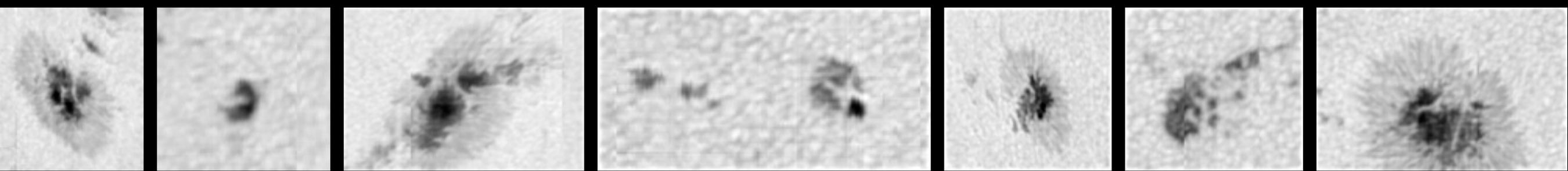


An Observational Study of the Formation and Evolution of Sunspots



a dissertation by Sarah Jaeggli¹
advisors Haosheng Lin¹ & Han Uitenbroek²

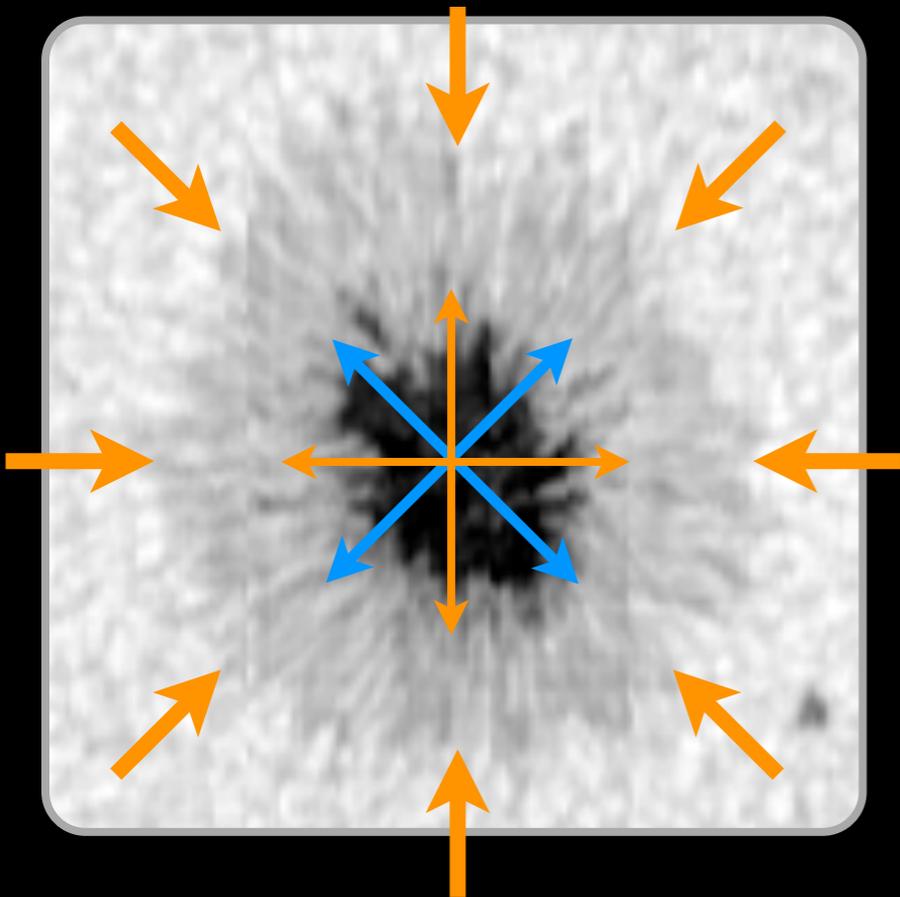


¹Institute for Astronomy, University of Hawai'i
²National Solar Observatory



A Problem with Sunspot MHSE

Sunspots are stable and are considered to be in equilibrium on dynamical timescales



For a circularly symmetric sunspot in equilibrium:

$$\begin{aligned} P_{qs}(z) &= n_{qs}(z)kT_{qs}(z) \\ &= n_s(r, z)kT_s(r, z) + \frac{1}{8\pi}(B_z^2(r, z) + F_c(r, z)) \end{aligned}$$

where

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

Assuming:

- (1) small curvature force, F_c
- (2) small changes in (z) height of observation due to RT effects
- (3) constant density, n

We get a linear thermal-magnetic pressure relation:

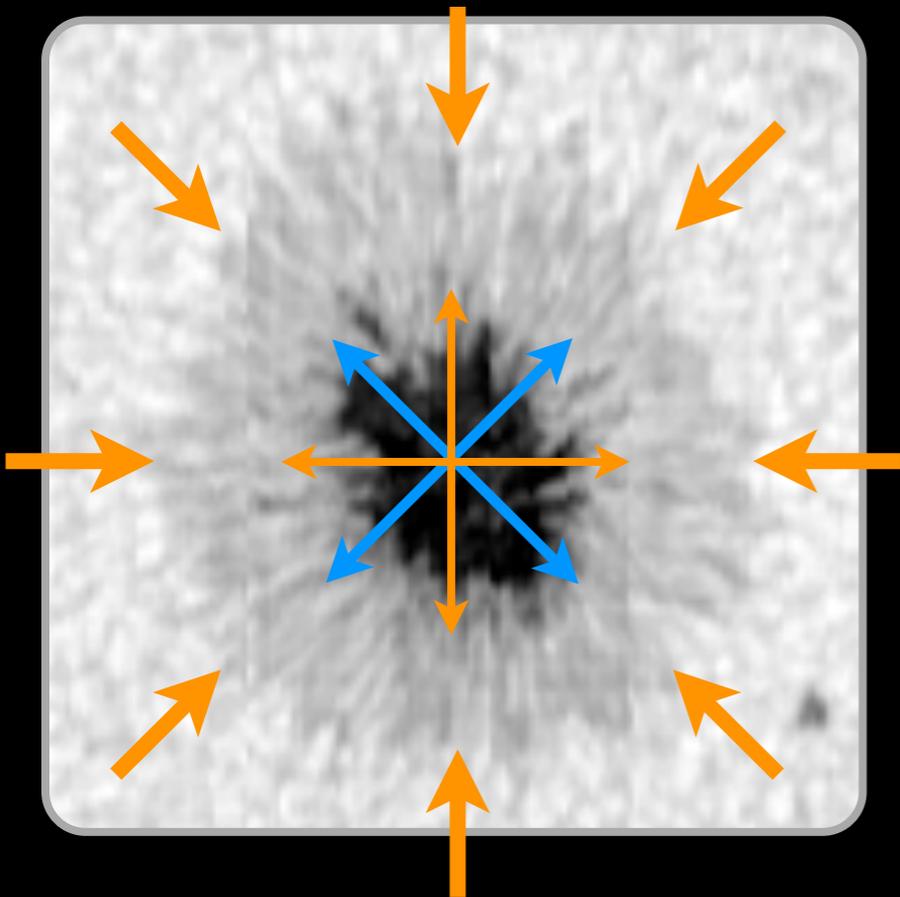
$$B^2(r, z) \propto T_{qs}(z) - T_s(r, z)$$

numerous other studies:

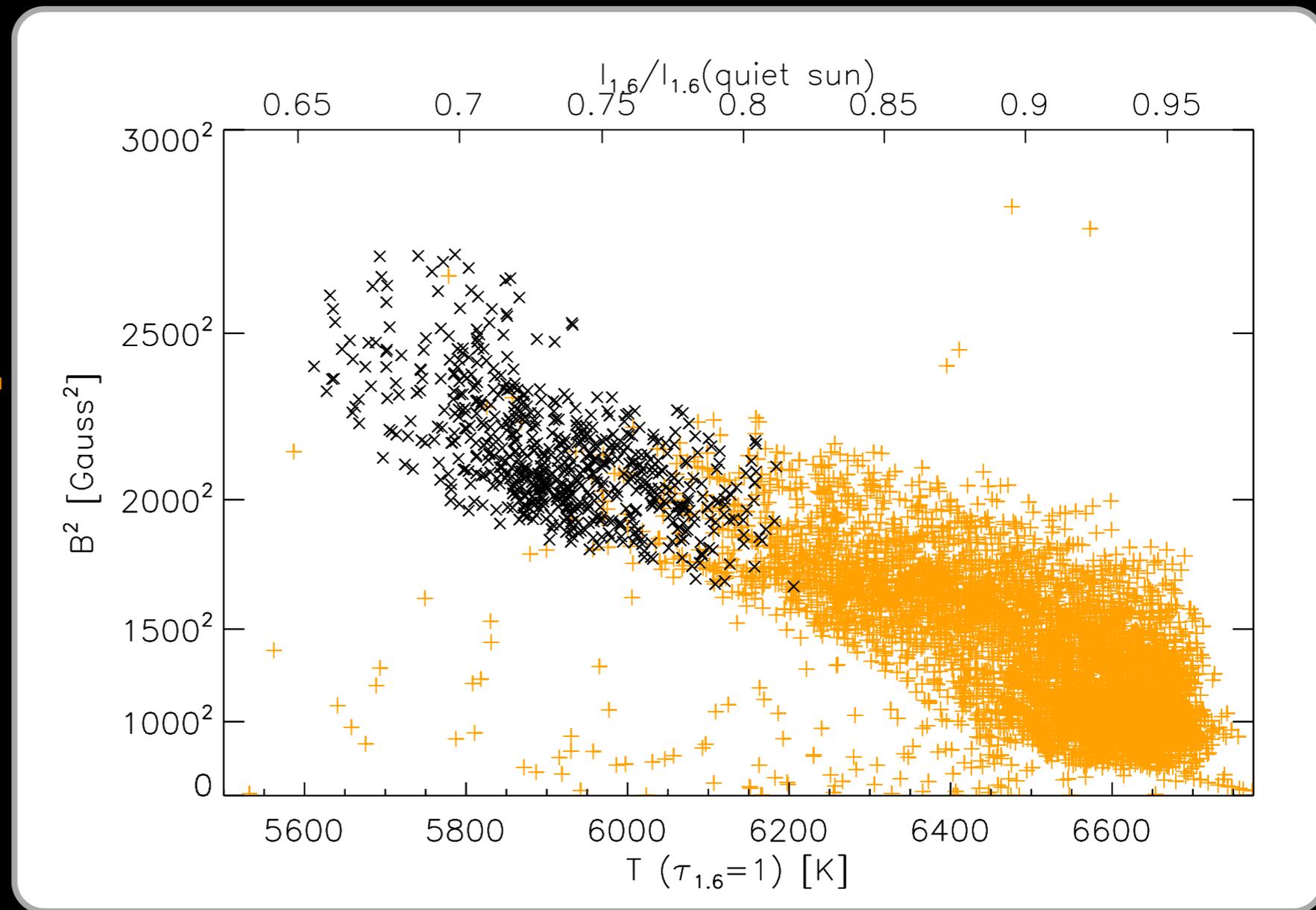
Gurman & House (1981), Kopp & Rabin (1993), Balthasar & Schmidt (1993), Lites et al. (1993), Matrinez Pillet & Vazquez (1993), Solanki et al. (1993), Stanchfield et al. (1997), Westendorp Plaza et al. (2001), Livingston (2002), Penn et al. (2002, 2003a, 2003b), Mathew et al. (2004)

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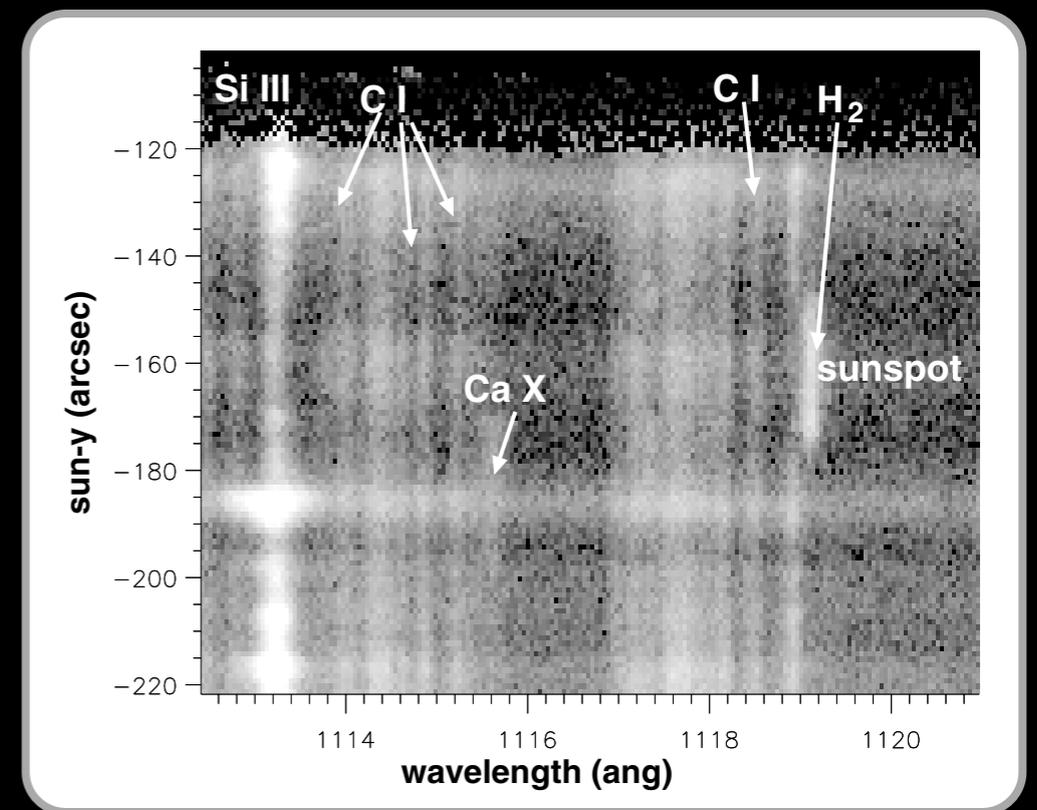
$$B^2(r, z) \propto T_{qs}(z) - T_s(r, z)$$

A Possible Solution

- In the umbra, F_c and effects of RT should be small and cannot explain isothermal increase in B
- BUT the assumption that number density is constant is not valid
 - Molecule formation
 - **decrease in number density**
 - release of dissociation energy
 - increase in heat capacity
 - H_2
 - Detections in the UV chromosphere
 - In the photosphere, from umbral models 5%

A Possible Solution

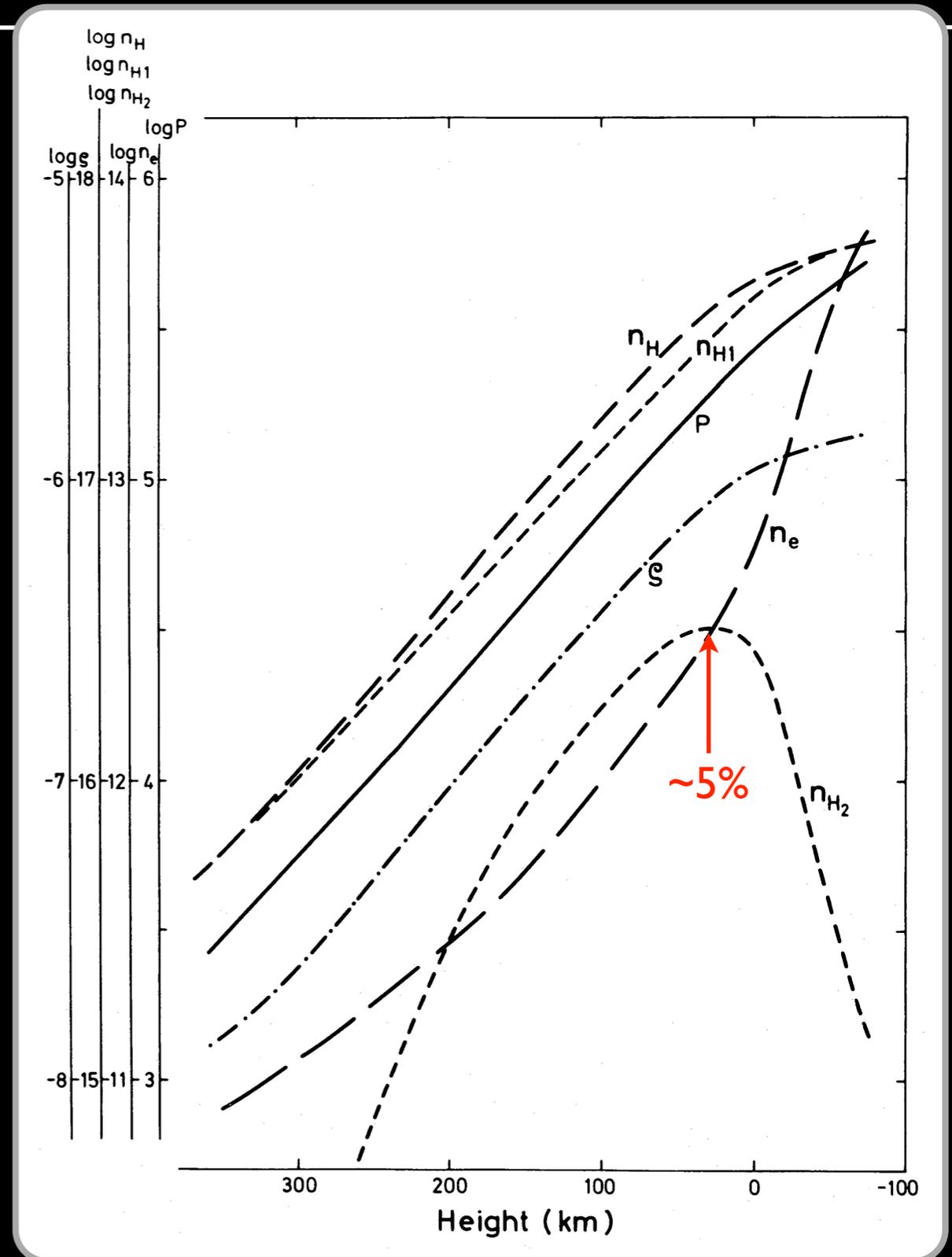
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SUMER spectrum from Innes (2008) fig. 1

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Model M (Teff~4000 K) from Maltby et al. (1986) fig. 9

Sunspot Survey

Measure H₂

- Direct detection is not easy
 - UV lines at chromospheric heights (and SUMER is no more)
 - Ro-vibrational lines in IR undetected
- Must use proxy molecule
 - Hydroxide (OH)
 - Similar dissociation energy (OH: 4.39 eV, H₂: 4.48 eV)
 - Falls within 15650 Å band

Characterization of B and T

- Spectropolarimetry of high B-sensitivity lines @ Fe I 15650 Å $g=3, 1.7$

Establish Evolutionary Effects

- Survey
- 65 observations of 23 sunspots and pores over 1.5 years



Facility IR Spectropolarimeter

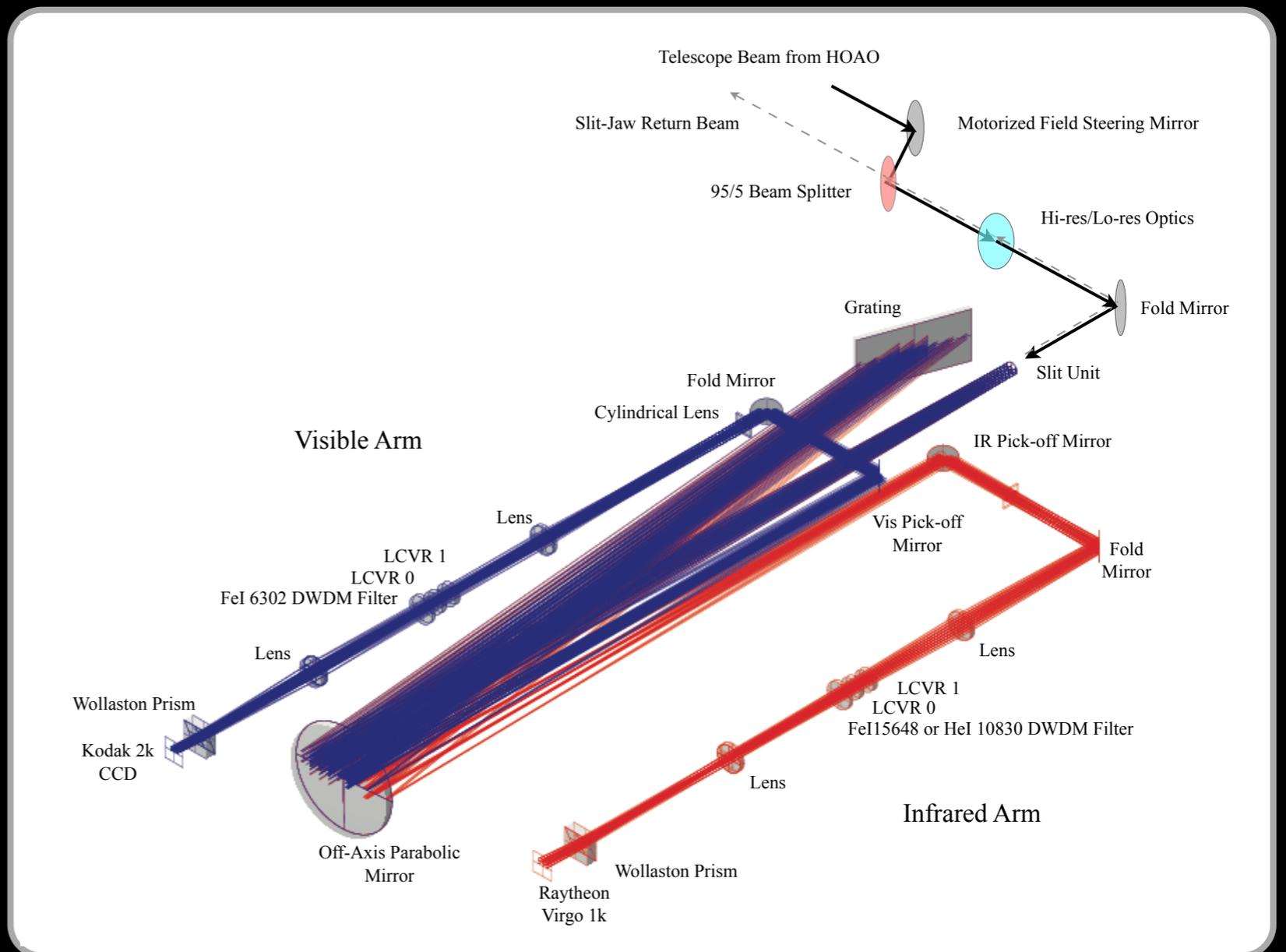
Telescope:
DST @ NSO/Sacramento Peak

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

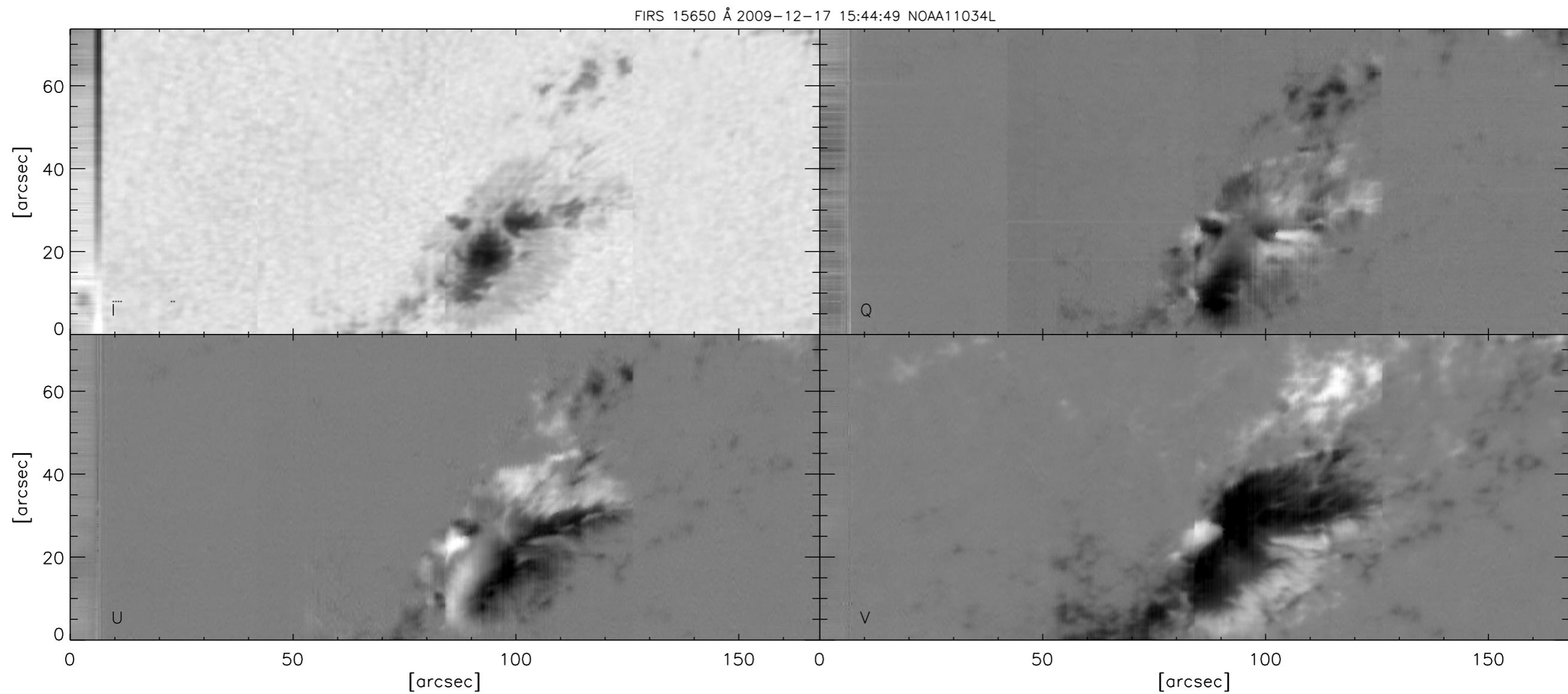
Wavelengths:
Fe I 6302 / Fe I 15650 Å
or
Fe I 6302 / Si I, He I 10830 Å

Runs concurrently with:
IBIS Ca II 8542 Å, H α , G-band
camera

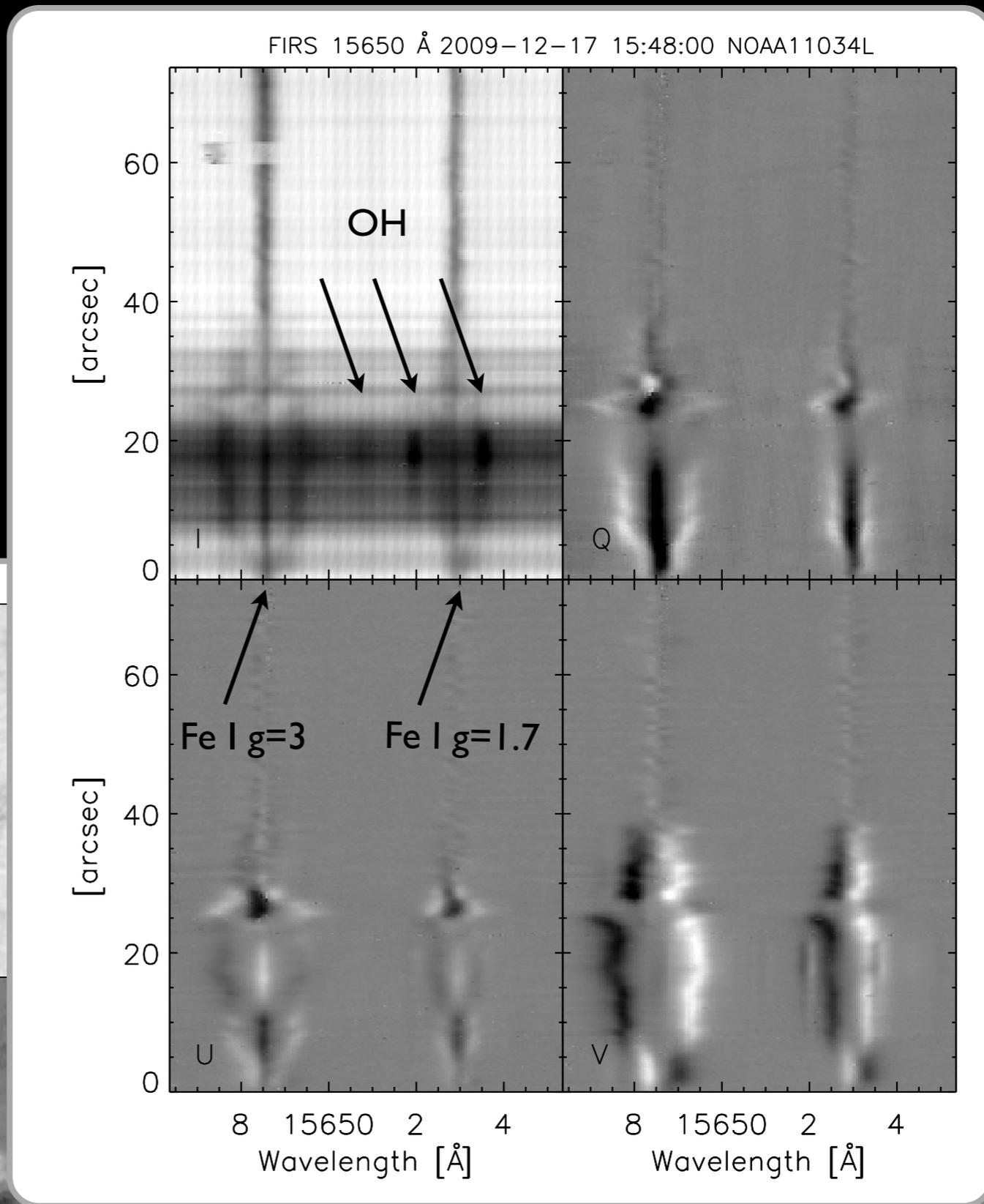
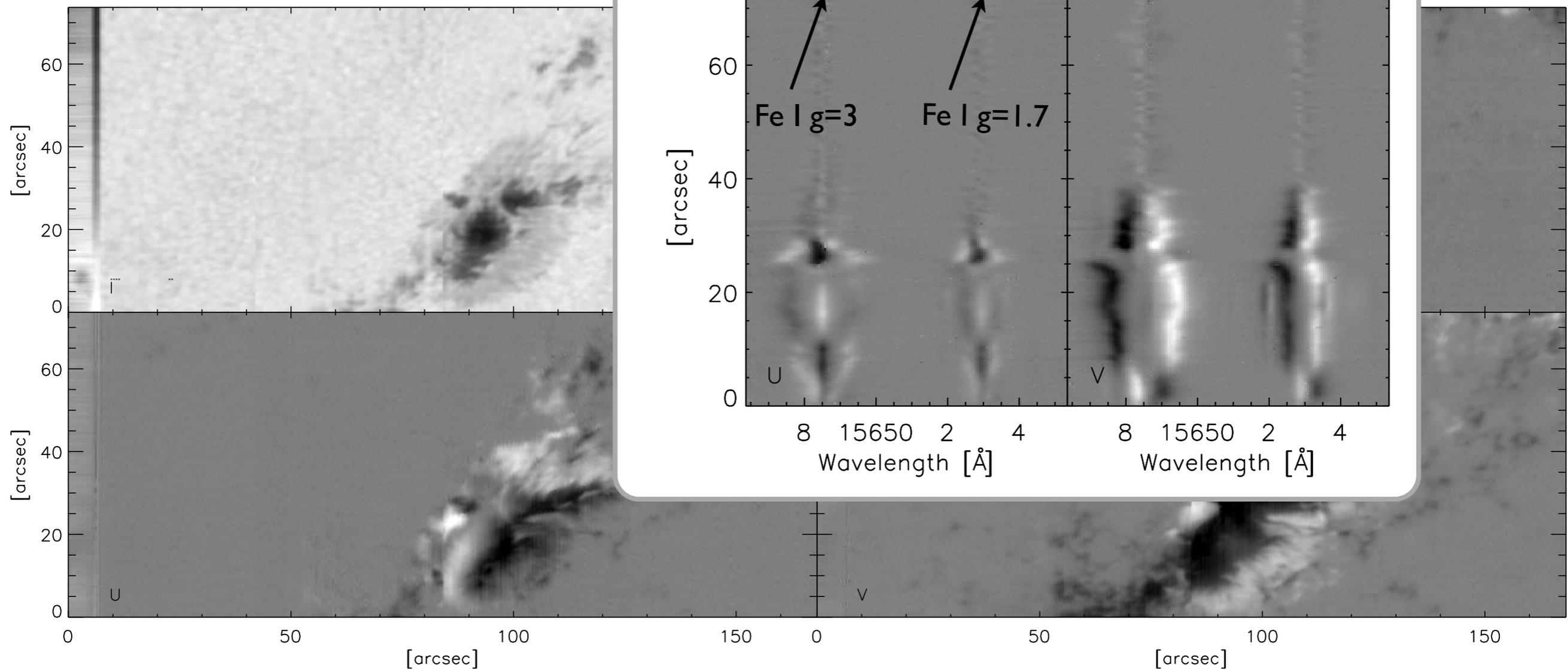
Now available for general use!
For more information see:
<http://kopiko.ifa.hawaii.edu/firs>



Fe I, OH @ 15650 Å FIRS Infrared channel



Fe I, OH @ 15650 Å FIRS Infrared channel



Inversion "2CMO"

2 Component Milne-Eddington Inversion

Magnetic component

full accounting for magneto-optical effect and damping wings using Voigt and Faraday-Voigt to fit Fe I Stokes profiles

Non-magnetic component

averaged quiet sun intensity profile

Magnetic Component

f magnetic filling factor

B magnetic field strength

γ magnetic field inclination

χ magnetic field azimuth

B_0 source function

B_1 source function gradient

λ wavelength

$\Delta\lambda$ doppler width

a damping parameter

η_0 line to continuum absorption ration

Non-Magnetic Component

λ_s wavelength of stray light component

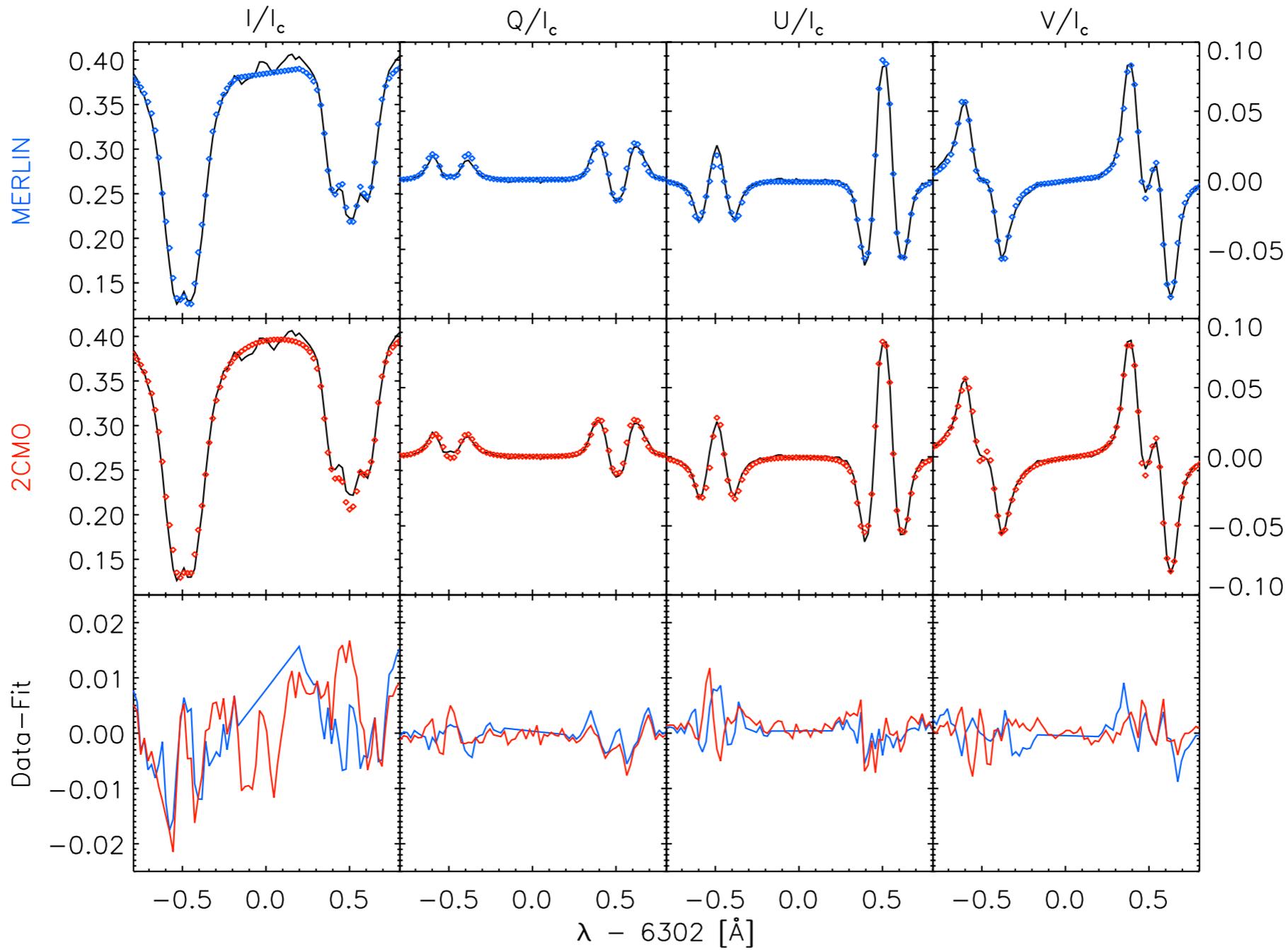
$l-f$ stray light filling factor

Inversion "2CMO"

2 Comp
Inversio

Ma

N



ption ratio

it component

I-f stray light filling factor

Inversion "2CMO"

2 Comp
Inversio

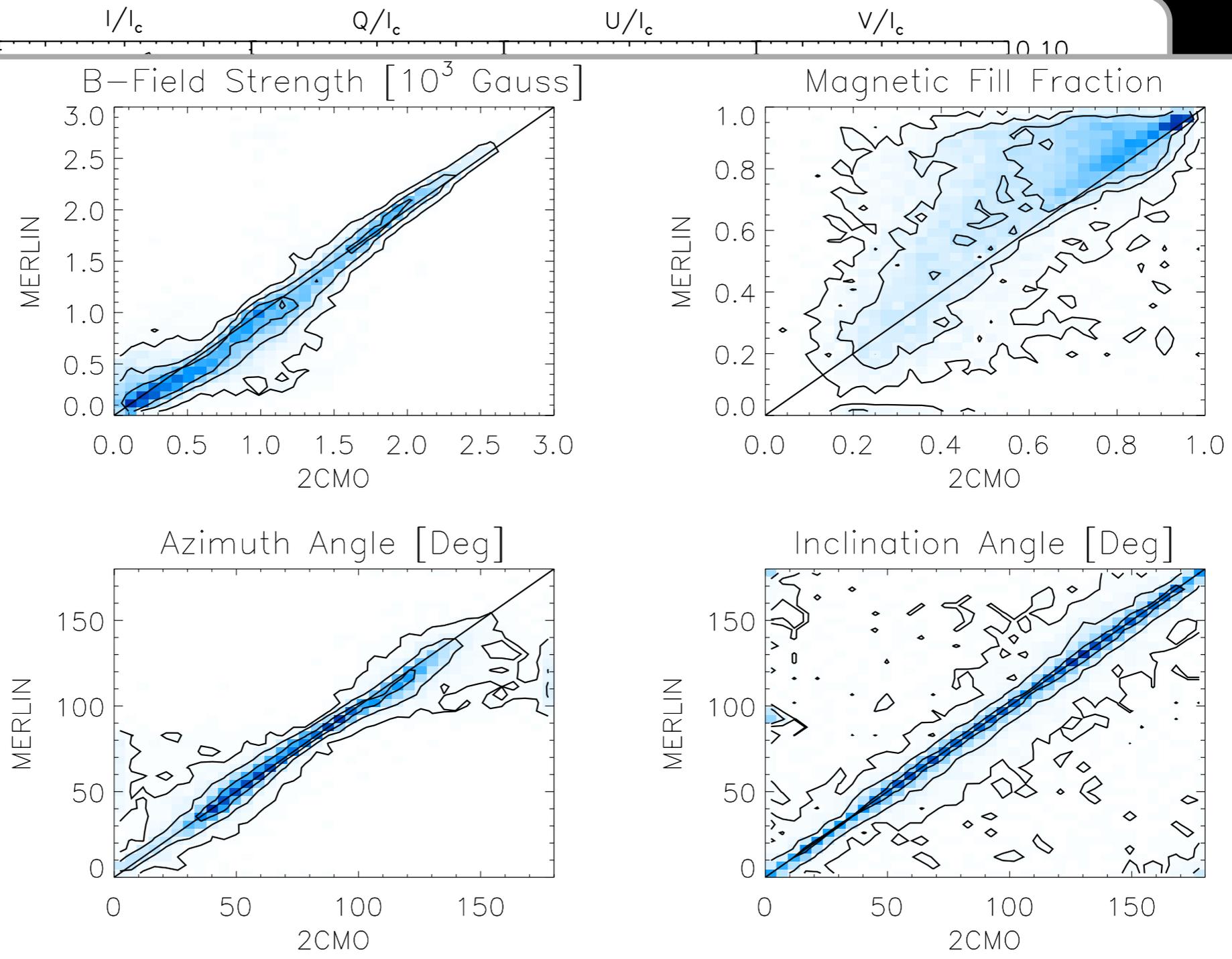
Ma

Z

MERLIN

2CMO

Data-Fit



1-1 stray light fitting factor

ration

onent

Atmospheric Modeling

Atmospheres

- Kurucz models 4000-7000 K
- Phoenix models 2600-3900 K

Generate spectral diagnostics

- Rybiki-Hummer (RH) radiative transfer and chemical equilibrium code
 - equilibrium molecular abundances
 - spectral synthesis

Atmospheric Modeling

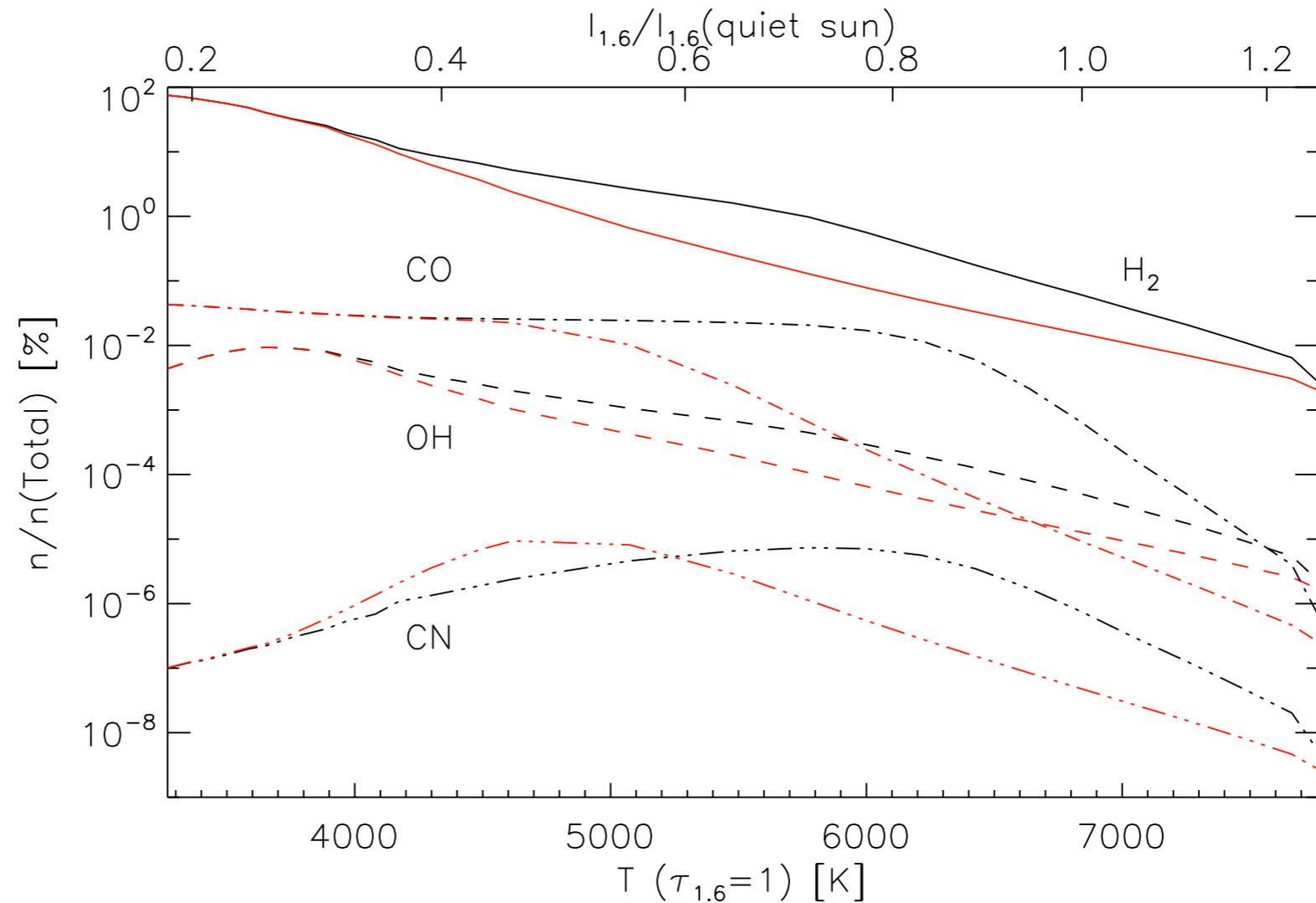
Atmospheres

- Kurucz models 4000-10000 K
- Phoenix models 2000-10000 K

Generate spectral diagnostics

- Rybicki-Hummer (radiation transfer and chemical equilibrium code)

- equilibrium molecular abundances
- spectral synthesis



Atmospheric Modeling

Atmospheres

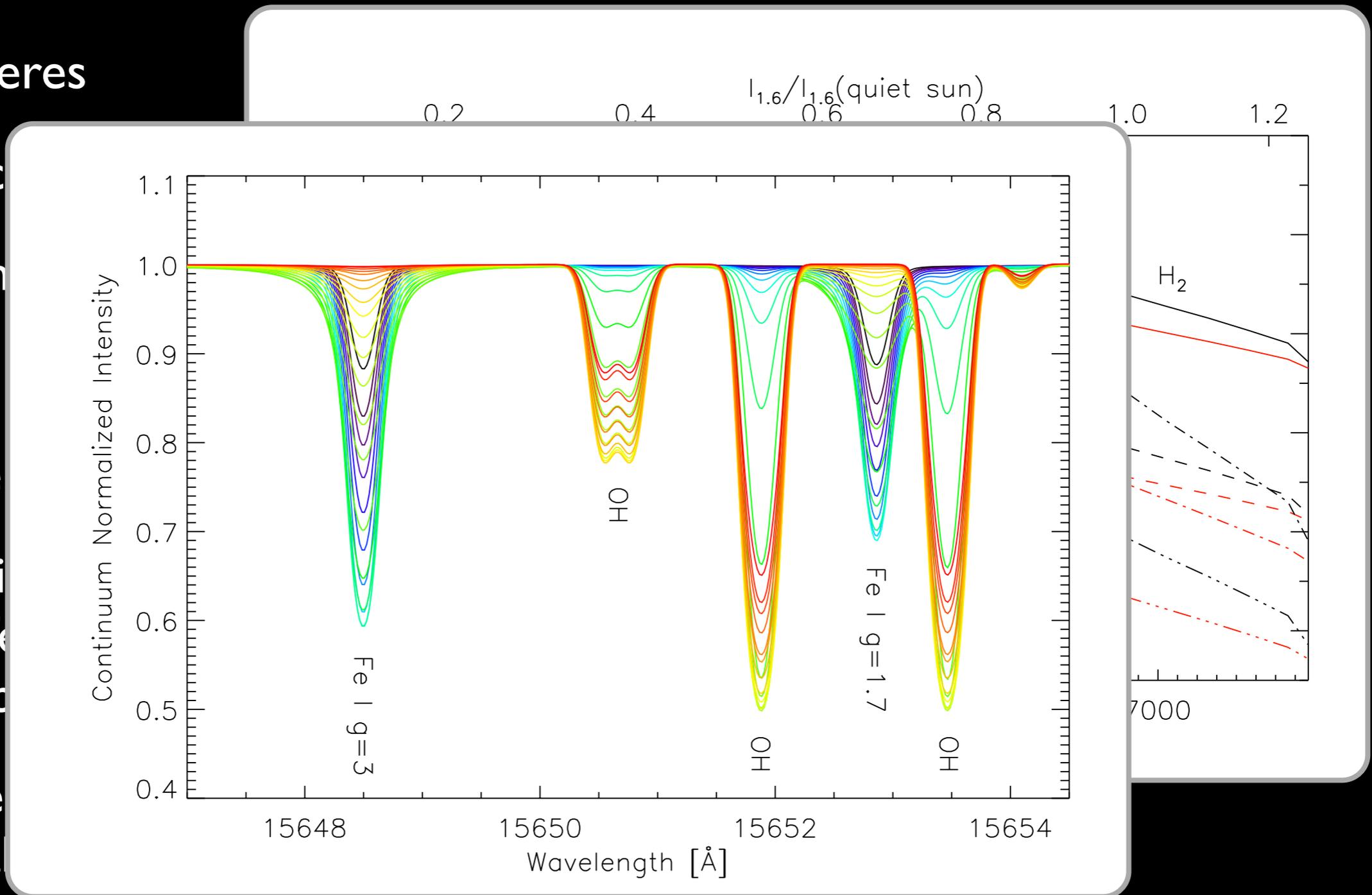
- Kurucz
- Phoenix

Generate

- Rybicki transfer equilibrium

- e
- a

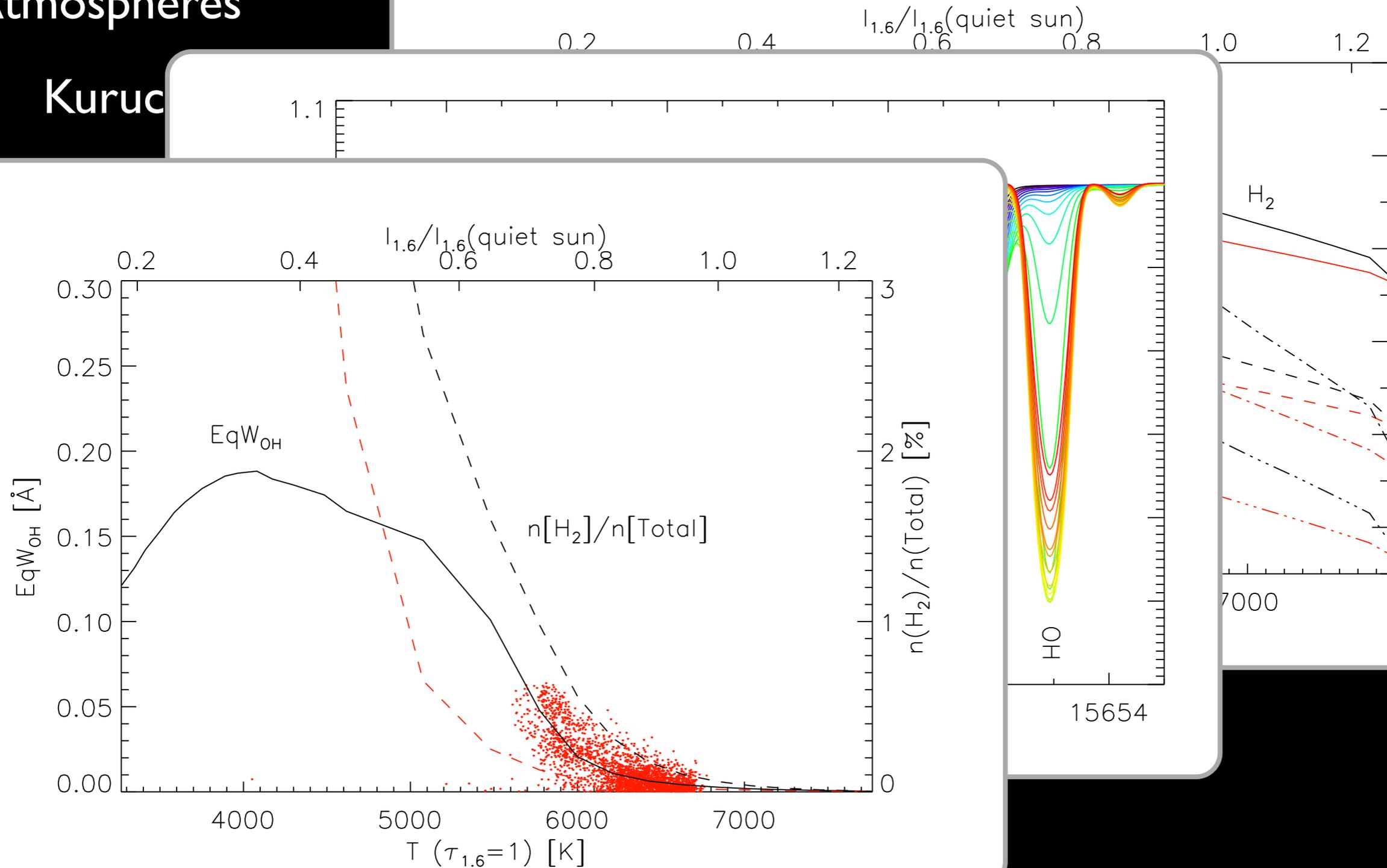
- spectral synthesis



Atmospheric Modeling

Atmospheres

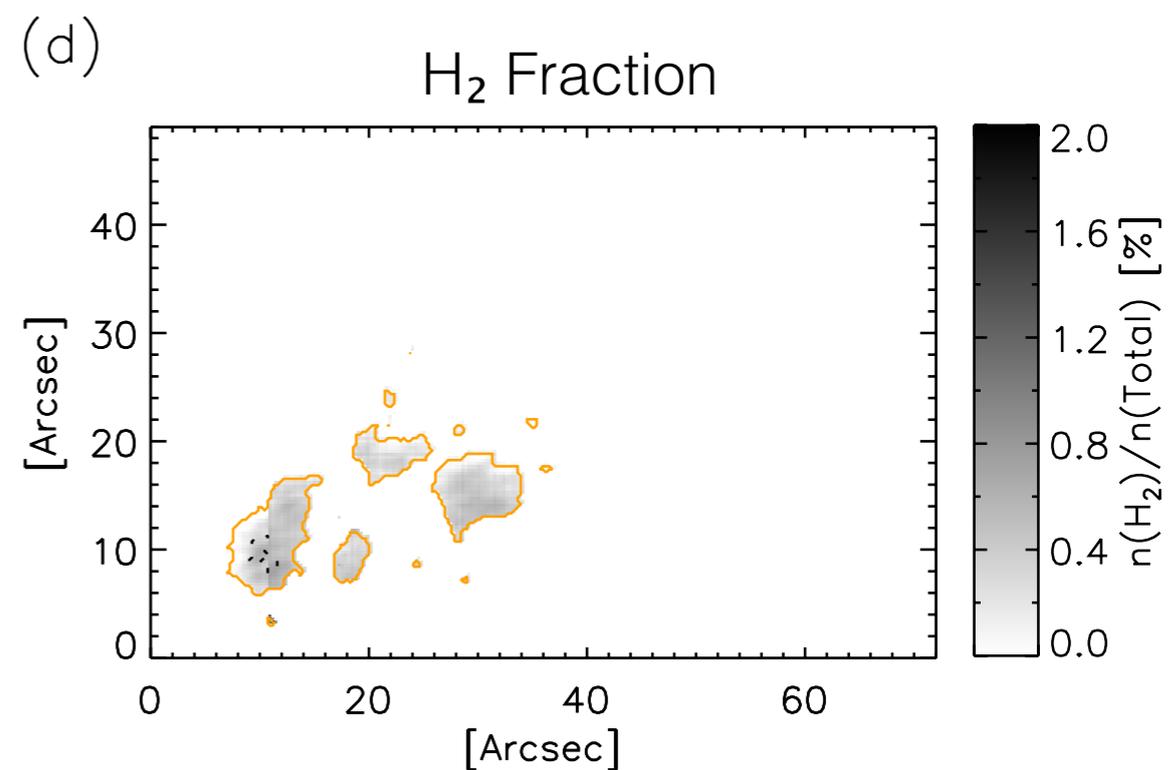
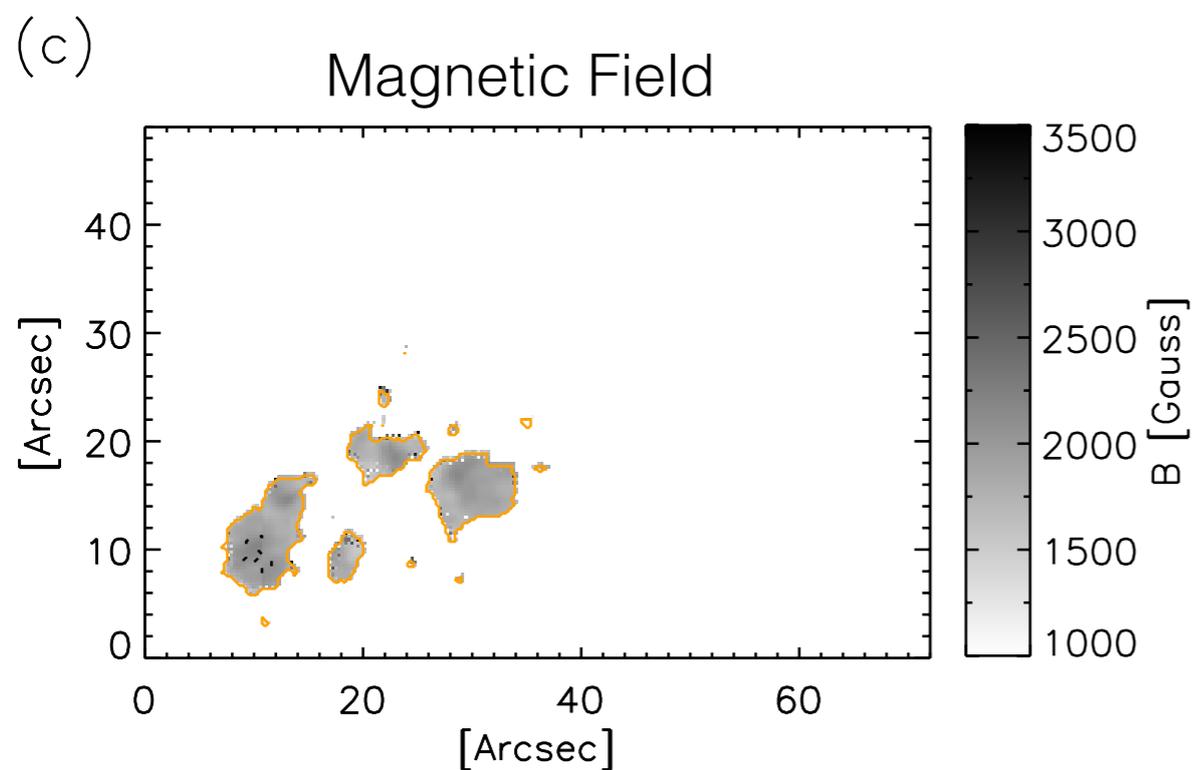
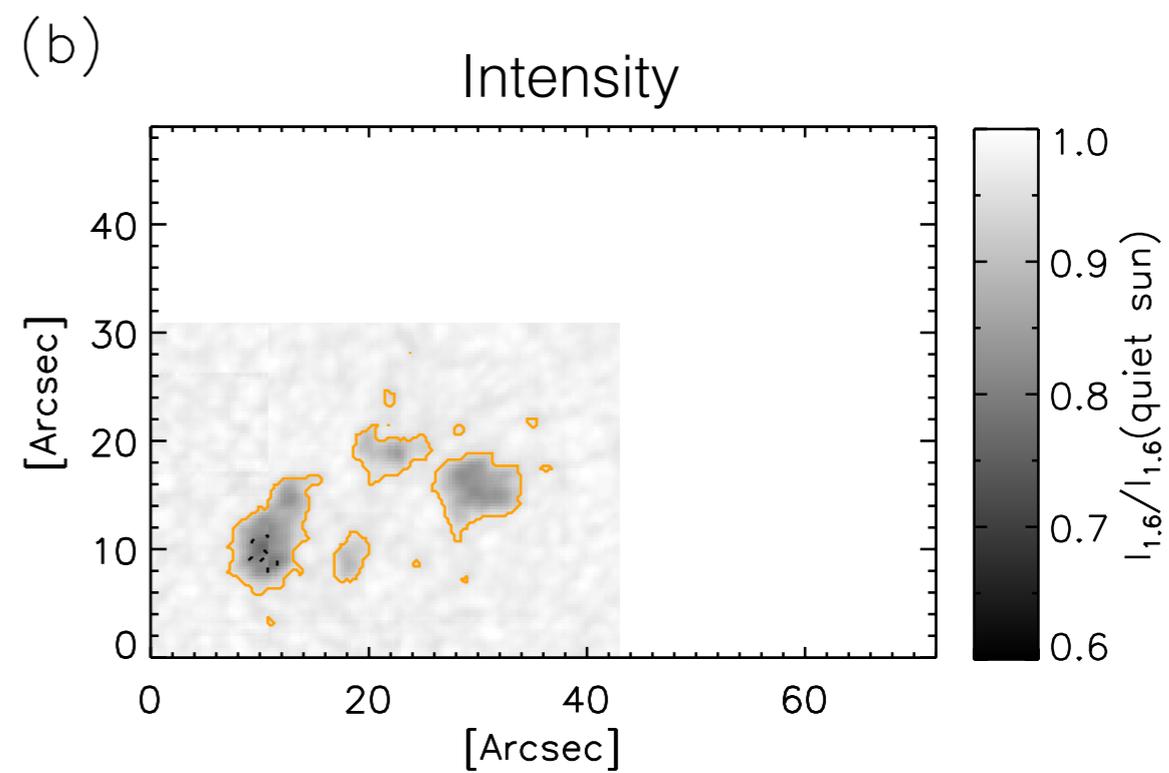
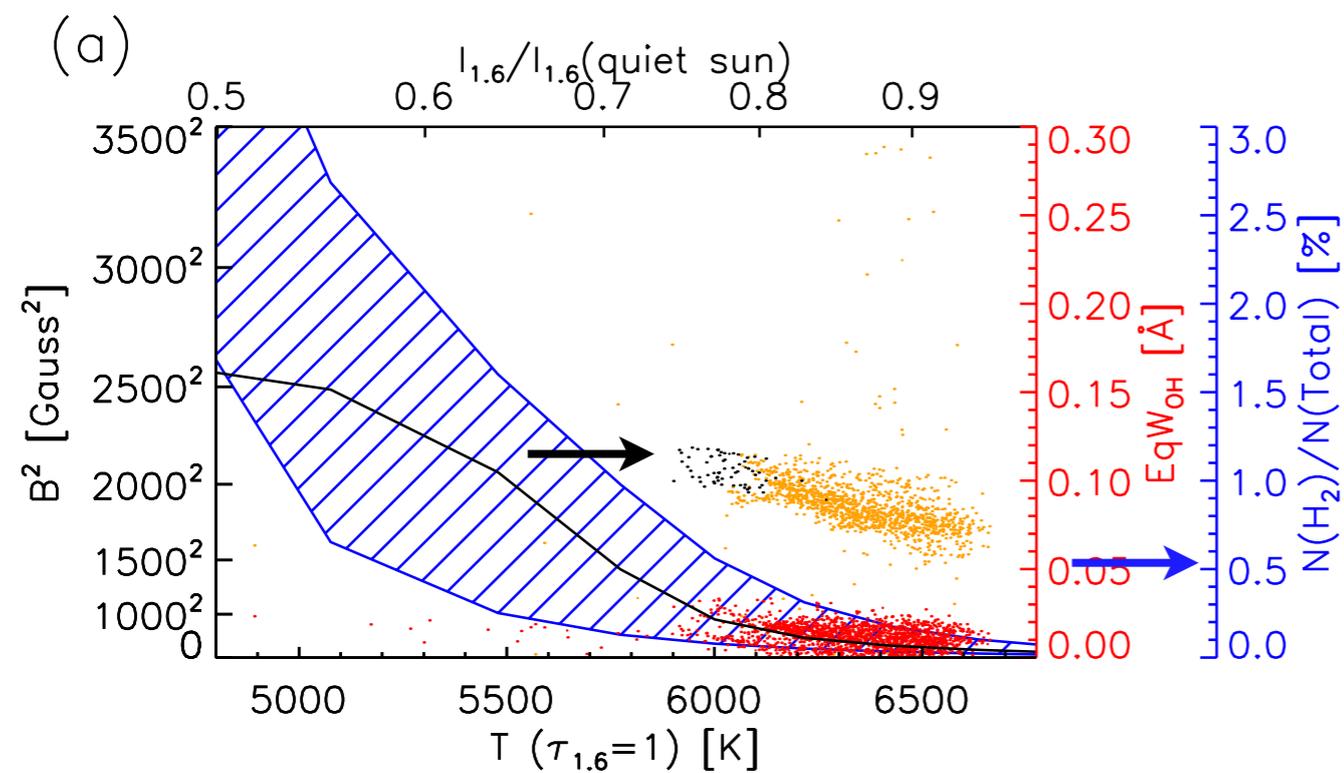
- Kuruc



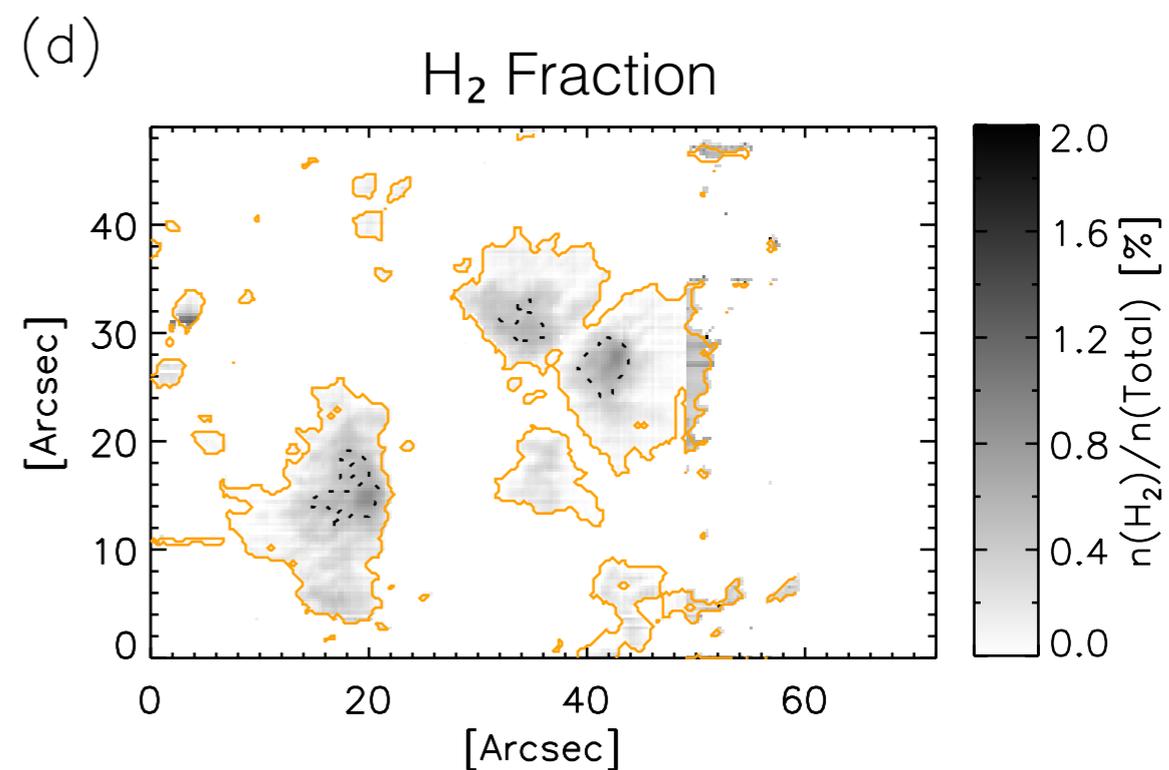
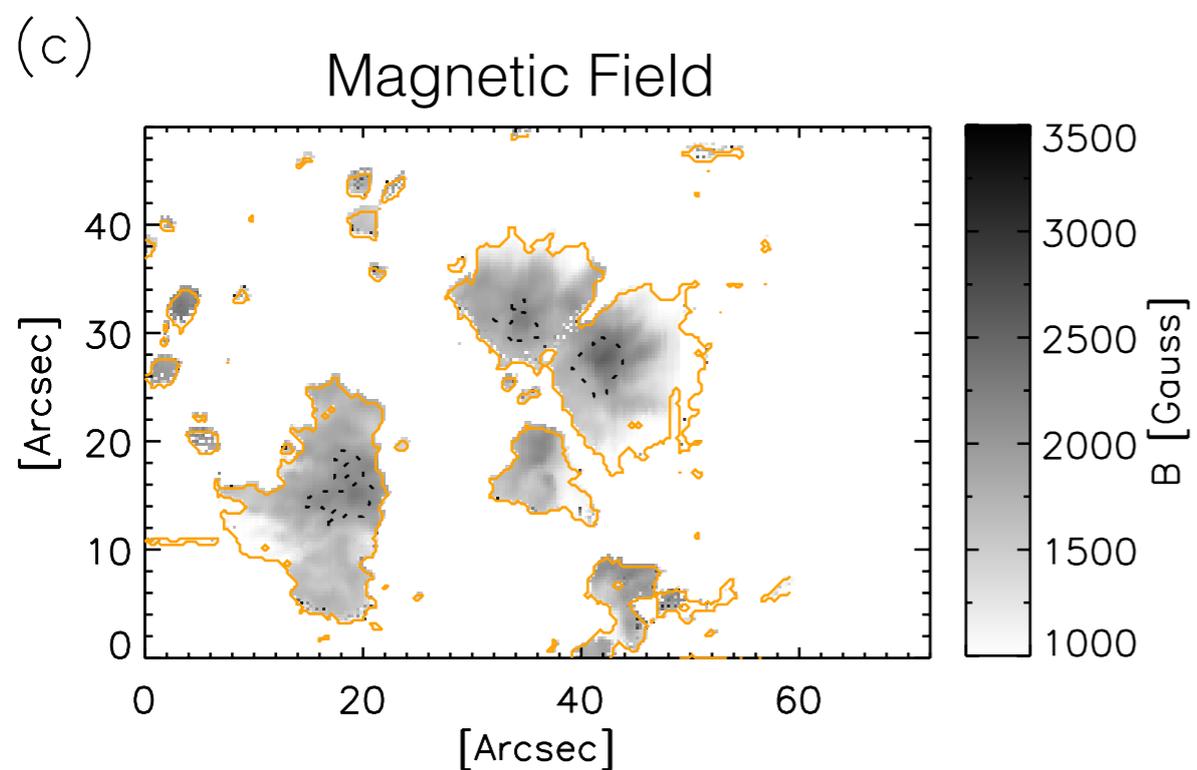
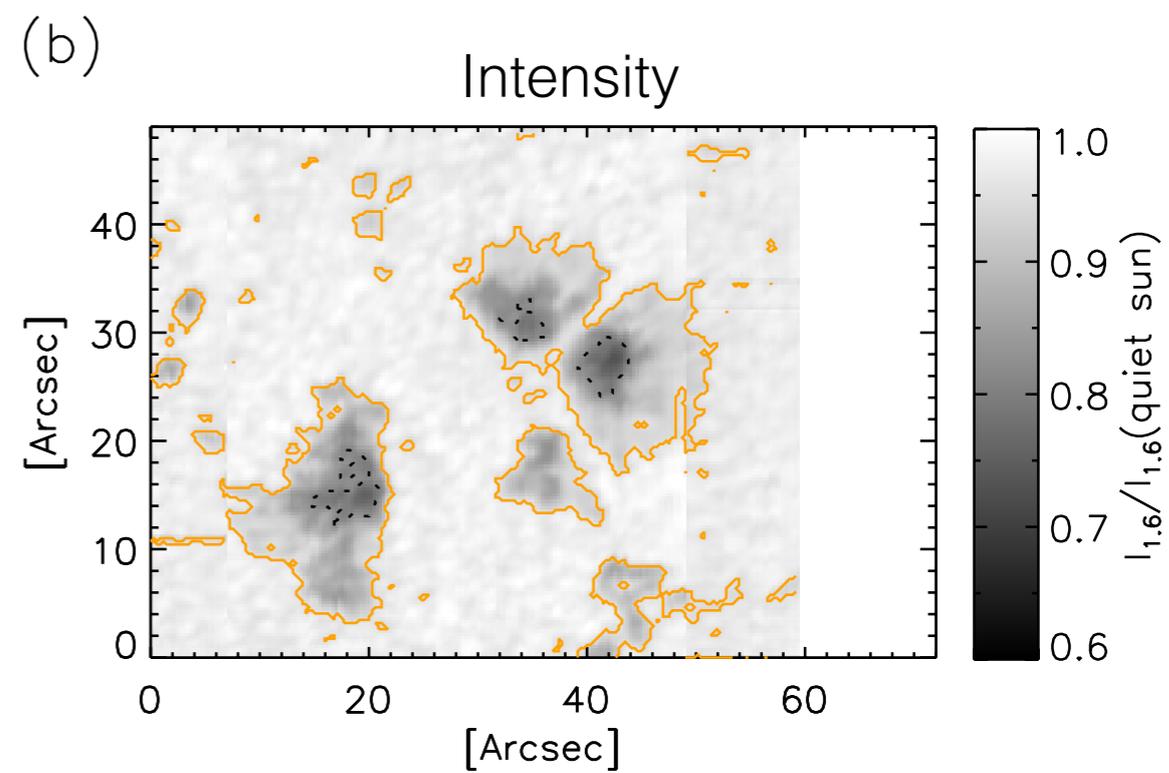
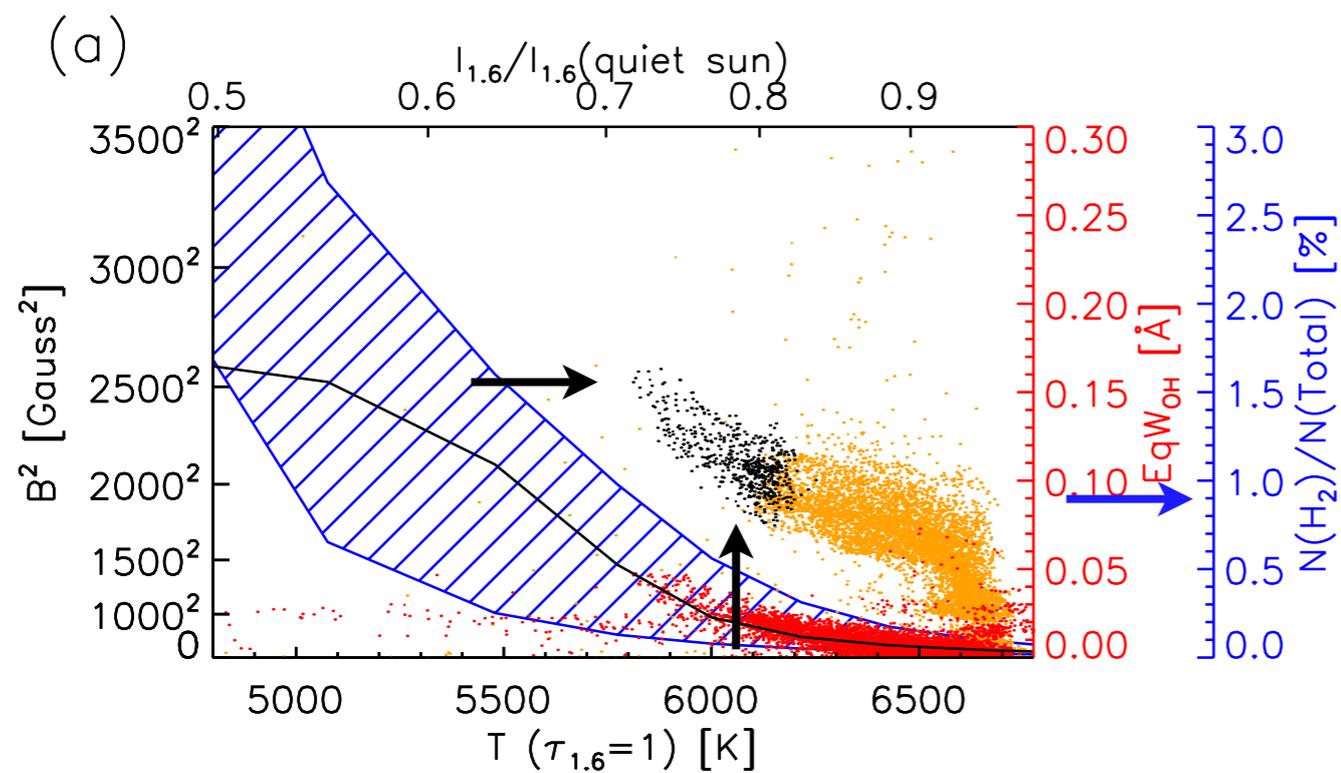
Survey Results

- Data inverted and model applied:
 - B
 - stray light corrected continuum T
 - OH EqW(also stray light corrected) / H₂ fraction
- Results from 6 examples from the survey

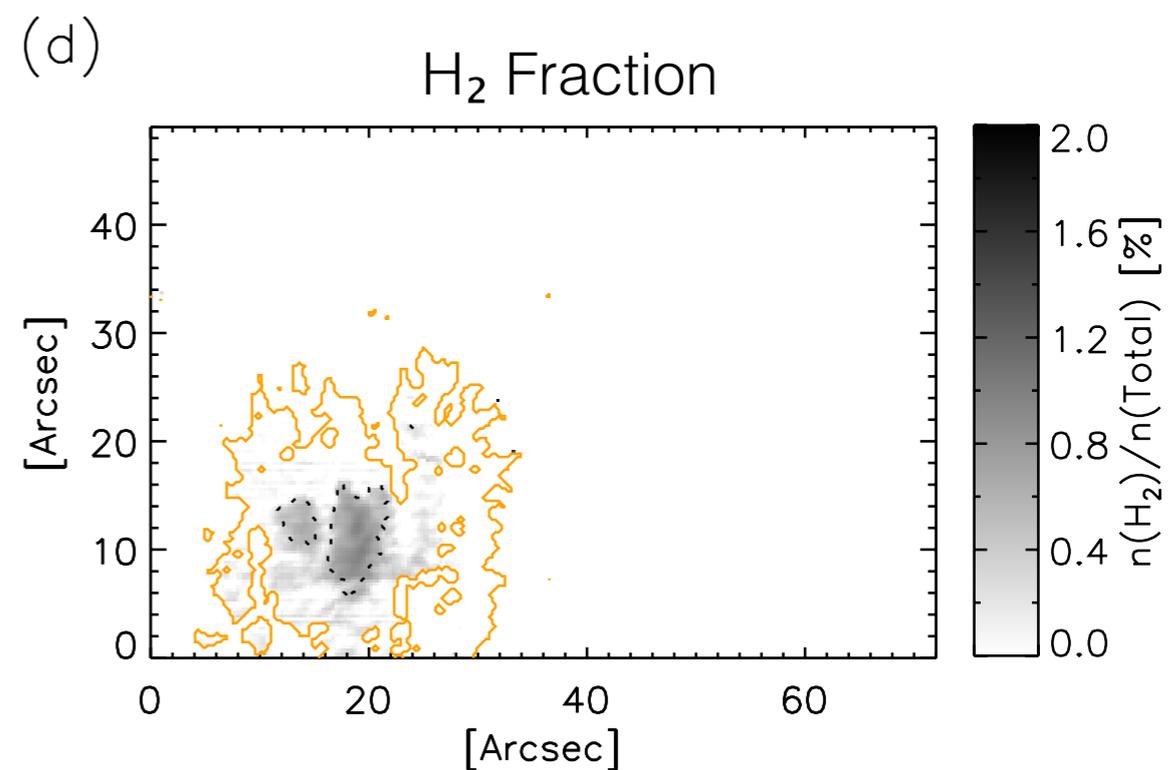
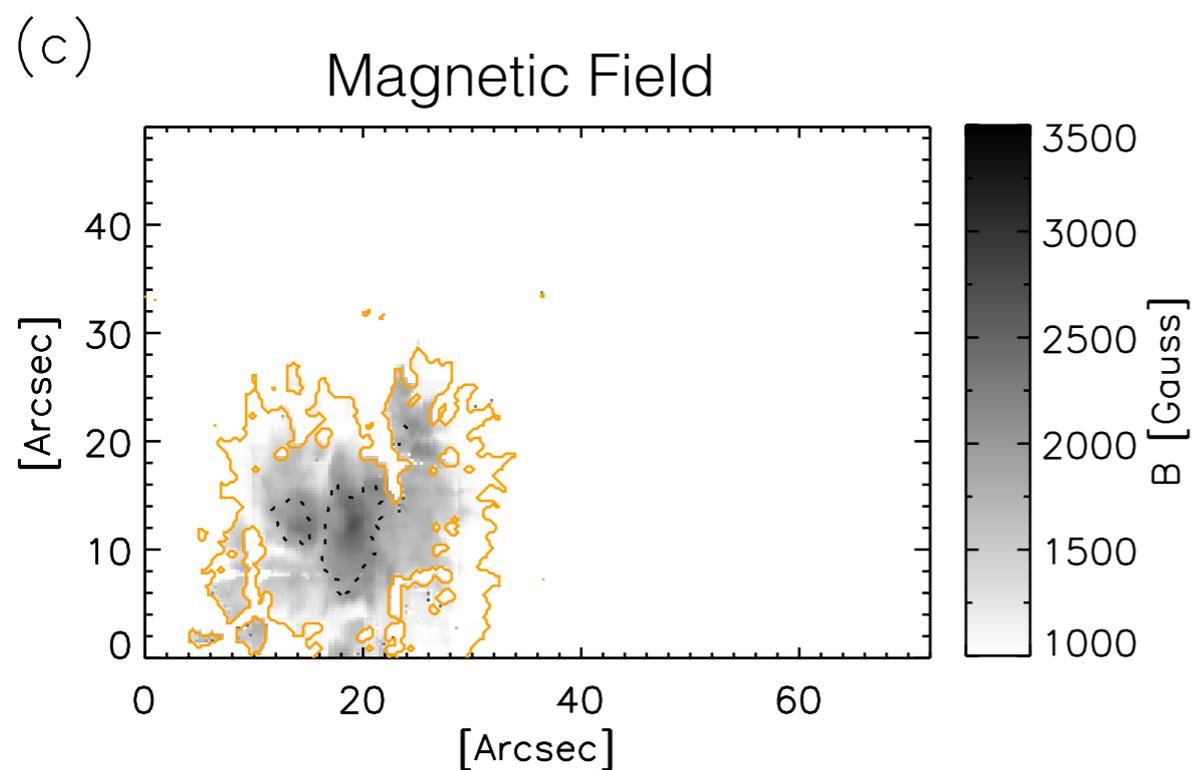
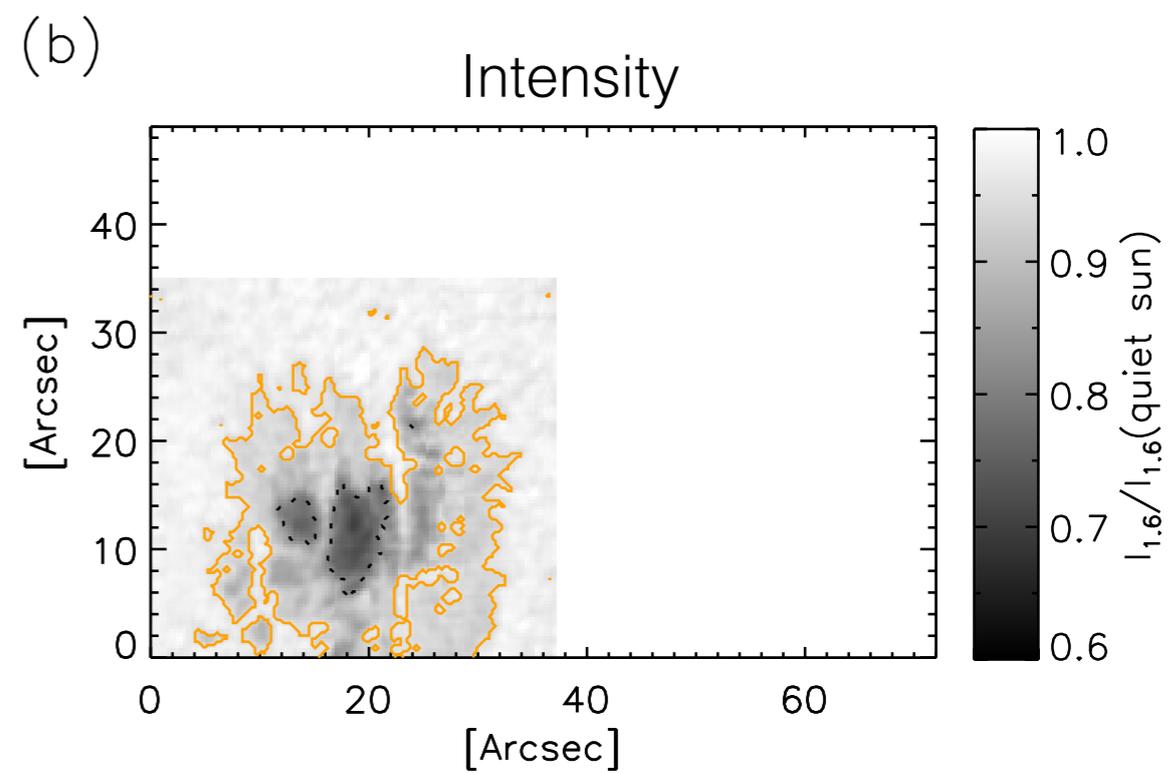
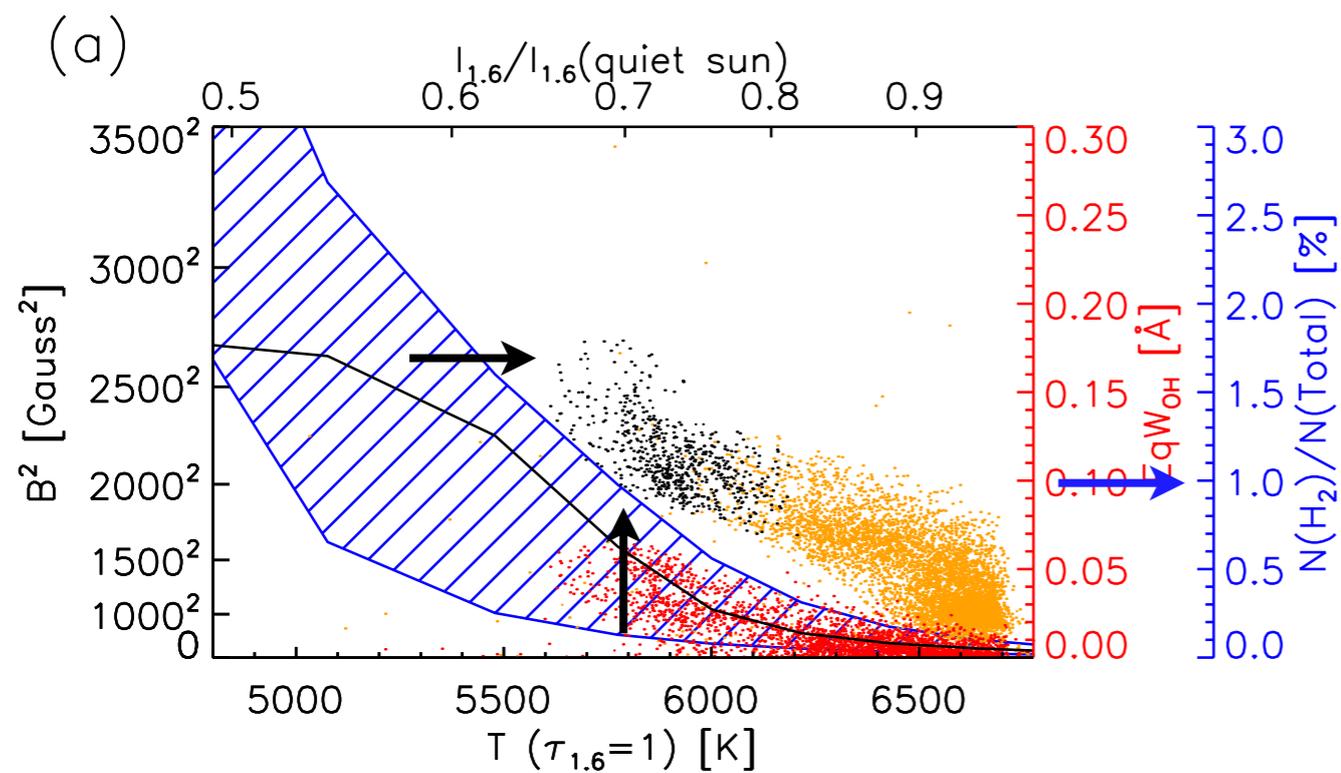
NOAA 11049, 2010-02-19



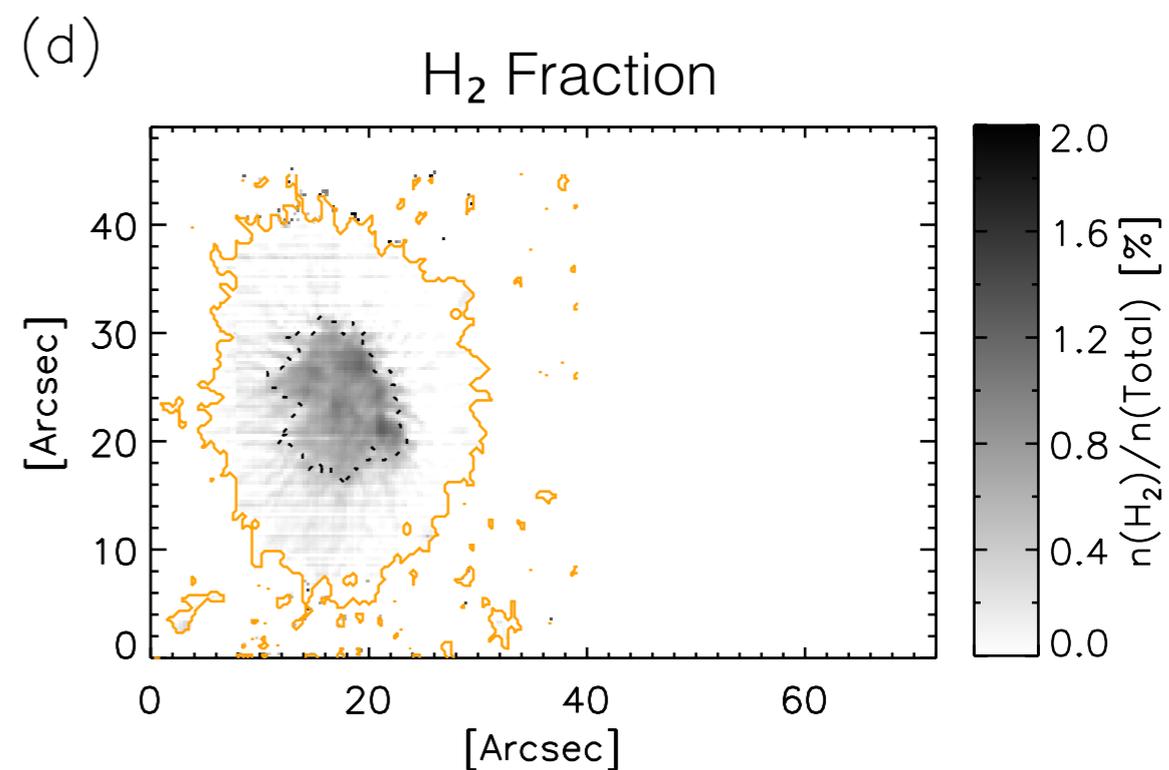
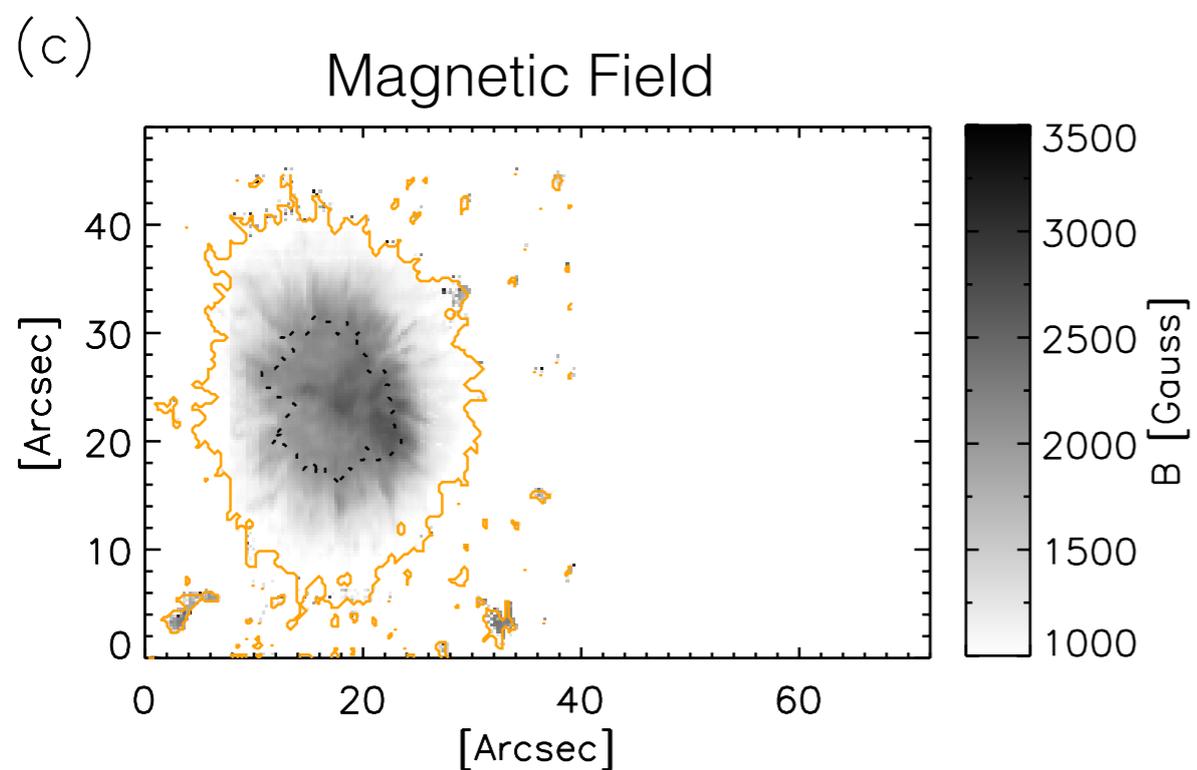
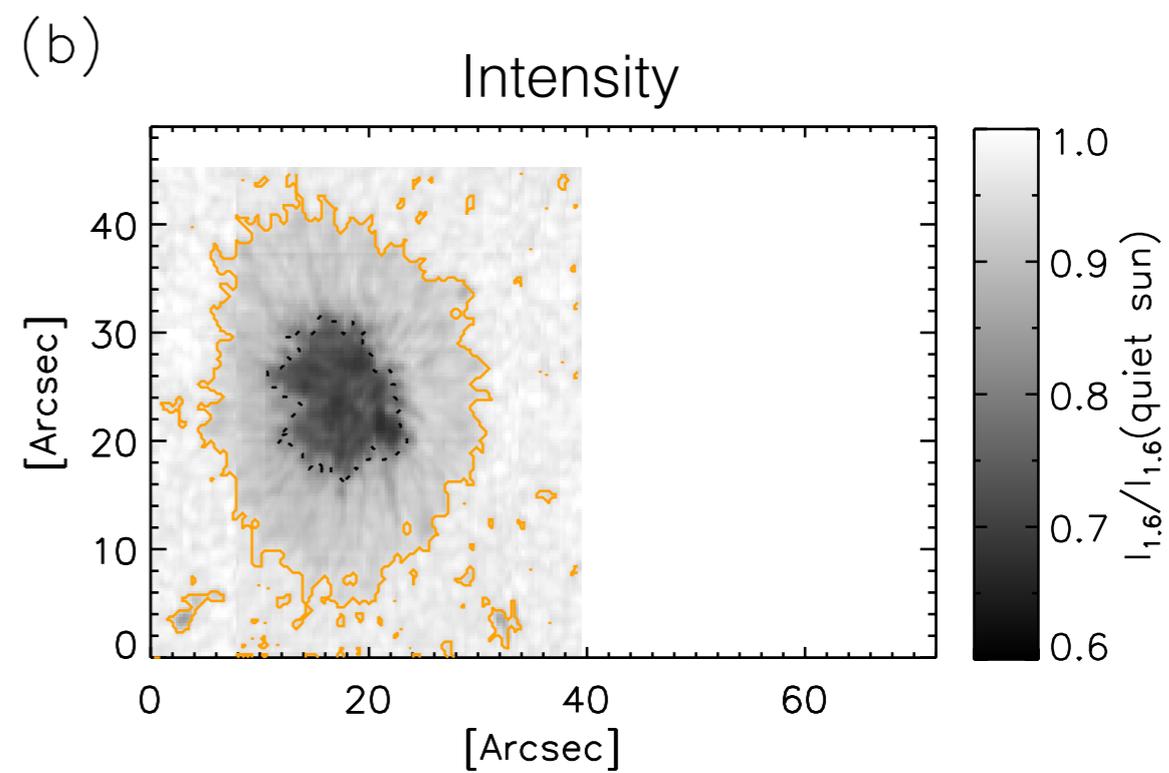
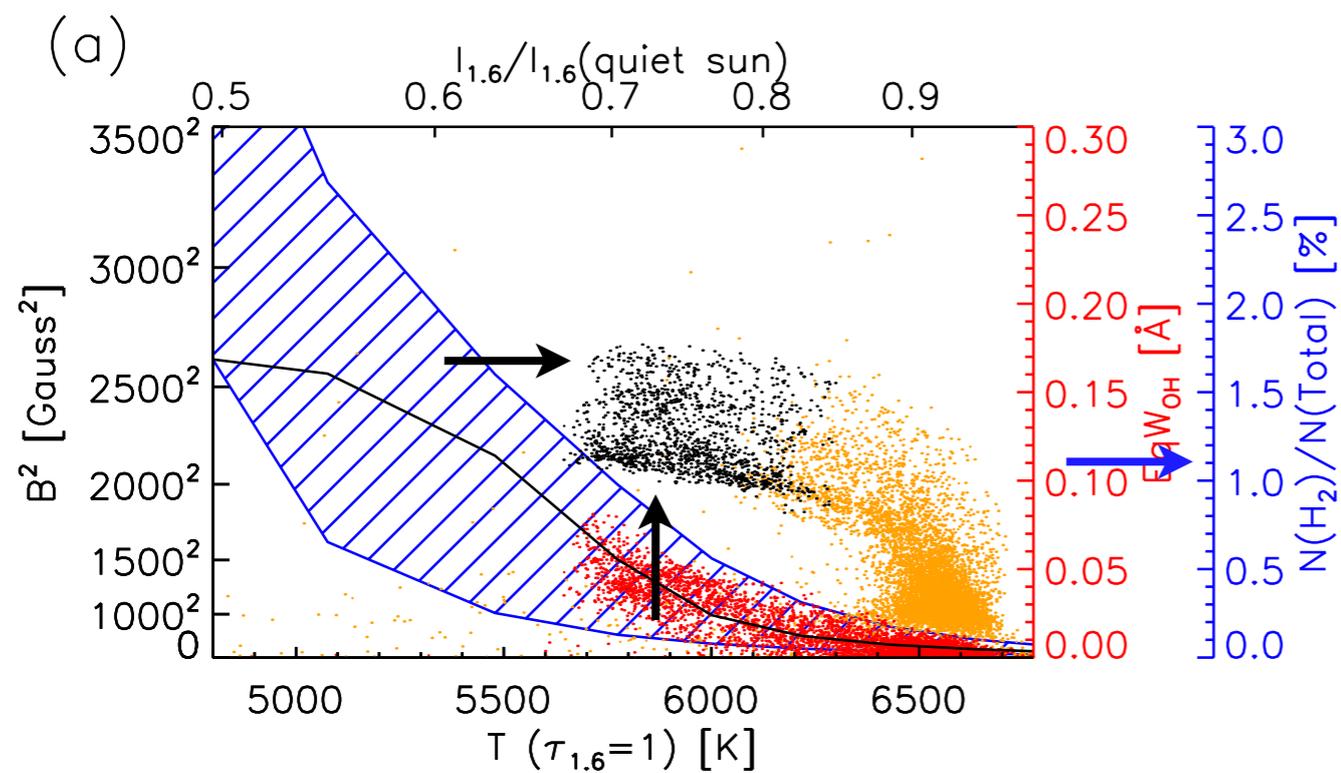
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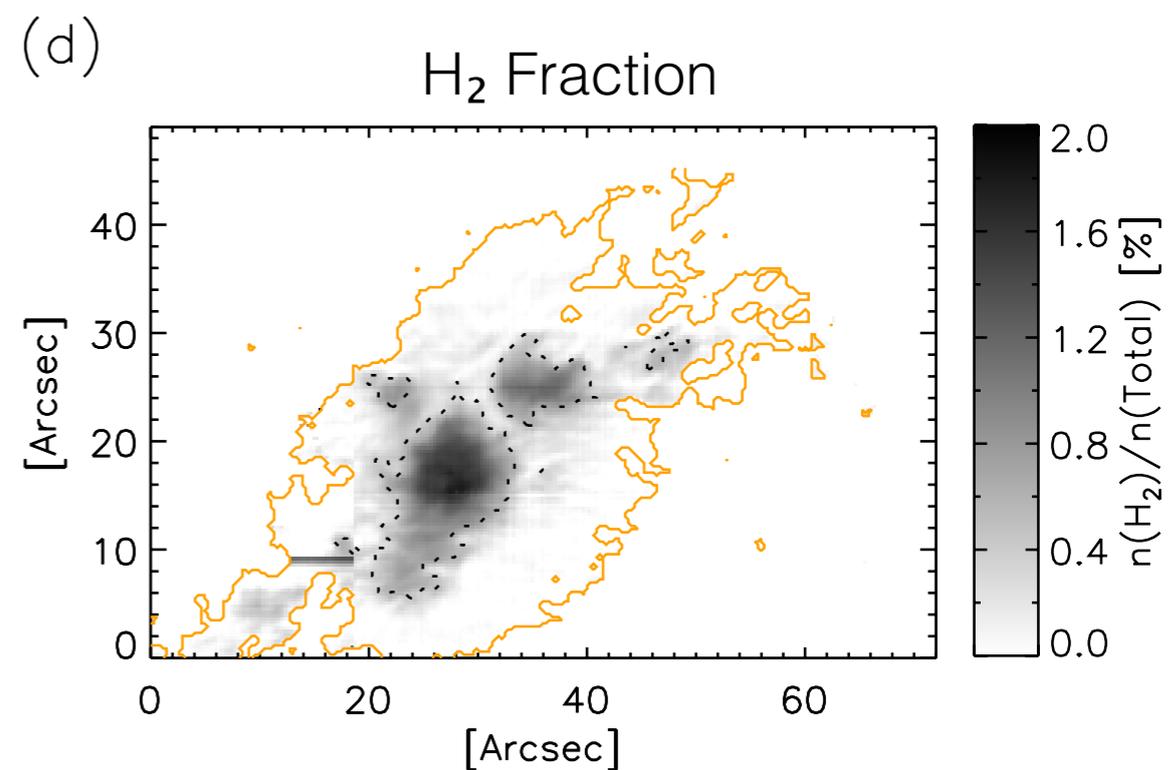
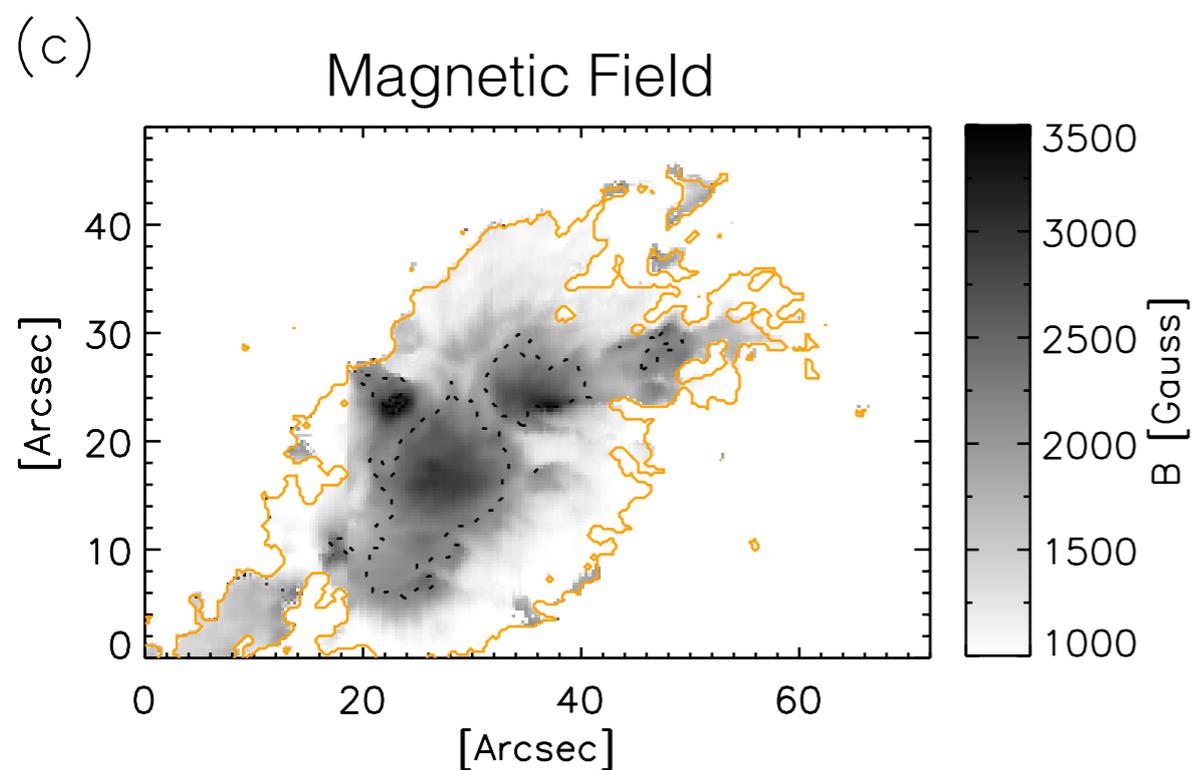
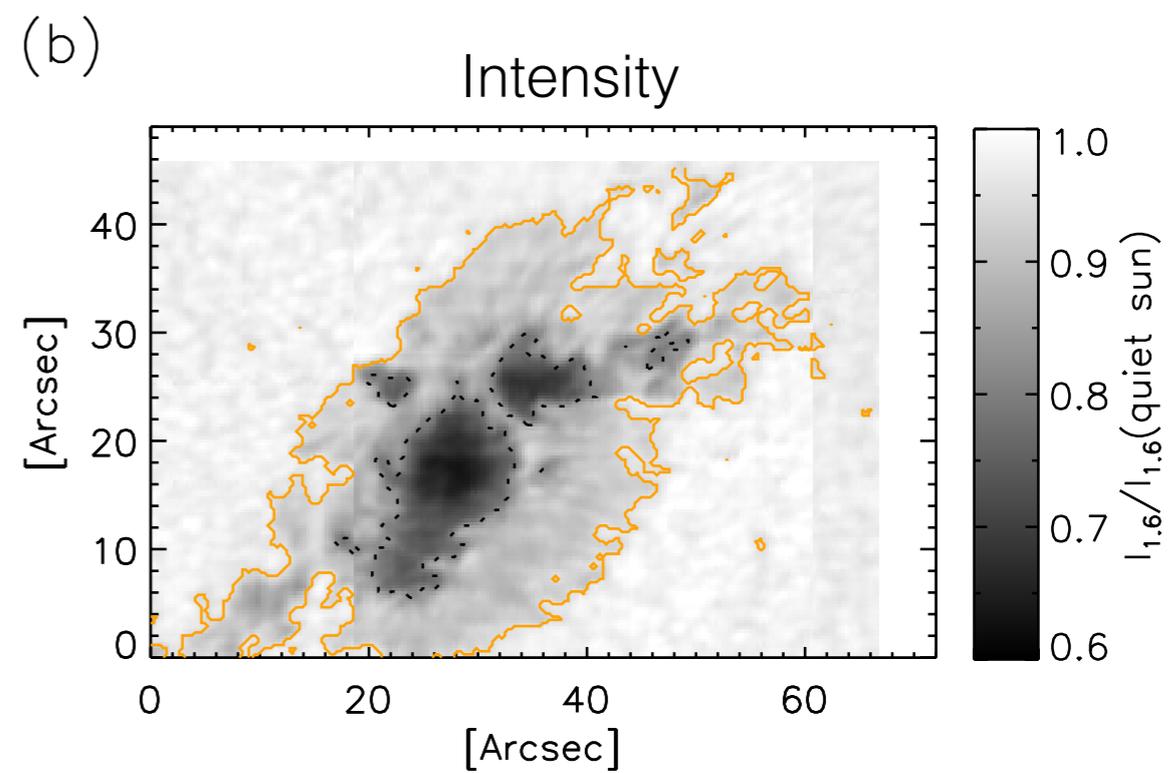
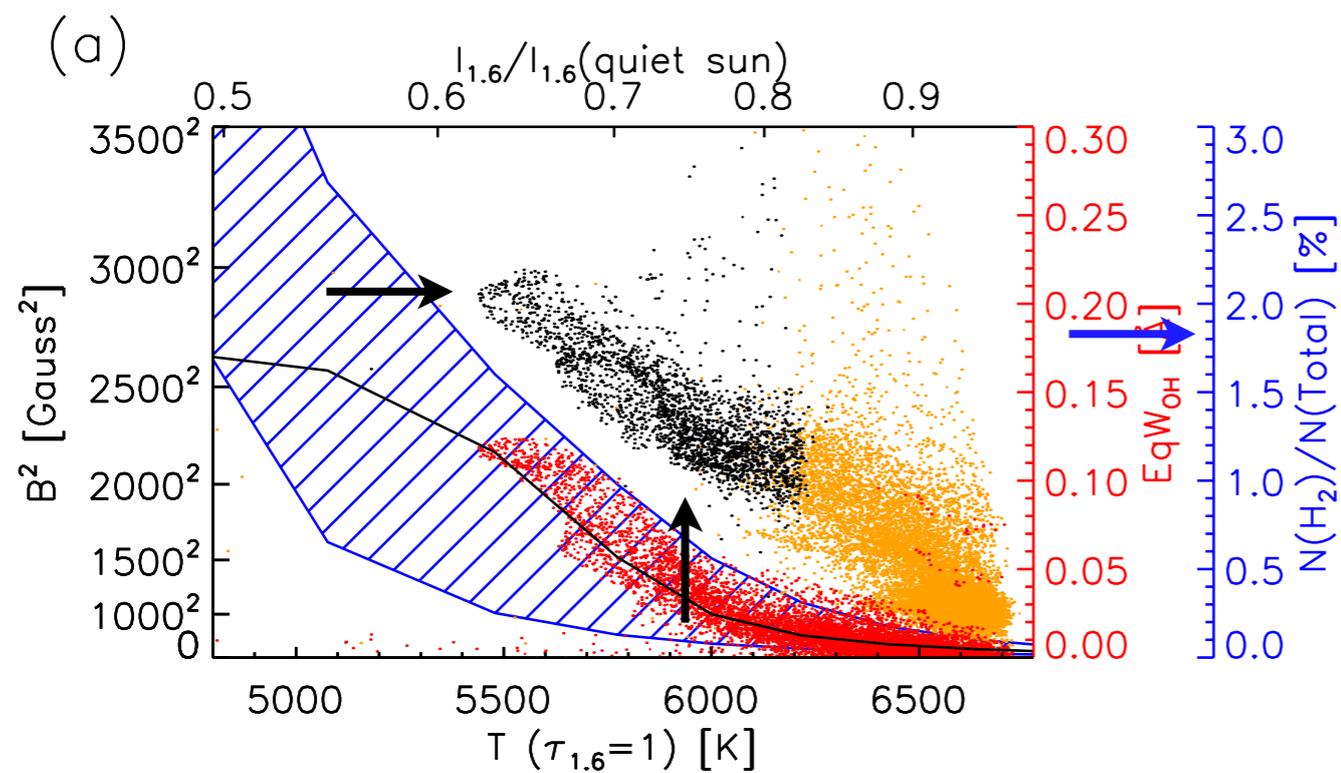
NOAA 1130, 2010-12-02



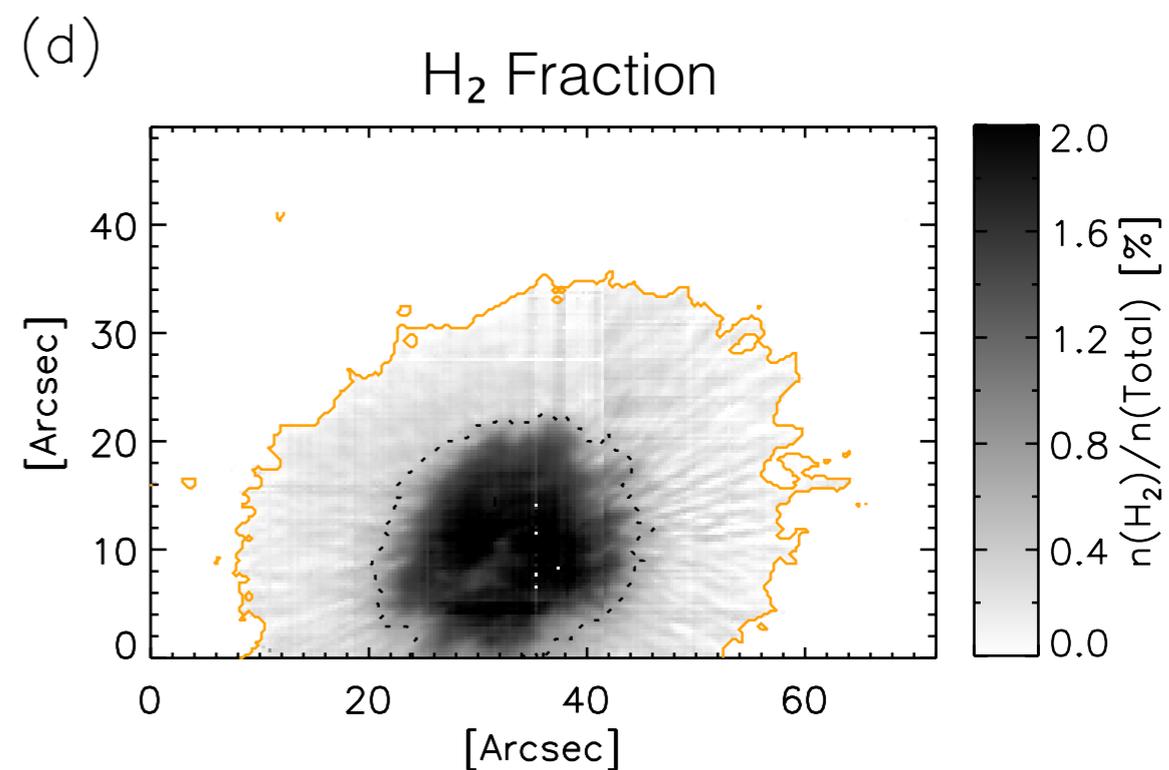
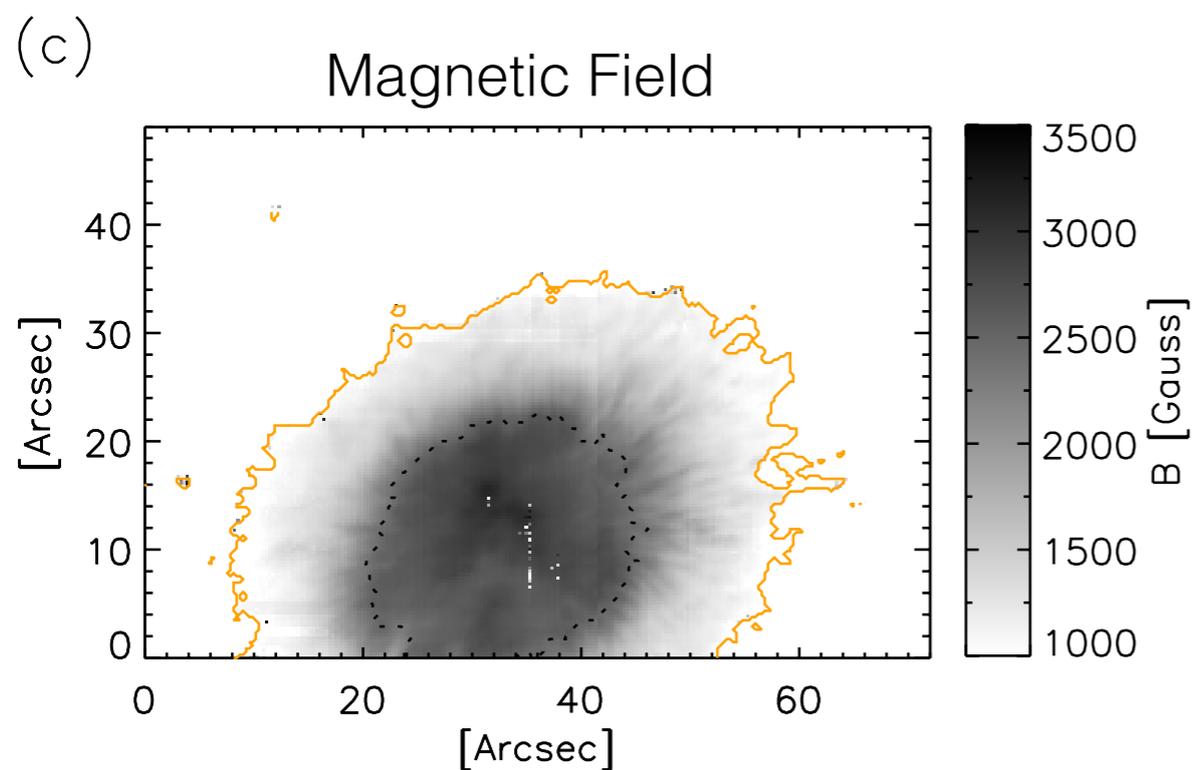
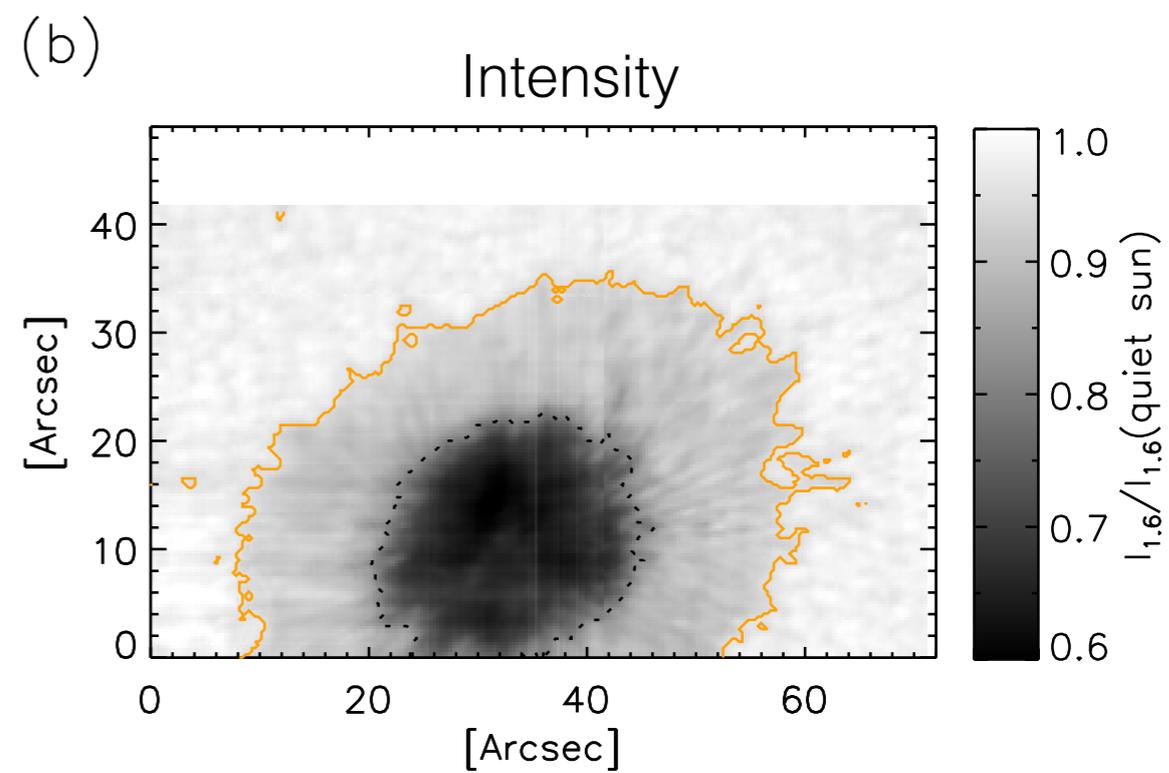
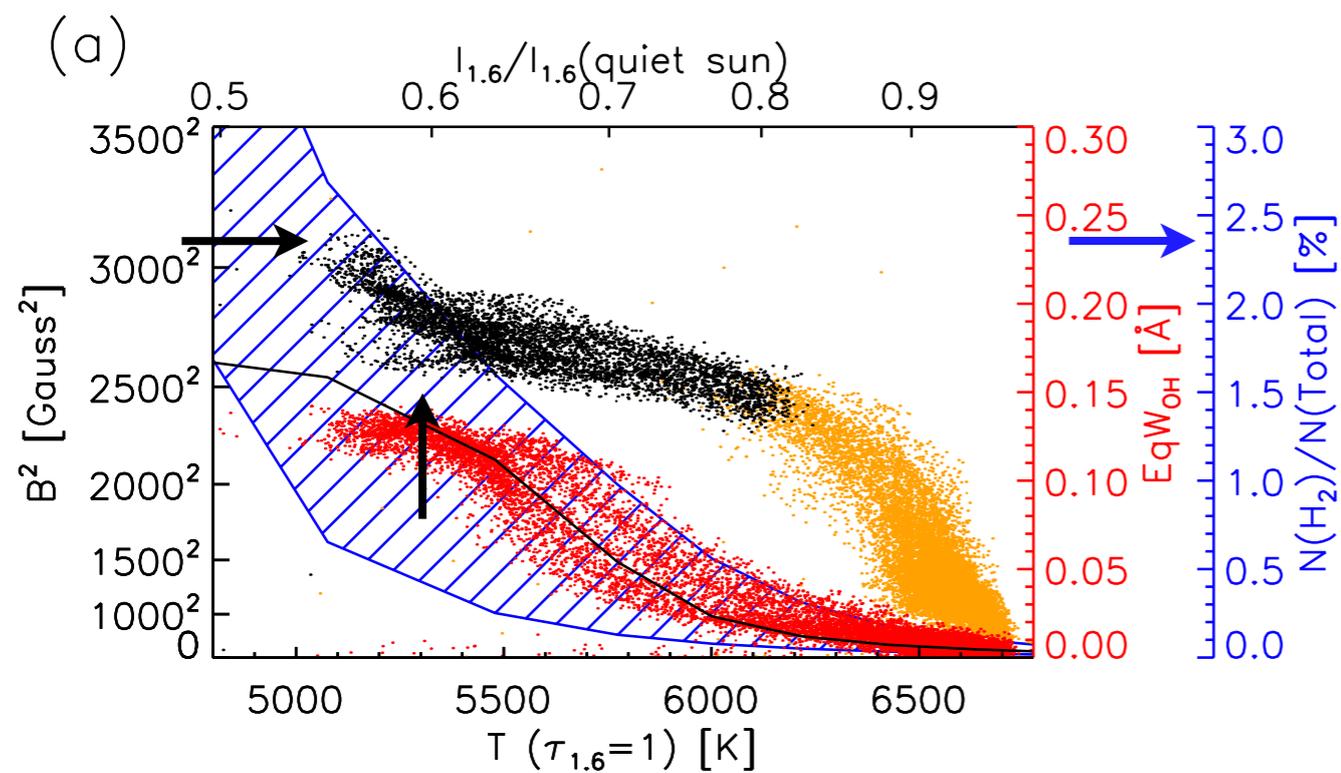
NOAA 11101, 2010-09-02



NOAA 11035, 2009-12-17



NOAA 1131, 2010-12-06



Survey Results

OH, H₂ vs. T

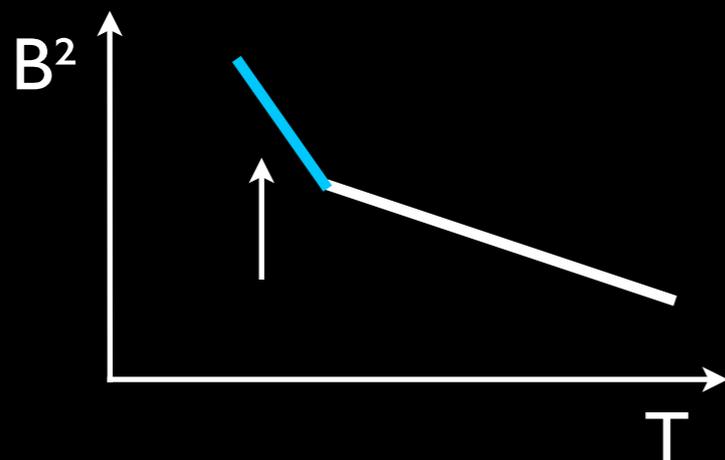
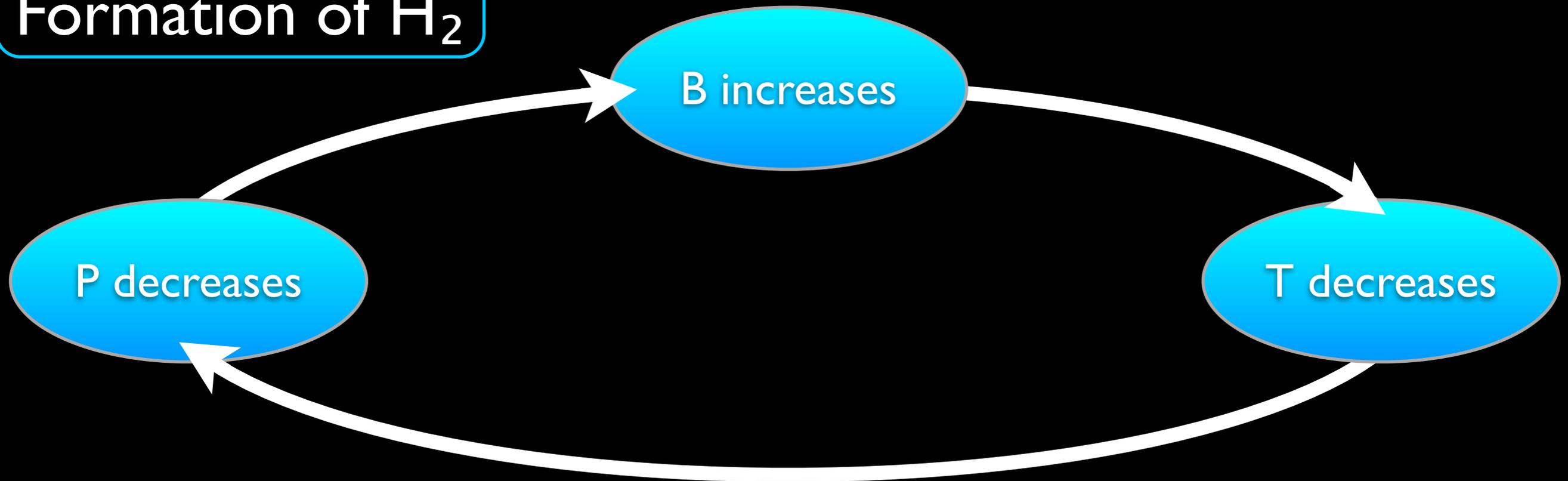
- good agreement of measured OH w/ synthetic spectra from models

B² vs. T

- Upturns
 - increase begins around 6000 K
 - spots with umbral fields > 2500 G, H₂ > 1%
 - steeper relations seen in mid-sized/strength spots
 - in quiescent/decay phase
- No upturn
 - weak fields, little or no H₂ (< 0.5%)

The Role of H₂

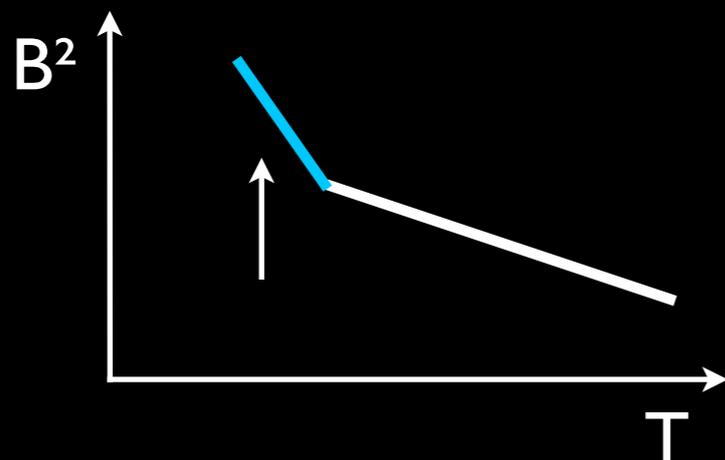
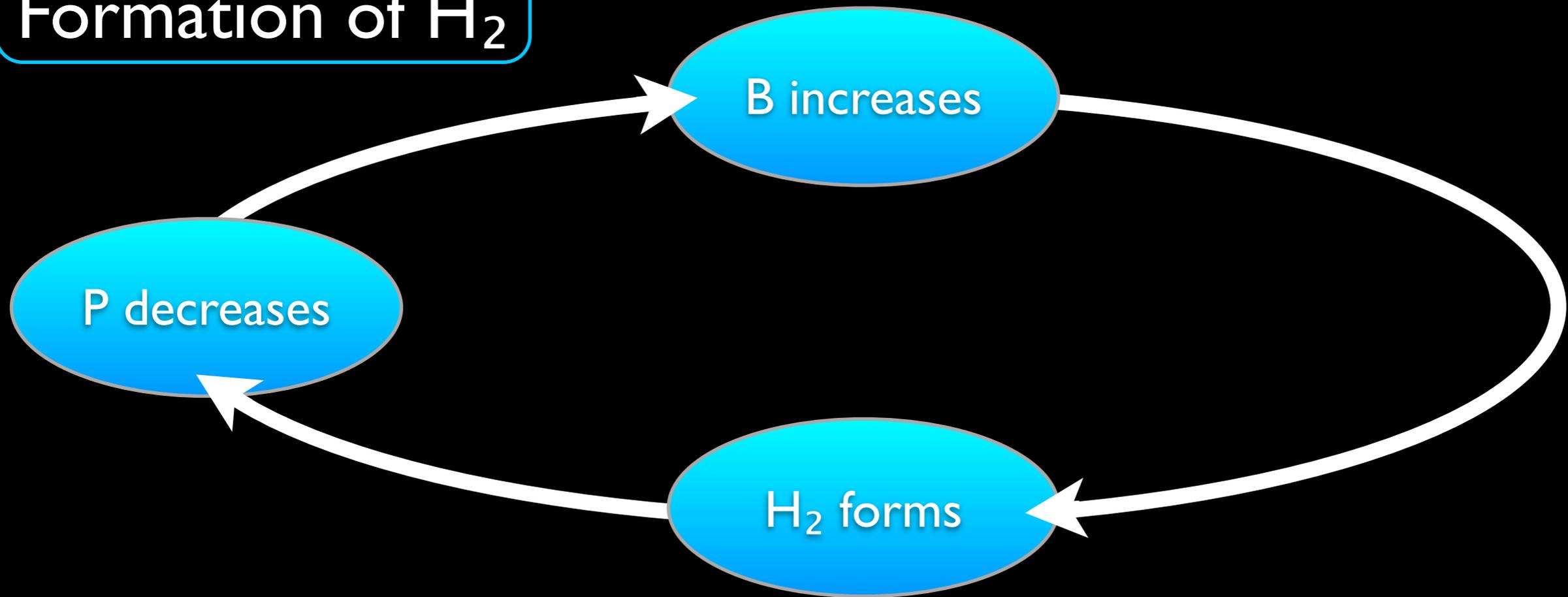
Formation of H₂



more rapid intensification
of B field
H₂ "runaway" formation

The Role of H₂

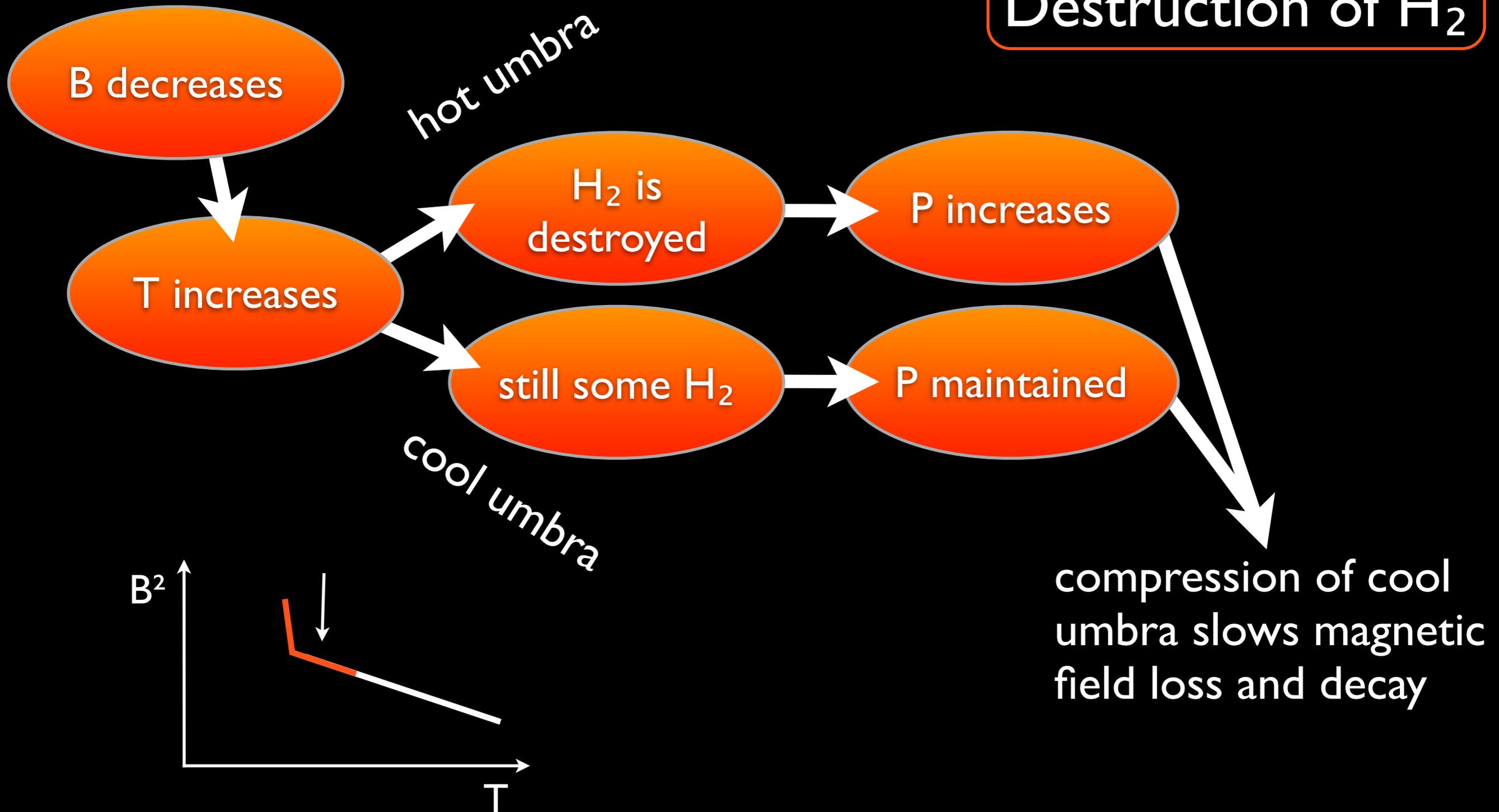
Formation of H₂



more rapid intensification
of B field
H₂ "runaway" formation

The Role of H₂

Destruction of H₂



Conclusions

- Formation of H_2 can explain the thermal-magnetic relation seen in larger sunspots
 - Upturns coincide with H_2 "turn-on"
- Other implications for sunspot science
 - increased heat capacity in sunspots
 - models must include multi-component gas

Future Work

- Characterization of the non-linearity due to RT effects and curvature force
- Using 6302/15650 Å sunspot survey
- In-depth comparison of observations and sunspot MHD models

Thank You!



NSO, for continuing mentorship and financial support.

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