THE SCIENCE OF SOLAR HURRICANES

2016 SWC Seminar Series

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CUA/Physics, NASA/GSFC
Special thanks: Dr. Antti Pulkkinen, NASA/GSFC
The newly opened CUA Space Weather Center (SWC) is a fully functional research and real-time analyses center dedicated to scientific investigations and forecasting of extreme space weather events – violent physical processes around the Earth driven by storms on the Sun.

Space weather events present a growing hazard to human technologies and society by disrupting satellite communications and navigation systems, damaging power grids, exposing astronauts to a harsh radiation environment, and causing an array of other detrimental effects in space and on the ground. Understanding the physics of such events has become a priority of NASA science programs which welcome contributions from educational institutions. Space weather has gained recent high-level attention, leading to the release of the space weather action plan by the Office of Science and Technology Policy at The White House.

SWC will enable scientific investigations of extreme space weather events associated with major solar flares, large coronal mass ejections, solar energetic particle events, and intense geomagnetic perturbations and their ionospheric footprints. Data-driven simulations and an advanced statistical analysis of past events will be used to produce student-generated experimental space weather forecasts which will be posted online and disseminated throughout the space weather research community.

At the opening ceremony, from left to right:

- Steve Kraemer, Head of the Physics Dept., CUA
- Antti Pulkkinen, Research Astrophysicist, NASA Goddard
- Claudia Bornholdt, Acting Dean, School of Arts & Sciences, CUA
- Vadim Uritsky, Head of the Space Weather Center, Physics Dept., CUA
- Robert Robinson, Director of Institute for Astrophysics & Computational Sciences, CUA
- Michael Hesse, Director of Heliophysics Science Division, NASA Goddard
- Robert McCoy, Director of Geophysical Institute, U of Alaska Fairbanks
The space weather impacts

credit: L. Lanzerotti/Bell Labs
The Sun-driven space weather system
The 1859 Carrington event

Telegraph systems all over Europe and North America failed, in some cases giving telegraph operators electric shocks. Telegraph pylons threw sparks. Some telegraph operators could continue to send and receive messages despite having disconnected their power supplies.

Comparable solar storm: July 23 2012 (missed the Earth).

History channel VIDEO: The biggest Solar Storm in history (5:46)
THE SUN - the space weather driver

Photosphere at 4300 K (top)

Granulation

Sunspots

Chromosphere at 25000 K (top)

Corona at \( \approx 10^6 \) K

Convection zone at 6600 K (top)

Radiation zone at \( 5 \cdot 10^5 \) K (top)

Core (Hydrogen into Helium) at \( 1.5 \cdot 10^7 \) K

Prominence at about 5000-10000 K

Credit: Wikipedia/sun
Nuclear fusion in the core of the Sun

- (primarily) Proton-proton fusion process operating in the solar core fuels everything.

150 g/cm³ hydrogen at 15 million Kelvin

Electromagnetic radiation

Proton-proton fusion chain (credit: Wikipedia)
The internal rotation rate of the Sun. The radial profiles are calculated for three different latitudes (Kosovichev et al., 1997).
The magnetic field of the Sun

• The Sun's magnetism could be a remnant of the magnetic field in the interstellar cloud that once collapsed to form the Sun (Ohmic diffusion time $\sim 10^{10}$ yrs)

• Differential rotation and its association to the migration of the sunspots point at a dynamo process near the bottom of the convection zone

• The problem of dynamo theory is to find solutions for the induction equation

$$\frac{\partial B}{\partial t} = \nabla \times (V \times B) + \eta \nabla^2 B$$

where the convection and diffusion together result in creation of new magnetic flux, or more exactly, **manifolding of the existing flux**.
Sunspots and solar magnetism

- A sunspot corresponds to an **intense magnetic flux** tube emerging from the convection zone to the photosphere.
- Diameter up to ~ 20,000 km
- The largest observed magnetic fields are about 0.3 T.
- Temperature is about 4100 K, lower than typical photospheric temperatures (4300K and up) due to strong B field.
- The magnetic field is measured by observing the **Zeeman splitting** of atomic spectral lines.

*Sunspot, courtesy NJIT’s New Solar Telescope*
The structure of a sunspot

$T_{\text{eff}} \approx 4500 \, \text{K}$

$T_{\text{eff}} \approx 5500 \, \text{K}$

$T_{\text{eff}} \approx 5800 \, \text{K}$
Zeeman splitting

* Splitting of a spectral in the presence of an external magnetic field
* The splitting is proportional to the magnetic field strength and the Lande factor.

Animation of solar emission line splitting due to magnetic field
Computing sunspot number

- The classic (since the 18th century) means to characterize the state of the Sun is the *relative sunspot number*:

\[ R = k(10g + f) \]  

(1)

- Observatory-dependent calibration factor
- Total number of spots
- Number of spot groups
8 groups and 15 individual spots: $R = 95$

\[ R = k(10g + f) \]

- Observatory-dependent calibration factor
- Total number of spots
- Number of spot groups
Monitoring solar magnetic field

Joint USAF/NOAA Solar Region Summary
SRS Number 304 Issued at 0030Z on 31 Oct 2003
Report compiled from data received at SWO on 30 Oct

I. Regions with Sunspots. Locations Valid at 30/2400Z
Nmbr Location  Lo  Area  Z   LL   NN Mag Type
0484 N01W95   356  0210 Dao  10   06 Beta-Gamma
0486 S18W23   284  2600 Fkc  18   80 Beta-Gamma-Delta
0487 N12E06   255  0280 Dko  07   23 Beta
0488 N08W28   289  1750 Fkc  17   34 Beta-Gamma-Delta
0489 S12W36   297  0130 Dao  06   09 Beta
0490 S12W14   275  0010 Hrx  01   03 Alpha
0491 S06W32   293  0120 Dso  07   10 Beta
0492 S23W62   323  0340 Eko  11   17 Beta
0494 S23E08   253  0010 Axx  00   01 Alpha
0495 S22E20   241  0240 Dso  08   10 Beta

Credit: SolarMonitor.org

Credit: NOAA SWPC
The Zurich sunspot number time series

A montage of Yohkoh SXT images demonstrating the variation in solar activity during one sunspot cycle

Solar Cycle Variations

Solar Irradiance (W/m²)

Irradiance (daily/annual) Sunspot Observations Solar Flare Index 10.7 Radio Flux
Long-term sunspot number variation after the 11-year cycle has been filtered away.
The butterfly diagram of sunspot appearance. Solid/dashed lines are contours of positive/negative polarity (Schlichenmaier & Stix, 1995).

Relative sunspot number introduced by Wolf in 1848: \[ R = k (10g + f) \]

\( g \) - number of spot groups, \( f \) - total number of spots
\( k \) - determined individually for each observatory.
Coronal magnetic field and the solar cycle

- Global structure of the solar magnetic field varies as a function of solar cycle.
The MHD energy balance describing coronal heating

magnetic energy entering as Poynting flux through the surface $\partial V$ of the volume $V$

\[-\int_{\partial V} \mathbf{E} \times \mathbf{H} \cdot d\mathbf{a} = \frac{\partial}{\partial t} \int_V \frac{B^2}{2\mu_0} \, dV + \int_V \frac{f^2}{\sigma} \, dV + \int_V \mathbf{V} \cdot \mathbf{J} \times \mathbf{B} \, dV\]

- increasing magnetic energy
- energy dissipated through ohmic heating
- energy dissipated through mechanical work by the magnetic force ($\mathbf{J} \times \mathbf{B}$)

![Diagram of the solar corona with temperatures: (1-3) x 10^6 K and 6 x 10^3 K]
Coronal heating mechanisms

- **Alfven waves**: can be nonlinearly damped as they propagate outward, with a fraction of wave energy transformed to heat. Damping mechanism involve *phase-mixing of Alfven waves* of different wavelengths and speeds propagating in the same spatial volume and *cyclotron resonance with the plasma ions* (Alfv’en waves become electromagnetic ion cyclotron waves at frequencies close to the local ion cyclotron frequency).

- **Nano- and microflares**: heating by larger numbers of (relatively) small explosive events (~20 000 events per minute). Nanoflares: energy ~ $10^{16}$ J; microflares: energy ~ $10^{19}$ J. To make a flare, one needs $10^6$ micro- and $10^9$ nano-flare events. These abundances remain to be proved. Magnetic reconnection (Parker's scenario) is a potential driver of such events.

- **Turbulent cascading**: combines the ideas of cyclotron heating and phase mixing. Short wavelength fluctuations are generated from the long wavelength ones which are damped at scales close to the ion gyro radii.
Solar irradiance

• The total solar irradiance (TSI):
  \[ S = 1367 \pm 3 \text{ W m}^{-2} \]

• \( S \approx 1366 \text{ W m}^{-2} \) during solar minima
• \( S \approx 1367 \text{ W m}^{-2} \) during solar maxima
• \( S \) varies by a factor of:
  \[ 10^{-6} \text{ over minutes} \]
  \[ 2 \times 10^{-3}(0.2\%) \text{ over several days} \]
  \[ \sim 10^{-3} \text{ over a solar cycle} \]
• The luminosity of the Sun:
  \[ L_\odot = 4\pi AU^2 S = (3.844 \pm 0.010) \times 10^{26} \text{ W} \]

(Ribas, 2010)
Solar spectrum from $\gamma$-rays to radio waves

$$\lambda (\text{m}) = 300 / f (\text{MHz})$$; e.g., 1 mm $\leftrightarrow$ 300 GHz
## SDO Atmospheric Imaging Assembly (AIA) channels

<table>
<thead>
<tr>
<th>AIA wavelength channel</th>
<th>Source $^{[16]}$</th>
<th>Region of solar atmosphere</th>
<th>Characteristic temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>White light</td>
<td>continuum</td>
<td>Photosphere</td>
<td>5000 K</td>
</tr>
<tr>
<td>170 nm</td>
<td>continuum</td>
<td>Temperature minimum, photosphere</td>
<td>5000 K</td>
</tr>
<tr>
<td>30.4 nm</td>
<td>He II</td>
<td>Chromosphere &amp; transition region</td>
<td>50,000 K</td>
</tr>
<tr>
<td>160 nm</td>
<td>C IV + continuum</td>
<td>Transition region &amp; upper photosphere</td>
<td>$10^5$ &amp; 5000 K</td>
</tr>
<tr>
<td>17.1 nm</td>
<td>Fe IX</td>
<td>Quiet corona, upper transition region</td>
<td>$6.3 \times 10^5$ K</td>
</tr>
<tr>
<td>19.3 nm</td>
<td>Fe XII, XXIV</td>
<td>Corona &amp; hot flare plasma</td>
<td>$1.2 \times 10^6$ &amp; $2 \times 10^7$ K</td>
</tr>
<tr>
<td>21.1 nm</td>
<td>Fe XIV</td>
<td>Active region corona</td>
<td>$2 \times 10^6$ K</td>
</tr>
<tr>
<td>33.5 nm</td>
<td>Fe XVI</td>
<td>Active region corona</td>
<td>$2.5 \times 10^6$ K</td>
</tr>
<tr>
<td>9.4 nm</td>
<td>Fe XVIII</td>
<td>Flaring regions</td>
<td>$6.3 \times 10^6$ K</td>
</tr>
<tr>
<td>13.1 nm</td>
<td>Fe VIII, XX, XXIII</td>
<td>Flaring regions</td>
<td>$4 \times 10^5$, $10^7$ &amp; $1.6 \times 10^7$ K</td>
</tr>
</tbody>
</table>
Multi-spectral SDO AIA: NOAA AR 11082
Multiscale intermittency in the solar corona

Probability distributions of coronal emission events
(Uritsky et al, PRL 2007)

$\tau_E = 1.73$
Solar flares

- Generally speaking in solar flares free magnetic energy converted into heat, non-thermal particle acceleration, electromagnetic radiation, waves and bulk flows.

- The flaring process can be divided into three steps:
  - Energy build-up.
  - Energy release.
  - Energy transport.
Complex magnetic fields produce solar eruptions

The emerging flux together with complex photospheric flows lead to complex structures such as filaments/prominences in the solar atmosphere.

Flux emergence in 3D MHD 80 Mm x 90 Mm x 68 Mm model (credit: Magara, 2007).
Unstable solar signatures

Complex solar atmospheric “beta-gamma-delta” structures having also, for example, sigmoid signature in soft X-rays (0.1 – 10 nm) indication of pending eruption.

Hinode 0.2–20 nm X-Ray Telescope (XRT) image of a sigmoid on February 12, 2007
Magnetic reconnection

At the formed localized boundary layer diffusion may become important and lead to global reconfiguration of plasma:

- Diffusion and field annihilation
- Reconnected field
- X-line (neutral point)
Examples of non-potential coronal structures

TRACE loop arcade

Convergent flow

Differential rotation

Neutral line + coronal hole
Reconnection events in the solar corona

- In flares energy build-up can generate these reconnecting thin current sheets and boundary layers in primarily two different ways (or combo):
  - Reconnection events in the solar corona
  - Two interacting magnetic domains (credit: Shibata, 2011)
  - Single erupting magnetic domain (credit: Manchester, 2001)
  - Current sheet and reconnection
  - Two interacting magnetic domains (credit: Shibata, 2011)
THE SOLAR WIND

Polar overlay plot of Ulysses/SWOOPS solar wind speed data (Apr 1998) and EIT/LASCO/Mauna Loa images of the solar corona.
Formation of the solar wind

- The million degree coronal plasma experiences continuous thermal expansion and escapes the gravitational potential → supersonic solar wind.

- Also other mechanisms such as plasma waves possibly contribute to the solar wind acceleration.

STEREO A white light coronagraphs and heliospheric imagers
December 2008

Credit: NASA GSFC
Coronal magnetic field

Total solar eclipse (08/01/2008), Miloslav Druckmuller et al.

Identifying open field coronal loops (V Uritsky et al, 2015)
Typical solar wind parameters at 1 AU

<table>
<thead>
<tr>
<th></th>
<th>slow wind</th>
<th>fast wind</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V$ (km s$^{-1}$)</td>
<td>350</td>
<td>750</td>
</tr>
<tr>
<td>$n_e$ (m$^{-3}$)</td>
<td>$1 \times 10^7$</td>
<td>$3 \times 10^6$</td>
</tr>
<tr>
<td>$T_e$ (K)</td>
<td>$1.3 \times 10^3$</td>
<td>$1 \times 10^5$</td>
</tr>
<tr>
<td>$T_p$ (K)</td>
<td>$3 \times 10^4$</td>
<td>$2 \times 10^5$</td>
</tr>
<tr>
<td>$B$ (nT)</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>$v_A$ (km s$^{-1}$)</td>
<td>20</td>
<td>70</td>
</tr>
</tbody>
</table>

$v_A = B / \sqrt{\mu_0 \rho_m}$ is the Alfvén velocity

**The Parker spiral**

$$\tan \psi = \frac{\Omega (r - R_\odot)}{V}$$
Turbulent space environment

<table>
<thead>
<tr>
<th></th>
<th>Solar Wind</th>
<th>Magnetosheath</th>
<th>Magnetotail</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Re$</td>
<td>$1 \times 10^{14}$</td>
<td>$1 \times 10^{12}$</td>
<td>$5 \times 10^{12}$</td>
</tr>
<tr>
<td>$Re_m$</td>
<td>$3 \times 10^{14}$</td>
<td>$1 \times 10^{13}$</td>
<td>$1 \times 10^{13}$</td>
</tr>
</tbody>
</table>

J Borovsky, H. Funsten  JGR 2003
THE MAGNETOSPHERE

Magnetosheath

Earth's atmosphere
0 - 100 km

Van Allen radiation belt

Polar cusp

Neutral sheet

Plasma sheet

Deflected solar wind particles

Incoming solar wind particles

Magnetotail

Solar wind

Bow shock

Interplanetary magnetic field

Earth magnetic field

cusp
day side
tail
lobe
plasmoid
night side

Magnetopause

Tail Lobe

Plasma Sheet

Neutral Sheet

Plasmasphere

Van Allen Radiation Belts
A magnetosphere and its bow shock
The magnetosphere and the large scale magnetospheric current systems.

<table>
<thead>
<tr>
<th></th>
<th>magnetosheath</th>
<th>tail lobe</th>
<th>plasma sheet boundary</th>
<th>central plasma sheet</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n$ (cm$^{-3}$)</td>
<td>8</td>
<td>0.01</td>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td>$T_i$ (eV)</td>
<td>150</td>
<td>300</td>
<td>1000</td>
<td>4200</td>
</tr>
<tr>
<td>$T_e$ (eV)</td>
<td>25</td>
<td>50</td>
<td>150</td>
<td>600</td>
</tr>
<tr>
<td>$B$ (nT)</td>
<td>15</td>
<td>20</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>$\beta$</td>
<td>2.5</td>
<td>3 \cdot 10^{-3}</td>
<td>0.1</td>
<td>6</td>
</tr>
</tbody>
</table>
Space weather and electric power

NOAA VIDEO: Space Weather Impacts (2:48)
NEXT SWC seminar

Schedule of talks

October 25, 2016 (Tuesday): AN INTRODUCTION TO SPACE WEATHER
November 01, 2016 (Tuesday): THE SCIENCE OF SOLAR HURRICANES
November 16, 2016 (Wednesday): FORECASTING EXTREME SPACE WEATHER
November 30, 2016: (Wednesday): SPACE HAZARDS AND THE HUMAN SOCIETY

Location: Rm 106, Hannan Hall   Time: 7:00pm

Practical experience

Students with sufficient backgrounds in physics and math will be offered a unique hands-on experience with space weather forecasting tools available at the SWC through its collaboration with the Community Coordinated Modelling Center at NASA Goddard Space Flight Center.

Contact information: Dr. Vadim Uritsky, 206 Hannan Hall, uritsky@cua.edu
THANK YOU !