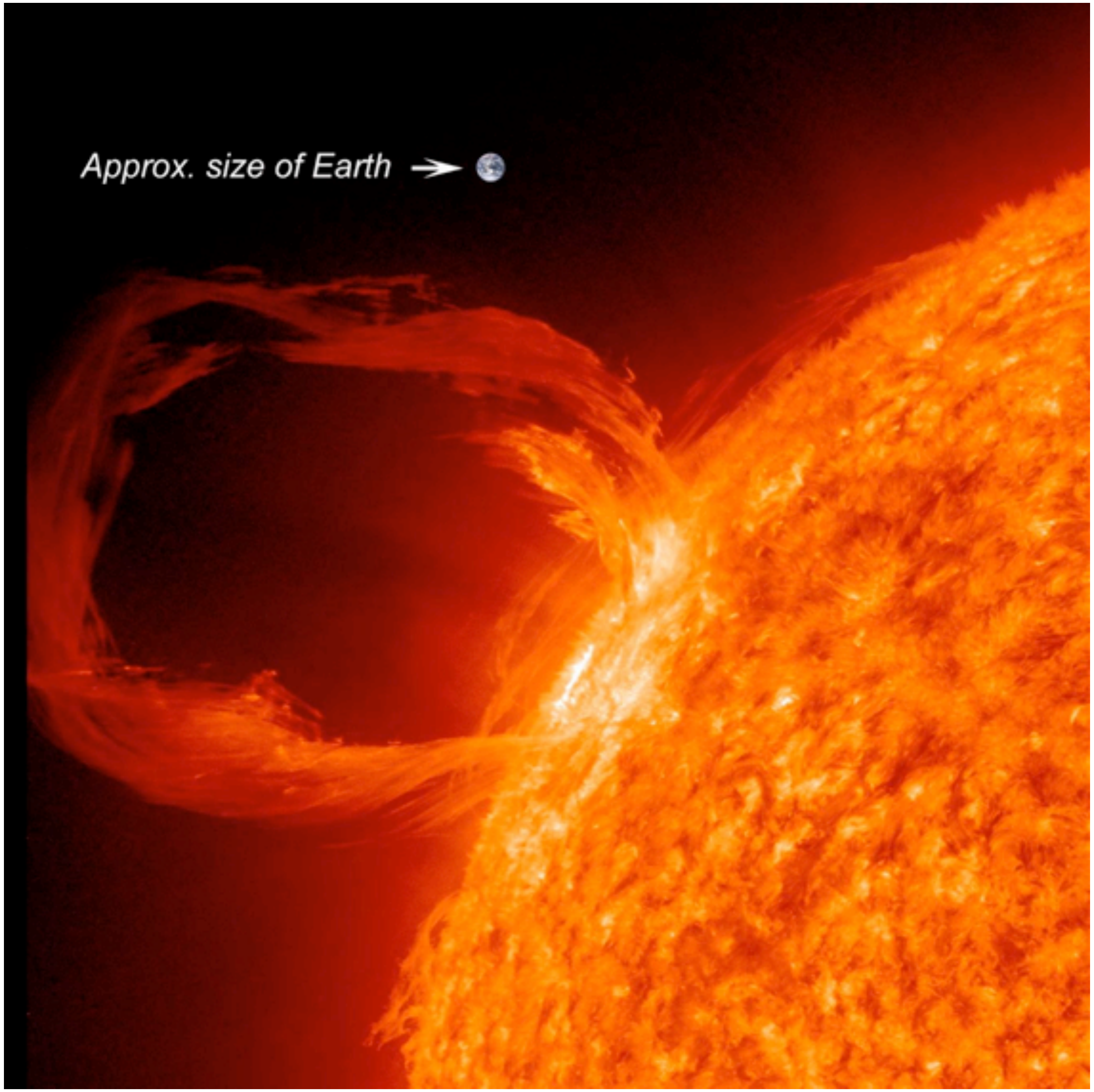


SOHO, TRACE, RHESSI
Flare Observations (April 22, 2002)

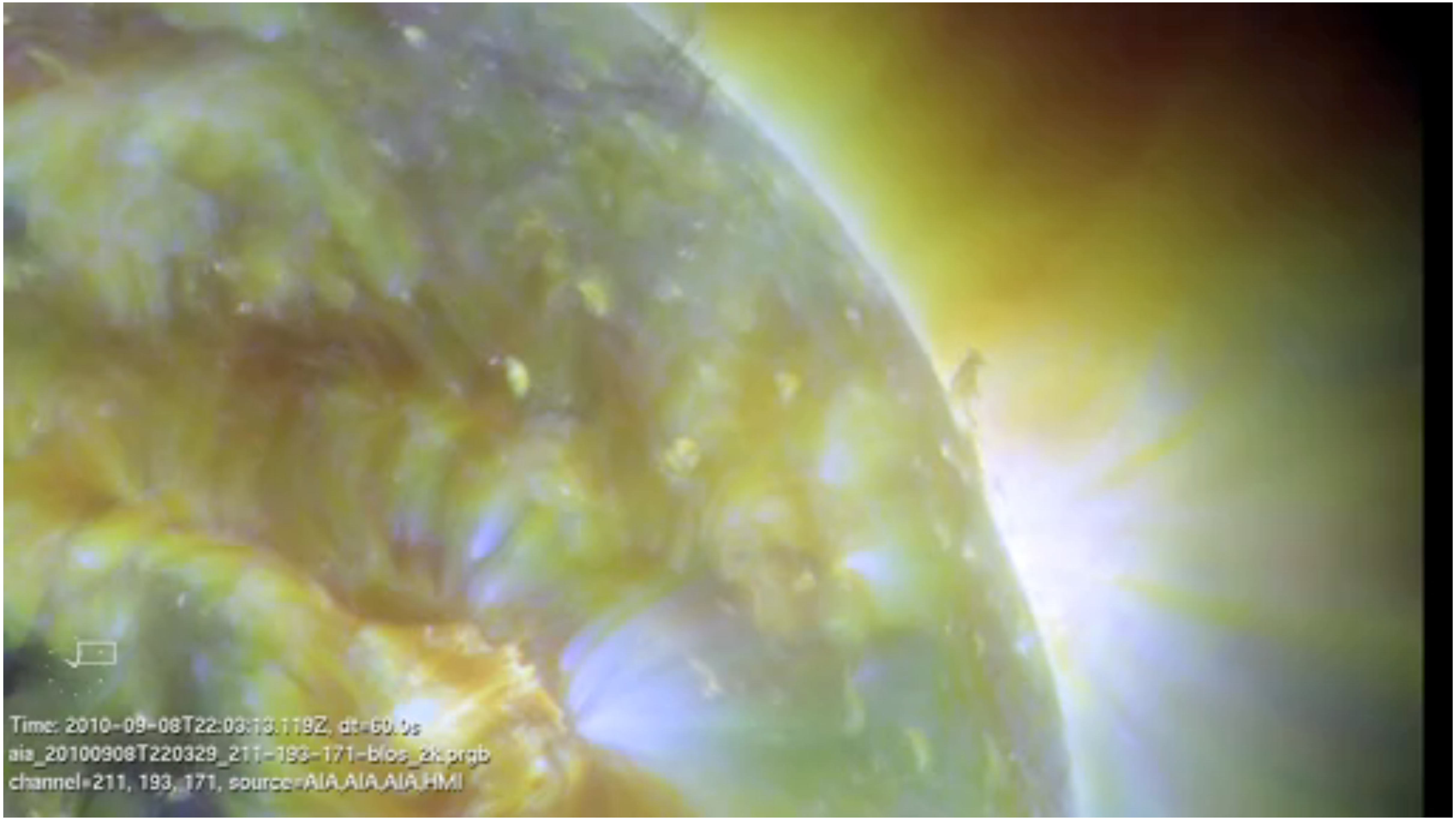
SDO



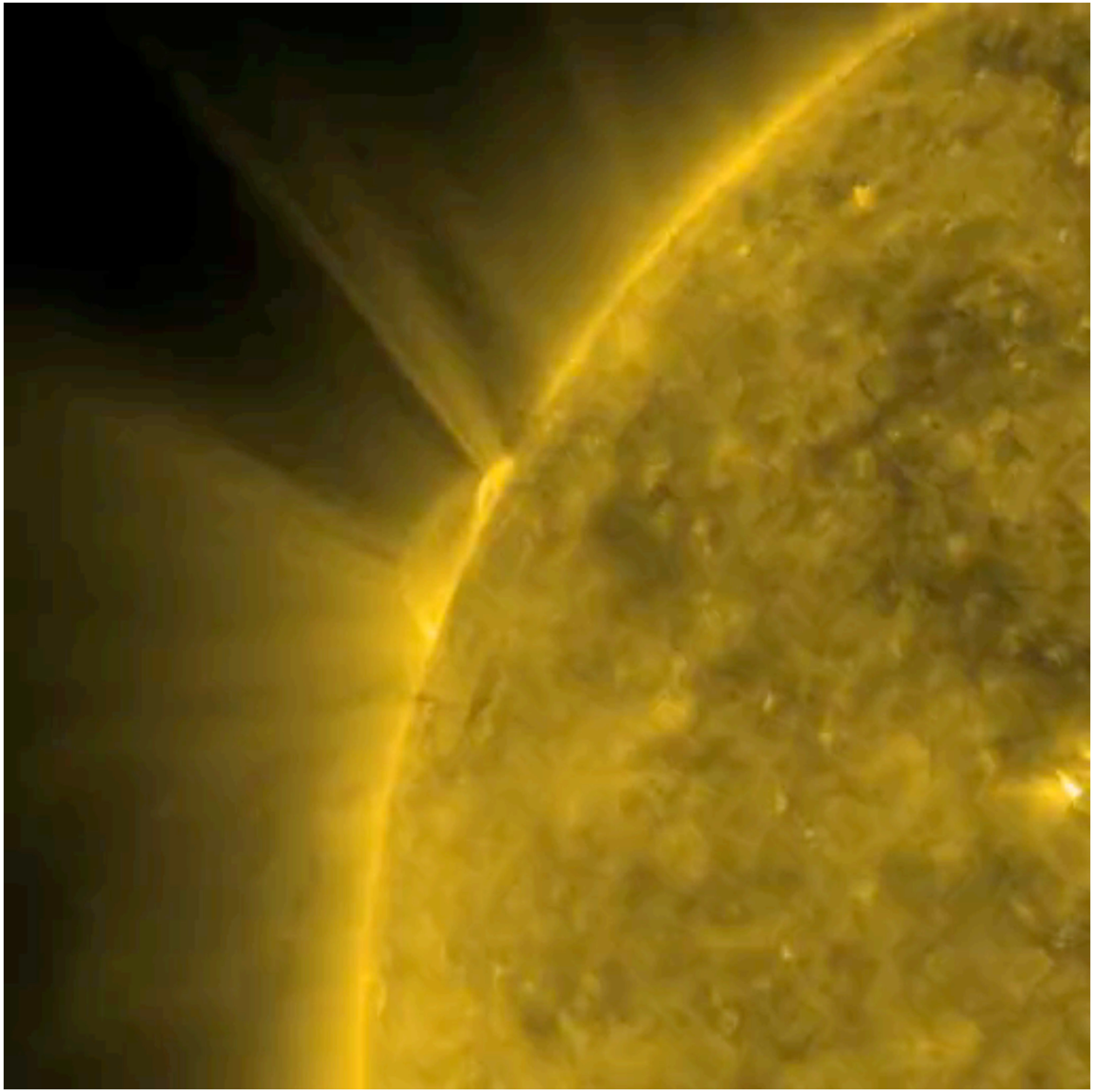
SDO



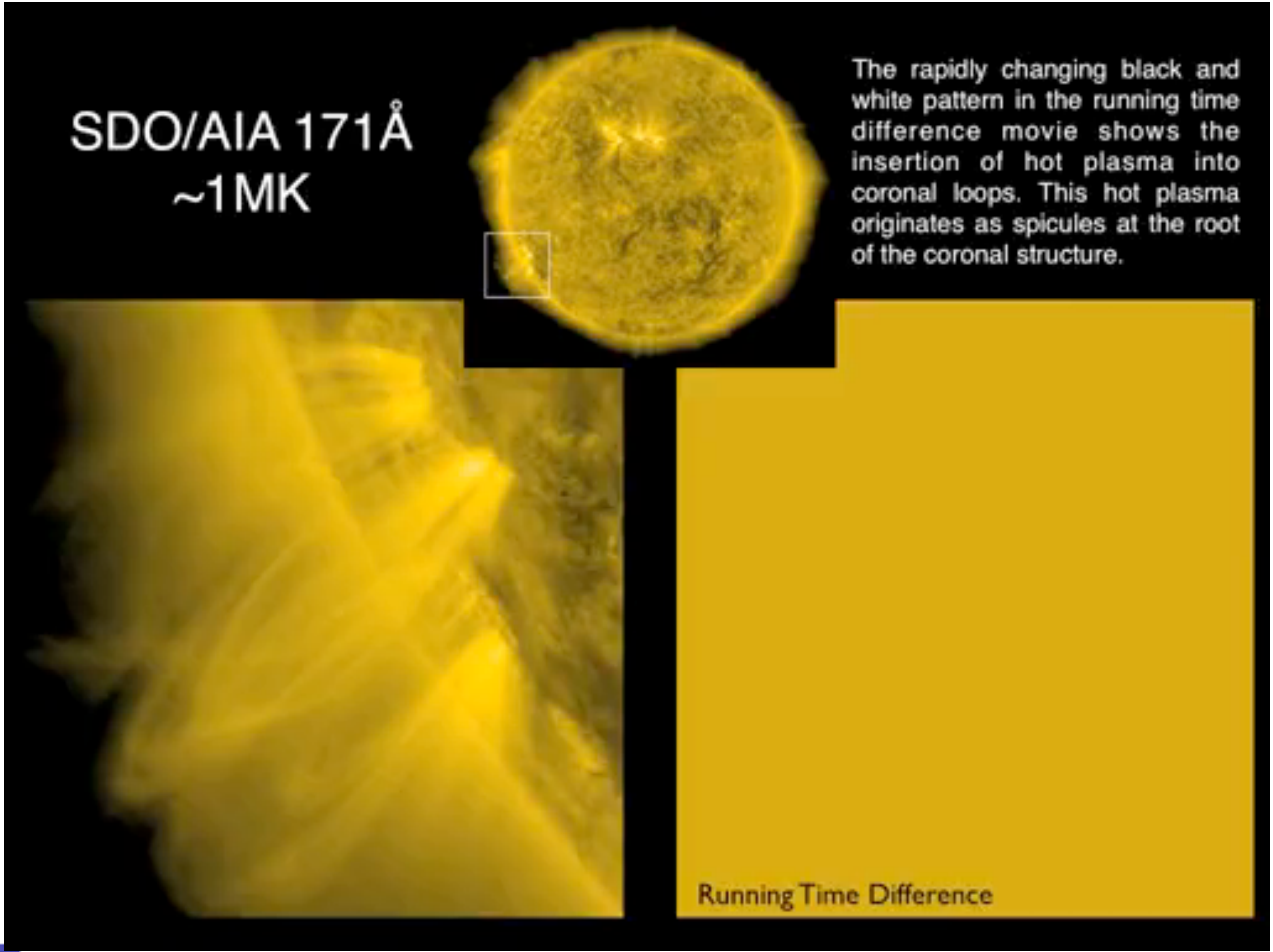
SDO


Time: 2010-09-08T22:03:13.119Z, dt=60.0s
aia_20100908T220329_211-193-171-blos_2k.prgb
channel=211, 193, 171, source=AIA,AIA,AIA,HMI

SDO



SDO


SDO/AIA 171Å
~1MK
The rapidly changing black and white pattern in the running time difference movie shows the insertion of hot plasma into coronal loops. This hot plasma originates as spicules at the root of the coronal structure.
Running Time Difference

An observation

- We have almost 40 years of spacecraft data. Why are we still arguing about the causes of
  - coronal dynamics, heating?
  - space weather?
  - variable UV radiation?
- I believe, in part, it is because we have become comfortable measuring just *effects:*
  - *density, abundance, temperature, velocity*
- It's time to measure *causes:*
  - *forces, free energy*
  - the magnetic free energy is a good place to start
- But, *if this were easy it would have been done decades ago*

Ansatz

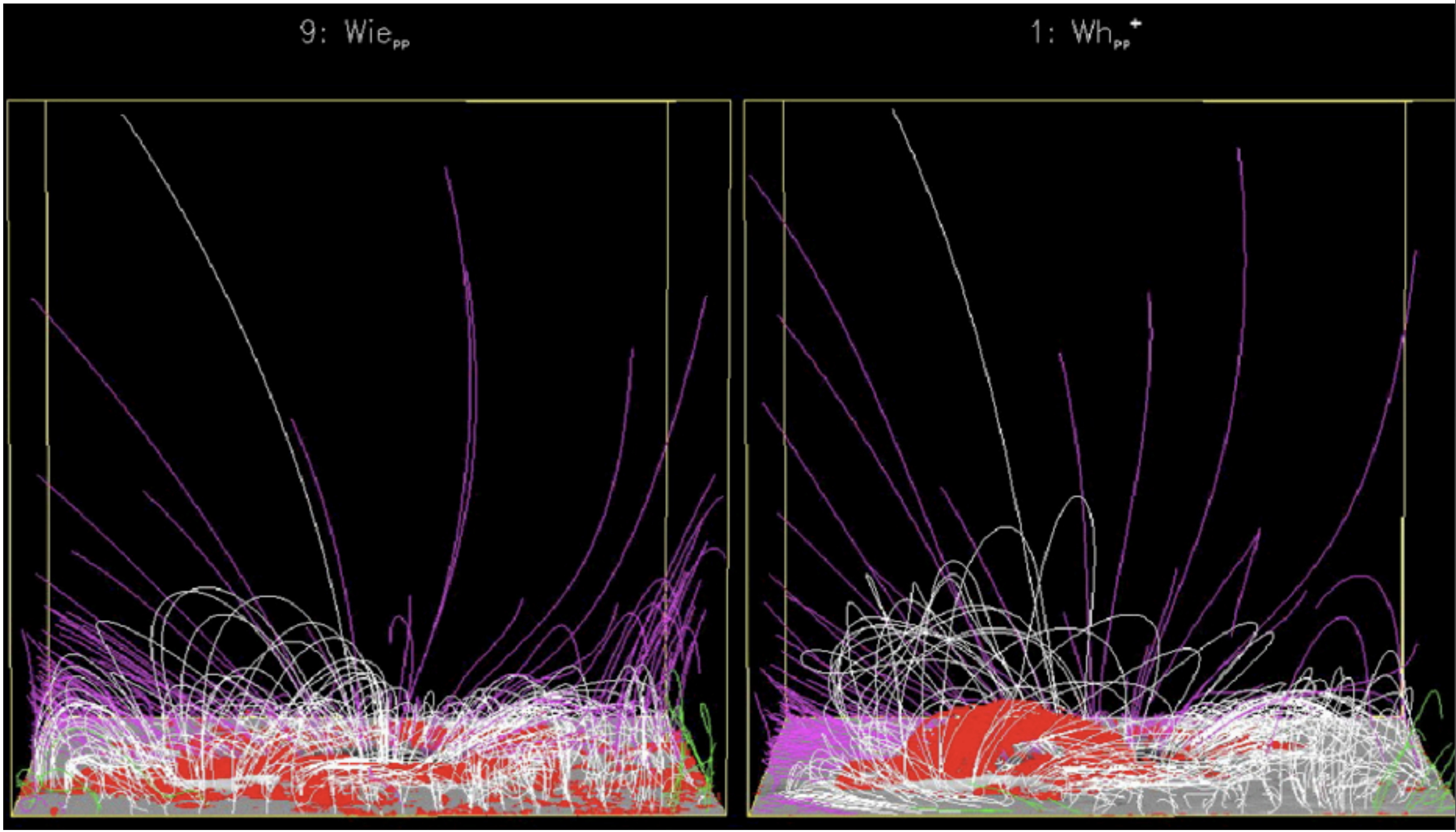
- Most "interesting" aspects of solar activity (heating, UV radiation, flares, loss of equilibrium) are related to
  - storage of magnetic free energy in low-β plasma
  - release of this energy on times as short as the Alfven crossing time
- This is because
  - flares, CMEs occur *fast and require a lot of energy*
  - low-β plasma occupies a large volume V, so $B^2/2\mu$ V can be large
  - low-β => fast Alfven speed
- Thus, we should try to measure the magnetic free energy within the corona

Difficulties and a path forward

- Free energy means-non potential fields
  - often free component << potential component
  - must measure vector field not just line-of sight
  - even in the photosphere, such work was not possible until 1980s
- Earlier work: extrapolate photospheric fields
  - essentially requires MHD, as fields are not force-free
  - force free extrapolations have essentially failed (Schrijver, de Rosa)
- A way forward:
  - measure vector fields at coronal base, top of active chromosphere
  - take advantage of a quirk of nature: He I 1083 nm multiplet
  - feasible (TIP- Solanki et al 2003, Casini, Centeno,...)
  - use MHD virial theorem and/or force-free extrapolations

nlff field extrapolation (Schrijver et al 2008)

red:
current



new chromospheric **B** constraints (including e.g., just fibrils) can provide boundary conditions compatible with the calculations let us recall the virial result of Chandrasekhar (1961):

$$\int_V \boldsymbol{r} \cdot [(\nabla \times \boldsymbol{B}) \times \boldsymbol{B}] dV = \int_V \tfrac{1}{2} B^2 \, dV + \int_{\partial V} [(\boldsymbol{B} \cdot \boldsymbol{r})\boldsymbol{B} - \tfrac{1}{2} B^2 \boldsymbol{r}] \cdot d\boldsymbol{s} \,, \quad (22)$$

given in standard notation. If the field $\boldsymbol{B}$ is force-free in a volume V, the left-hand side vanishes and the total energy is determined uniquely by the surface vector field, let us recall the virial result of Chandrasekhar (1961):

$$\int_V \boldsymbol{r} \cdot [(\nabla \times \boldsymbol{B}) \times \boldsymbol{B}] dV$$

$$= \int_V \tfrac{1}{2} B^2 \, dV + \int_{\partial V} [(\boldsymbol{B} \cdot \boldsymbol{r})\boldsymbol{B} - \tfrac{1}{2} B^2 \boldsymbol{r}] \cdot d\boldsymbol{s} \,, \quad (22)$$

given in standard notation. If the field $\boldsymbol{B}$ is force-free in a volume V, the left-hand side vanishes and the total energy is determined uniquely by the surface vector field,

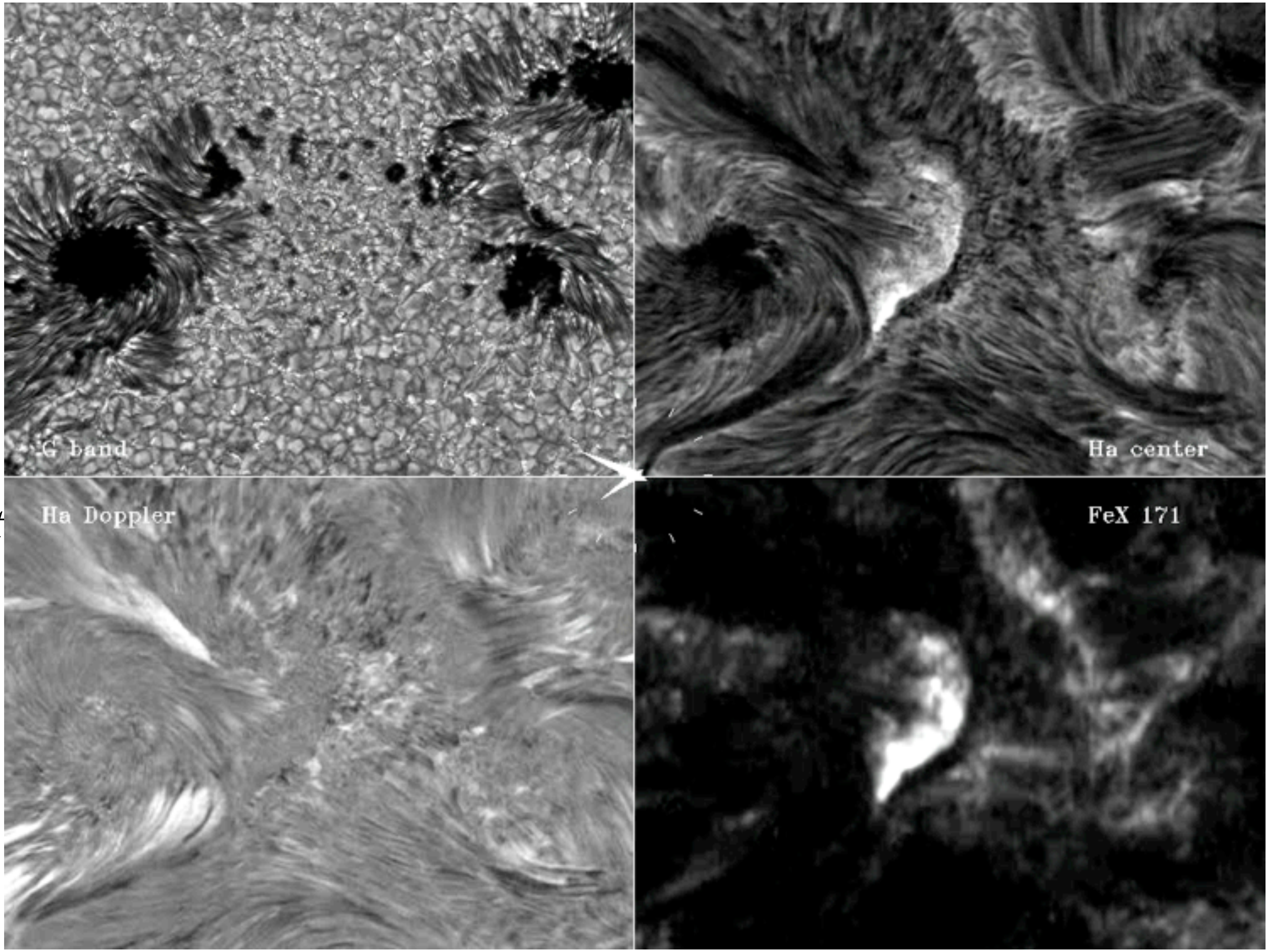
Coronal magnetic free energy can be derived from measurements of magnetic fields at the boundaries, under force-free conditions

The active chromosphere is in a low beta state, more like the corona than the photosphere

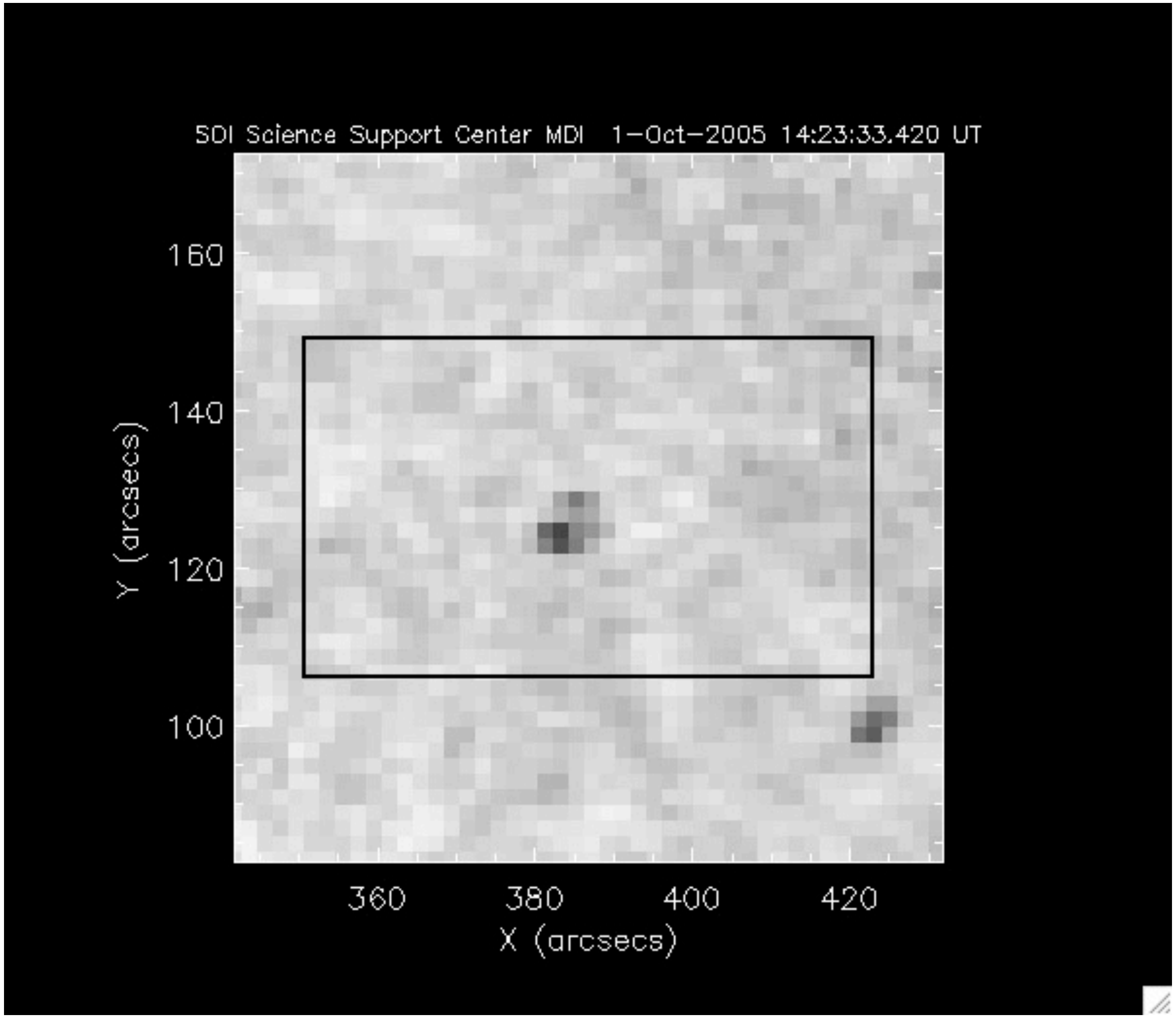
DOT and TRACE: 9 Jul 2005
(A.G. de Wijn, R. J. Rutten)

photosphere
chromosphere
corona

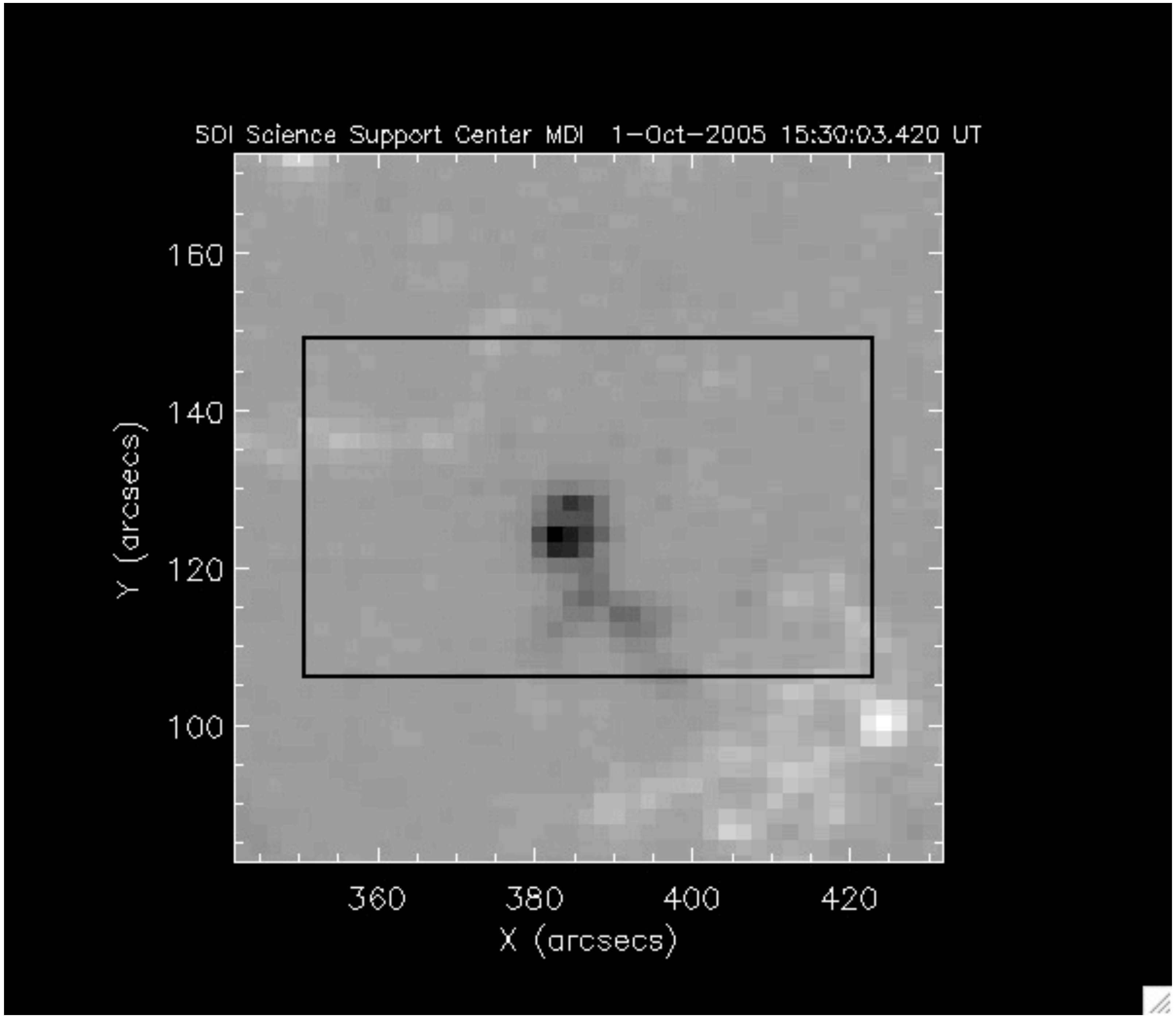
coronal structure is already present in the chromosphere



Small AR, pores

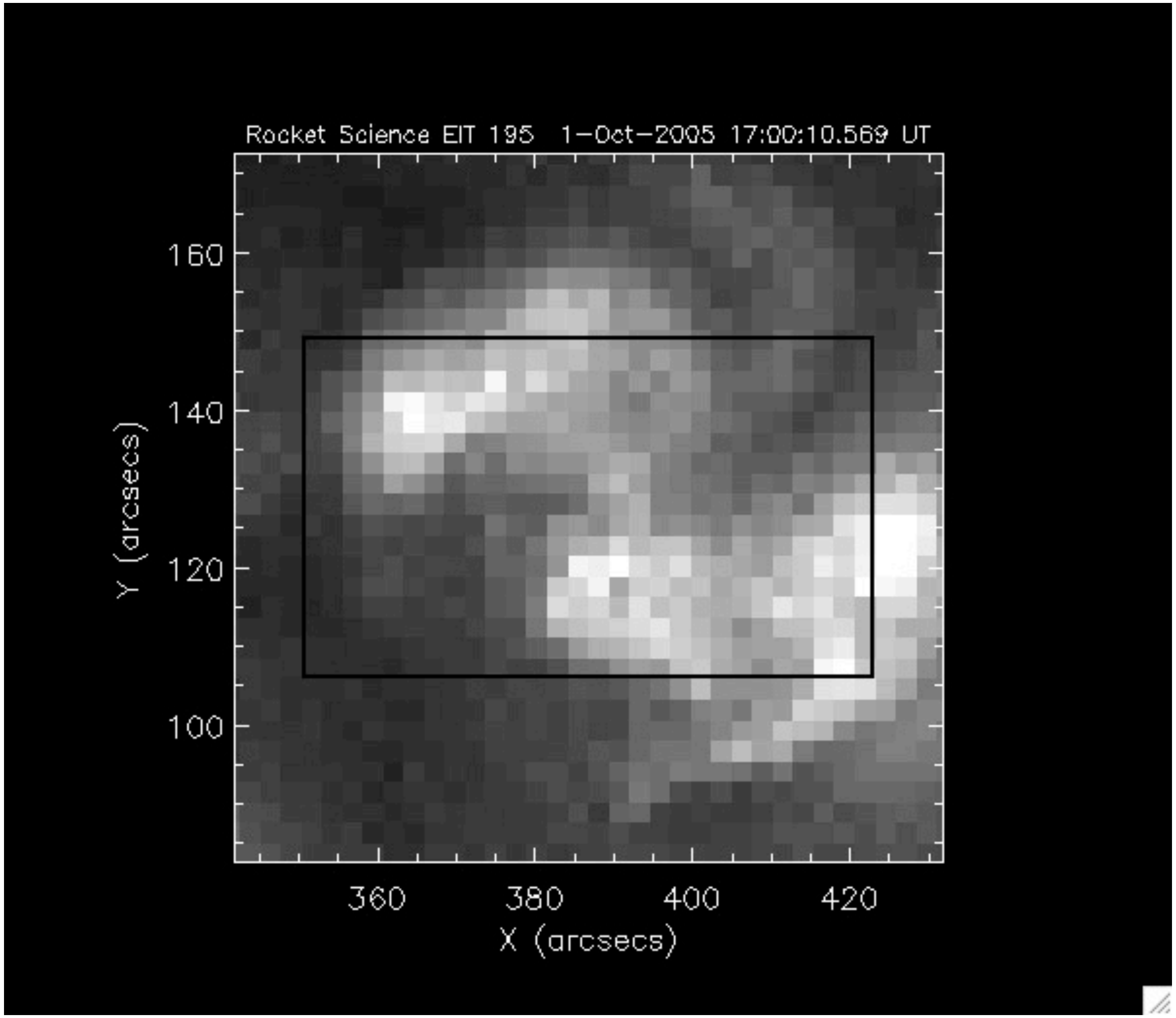


Small AR, pores



Small AR, pores

Small AR, pores



Chromosphere as seen with IBIS

- Ca II 854.2 nm
- samples many pressure scale heights
- high resolution
  - resolution ≈ 0.3” (DST limit 0.24”)

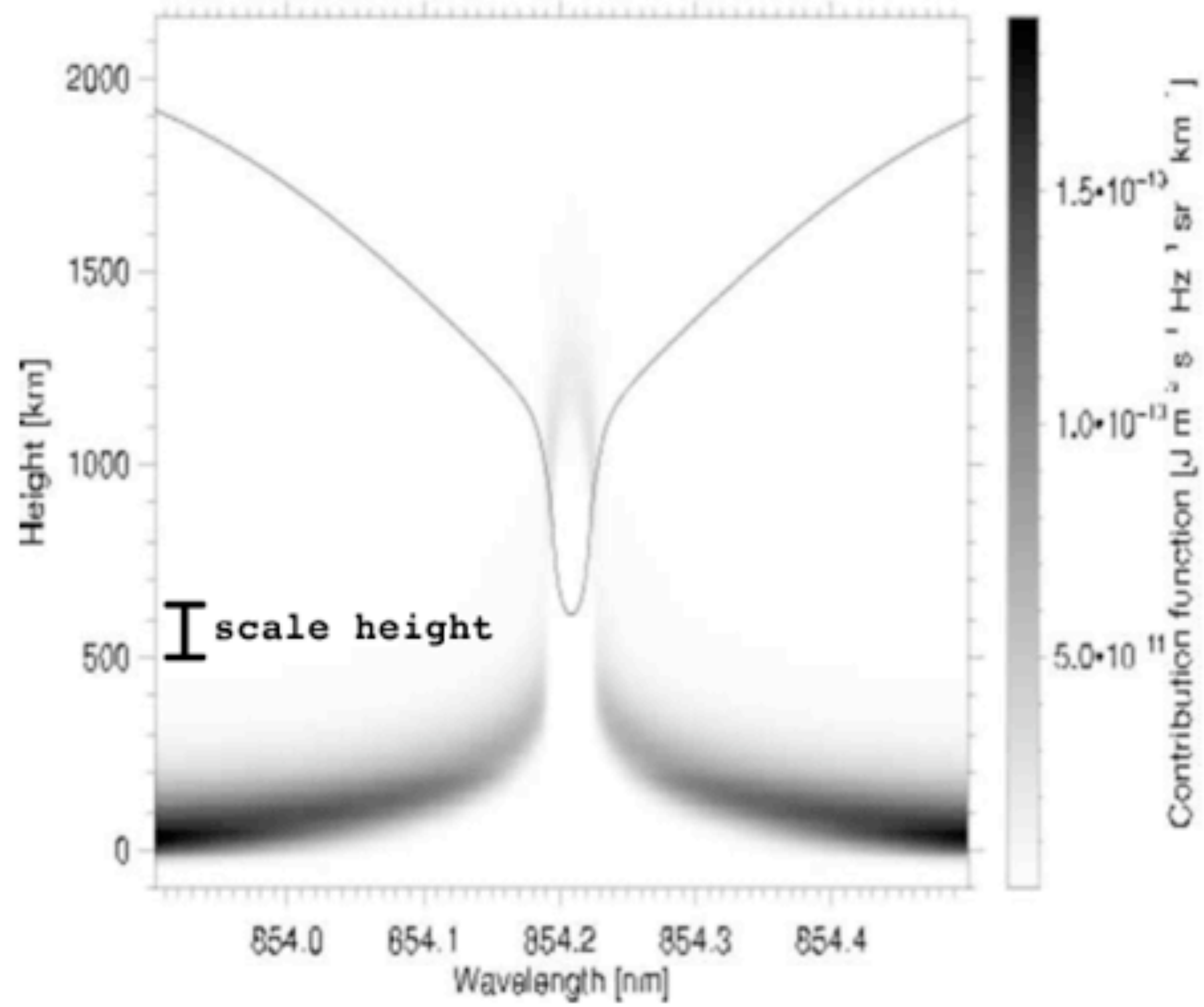


Fig. 5. Contribution function for Ca II 8542 computed in plane-parallel, hydro-static average quiet-Sun atmosphere (Fontenla et al. 1993). Height zero refers to level at which optical depth in the continuum at 500 nm is unity.

G. Cauzzi et al 2008, A+A

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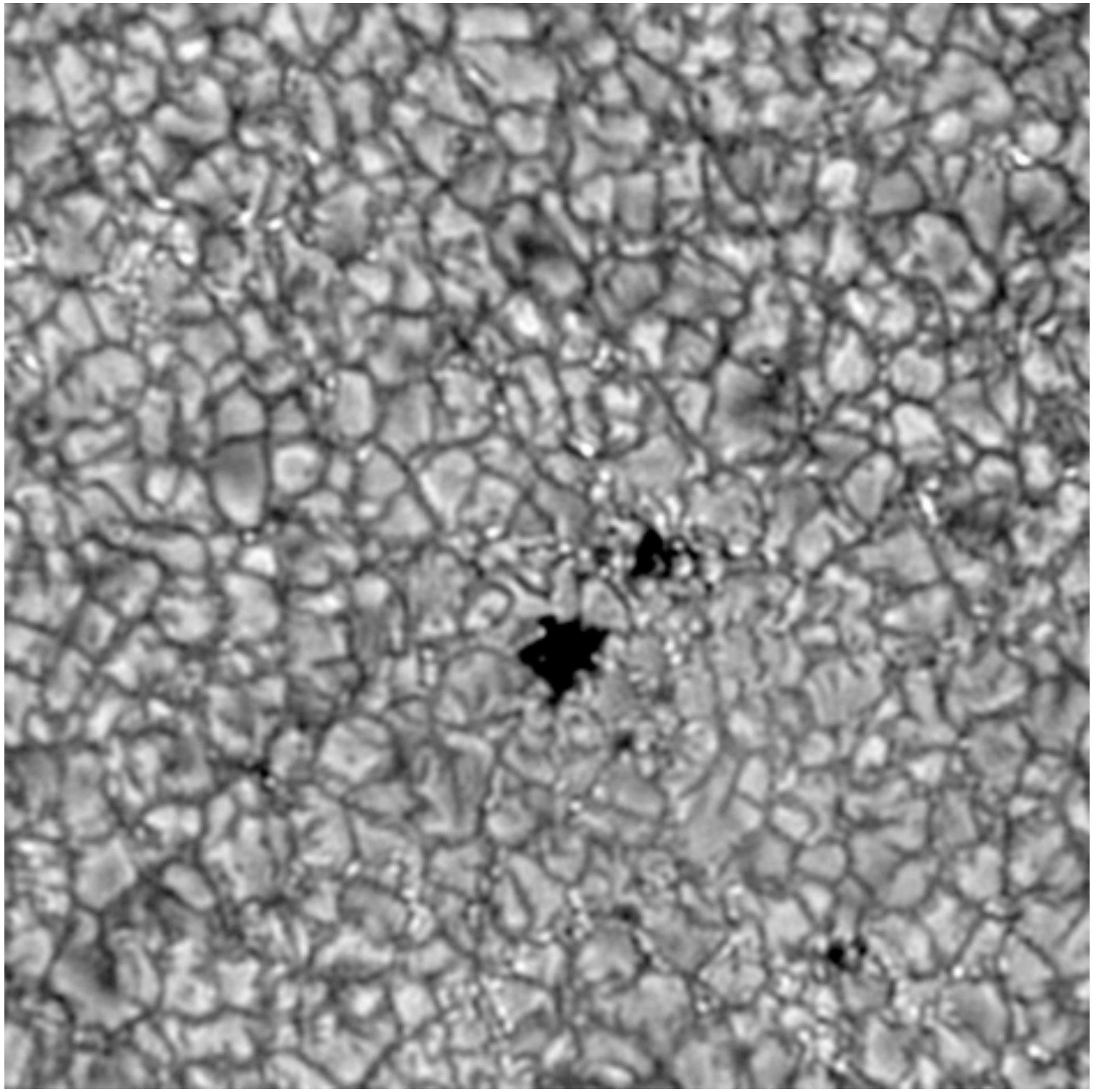
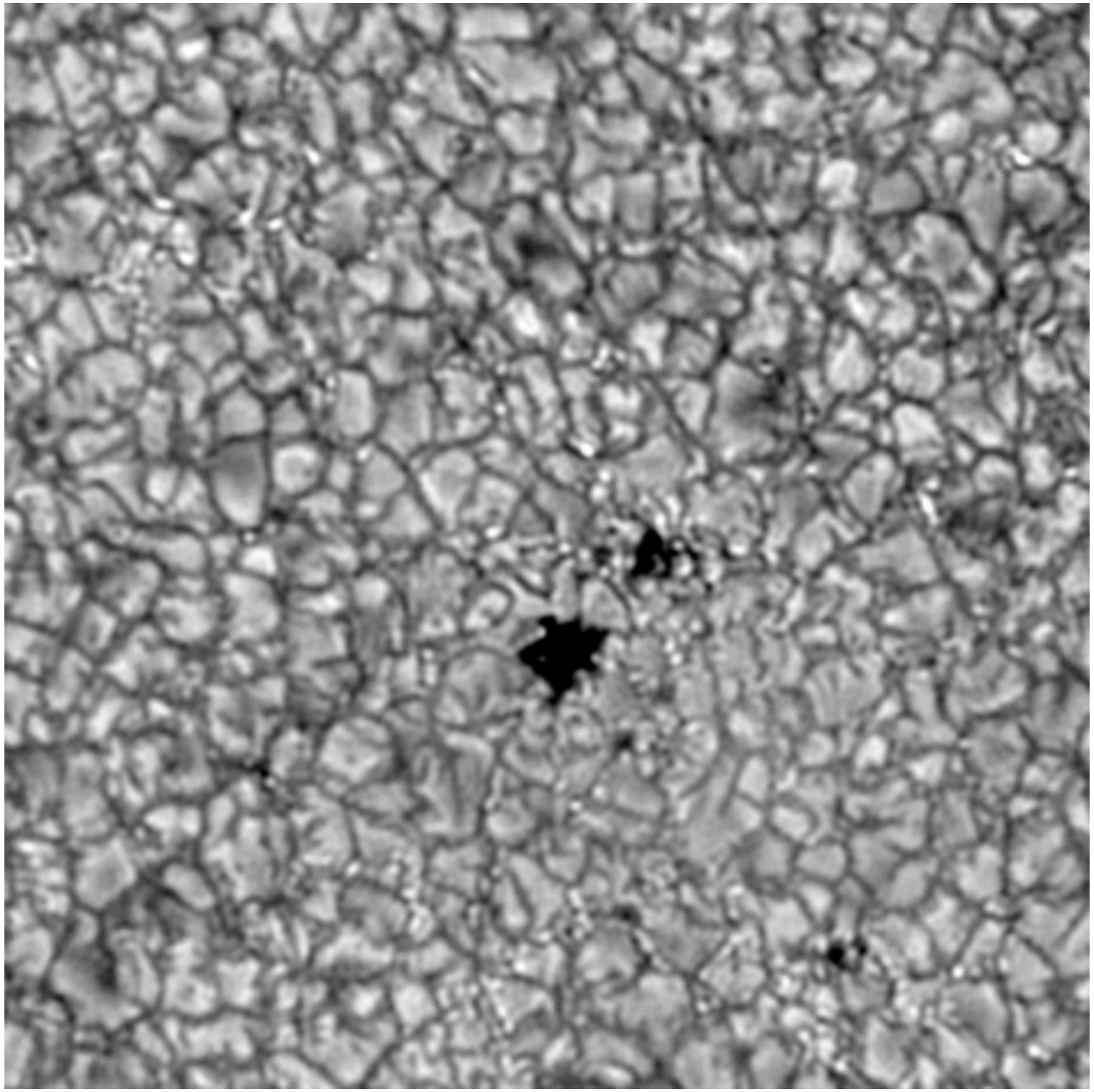


G. Cauzzi et al 2008, A+A

Chromosphere as seen with IBIS

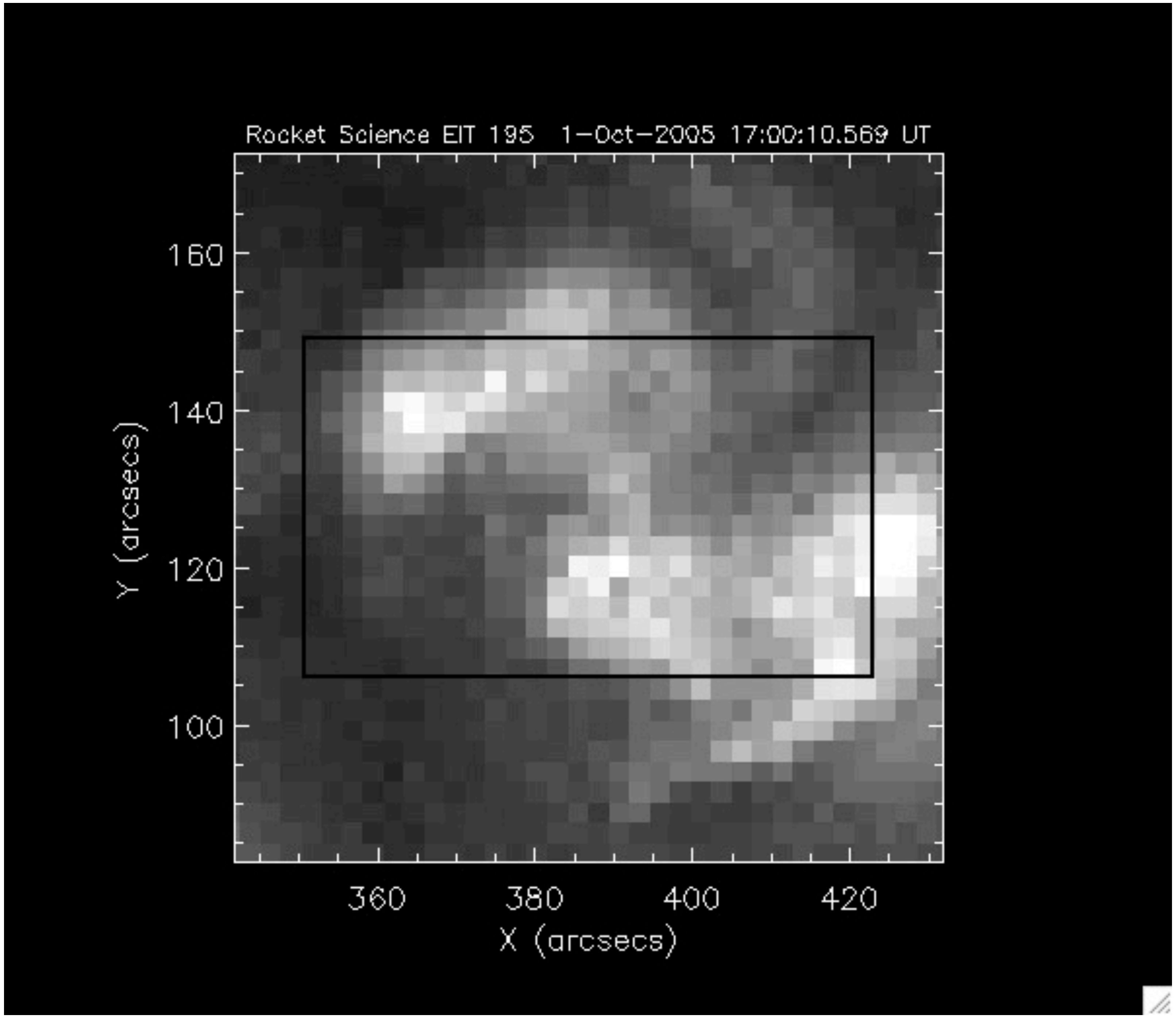
- Ca II 854.2 nm
- samples many pressure scale heights
- high resolution
  - resolution ≈ 0.3” (DST limit 0.24”)

again, base of corona is very different from photosphere



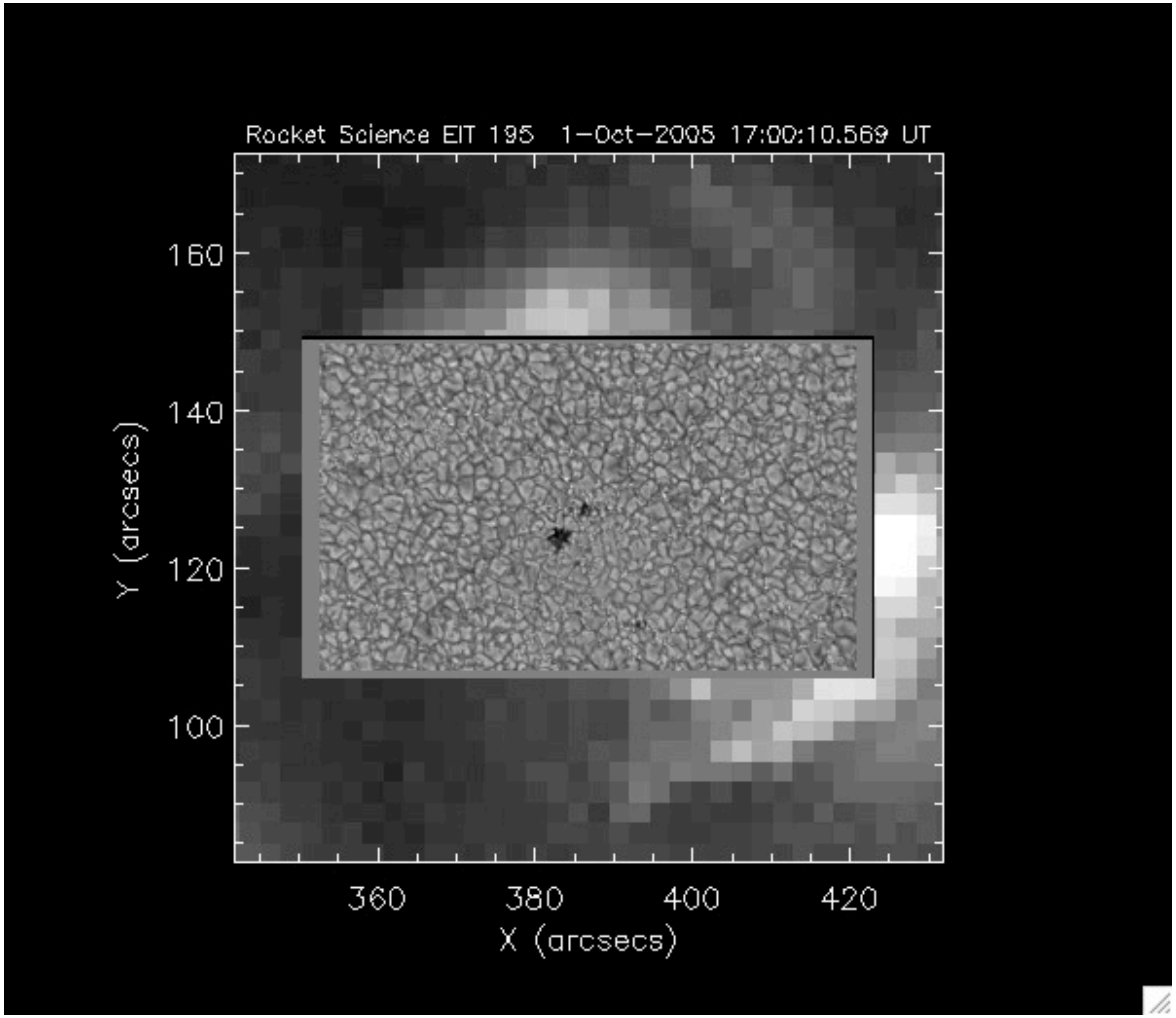
G. Cauzzi et al 2008, A+A

Small AR, pores: including the chromosphere



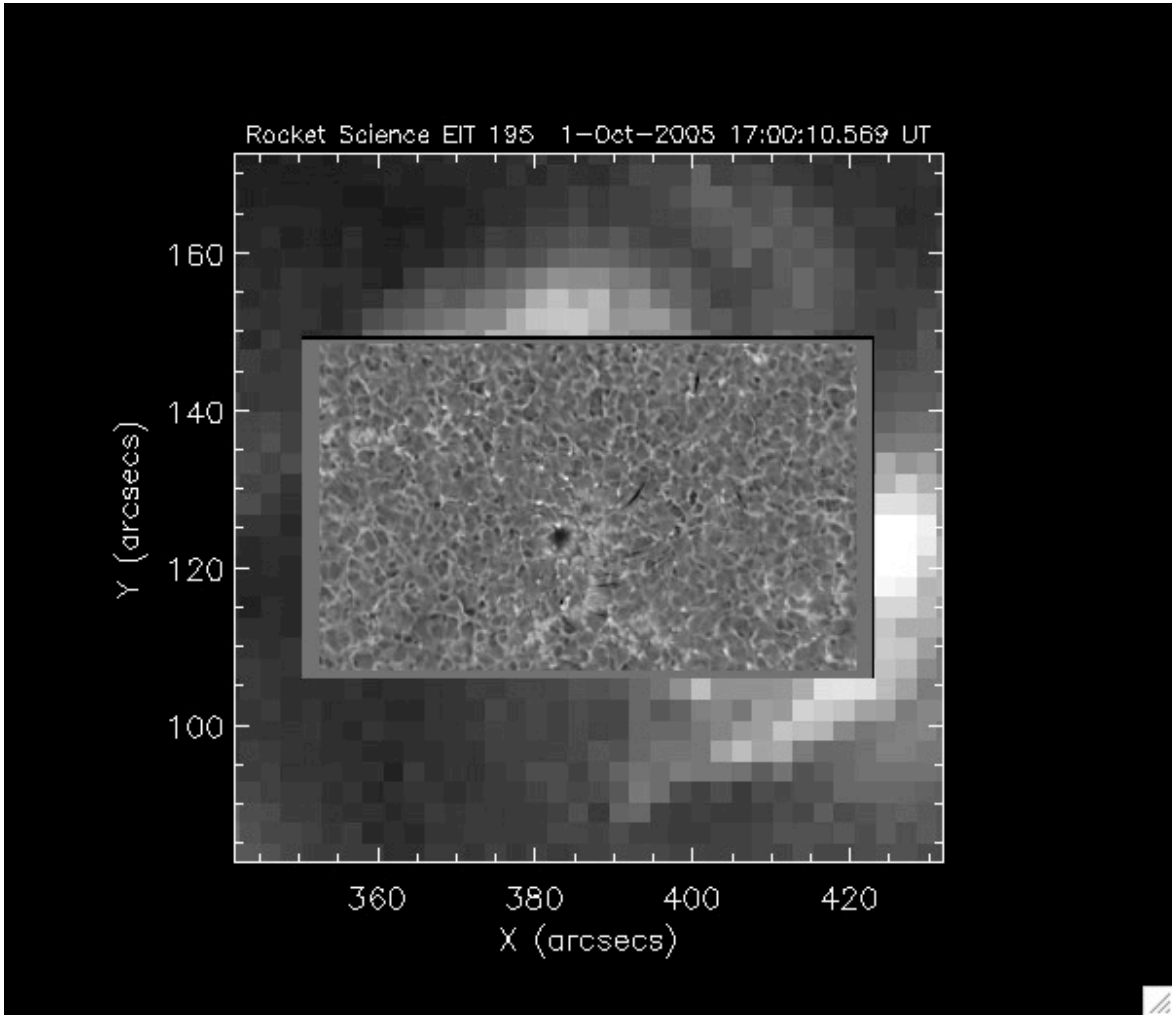
detailed study of IBIS data: G. Cauzzi et al 2008, A+A

Small AR, pores: including the chromosphere



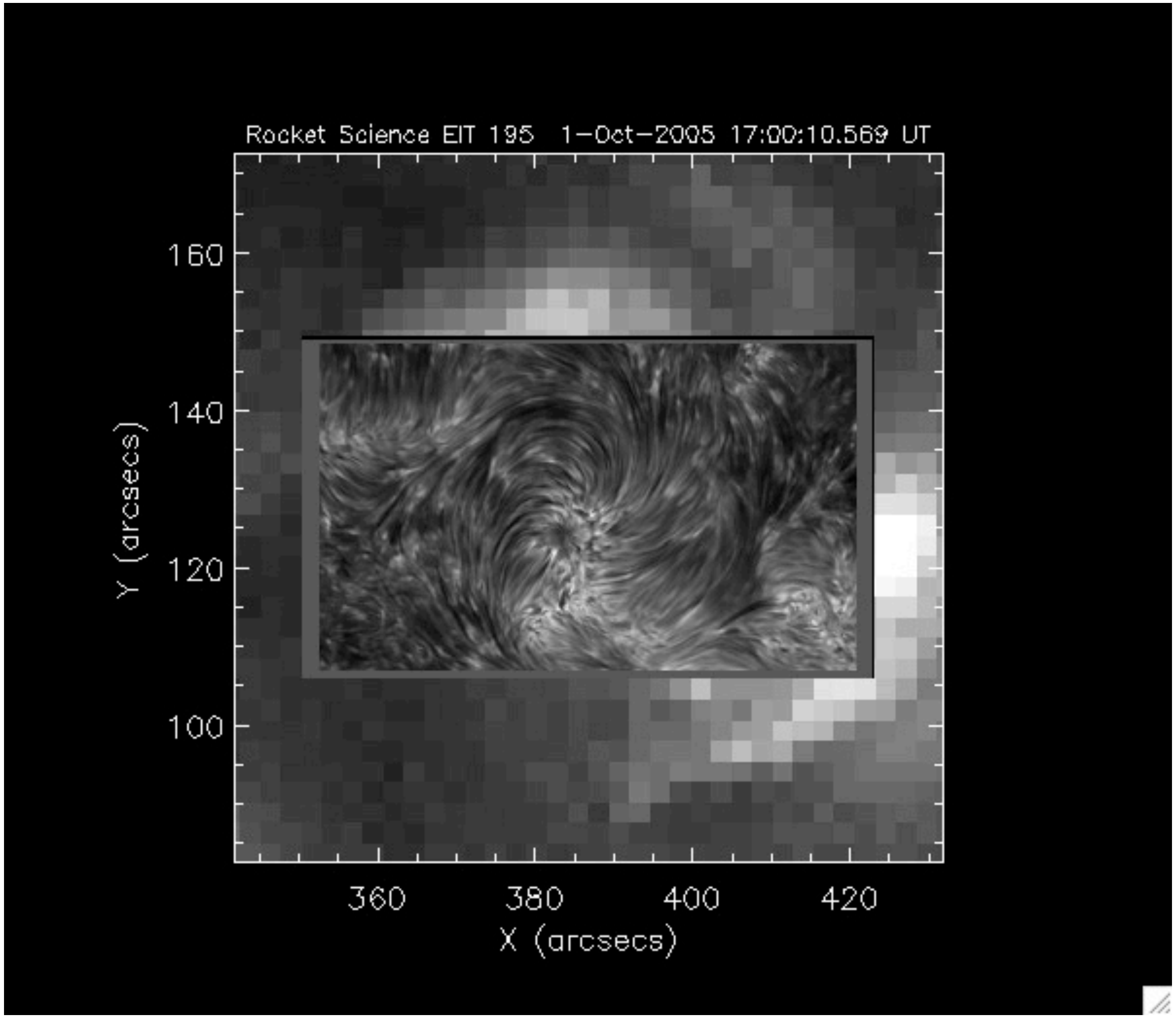
detailed study of IBIS data: G. Cauzzi et al 2008, A+A

Small AR, pores: including the chromosphere



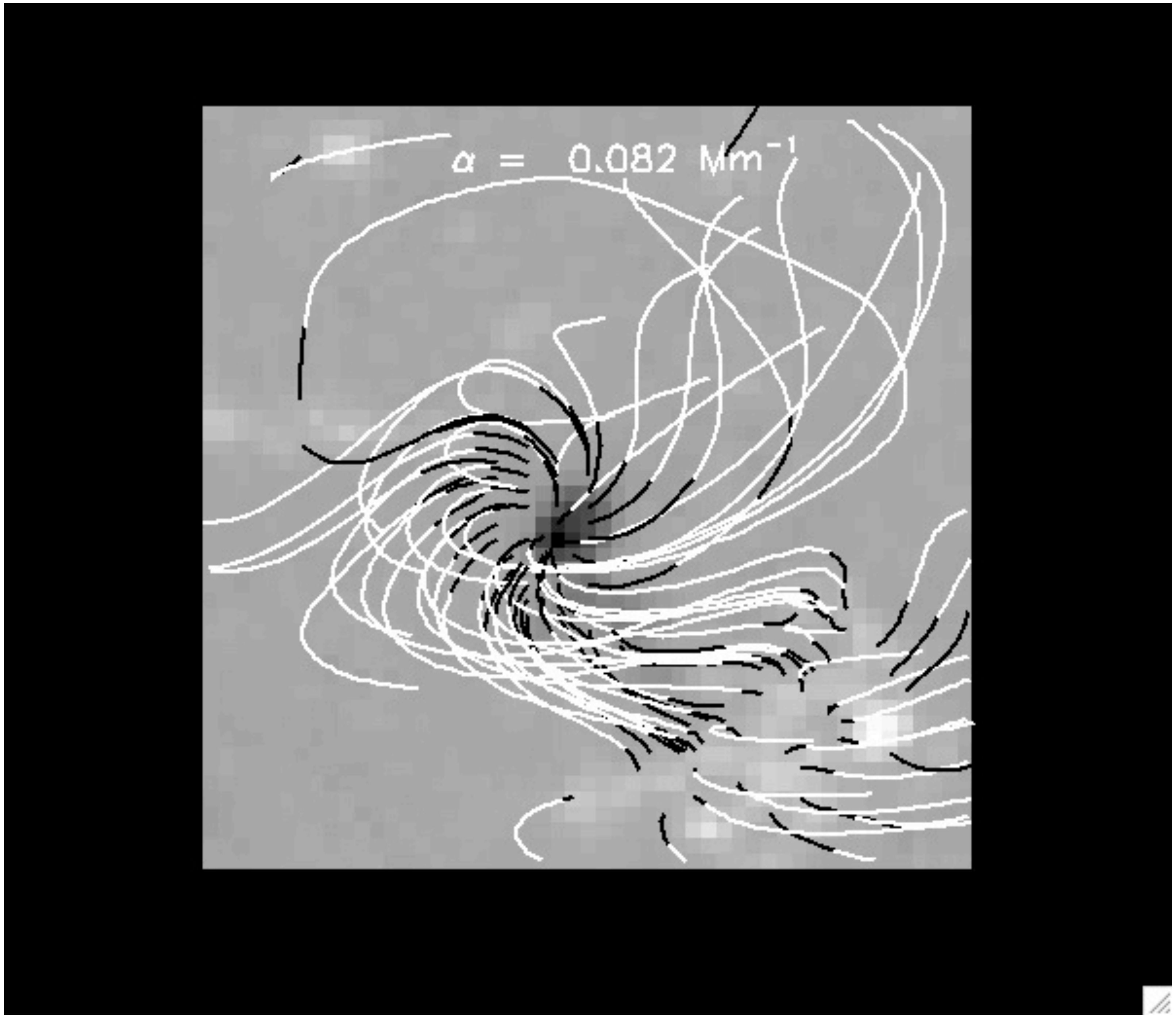
detailed study of IBIS data: G. Cauzzi et al 2008, A+A

Small AR, pores: including the chromosphere



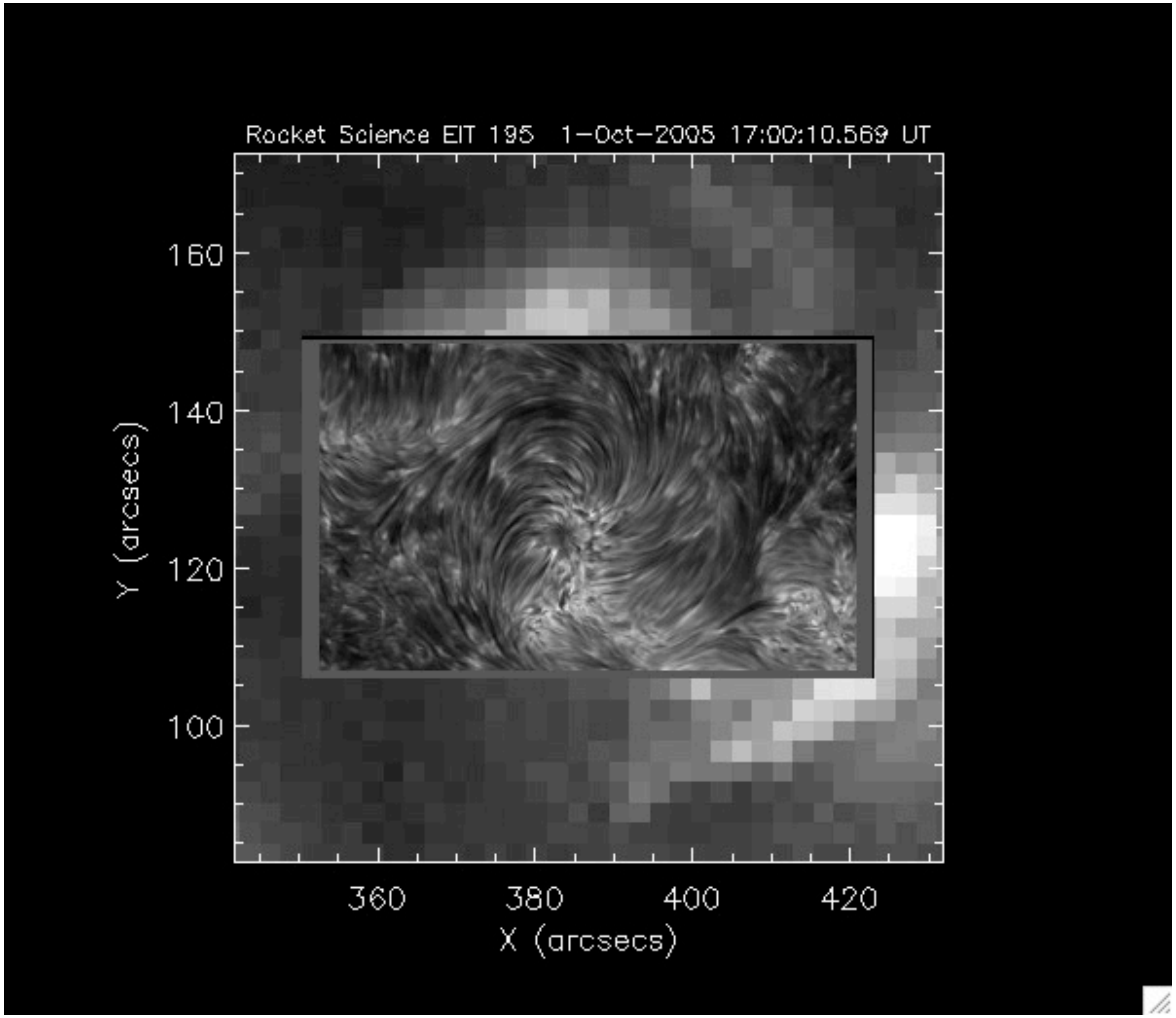
detailed study of IBIS data: G. Cauzzi et al 2008, A+A

Small AR, pores: including the chromosphere



detailed study of IBIS data: G. Cauzzi et al 2008, A+A

Small AR, pores: including the chromosphere



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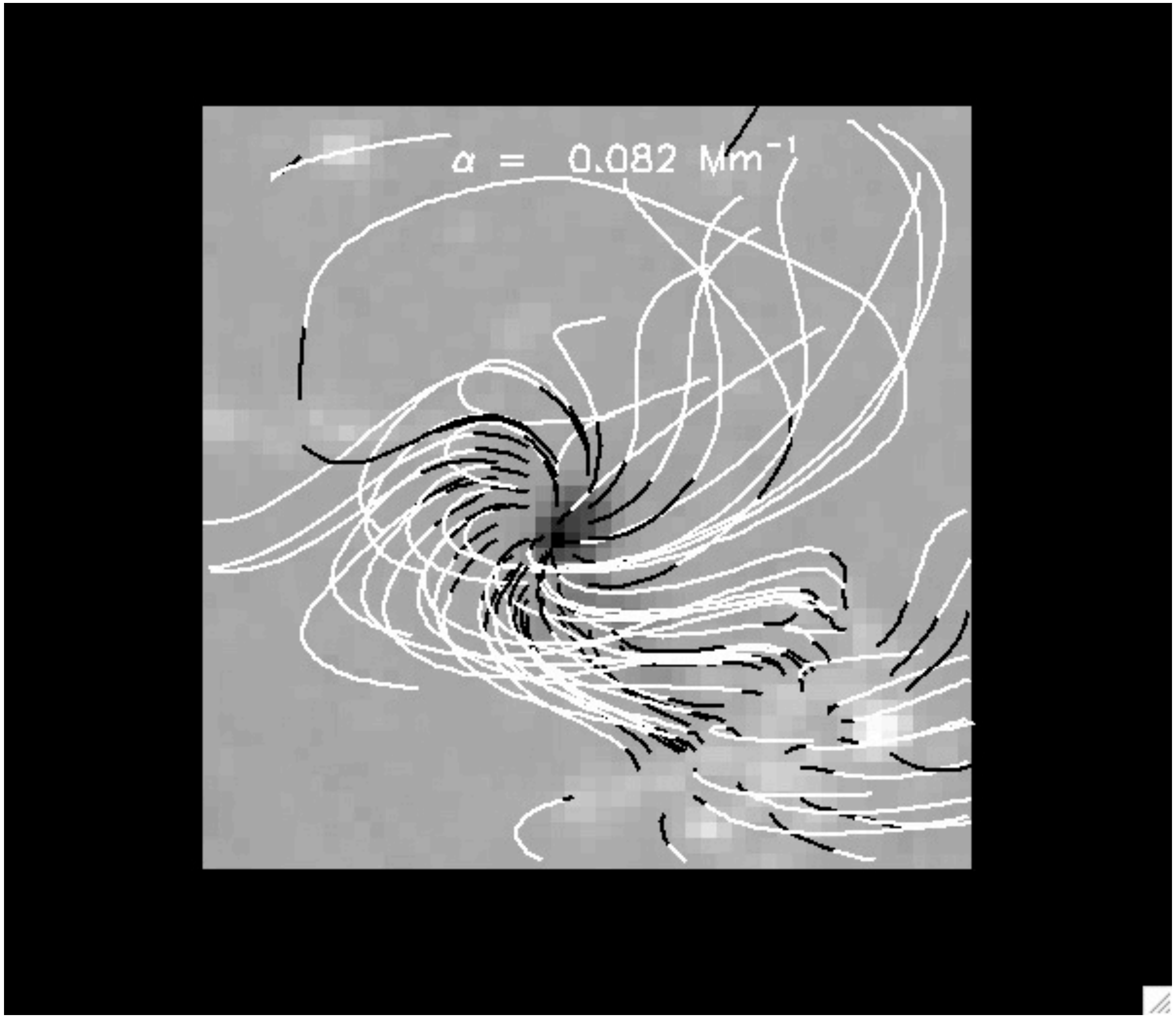
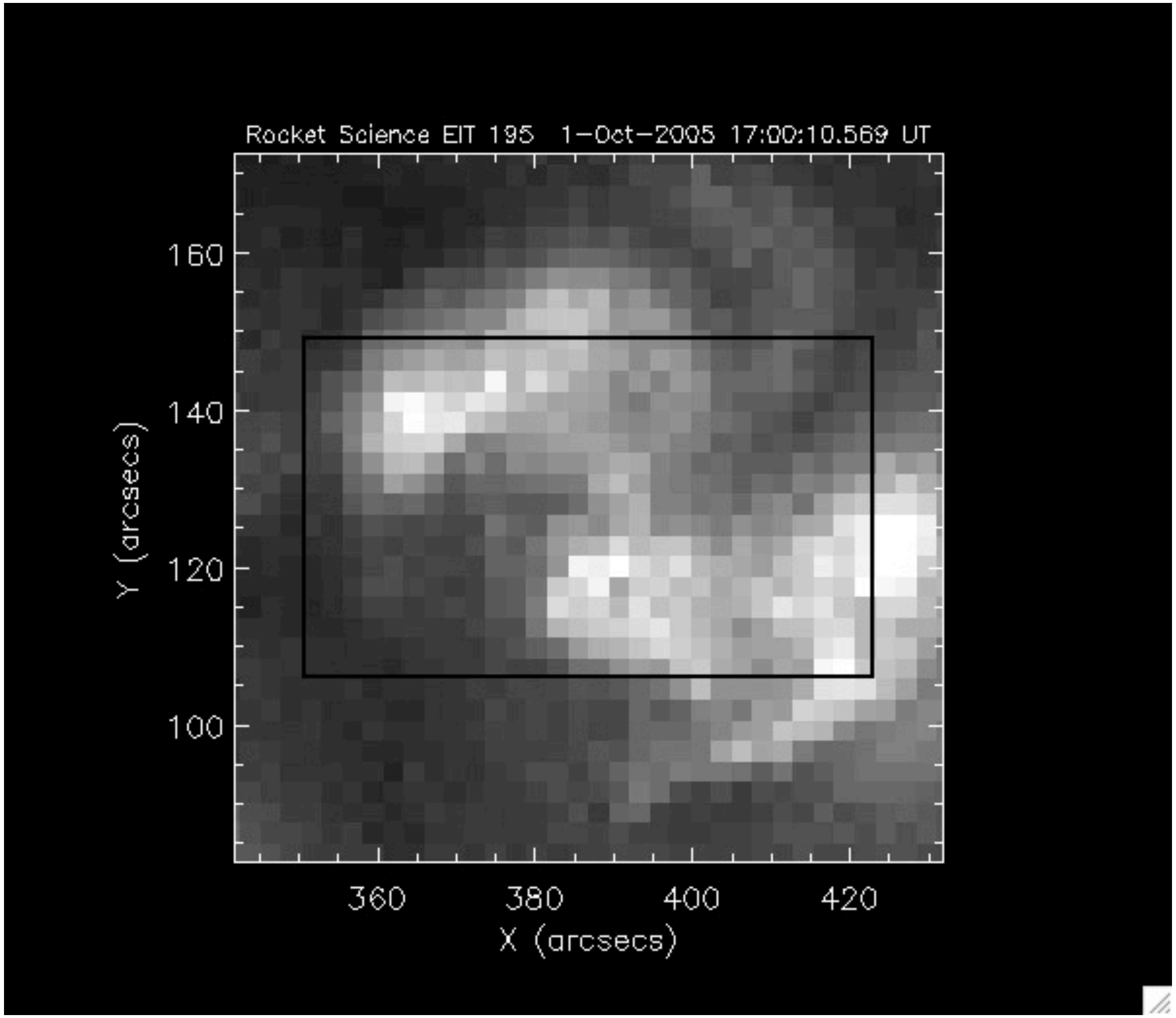
Small AR, pores: including the chromosphere



detailed study of IBIS data: G. Cauzzi et al 2008, A+A

Small AR, pores: including the chromosphere



detailed study of IBIS data: G. Cauzzi et al 2008, A+A

Imaging and infrared spectropolarimetry using facilities at NSO/Sacramento Peak

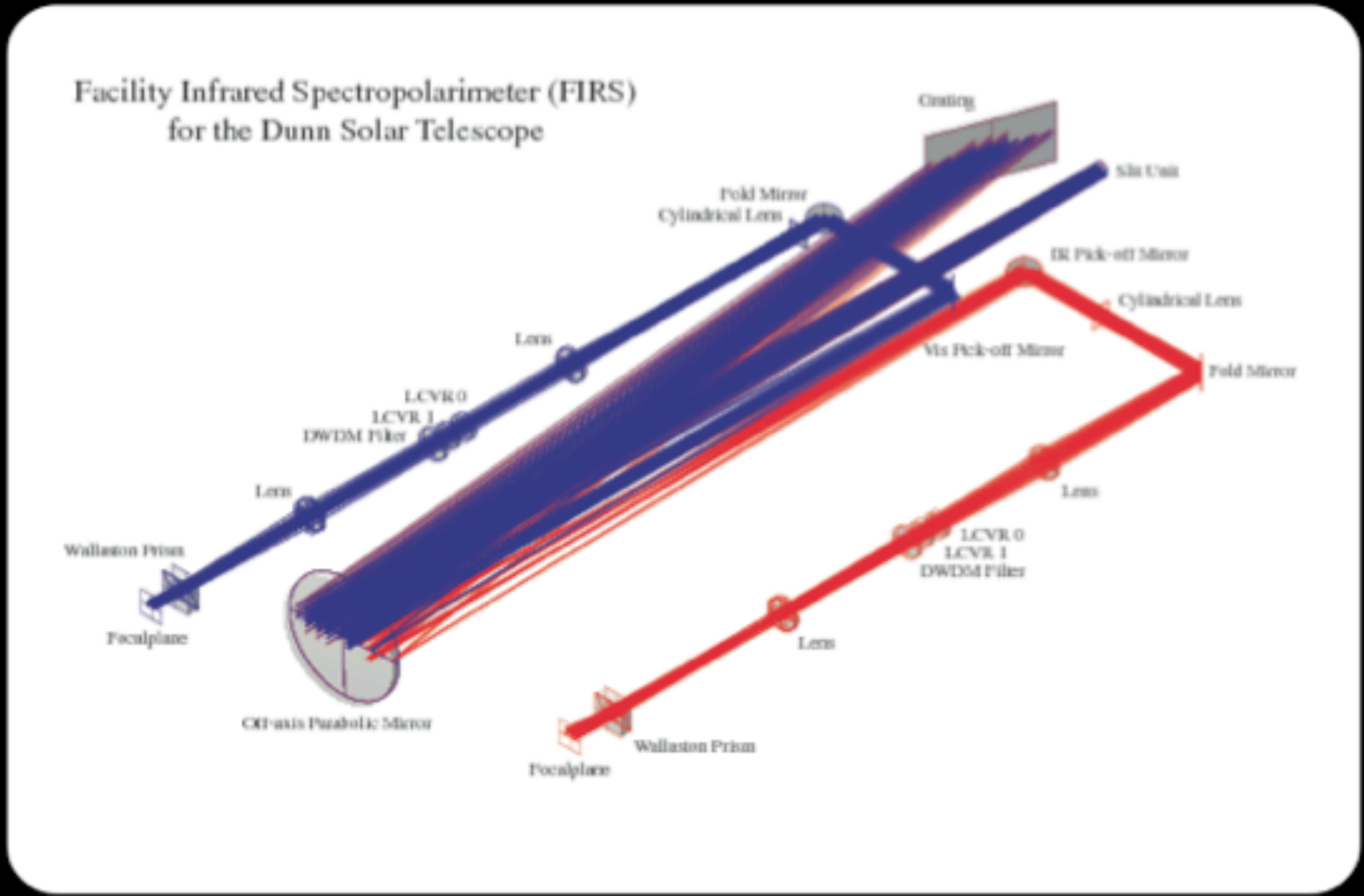
Facility InfraRed Spectropolarimeter

Telescope: DST

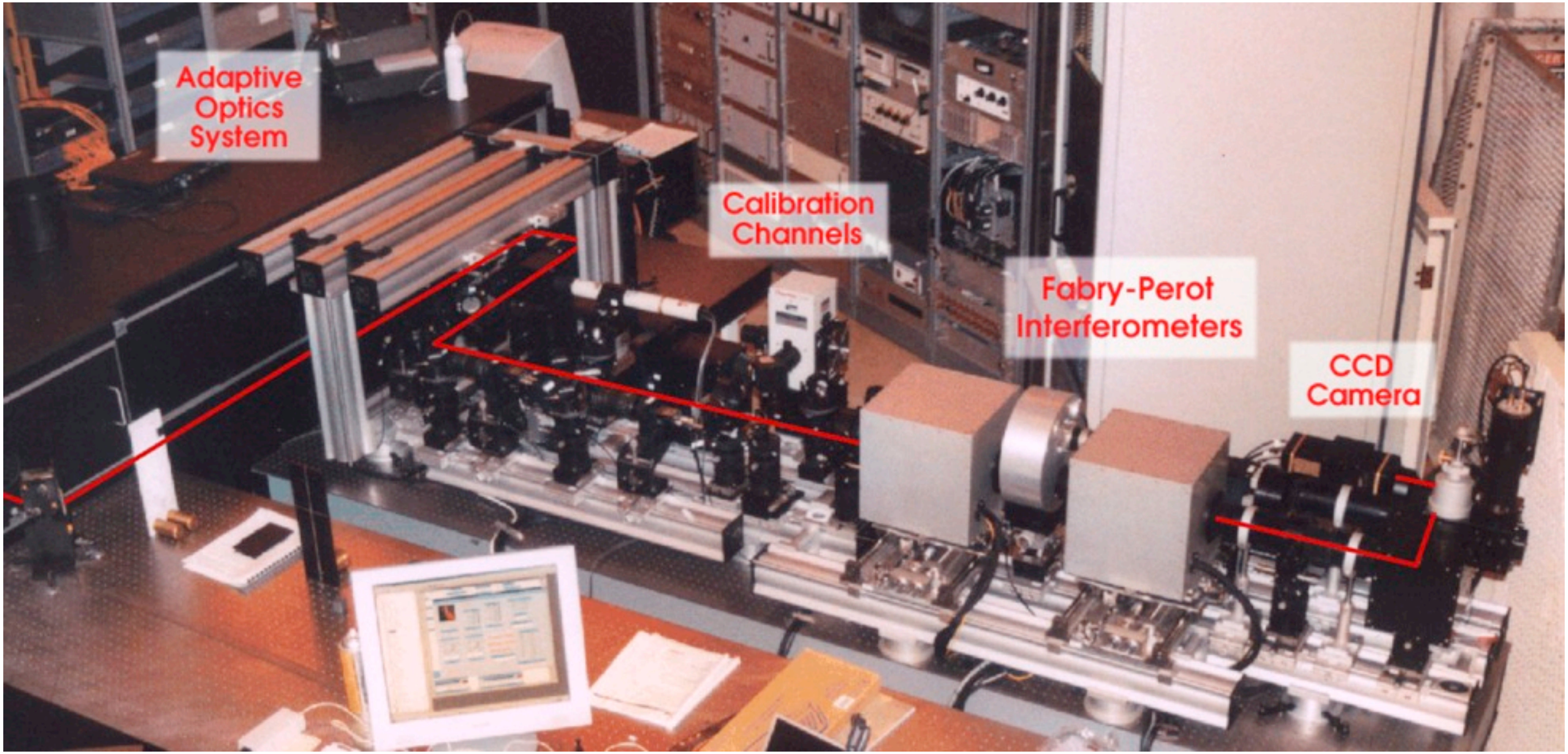
Features: diffraction limited, dual beam, 4-slits for high cadence (20 min.) rasters

Wavelengths: simultaneous 6302, 15650 or 6302, 10830 and runs concurrently with IBIS 8542, G-band camera

Now available for general use!



IBIS- Cavallini & colleagues



Also TESOS, CRISP, GFPI,...

IBIS - Interferometric Bidimensional Spectrometer

Dual Fabry-Perot Imaging Spectrometer

(see Cavallini, 2006 for further details)

- High Throughput *(photon starved regime)*
- Extended FOV *(80 " diameter)*
- High Spatial Resolution *(0.085"/pixel)*
- Rapid Scanning *(2-5 frames/sec)*

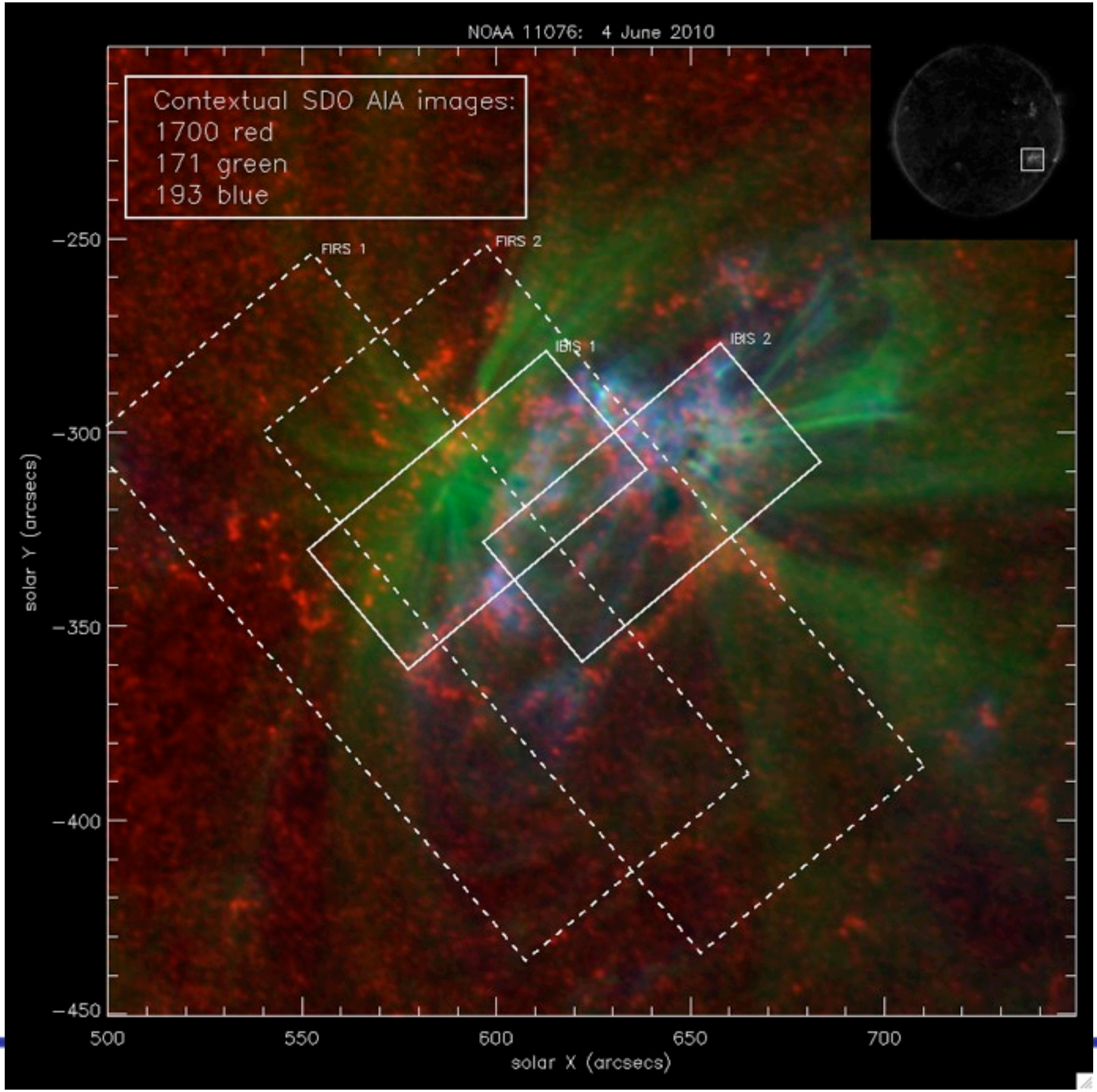
Available Filters

- 589.0 – Na D_2
- 589.6 – Na D_1
- 617.3 – Fe I (SDO/HMI)
- 630.1/630.2 – Fe I
- 656.3 – Hα
- 676.8 – Ni I (MDI ; GONG)
- 709.0 – Fe I [g=0]
- 722.4 – Fe II [g=0]
- 854.2 – Ca II

Operational Range:

550 - 860 nm

Case study: NOAA 11076 4 June 2010

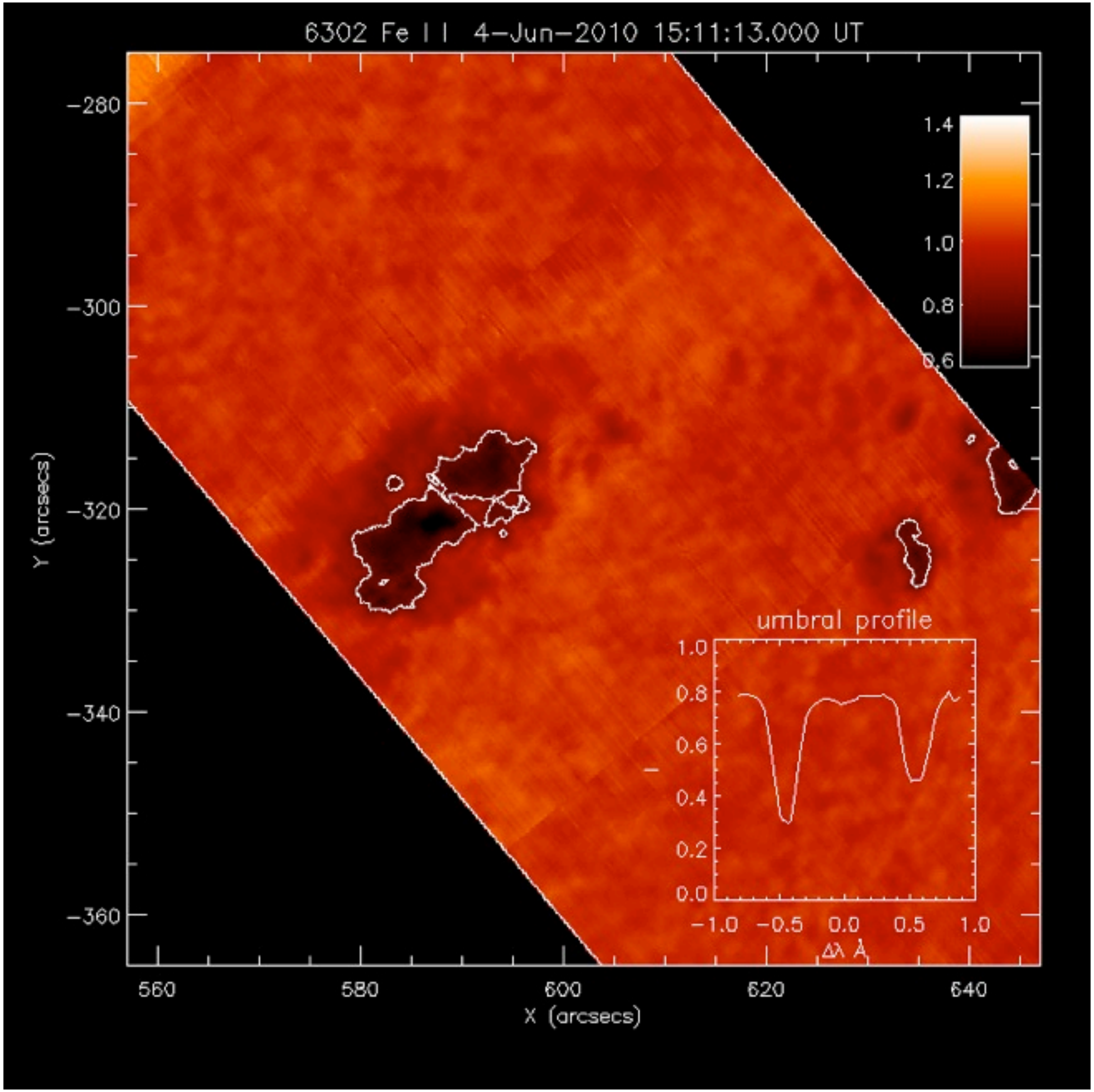


FIRS a 4-slit scanning slit spectropolarimeter

- Jaeggli, Lin, Kuhn, Mickey (IfA Hawaii), Hegwer, Rimmele, Penn (NSO)
- Newly commissioned at the Dunn Solar Telescope, Sunspot NM
- Fe I 630.15 and 630.25 lines (photospheric vector **B**): R ~600,000
- He I 1083 lines (chromospheric/coronal base vector **B**): R ~300,000
- Maps of 145 steps of 10s duration, spanning 175” x 75”
- 4 state polarization modulation
- 1083 QUV, B sensitivities per 0.33x0.33” pixel, Σ 25 wavelengths/profile
  - σ(QUV)=0.0009 I_C (random, high frequency noise)
  - σ(QUV)=0.0014 I_C (measured rms fringes/systematic errors)
  - $\sigma(B_{LOS})$~ 5-10 G (formal)
  - Fringes+noise dominate QU => no vector field (but see below)

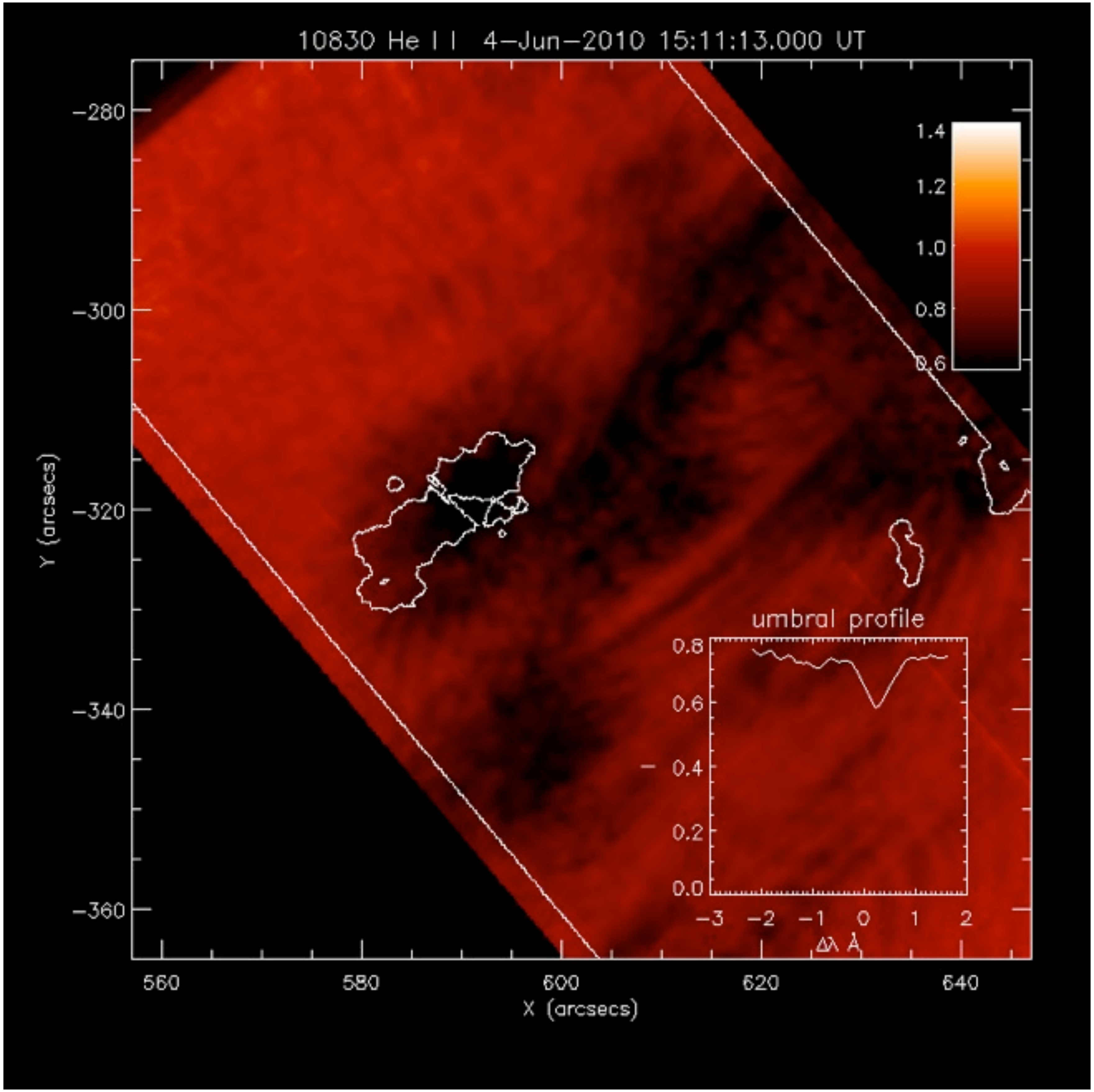
HAO

FIRS: NOAA 11076 4 June 2010



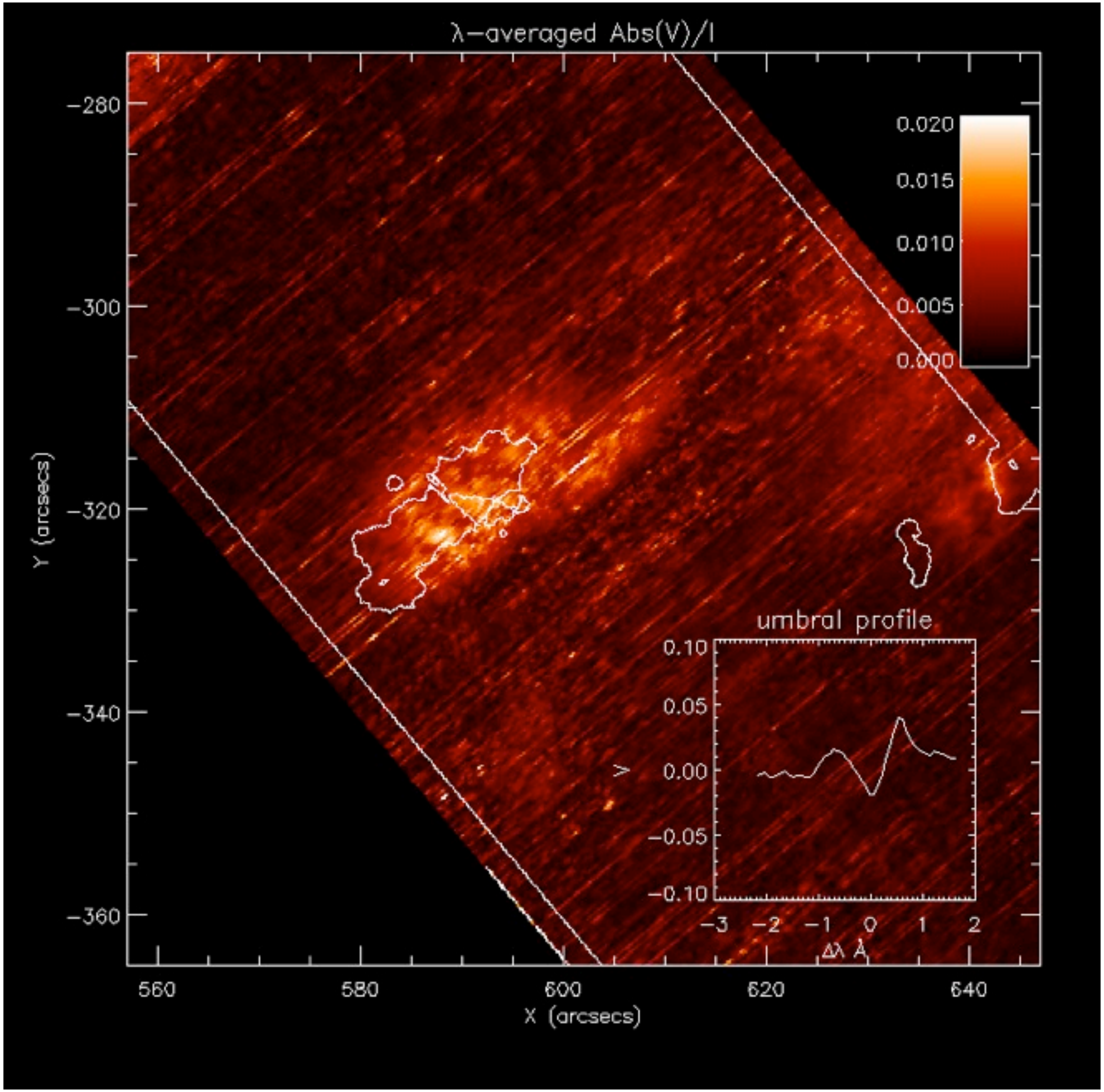
24 minute scan

FIRS: NOAA 11076 4 June 2010



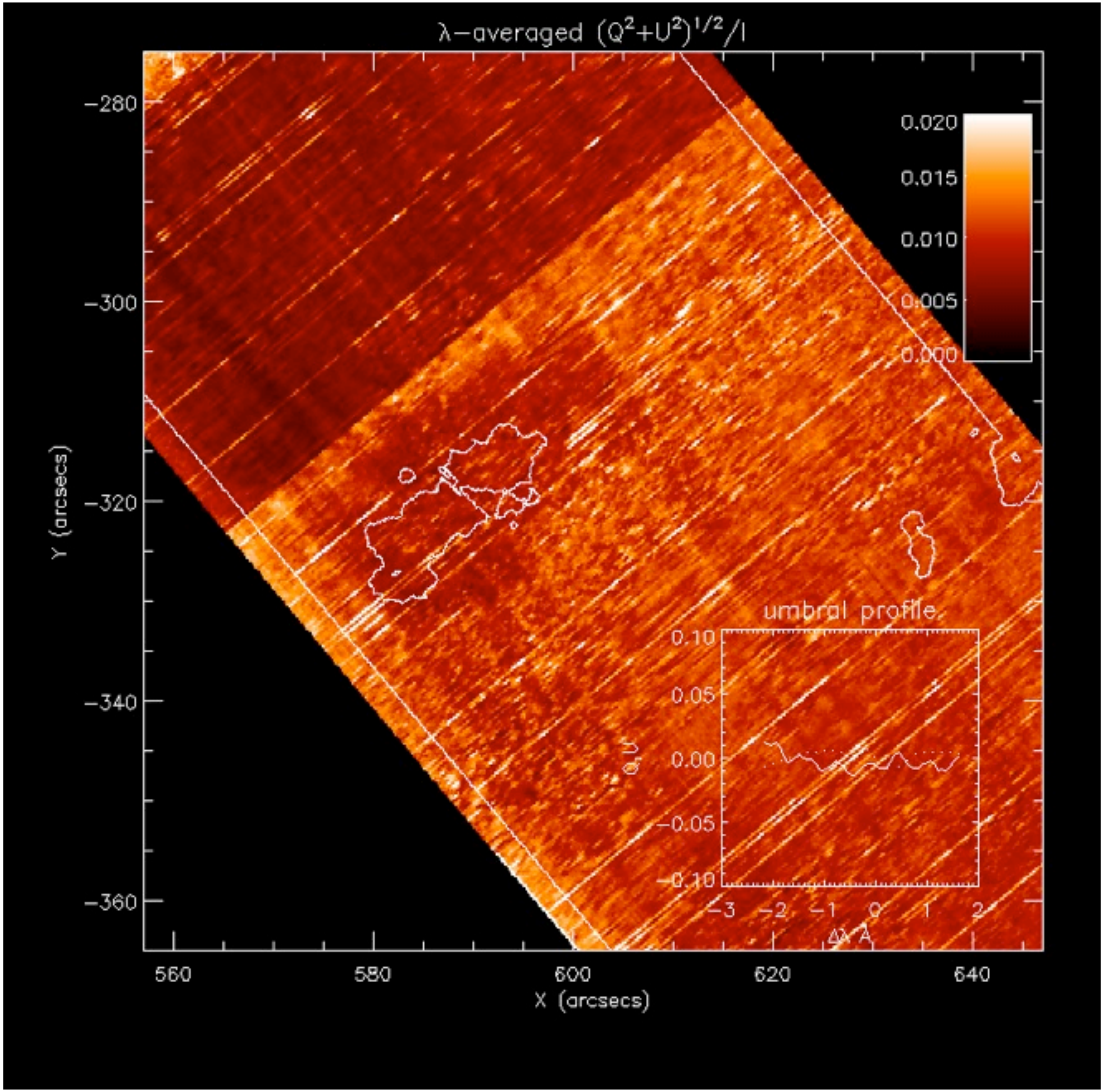
24 minute scan

FIRS: NOAA 11076 4 June 2010



24 minute scan

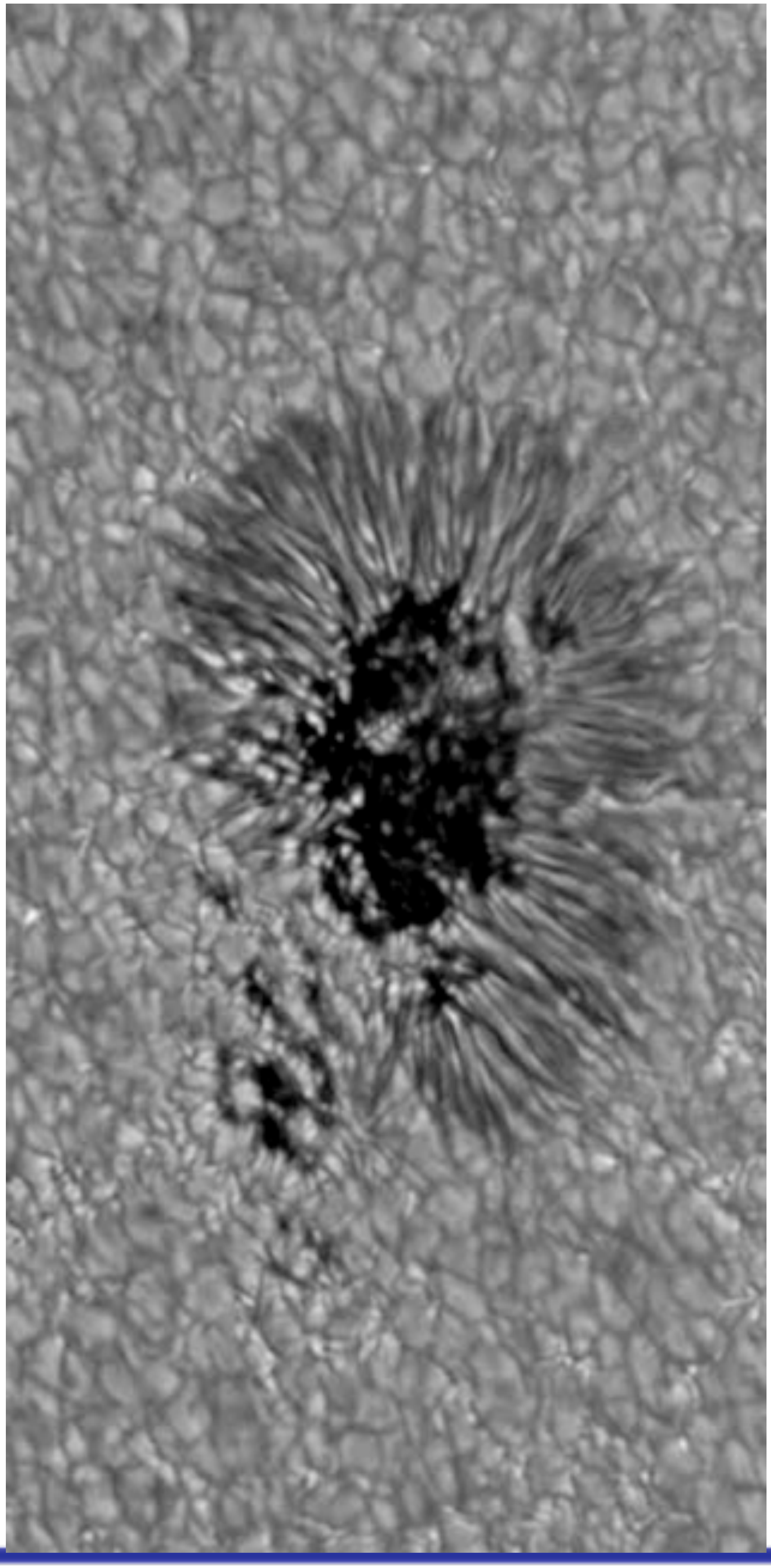
FIRS: NOAA 11076 4 June 2010



24 minute scan

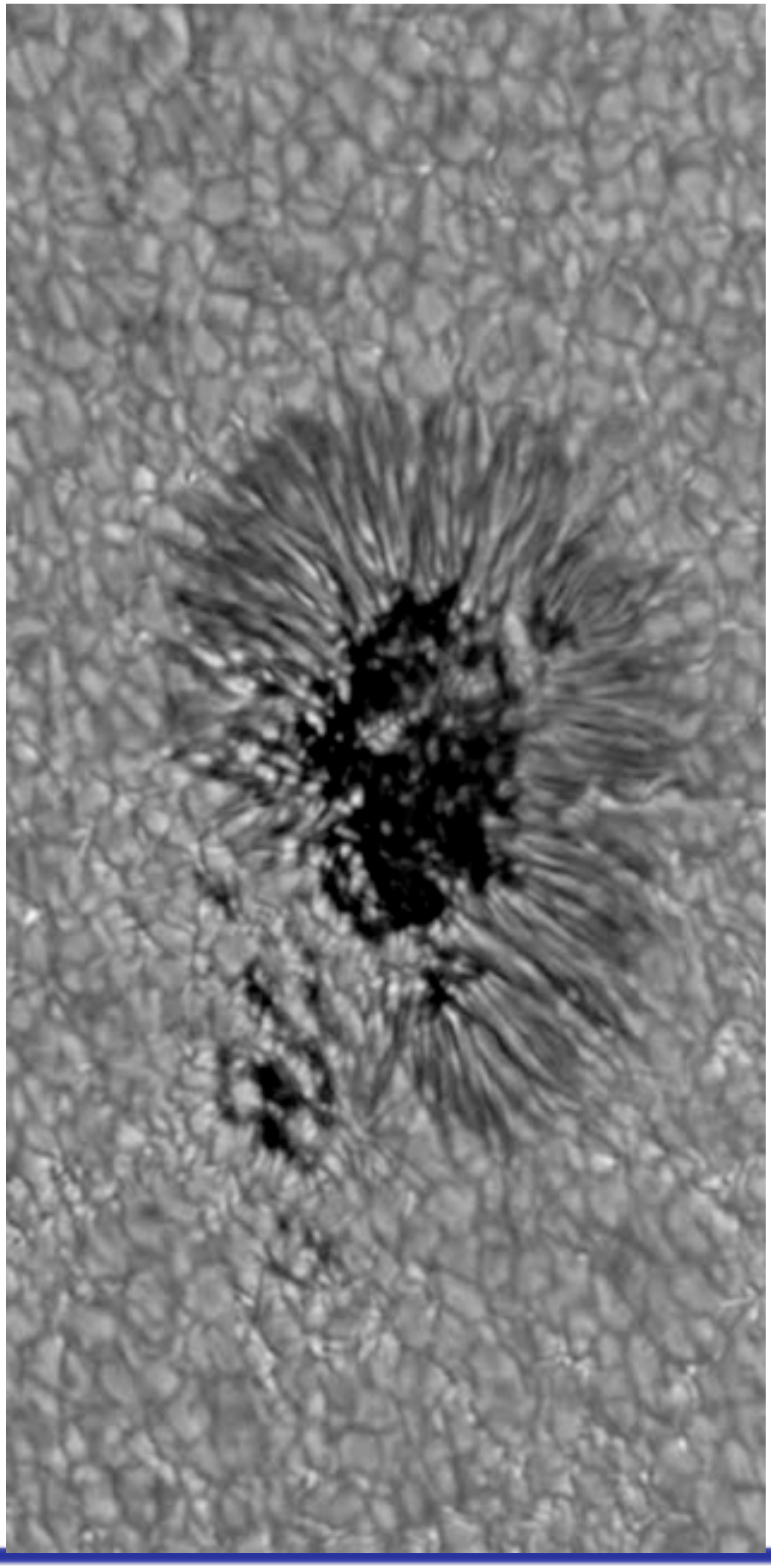
IBIS: NOAA 11076 4 June 2010

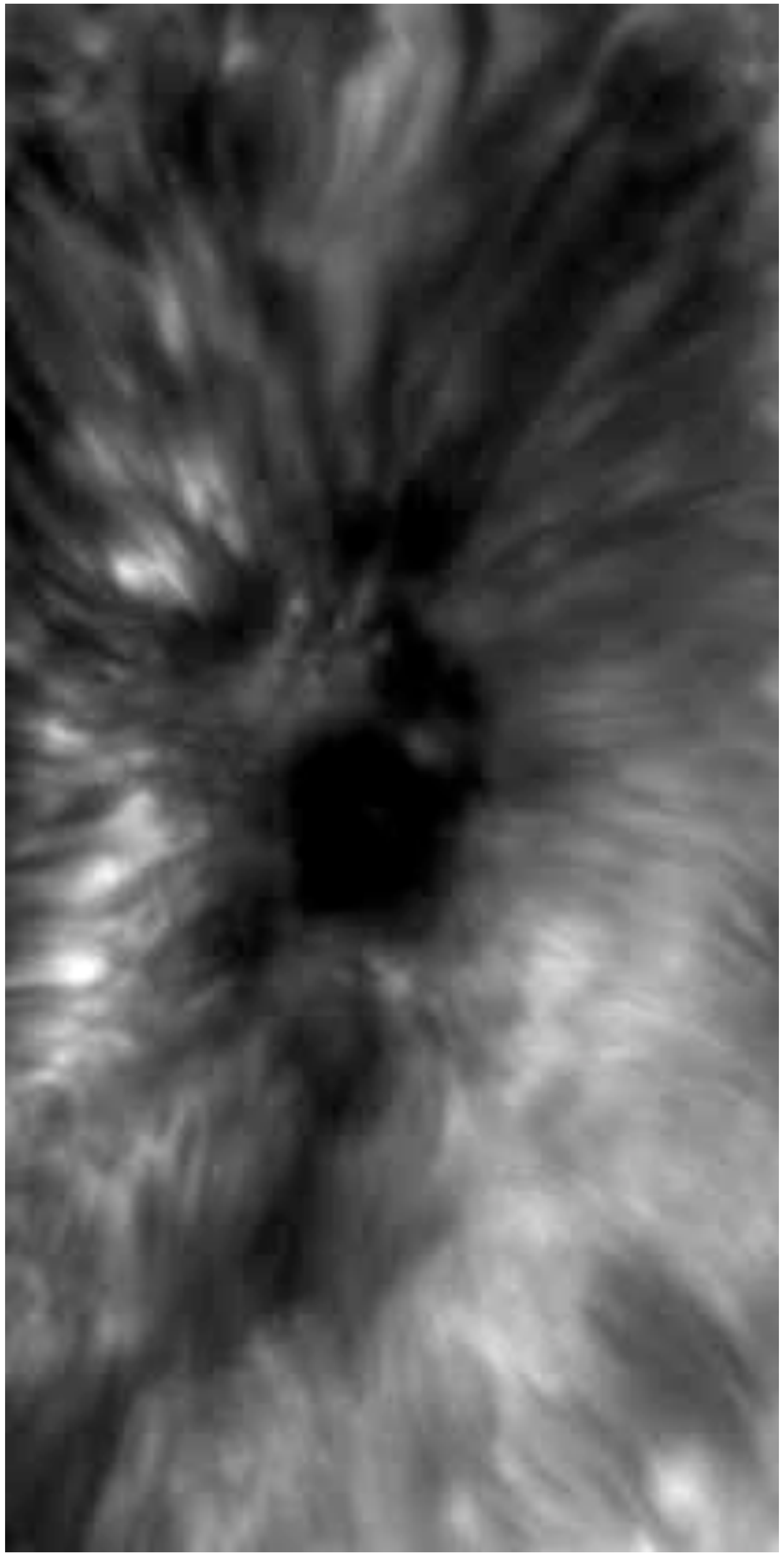
Speckle whitelight and Ca II 8542 core



IBIS: NOAA 11076 4 June 2010

Speckle whitelight and Ca II 8542 core

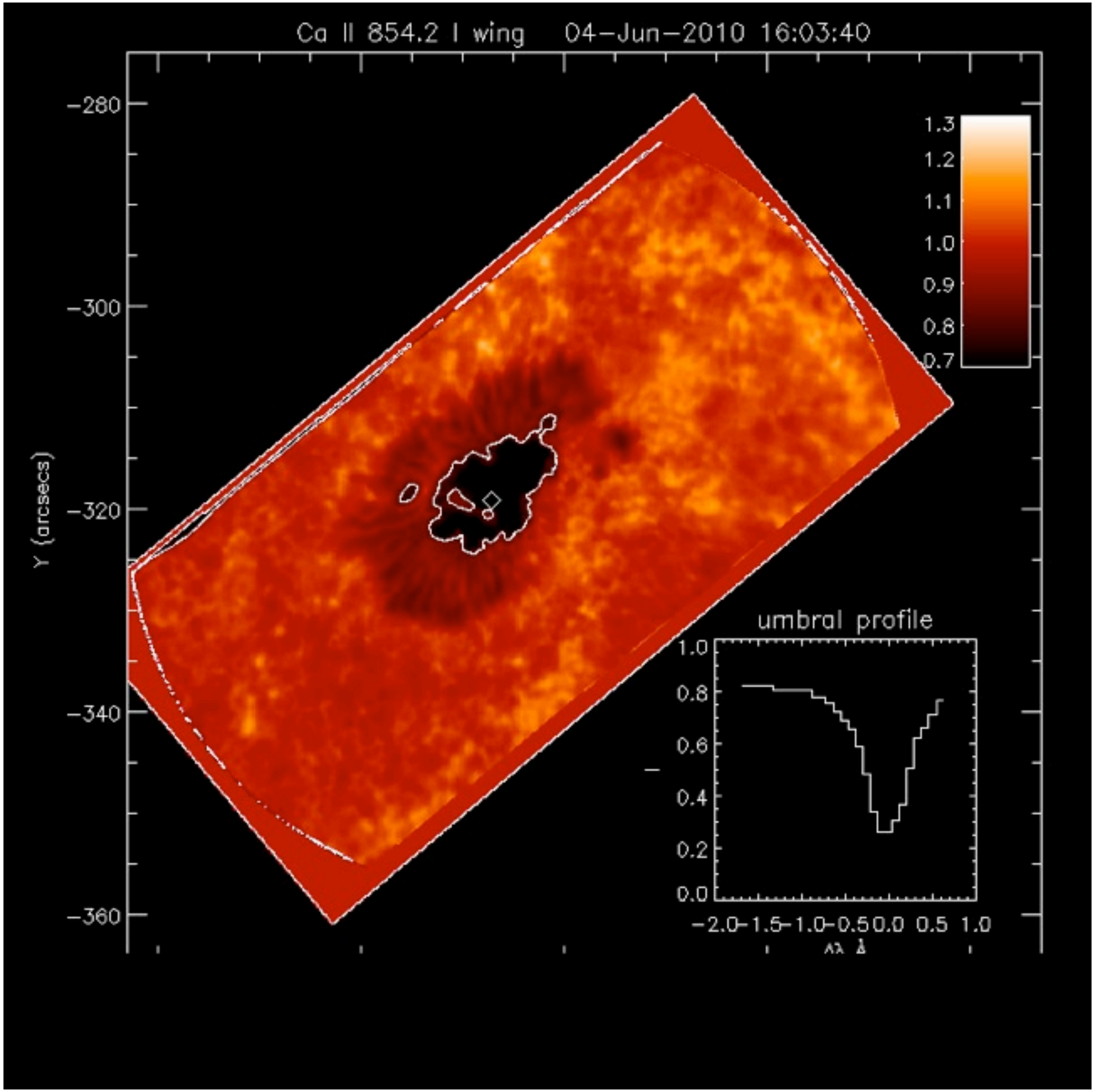




IBIS Fabry-Pérot spectropolarimeter

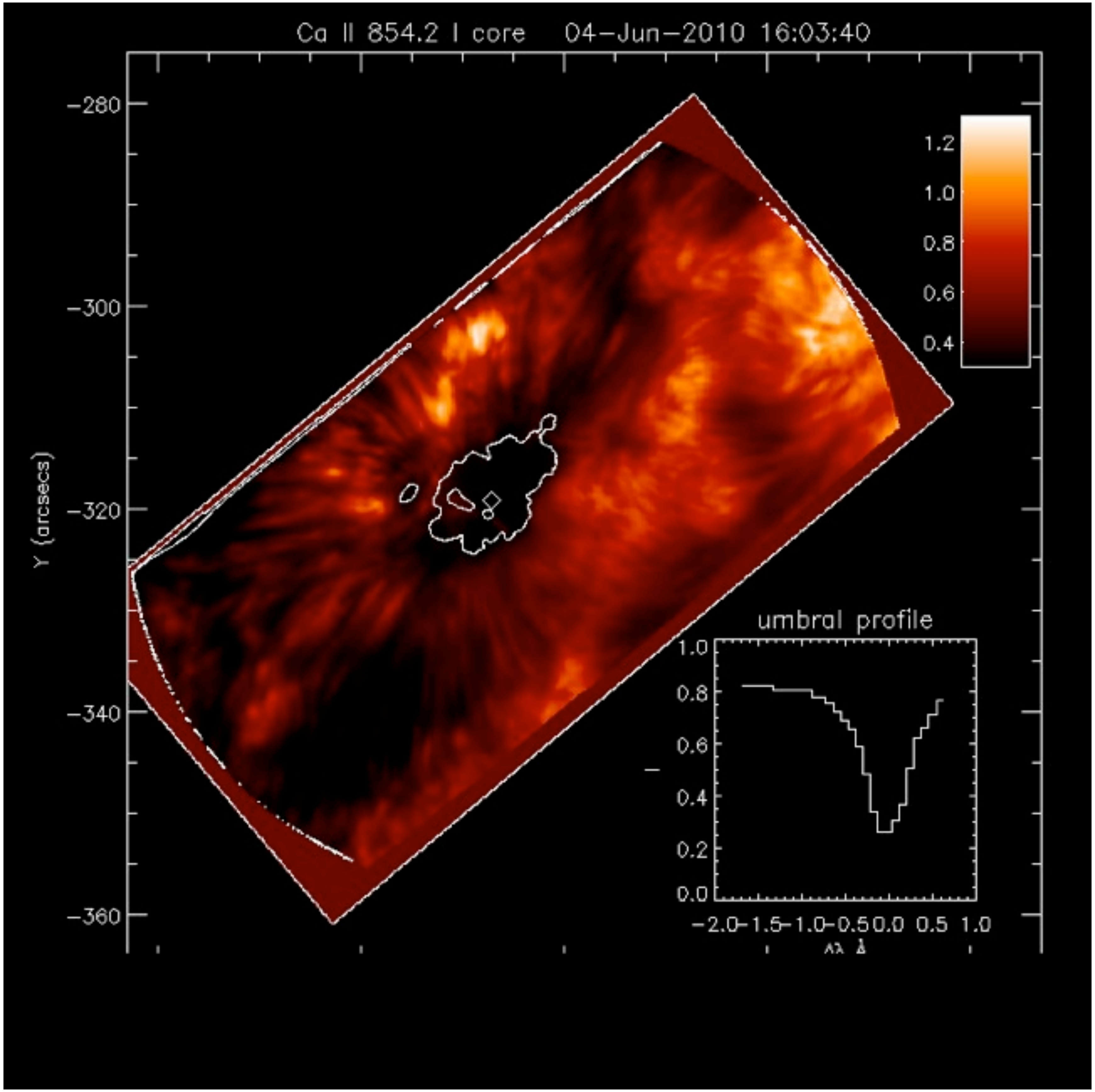
- Ca II 854.2 nm, photospheric/chromospheric vector **B**: R >200,000
- Images 40”x80”, scans 20 wavelengths 6 polarization states, dual beam, 34 s cadence
- 854.2 Sensitivity per 0.17”x0.17” pixel
  - σ(QUV)=0.006 I_c (photon noise limited)
  - $\sigma(B_{LOS})$~38 G (for one 34s scan), but small crosstalk
  - Similar to FIRS 1083, but acquired *every 34 s with superior image quality*

IBIS: NOAA 11076 4 June 2010



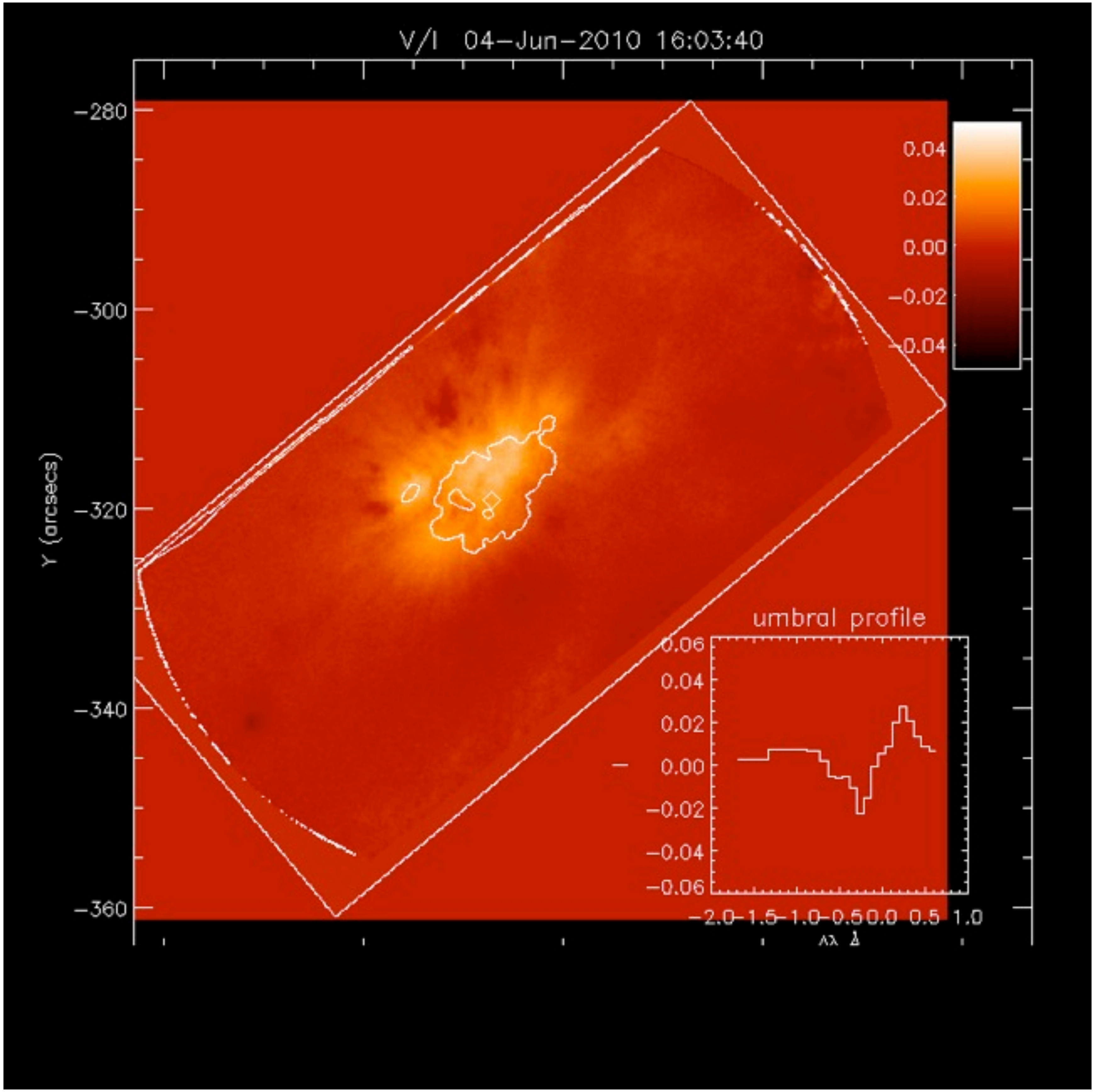
34s scan

IBIS: NOAA 11076 4 June 2010



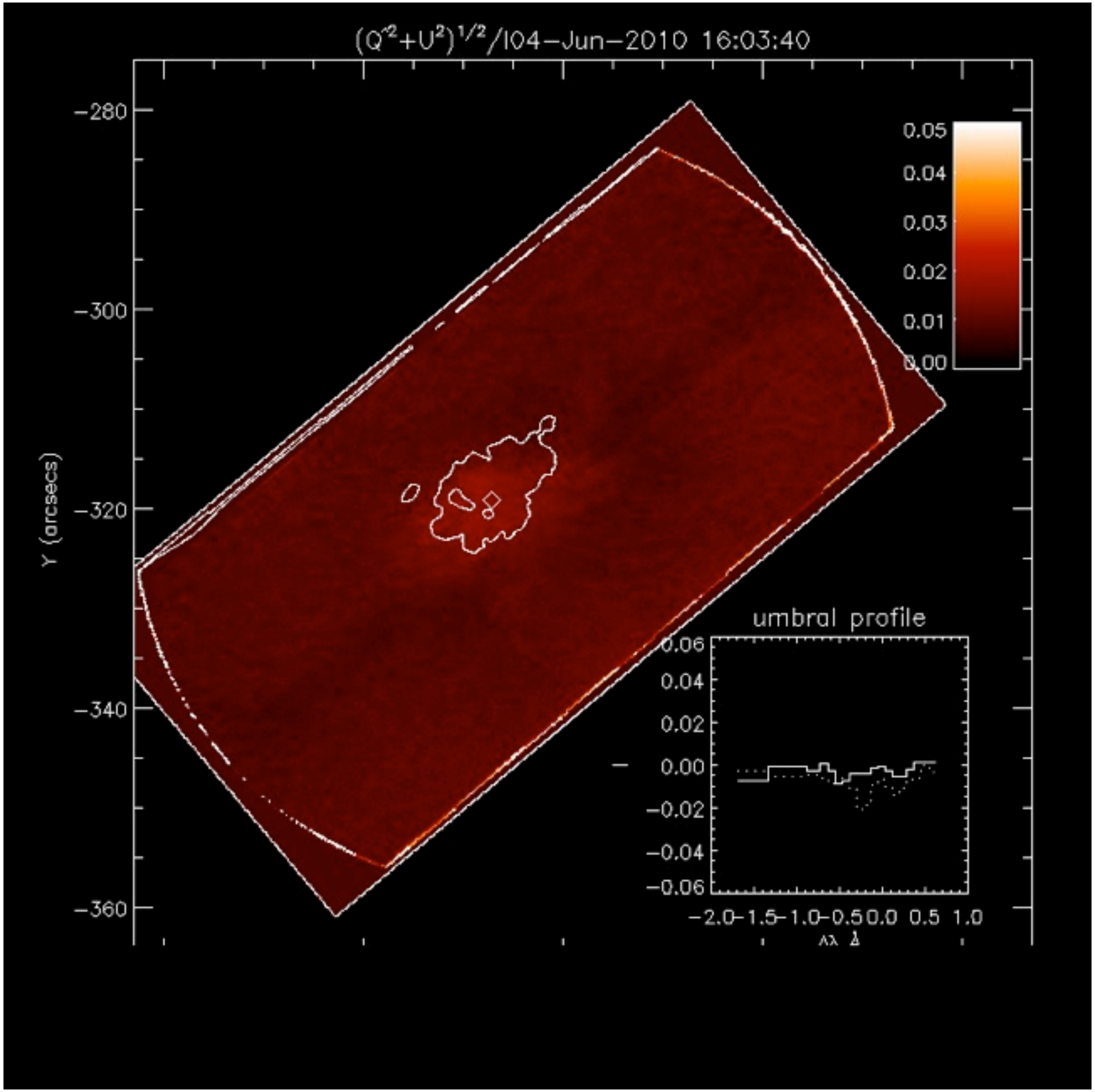
34s scan

IBIS: NOAA 11076 4 June 2010



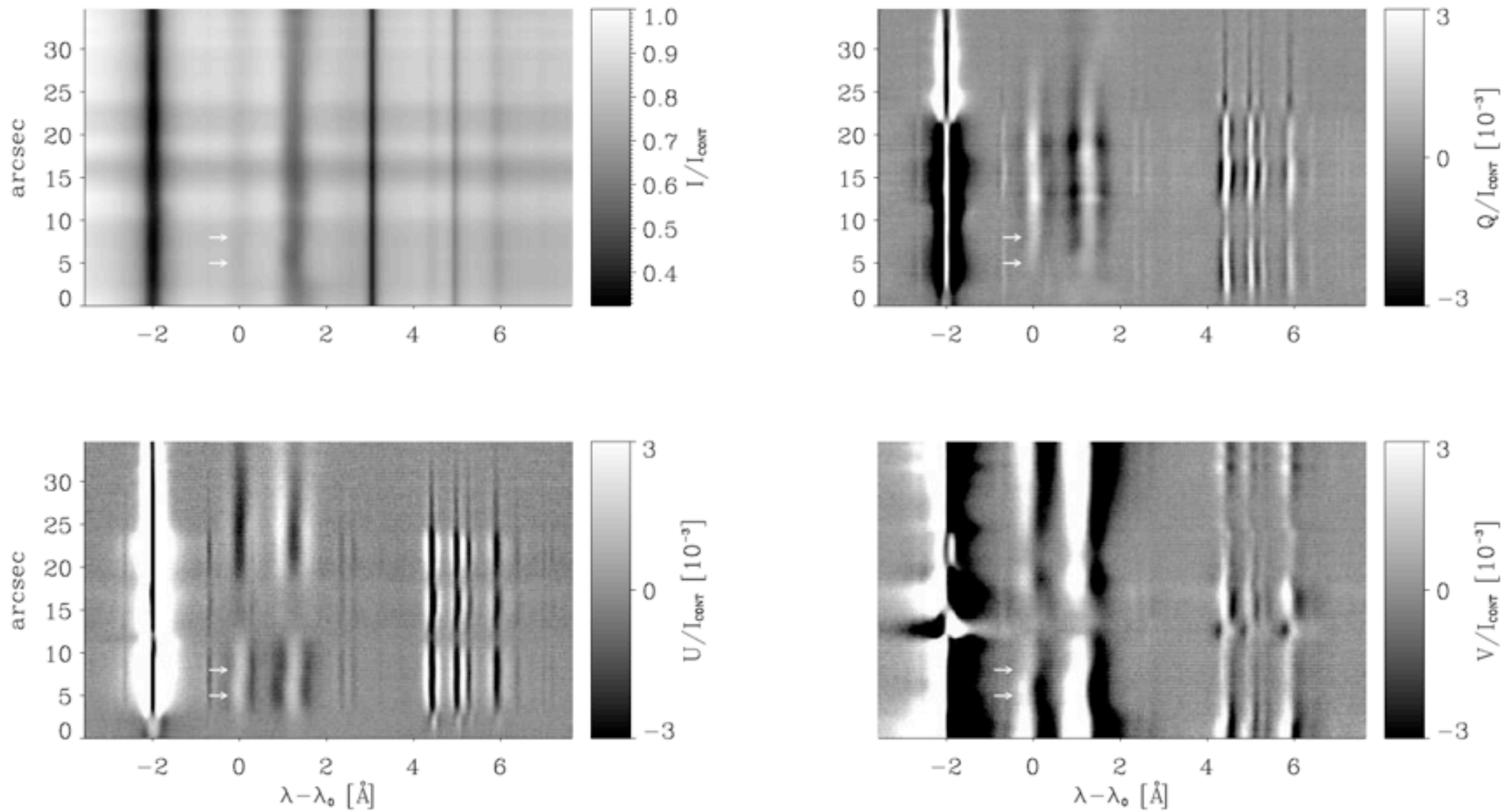
34s scan

IBIS: NOAA 11076 4 June 2010



34s scan

S/N ratios with FIRS are currently too small to measure the chromospheric vector field. Mature instruments (TIP) do better.



Kuckein et al. 2009,TIP 10830 data. s/n ~ 4000
cf. FIRS s/n ~ 600. FIRS is a "work in progress"

In the meantime...

MEASURING CHROMOSPHERIC VECTOR FIELDS: B(strength), θ (inclination), φ (azimuth)

Line	region	Product (technique)	instrument
Fe I 6302	photosphere	Vector **B** (Milne-Eddington inversions + NLFFF extrapolations)	HMI/SDO
Ca II 8542	chromosphere	Vector **V** **(fibril kinematics)** Vector **B** (not done - requires NLTE inversions)	IBIS
He I 10830	Chromosphere/ Coronal base	B_{LOS} (HAZEL inversions)	FIRS

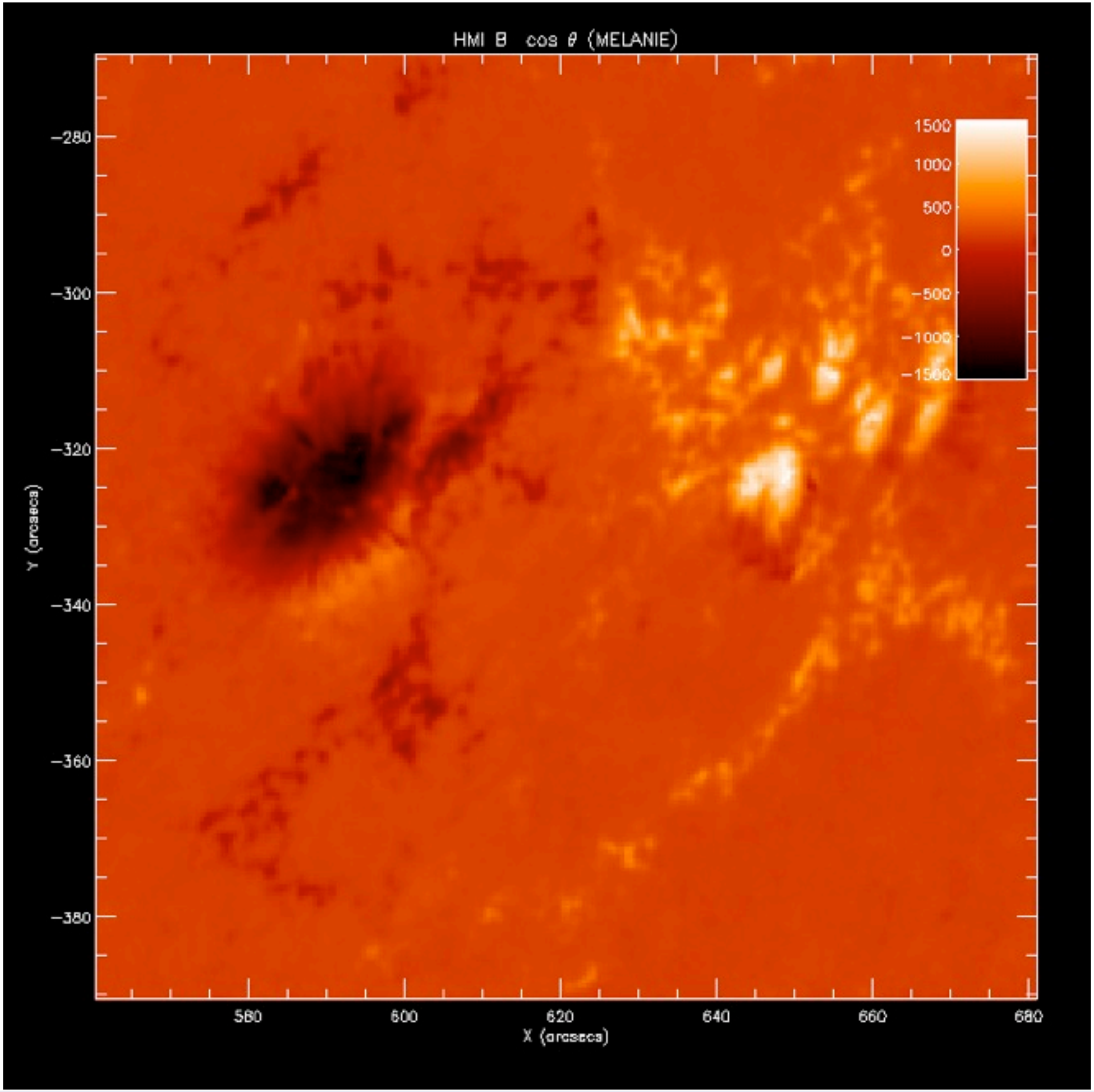
Critical Assumptions

- **vectors V and B are parallel (or anti-parallel)**
- ***Ca II and He I lines form in the same overall hydromagnetic structure.***

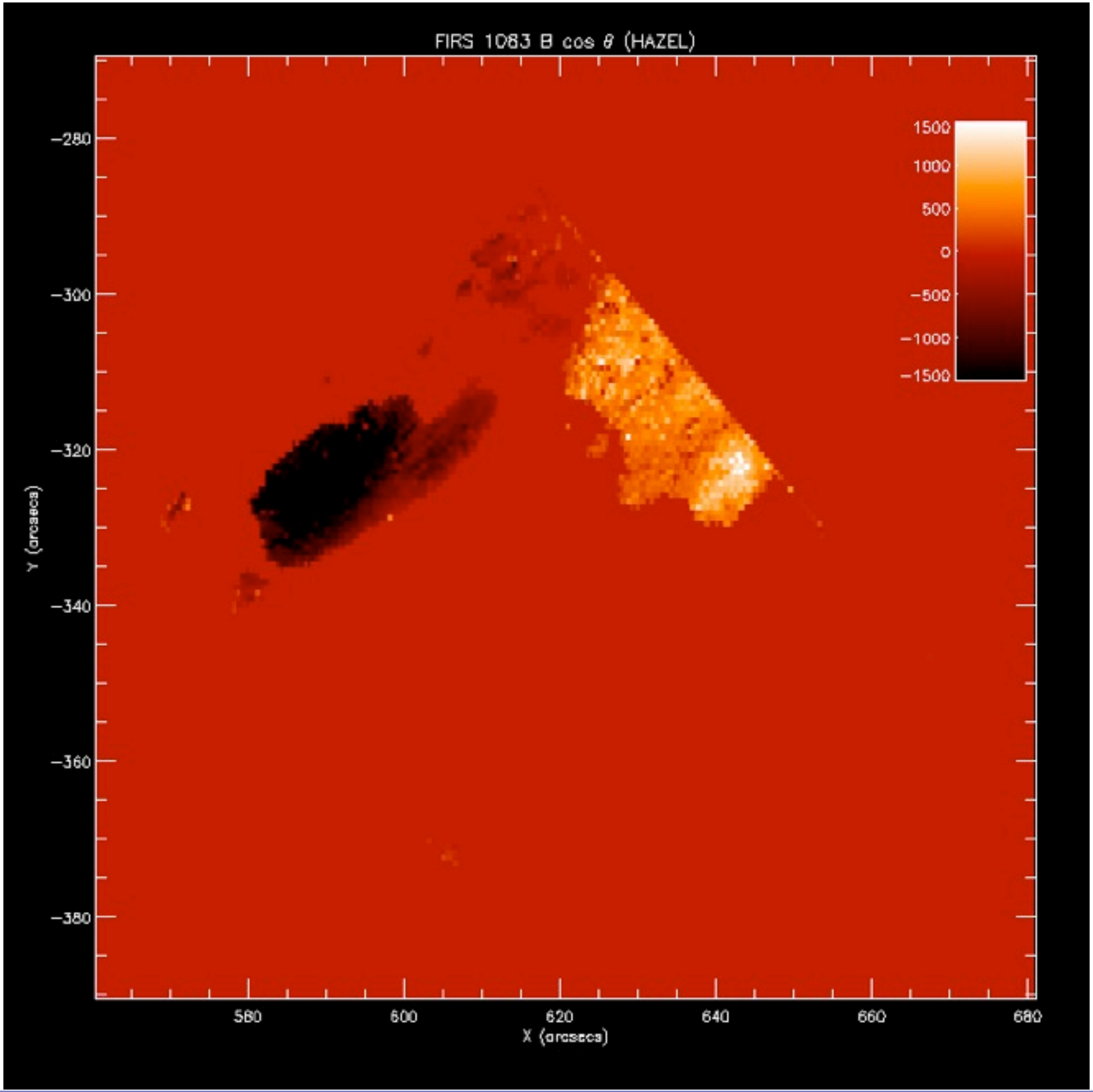
- FIRS I(QU)V → B cos θ, HAZEL inversions of 1083, z ~ 2Mm ?
- IBIS (QU) fibrils→ φ; kinematics → θ,φ; V,I → B cos θ

  B cos θ VERY crude, inversions required

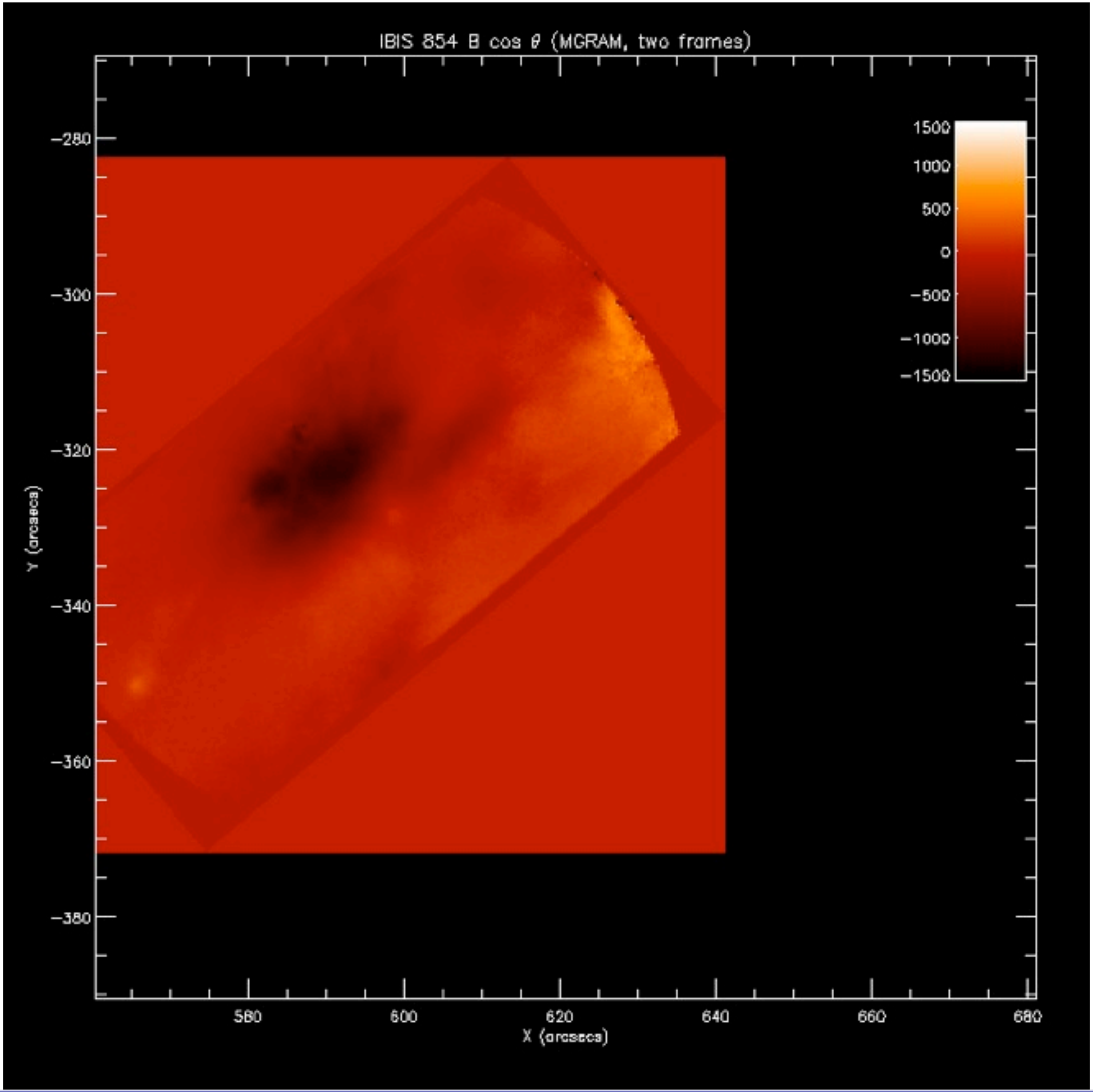
NOAA 11076 4 June 2010 again



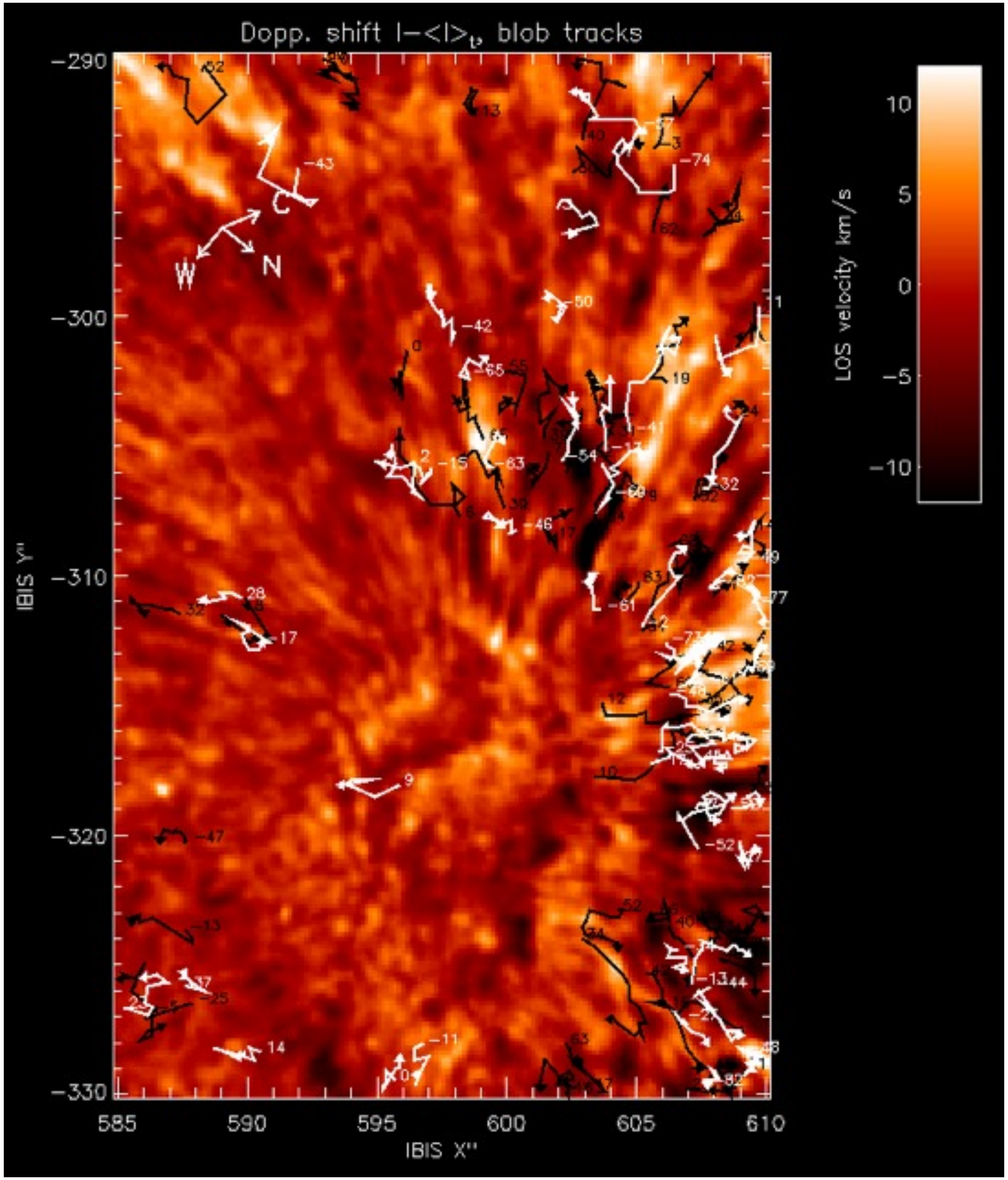
NOAA 11076 4 June 2010 again



NOAA 11076 4 June 2010 again



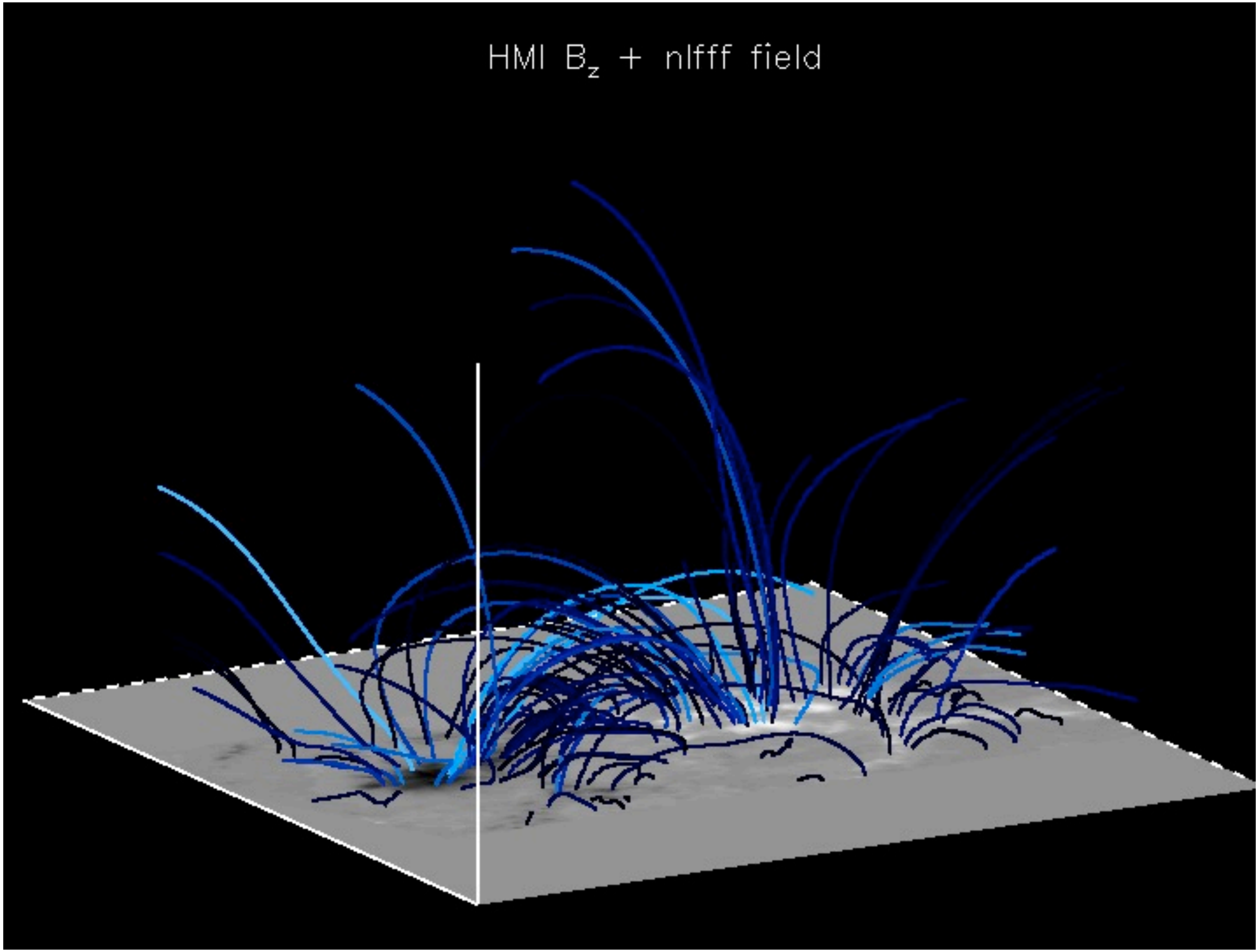
NOAA 11076 4 June 2010: vector V



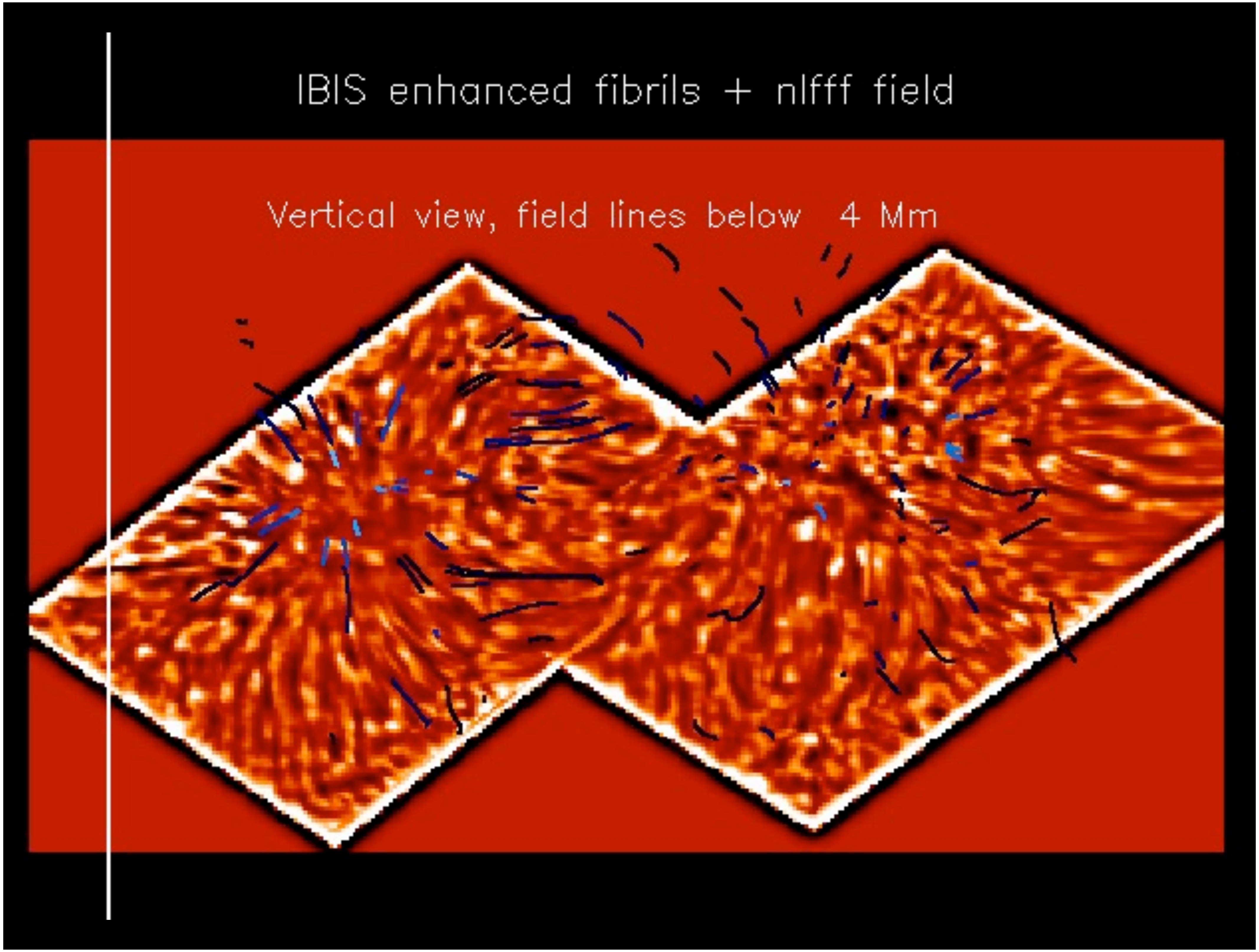
First feature tracking results combined with Doppler shifts

Tracking is easiest over penumbrae, where B is harder to measure

A curiosity?



A curiosity?


IBIS enhanced fibrils + nlfff field
Vertical view, field lines below 4 Mm

NOAA 11076 4 June 2010: conclusions

- Chromospheric vector fields are not yet possible with FIRS
- FIRS was recently commissioned, its performance is not fully understood
- mismatch in morphology NLFFF vs. IBIS fibrils
  - magnetic field, or thermodynamics, or both?
- IBIS cannot observe 10830, the "ideal"line
- TIP can and has a sensitivity almost an order of magnitude higher than FIRS
- *An infrared Fabry-Perot is highly desirable*
  - Si I 10827, He I 10830, Fe I 1.56 microns
- *If this were easy it would have been done decades ago*

for the future:
Infrared imaging spectroscopy/ spectropolarimetry

capabilities:

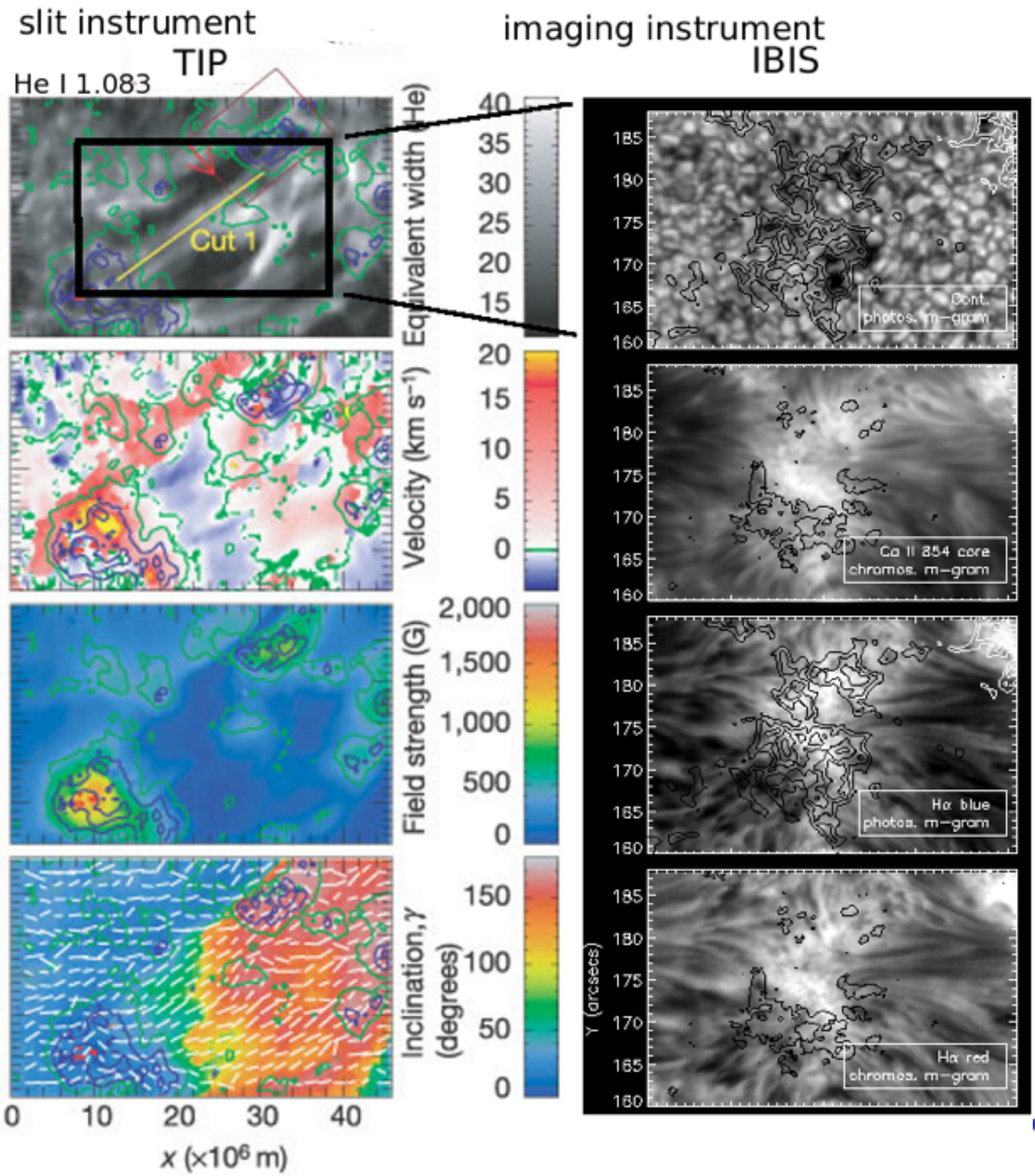
- Extended periods of excellent seeing over bigger FOV
- Zeeman effect enhancement (Fe I 1560nm, ...)
- He I 1083nm as a diagnostic of the magnetic and velocity fields at the coronal base

HAO

potential of IR Fabry-Perot Interferometers

TIP - Solanki et al 2003
  magnetic field at coronal base

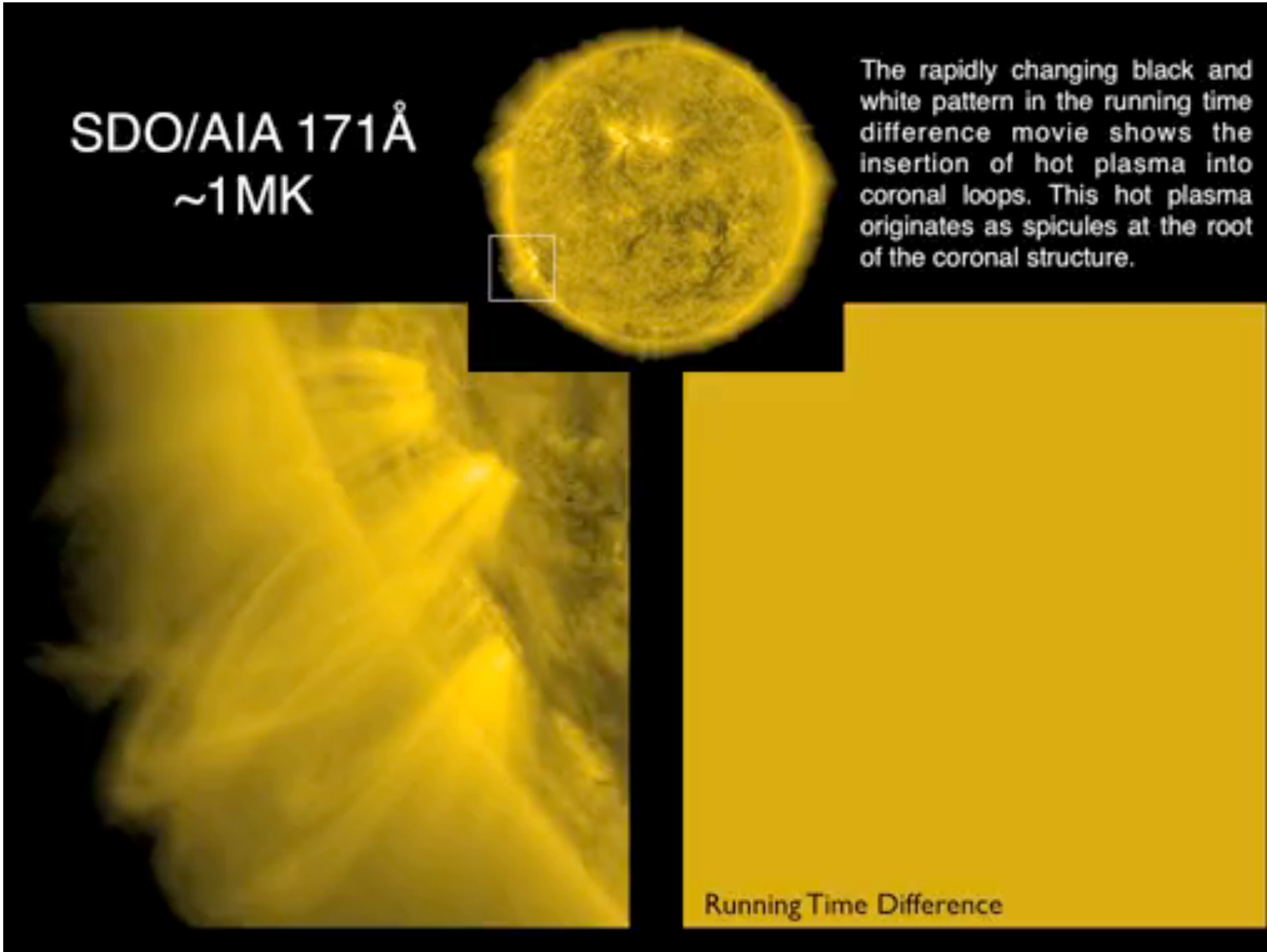
IBIS - Judge et al 2009
  advantages of images



Spicules, coronal heating paradoxes, and other animals

Figure: Scott McIntosh

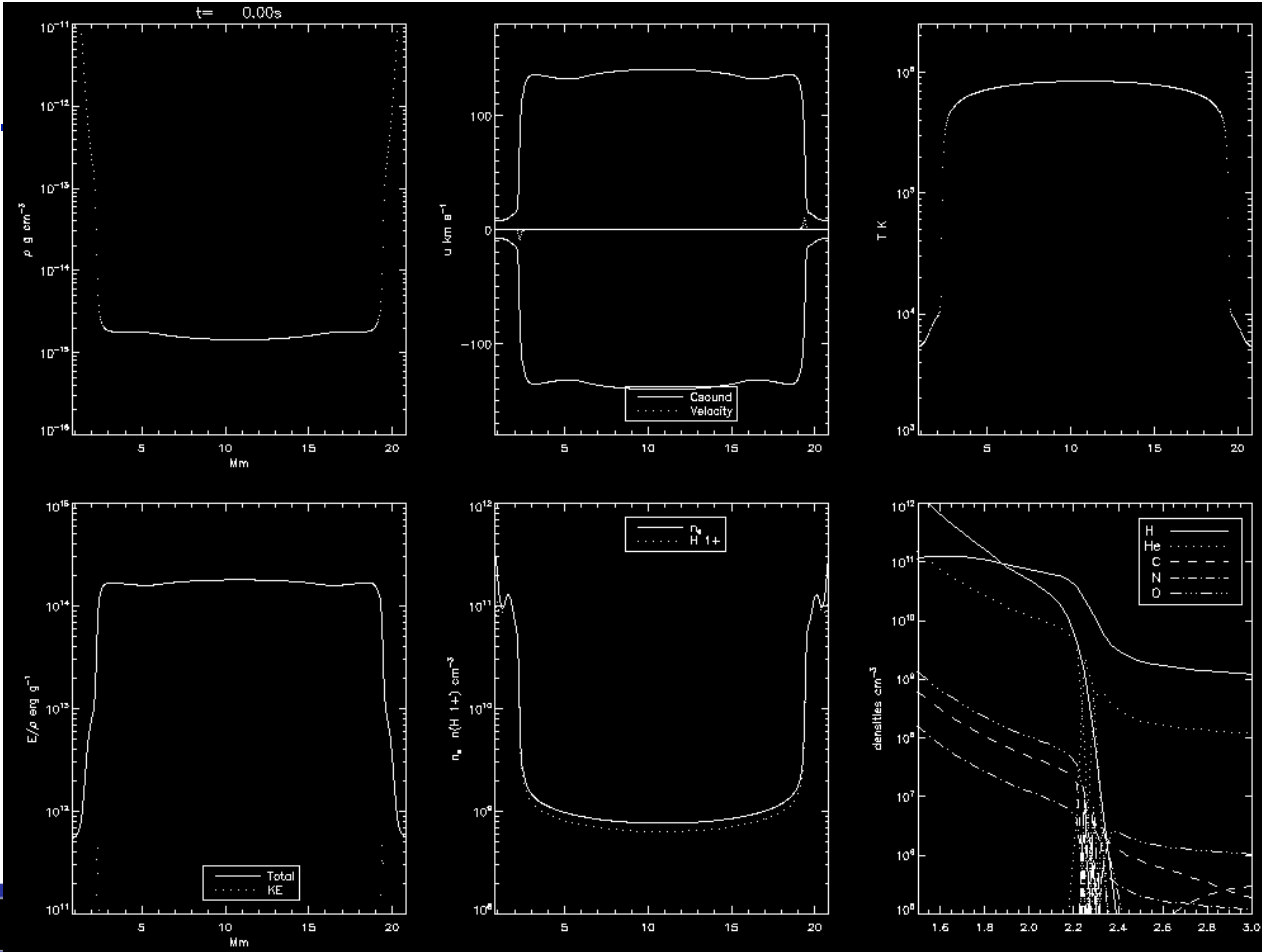
Type II spicules as agents for mass and heat supply to the corona



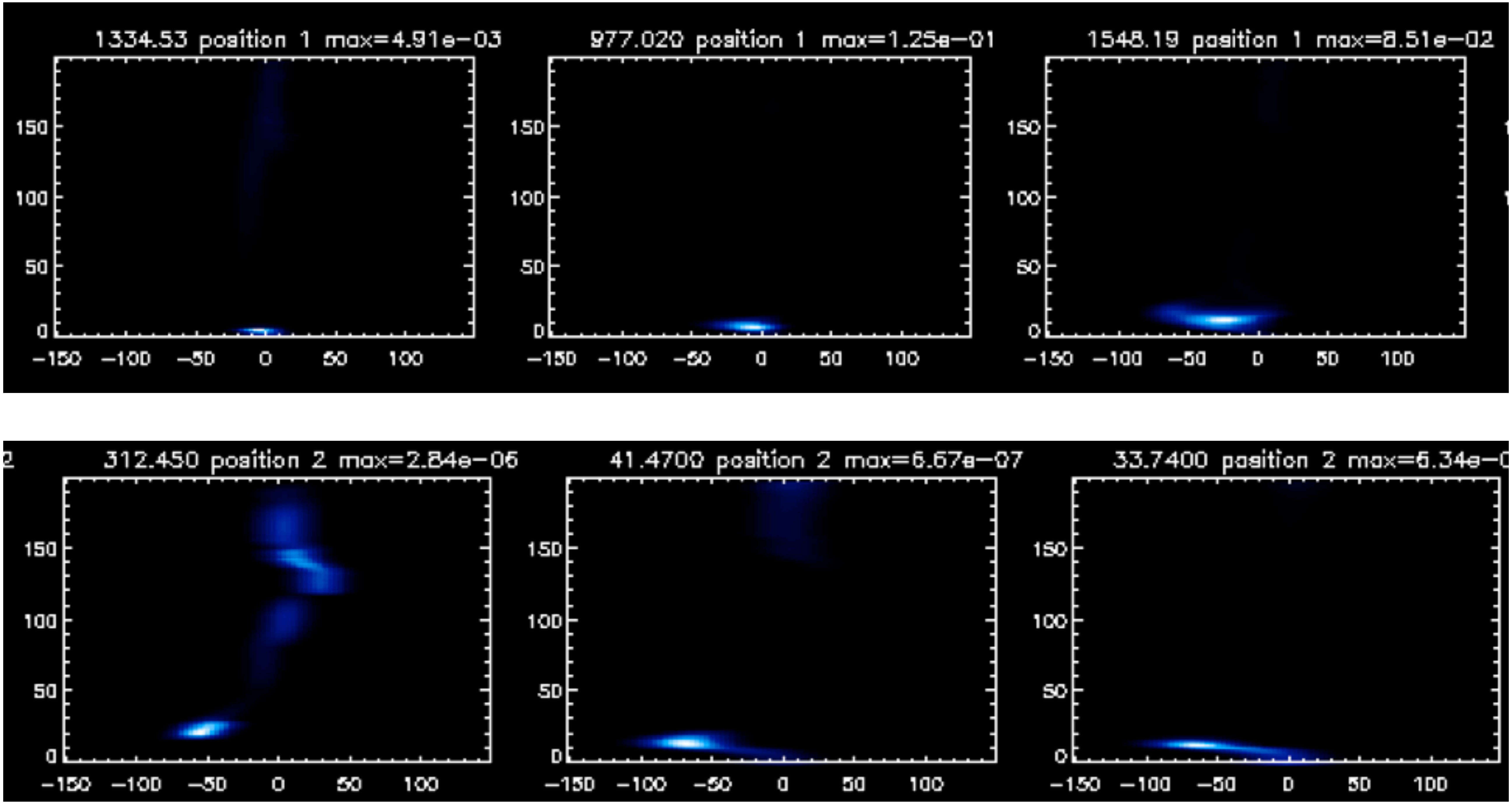
Observations (de Pontieu, McIntosh, ...)

- Type I spicules go up and down, < 40 km/s
  - pressure driven field-aligned flows (Hansteen)
  - no supply of mass to corona
- Type II spicules
  - 50 to > 150 km/s apparent speeds
  - "often disappear over their whole length within one or a few time steps (5–20 s) .. some have apparent velocities >250 km/s"
  - velocity distributions similar to spectra of coronal features
  - On-disk counterparts Doppler motions < 50 km/s (RBEs)
  - estimates between 10^5 and 10^7 on the Sun
- relationships to Beckers' "classical" spicules: unclear

A gas dynamic calculation in 1D: field aligned flows generated by a chromospheric forcing and heating. Atomic systems solved along with gas dynamics


t= 0.00s
ρ g cm^-3
Mm
u km s^-1
Csound
Velocity
T K
E/ρ erg g^-1
Total
KE
Mm
n_e n(H 1+) cm^-3
n_e
H 1+
densities cm^-3
H
He
C
N
O

computed line profiles: carbon II-VI

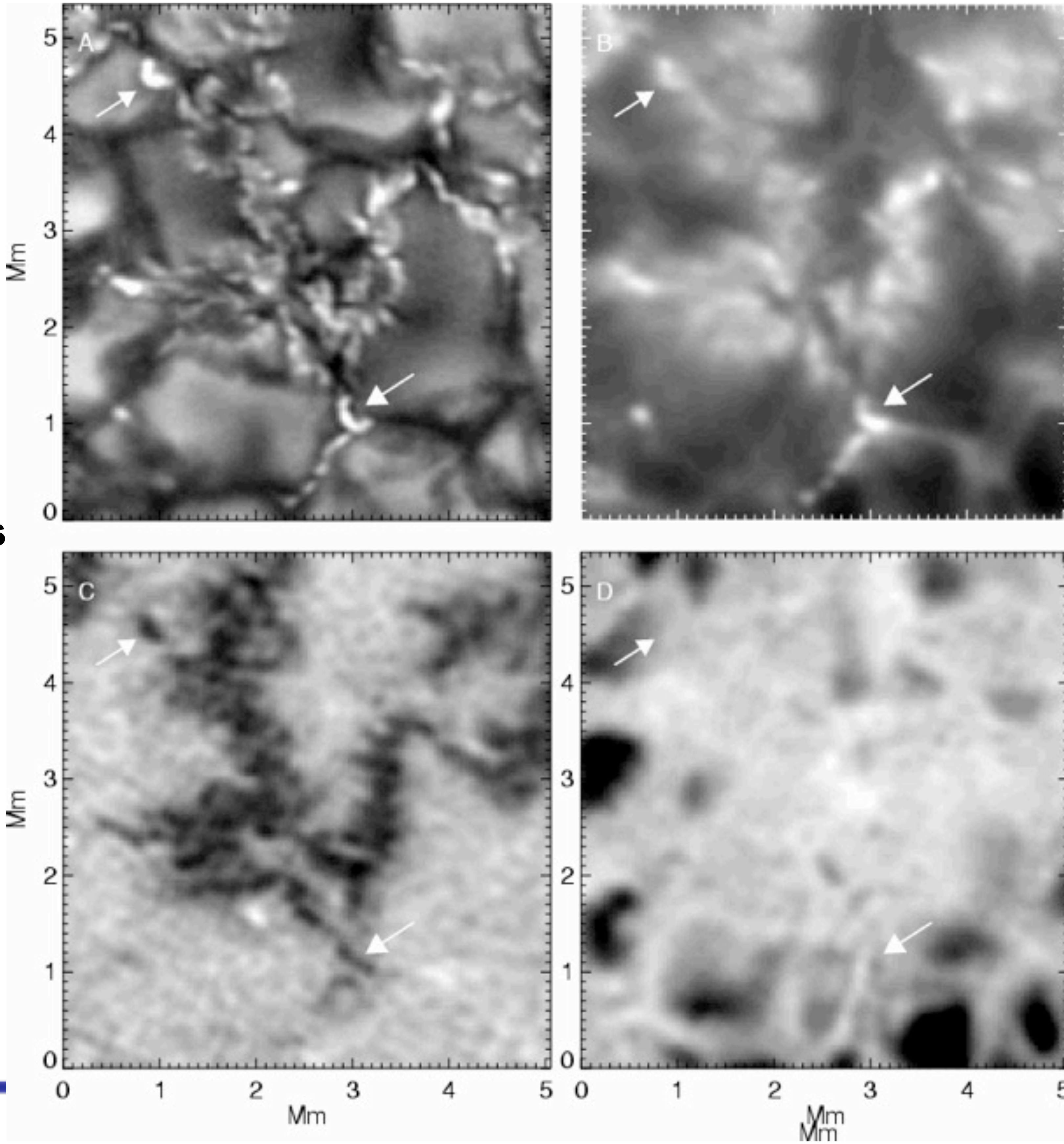


Spicules, coronal heating paradoxes, and other animals

Judge, Tritschler, Low, 2011 ApJL in press

Spicules and fibrils are sheets? Parker's tangential discontinuities?

potentially serious consequences



Data from Berger et al 2004

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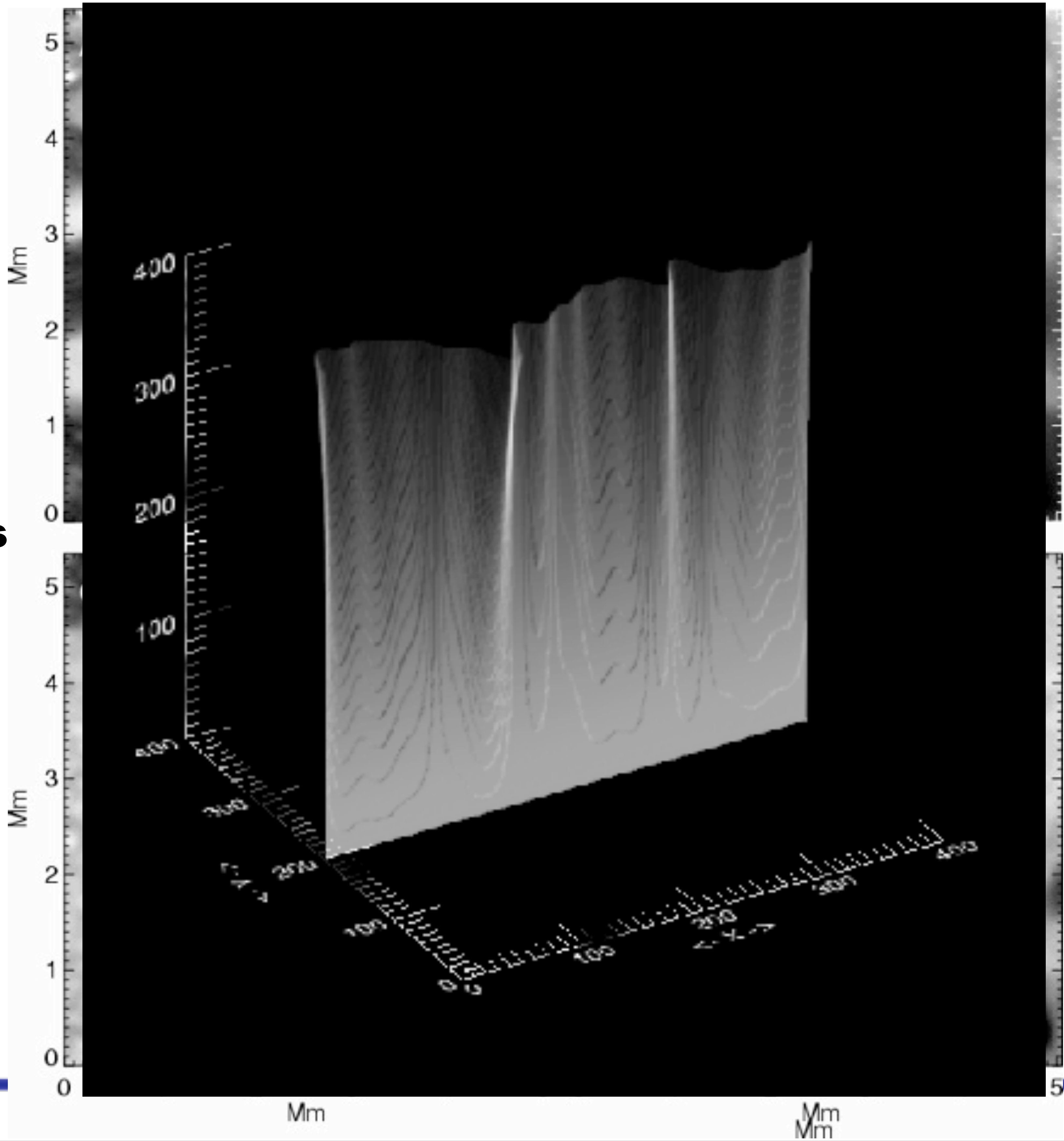
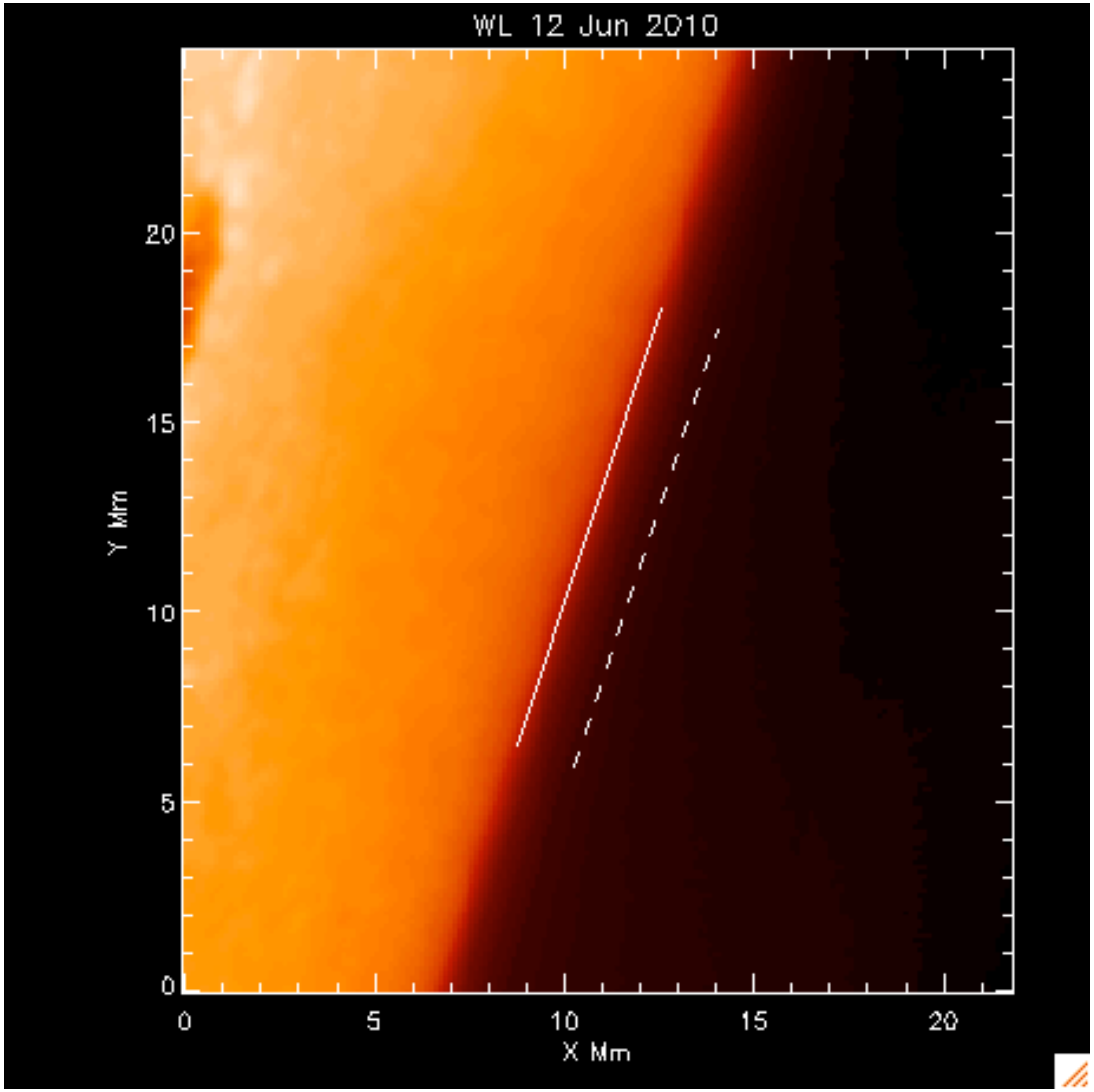


Data from Berger et al 2004


WL 12 Jun 2010
Y Mm
X Mm
0
5
10
15
20
0
5
10
15
20

the chromosphere:

why should anyone care?

You should, if you care about...

- the corona
- space weather
- partially ionized plasmas
- dynamos
- heliospheric UV radiation
- the transition region
- solar MHD

HAO

the chromosphere:
why should anyone care?
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(Oh, and the chromosphere too)

HAO