Modeling Solar Eruptions: Where Do We Stand?

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Past...

2000-2003
AIP (Germany)
Bernhard Kliem

2003-2004
St.Andrews (UK)
Thomas Neukirch

2004-2007
MSSL (UK)
Lidia van Driel-Gesztelyi

2007-2010
Meudon (France)
Guillaume Aulanier
• Introduction
  • What are solar eruptions?
  • Modeling eruptions (constraints & methods)

• Two (still) open questions:
  1. How are eruptions triggered & driven?
  2. Are solar eruptions coupled?

• State-of-the-art: global & thermodynamic simulations

• Summary & Outlook
What are solar eruptions?

- Largest energy release events in the solar system: up to several $10^{25}$ J
  (current annual world energy consumption: $5 \times 10^{20}$ J)

- Occur in the solar atmosphere (corona)

- Three main types: flares, prominence eruptions, and CMEs
(Eruptive) Flares

- Sudden, localized increase of emission (mostly EUV & X-ray)
- First observed in the 19th century (in white-light)
- Produce two “ribbons” and “post-flare” arcade

drawing by R.C. Carrington (first recorded flare 1859)

courtesy of T. Forbes
14 July 2000 ("Bastille Day Event")

21 April 2002 (TRACE 195 Å)

13 December 2006 (Hinode/SOT)
Prominence (filament) eruptions

- Dense and cool ($10^4$ K) structures suspended in hot ($10^6$ K) corona
- Lengths up to several 100,000 km (smaller in active regions)
- Can exist for weeks or even months
- Most prominences/filaments eventually erupt
Coronal Mass Ejections (CMEs)

- Huge expulsions of plasma (and magnetic field) from the corona
- Masses up to $\approx 10^{16}$ g; speeds up to $\approx 3500$ km/s
- Can occur several times a day (during maximum solar activity)
- Discovered only in the 1970s
“Halloween Events” (Oct/Nov 2003) observed by SOHO/LASCO coronagraph
Why do we care? ... space weather

- CMEs can hit the Earth and cause “geomagnetic storms”
- CMEs & flares can destroy satellites, power grids, harm astronauts...
- One main research goal: forecast occurrence and impact of eruptions
Observational constraints: where do eruptions come from?

- Strongest events originate in large active regions (above sunspot groups)

- ... but also in dispersed regions (quiescent prominences)

- Always above (sheared) magnetic polarity inversion lines
Different observational manifestations of violent disruption of magnetic field?

- Flares, PEs & CMEs **typically occur together** (especially in large events)
- Different observational manifestations of violent disruption of magnetic field?

eruption on 7 June 2011 observed by SDO/AIA (courtesy of C. Schrijver)
Further constraints

- Eruptions originate in the low corona
  - plasma environment dominated by magnetic fields
  - eruptions are *magnetically driven* (non-magnetic models ruled out)

- Slow surface evolution of active regions not significantly affected by eruptions
  - foot-points of coronal field lines effectively stationary (“line-tied”)

- Required (“free”) energy stored in current-carrying, sheared/twisted core field

- Core field formed by flows/emergence & stabilized by overlying potential fields

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**Table 1. Energy Requirements for a Moderately Large CME**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinetic energy (CME, prominence, and shock)</td>
<td>$10^{32}$ ergs</td>
</tr>
<tr>
<td>Heating and radiation</td>
<td>$10^{32}$ ergs</td>
</tr>
<tr>
<td>Work done against gravity</td>
<td>$10^{31}$ ergs</td>
</tr>
<tr>
<td>Volume involved</td>
<td>$10^{30}$ cm$^3$</td>
</tr>
<tr>
<td>Energy density</td>
<td>100 ergs cm$^{-3}$</td>
</tr>
</tbody>
</table>

**Table 2. Estimates of Coronal Energy Sources**

<table>
<thead>
<tr>
<th>Form of Energy</th>
<th>Observed Average Values</th>
<th>Energy Density ergs cm$^{-3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinetic ($m_n v^2/2$)</td>
<td>$n = 10^9$ cm$^{-3}$, $V = 1$ km s$^{-1}$</td>
<td>$10^{-5}$</td>
</tr>
<tr>
<td>Thermal ($nkT$)</td>
<td>$T = 10^6$ K</td>
<td>0.1</td>
</tr>
<tr>
<td>Gravitational ($m_n g h$)</td>
<td>$h = 10^5$ km</td>
<td>0.5</td>
</tr>
<tr>
<td>Magnetic ($B^2/(8\pi)$)</td>
<td>$B = 100$ G</td>
<td>400</td>
</tr>
</tbody>
</table>

Pre-eruption phase: source region formed and energized by flows & flux emergence ➞ current-carrying sheared core field stabilized by overlying field

Initiation phase: stress exceeds threshold ➞ opening of closed field ➞ CME (+ PE)

Main phase: - huge expansion + formation of vertical current sheet below eruption ➞ re-configuration of coronal field by magnetic reconnection ➞ flare
Solar eruption models (see Forbes 2001)

• Virtually all eruption models formulated as initial boundary-value problems:
  - System of differential equations (single-fluid MHD)
  - Set of boundary conditions (quite well constrained by observations)
  - Initial state (less well constrained)

• Limitations:
  - MHD approximation: no kinetic physics (e.g. particle acceleration)
  - Coronal magnetic field not known → initial state more or less ad-hoc
  - Computer power limited → complexity & length scale range not covered

Models still valuable to test proposed physical mechanisms
1. How are eruptions triggered & driven? ...many models...

- **Tether Cutting:**
  - "runaway" reconnection

- **Magnetic Breakout:**
  - unstable arcade, triggered (& driven?) by reconn.

- **Flux Cancellation**
  - at neutral line forms flux rope

- **Driven Flux Rope:**
  - photospheric $I$ injection & hoop force

- **Flux Rope Catastrophe:**
  - end point in equil. sequ. & jump

- **Flux Rope Instability:**
  - ideal MHD instability (kink & torus instab.)
Flux rope instability models

- Eruptions often show:
  - single, loop-shaped structure
  - signatures of internal twist
  - helical deformation of rising loop

- Suggests flux rope geometry + occurrence of ideal MHD kink instability
  (occurs if flux rope twist exceeds threshold ➞ helical deformation)
The helical kink instability (KI)

- Simulate KI using analytical coronal flux rope model
- Morphology & rise of kinking filament well reproduced
- Similar model at the same time by Fan & Gibson (HAO)
- However: flux rope does not fully erupt (no CME)

Fan & Gibson (2004)

Titov & Démoulin (1999)

Török & Kliem (2005)
Torus instability (TI)

- Current ring + external poloidal field:
  
  \[ f_I = \frac{I^2}{4\pi^2a^2R^2}(L + \mu_0 R/2) \quad \text{“hoop force”} \]
  \[ f_B = -\frac{IB_{\text{ex}}}{\pi a^2} \quad \text{restoring force} \]

- TI occurs if restoring force drops faster than hoop force during expansion of the ring after perturbation in \( R \)
  
  \[ B_{\text{ext}}(R) = B_0 R^{-n} \quad \rightarrow \quad n_{\text{crit}} \approx 3/2 \]

  Bateman (1978); van Tend & Kuperus (1978); Kliem & Török (2006)

- On the sun: slowly rising flux rope (filament) has to reach height at which \( n > n_{\text{crit}} \)
That’s just part of the story ... role of reconnection?

- Within / below core field (“tether cutting”):
  - slow: arcade-to-rope transition (slow rise phase)
  - fast: flare reconnection → eruption driver

- Above core field (“breakout”):
  - can trigger eruption
  - can speed it up significantly

these processes (and TI) work together in eruptions!

(which one dominates depends on the circumstances)
2. Are solar eruptions coupled ("sympathetic")?

- Near-simultaneous eruptions from different source regions
- Statistical studies indicate that such eruptions are sometimes causally linked
- Various linking mechanisms were suggested (waves, magnetic reconnection, surges, sub-surface connection...), but no model has been developed

sympathetic eruptions on 25 December 2011
(courtesy of C. Schrijver)

Jiang et al. (2008)
The eruptions on 1-2 August 2010

- Global event; half a dozen individual eruptions involved
- All source regions appear to be magnetically connected
Modeling: subset of three eruptions

- Eruption sequence apparently triggered by eruption of filament 1
- Note: filament further away from 1 erupts first!
- Before eruptions: large filaments 2 and 3 located in *pseudo-streamer*
Numerical setup

- Idealized model: two TD flux ropes in pseudostreamer & two ropes next to it
- Ignore details like field asymmetries & different size of filaments
- $\beta = 0$ approximation & ideal MHD equations (reconnection due to num. diffusion)
Simulation results

Török et al. (2011)

• Initiate eruption of flux rope 1 by converging flows (ad-hoc)

• Eruption leads to two consecutive reconnection events, each of which triggers a new eruption

R1: “breakout” reconnection at pseudostreamer separator

R2: “flare” reconnection in the wake of erupting FR 2
Validity of idealized model

- Model:  
  - suggests how one eruption can trigger subsequent eruptions
  - reproduces correct order of eruptions

- However: difficult to confirm whether this happened in the real event

- Further support from data-based analysis of coronal magnetic topology

- More detailed, data-based simulations are needed
State-of-the-art: global & “thermodynamic” simulations

- Idealized models computationally inexpensive study & test basic physical mechanisms

- State-of-the-art models aim for more realism by using:
  - large spherical domains to model extended corona & solar wind
  - observed photospheric magnetic fields as boundary condition
  - improved energy transport: coronal heating, thermal conduction, radiation losses

Thermodynamic modeling of the corona

1. Extrapolate initial magnetic field from synoptic (1 month) photospheric magnetogram
2. Run thermodynamic simulation until steady-state (including solar wind) is reached
3. Produce synthetic satellite images (allows direct comparison to observations)
Thermodynamic CME simulations

• Energize eruption source region:
  - insert stable or unstable analytical flux rope
  - impose boundary evolution to create flux rope

• Trigger eruption by, e.g., converging flows toward source region neutral line
Comparison with white-light CME observations

- Compare synthetic polarization brightness images to observations
  - Result depends strongly on viewing angle
  - Important for estimations of CME mass & kinetic energy
Interplanetary CME propagation

Thermodynamic simulations are computationally very expensive

Couple with heliospheric codes that use reduced set of equations

- model CME propagation to Earth (and beyond)
- produce synthetic in-situ measurements at 1 AU

Lionello et al., submitted
Modeling observed eruptions

1-2 August 2010

AIA 211
XRT Ti-poly
β = 0

14 July 2000 (Bastille Day event)

β = 0
Summary

• **Idealized simulations** improve our understanding of physical mechanisms at work in solar eruptions ➞ e.g. initiation & driving of eruptions and coupling between eruptions

• **Global simulations** using real data & improved coronal plasma descriptions emerging ➞ deeper insight & semi-realistic modeling of observed eruptions

• **Coupling of coronal & heliospheric models** will allow us soon to simulate observed events from Sun to Earth ➞ important for understanding and predicting space weather

• Still, it will be many(?) years before we have models that:
  
  - resolve the enormous range of length scales present in solar eruptions
  - solve the complete set of plasma equations
  - use boundary & initial conditions that match reality
Outlook (some current & next steps)

- Adaptive mesh refinement ➞ improve modeling of reconnection, shocks, etc.

- Couple MHD and PIC (kinetic) codes ➞ modeling of particle acceleration

- Couple FE or NLFFF & CME models ➞ more realistic pre-eruption configurations

- Develop evolutionary MHD models ➞ overcome present “static” modeling of corona ➞ simulate CMEs in real time
Many thanks to AAS/SPD

Thank you for your attention