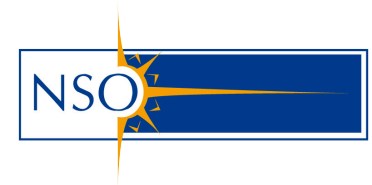
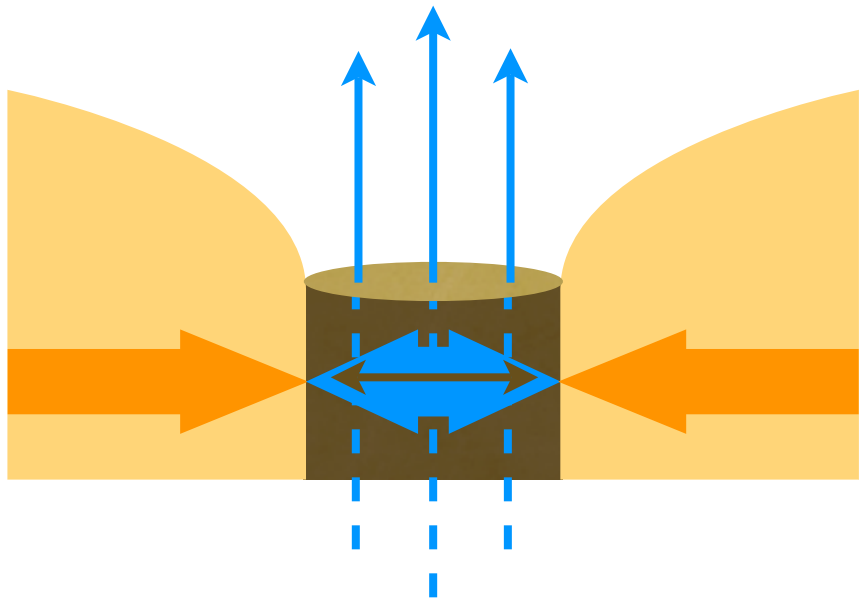
Molecule Formation and Magnetic Field Evolution in Sunspots

Sarah Jaeggli
Haosheng Lin & Han Uitenbroek



An Old Problem

How do sunspots maintain horizontal stability?



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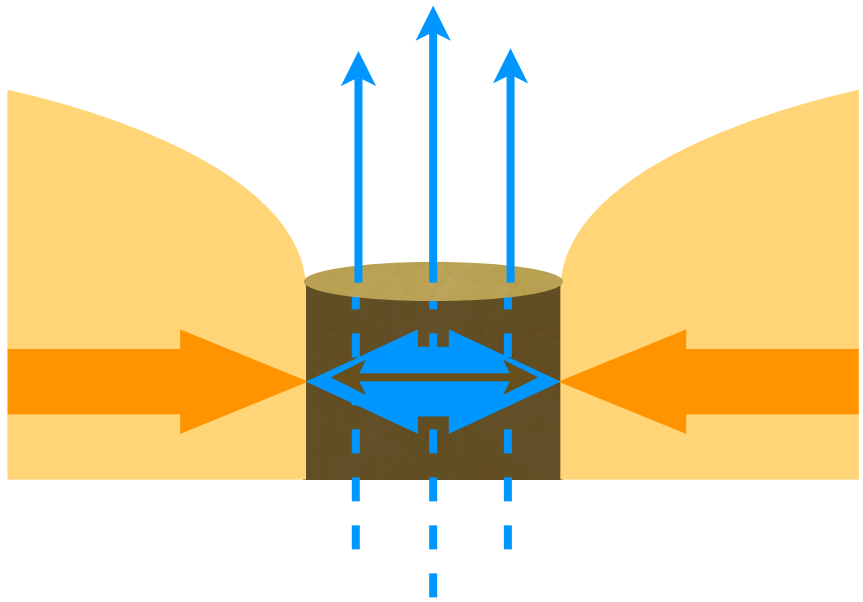
$$\frac{1}{8\pi}(B_z^2(r) + F_c(r)) = nk(T_p - T_s(r))$$

where

$$F_c(r) = 2\int_r^a B_z(r')\frac{\partial B_r(r')}{\partial z}dr'$$



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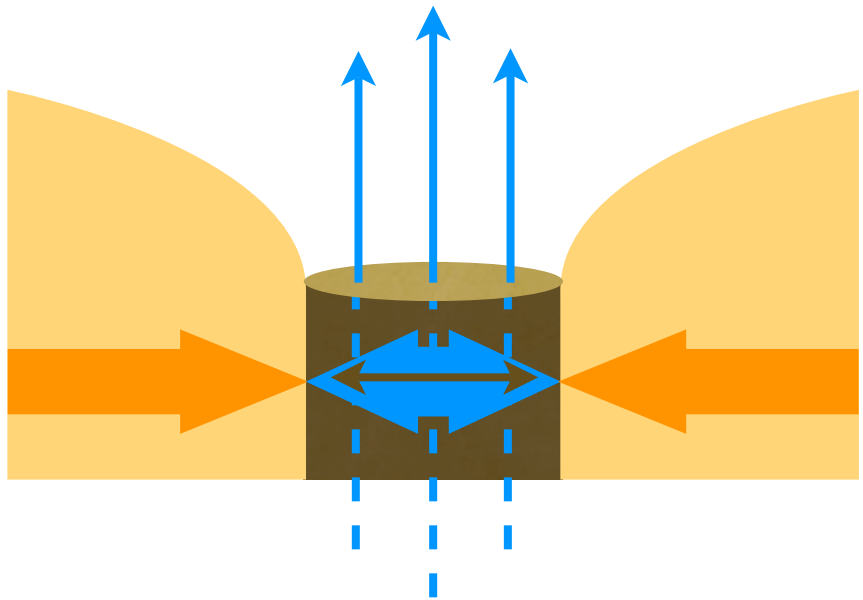
but in the umbra B is mostly vertical

$$\frac{1}{8\pi}(B_z^2(r) + \cancel{F_c(r)}) = nk(T_p - T_s(r))$$



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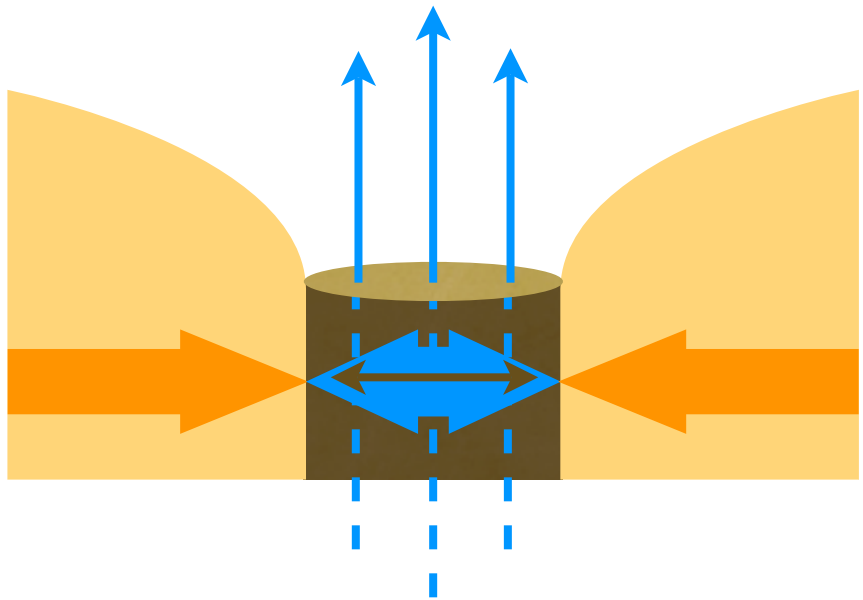
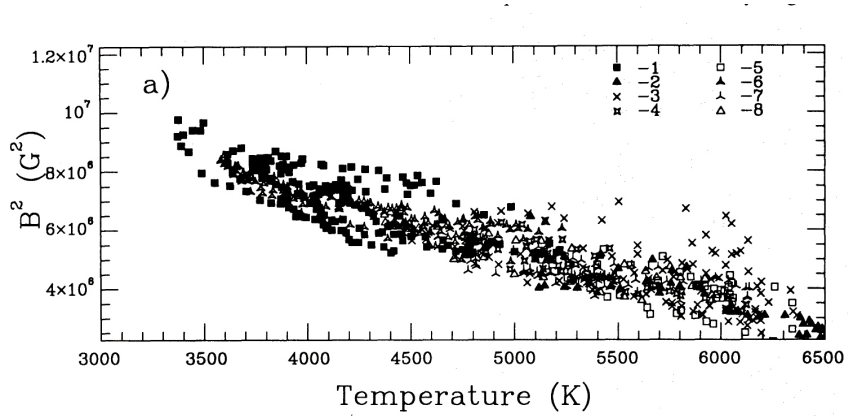
$$\frac{1}{8\pi}(B_z^2(r) + \cancel{F_c(r)}) = nk(T_p - T_s(r))$$

so

$$B^2 \propto T_s$$



Previous Investigations

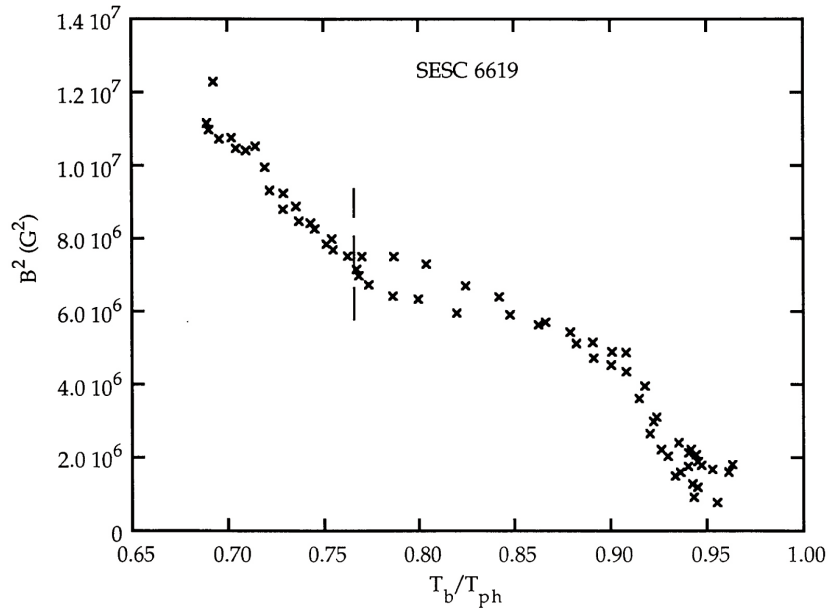


Martinez Pillet & Vazquez (1993)

Fe I g=2.5 6302 Å:
Gurman & House 1981
Balthasar & Schmidt 1993
Lites et al. 1993
Martinez Pillet & Vazquez 1993
Stanchfield et al. 1997
Westendorp Plaza et al. 2001

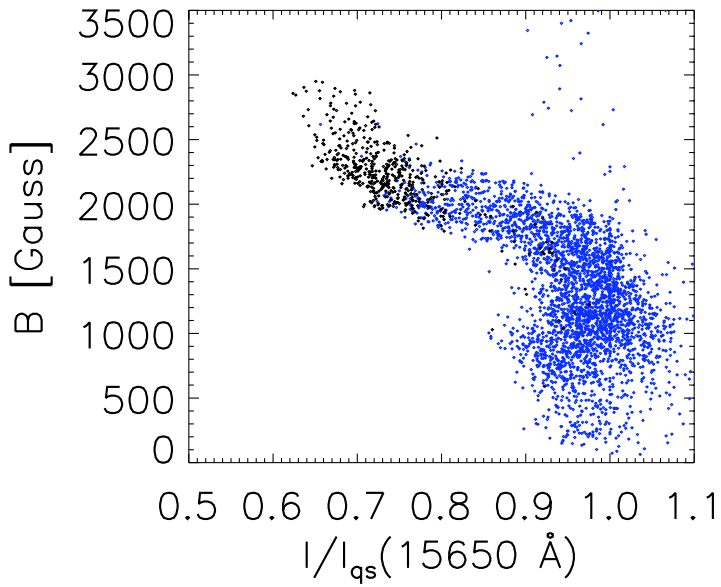
Fe I g=3 156548 Å:
Kopp & Rabin 1992
Solanki et al. 1993
Livingston 2002
Penn et al. 2002, 2003a
Mathew et al. 2004

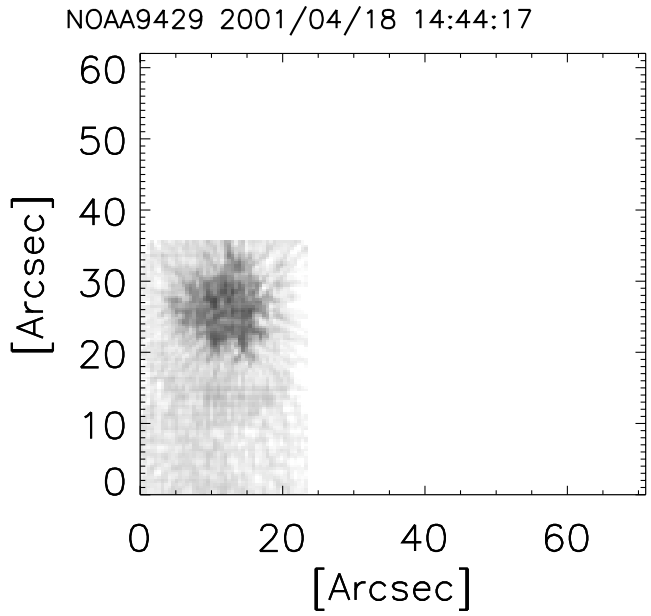
Ti I g=2.5 22310 Å:
Penn et al. 2003b



Kopp & Rabin (1992)

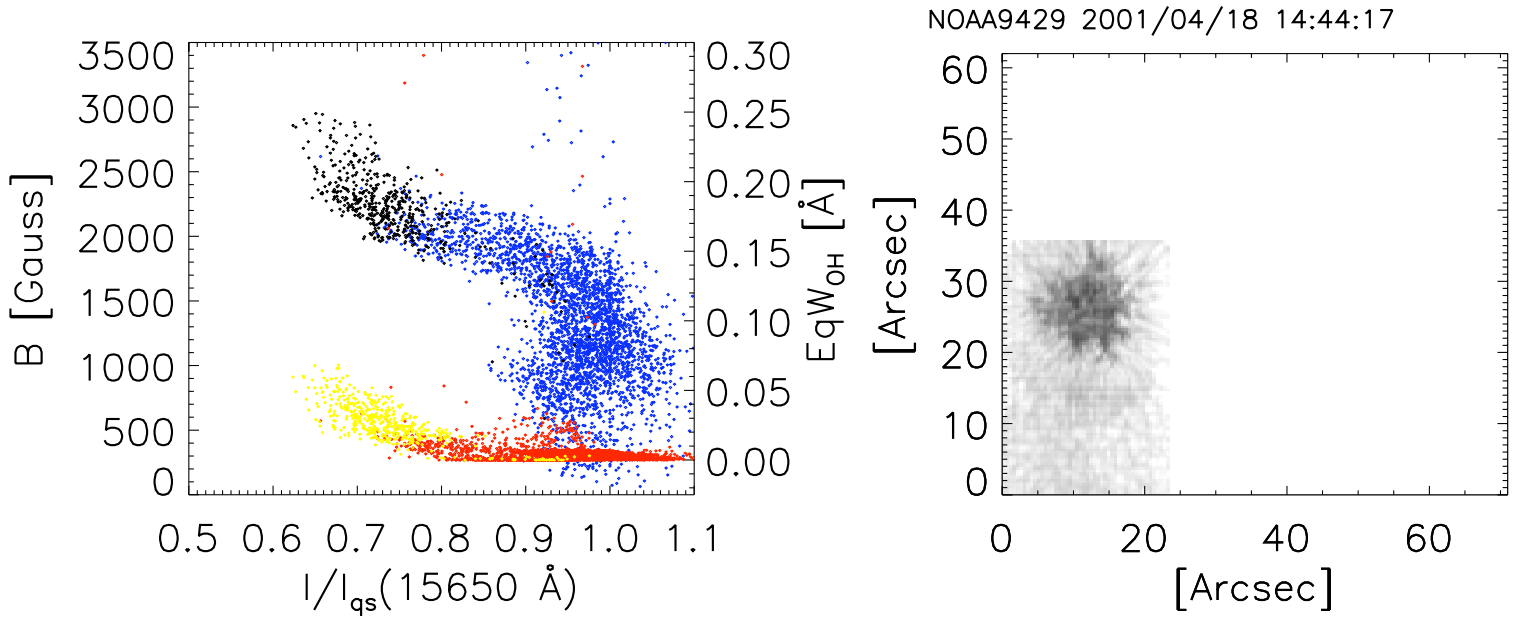
Umbral Mystery





What is going on?

Umbral Mystery



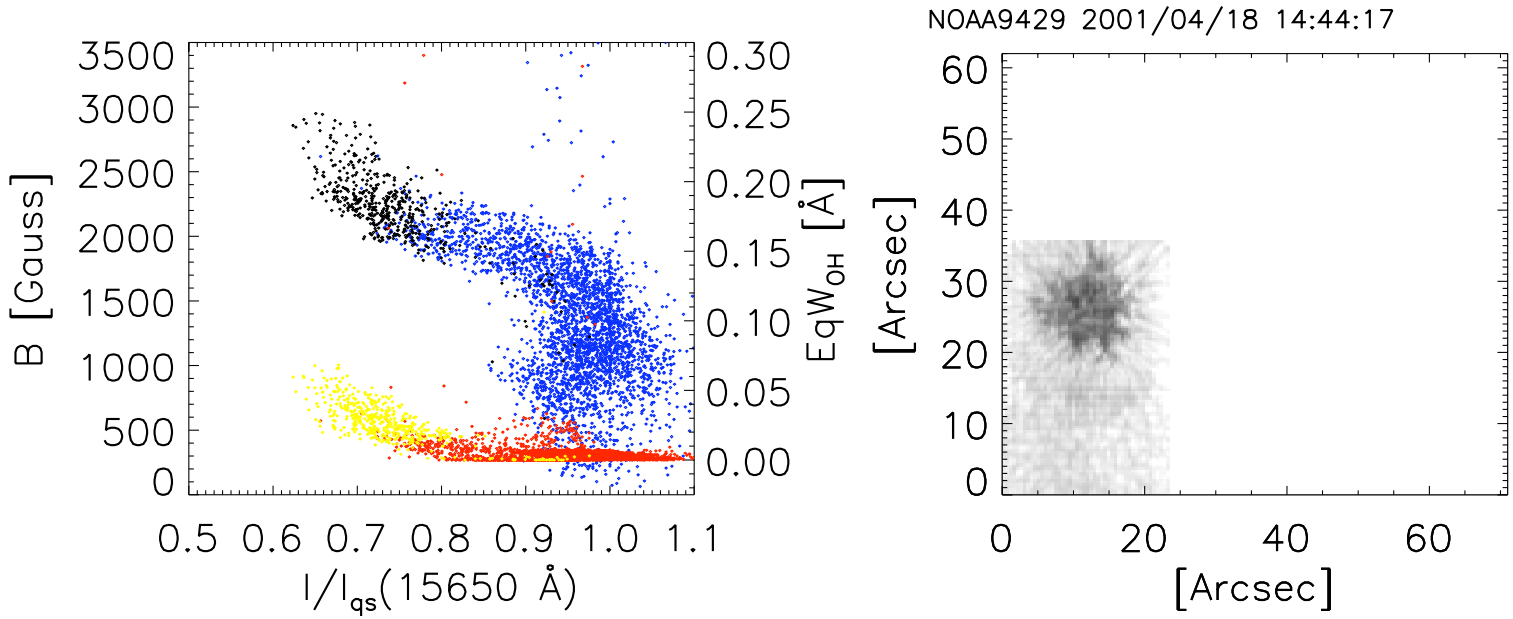
What is going on?

OH is a clue

In a realistic atmosphere we cannot assume the number density is equal to the photospheric value or a constant

$$\frac{1}{8\pi}(B_z^2(r) + F_c(r)) = n_p k T_p - n_s(r) k T_s(r)$$

Umbral Mystery



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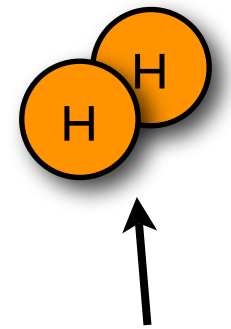
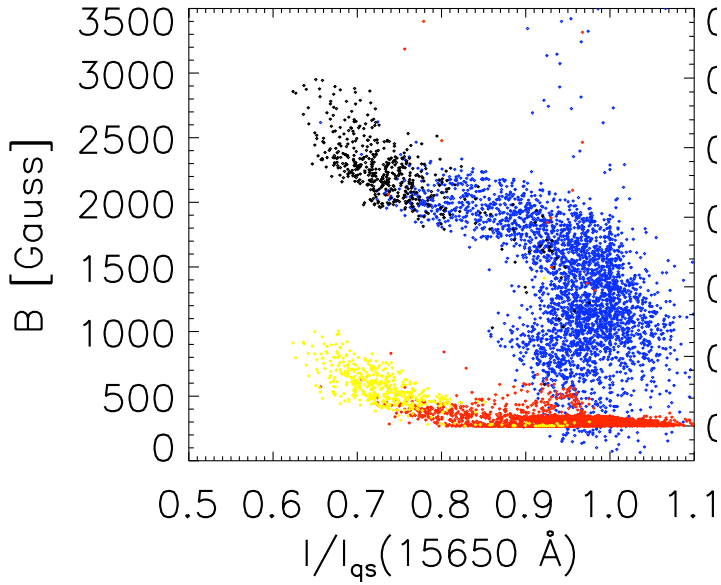


$$\frac{1}{8\pi}(B_z^2(r) + F_c(r)) = n_p k T_p - n_s(r) k T_s(r)$$

Umbra



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$$\frac{1}{8\pi}(B_z^2(r) + F_c$$

1986ApJ. . . 306. . 284M

Maltby Model M

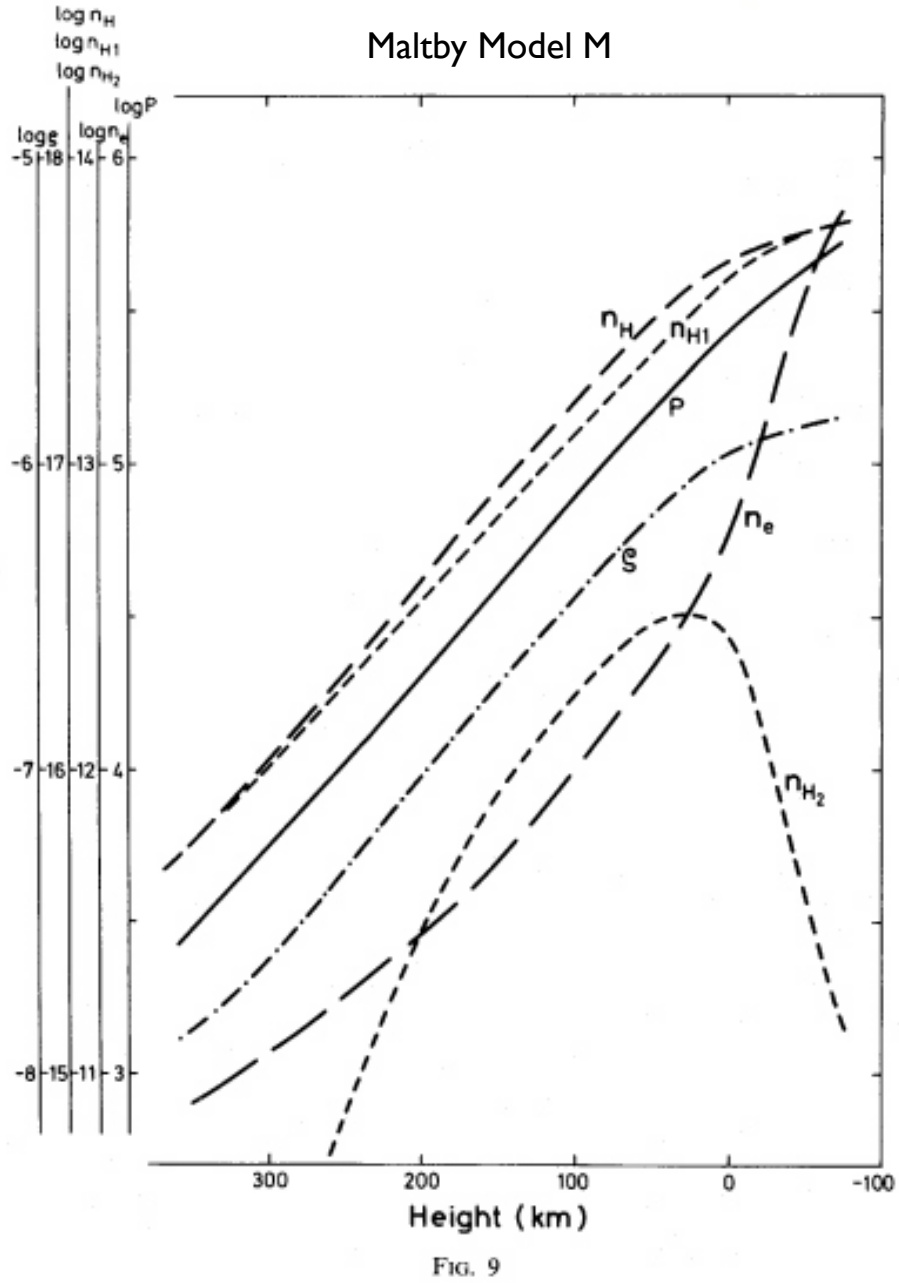
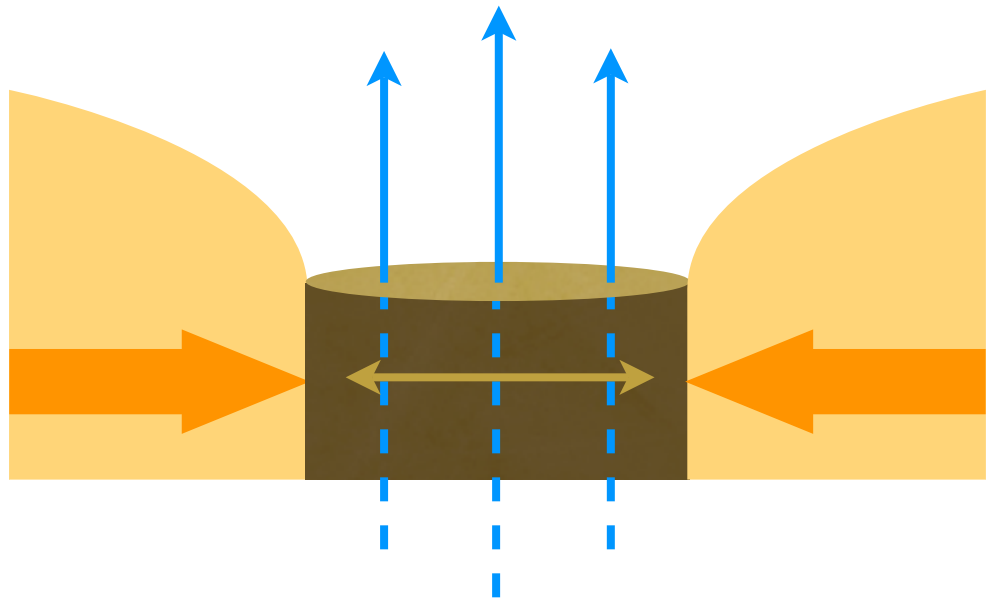


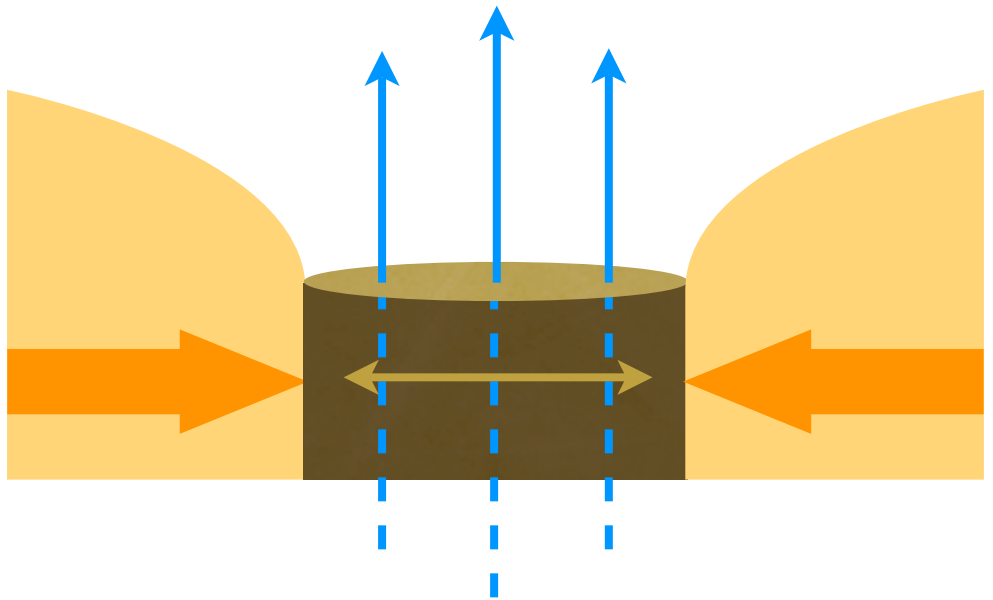
FIG. 9

An Idea About Sunspot Evolution



An Idea About Sunspot Evolution

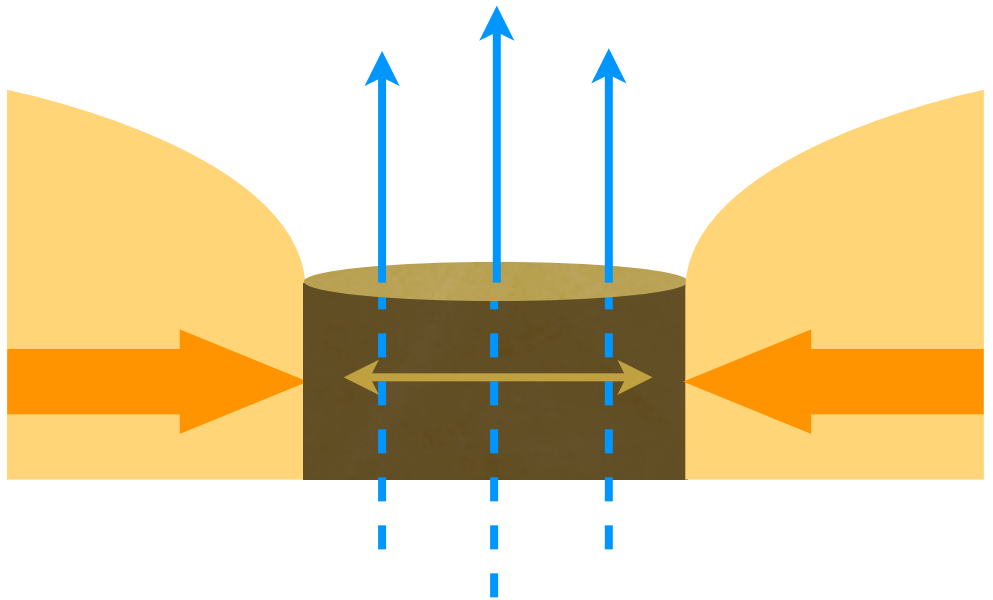
B increases



An Idea About Sunspot Evolution

B increases

then T decreases

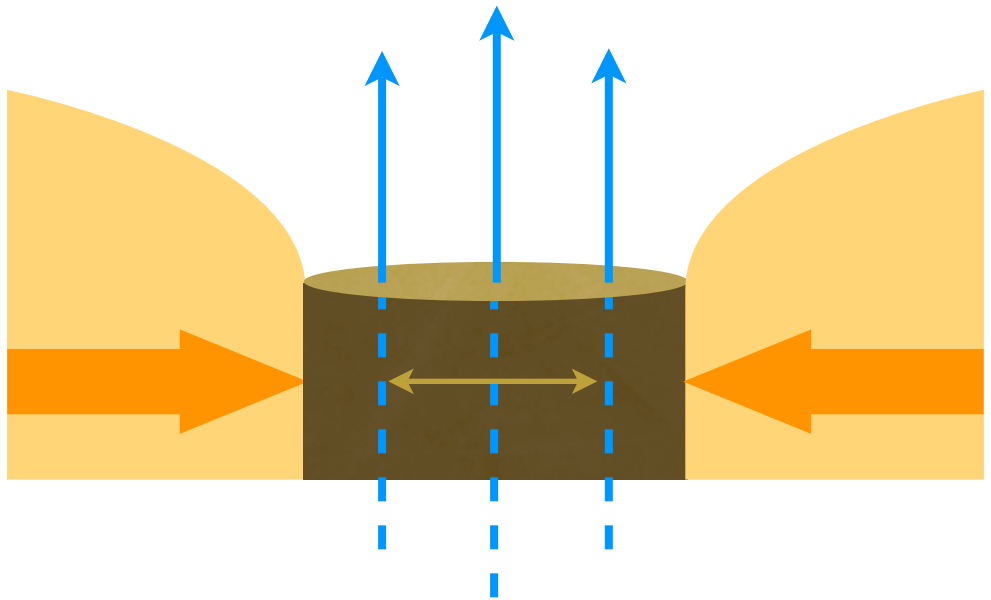


An Idea About Sunspot Evolution

B increases

then T decreases

then the H_2 fraction increases and n and P decrease



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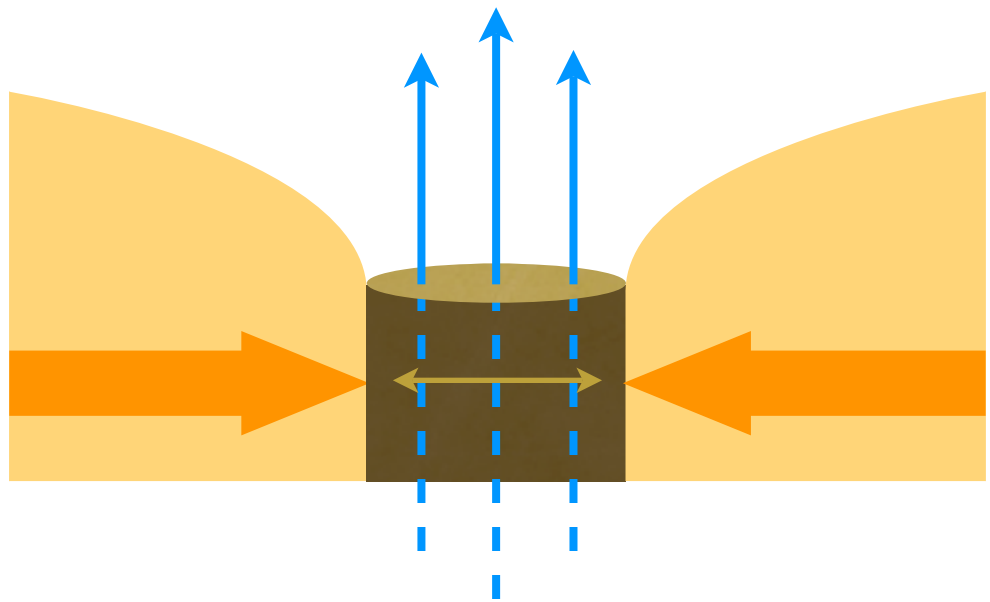
region compresses



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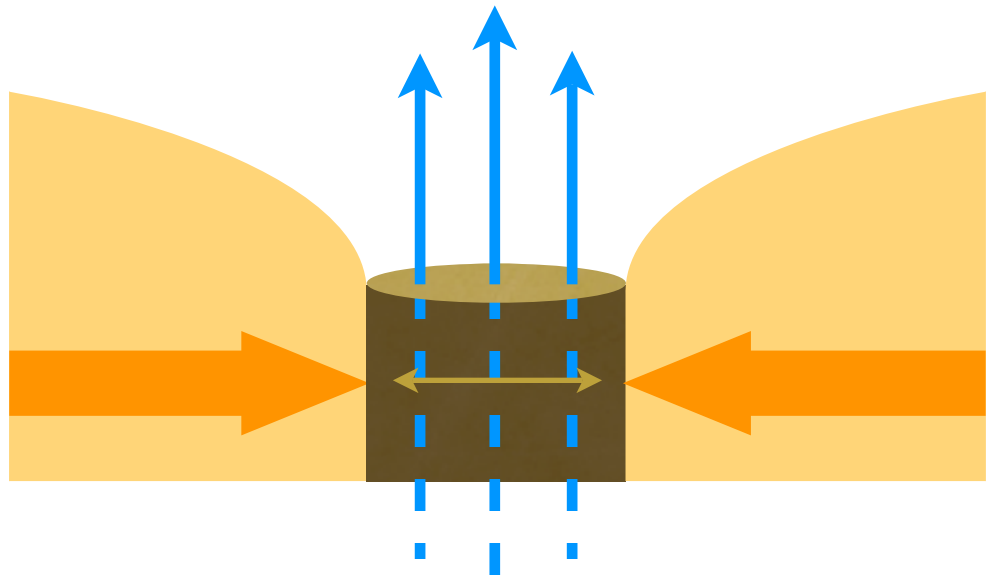

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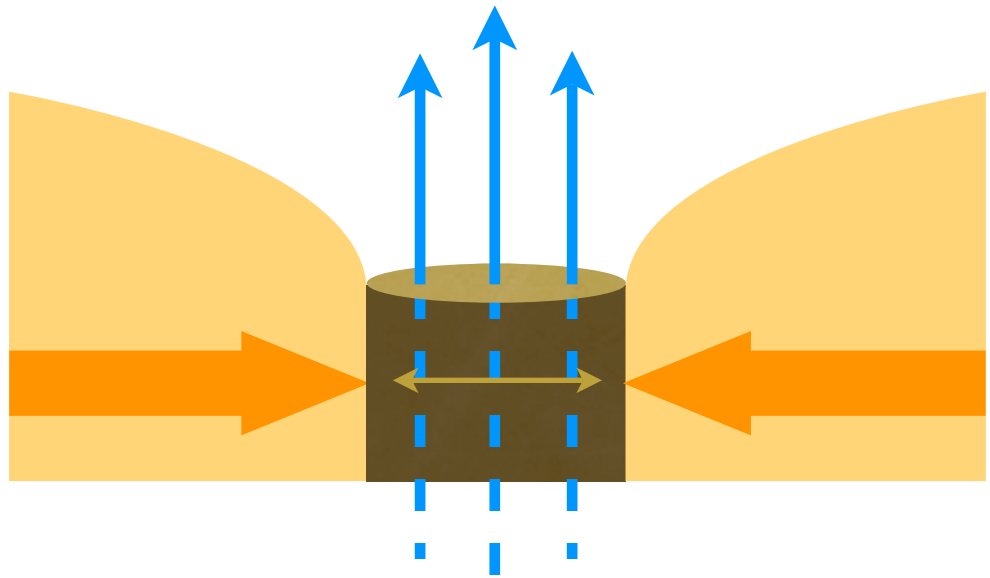
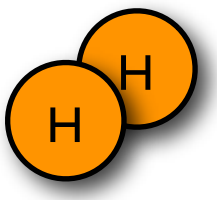


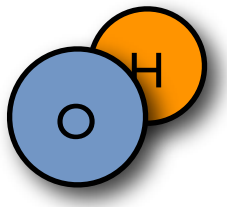
*Formation of a large molecular fraction has widespread implications

The Problem with H_2



We cannot observe it!

- Ro-V lines are too weak to measure in the photosphere
- Florescent transitions exist in the UV, but:
  - Samples chromospheric H_2
  - 120-160 nm, need SUMER



OH a reasonable proxy?

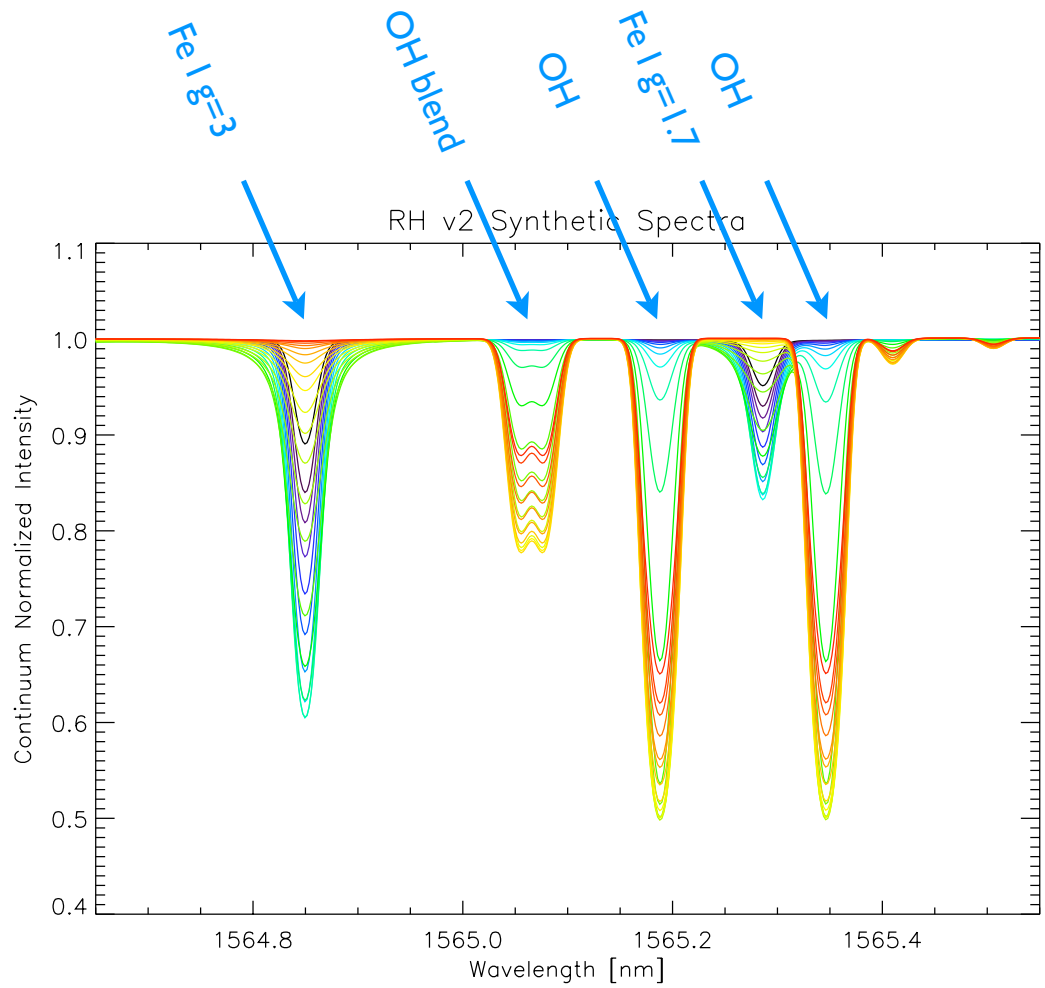
- Similar dissociation energies (H_2 4.48 eV, OH 4.39 eV)
- Conveniently located near Fe I g=3 15648 Å line
- Some uncertainty, competes with CO formation

Try a Model

Solve for abundances/generate spectra for a solar atmosphere in radiative equilibrium using:

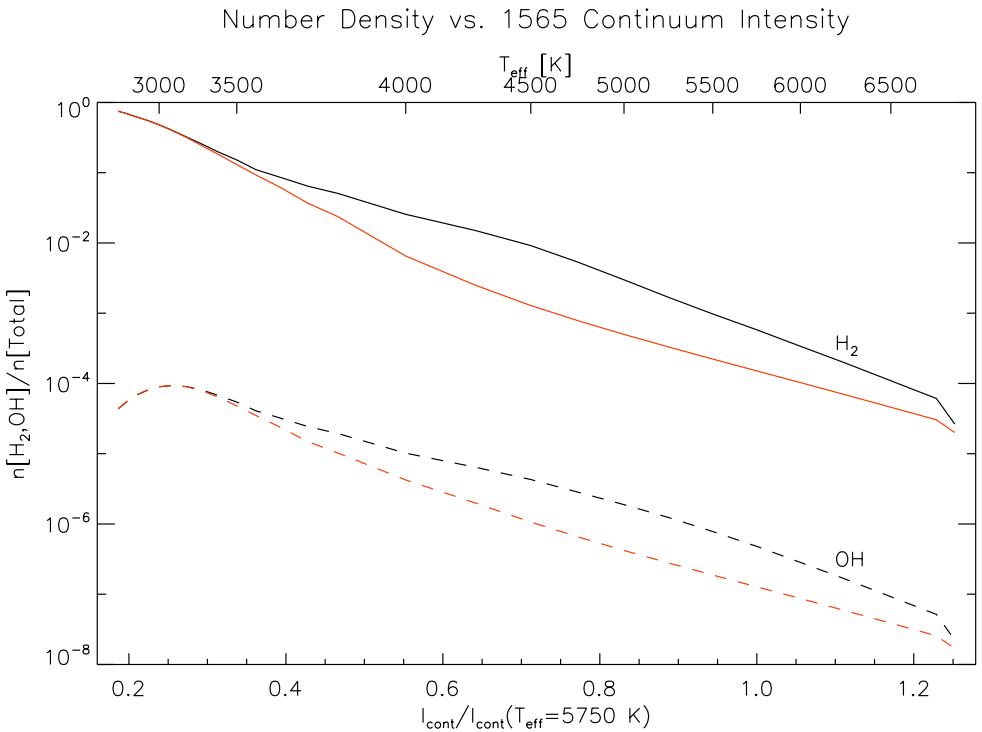
(Non)LTE Rybicki-Hummer radiative transfer and chemical equilibrium code by Han Uitenbroek

Atmospheric Models:
Kurucz 7000-4000 K ΔT=250 K
Phoenix* 3900-2600 K ΔT=100 K

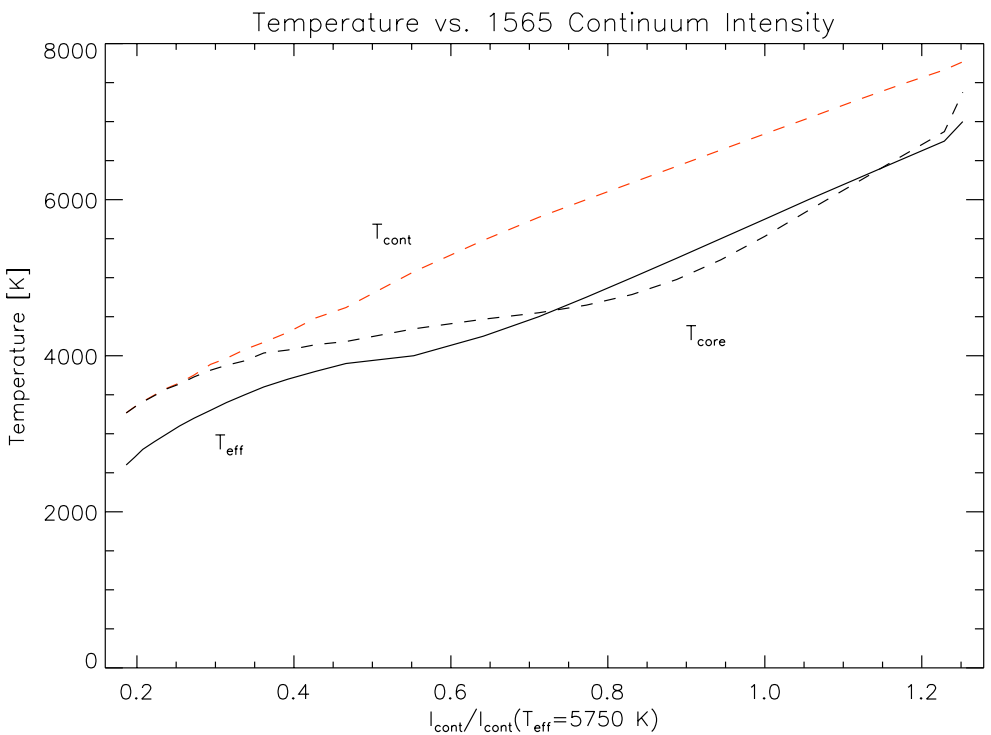


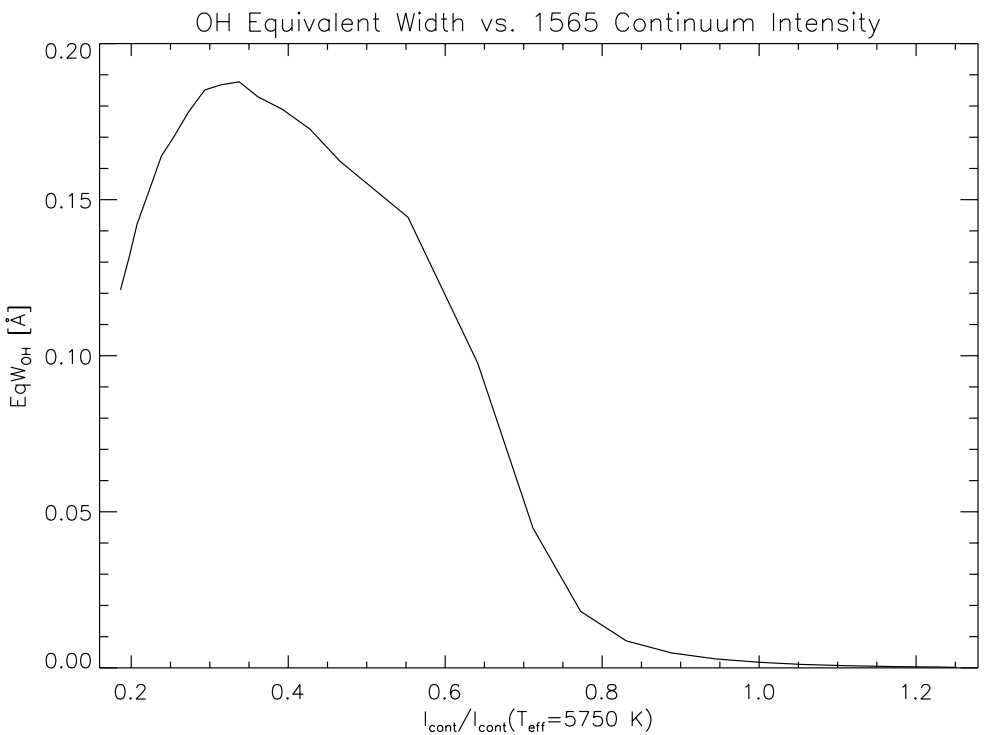
*Phoenix atmosphere grids courtesy of Peter Hauschildt

Some Useful Results from RH



- value at height of line core formation
- value at height of continuum formation





Active Region Survey

Establish magnetic field configuration and OH abundance:

1. Random sunspots at different developmental stages

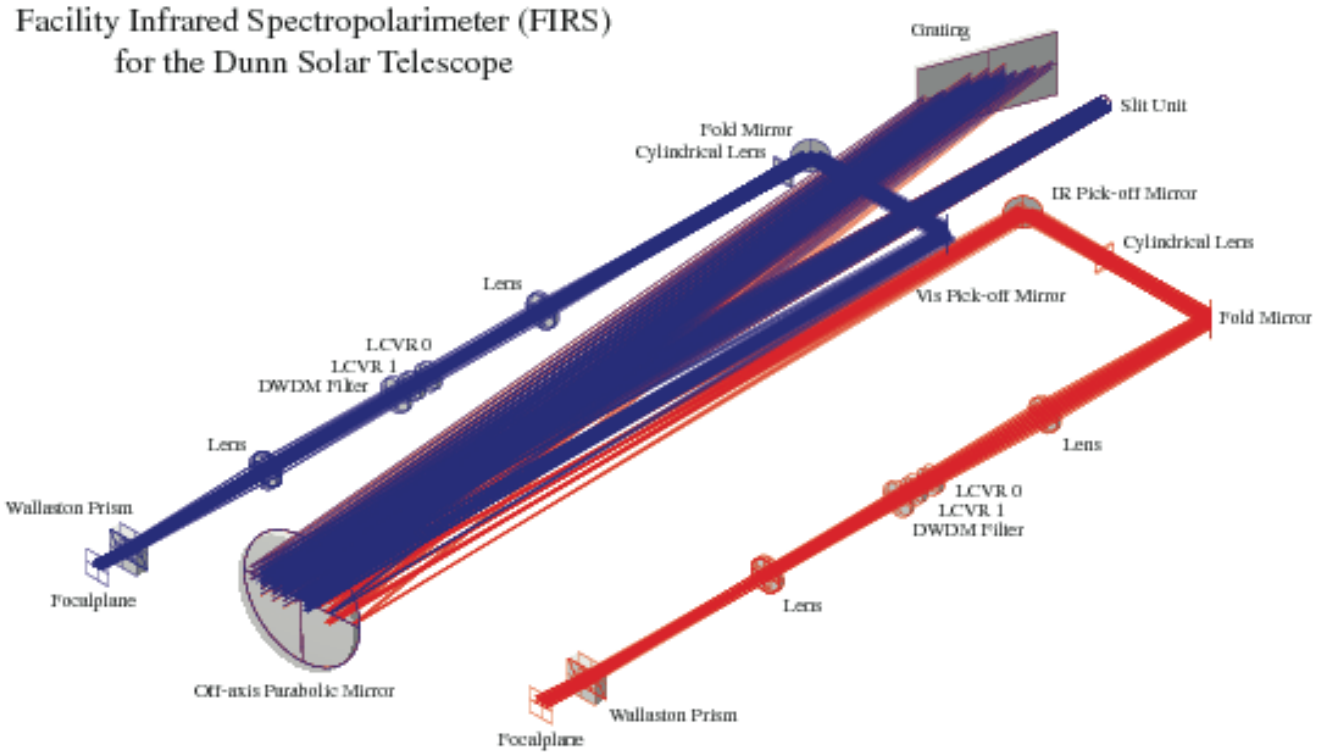
2. Emergence and evolution of a single sunspot

A Selection of FIRS and HSG Data

Region	Observation Date	Max. Field Strength [Gauss]
NOAA 10743	2005-03-12	3200
NOAA 11035 L	2009-12-17	3200
NOAA 11035 F	2009-12-17	3000
NOAA 10953	2007-04-30	2900
NOAA 9429	2001-04-18	2900
NOAA 10999	2008-06-17	2900
NOAA 10742	2005-03-12	2600
NOAA 11024	2009-07-06	2700
NOAA 11035 F	2009-12-16	2800
NOAA 11072	2010-05-21	2700
NOAA 11072	2010-05-23	2600
NOAA 11049	2010-02-17	2600
unnamed pores	2005-03-10	2500
NOAA 11046	2010-02-12	2400

What's FIRS?

Facility InfraRed Spectropolarimeter

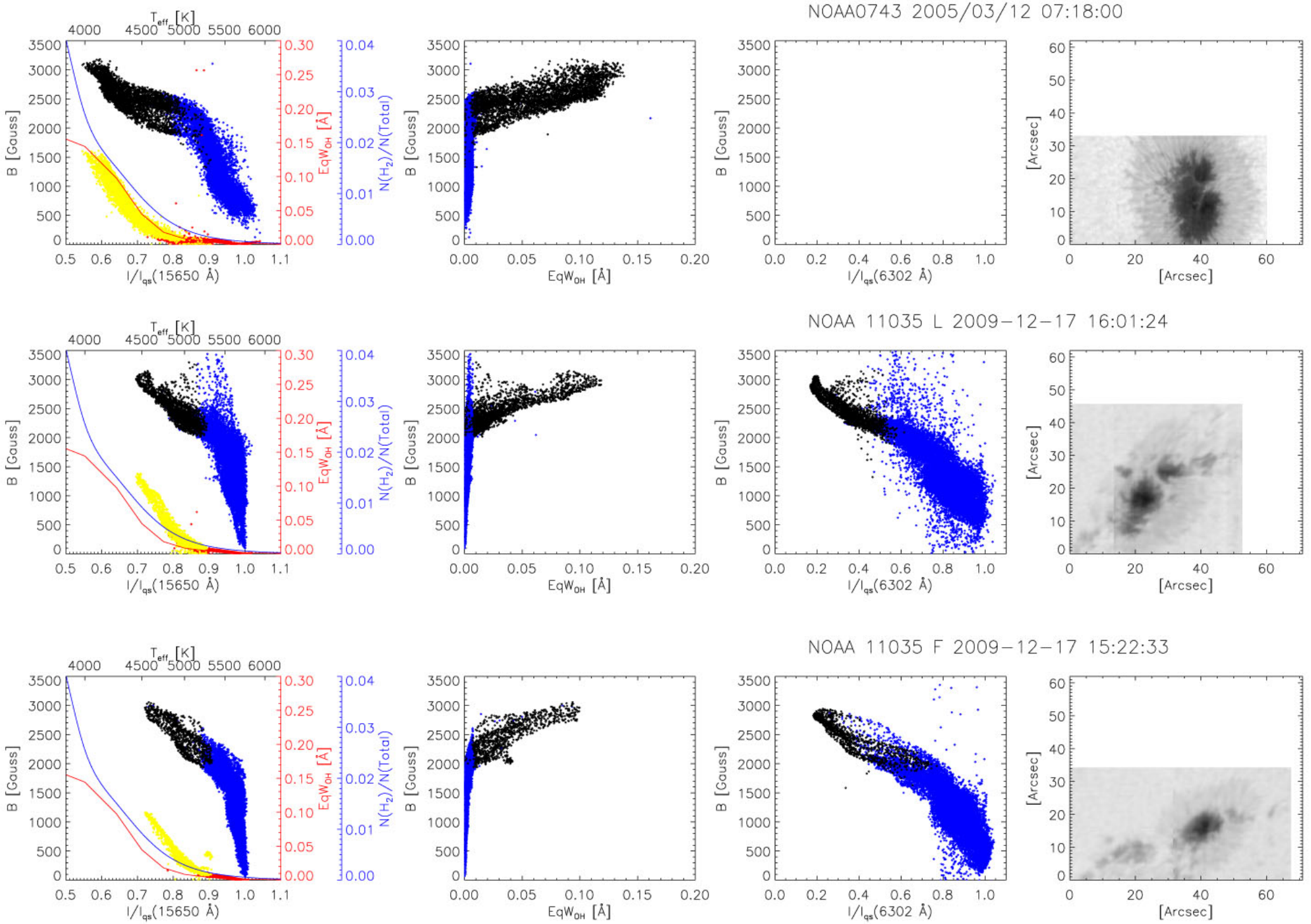


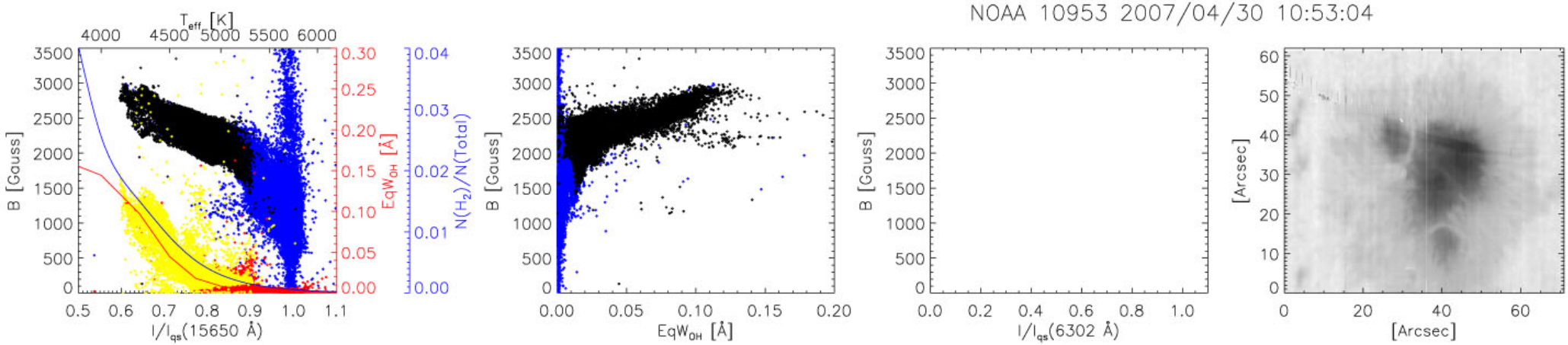
Telescope:
DST @ NSO/Sacramento Peak

Features:
Diffraction limited with AO
Dual beam
4-slits for high cadence (20 min.)
High and low resolution modes

Wavelengths:
Simultaneous Fe I 6302/15650 Å
or Fe I 6302/He I 10830 Å
Runs concurrently with:
IBIS Ca II 8542 Å, G-band camera

Now available for general use!
For more information see:
http:/kopiko.ifa.hawaii.edu/firs


NOAA0743 2005/03/12 07:18:00
NOAA 11035 L 2009-12-17 16:01:24
NOAA 11035 F 2009-12-17 15:22:33
T_eff [K]
B [Gauss]
EqW_OH [Å]
N(H2)/N(Total)
I/I_qs(15650 Å)
I/I_qs(6302 Å)
[Arcsec]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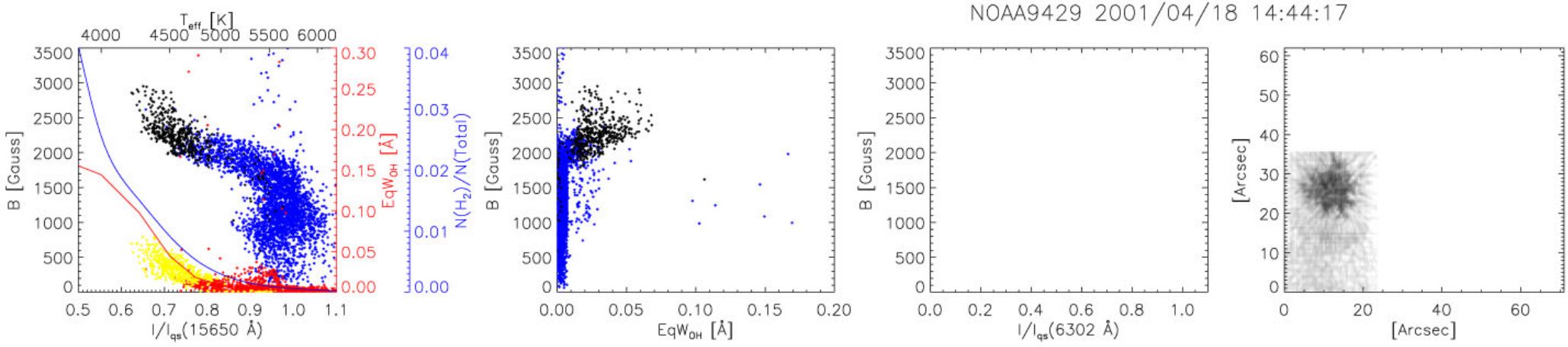
I/I_qs(15650 Å)
EqW_OH [Å]
I/I_qs(6302 Å)
[Arcsec]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I/I_qs(15650 Å)
EqW_OH [Å]
I/I_qs(6302 Å)
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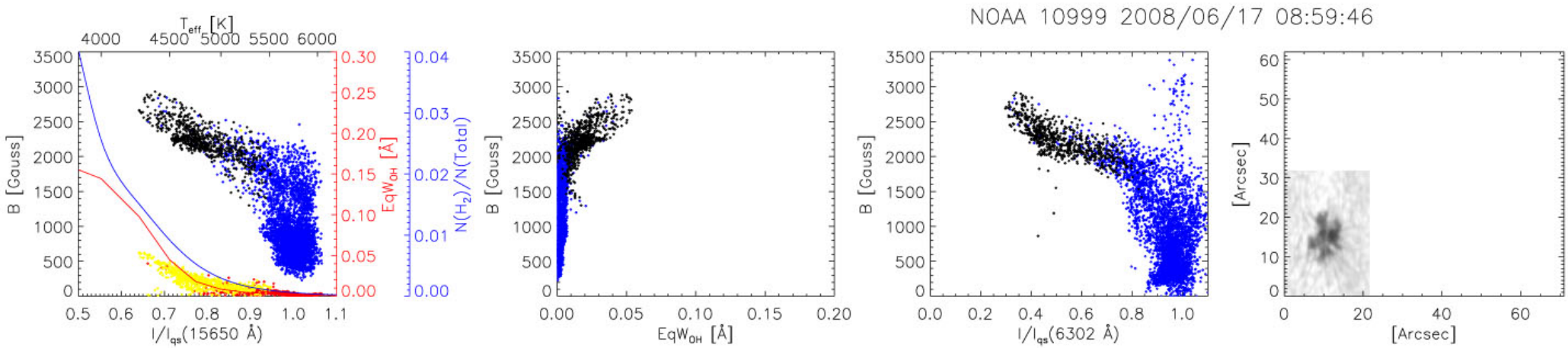
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EqW_OH [Å]
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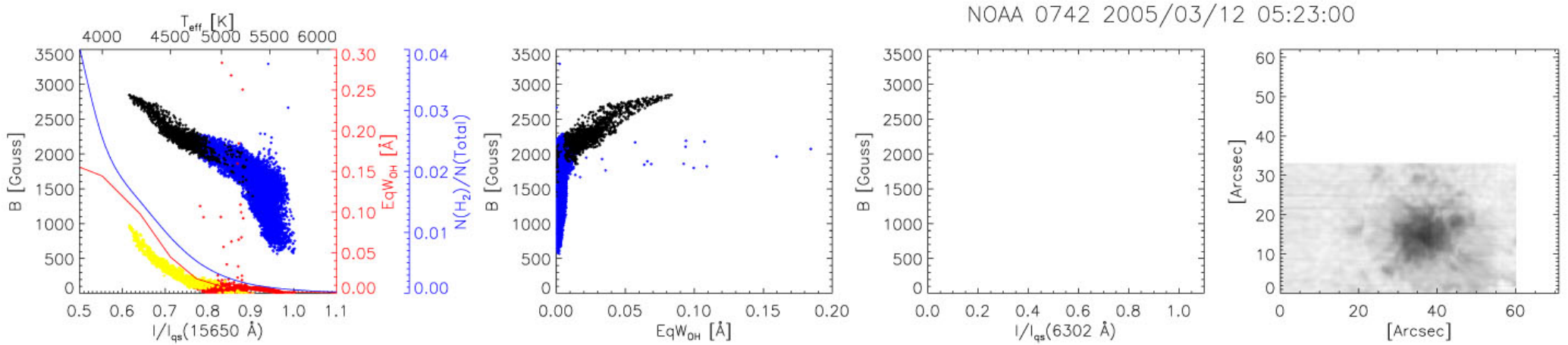
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T_eff [K]
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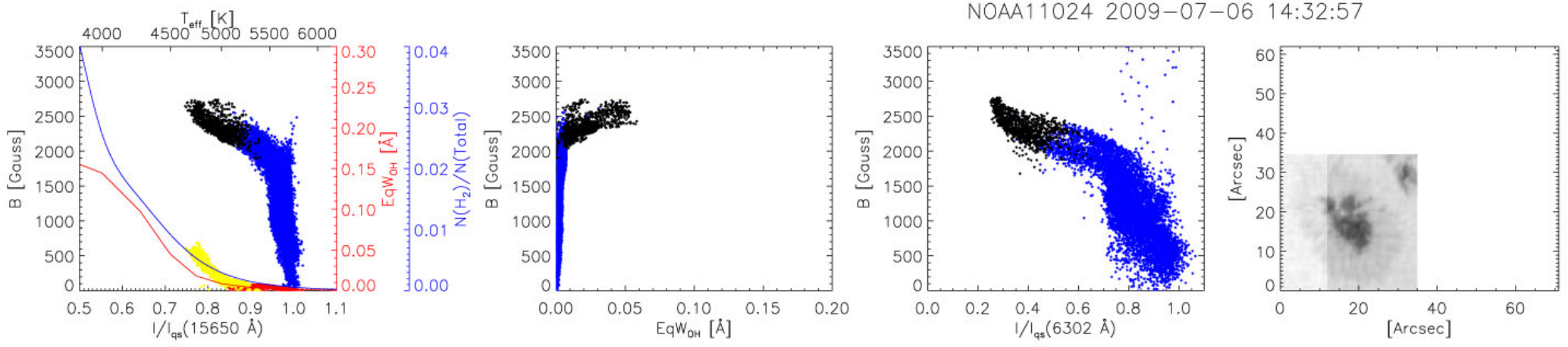
B [Gauss]
EqW_OH [Å]
N(H2)/N(Total)
I/I_qs(15650 Å)
EqW_OH [Å]
I/I_qs(6302 Å)
[Arcsec]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B [Gauss]
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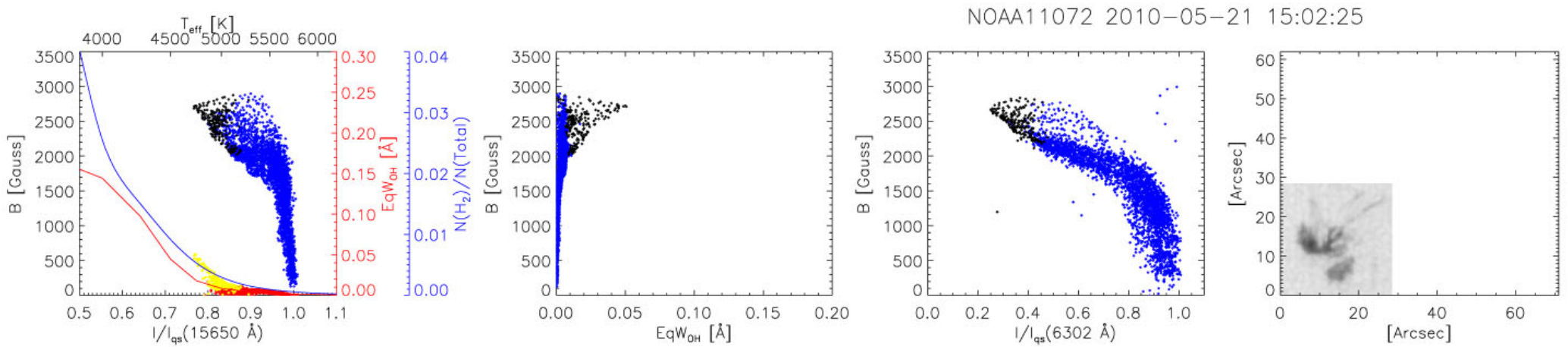
EqW_OH [Å]
I/I_qs(6302 Å)
[Arcsec]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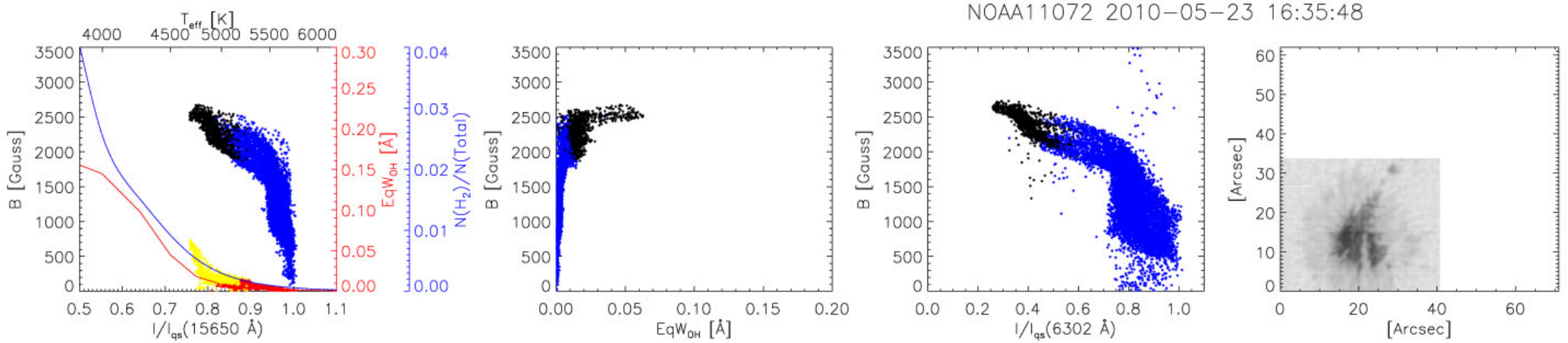
I/I_qs(15650 Å)
EqW_OH [Å]
I/I_qs(6302 Å)
[Arcsec]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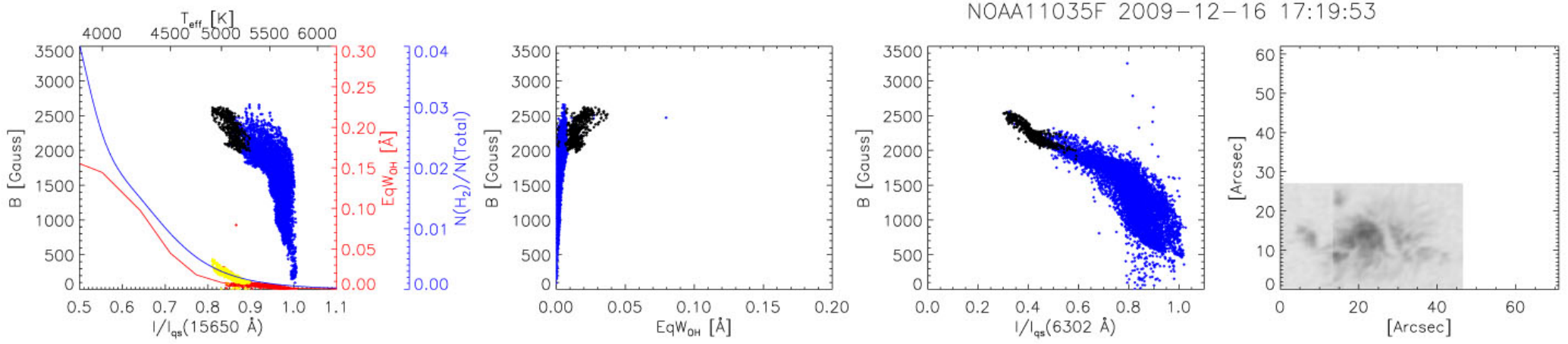
I/I_qs(15650 Å)
I/I_qs(6302 Å)
[Arcsec]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I/I_qs(15650 Å)
I/I_qs(6302 Å)
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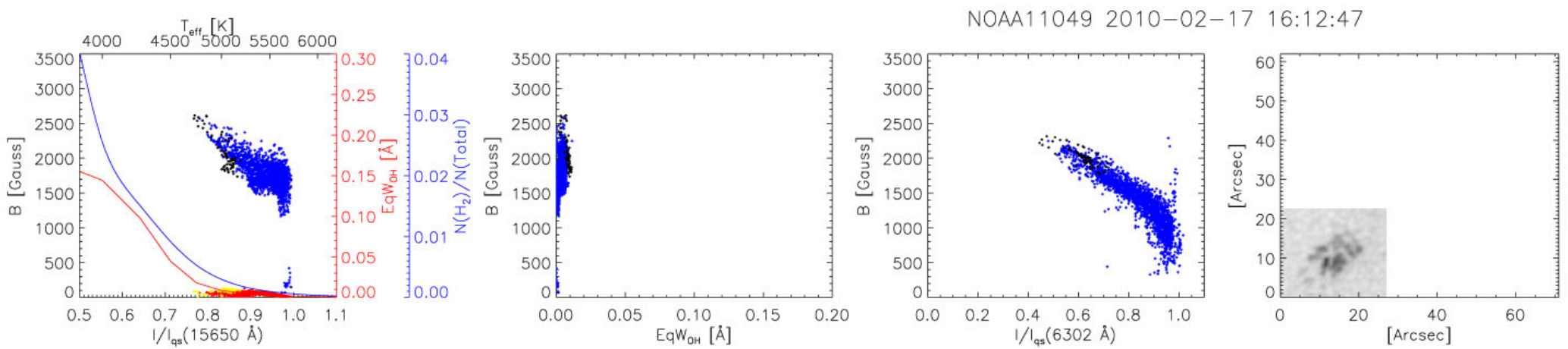
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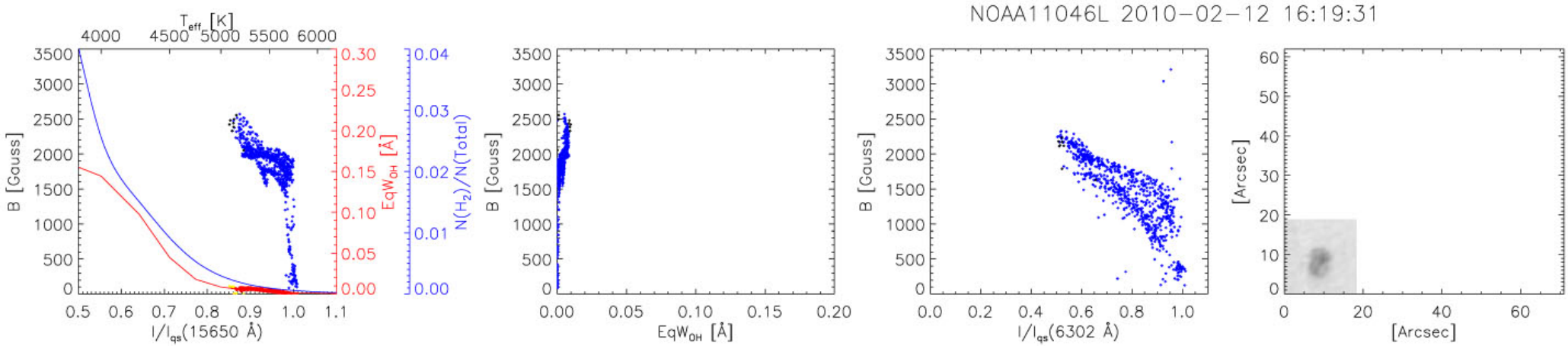
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B [Gauss]
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N(H2)/N(Total)
I/I_qs(15650 Å)
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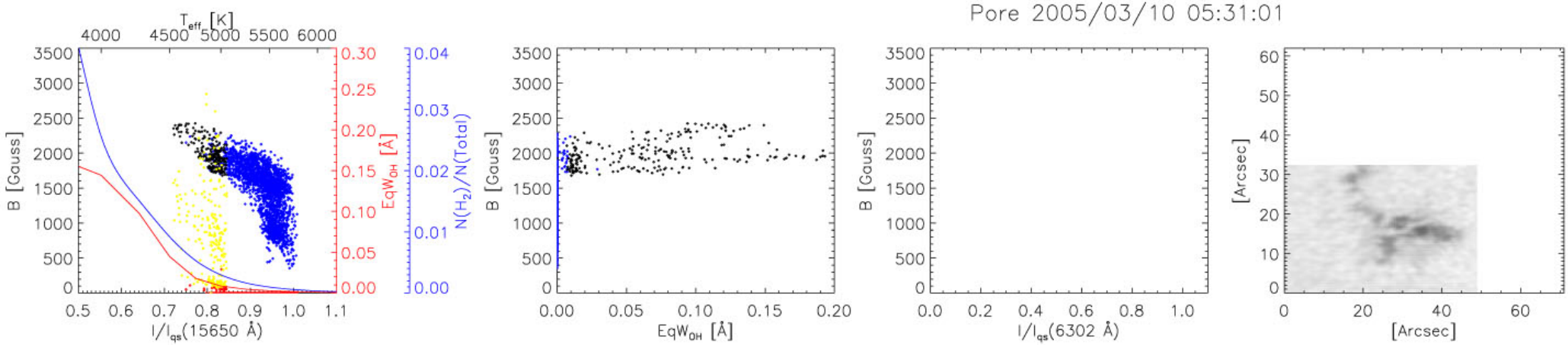
[Arcsec]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B [Gauss]
EqW_OH [Å]
N(H2)/N(Total)
I/I_qs(15650 Å)
EqW_OH [Å]
I/I_qs(6302 Å)
[Arcsec]

Discussion

- Discernible changes in equilibrium state of darkest umbral points
  - In observed spots up to few% possible H_2 content
  - Maybe up to 10% in very cool spots
- Implications
  - Concentration of magnetic field during sunspot formation
  - Molecules are energy sources and sinks
    - More degrees of freedom which do not contribute to the thermal signature
    - May play a role in the sunspot irradiance problem
  - For sunspot models:
    - Use multi-component gas
    - Correct equation of state, accounting of energy
    - Inclusion of magnetic field and horizontal force balance

Thank You!

And thanks to the NSO/SP for putting me up/putting up with me for the last 4 months!