Commentary

Multimessenger solar astrophysics

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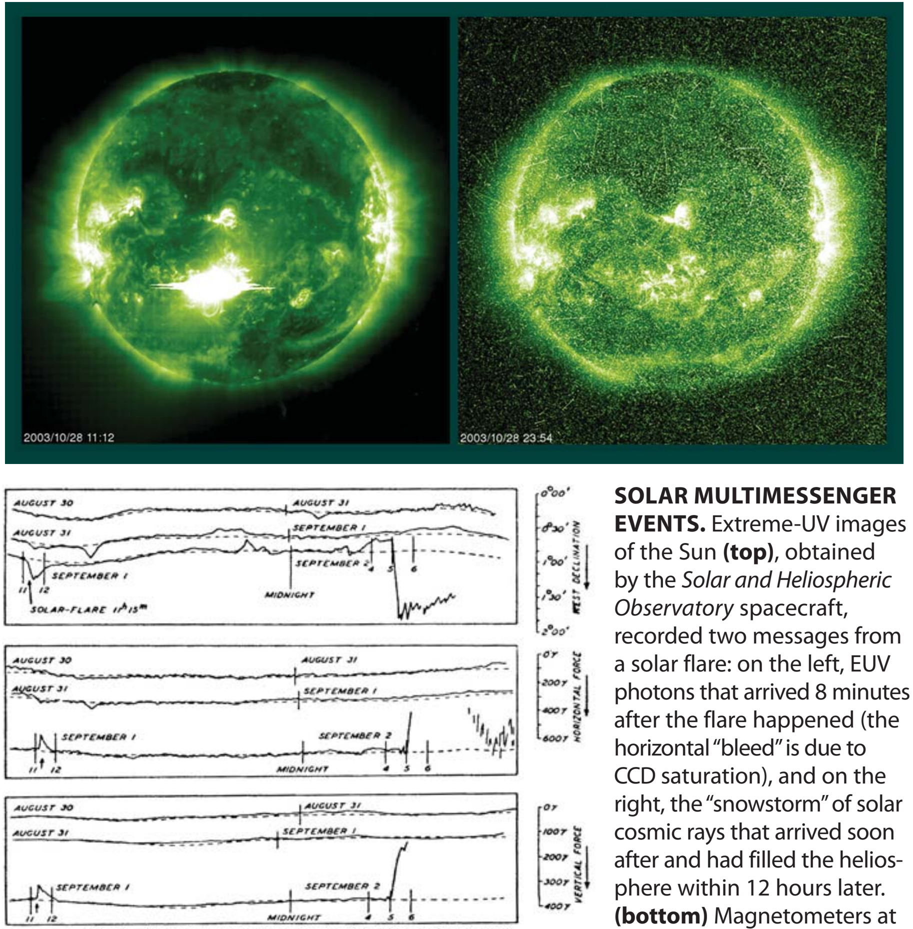

SOLAR MULTIMESSENGER EVENTS. Extreme-UV images of the Sun **(top)**, obtained by the *Solar and Heliospheric Observatory* spacecraft, recorded two messages from a solar flare: on the left, EUV photons that arrived 8 minutes after the flare happened (the horizontal "bleed" is due to CCD saturation), and on the right, the "snowstorm" of solar cosmic rays that arrived soon after and had filled the heliosphere within 12 hours later. **(bottom)** Magnetometers at London's Kew Observatory recorded several messages during the solar flare and geomagnetic storm on 1–2 September 1859. (Bottom panel from S. Chapman, J. Bartels, *Geomagnetism*, 2nd ed., Oxford U. Press, 1962, p. 333.)

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 waves[1] (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. What's more, multimessenger solar astrophysics began as long ago as 1722, when London clockmaker George Graham noted a new solar messenger: diurnal variations in Earth's magnetic field.

Multimessenger information routinely forms a major part of current research in solar and heliospheric physics. One such example, shown in the figure, is a "snowstorm" of solar cosmic rays directly detected by a space-borne extreme-UV imager. Scott Forbush identified similar signals detected at ground-based cosmic-ray stations in 1942 and 1946 as being due to energetic solar protons.[2] Such dangerous ionizing particles are a messenger no spacecraft or space traveler can afford to ignore.

The first recognized messengers of unusual solar activity were sunspots. The arrival in the 17th century of visual evidence of solar structure and rotation possibly caused as much scientific excitement then as the new gravitational-wave messenger has today. As additional messengers from the Sun arrived over the centuries, they were not always recognized as such because the physics had not yet been understood. Graham's diurnal geomagnetic variations, for example, are now known to be a signature of ionization that is produced by solar EUV radiation and dragged across Earth's magnetic field by high-altitude thermal winds. That message has now been translated, and we have most of the physical and phenomenological basis (far in the future in 1722) for interpreting it: Maxwell's equations and the independent characterization of the ionosphere and solar wind.

Other variations of the geomagnetic field allow the detection of sunspots—and would do so even if terrestrial clouds never parted. Swiss sunspot-research patriarch Rudolf Wolf in 1859 famously wrote, "Wer hätte noch vor wenigen Jahren an die Möglichkeit gedacht, aus den Sonnenfleckenbeobachtungen ein terrestrisches Phänomen zu berechnen?"[3] ("Who would have thought just a few years ago, about the possibility of

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computing a terrestrial phenomenon from observations of sunspots?")

Those early discoveries initiated multimessenger exploration of the quiet Sun. In addition to individual photons, leptons, and cosmic rays, we also receive organized plasma structures, such as the solar wind and various current systems in Earth's ionosphere, each of which transmits its own messages. The information they've delivered has allowed us to learn a great deal about the magnetic history of the Sun, including the behavior of the still poorly understood 22-year Hale cycle of global polarity changes in alternate 11-year sunspot cycles.

Other kinds of messengers debuted in conjunction with the first recognized solar flare.[4] As shown in the figure, magnetometers on 1 September 1859 recorded a short, sharp jump in Earth's field—a "geomagnetic crochet"—as solar x rays triggered enhanced currents in the ionosphere. Fourteen hours after those messages were received, there arrived a physical object now known as a coronal mass ejection (CME), well recognizable in the direct geomagnetic record (accomplished without electronics!). Rather appropriately, the CME announced itself directly in the telegraph system, not in Morse code but by actually setting instruments on fire! That type of messenger could never reach us from the distant cosmos; it is intrinsically local in the heliosphere.

A third new messenger in the 1859 flare was an interplanetary shock wave, analogous to those seen around supernovae, that preceded the CME and produced a distinct geomagnetic signature as it compressed Earth's magnetosphere. A fourth messenger produced by flare and CME disturbances was recognized only in 1942: Forbush's solar energetic particles.

As our knowledge of physics grew stronger over recent decades, the list of solar messengers expanded. It now includes neutrinos from the solar core; the solar gravity field, revealed in the precession of Mercury's perihelion, with implications for general relativity; and possibly axions. The axion messenger as yet is only hypothetical; many research programs are searching the possible parameter space, and its discovery would have far-reaching consequences in many fields of physics and astrophysics. For solar physics, the axion messenger would provide unique information not only about the solar interior but also about how the solar magnetic field penetrates the Sun's photosphere and eventually extends beyond Earth. Such information might help to explain the modulation at Earth of the cosmic-ray flux, which has been reconstructed[5] across the 9000 years of the Holocene epoch from yet another messenger: deposits of the cosmogenic radioisotopes carbon-14 and beryllium-10.

Also on the messenger list for flare and CME events are energetic neutral atoms and free neutrons. Because of the neutron's finite half-life, only those with sufficiently high energies will reach us. For the same reason, neutron messengers from any source outside the solar system cannot be detected.

Including the basic photons, neutrinos, and cosmic rays, we can count about a dozen distinct messengers from the Sun. We are highly unlikely to detect solar gravitational waves because of the minuscule masses involved, but then again, many physicists also doubted that LIGO would ever succeed!

References

1. B. P. Abbott et al., *Astrophys. J.* **851**, L35 (2017).
2. S. E. Forbush, *Phys. Rev.* **70,** 771 (1946).
3. R. Wolf, *Astron. Mitteil. Eidgenössischen Sternw. Zürich* **9**, 207 (1859), p. 217.
4. R. C. Carrington, *Mon. Not. R. Astron. Soc.* **20**, 13 (1859).
5. C. J. Wu et al., *Astron. Astrophys.* **615**, A93 (2018).

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LETTERS

The inventor of puffed rice

As I read the July 2018 issue of PHYSICS TODAY, the Quick Study "Engineering puffed rice" by Tushar Gulati, Mayuri Ukidwe, and Ashim Datta (page 66) immediately caught my attention.

During the last 15 years of my career, I had the opportunity and privilege to teach physical science to students at the Tower View Alternative High School here in Red Wing, Minnesota. The school is housed on the campus of the Anderson Center for the Arts, the legacy of Alexander Pierce Anderson (1862–1943).

Anderson invented a process to make puffed rice. The invention led to a successful exhibit and demonstration of the process and the product at the 1904 World's Fair in St Louis, Missouri. The Quaker Oats Company eventually used Anderson's process to manufacture puffed rice for public consumption.

The Anderson Center staff always encourage teachers, students, and school personnel to utilize the center and to interact with visiting artists and writers as part of their daily experience. Anderson's inventiveness and spirit carry on today in the lives of those who are part of this vibrant family.

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How to keep a scientist's mind

In his article "Who owns a scientist's mind?" (PHYSICS TODAY, July 2018, page 42), Douglas O'Reagan lays out all the concerns and fears of the competitive business leaders and scientists regarding the "ownership"—and loss thereof—of knowledge that resides in and travels with human beings. One might think of knowledge management as just another engineering problem, the solution to which is creating an environment for the knowledge bearers that provides meaningfulness to them. That is to say, a truly happy person may want to remain in the place that gives one's life meaning rather than run off for greener pastures. Greed at the top seems the bigger problem to solve.

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Douglas O'Reagan's article "Who owns a scientist's mind?" (PHYSICS TODAY, July 2018, page 42) ought to make us grateful that at the times of their momentous discoveries, both Sadi Carnot and Lise Meitner were effectively unemployed.

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