Multi-Messenger Solar Physics Through Time

Leif Svalgaard
Stanford University
w/ Hugh Hudson

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The term “multimessenger astronomy”—combining different signals, or messengers, from the same astrophysical event to obtain a deeper understanding of it—is in the air nowadays, largely because of the remarkable success of the Laser Interferometer Gravitational-Wave Observatory (LIGO) in detecting gravitational waves¹ (see PHYSICS TODAY, December 2017, page 19). Four messengers reach us from beyond the solar system: photons, neutrinos, cosmic rays, and now gravitational waves. Lost amid the current buzz, though, is that the Sun produces many other messengers.

Lost amid the current buzz, though, is that the Sun produces many other messengers.

And each messenger often sends us several different messages.
The Carrington Event 1859
Several Messages

Geomagnetic Record

SFE

Ring Current

SSC

Sep. 2

Storm

AUGUST 30
AUGUST 31
SEPTEMBER 1
SEPTEMBER 2
MIDNIGHT
We all Know about Marconi’s Long-Distance Radio Transmissions

At this medium wavelength, reliable long distance transmission in the daytime is not really possible because of heavy absorption of the sky wave in the ionosphere (Marconi didn’t know that, but he was lucky...)

Later he managed to send a message from US president Theodore Roosevelt to the King of the UK via his Glace Bay station in Nova Scotia, Canada, across the Atlantic on 18 January 1903.
Kennelly Suggested a Wave Guide

On the Elevation of the Electrically-Conducting Strata of the Earth’s Atmosphere. 1902

and also upwards, until the conducting strata of the atmosphere are encountered, after which the waves will move horizontally outwards in a 50-mile layer between the electrically-reflecting surface of the ocean beneath, and an electrically-reflecting surface, or successive series of surfaces, in the rarefied air above.

Oliver Heaviside Got the Same Idea

And then comes the most famous part of the article. “There is another consideration. There may possibly be a sufficiently conducting layer in the upper air. If so, the waves will, so to speak, catch on to it more or less. Then the guidance will be by the sea on one side and the upper layer on the other.”

10th ed. of Encyclopedia Britannica

“there seems to be grounds for imagining that their conductivity may be much greater than has hitherto been supposed.” B. Stewart 1882
An effective dynamo process takes place in the dayside E-layer where the density, both of the neutral atmosphere and of the electrons are high enough.

We thus expect a geomagnetic response due to electric currents induced in the E-layer.

We need 1) something to produce the charges and 2) something to move them across the magnetic field.
The Source of the Ionization

Extreme Ultraviolet (EUV), wavelengths 17.1-21.1-30.4 nm from chromosphere and corona with temperatures from 50,000 K to 2 million K.
The Diurnal Variation of the Direction of the Magnetic Needle

George Graham [London] discovered [1722] that the geomagnetic field varied during the day in a regular manner.
We plot the yearly average range to remove the effect of changing solar zenith angle through the seasons. What remains is the solar cycle modulation.
EUV and its proxy: F10.7 Microwave Flux

The Microwave Flux Record Extends 70 years in the Past

EUV Flux (1-103 nm) and F10.7 Flux

Spacecraft Data

10.7 cm = 2800 MHz
The Effect of Solar EUV

The EUV causes an observable variation of the geomagnetic field at the surface through a complex chain of physical connections.

The physics of each link in the chain is well-understood in quantitative detail and can be successfully modeled.

We use this chain in reverse to deduce the EUV flux from the geomagnetic variation.
Reconstructions of EUV and F10.7

\[ F_{10.7} = \frac{(rY/4.00)^2}{21.55} \]

\[ EUV = \frac{(rY/21.55)^2}{21.55} \]

\[ R^2 = 0.98 \]

\[ R^2 = 0.96 \]
Observations in the 1740s

Right: Hjorter’s measurements of the magnetic declination at Uppsala during April 8-12, 1741 (old style). The curve shows the average variation of the magnetic declination during April 1997 at nearby Lovö (Sweden).

Left: Variation during strong Northern Light on March 27th. Also observed by Graham in London, showing that the aurorae and magnetic field are connected on a large scale and not just local meteorological phenomena.

Note there are really two phenomena going on, regular daily variation and sporadic, large aurora-related excursion…

This is from Hjorter’s original notebook for that day. Observations were made with an instrument constructed by Graham.

Olof Petrus Hjorter was married to Anders Celsius’ sister and made more than 10,000 observations of the magnetic declination in the 1740s.
The Science of Solar-Terrestrial Relations Began With Mairan’s 1733 Book on the Aurora

The extraordinary Auroral Display observed in much of Europe [but not in cloudy Paris] on 6 March 1716 was considered by E. Halley to be a purely Terrestrial phenomenon of “Magnetic Vapors” rising from the polar regions into the sky.

Following a similar strong display in 1726 that caused great panic in France, the French Government charged J.-J. Dortous de Mairan to provide a scientific explanation for the display just like the Royal Soc. had asked Halley to give ten years earlier.
Mairan speculated that the Aurora is due to the interaction of a material solar atmosphere [extending out past the orbit of the Earth] and visible during total eclipses. He raised the question whether the variation of the number of sunspots were also related to variations of the solar atmosphere.
There Must be More than One Cause

John Canton [1759] made more than 4000 observations of the Declination on 603 days in London. Most days were regular, but some were not, and on those an aurora was always seen. He concluded that “The irregular diurnal variation must arise from some other cause than that of heat communicated by the sun”.

The different seasonal variations are important clues to the physical processes at work:

- Solar ‘Rays’ dependence on Zenith Angle
- Solar ‘Matter’ Semiannual variation

But a century would now pass before further progress could be made …
The Aurorae are Due to that “Other Cause” (Solar Wind)

Number of days per decade with Aurorae (30-yr averages) during the Middle Ages

Observation in May 1921 of an Aurorae at Apia [Geom. Lat. 15 degrees] is the lowest latitude aurora known

Calibration is very difficult
We do have some Auroral data much further back in time …

567 BC

But it is hard [impossible] to ‘calibrate’ such observations

Another possible aurora was described by the prophet Ezekiel (I: 1-28) in 593 BC in Baghdad

The geomagnetic Latitude of Baghdad back then was higher than today
400-year Sunspot Cycle Record

“Who would have thought just a few years ago that one could calculate a terrestrial phenomenon from observations of sunspots”

Rudolf Wolf, 1852
The old ‘official’ sunspot number [maintained by SIDC in Brussels] showed a clear ‘Modern Maximum’ in the last half of the 20th century.

Correct GSN by +40% before ~1885
Correct WSN by -20% after 1946, because of weighting of the count introduced then (the Waldmeier Jump)

The new SSN series suggest that there likely was no Modern Grand Maximum.
Geomagnetic Storms Due to Much Enhanced ‘Ring Current’

Oppositely particles trapped in the Van Allen Belts drift in opposite directions giving rise to a net westward ‘Ring Current’.

The Dst geomagnetic index [departure from quiet conditions] is a measure of the energy in the Ring Current

The storms have a clear solar cycle dependence

In 1852, Sabine recognized that the irregular magnetic variations correlated very closely with the number of sunspots.
Since the daily variation is fairly regular from day to day we can eliminate it by considering the difference between consecutive days. The new IDV-Index is the difference from one day to the next without regard of the sign between the midnight values of the horizontal component H. The importance of this quantity was first recognized by the Scotsman Broun in 1861.

The IDV-index is a good proxy for the negative part of Dst.
IDV is a Good Proxy for HMF B

IDV index depends on HMF B but is blind to speed V.
Applying the relationship we can reconstruct HMF magnetic field $B$ with Confidence:

![Diagram showing InterDiurnal Variability Index (IDV) and Reconstructed Heliospheric Magnetic Field ($B$)]

![Diagram showing Two Reconstructions of Heliospheric Magnetic Field Strength at Earth]
The main sources of low-latitude large-scale solar magnetic field are large active regions. If these emerge at random longitudes, their net equatorial dipole moment will scale as the square root of their number. Their contribution to the HMF strength should then vary as $Rz^{1/2}$ (Wang and Sheeley, 2003).

There does not seem to be evidence that the last 50 years were any more active than 150 years ago.
The total magnetic flux has a strong linear correlation with the Sunspot Group Number.

There is an offset for zero GN giving us a ‘floor’ of the magnetic flux.

Total Disk Unsigned LOS magnetic flux from WSO, MWO, MDI, HMI (normalized to HMI)

“The results of this work strengthen support for the hypothesis that variation in solar irradiance on timescales greater than a day is driven by photospheric magnetic activity”.

Yeo et al., A&A 570, A85 (2014)
The TSI record is that by the Belgian Meteorological Institute [RMIB]
Tension Between B and Modelled TSI

Heliospheric Magnetic Field B (Cycle Averages)

Reconstructions of TSI

Egorova et al. A&A 2018

CHRONOS, MC17
CHRONOS, SSR11
CHRONOS, US16
CHRONOS, MU16
SATIRE
NRL

NOAA CDR
Magnetic Fields on Earth and in Space

The solar system is permeated by magnetic fields coming from the Sun with the Solar Wind and connecting with the field of the Earth [and other planets].

The records from Earth’s polar regions show the Sun’s fields.

Look how accurately we can see the field in space from Earth.
Annual Variation of Dominant Polarity: Rosenberg-Coleman Effect

Caused by ‘flatness’ of the Heliospheric Current Sheet

Balance between polar fields and low-latitude fields determines the Flatness of HCS

Proves Polar Field Reversals in the Past. Using the Svalgaard-Mansurov effect we can see the R-C effect all the way back to 1844
Latitudinal Extent of the HCS

Not the ‘Tilt’


Synoptic Map Calculated by PFS at 2.6 $R_\odot$

Sub-Earth Path

Sector Structure

Solar Eclipse 1954

Carrington Rotation
The Heliospheric Current Sheet


Artist: Werner Heil

Cosmic Ray Modulation mainly caused by latitudinal variation of HCS and CIRs
Nine Millennia of Solar Activity

10Be and 14C

Non-stationary and intermittent ‘periodicities’ [if any]
The Sun blocks cosmic rays arriving at the Earth from the direction of the Sun and casts a shadow in the cosmic-ray intensity. Cosmic rays are charged particles and their trajectories are deflected by the magnetic field between the Sun and Earth, depending (inversely) on the magnetic field strength $B$ and polarity, and can thus be used as probes of the field: yet another Messenger. Shows that the popular PFS model underestimates the field by at least 50%.
The Gamma-Ray Spectrum of the Sun

The solar disk is a bright, hard-spectrum gamma-ray source due to its constant bombardment by cosmic rays, which interact with the solar atmosphere (including deep under the optical photosphere) and produce gamma rays. The gamma rays from the solar disk (SAγ), are a new probe (Messenger) of cosmic rays in the solar system and of solar atmospheric magnetic fields.

The production of SAγ also produces solar atmospheric neutrinos (yet another Messenger). The Sun can be detected by large neutrino telescopes, such as IceCube, where a search is ongoing. These neutrinos are backgrounds for solar dark matter searches…

The 9-year averaged SAγ flux and the solar minimum SAγ flux. The ‘dip’ around 40 GeV is not understood. The theoretical maximum gamma-ray flux that the Sun can produce with cosmic rays is shown by the black solid line.
Solar Neutrinos [Not a Problem Anymore]

The Standard Solar Model Strongly Confirmed

The problem was Neutrino Flavor (e,μ,τ) oscillations

Super-K solar rate measurements are fully consistent with a constant solar neutrino flux emitted by the Sun.
Helioseismic Probing of the Interior

Helioseismology aims to measure Doppler data of the travel times of waves propagating between two points located on the solar surface. The travel times are then inverted to infer sub-surface properties.

Are there one or multiple cells of meridional circulation? Important for the solar dynamo

Surprise: ‘solid body’ rotation in radiative interior
Perhaps: ‘rapid’ rotation in solar core [??]
Spectroscopy: John W. Draper, first president of the American Chemical Society declared in 1876 in his inspiring presidential address:

“And now, while we have accomplished only a most imperfect examination of objects that we find on the earth, see how, on a sudden, through the vista that has been opened by the spectroscope, what a prospects lies beyond us in the heavens! I often look at the bright yellow ray emitted from the chromosphere of the sun, by that unknown element, Helium, as the astronomers have ventured to call it. It seems trembling with excitement to tell its story, and how many unseen companions it has. And if this be the case with the sun, what shall we say of the magnificent hosts of the stars. […] Is not each a chemical laboratory in itself?”
The ‘Xenon Paradox’ May be Another Solar Messenger

Atmospheric xenon is strongly mass fractionated and Xe is the only noble gas that can escape as an ion in a photo-ionized hydrogen wind. Models suggest that a minimum requirement for Xe escape is that solar EUV irradiation needs to exceed 10×that of the modern Sun (Zahnle et al. 2018).

Terrestrial atmospheric Xe has two unique features. First, atmospheric Xe is depleted by a factor of 20 compared to the Ar/Kr/Xe elemental pattern defined by chondrites. Second, atmospheric xenon is strongly enriched in heavy relative to light isotopes compared to other known solar system components. These two features form the “xenon paradox”.

The Rosetta-Mission to Comet 67P/C-G found Xe isotopical abundances similar to that of the early Earth and very dissimilar to that in Chondrites and the Solar Wind possibly indicative of different conditions for solar activity [EUV] of the early Sun.

We have not yet fully decoded this particular message, but it is an example of messages hiding in unexpected places. There are undoubtedly many more…
M. Faraday wrote to R. Wolf on 27th August, 1852: “I am greatly obliged and delighted by your kindness in speaking to me of your most remarkable enquiry, regarding the relation existing between the condition of the Sun and the condition of the Earths magnetism. The discovery of periods and the observation of their accordance in different parts of the great system, of which we make a portion, seem to be one of the most promising methods of touching the great subject of terrestrial magnetism...
Abstract

The concept of Messengers from space that tell us about the physics of objects in the Universe has been much in the news lately with the discovery of gravitational waves, but the Sun is also sending us a diverse suite of astrophysical 'messages', some that only recently have been decoded and read. The true dawn of multi-messenger astronomy actually occurred with observations of phenomena caused by solar emissions. The [growing] list of such 'messengers' includes, among others, electromagnetic radiation, solar wind plasma interactions with the Earth's magnetic field, using the ionosphere for radio propagation, modulation of cosmic rays, neutrinos, and more. In fact, we have a broader array of messengers from the Sun than from any other astronomical object. In this talk, I'll discuss several of those messengers and what they teach us about the sun and especially about the long-term evolution of solar activity.