

An Observational Study of the Formation and Evolution of Sunspots



a dissertation by Sarah A. Jaeggli



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NSO

S.A. Jaeggli -- IfA -- 26 Aug 201 I

Outline

Introduction with sunspot equilibrium A Problem Methods a survey Instrument **Observations** Analysis I inversions Analysis II modeling Survey Results Speculation and Discussion **Conclusions and Future Plans**

Introduction

Our star, the Sun

Local Big: 99% of mass in the solar system

Bright: I300 W/m² at Earth

Unique: the only dwarf star on which we resolve surface features (730 km/")

GalacticView

Compared to O stars...

Small: 7×10^5 km, $15 \times$ smaller, 50 × less massive

Dim: Mv~4.8, 10⁶x fainter

Ubiquitous: 1 in 10







00/HMI Quick-Look Continuum: 2011.08.18_23:26:15_TAI



00/HMI Quick-Look Con SDO/HMI Quick-Look Magnetogram: 2011.08.18_23:26:15_TAI





00/HMI Quick-Look Con SD0/HMI Quick-Look Magnet

SDO/AMA- 211 20110818.232614 SDO/AMA- 193 20110818_232608

Solar Dynamo

$$\times \vec{B} = \mu_0 \vec{J}$$

Ist order: dipolar magnetic field from rotation

2nd order: advancement of equatorial field, differential rotation

3rd order: change of rotation speed with depth, shear



The Importance of Sunspots



Earth-Sun Connection

- site/source of solar activity
- sunspot configurations and events

Understanding solar magnetic fields

signature of the dynamo

Analog for cool stellar atmospheres

 atmospheric chemistry, molecule formation



Sunspot Properties



	sunspots		granulation	
fetime	hours - weeks		20 min.	
size	~1000-100,000 km		1000 km	
	umbra	penumbra	quiet sun	
Т	3500-4500 K	5000-5500	K 5770 K	
B	3500-1500 G	1000-700 (G 0-500 G	



SST: G. Scharmer, K. Langhans, M. Lofdahl

How Sunspots Work

"Frozen-In Field"



Due to high conductivity of plasma, gas and fields are linked

Suppression of convection by vertical magnetic field -overturning motion



Cool, less dense atmosphere supported against higher quiet sun pressure by magnetic field

Sunspot MHSE

Assuming: (0) Sunspots are stable and are considered to be in magneto-hydrostatic equilibrium (MHSE) on dynamical timescales

For a circularly symmetric sunspot in equilibrium:

$$P_{qs}(z) = n_{qs}(z)kT_{qs}(z)$$

= $n_s(r,z)kT_s(r,z) + \frac{1}{8\pi}(B_z^2(r,z) + F_c(r,z))$

where

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

Also assuming:

(I) magnetic fields are vertical, small curvature force, Fc

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

We get a linear thermal-magnetic pressure relation:

$$B^2(r) \propto -T_s(r)$$

A Problem

B²-T relation is not linear!



numerous other studies: Gurman & House (1981), Kopp & Rabin (1993), Balthasar & Schmidt (1993), Lites et al. (1993), Martinez 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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problems with past work

- both linear and non-linear relations observed
- different magnetic
- diagnostics
- limited spatial resolution and sampling
- individual sunspots

Review Assumptions

- (0) Sunspots evolve
- must be inherently out of balance
- (I) Sunspots are not flat
- effect of radiative transfer, atmosphere is cooler so we see deeper, quiet sun pressure is greater
- (2) Magnetic fields are not vertical
- curvature force is poorly determined







A Possible Solution

In the umbra, evolution, effects of RT, and Fc should be small and cannot explain isothermal increase in B

- BUT the assumption of a constant number density in the umbra is constant is not valid
 - Molecule formation
 - decrease in number density
 - release of dissociation energy
 - increase in heat capacity
 - H₂
 - Detections in the UV chromosphere
 - In the photosphere, from umbral models 5%

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SUMER spectrum from Innes (2008) fig. I

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

Objectives

- Confirm the presence of H₂ in the umbral photosphere
- Prove H₂ formation corresponds to the magnetic field intensification seen in the thermal-magnetic relation
- Identify evolutionary effects of H₂ formation

Methods

Methods

Measurement of $H_2 \dots$

Direct detection is not easy

- UV lines at chromospheric heights (and SUMER is no more)
- Ro-vibrational lines in IR
 - Seen in cool, low-density environments: nebulae (Gautier et al., 76), K and M giants (Spinrad, 66)
 - Should be highly forbidden in the solar photosphere

Must use proxy molecule

- Hydroxide (OH)
 - Similar dissociation energy (OH: 4.39 eV, H₂: 4.48 eV)
 - Strong lines throughout visible and infrared

Methods

Characterization of B and T

- Spectropolarimetry of high B-sensitivity lines of Fe I @ I5650 Å
- Establish Evolutionary Effects
 - Survey of spots with different temperatures, evolutionary states

Zeeman Spectropolarimetry

Zeeman Effect -- Pieter Zeeman 1896

Magnetic field lifts the level degeneracy (weak field limit)

Dipole moment of the electrons partially coupled to the magnetic field

resulting changes in energy/wavelength:

 $B = 0 \qquad \qquad B \neq 0$



$$\Delta \lambda = \frac{\pi e}{m_e c} g_{eff} \lambda^2 B$$

 $0 \le g \le 3$

Line [Å]	Species	Landé g	Formation Height
6302	Fe I	1.67, 2.5	mid-photosphere
8542	Ca II	1.1	low chromosphere
10827	Si I	1.5	photosphere
10830	He l	2.0, 1.75, 1.25	high chromosphere ?
15650	Fe I	3, 1.53	low photosphere

also results in polarization!

First measurement of magnetic fields in sunspots, Hale (1908)

Zeeman Spectropolarimetry

How can we fully analyze/describe the polarization? The Stokes vector provides a formalization:



Zeeman Spectropolarimetry



Instrument and Observations

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, Hα, G-band camera

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



FIRS Properties

Property	FIRS f/36*	FIRS f/108*	Hinode SOT/SP
Telescope	76.2 cm Solar Tower	••••	50 cm Aplanatic Gregorian
Rayleigh limit @ 6302	0.21"	••••	0.32"
Rayleigh limit @ 10830	0.36"	•••	•••
Rayleigh limit @ 15648	0.52"	•••	•••
Field	174" x 75"	58" x 25"	160" (320" max) x 151"
Vis Spatial Sampling	0.30" x 0.08"/pix	0.10" x 0.03"/pix	0.15" x 0.16"/pix
IR Spatial Sampling	0.30" x 0.15"/pix	0.10" x 0.05"/pix	•••
Nominal Scan Time**	20 min	••••	83 min
6302 Spectral Resolution (Sampling)	0.013 (0.01) Å	•••	0.03 (0.02) Å
10830 Spectral Resolution (Sampling)	(0.04) Å	•••	•••
15648 Spectral Resolution (Sampling)	0.066 (0.05) Å	••••	•••

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Rayleigh limit @ 6302	0.21"		0.32"
Rayleigh limit @ 10830	FIRS	Vis	FIRS IR
Rayleigh limit @ 15648		$\sigma = 13 \text{ mÅ}$	$\sigma = 66 \text{ mÅ}^2$
Field	κ−4ου,000 > ^{0.8}		0.8
Vis Spatial Sampling	l l l l l l l l l l l l l l l l l l l	Intensit	
IR Spatial Sampling	alized	alized	
Nominal Scan Time**			0.4
6302 Spectral Resolution (Sampling)	0.2		
10830 Spectral Resolution (Sampling)			
15648 Spectral Resolution (Sampling)	-0.2 -0.1 0. $\lambda - 63$.0 0.1 0.2 328 [Å]	-1.0 -0.5 0.0 0.5 1.0 λ - 15230 [Å]

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Property	FIRS f/36*	FIRS f/108*	*	T/SP
Telescope	76.2 cm Solar Tower	•••		hatic In
Rayleigh limit @ 6302	0.21"	•••	Do not look Into be with remaining ey	am ye
Rayleigh limit @ 10830	FIRS	Vis	FIRS	IR
Rayleigh limit @ 15648		σ =13 mÅ		σ =66 mÅ
Field	K=480,000	 	K=240,000	- - -
Vis Spatial Sampling				-
IR Spatial Sampling				-
Nominal Scan Time**			0.4	-
6302 Spectral Resolution (Sampling)	0.2		0.2	
10830 Spectral Resolution			0.0 <u></u>	
15648 Spectral Resolution (Sampling)	-0.2 -0.1 0.0 $\lambda - 632$	0.1 0.2 8 [Å]	-1.0 -0.5 0.0 $\lambda - 152$) 0.5 1.(30 [Å]

1.0




















Fe I @ 6302 Å FIRS Visible Channel



Fe I @ 6302 Å FIRS Visible Channel



FIRS 6302 Å 2009-12-17 15:48:20 NOAA11035L

He I, Si I @ 10830 Å FIRS Infrared channel



He I, Si I @ 10830 Å FIRS Infrared channel





Fe I, OH @ 15650 Å FIRS Infrared channel



Fe I, OH @ 15650 Å FIRS Infrared channel





IBIS = Interferometric BI-dimensionsal Spectrograph another spectropolarimeter on the DST



K. Reardon

Survey Observations

Date	# Days	Description
30 Apr 2007		FIRS commissioning
Oct 2007		11
10 Dec 2007	8	11
26 Feb 2008	3	11
9 Jun 2008	9	",VIk in place
6 Sep 2008		11
8 Dec 2008	9	",VIk upgraded to Sci. array
17 Feb 2009	3	11
15 May 2009	9	11
7 Jul 2009		", final optics config.
10 Sep 2009		••
9 Dec 2009	10	••
10 Feb 2010	12	SJ dissertation obs.
10 May 2010	10	SJ dissertation obs.
26 Aug 2010	8	SJ dissertation obs., laser profiles, linearity
28 Nov 2010	9	SJ dissertation obs.



=153 days

Survey Observations

Most observations consist of:

- Simultaneous FIRS of Fe I 15650/6302 Å observations
- Concurrent IBIS observations of Ca II 8542 Å
- or HSG
 observations of
 15650 Å



66 observations of 23 sunspots and pores over 1.5 years



Data Reduction



IR Detector Response



(4) gain is not constant

IR Detector Response



(4) gain is not constant

Instrumental Polarization

Polarization cross-talk introduced by telescope/instrument system

 $I \rightarrow Q, I \rightarrow U, I \rightarrow V, Q \leftrightarrow V, U \leftrightarrow V$

DST is the worst telescope for a polarization survey

- Methods of removal
 - construct a time-dependent model of the telescope and instrument (Elmore et al. 2010, Socas-Navarro et al. 2011)
 - apply symmetry arguments to determine cross-talk (Kuhn et al. 1994, Collados 2003)



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Comparison with Hinode Data

Serendipity! FIRS and Hinode observations are 4 min. apart! 2009-07-06

Comparison with Hinode Data



Comparison with Hinode Data



Analysis, Part I: Inversions





the typical "inverse problem" for solar spectropolarimetry "inversions"























- 2 Component Magneto-Optical (2CMO) Milne-Eddington Inversion code
 - 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
- B₀ source function
- B₁ source function gradient
- λ wavelength
- $\Delta\lambda$ doppler width
 - a damping parameter
- η_0 line to continuum absorption ratio

Non-Magnetic Component

- λs wavelength of stray light component
- I-f stray light filling factor



Comparison with MERLIN

New technique

- must compare with an existing code
- Milne-Eddington gRid Linear Inversion Network (MERLIN)

Comparison with MERLIN



Analysis, Part 2: Modeling

Inference of H₂: 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 by Han Uitenbroek
 - equilibrium molecular abundances assuming LTE
 - spectral synthesis








Measurement of OH EqW

Setback!

- Measured EqW do not match synthetic
- Apply universal factor of 1.55

Cause?

- Problem with RH?
- Stray light?



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Survey Results



NOAA 11049F, 2010-02-19



NOAA 11132, 2010-12-05



Smallest Sunspots and Pores

- Linear B² vs.T
- Max. umbral field below 2500 G
- Continuum temperature higher than 6000 K
- H₂ fraction below 0.75%

NOAA 11046, 2010-02-13



NOAA 11024, 2009-07-06



NOAA 11101, 2010-08-29



NOAA 11035F, 2009-12-17



NOAA 11035P, 2009-12-17



Mid-Sized Sunspots

- 3-segment B² vs.T, upturn near 6000 K
- Max. umbral field above 2500 G
- Continuum temperature less than 5800 K
- H₂ fraction above 0.75%

NOAA 9429, 2001-04-18



NOAA 11130, 2010-12-02



NOAA 11049P, 2010-02-20



NOAA 11101, 2010-09-02



Special Cases

- Isothermal increase in B² vs.T around 5800 K
- Max. umbral field below 2600-2700 G
- H₂ fraction just under 1%
- Show discrete magnetic features

NOAA 10743, 2005-03-12



NOAA 11131, 2010-12-06



Largest Sunspots

- Upturn in B² vs.T at 5500 K or lower
- H₂ fraction 1.5% and higher
- Formation of molecules is a temperaturedependent process we would expect the upturn always to occur near the same temperature

Survey Results

OH, H₂ vs.T

- good agreement of scaled OH w/ synthetic spectra from models
- B^2 vs.T
 - No upturn
 - weak fields, little or no H₂ (< 0.5%)
 - Upturns
 - increase begins around 6000 K
 - spots with umbral fields > 2500 G, $H_2 > 1\%$
 - steeper relations seen in mid-sized/strength spots
 - in decay phase

Discussion









Other Effects

Radiative Transfer Effect

- See deeper in cooler atmospheres
- Quiet sun pressure at equivalent depth is higher

Curvature Force

- Poorly constrained, may contribute up to 1/2 magnetic support (Martinez Pillet & Vazquez 1993, Mathew et al. 2004)
- Contribution should be lower in the umbra, might make umbra fields look boosted

But neither can account for isothermal increases in magnetic fields

Conclusions

Conclusions

- Measurement of OH implies a H₂ fraction of about 3% in the umbra of the largest sunspots
- Process of H₂ formation and destruction can explain the intensification of magnetic field
- Magnetic field intensification coincides with H₂ "turn-on" at a continuum temperature around 5800-6000 K
 - Clearest in small decaying spots, occurs in discrete regions within the umbra
- Important implications for sunspot science:
 - Increased heat capacity in sunspots, hidden energy reservoir
 - Inclusion multi-component gas is necessary for a realistic model

Future Work

- I. Further investigation with existing dataset
- 2. FIRS tune-up
 - Recenter field, camera upgrade, stray light measurements
- 3. Characterization of the RT effects and curvature force
 - Using 6302/15650 Å sunspot survey
 - In-depth comparison of observations and Rempel sunspot MHD models
 - Reproduce thermal-magnetic relation in "observed data"
- 4. Extended thermal-magnetic survey with FIRS and Hinode
 - Observe bigger spots, more early phases, as cycle 24 picks up
 - Exploration of Hinode SOT/SP data

Preliminary comparison with model sunspot


Future Work

- 5. Extension to chromospheric heights: FIRS and IBIS
 - Multi-wavelength inversion, RH as forward model?
- 7. The growth of starspots in cooler/more magnetic atmospheres
 - observations from Kepler and other transit surveys
- 6. Coordinated FIRS/IBIS magnetic field observations with IRIS

Interface Region Imaging Spectrograph







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If you wonder about ambipolar diffusion

eg. Kuhn & Morgan (2006)

signs of a neutral wind: no obvious OH overabundance at umbral boundary

but...RT effects make this really difficult

