Spectral Characteristics of the Solar Transition Region

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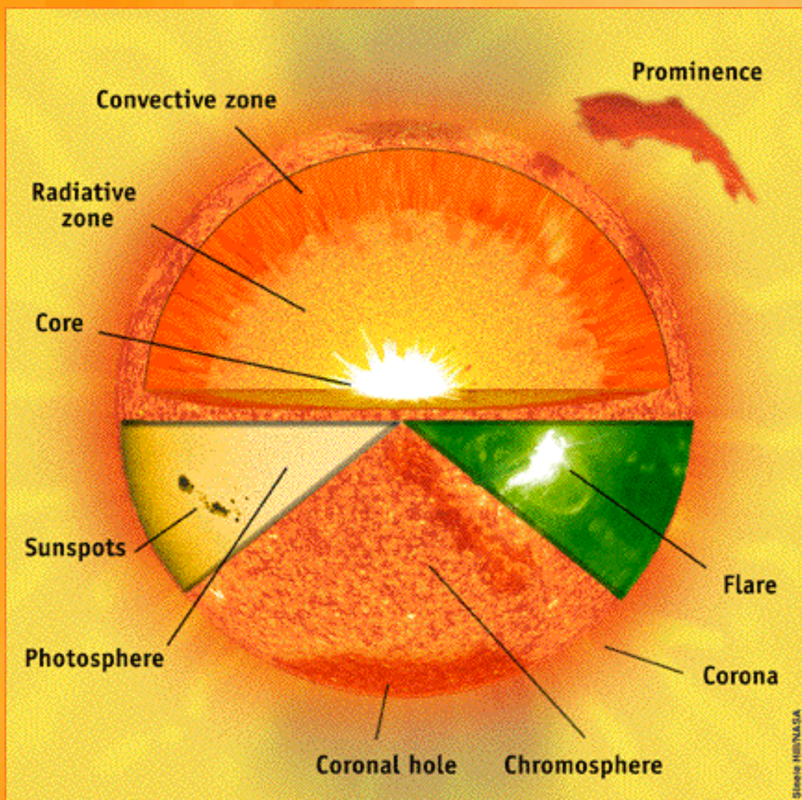
Mentor: Scott McIntosh (HAO)

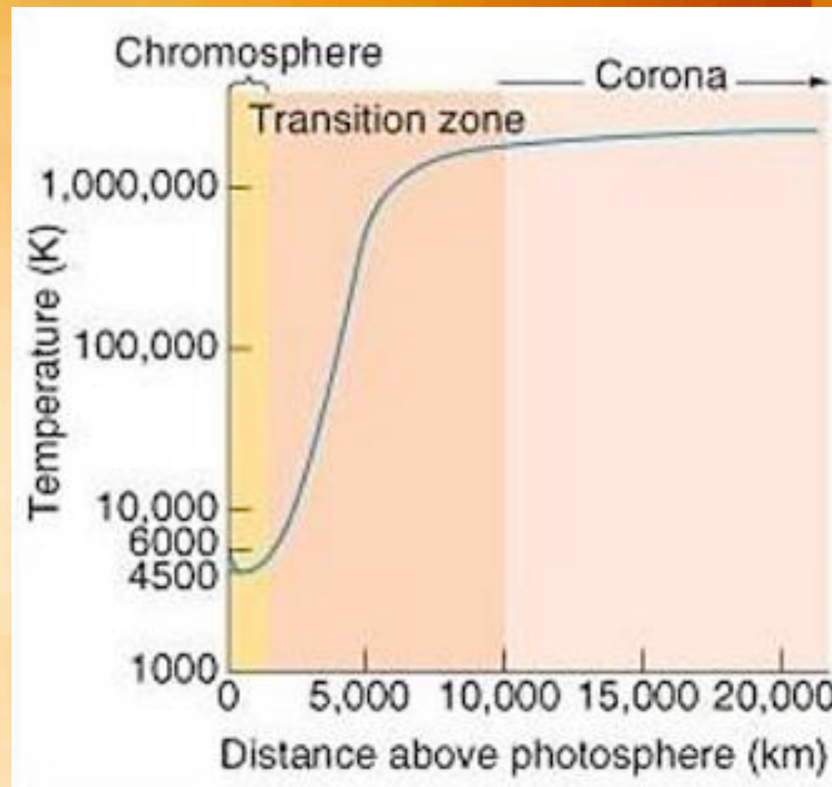
The Coronal Heating Problem

The Structure of the Solar Atmosphere:



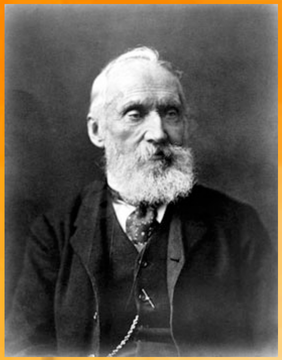
- Photosphere: the ‘surface’
- Chromosphere: up to about 10,000 km
- Transition Region: ~100km thick
- Corona: extending out to millions of km

Looking at the temperatures….



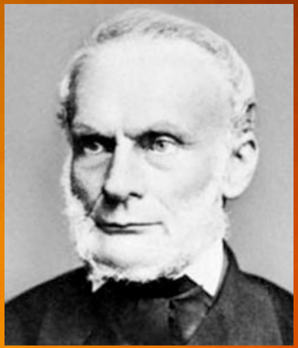
… a very large and sudden increase is observed outward through the transition region. (10^4 to 10^6 K)

Lord Kelvin



So what's the problem?

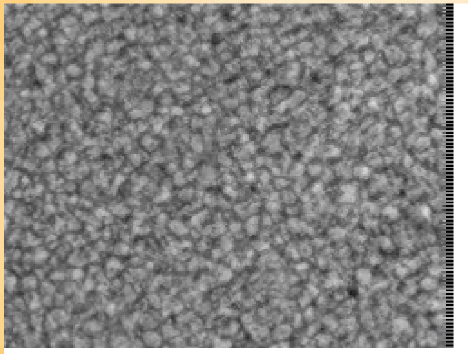
Rudolf Clausius

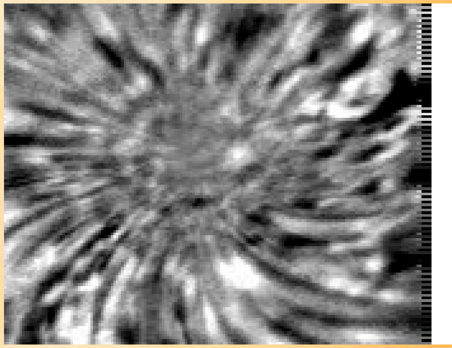


- The Second Law of Thermodynamics: heat will not spontaneously flow towards hotter temperatures.
- Then how can the sun's energy production create an outwardly increasing temperature gradient in the atmosphere?

The answer is that the sun does not have the uniform, static atmosphere implied by the temperature vs. height plot. There must be some dynamic process that is transporting energy into the corona, allowing it maintain it's hot temperatures.

The not-so-static sun:





videos:
Big Bear Solar Observatory

The question is exactly what dynamic process is responsible for coronal heating…

One Idea: Waves

Hannes Alfven

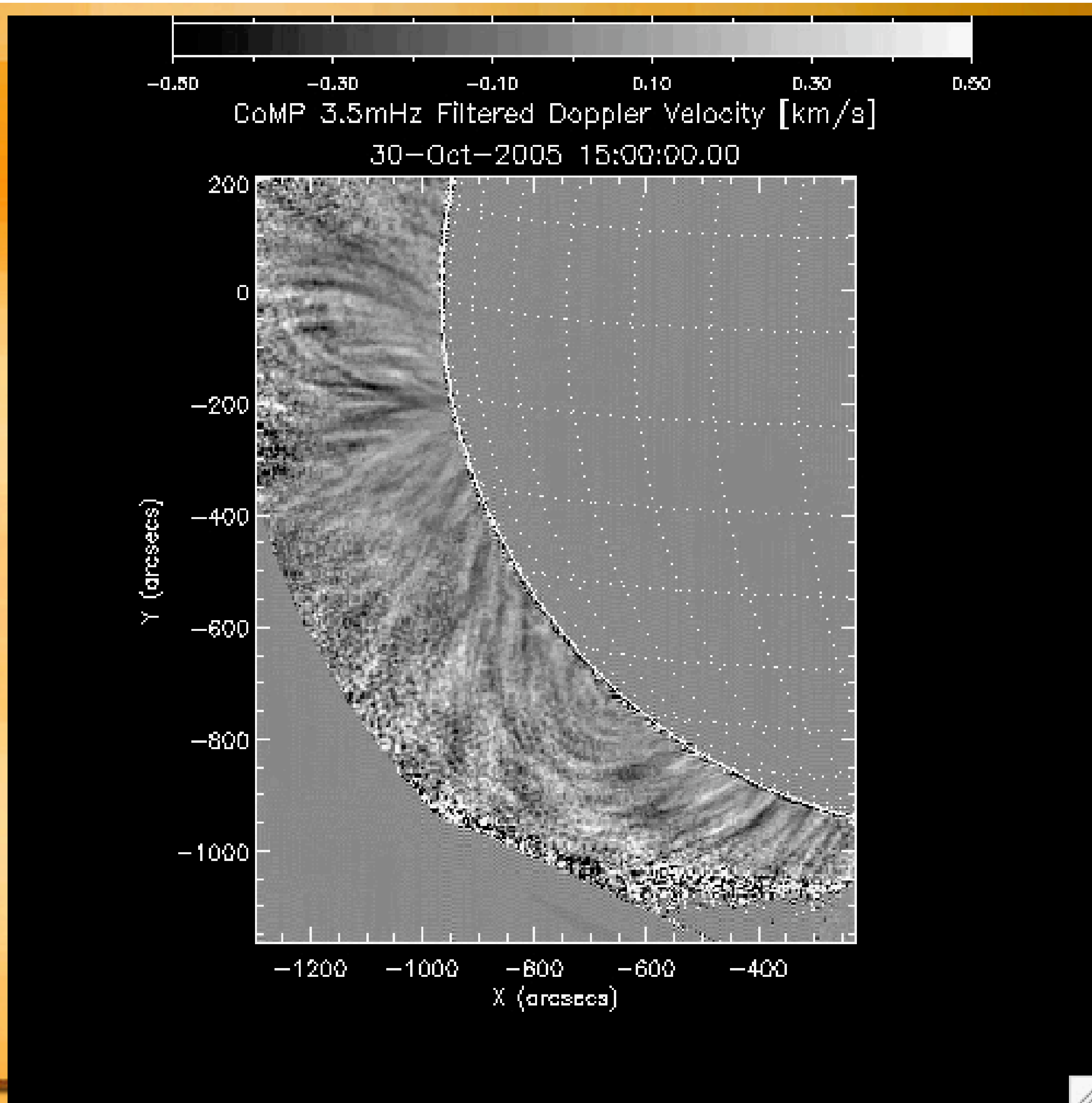
- In 1942, Hannes Alfven proposed the idea of magneto-hydrodynamic waves.
- In 1947, he proposed transverse MHD waves as a likely mechanism behind the heating of the solar corona. Waves are generated at the photosphere and propagate outwards, where they are dissipated into thermal energy in the corona.
- However, a lack of direct 'Alfven' wave observations has kept the theory controversial for 60 years.

It wasn't until 2007 that researchers detected Alfven waves and used these observations to confirm the feasibility of waves as the power source of the solar corona. Much of this work was done locally (Steve Tomczyk and Scott McIntosh of HAO).

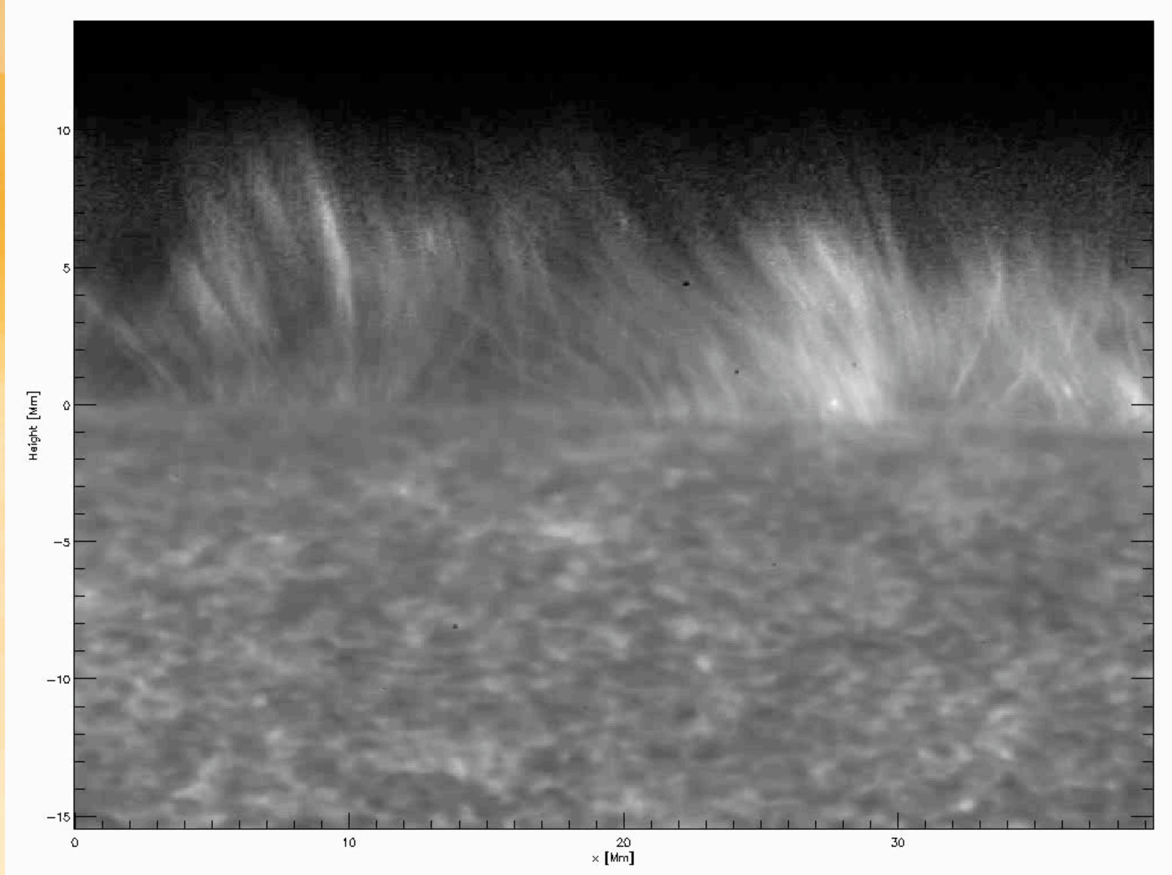
The waves were first observed using HAO's Coronal Multichannel Polarimeter (CoMP), and then seen in the motion of spicules observed by Hinode's Solar Optical Telescope (SOT).

Our research this summer focuses on this 'wave model' of the Coronal Heating Problem.

CoMP imaging of waves:



Hinode SOT imaging of spicule wave motions:



What's a Spicule?

- A short lived 'jet' of plasma extending from the photosphere into the chromosphere.
- Lengths vary from 1000km to 10,000km and widths from less that 120km to 700km
- They act as tracers, allowing us to observe wave motions along the sun's limb. Spicules exhibit significant transverse motions at ~20 km/s.

Two Types of Spicules

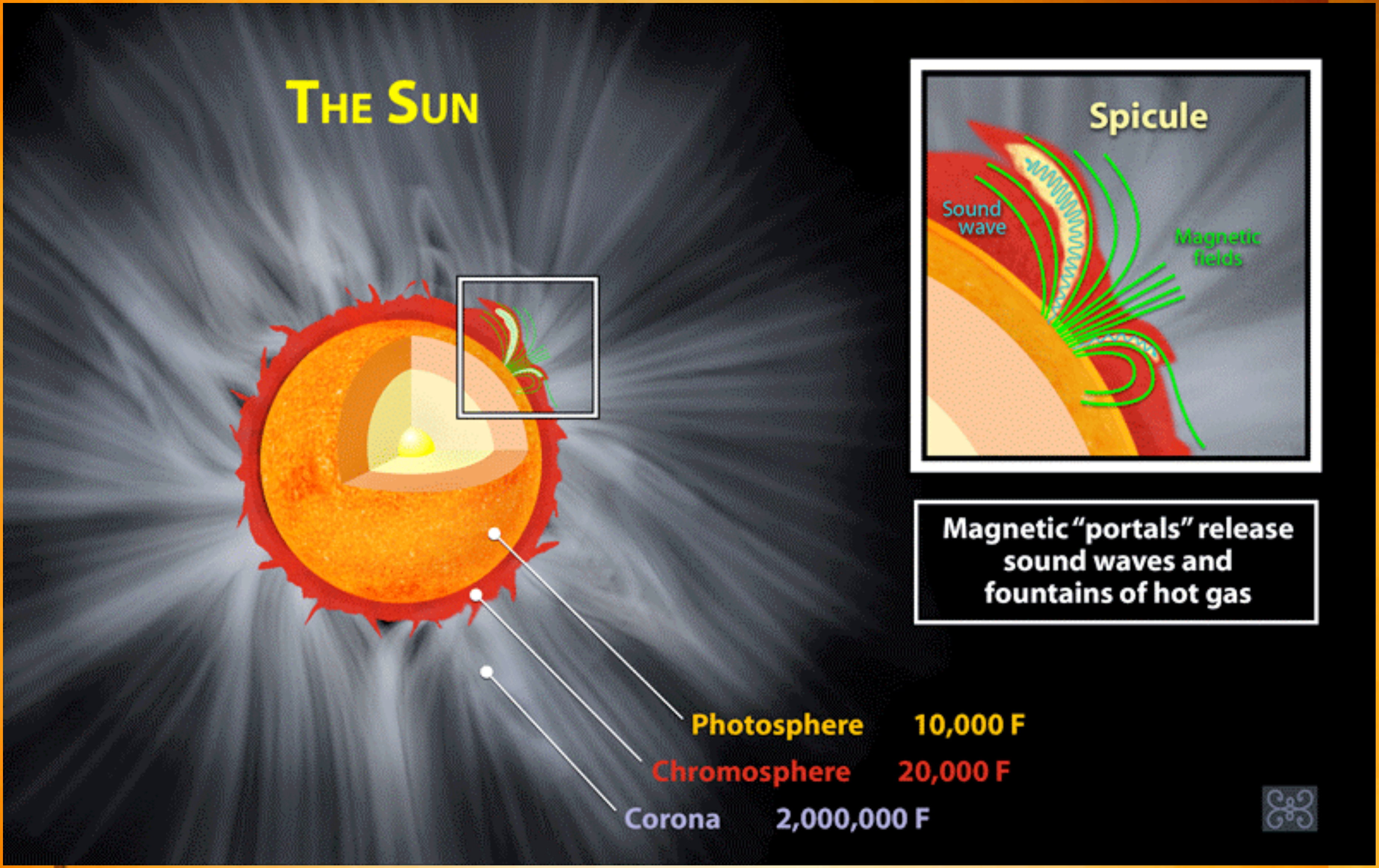
• Hinode revealed a second type of spicule with very different characteristics.

•Type-I: Jets with upward and downward motion. Lifetimes of around 3-7 minutes and maximum velocities of ~40km/s

•Thought to be formed by convective motions and oscillations in the photosphere. On boundaries where the magnetic field dominates they form shockwaves driving plasma upwards.

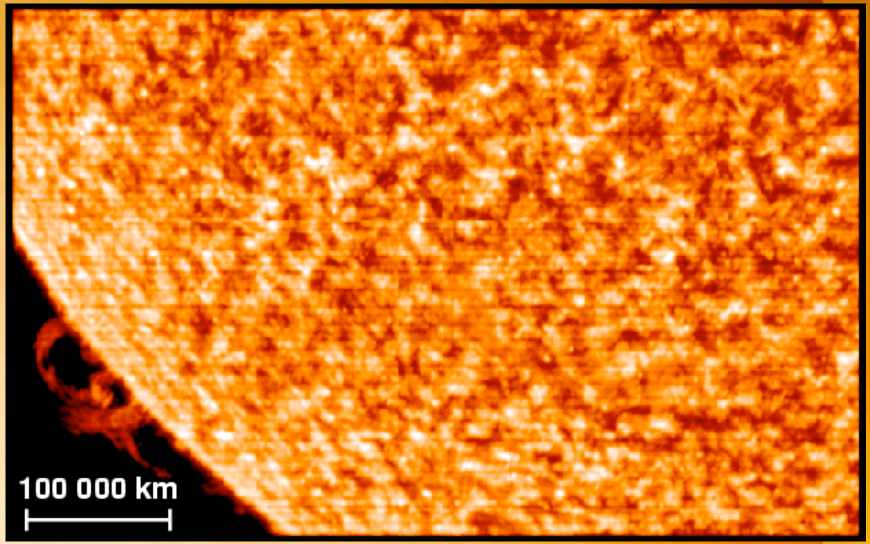
•Their heights (energy) are set by the inclination of the spicule to the field. The inclination lowers the plasma cut off frequency resulting in shorter spicules (vertically). Less Type I's in a coronal hole.

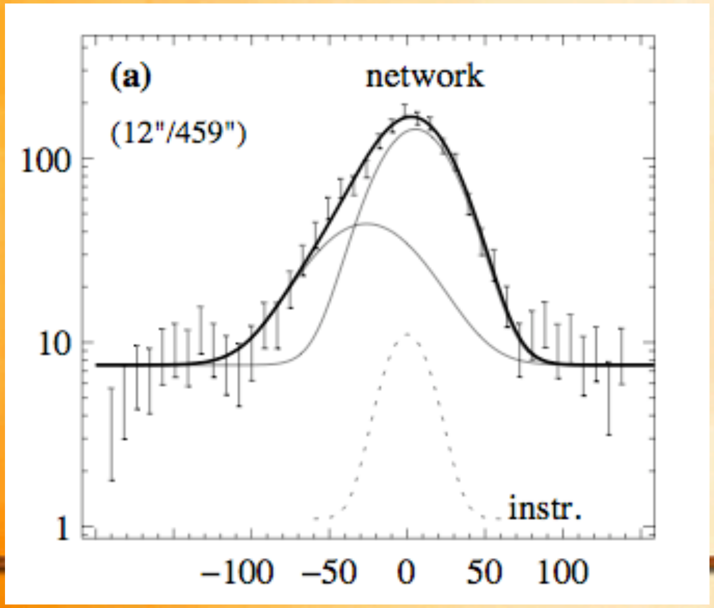
•Type-II: Much fainter with less observed. Lifetimes of around 45 seconds. Only show fast upward motion. Velocities between 50 and 150 km/s. Most have narrow widths < 200 km.


THE SUN
Spicule
Sound wave
Magnetic fields
Magnetic "portals" release sound waves and fountains of hot gas
Photosphere 10,000 F
Chromosphere 20,000 F
Corona 2,000,000 F

The Chromospheric Network

- The chromosphere and transition region appear as a patchwork of bright ‘network’ regions of high magnetic activity and darker ‘inter-network’ regions.
- For about 25 years it has been observed that transition region spectra in the active ‘network’ regions deviate from a single Gaussian shape. These emission line profiles are better fit by the combination of a single Gaussian ‘core’ curve and a less intense, broader ‘second component’ Gaussian curve.

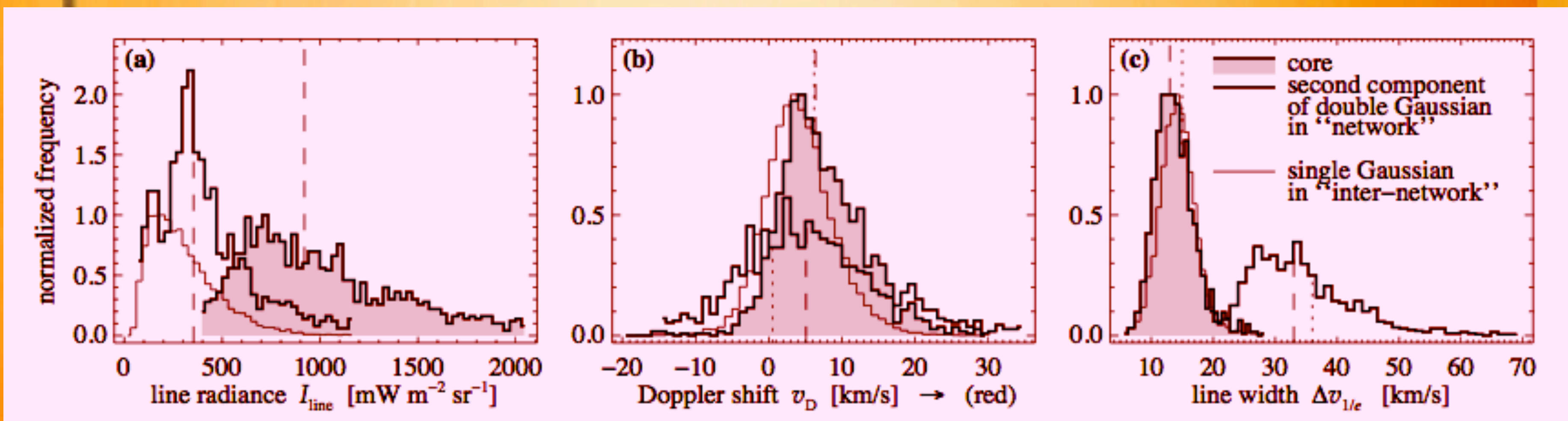




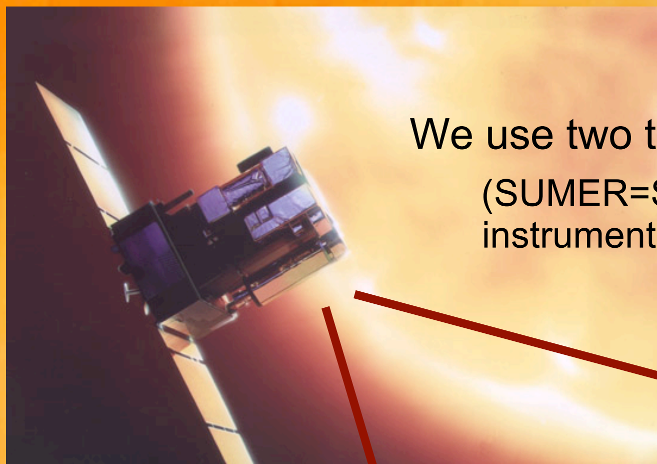
- The two curves are believed to be caused by two different processes/structures in the solar atmosphere that are below the resolution of the observations. However, what exactly is causing the double feature is still under debate.

Line Profiles

- The line profiles exhibit a variety of features.
- In general component is blue shifted relative to the core and broadened further.
- The core component is much brighter ~3-4 times than the second.
- Are these signatures of dynamic spicules? Type II?

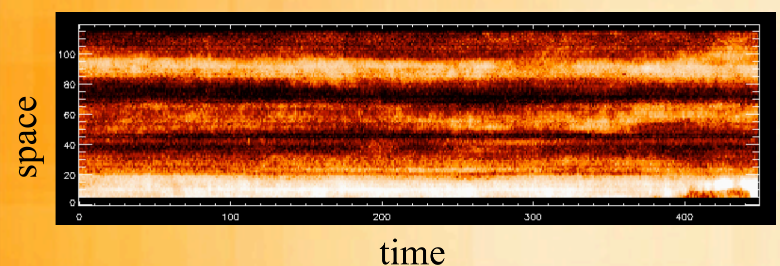


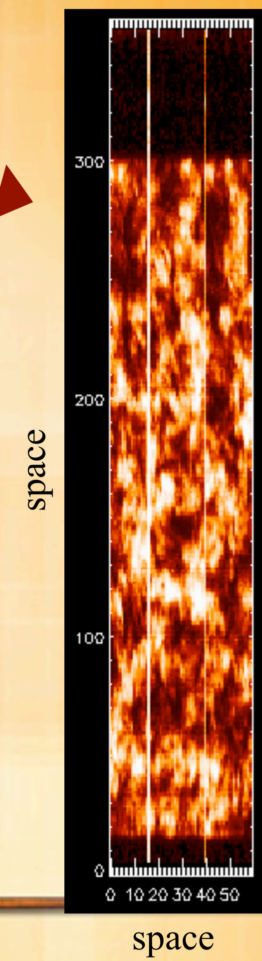
Our Project: Transition Region Spectra



We use two types of SUMER EUV observations:

(SUMER=Solar Ultraviolet Measurements of Emitted Radiation spectral instrument aboard the SOHO spacecraft)





'Raster' Images

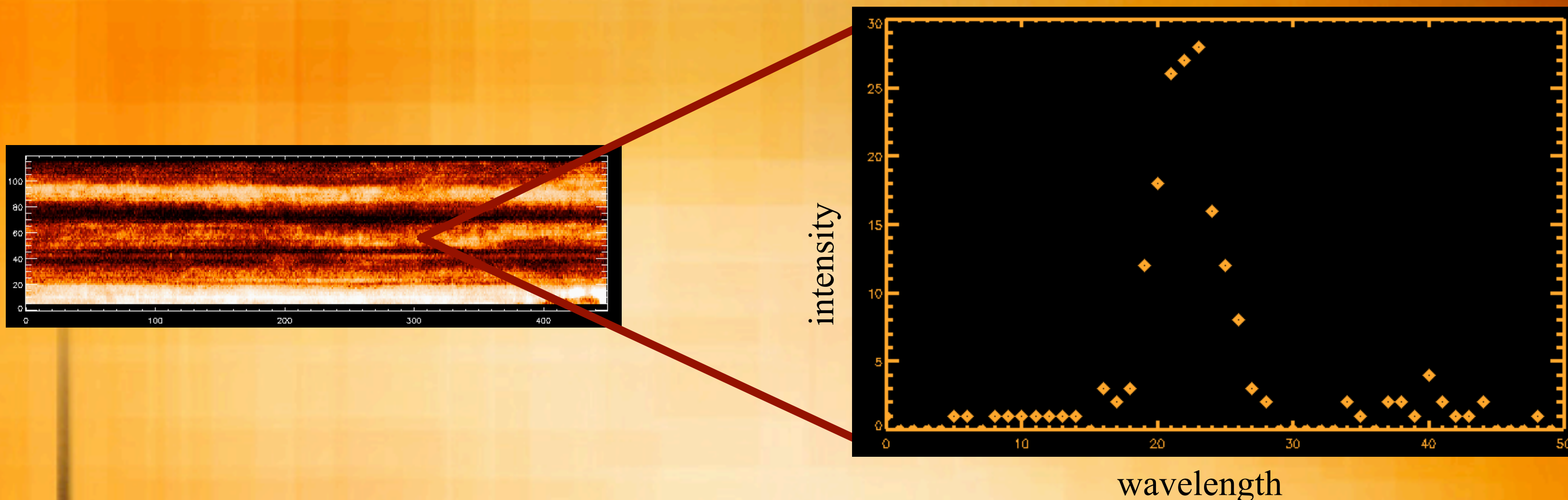
- Observe a 360'' by 120'' area of the sun by sequentially taking 360'' by 1'' slit spectrograph images
- N IV, C IV, Si II, Ne VIII, O VI emission lines

'Sit and Stare' Images

- Observe the same 120'' by 1'' slit of the sun for multiple time steps
- Images for six different emission lines

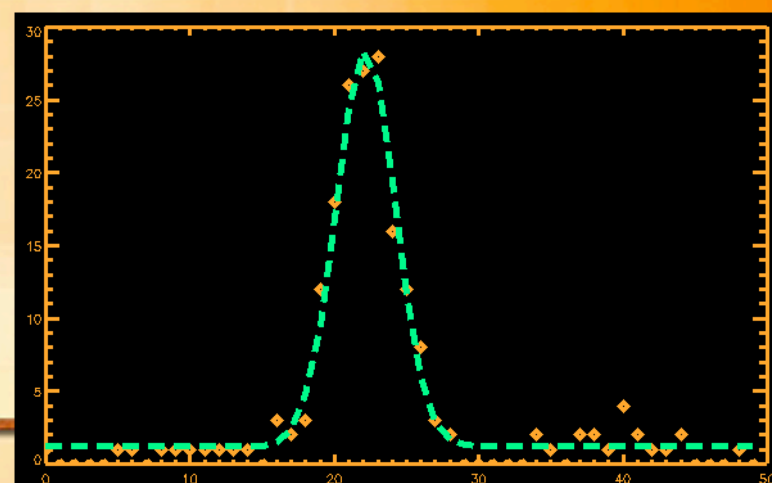
  (758,760,765,770,780,786 angstroms)

Every pixel in each SUMER image contains spectral data:



Currently, our work involves fitting Gaussian curves to the spectral profile from every pixel in each SUMER image.

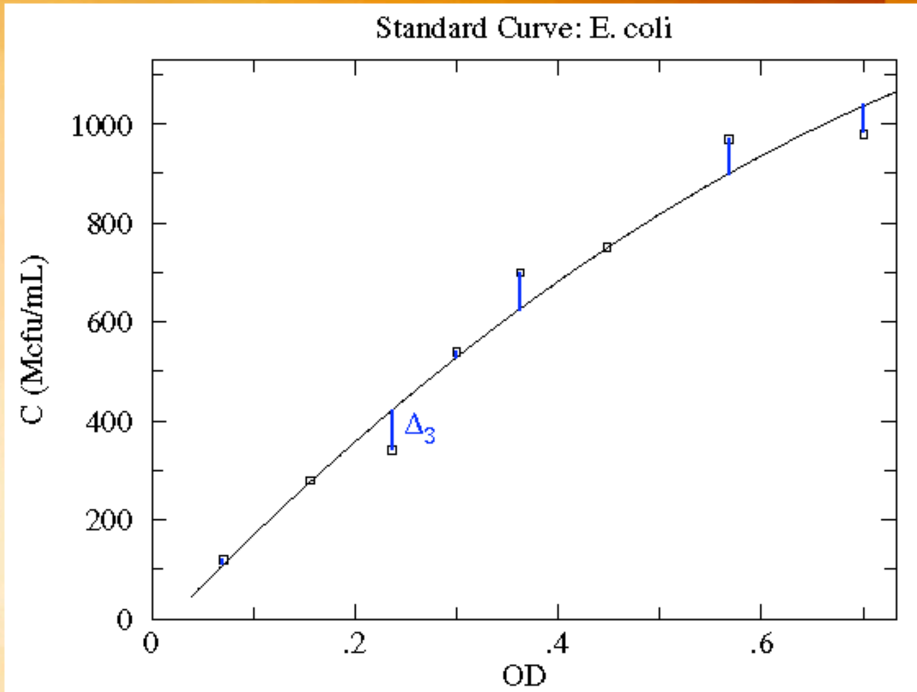
To do this, we use Genetic Algorithms along with traditional “downhill slope” maximization/minimization procedures in IDL.



What's a Genetic Algorithm?

- To determine a Gaussian curve for a given spectra, we try to minimize the 'X^2' value, which is a measure of the goodness of fit of the curve to the actual data.

$$\chi^2 = \frac{\sum_{i=1}^{ndata} \frac{(real_i - model_i)}{\sigma_i^2}}{ndata - nparameters}$$



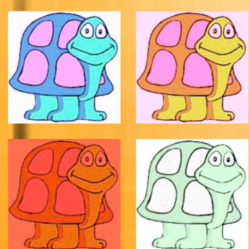
- While traditional derivative/gradient based minimization techniques are very fast, they are heavily dependent on an initial guess, and can easily become 'stuck' in a local minimum of a function, instead of finding the global minimum.
- One solution is a brute force style approach of randomly testing a huge number of curve parameters until a good fit is found. However, this is very slow.
- A Genetic Algorithm improves upon straight random number generation.

- A Genetic Algorithm (GA) improves this technique by starting with a random 'population' of curve parameters. It then 'evolves' the population through several generations, using rules that mimic natural selection in an attempt to improve the curve parameters.

Genotype: Curve Parameters

Phenotype (fitness): X^2

Random Parent Generation:



Only the fittest turtles can reproduce

Position Width Height	Position Width Height
Position Width Height	Position Width Height

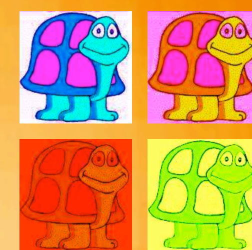
Only the parameter sets with the best X^2 can reproduce

Reproduction:

Turtles' genes are traded and combined. Possible mutations.

Numbers are mixed at arbitrary points. Possible random 'mutation' of digits.

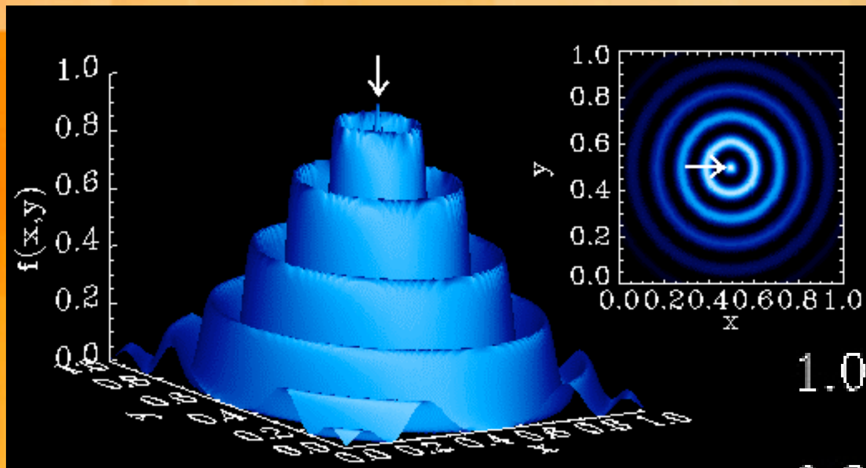
Offspring:



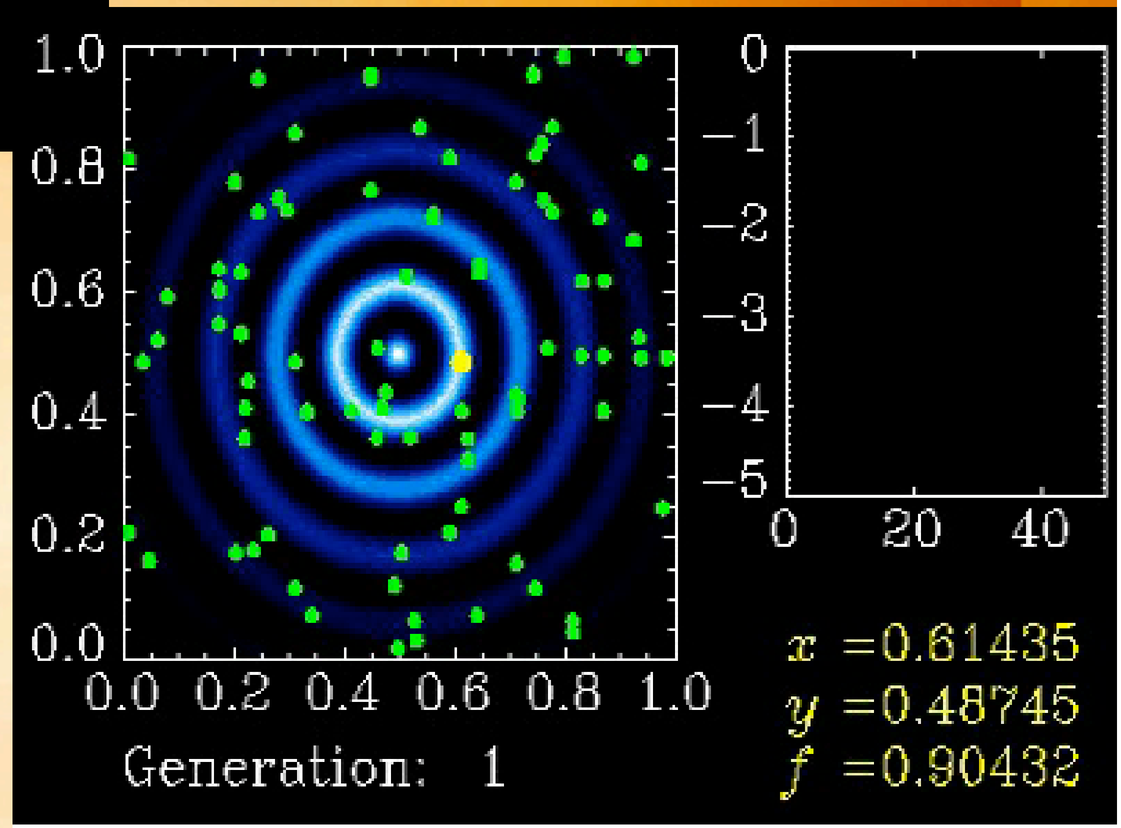
Fitter Turtles!

Position Width Height	Position Width Height
Position Width Height	Position Width Height

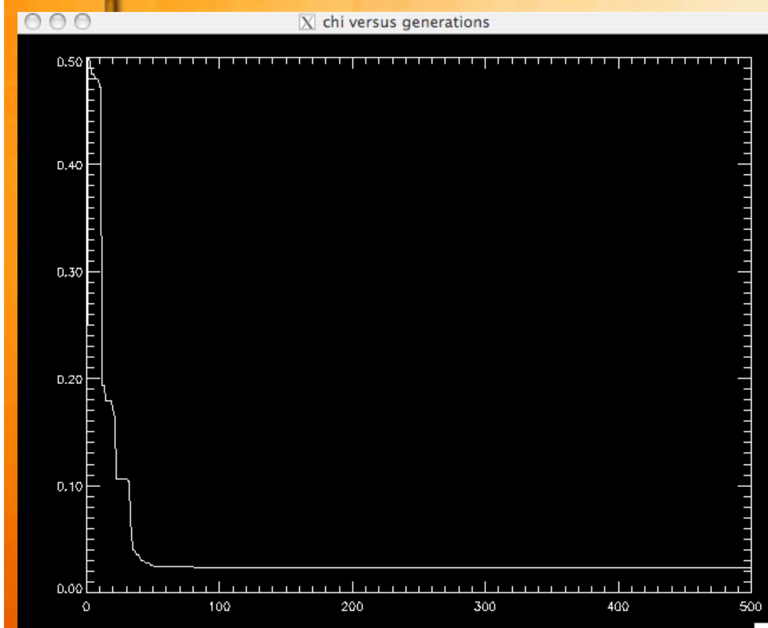
Better X^2 !



"Pikaia" genetic
algorithm example
from HAO website



Chi square progression
from our own GA:



Previous Work…

- One of the main papers dealing with the subject is by H. Peter (2000).
- He found that double-component spectra were 'basically restricted' to the bright chromospheric network.

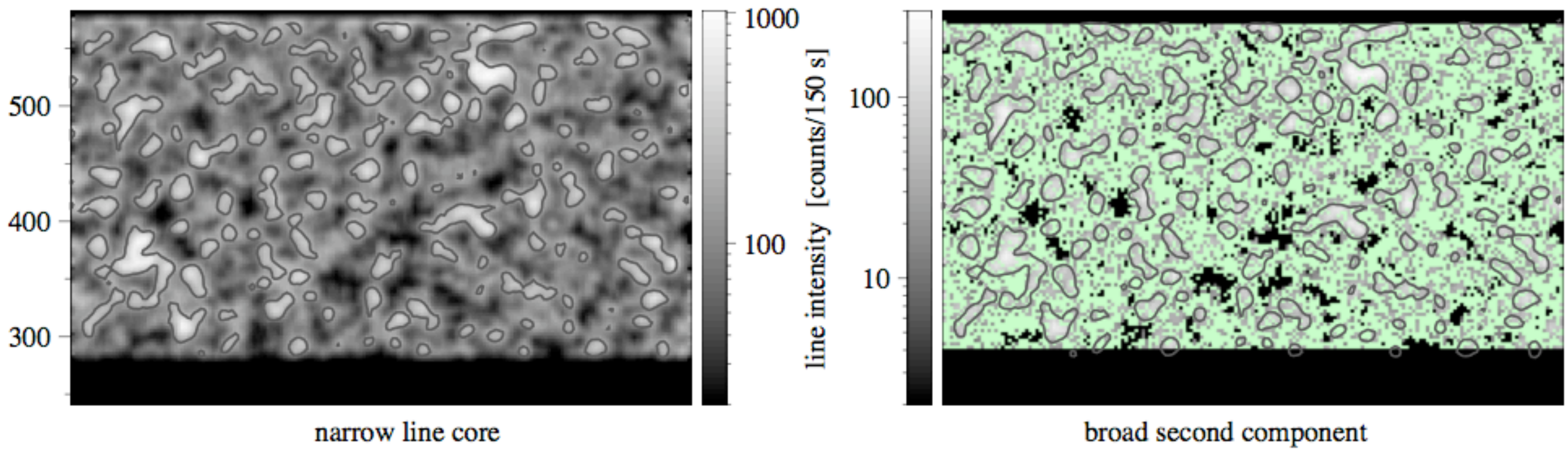


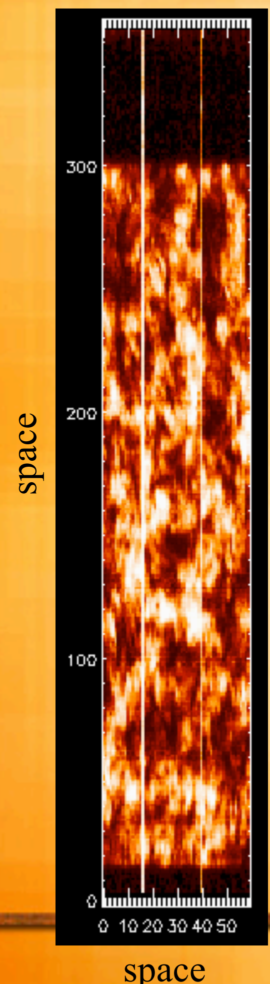
Fig. 3. Spatial image of the line intensity and the line shift of the line core (left) and the second component (right). In the images showing the second component all points, where no second component could be detected, are blended out in green. The black areas mark regions where the signal was too low to perform a reliable fit at all. The contours enclose the bright "network". Please note that the images are plotted using square pixels, but the data are under-sampled by a factor of 3 in the solar X direction.

Peter, H. 2000, A&A, 360, 761

Round One:

- We first ran our completed Genetic Algorithms on a raster image from April 2008 of the Nitrogen-IV emission line.
- We used adaptive pixel binning to improve the signal to noise ratio in dark areas.

Raw Data



Blending

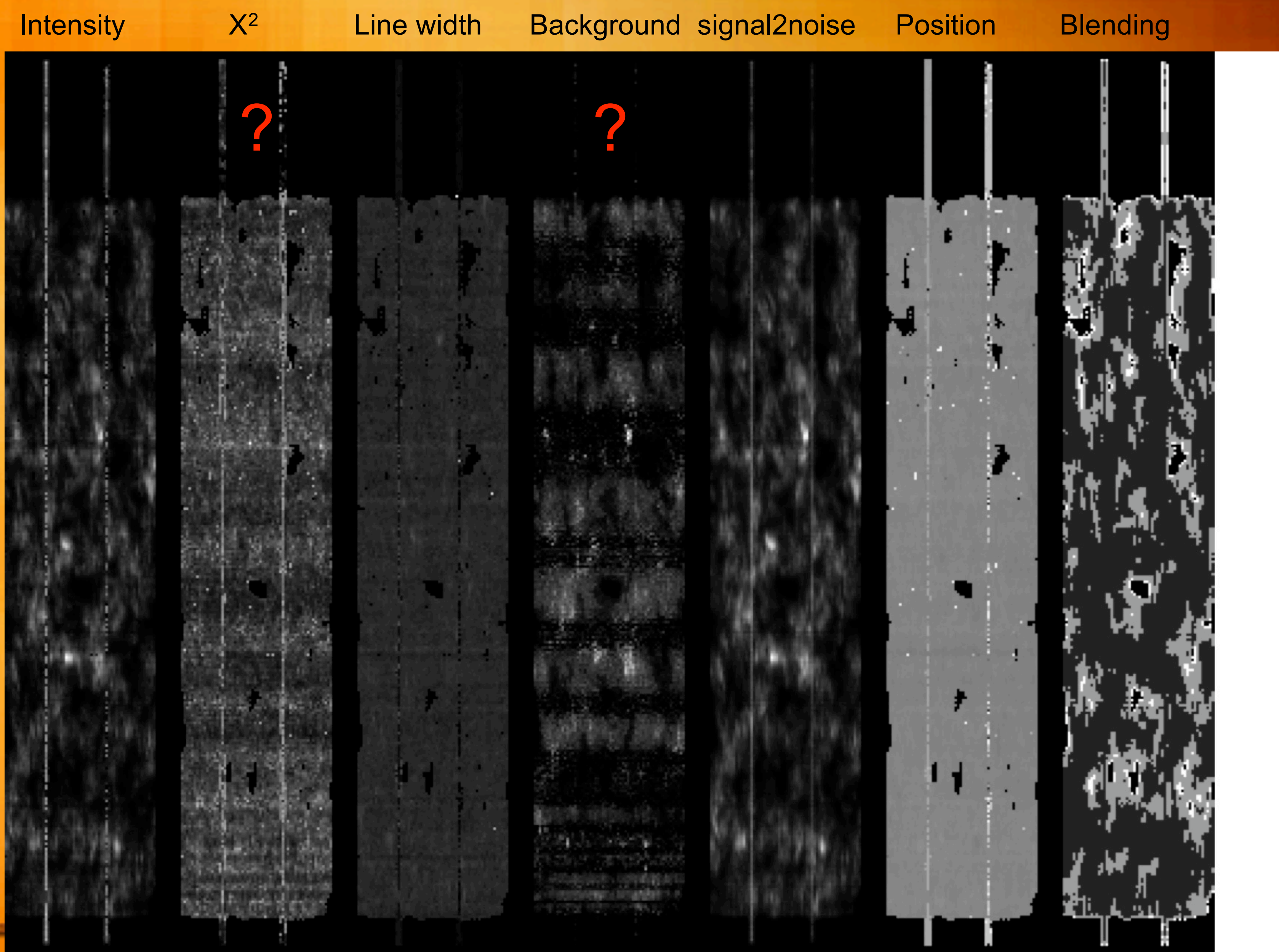
(white = blending)

X^2 Map

a pattern?

(brighter = higher X^2 = worse fit)

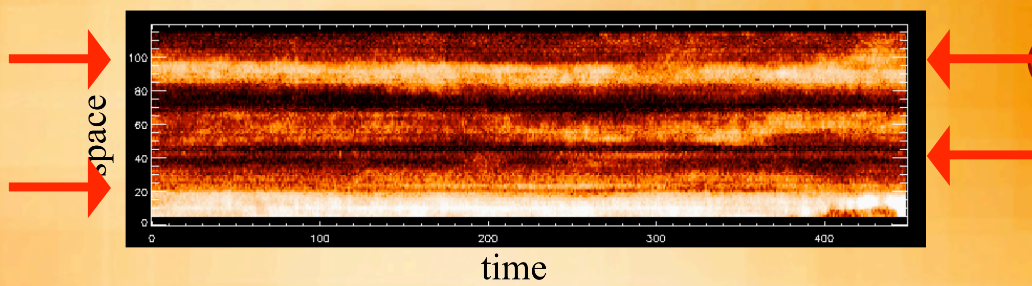
More data from the single Gaussian fit of the Nitrogen raster:



Stripes???

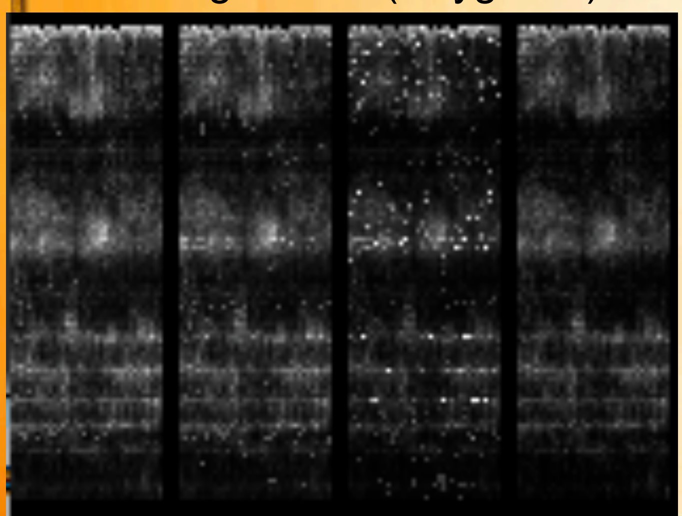
- There was a recurring pattern in our fitted X^2 maps for all the April 2008 data sets and for all the different types of fits we tried (single/double, constant/linear/quadratic backgrounds)…
- But tiger stripes on the sun are definitely not physical…

The other data sets from April 2008 were Sit and Stares:



(binned in time for better signal to noise ratio)

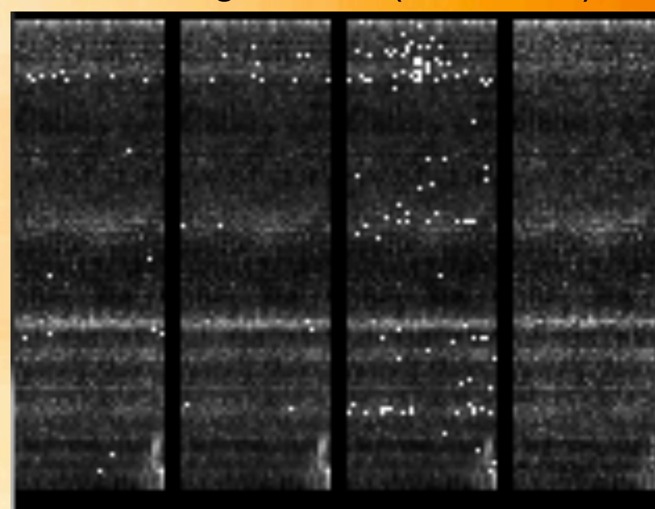
760 Angstroms (Oxygen V)



Constant Linear Quadratic Double

X^2 Maps

770 Angstroms (Neon VIII)

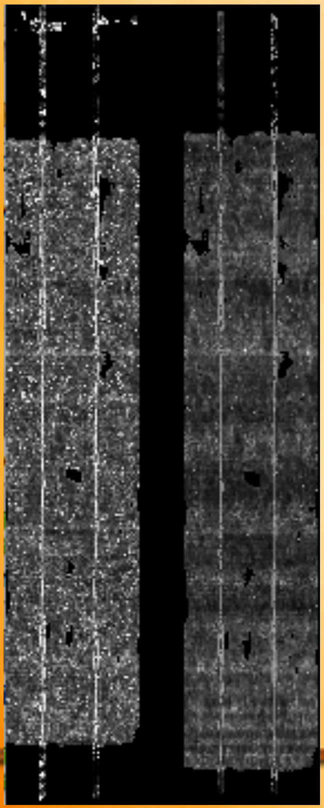


Constant Linear Quadratic Double

What's going on?

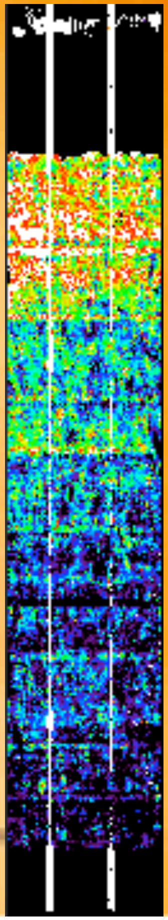
- After making sure the pattern was not an effect of the GA, and knowing the stripes were not physical, we looked to the SUMER data reduction methods.
- One major step in the standard SUMER data reduction scheme is geometric correction for electronic distortion of the image, which can skew line positions.
- The 'de-stretching' of SUMER data has been known to have problems in the past, and after removing this step from the data reduction process, our April 2008 data appeared problem free:

New: Old:

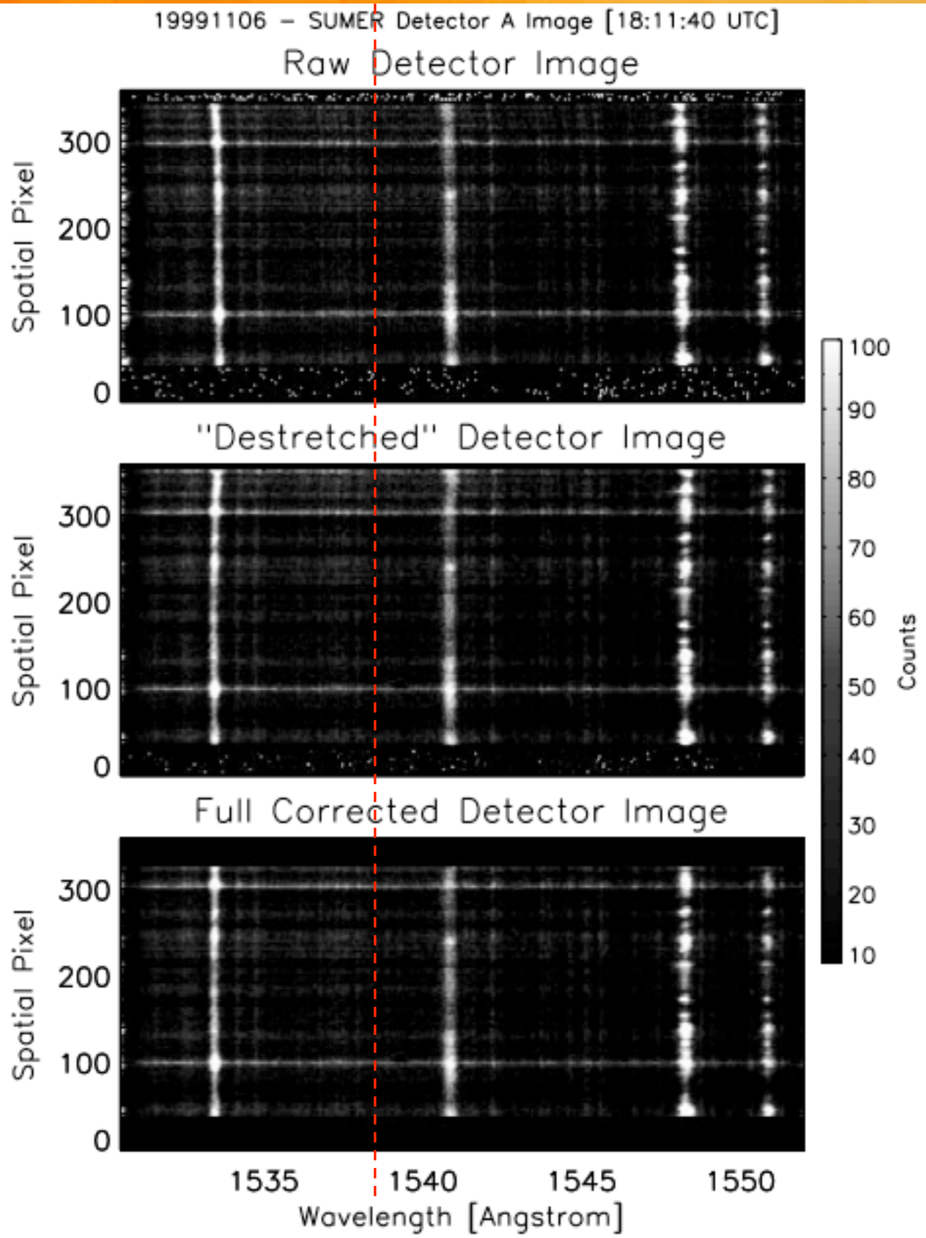


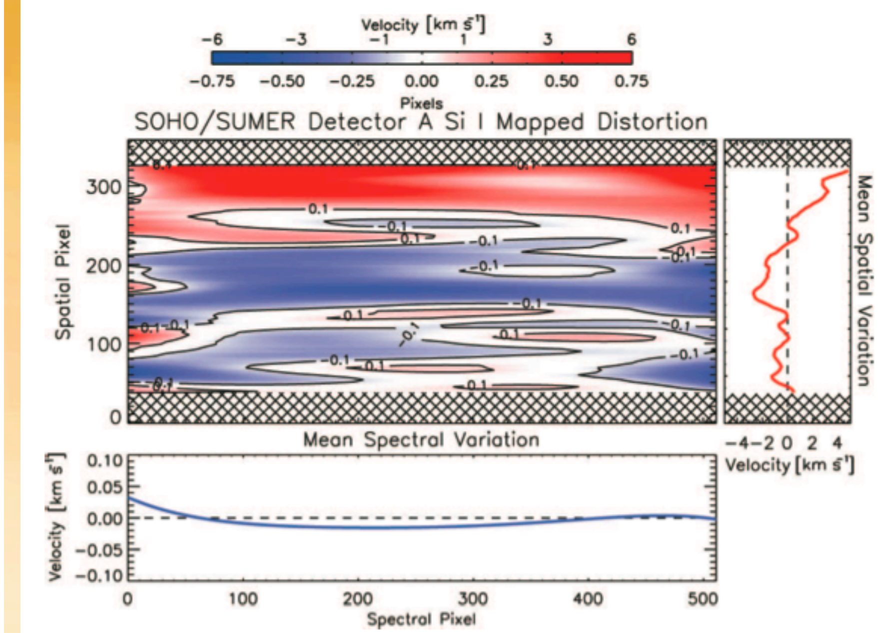
- However, removing the geometric de-stretching leaves problems of non-physical shifted line positions, as you can see in a map of Gaussian center position of the same Nitrogen raster:

  (there is an obvious large scale Doppler shift along a diagonal across the raster)



- Here is an example of a previous investigation of SUMER de-stretching and a solution: (Davey, A.R., McIntosh, S.W., & Hassler, D.M. 2006, ApJ, 165, 386)

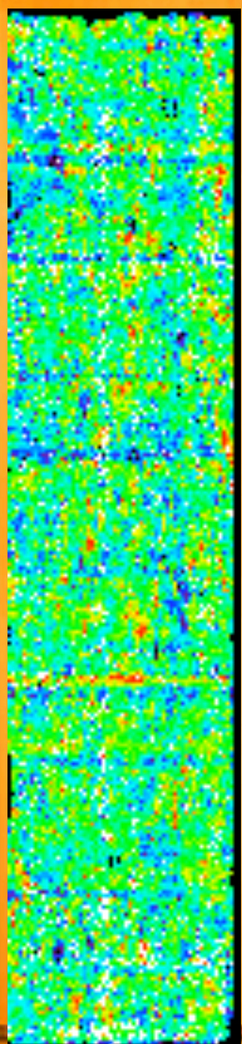




- Large-scale systematic variations can be removed by manually correcting for mean variations across pixels. We used this approach to correct the April 2008 data set.

The corrected April 2008 data:

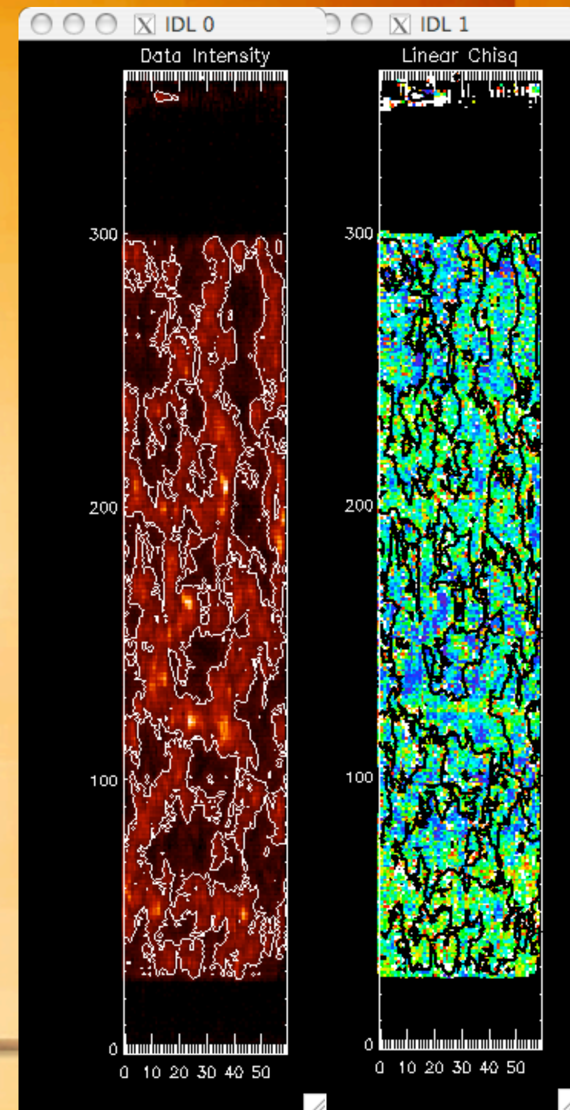
- The position map of the corrected raster. No large scale Doppler variations:



But is it good enough…

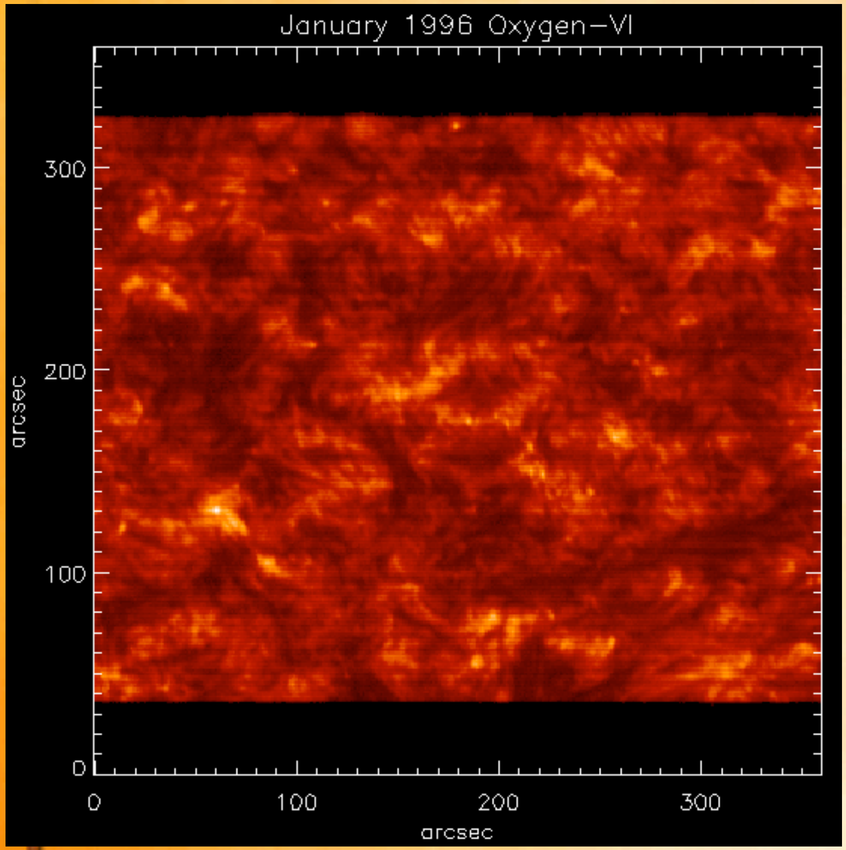
- With the de-stretching corrected and the tiger stripes removed, we were finally able to get a clean view of the results of the GA run on the Nitrogen raster.
- With a single Gaussian fit, we expect to see the bright network in maps of X^2, since the single fits should have difficulty fitting double-components.
- However, after contouring the ‘bright’ network, no such correlation of X^2 is visible.
- Even with heavy binning, most of the April 2008 data turned out to be too noisy and dark to fit reliably (short exposure times, especially for the Sit and Stare images)

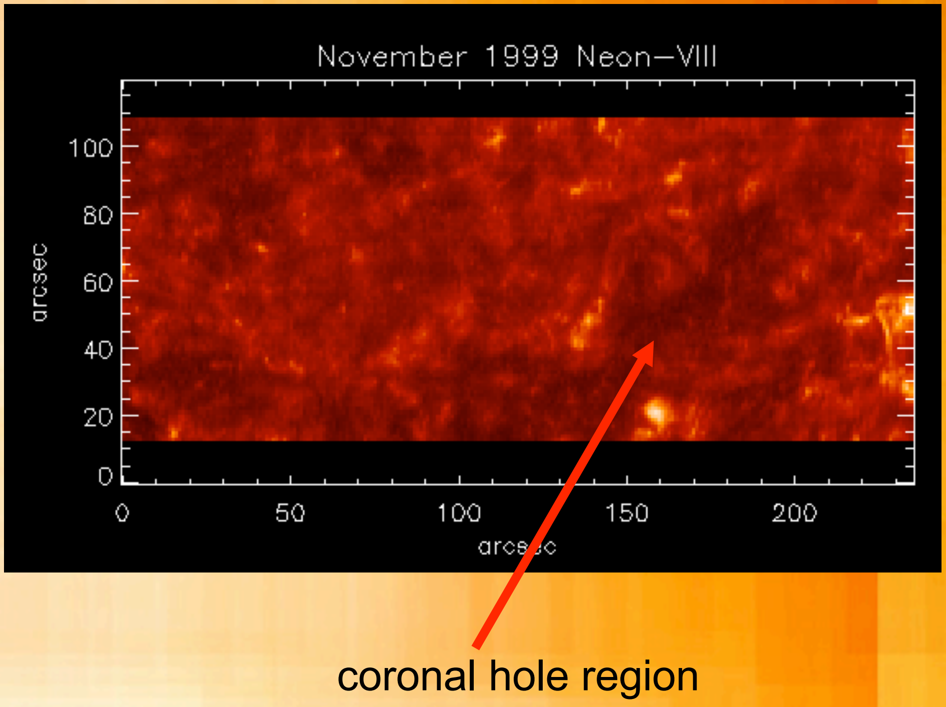
Data Intensity: Single Fit X^2:



A New Hope

- We turned to older data sets from SUMER, including coronal hole data from 1999 and some of the very first rasters done with the instrument on quiet-sun regions in 1996
- These sets have much better signals, due to much longer exposure times than the April 2008 data, and being from much earlier in the instruments life (less degradation due to time in flight).



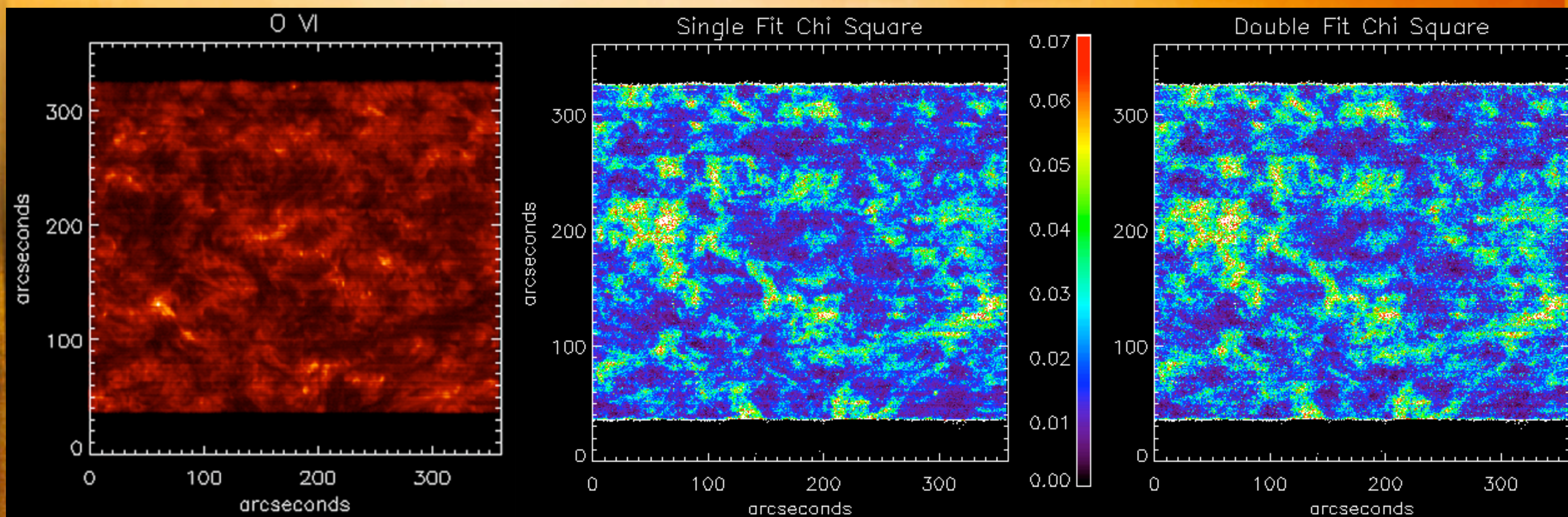


Results

- With the new data, maps of X^2 reveal network structure, which is indicative that our results are physical
- However, we must be careful, since the brightness alone could influence the fits: brighter network regions have a better signal and therefore a lower X^2

Oxygen VI :

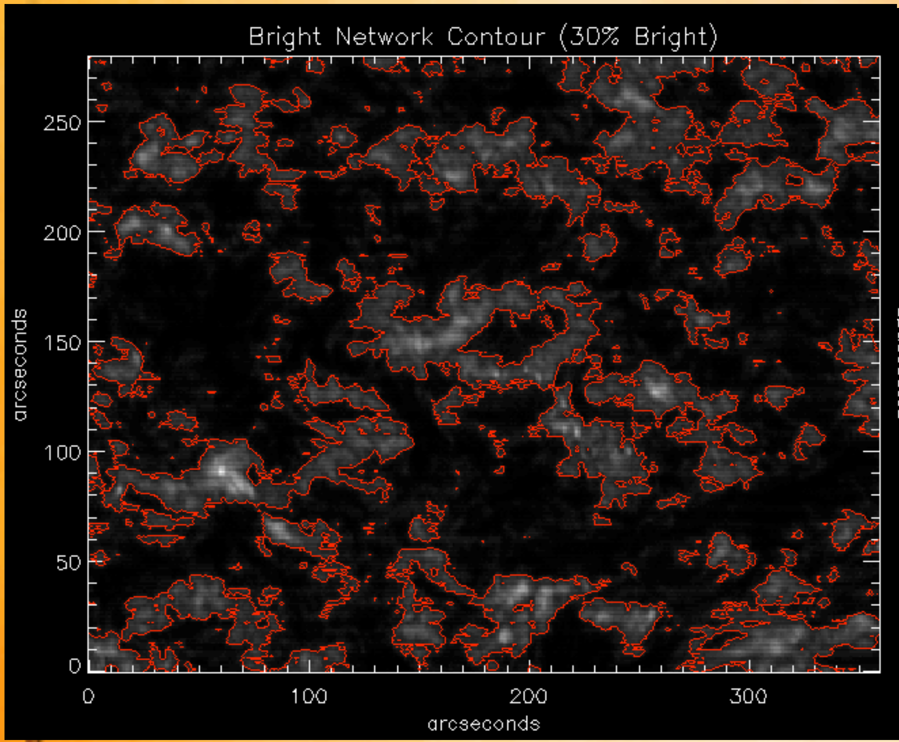
Raw Data Intensity: Single X^2: Double X^2

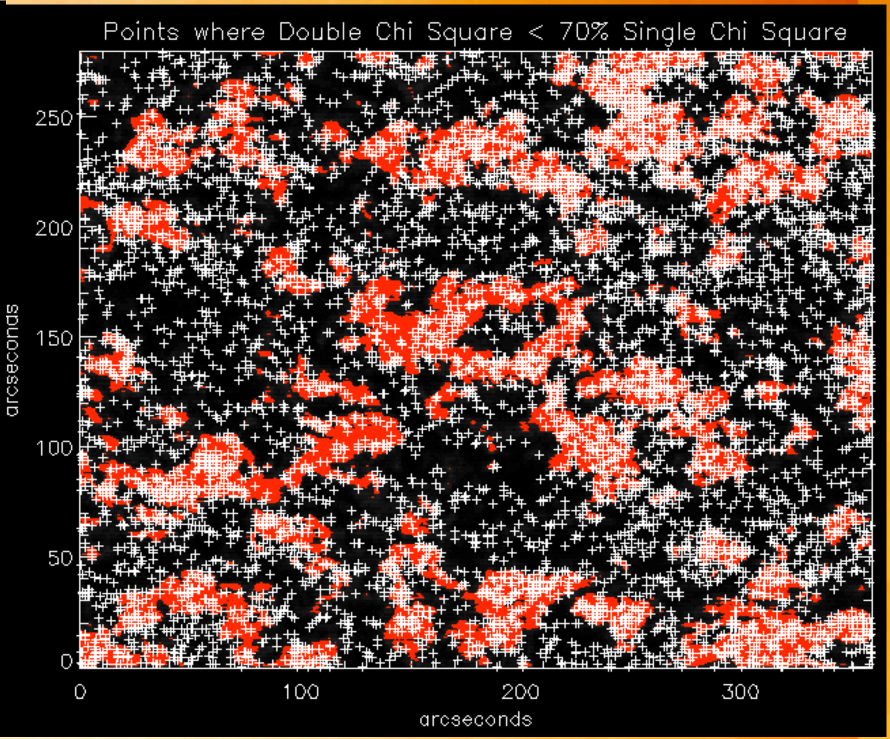


- The clear network pattern in the double fit map shows this effect of improved signal in bright areas: we would expect a more uniform map from the double fits, considering the extra degrees of freedom.
- This effect also dominates the single fits: if our assumption of double-components in the bright network is true, the single fits should be better in dark regions, not worse.

Spatial Structure of Double Components

- The real test we are interested in is how X^2 values compare between single and double Gaussian fits of the same data. This way we can determine what regions can be deemed 'double-component' and which are better represented with just single fits. (and compare our results with previous ones that claim the double-components are limited to the bright network).
- To do the comparison, we necessitate that (double X^2) < constant*(single X^2) in order for a given pixel to be deemed 'double-component'.

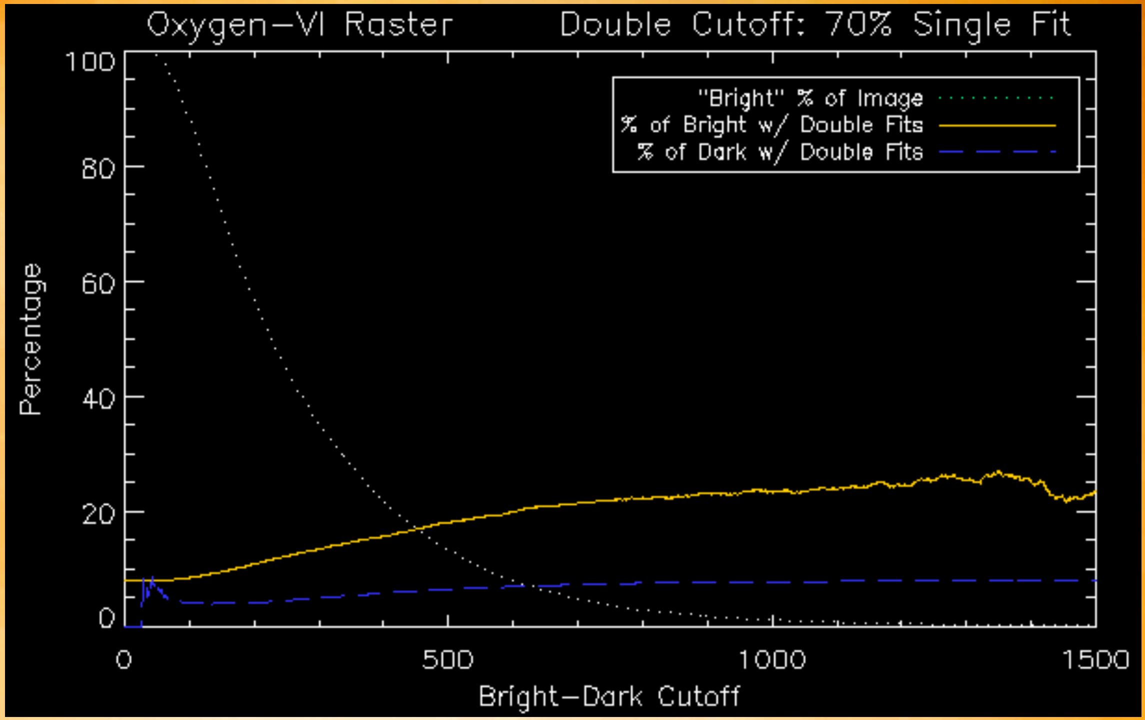




The red contour indicates 'bright' network regions. There does seem to be some correlation between double-component pixels and the bright network.

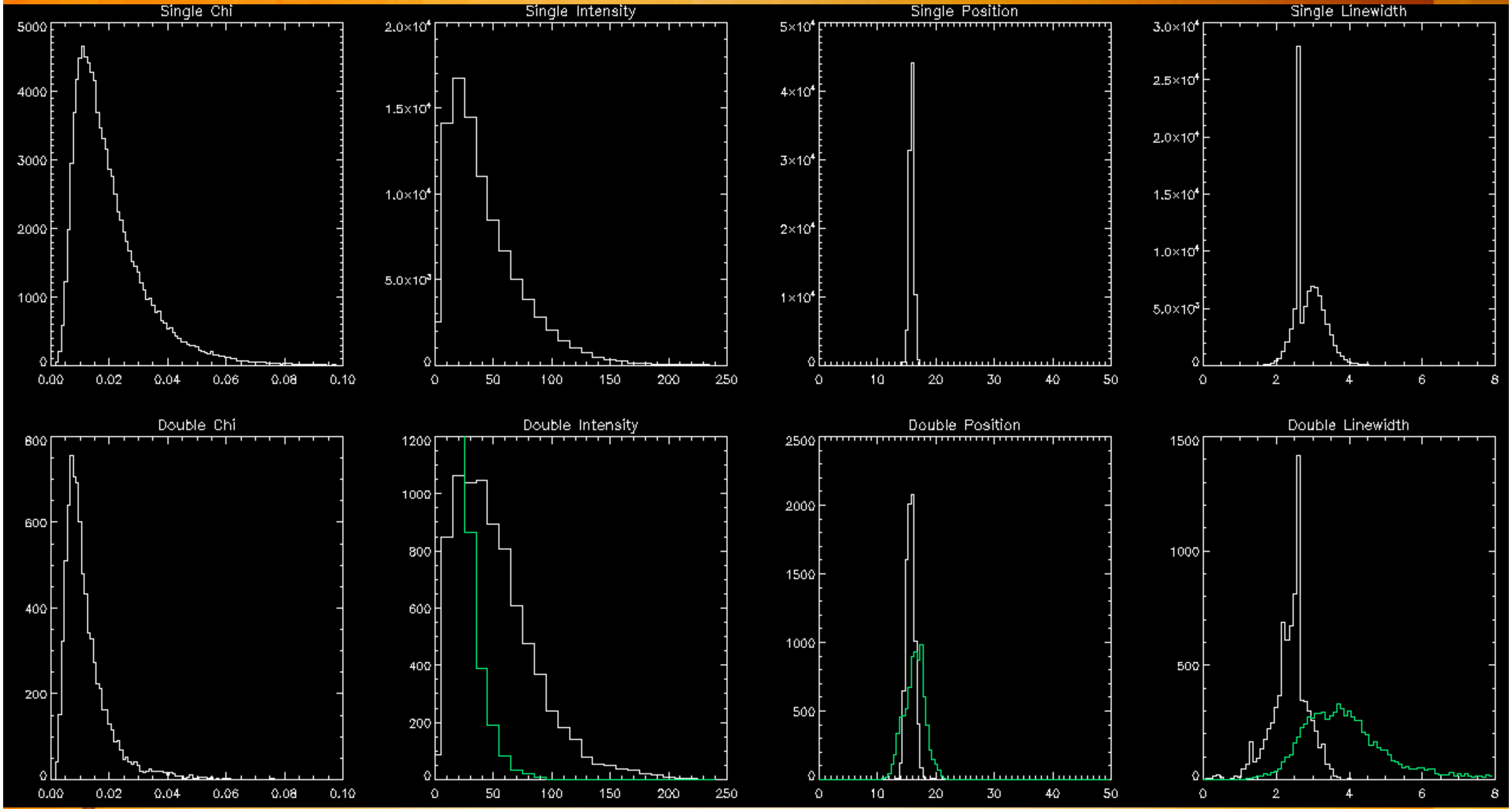
However, 'chiballing' the data is not exactly quantitative….

- A more exact way to tell if the double-components are restricted to the bright network is to calculate the percentage of bright pixels that are double-component fits and the percentage of dark pixels that are double-component fits.
- Plotted below are these percentages for the Oxygen VI raster, as a function of the cutoff intensity that determines 'bright' or 'dark':



So as the 'bright network' is limited to higher and higher intensities, there is an upward trend in the bright double-component percentage, while the dark double-component percentage remains relatively constant. This seems to support the claim that double-components are found in the bright network. However, the percentages are still very low, and the dark network appears to be filled with a constant population of double-components.

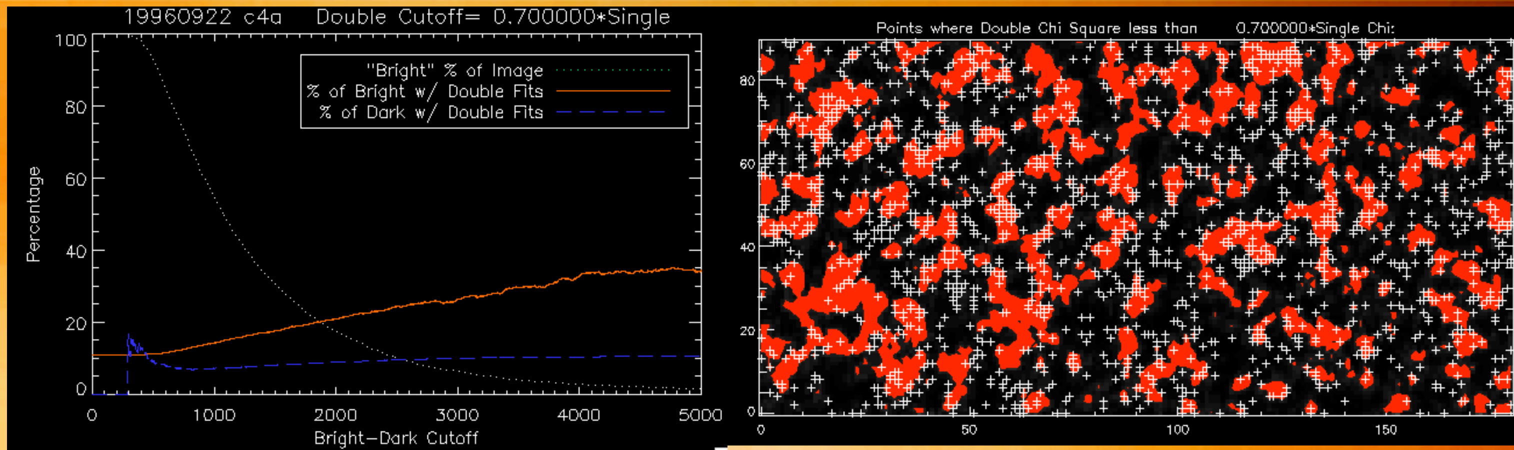
Histograms of single and double parameters of the Oxygen VI raster:



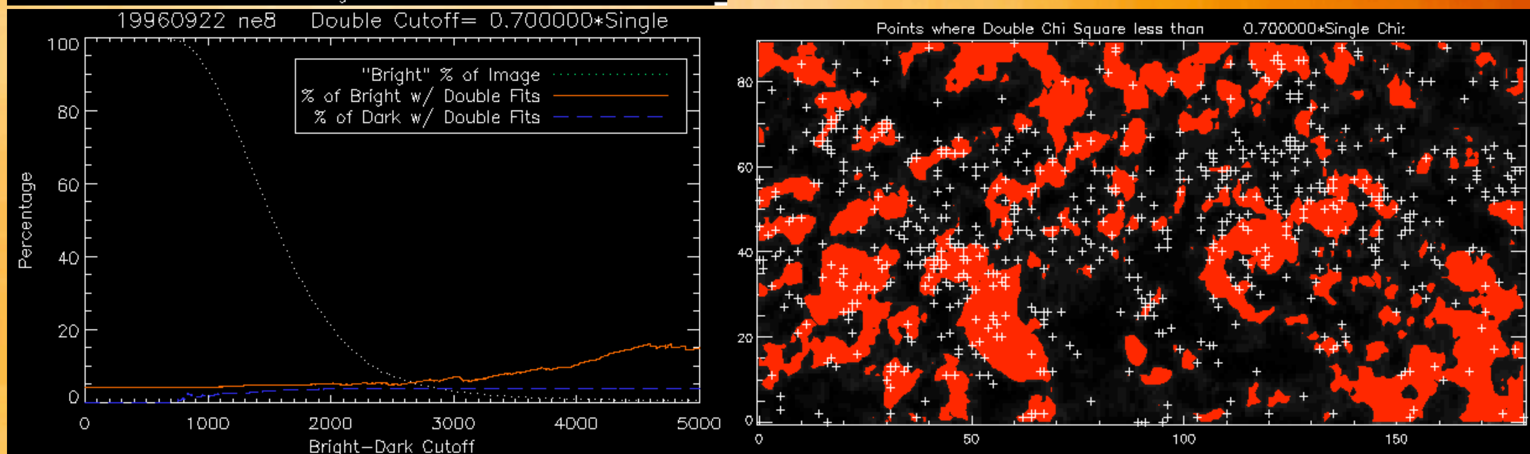
(Green lines are the second Gaussian of the double fits)

- Some examples from other wavelengths:

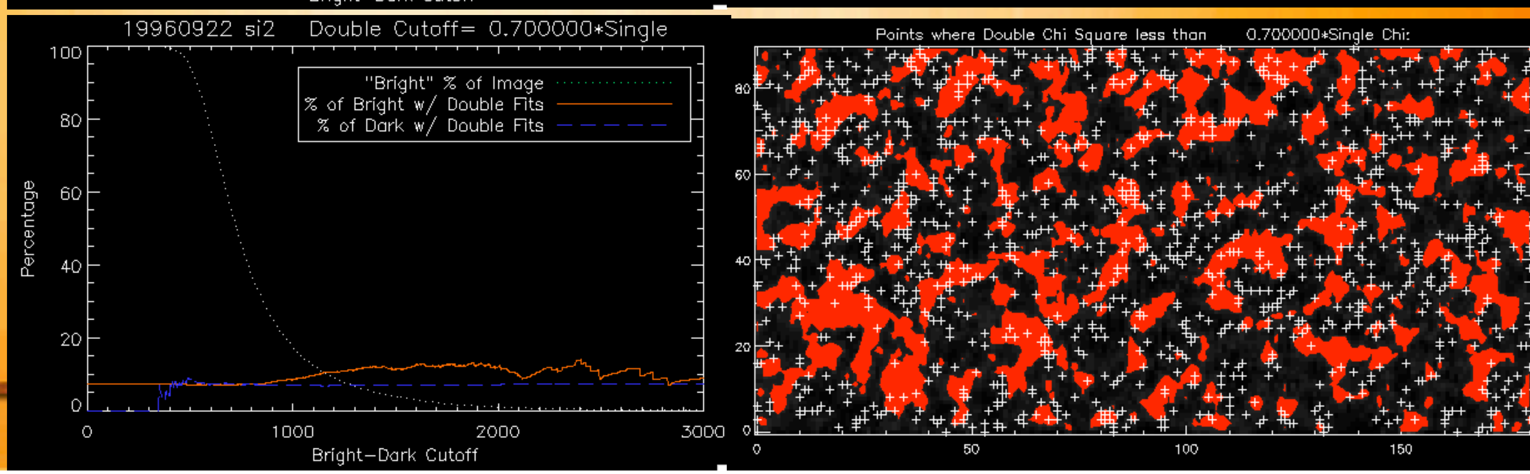
C IV:



Ne VIII:

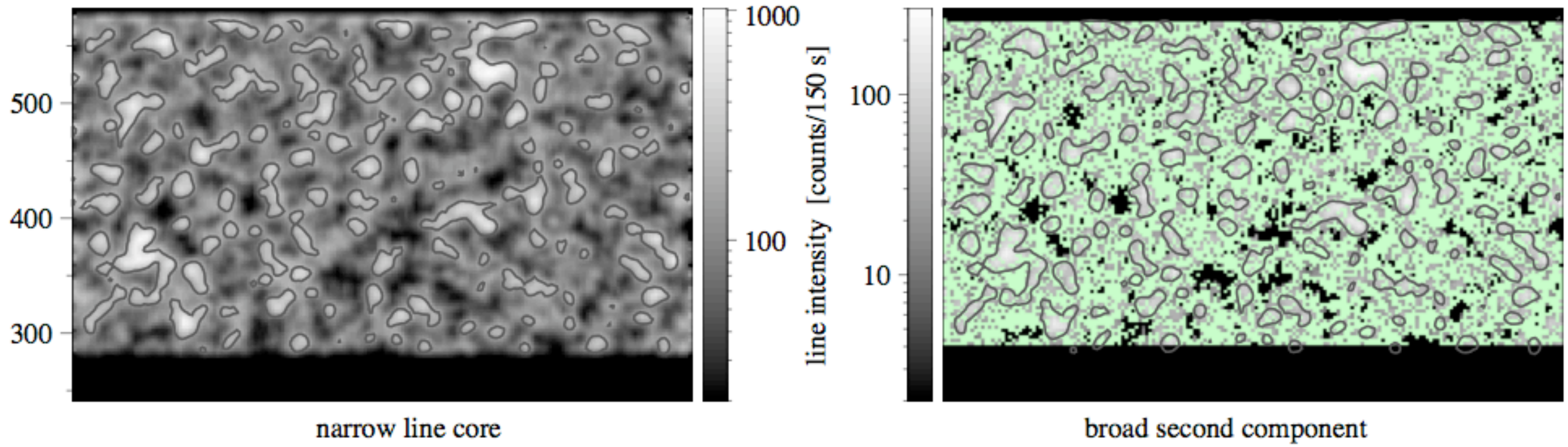


Si II:



So why is our data so different from previous work?

- The results from previous studies seemed very conclusive that the double-component spectra were exclusive to the bright network. How come our results do not seem anywhere near as clean?

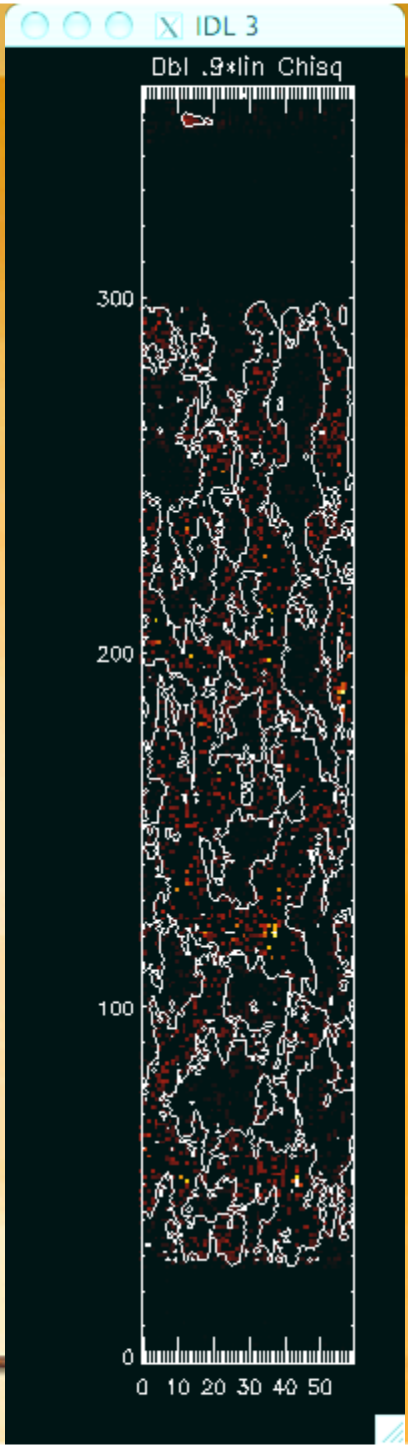


- There is a sneaky trick that was used to visualize double-components in the paper we looked at earlier. The double-component pixels were plotted with their corresponding intensity - of course the bright network pixels then stand out… they are brighter! Looking closely, darker grey double-component fits cover most of the image.

Subtle tricks….

- Remember the original Nitrogen raster that was too dark to get any good information from?
- Even this data set appears to have a definite pattern of double-components in the bright network when plotted with intensity:

(white contour outlines the bright network, points indicate double-component spectra)



Conclusions

- While there are definite trends relating double-component spectra to bright network regions, there is also a noticeable amount of outliers.

- More work is needed to determine which of these outliers are a product of data noise and fitting algorithms.
- Maybe some represent a constant background population of double-component spectra throughout the transition region, regardless of network and inter-network regions.

- What is clear is that previous work on the subject has been slightly misleading in its representation of double-component spectra as being ‘basically restricted’ to the bright network.

- Our findings contradict this over-simplified assumption and call for new interpretations of the phenomena (possibly spicules).

Some new ideas…

- Our newest idea is to let the Genetic Algorithm itself ‘choose’ between double or single Gaussian fits by adding a new parameter.
- So far our results have been mixed using this technique, but it’s too soon to tell whether this could be useful (have only started using it this week).

- Also, we plan to create some ‘synthetic’ spectral data sets.
- We could then run our different GA programs on this control set to determine how effective fitting algorithms are.
- By varying the random noise induced on our fake spectra, we could determine at what point the GA’s are no longer able to fit noisy spectra.

Future Goals:

We plan to determine the height at which this double Gaussian feature disappears by using SUMER spectral data at different wavelengths, and by using SUMER spectral images at the solar limb to observe the terminating height spatially.

The idea is that these double curve features are due to the two types of spicules. We will use Hinode data, of the same location and time, to look for a correspondence between spicule heights and the terminating double curve feature heights.

If successful, this will be one more step towards understanding the structure of the solar chromosphere and transition region, and hopefully bring us closer to a full understanding of the dynamics of the solar atmosphere.