SOLAR PHYSICS

Solar flares add up

Solar flares are the most energetic events in our Solar System, but relatively little is known about their contribution to the total energy the Earth receives from the Sun. The detection of a moderate solar flare in the total solar irradiance suggests their impact on the variability of the Sun's output could be larger than expected.

Hugh S. Hudson

Some of the energy output of the Sun, and indeed of many stars, is diverted by intense stellar magnetic fields. This diverted energy drives many different astrophysical phenomena, including heating the corona and chromosphere of the Sun, the solar wind, and the generation of solar flares. But although solar flares represent the most extreme component of this energy, the exact amount of their contribution is difficult to characterize, owing to the Sun's unusually bright and constantly fluctuating photosphere[1], and the general lack of ultraviolet spectroscopic data. It has been argued[2] that flare-like energy release dominates the heating component of the diverted luminosity, but that the significance of the smallest flares (the so-called nanoflares) is obscured in the noise of the Sun's turbulent atmosphere. Even though these faintest flares have not been detected individually, their cumulative contribution to the total solar luminosity could be significant. In stars that are more active than our Sun, the fraction of diverted luminosity can be much larger, and the individual flares can be much more energetic. But so far, only one solar flare event has ever been detected directly through 'sun-as-a-star' observations[3] (that is, by means of bolometric changes of the total brightness), and even then at a level only just above the noise. Now, writing in *Nature Physics*[4], Kretzschmar and colleagues describe a statistical analysis of bolometric irradiance data that enables them to quantify the energy of weaker flares and improve our observational understanding of what typical fraction of the solar luminosity is diverted to such events.

The frequency with which solar flares occur roughly follows the 10.7-year solar cycle, but their energy distribution remains relatively stable throughout. This distribution is described by the power law, $dN/dW \sim W^{-\alpha}$, where W is either the flare energy or an observable proxy for it. Here N is the number of flares, and α is a dimensionless constant. This power law is analogous to the Gutenberg–Richter law for earthquake occurrence[6] and holds over several decades. But if the total flare energy is not to diverge to infinity, this law must fail at some point[7]. It turns out that the magnitude of α is definitely smaller than 2.0, which means that the value of the total flaring energy is dominated by the energies of the largest flare events.

The infrequency of the most powerful flares means that the limit to the distribution is difficult to identify over timescales comparable to the solar cycle. Nonetheless, something closely related to an upper flare energy limit can be seen indirectly, through solar energetic particles, for which the acceleration is known to be correlated with solar flares. The particles produce radionuclides, such as ^{14}C obtained from tree rings[8] and other fossil radioactivity in the lunar regolith[9], as well as NO_3 events found in the Greenland ice caps[10]. These data provide a proxy for solar flare activity by estimating the integrated solar particle fluences over million-year timescales. The distribution inferred from these proxies (Fig. 1) exhibits a distinct downward break in particle fluences that corresponds to flares about as energetic as the most powerful ones ever observed by other means. This fall-off suggests that the total integrated solar flare contribution does indeed converge, and its value as a fraction of solar luminosity can be estimated at $\sim 10^{-7}$ — somewhat less than the energy in the solar wind or in coronal radiation. These estimates are difficult because of the inherent variability, and because in the superposed-epoch analysis of such a power-law distribution, the background noise does not average down as rapidly as for the white-noise case.

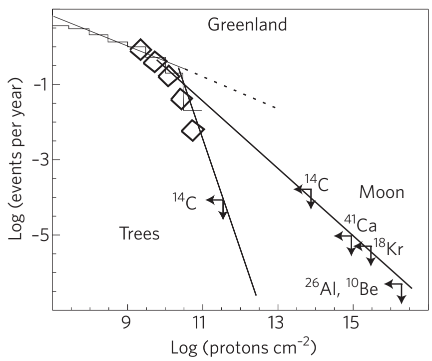

Figure 1 | Integrated distributions of fluences of solar energetic particles (>10 MeV) directly observed (histogram at upper left), and determined from various proxies: radioactive nuclides in tree rings[8] and on the Moon[9], and NO_3 events observed in Greenland ice cores[10].

Kretzschmar *et al.*[4] explore the lower energy end of the solar flare distribution, using superposed-epoch analysis to detect fainter solar flares bolometrically. In this technique one co-adds time series relative to a set of key times determined from an independent data set; ideally the relative background noise will decrease as more events are added. The new results suggest the total radiated energy is proportional to the standard soft-X-ray signature of a flare. The solar X-ray standard is the Geostationary Operational Environmental Satellite (GOES) 1-8A flux that corresponds to the main coronal flare emissions in the 10 MK–30 MK temperature range. We can therefore make a statistically sound estimate of the total flare energy as a fraction of the Sun's luminosity through scaling from the GOES energy fluxes, and it turns out to be about an order of magnitude larger than we had expected. It should be mentioned, however, that there is room for the authors' technique to be improved and applied to other databases. For example, unwanted correlated noise is clearly still evident in their data, as noted elsewhere[5], reducing the apparent statistical significance of their finding.

The Kretzschmar analysis also provides some interesting insights into the timing of flare energy. The superposed-epoch analysis of total irradiance points to the impulsive phase of the flare for the bulk of the flare's energy. This is the flare phase responsible for particle acceleration, hard X-rays, gamma rays, the white-light flare, and the acceleration of coronal mass ejections that may impact the Earth. Most of the extensive phenomenology of solar flares thus derives from this impulsive phase, which despite its name may extend for tens of minutes in some important events. The impulsive phase is always characterized by the powerful acceleration of energetic particles, both at the Sun and further out in the heliosphere, as a result of the formation of a global shock wave. These aspects of solar activity are the ones that can have damaging effects on satellites, communications and power systems on Earth. ❐

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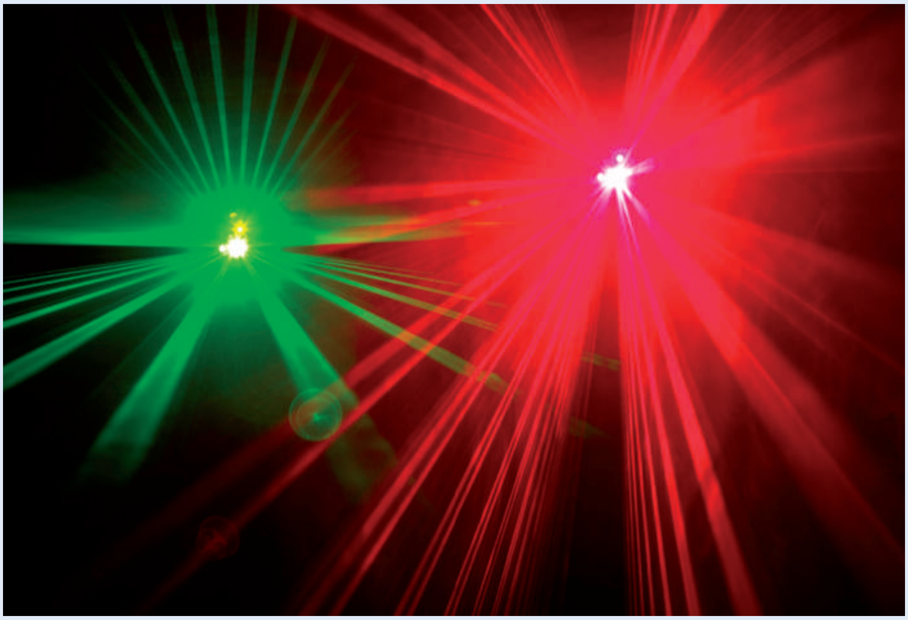
LASER PHYSICS

Lasing at the limit



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The peak intensity that conventional solid-state lasers can achieve is limited by the dielectric strength of their lasing media. However, the invention of chirped-pulse amplification (CPA) means that this limit can be exceeded by many orders of magnitude. CPA works by using a diffraction grating to split a seed pulse into an arbitrary number of components, which are then amplified individually and recombined to produce a much more intense pulse in free space. Pulsed-laser powers can exceed a petawatt, and could soon reach up to an exawatt.

CPA is limited only by the ability to build bigger diffraction gratings to split and then recombine a pulse in sufficiently small chunks to avoid damaging any of the lasers' optical components during amplification. This suggests that we might eventually be able to generate laser intensities at the so-called Schwinger limit, where the dielectric response of the vacuum itself becomes strongly nonlinear and a host of exotic quantum phenomena are expected to emerge. But according to a new analysis carried out by Alexander Fedotov and co-workers — who include Gerard Mourou, co-inventor of CPA — this limit may occur at much lower laser intensity than had previously been thought (*Phys. Rev. Lett.* **105,** 080402; 2010).

At the Schwinger limit — named after theoretical physicist Julian Schwinger — the electric field is strong enough to split electron–positron pairs that are spontaneously created by quantum fluctuations of the vacuum. The conversion of virtual electrons and positrons into real electrons and positrons saps energy from the field, making it difficult to increase the field much further. The limit is expected to be reached at a critical laser intensity of about 10^{29} W cm^{-2}.

But it has been suggested recently that collisional effects arising at the focal point of one or more laser beams could lead to pair production at intensities two orders of magnitude lower than the Schwinger limit (*Phys. Rev. Lett.* **104,** 220404; 2010). Fedotov *et al.* build on this suggestion to consider what happens immediately after a pair is created.

They point out that electrons and positrons are not only created by the laser field but rapidly accelerated to extreme relativistic velocities by it. Their inevitable collision with photons in the field results in the emission of gamma particles of sufficient energy to decay into further electron–positron pairs and other exotic high-energy particles. This leads to a quantum electrodynamic cascade similar to the avalanche processes that limit the laser intensities supported by conventional dielectrics.

The authors' calculations suggest that such breakdown of the vacuum could become a problem at focused laser intensities of around 10^{26} W cm^{-2} — well below the Schwinger limit, and just a few orders of magnitude greater than the intensities expected to be attained by several laser facilities that are currently under construction.

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