Early note on solar-terrestrial relations

from Richard A. Proctor:  
"Other Worlds Than Ours", 1870.  Chapter II. What we Learn From the Sun.

[In] 1859, the eminent solar observer, Carrington noticed the apparition of a bright spot upon the Sun’s surface.

The light of this spot was so intense that he imagined the screen which shaded the plate employed to receive the solar image had been broken. (…)

Now it was found that the self-registering magnetic instruments of the Kew observatory had been sharply disturbed at the instant when the bright spot was seen. (…)

Telegraphic communication was interrupted, and at a station in Norway the telegraphic apparatus was set on fire;

auroras appeared both in the northern and southern hemispheres during the night which followed.
What is space weather?

Space weather happens when a solar storm from the Sun travels through space and impacts the Earth’s magnetosphere.

Studying space weather is important to our national economy because solar storms can affect the advanced technology we have become so dependent upon in our everyday lives.

Energy and radiation from solar flares and coronal mass ejections can

- Harm astronauts in space
- Damage sensitive electronics on orbiting spacecraft…
- Cause colorful auroras, often seen in the higher latitudes…
- Create blackouts on Earth when they cause surges in power grids.
Effects of space weather

- many things can be affected by the space environment
- and often in many ways…

Power transformer and the Sun

Severe internal damage caused by the space storm of 13 March 1989

but be careful:
this was the only extreme case we know of…
What is space weather?

Current Space Weather
Learn more about Space Weather

http://sohowww.nascom.nasa.gov/spaceweather/

What questions to ask?

- solar irradiance
- solar (coronal) eruptions
- particle acceleration

propagation:
- magnetic disturbances in interplanetary space
- energetic particles

effects on Earth:
- geomagnetic storms
- energy input into atmosphere
- energetic radiation and life
- advanced technology

selected physical problems to address:
- small & large scale structures: sunspots / faculae
- magnetic instabilities for CMEs and flares
- relativistic description of acceleration process
- wave-particle interaction
- kinetic description of transport phenomena
- interaction of large scale solar wind/CME structures
- interaction of solar wind with Earth’s magnetosphere
- intrusion of particles into Earth’s magnetosphere
- reconnection and acceleration in magnetosphere

alternative definition of space weather:
integration of many problems from the Sun to the Earth into an engineering model to predict effects on Earth.

COMPLICATION:
we have not yet understood most of the relevant individual problems...

- energetic radiation and life
- advanced technology
**Solar–terrestrial relations I: solar irradiance**

- Total solar irradiance: \( \sim 1366 \pm 1 \text{ W/m}^2 \)

**Sunspot**

- What is the physical basis of solar variability?
- How do sunspots form and evolve?
- What causes “faculae” to be bright?
- How do small and large structures interact?

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**Solar–terrestrial relations II: X-ray & EUV**

- EUV affects the Earth:
  - thermosphere (heating)
  - chemical reactions (e.g., ozone)
  - ionization / ionosphere expansion

- How does coronal heating work?
- And how does it control the X-ray and EUV brightness?
Solar–terrestrial relations III: mass ejections

- Large magnetic structures become unstable
  - coronal mass ejections (CME)
  - flares → high-energy particles
- interaction with Earth’s magnetosphere
- danger to instrumentation and life (in space)

What is the basic physical mechanism driving the corona unstable?

Observations:
- EIT / Lasco / SOHO

Sketch:
- Earth’s magnetosphere

Prominences and magnetic field

Prominences are found above magnetic neutral lines

Source: NSO and NOAA/SEL/USAF

HAO A–301
What is a prominence?

the "hammock" of Kippenhahn & Schlüter (1957):

- cool dense plasma (~10^4 K) in a hot surrounding (~10^6 K)
- enough (cool) plasma for significant absorption of photospheric emission

modern idea:
complex helical structure

over-arching magnetic field holding prominence down

Prominence vs. coronal loop

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- cool dense plasma (~10^4 K) in a hot surrounding (~10^6 K)
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What is a coronal loop?
emission of hot plasma (~10^6 K) with enhanced density as compared to the background corona along the magnetic field
Filaments and prominences

- Filament: cool plasma held by magnetic field absorbs photospheric light
- Prominence: cool plasma seen in emission

Filament / prominence eruption

1. First one prominence behind the limb seen in emission erupts
2. Then the prominence in the front seen in absorption takes of…
Eruptive Prominences: many flavors

almost always:
- single magnetic flux rope
- topology preserved

mostly:
- helical shape
- signature of twist

often:
- ejection (CME)
- high speeds (~$v_A$)

Coronal mass ejections

eruption on 4 Jan 2002

Lasco C2
- rapid acceleration

Lasco C3
- and huge expansion

Eruption of prominence
(seen dark in absorption)
and subsequent brightening of
"reconnected" post flare loops

EIT 195Å / Fe XII ~1.5 MK
CME properties

- huge expansion $> 10^3$
- huge solid angle $> \pi/2$
- often twisted flux ropes

Two CME classes: fast & slow

- fast – rapid acceleration
  - from active regions
- slow – gradual acc.
  - from prominences
  - outside AR

Three-part structure:
- core – prominence
- cavity – expanding flux rope?
- front – swept up plasma

A very simplified scenario for a CME

cutting the tethers
A very simplified scenario for a CME

two ribbon flare
post-flare loops

Modern CME scenarios / models

tether cutting: “runaway” reconnection
magnetic breakout: unstable arcade triggered (& driven ?) by reconnection

flux rope instability

flux cancellation at neutral line forms flux rope

Antiochos et al. (1999…)

Török & Kliem (2005)

Traveling to Earth...

to understand the interaction with the Earth:
first understand the origin of the magnetic cloud, namely the CME ejection

The kink instability

- kink is an ideal MHD instability
- twisting a flexible tube if twist is above threshold:
  - twist "transformed" into writhe
- conserved: helicity ~ twist + writhe
- twist threshold: $\Phi = 2\pi N$ with $N \approx 1 \ldots 2$
Kink instability in solar eruptions

- many erupting filaments / prominences:
  - suggest twisted field
  - develop helical shape

- Sakurai (1976) suggested
  kink instability as driver of prominence eruptions

- recent years:
  kink instability as explanation only for confined events

- very recently:
  kink instability
  triggers also
  ejective events
  (CMEs)
  (Török & Kliem 2005,
   Fan 2005)

A confined filament eruption

- one possible driver is
  rotational motion of foot points
  - energy stored in twist of
    magnetic field

- helical kink instability
  triggers event

HERE:
- filament eruption is confined
  - no outbreak / CME

investigate models with different
- flux rope twist
- overlying field
- strong overlying magnetic field
  can prevent eruption
X-ray sigmoids and flux eruption

Ideal MHD simulation of flux rope eruption through kink instability

Magnetic field lines

Inner flux rope

Current sheets

Assumption:
- Heating concentrated in current sheets
- Current sheets outline expected hot X-ray emission
- Very good qualitative match to observations

Ejective filament eruption

TRACE 1600 Å – cool ejected material

Chromospheric temperatures + C IV (10⁵ K)

Flux rope kink instability

Small overlying $B$ allows ejection

(some) open questions for kink instability-based models

- Huge expansions of CMEs by $> 10^3$
- Eruptions with little or no apparent helical shape

Torus instability?
Finally: a complete "space weather" model

Virtual space weather from the sun to Earth

The perfect storm packs the energy of 100 million atomic bombs

Solution at 6 hours

Simulating space weather: numerical challenge

needed for these global models:
advanced codes for many different physical problems:
- adaptive mesh refinement (AMR) to resolve large and small scales
- MHD codes
- particle codes
- ....

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CME eruption and propagation to Earth

initial state:
observed $B$ in photosphere
→ field extrapolation
→ add flux rope in AR (white)

$t = 0.0$

$t = 2.0$ hours

spatial resolution of simulation in corona and heliosphere:
$1/32 R_\odot = 21$ Mm (!)
to $4 R_\odot 
= 14 \cdot 10^6$ cells ($\sim 256^3$)

Interaction with Earth

just before the CME hits the Earth

Earth's magnetosphere after the interaction

$t = 65$ hours
hitting the Earth
Limitations of this approach

The global space weather model puts together many modules: a good "engineering model" of physical phenomena

- a general problem: **not yet in real time**
  - many weeks to simulate an event which last for only some days...
- there are important physics pieces still missing!
  - **for the coronal parts:**
    - solar wind heating and acceleration
    - problem of CME initiation
    - reconnection processes
- spatial resolution in corona:
  - currently AMR with smallest cells 1/32 $R_\odot = 21$ Mm (!)
  - this resolution certainly cannot catch the relevant physics
  - for comparison: coronal box models: computational domain ~ 60x60x40 Mm

However: if one is interested in an engineering approach
i.e. only predict when, where and how a CME hits the Earth
this might be an appropriate approach

Summary / lessons learnt

- there are many ways in which the Sun affects the Earth
  - Luminosity: bolometric, X-rays, VUV etc.
  - particle radiation: CMEs, energetic particles
  - magnetic field: cosmic rays

- the most relevant phenomenon concerning corona: CME
  - different scenarios for CME initiation
  - instabilities, tether cutting, breakout...
  - all scenarios are (in the end) driven by photospheric shuffling of magnetic field

- global models of CME initiation to Earth interaction needed for "space weather"
  - global models currently in an "engineering state"
  - detailed physics CME and/or interaction with Earth are not really included