From Emergence to Eruption: The Physics & Diagnostics of Solar Active Regions

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Magnetic Flux Emergence

How does flux emerge? What does it look like?

SoHO/MDI magnetogram

Flux Emergence (Theory) - Cheung & Isobe (Living Reviews in Solar Physics, 2014)
Life Cycle of Active Region Magnetic Fields - Cheung, van Driel-Gesztelyi, Martinez-Pillet & Thompson (Space Science Rev., 2016)
Science questions

• What are the physical properties of subsurface magnetic structures that rise and eventually emerge onto the surface?

• How do convective flows impact the morphology and physical character of emerging flux?

• How does emerging flux transport the magnetic energy and helicity?

• What is the role of emerging flux in free energy build-up and triggering of the transient events such as jets, flares and coronal mass ejections (CMEs)?

• What are the fundamental physical mechanisms that drive eruptive events on the Sun and on other stellar objects?
Observational Studies of Emerging Flux

Extremely large volume of papers studying photospheric magnetic observations of flux emergence.

**Ground-based instruments:** Leka et al. (1996); Strous et al. (1996); Lites, Skumanich & Martinez Pillet (1998); Strous & Zwaan (1999); De Pontieu (2002); Kubo, Shimizu & Lites (2003); Watanabe et al. (2008, 2011); Guglielmino et al (2010); Yurchyshyn et al. (2010), Rutten et al. (2013); Ortiz et al. (2014, 2016), de la Cruz Rodriguez (2015)

**Balloons:** Flare Genesis Experiment Bernasconi et al. (2002); Georgoulis et al. 2003; Pariat et al (2004)

**SUNRISE** Guglielmino et al. (2012)

**MDI** Many many papers, e.g. Hagenaar et al. (2003)

**Hinode** Centeno et al. (2007); Cheung et al. (2008); Okamoto et al. (2008); Magara (2008); Gonzalez & Bello Rubio (2009); Otsuji et al. (2009, 2011); Ishikawa, Tsuneta & Jurčák (2010), Shimizu, Ichimoto & Suematsu (2012)

Active Regions & Ephemeral Regions

K. Harvey (1993, PhD thesis) - Kitt Peak
Size distribution of Bipolar Regions

Hagenaar et al. (2003) - MDI
Occurrence rate of bipolar regions
0.5 km upflow
1.0 km downflow

From Cheung (2006, PhD thesis)
See also Cheung et al (2007, 2008), Martinez-Sykora et al. 2008, 2009)
Tortosa-Andreu & Moreno-Insertis (2009)

2005 Cheung seminar @ LMSAL: “This is what you’ll see with Hinode/SOT.”
From Cheung et al. (2008): SOT/NFI observations of dark lanes in emerging flux regions. See also Strous & Zwaan (1999).
Figure 5: Models of magnetic flux emergence can be roughly divided into three categories, though there are large areas of overlap between them. So-called ‘realistic’ models attempt to include all the known important physical ingredients, while idealize models generally focus on studying a more limited set of effects. For case studies of certain observed emerging flux studies, data-driven models are used.

Consider a blob of plasma threaded by $B$, which exhibits magnetic pressure $B^2/8\pi$. When the blob is in pressure balance with its surroundings,

$$p_{in} + B^2/8\pi = p_{ext}.$$

If the plasma blob has the same temperature or specific entropy as the surrounding (i.e. $T_{in} = T_{ext}$, or $s_{in} = s_{ext}$), then it will have a **density deficit**, and hence will rise like an air bubble.
The solar convection zone is highly stratified.
The solar convection zone is highly stratified. Depth = 200,000 km

Toriumi & Yokoyama (2011)
Scaling Relation Between $B$ and $\varrho$

(a) Horizontal tube expanding as it rises

$B \propto \varrho$

(b) Crest of tube expanding predominantly in the horizontal directions

$B \propto \varrho^{1/2}$

Mass discharge

Schematic scenario in 2D

Top: Dark blue indicates high density
Bottom: Red indicates downflow

From Cheung, Rempel, Title & Schüssler (2010). See also Rempel & Cheung (2014).

Same mechanism as suggested by Kubo, Low & Lites (2010).

Courtesy: Stein
Buoyant magnetic structures which arise from the cores of toroidal magnetic fields over radius and latitude. The rising magnetic loop A is seen in the cross section starting at 0.81.

Figure 3. BUOYANT MAGNETIC LOOPS

Here we will discuss buoyant magnetic structures which arise from the cores of toroidal magnetic fields. The large-scale toroidal wreaths are highly nonuniform and extend in the southern hemisphere extending roughly every two days in Figure 6 days. Perspective is looking down along the rotation axis toward the equatorial plane. Coloring indicates field magnitude. Dashed lines indicate radial position. Dotted line shows the cutting plane use.

Analyzing a rising loop. (a) Two-dimensional cuts in longitude at successive times (tracking in longitude at the local rotation rate of the loop) show.

(b). Eight loops are seen in the northern hemisphere spanning 95° - 15 days. Proto-loop B is also seen rising starting at 8.6 days, but the top of loop B never rises above 0.88.

Advection by convective upflows (blue lines).

To demonstrate in cases D3 (B10) and D5 (B11), these magnetic wreaths are highly nonuniform and ap positive polarity wreath in the northern hemisphere spanning 95°15 days. Proto-loop B is also seen rising starting at 8.6 days, but the top of loop B never rises above 0.88.

Individually, portions of the wreath. A single wreath of a given polarity may not form a coherent core at all or may have more than one core, connectivity with the rest of the domain or even the other.

A single core may produce multiple buoyant loops. Of the nine buoyant loops investigated here to rise past 0.90, three, and two more cores each yield a single buoyant loop. Three, and one in the southern hemisphere. We expect that the apparent asymmetry is simply the result of having studied only two magnetic cycles.

Protopast 0.90, the strong Lorentz forces result in highly suppressed convective motions. If we examine extended regions in the cores of wreaths.

Some of the coherent wreath cores can become buoyant magnetic loop progenitors or proto-loops. In these proto-loops magnetic field strengths exceed 35 kG the proto-loops become significantly underdense as magnetic pressure displaces fluid, causing buoyant acceleration. With some rise a proto-loop can enter a region of less suppressed giant cell convection. These proto-loops do not evolve into mature buoyant loops, generally due to unfavorable interactions with convective flows. When proto-loops do not evolve into mature buoyant loops, generally, we identify at least 35 proto-loops at the times where the nine buoyant loops arise. Thus the large majority of.

Analyze a rising loop. (a) Two-dimensional cuts in longitude at successive times (tracking in longitude at the local rotation rate of the loop) show.

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Fan & Fang (2014): Super-equipartition magnetic flux ropes generated by a global distributed dynamo at solar rotation with luminosity carried by enthalpy flux and thermal conduction. See F. Chen’s talk (405.01) for dynamo-driven AR emergence.
Figure 13: The solar atmosphere is strongly stratified: the mass contained in a single granule (left, Hinode SOT image of a sunspot surrounded by granulation) is comparable to the mass content of the largest CMEs (right, composite of running difference images from the SOHO/LASCO C2 and SDO/AIA instruments. Both quantities are of order $10^{16}$ g. (Credit for right image: NASA CDAW Data Center.)
Buoyancy Instabilities
Energization of the Corona

• “Current shunting” model for twisted active region emergence

• Idealized emerging active region has net twist

• Matched to force-free coronal field

• At the interface (photosphere), a horizontally diverging current drives a torque, which sends a torsional Alfvén wave down the tube.

• Over an Alfvén crossing time ~ 1 day (100 Mm @ 1 km/s), the tube unwinds while the coronal field is twisted up.
MHD Simulations of twisted flux emergence into the corona (see Fan 2009; Leake, Linton & Török 2013) support the Longcope & Welsch (2000) model. As flux emergences into the coronal, field lines lengthen, creating torsional gradients. Energy & helicity injection occurs on photospheric timescales < flare/CME time scales ⇒ store & release model for solar eruptive events.
Figure 38: Evidence for twisted flux tube emergence. The top row shows three SoHO/MDI magnetograms of NOAA AR 10808. The positive and negative polarities have ‘magnetic tongue’ morphology. The bottom row shows three synthetic magnetograms from the simulation of the emergence of a twist flux tube. The striking resemblance in morphology suggests a twisted flux rope structure for NOAA AR 10808. Image reproduced with permission from Archontis and Hood (2010), copyright by ESO.

Fan (2009): Distribution of vorticity (vertical component) at the photosphere from a simulation of the emergence of a twisted flux rope. The two ‘spots’ have the same sign of rotation.

Manchester et al. (2004): Lorentz-force driven shear flows
See also Sturrock et al. (2015), Sturrock & hood (2016)
Interaction with Pre-existing Field

Yokoyama & Shibata (1996): 2D MHD simulation of current sheet formation, leading to plasmoid ejections

Moreno-Insertis et al. (2008): 3D jet simulation from flux emergence into a coronal hole

Nishizuka et al. (2008): Alfvén wave generation in jet simulation
MHD Studies of Emerging Flux

“Realistic” models

Energy sinks/sources

Idealized models

Thermal Conduction

Real Data

Parameter Studies

Real Data

Convective Flows

Active Region Sizes

Magnetic Reconnection

Data-driven models

Radiative Transfer

NLTE effects

Active Region Sizes

Neutral-ion effects

Convective Flows

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Data-driven Magnetic Modeling

For the sake of discussion:

- **Data-inspired Models**: Simplified setups to mimic observed scenarios

- **Data-constrained Models**: Time-independent models satisfying observations at an instant in time. Includes models that may start with a data-constrained initial condition but driven by idealized boundary conditions.

- **Data-Driven Models**: Time-dependent models evolved in response to evolving boundary conditions
Doppler shift maps using the Si IV 1394 line ($\log T = 4.8$) observed by IRIS shows helical motion in all four jets.

Similar pattern reported by Pike & Mason (1998) using a TR line observed by SoHO/CDS.
Parasitic (+) pore inside a supergranule with network flux.
Fig. 7.— SDO/HMI vector magnetograms of the parasitic pore and its surroundings. 

Left: Vertical component of ~$B$ (greyscale saturated at ±200 Mx cm$^2$). 

Middle: Horizontal components of current-free (i.e. potential) part of ~$B$. 

Right: Horizontal components of the current-carrying part of ~$B$. A strong, persistent patch of current-carrying field is found on the west side of the pore. Comparison with the $B_z$ distribution shows this current-carrying patch is coincident with an emerging flux region (just northwest of the parasitic pore). Contours for $B_z$ = 500 and 1000 Mx cm$^2$ are shown on all panels to indicate the position of the pore.
Magnetofriction model of homologous helical jets driven by HMI vector magnetograms (Cheung & the IRIS team, 2015).

For MHD models of helical jets, see Pariat et al. (2009, 2010, 2016), Fang et al. (2014), Lee et al. (2015), Wyper & DeVore (2016). Jet-like reconfigurations of the magnetic field occur after accumulation of one turn (consistent with Pariat's MHD simulations).
HMI vector magnetogram sequence of NOAA AR 11158
Credit: Keiji Hayashi (HMI)
CGEM Magnetofriction model of AR 11158 over 5+ days (Fisher et al. 2015, Sp. Weather, 13). Driven by electric field inversions (Kazachenko et al. 2014) from HMI vector magnetogram.

Bz at 2011-02-11T16:36

\[ z = 8.1 \text{ Mm} \quad z = 54.2 \text{ Mm} \quad z = 135.4 \text{ Mm} \]
What does one see in AIA EUV images?
Problem Statement

\[ y = Kx \]

rows of \( K \) = Temp resp of AIA channel

\[ y = \text{AIA counts} \]

\[ x = Dm, \]

cols. of \( D \) = basis funcs

\[ m = \text{emission measure (EM) in temperature bins} \]
Sparse Differential Emission Measure Inversion

Choose a `simple' DEM solution.

1) It tends not to overfit (consistent with the principle of parsimony, i.e. Ockham’s Razor).
2) It ensures positivity of the solution (if solutions exist).
3) It is an L1-norm minimization problem, so we can use standard techniques from compressed sensing (c.f. Candes & Tao 2006).
   BTW the L1-norm of a vector \( x = \sum |x_i| \)
4) Speed: \( O(10^4) \) solutions / sec with single IDL thread.

Cheung et al. (2015), http://tinyurl.com/aiadem

\( \chi^2 \) minimization methods:
Parameterization: e.g. Guennou et al (2012a,b), xrt_dem_iterative2.pro (M. Weber in SSW, see also Cheng et al 2012)
Regularization: e.g. Hannah & Kontar (2012), Plowman et al. (2013)
See Aschwanden et al. (2015, Sol Phys, 290, 2, 2733) for comparison between previously existing methods.
Handling noise

In practice, measurement uncertainties imply that the equality \( y = Kx \) may not be satisfied. So our method solves the followed modified linear program:

\[
\text{minimize} \quad \sum_{j} x_j \quad \text{subject to} \quad K\bar{x} \leq \bar{y} + \bar{\eta}, \\
\quad \bar{x} \geq 0, \quad K\bar{x} \geq \max(\bar{y} - \bar{\eta}, 0).
\]

The vector \( \eta \) is a measure of the uncertainty in the count rate and provides tolerance for the predicted counts \((Kx)\) to deviate from the observed values \((y)\). To enforce positive counts the lower bound is set to \( \max(y - \eta, 0) \).
Crossmarks are observed counts

Subspace of allowed solutions in our method
Side benefit: Image Denoising

\[ y \quad (\text{AIA 131 Level 1.5}) \]

\[ D x^\# \quad (\text{from inversion}) \]
• GOES SXR flux shows a small enhancement before the impulsive phase of this M-class flare.

• This enhancement occurs when Hα brightenings propagate along the polarity inversion line.
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• **AIA DEMs show 10 MK plasma in loops parallel to the PIL during the precursor phase, which is observational evidence for tether cutting reconnection.**

• **Plasma cools in flare loops before the onset of catastrophic cooling by thermal instability.**
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• Plasma cools in flare loops before the onset of catastrophic cooling by thermal instability.
Application to a limb flare to track chromospheric evaporation

M7.7 limb flare

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Application to a limb flare to track chromospheric evaporation

M7.7 limb flare
Chromospheric evaporation

Downward mass pumping from reconnection outflow

Dashed contours: Total EM $= 10^{29}$ cm$^{-5}$

Solid contours: Total EM $= 10^{30}$ cm$^{-5}$
NASA Heliophysics Grand Challenges Research (HGCR): Physics and Diagnostics of the Drivers of Solar Eruptions

Physics and Diagnostics of the Drivers of Solar Eruptions

- Better understanding of a key subdomain of the Sun-Earth system, namely the convection zone of the Sun up to the corona. It is in this region that the dominance of gas pressure over magnetic pressure is reversed and where the magnetic field becomes the dominant player in driving solar eruptions. The proposed deliverables will help researchers quantify the physical conditions in this important subdomain.

- The investigation is also relevant to the third goal of the LWS: "Human Exploration and Development: LWS provides data and scientific understanding required for advanced warning of energetic particle events that affect the safety of humans". The science and tools resulting from this project will advance our understanding of the driver(s) of solar eruptions and assist the community with forecasting eruptions.

- This proposal draws heritage from the 2007 LWS TR&T Focus Science Team targeting the topic "Solar Active Regions". Three PIs (DeRosa, McIntosh and De Pontieu) from that Focus Science Team are Co-Is on this proposal. Techniques on synthetic diagnostics, MHD simulations as well as magnetofrictional simulations were developed as part of the efforts funded by TR&T. As part of this project, we will use data from NASA's SDO, Interface Region Imaging Spectrograph (IRIS), Hinode, STEREO missions, and NSF's CoMP and DST/IBIS instruments. The goals of this proposal are directly aligned with the science goals of these missions and instruments.

3. PROJECT ELEMENTS

We now lay out the tasks of the project. For the work schedule, please refer to Section 4. For milestones for each task, please refer to Table 1 in Section 4.

- Radiative MHD simulations of AR eruptions
- Forward synthesis of observables
- Understand driver(s) of solar eruptions
- Evaluate diagnostics as probes of drivers of eruptions
- Data-driven simulations
- Force-free field reconstructions

A collaboration between LMSAL (PI: Cheung), HAO, BAERI, SAO & U Oslo, supported by NASA Grant NNX14AI14G
NOAA AR 12017: one X-class ("Best Observed X-flare"), 3 M-class, and about two dozen C-class flares

Sunquake: Judge et al. (2014)
Filament Eruption before X-flare: Kleint et al. (2015)
IRIS Fe XXI FUV spectra: Young et al. (2015)
Chromospheric Evaporation: Li et al. (2015)

Other panels:
EM in various log T bins

Lower right panel only:
Greyscale:
B_{los} from HMI
Green: 6MK EM
Yellow/Red: 10 MK EM
Data-inspired Radiative MHD Simulation

Top down view

Log EM [cm⁻⁵]

EM-weighted log T/K

Bz @ τ=0.1 [kG]

SDO/AIA 193

SDO/AIA 211

SDO/AIA 335

SDO/AIA 94

SDO/AIA 131

SDO/AIA 171
C4 flare if measured by detectors on GOES 15. The free magnetic energy dropped by $\sim 5 \times 10^{30}$ erg ($\sim 10\%$) over 5 minutes.
Synthetic Doppler Maps from Optically Thin Radiation

Doppler V @ T = 1.0 MK  Doppler V @ T = 10.0 MK  Doppler V @ T = 25.1 MK

+- 300 km/s

Up
Down
Synthetic Doppler Maps from Optically Thin Radiation

Doppler V @ T = 1.0 MK  Doppler V @ T = 10.0 MK  Doppler V @ T = 25.1 MK

 +/- 300 km/s

x [Mm]  y [Mm]

Doppler V [100 km/s]

T [million K]

Up  Down
T-dependence of flows at flare footpoints

Downflows for $T \lesssim 2\text{MK}$, Upflows for $T \gtrsim 2\text{MK}$

Milligan & Dennis (2009) - Analysis of EIS observations of a C1.1 flare. See also Del Zanna et al. (2006); Liu, Petrosian & Mariska (2009).
Hard x-rays $\geq 25$ keV

$6 \leq$ Soft x-rays $\leq 12$ keV

Using using thermal bremsstrahlung, the model yields power law-like shapes for the X-ray spectrum.

The multi-thermal nature of the magnetic structure gives rise to the apparent non-thermal behavior.

Above-the-loop-top harder X-ray sources ($> 25$ keV) are located above softer loop sources.
Using using thermal bremsstrahlung, the model yields power law-like shapes for the X-ray spectrum.

The multi-thermal nature of the magnetic structure gives rise to the apparent non-thermal behavior.

Above-the-loop-top harder X-ray sources (> 25 keV) are located above softer loop sources.

**Hard x-rays ≥ 25 keV**

**6 ≤ Soft x-rays ≤ 12 keV**
8-week accelerator program
AI x Science
hashtag #NASAFDL17

Mark Cheung is an astrophysicist at Lockheed Martin Solar & Astrophysics Laboratory and Stanford University. His scientific interests cover the Sun, space weather, cool stars and plasmas and magnetic fields pervading the universe. He is the Principal Investigator for the Atmospheric Imaging Assembly on board NASA's Solar Dynamics Observatory. He loves having thousands of computers work for him.

Monica Bobra is a scientist at Stanford University in the W. W. Hansen Experimental Physics Laboratory, where she studies the Sun and space weather as a member of the NASA Solar Dynamics Observatory science team.

She previously worked at the Harvard-Smithsonian Center for Astrophysics, where she studied solar flares as a member of two NASA Heliophysics missions called TRACE and Hinode. Monica Bobra received a B.A. in Astronomy from Boston University and a M.S. in Physics from the University of New Hampshire.

Graham Mackintosh is a pioneer in the field of advanced analytics and has applied his thought leadership into multiple new domains for big data analysis, high performance cloud computing, AI and Deep Learning. As a member of IBM’s Emerging Technology Group, he is currently spearheading the challenge of applying Apache Spark, deep learning methodologies, and other cloud services to address complex business and scientific analytic needs.

Andres is a Colombian scientist that loves innovative techniques of interrogating and visualizing data, and loves to mentor and empower students and young scientists to become the best possible version of themselves. He believes that talent is not something that we are born with, but something acquired through hard work and constant practice. His research focuses on understanding how solar activity changes in time and how this affects the Earth and our technological infrastructure.

Troy Hernandez is an American statistician and data scientist from Chicago, IL. He obtained his PhD in statistics and machine learning from the University of Illinois at Chicago in 2013. Troy has applied his machine learning expertise to diverse fields such as digital advertising, economic modeling, and virology. He is currently employed by IBM and remains an active community volunteer.

Ryan McGranaghan is a NASA Living With a Star postdoctoral fellow at the Jet Propulsion Laboratory, where he passionately blends space physics and data science to investigate the solar-terrestrial connection. He received his Ph.D. in Aerospace Engineering from the University of Colorado at Boulder in 2016.
Demonstrates feasibilty of DEM inversion using deep learning.

Emission Measure at $T = 1.3$ Million Kelvin (Fully Connected)

Emission Measure (Basis Pursuit, Cheung et al. 2015)

Trained deep neural net (7x speed up, on GPU)  Sparse inversion
Demonstrates feasibility of DEM inversion using deep learning.

Trained deep neural net (7x speed up, on GPU)  
Sparse inversion
Summary

• The convection zone and atmosphere are highly stratified.
• Flux emergence requires decoupling the mass from the magnetic field to allow it to enter more tenuous regions: turbulent convection and magnetic buoyancy instabilities.
• SDO/HMI enables data-driven models of active regions (under-exploited capability)
• SDO/AIA enables tracking of thermal history of coronal plasma (under-exploited capability)
• Synthetic observables in data-inspired flare simulation qualitatively match observations of flares. This gives important lessons for other astrophysical objects.
• **Theory + Observation / Experiment + Scientific Computation**
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