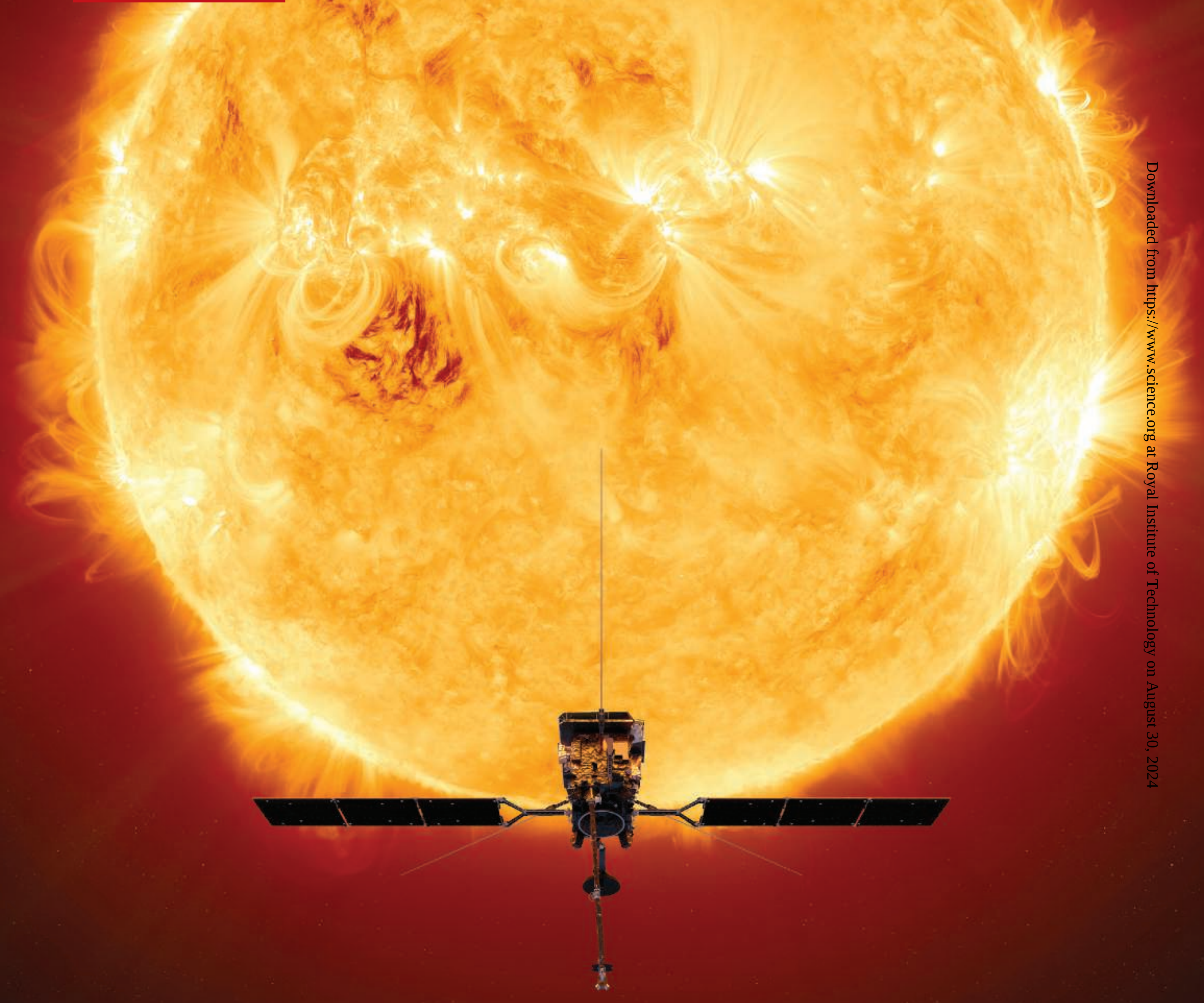
INSIGHTS

PERSPECTIVES



HELIOPHYSICS

Interplanetary rendezvous at a solar wind stream

A rare alignment of two spacecraft near the Sun captures energetics in the heliosphere

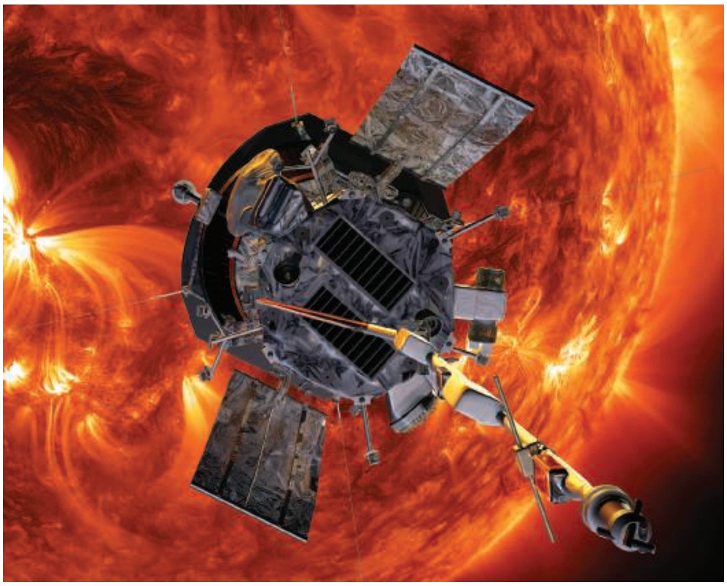
By **Luca Sorriso-Valvo**[1,2] *and* **Francesco Malara**[3]

The outermost layer of the Sun's atmosphere—the corona—releases plasma, a continuous stream of charged particles that constitutes the solar wind. This stream travels past the planets into interstellar space and fills up a region called the heliosphere. Capturing the energetics of the solar wind can provide information regarding the origin, evolution, and habitability of stellar systems (*1*). Spacecraft, including the Parker Solar Probe and the Solar Orbiter, were launched to study the inner part of the heliosphere that is close to the Sun. On page 962 of this issue, Rivera *et al.* (*2*) report on the energetics of the solar wind based on measurements from the two spacecraft while they were radially aligned near the Sun and observing the same solar wind stream. The results support the importance of Alfvén waves—a common type of plasma wave originating in the solar corona—and suggest other potential factors that drive heating and acceleration of the solar wind.

Satellites provide in situ measurements of interplanetary plasma and magnetic fields across the heliosphere. These measurements have shown that the temperature and velocity of the solar wind do not match predictions made on the basis of the adiabatic expansion model, which assumes no heat is exchanged or produced within the solar wind nor is traded with the interstellar medium (*3*). This mismatch indicates that the solar wind must be further heated as it expands away from the corona. As in any physical system, energy can change its form but must remain conserved. For the solar wind, large-scale mechanical and magnetic energies from the corona can convert to thermal energy. However, the complexity of these energy conversion processes makes understanding the solar wind energetics a difficult task.

One of the primary challenges in deciphering the solar wind energetics is the lack of knowledge regarding how and how much of the solar wind is heated, accelerated, and perturbed as it expands away from the corona in the heliosphere. Thermal pressure–driven expansion of the solar wind coexists with a broad spectrum of plasma waves and fluctuations driven by the chaotic motion of the Sun's photosphere—the outer shell from which light radiates—and magnetic fields near the Sun (*4*). Thus, solar activities at the corona coincide with the expansion to affect the dynamics of the solar wind. At the base of the corona, fast, explosive reconfiguration of magnetic fields, called magnetic reconnection, produces intense plasma heating and acceleration like that in solar flares that may inject energy to the solar wind (*5*). Fluid instabilities of plasmas can add energy to the large-scale structure of the solar wind, which is generated by the inhomogeneity of the corona. Additionally, sudden reversals of the radial magnetic field at the corona, called switchbacks, may also contribute to adding more energy to the solar wind (*6*). Moving away from the corona, the spherical expansion of the solar wind associated with the quasi-dipolar magnetic field may introduce additional sources of energy—for example, through plasma wave reflection and magnetic field shearing (*7*). All of these processes contribute to depositing energy into the solar wind at large scales. However, in situ measurements have shown that the injected energy is damped as it moves away from the Sun (*3*). Hence, where does the large-scale energy go as the solar wind expands?

The European Space Agency's Solar Orbiter measures the solar wind parameters.



NASA's Parker Solar Probe flies close to the corona and collects measurements.

Turbulence breaks the large-scale energy of the fluctuations down to microscopic scales by producing a cascade of vortices in normal fluids such as air or water. This enables friction to convert kinetic energy into heat. Turbulence is also ubiquitous in space plasmas, where it controls the cross-scale energy transfer in the solar wind. However, this transfer is complicated by magnetic fields, spherical expansion geometry of the solar wind, and coexistence with transient solar events such as coronal mass ejections, which generates anisotropic, inhomogeneous, and nonstationary effects (*8*). Moreover, although energy dissipation in normal fluids is described by viscosity and resistivity, the solar wind is nearly collision-less. Thus, the interactions between electromagnetic fields and the charged particles may dictate its microscopic dynamics instead (*9*). However, how the large-scale injected energy is eventually converted into heat is not completely understood.

Clearly, how energy transforms as the solar wind travels away from the Sun is a multifaceted, complex problem. Unsteady and inhomogeneous solar activities affect different steps of the energy transfer in the solar wind, from injection and cross-scale transfer by turbulence to microscale dissipation into heat (*10*). Single-point satellite measurements can hardly disentangle the effects from a multitude of variabilities during the solar wind expansion. Statistical analysis of a collection of single-point measurements can only roughly estimate the amount of the solar wind energy processed by turbulence. Although these estimates were compatible with the energy required to heat the plasma to the observed temperature (*11*), modeling the heliosphere without adequate understanding of its energetics is a challenging task and reflects, for example, the inadequate performance of some space weather prediction models (*12*).

Rivera *et al.* tackle this issue by using joint observations from NASA's Parker Solar Probe and the European Space Agency's Solar Orbiter when they were radially aligned. This rare occurrence allowed for sampling the same parcel of the solar wind at different distances as it expands from the Sun. These measurements at two conjunction points mitigated extreme variabilities in the measurements caused by solar activities and captured the sole expansion process. The authors quantified the different energy contributions in the expanding

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IMAGES: (LEFT TO RIGHT) ESA; PARKER SOLAR PROBE/NASA solar wind and show that in the fast solar wind, magnetic switchbacks and similar large-scale plasma waves provide a substantial fraction of the energy necessary for the turbulence and kinetic processes to produce the observed solar wind heating. The results support the solar wind energy models that include plasma wave and turbulence heating and highlight the importance of multipoint space observations.

Although the rendezvous of two spacecraft has been rare in the past, there is an exceptional fleet of spacecraft currently deployed in the inner and outer heliosphere, including Parker Solar Probe, Solar Orbiter, BepiColombo, Stereo, and Wind. In the future, there will be an increased chance of alignments of two or more spacecraft (*13*). Collaborative efforts within the international community are growing. For example, projects involving multinational teams on coronal mass ejections (*14*) and on the modeling of the turbulent fluctuations in the solar wind (*15*) are underway.

The ability to study the heliosphere in situ from multiple vantage points will be key to understand how it functions. Moreover, it is likely that stellar systems comparable to that of the Sun behave similarly. Hence, remote observations of stars' parameters might be sufficient to predict the conditions of their environments that could affect the habitability of any planets orbiting them. Other astrophysical objects such as supernova remnants, protostellar disks, galactic jets, and intracluster clouds may also share dynamics similar to that of the solar wind. For this reason, experimental heliosphere research is relevant to most fields of plasma astrophysics. ■

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CELL BIOLOGY

Micronuclear collapse mechanisms in cancer

Oxidative damage triggers micronuclear membrane rupture and defective repair

By **Marianna Maddaluno**[1,2] and **Carmine Settembre**[1,2]

Errors in chromosome segregation during cell division (mitosis) can lead to chromosomal instability, a hallmark of human cancer. These mitotic errors give rise to the formation of micronuclei—small cytoplasmic structures that are spatially separated from the primary nucleus and contain lagging chromosomes or chromosome fragments. Unlike the primary nucleus of a cell, micronuclei frequently undergo irreparable rupture and collapse. This breakdown releases micronuclear DNA into the cytosol, causing DNA damage, chromosomal rearrangements, and genomic instability, thereby contributing to cancer progression. The rupture of micronuclei also activates a component of the innate immune system called the cyclic guanosine monophosphate–adenosine monophosphate synthase (cGAS)–stimulator of interferon genes (STING) pathway, leading to tumor-related inflammation and metastasis (*1*). On pages 951 and 952 of this issue, Di Bona *et al.* (*2*) and Martin *et al.* (*3*), respectively, report the molecular underpinnings of micronuclear collapse.

Cells have evolved very efficient mechanisms to repair nuclear membranes. One mechanism involves activation of the barrier-to-autointegration factor (BAF) protein, which upon nuclear rupture, recruits the endoplasmic reticulum (ER) membrane at the rupture site to repair the damage. In addition, BAF interacts with the nuclear envelope proteins LEMD2 (LEM domain–containing protein 2) and emerin, which facilitate the recruitment of CHMP7 (charged multivesicular body protein 7)—a subunit of the endosomal sorting complex required for transport (ESCRT)–III complex—to the rupture site (*4*).

The ESCRT complex is a group of proteins that plays a crucial role in several important cellular processes that require membrane remodeling, including sorting membrane proteins for degradation, aiding in cell division, repairing the plasma membrane from damage, and repairing the nuclear envelope (*5*). It consists of four main subcomplexes—ESCRT-0, ESCRT-I, ESCRT-II, and ESCRT-III—along with associated accessory proteins. CHMP7 is a scaffolding protein that promotes ESCRT-III complex assembly at the nuclear envelope to seal the membrane (*6*).

> **"…these studies add important insights into the reported role of p62 in tumor progression."**

In micronuclei, however, the BAF and ESCRT-III nuclear repair mechanisms are ineffective. BAF is enriched at micronuclear envelope fracture sites but fails to seal the membrane for unclear reasons. Notably, CHMP7 and other ESCRT-III components present at ruptured micronuclei also do not participate in normal repair processes; rather, their unrestrained accumulation contributes to micronuclear collapse (*7*).

Martin *et al.* and Di Bona *et al.* show that mechanisms that compromise micronuclear envelope integrity and disrupt normal activity of the ESCRT-III nuclear membrane repair complex coexist, and both contribute to catastrophic membrane collapse (see the figure). Moreover, both mechanisms are triggered by reactive oxygen species (ROS) produced by mitochondria located proximal to micronuclei. Di Bona *et al.* used proteomic analysis and genetic manipulations to demonstrate that increased amounts of ROS inhibit normal micronuclear export, leading to excessive accumulation of the CHMP7 scaffolding protein inside the micronuclear membrane. In addition, ROS-induced oxidation of CHMP7 triggers its oligomerization and abnormal binding to the nuclear membrane protein LEMD2, which causes deformation and rupture of the micronuclear membrane.

Martin *et al.* compared the protein composition of micronuclei and primary nuclei

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