SOLAR PHYSICS

Swirls in the corona

Observations made by NASA's Solar Dynamics Observatory have been used to identify signatures of a conduit through which energy could be transported from the surface of the Sun into its corona. SEE LETTER P.505

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The Sun's outer atmosphere is called the corona (Fig. 1). It can be observed by eye during solar eclipses, when the Moon blocks the bright disk of the Sun, as a wispy halo of gas. One of the most surprising properties of the corona is that it is hundreds of times hotter than the surface of the Sun. To understand how this can be so, we must discover the source of the energy that heats the corona, how that energy is transported into the corona and how it is dissipated. For example, do waves of energy surge away from the surface and travel along magnetic-field lines to the corona? Or do these field lines behave more like elastic bands, becoming twisted and tangled by surface flows, then snapping and reconnecting? On page 505 of this issue, Wedemeyer-Böhm *et al.*[1] present results that may shed light on this puzzle.

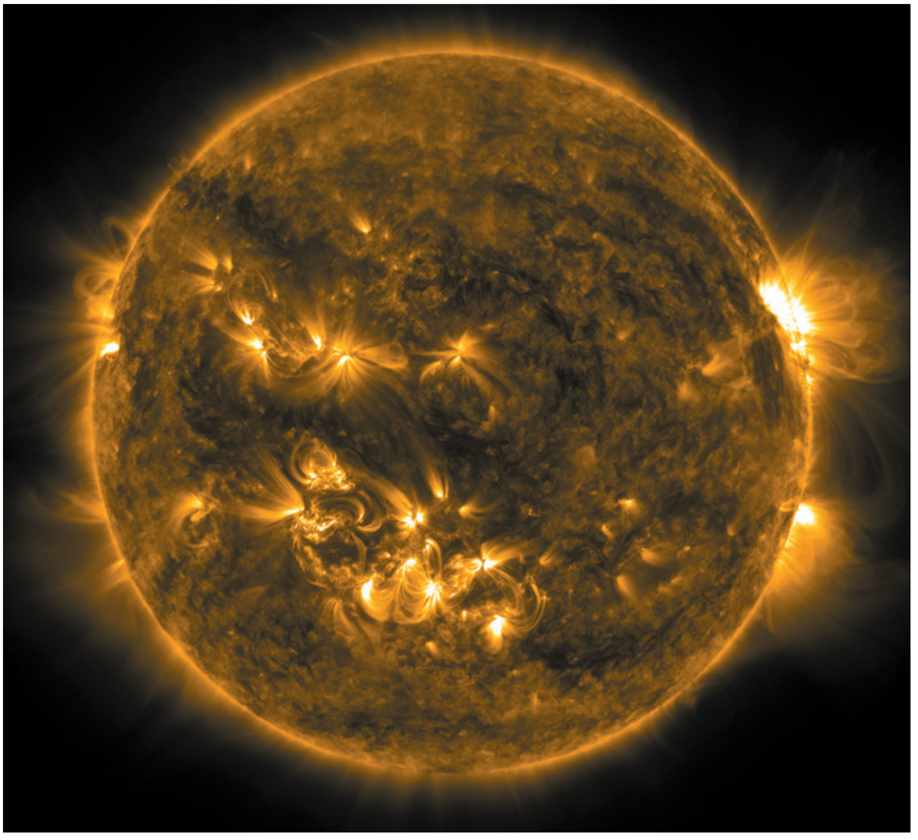
The high temperatures associated with the Sun's corona have made explaining its existence one of the most long-standing problems in astrophysics. In 1869, William Harkness and Charles Young, while independently making observations of the corona during an eclipse, discovered a spectral emission line at 530.3 nanometres in the green part of the visible spectrum, and yet no known chemical emitted a spectral line at this wavelength. The mystery of this line's provenance persisted for 70 years before the combined efforts of Walter Grotrian and Bengt Edlén identified a highly charged state of iron (Fe^{13+}) as responsible (see, for example, ref. 2).

Their discovery provoked a further question. An iron atom in the corona can be stripped of 13 electrons when each one is knocked out of its bound orbit by colliding with a free electron. The energy needed by the free electron to release the thirteenth bound electron corresponds[3] to a gas temperature of 2 million kelvin. The surface temperature of the Sun is a 'mere' 5,800 kelvin. How could the corona be more than 300 times hotter than this? It is a measure of the difficulty of this question that its answer has eluded scientists for longer than the 70 years that it took to solve the original problem.

One challenge has been to detect visible signatures of the transport of mass and energy to the corona that can be unambiguously linked to the mechanisms that have been proposed to create and sustain it. Wedemeyer-Böhm and colleagues' results may offer one such signature. The authors have analysed observations made by the Atmospheric Imaging Assembly[4] on board NASA's space-based Solar Dynamics Observatory, and have detected vortex-like flows, or 'swirls', of coronal gas at temperatures of around 1 million kelvin. It is known that vortex flows of gas at the Sun's surface arise through thermal convection in the layer below. By identifying a coronal counterpart to these swirls, Wedemeyer-Böhm *et al.* have found evidence that the surface and coronal vortices are connected.

Visually, the entire structure resembles a super-tornado. The connection between these swirling layers is provided by the Sun's magnetic field. The field lines pass through the surface of the Sun, where they are forced to follow the swirling motions of the gas, and extend into the corona. The tension in the field lines transmits the swirling motions from the surface into the corona, where the gas is forced to follow the field; swirling gas at the surface then gives some of its energy to drive swirling gas in the corona. The field lines are not perfectly vertical, and the vortex flow gives rise to a centrifugal force that accelerates gas along the field lines, so that it follows a spiral trajectory up into the corona.

In summary, Wedemeyer-Böhm *et al.* have observed connected swirls of gas, at temperatures from a few thousand to more than



SDO/NASA

Figure 1 | The halo effect. Wedemeyer-Böhm *et al.*[1] have discovered swirling motions of gas in the solar corona, which is seen here in an image taken by the Atmospheric Imaging Assembly instrument on board NASA's Solar Dynamics Observatory. These motions of coronal gas seem to be connected to swirling gas at the Sun's surface.

1 million kelvin, that are signatures of mass and energy transport from the surface of the Sun into the corona. The authors have calculated that the swirling motions can transport sufficient energy to satisfy the heating requirements of the corona, and they have connected them with a known energy source — the convective motions of the Sun's interior, which are in turn driven by the heat generated in nuclear reactions at the core.

Wedemeyer-Böhm and colleagues' findings apply to the quiet (non-flaring) Sun. But it is less clear what role the authors' proposed energy-transport mechanism has in sunspots (areas of intense magnetic activity that are cooler, and hence darker, than the typical surface temperature of the Sun), and in the active regions overlying sunspots. In these regions, the energy requirements for heating are greater and the magnetic field is strong enough to inhibit the convection associated with the surface swirling motions. In addition, it is not known how the transported energy can be dissipated as heat in the corona. The authors have identified 14 super-tornadoes, from which they estimate that a total of slightly more than 10,000 are continuously present in the quiet Sun — although more observed cases would be necessary for greater confidence in this number. Nonetheless, the great potential of these results for contributing towards a resolution of the coronal heating problem will encourage the pursuit of related investigations. ■

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3. Dere, K. P. *et al. Astron. Astrophys.* **498,** 915–929 (2009).
4. Lemen, J. R. *et al. Solar Phys.* **275,** 17–40 (2012).