1. Bordenstein, S. R., O'Hara, F. P. & Werren, J. H. *Nature* **409,** 707–710 (2001).
2. Werren, J. H., Windsor, D. & Gao, L. *Proc. R. Soc. Lond. B* **262,** 197–204 (1995).
3. Jeyaprakash, A. & Hoy, M. A. *Insect Mol. Biol.* **9,** 393–405 (2000).
4. Wade, M. J., Chang, N. W. & McNaughton, M. *Heredity* **75,** 453–459 (1995).
5. Shoemaker, D. D., Katju, V. & Jaenike, J. *Evolution* **53,** 1157–1164 (1999).
6. Hurst, G. D. D. & Schilthuizen, M. *Heredity* **80,** 2–8 (1998).
7. Thompson, J. N. *Biol. J. Linn. Soc.* **32,** 385–393 (1987).
8. Futuyma, D. J. *Evolutionary Biology* 541 (Sinauer, Sunderland, MA, 1998).
9. Reiseberg, L. H. *Annu. Rev. Ecol. Syst.* **28,** 359–389 (1997).
10. Wu, C. I. & Palopoli, M. F. *Annu. Rev. Genet.* **28,** 283–308 (1994).
11. Clancy D. J. & Hoffmann, A. A. *Am. Nat.* **149,** 975–988 (1997).

Astronomy

The day the solar wind nearly died

Mike Lockwood

On 11 May 1999, the density of the solar wind dropped almost to zero. Space scientists are now giving their first reports of this rare opportunity to study the complex relationship between the Sun and Earth.

The study of space is generally passive, as the input factors to an environment cannot be adjusted in a controlled manner to study one isolated mechanism, as they can in a laboratory. Instead scientists have to monitor all the inputs and try to disentangle the various effects that are taking place simultaneously. For instance, the Sun emits a continuous stream of ionized gas (containing mostly protons and electrons) called the solar wind, which varies in concentration, flux, speed, temperature and composition. All of these factors affect the magnetosphere — the cavity formed by the Earth's magnetic field in the solar wind — and separating their various effects is difficult. This is why rare events such as the one centred around 11 May 1999 are so valuable. In this period, the solar wind remained completely normal except that its density plummeted to 5% of typical values. The first studies from this period are now published in a special issue of *Geophysical Research Letters*[1].

When the density dropped, many aspects of the magnetosphere's behaviour were as scientists had predicted, which was a satisfying triumph for current theories. But the event also had some puzzling characteristics. Some of these are apparent in the data presented in these initial papers, although not all are commented on. Others aspects are so intriguing that further study is required.

Earth's magnetic field is confined to the low-density, high-field magnetosphere by the dynamic pressure of the solar wind on the side of the Earth facing the Sun, and by thermal pressure on the long tail that trails away from the Sun (Fig. 1). Both these pressures depend on the concentration of the solar wind, so the magnetosphere grew to exceptionally large dimensions (100 times its typical volume) as the solar wind decayed. Another feature was the appearance of highly energetic flows of electrons parallel to the direction of the magnetic field in the vicinity of Earth. These so-called 'strahl' electrons (red arrows in Fig. 1) are continuously emitted by the Sun but their flow is usually disrupted by the solar wind, making their fluxes

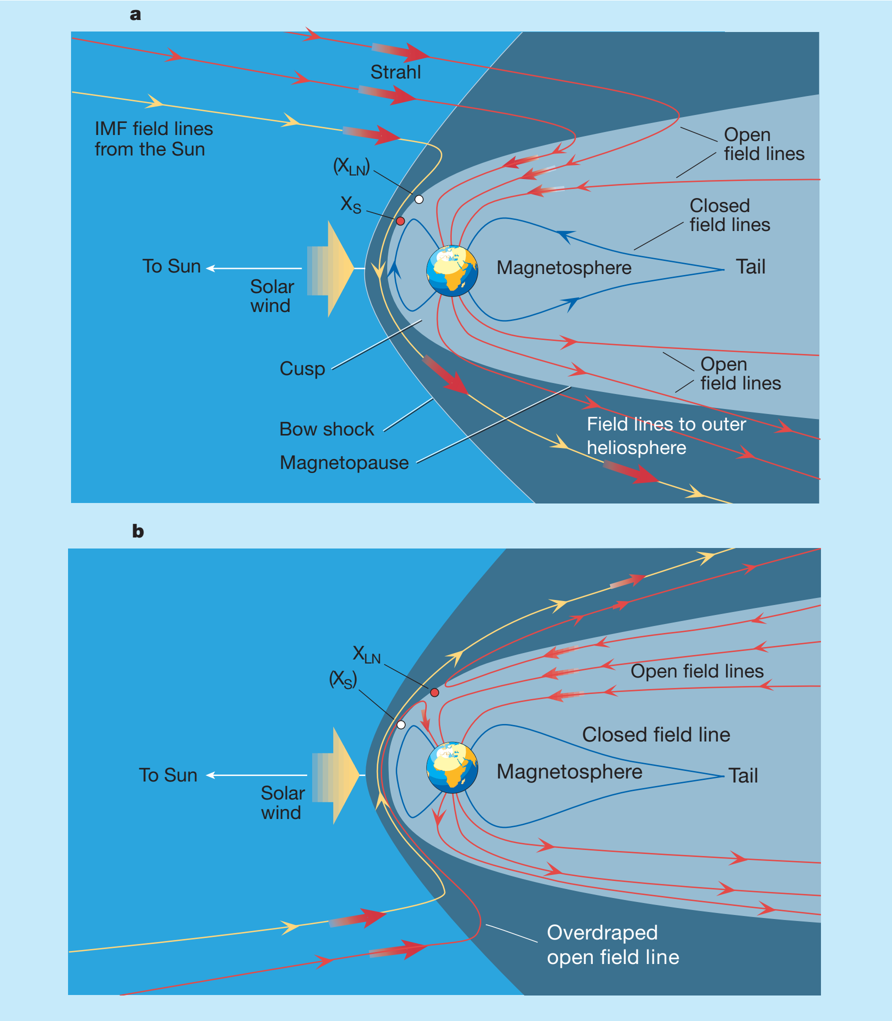

Figure 1 **Earth's magnetosphere and the solar wind.** a and b **show two possible ways in which the interplanetary magnetic field (IMF) can interconnect with Earth's magnetospheric field.** a, **New open field lines (red lines) are produced at a reconnection site X_S and solar wind energy is directly deposited in the inner magnetosphere and upper atmosphere, as well as being stored in the tail of the magnetosphere because open field lines accumulate there.** b, **Field lines that are already open are reconfigured by reconnection at X_{LN}, in this example in the Northern Hemisphere. In this instance, solar-wind energy is not added to the tail because no new open flux is produced. Closed field lines are shown in blue; unconnected IMF lines are yellow; strahl electrons are represented by red arrows. The magnetopause is the boundary between the magnetosphere and the solar wind, and the bow shock is the edge where the supersonic solar wind abruptly drops in velocity. The solar wind behind the bow shock (dark blue) is denser than the incoming solar wind (medium blue), whereas the magnetosphere (grey) is the least dense of the three regions. A study of Earth's magnetosphere during a period of exceptionally low solar-wind flux promises to explain the complex interplay between these two situations**[1]**.**

weak near Earth. One surprise in this event was how brightly the Earth's northern polar cap emitted X-rays in response to the strong strahl precipitation[2].

Because the flow of strahl electrons was so strong, the event provided a uniquely clear demonstration of 'magnetic reconnection' between the Earth's field and the interplanetary magnetic field (IMF; yellow lines in Fig. 1) — the part of the Sun's magnetic field that is carried by the solar wind. Magnetic reconnection occurs when oppositely directed magnetic fields come together and form a new configuration that results in particle energization. Reconnection produces 'open' magnetic field lines that directly connect the magnetosphere with interplanetary space. (In contrast, a 'closed' magnetic field line never crosses the magnetosphere's boundary, the magnetopause; Fig. 1.) Because the IMF was pointing away from the Sun during this event, open field lines in the Northern Hemisphere were connected directly to the Sun, whereas those in the southern polar cap were connected to the outer heliosphere — a region of space around the Sun that stretches well beyond Pluto (Fig. 1a). As a result, strahl electrons from the Sun flooded directly into the northern polar cap, but not into the south. This was an outstanding re-verification of an early prediction of reconnection theory[3].

Closer examination of where the strahl electrons were seen revealed some surprises. Because they enter the magnetosphere by flowing along field lines, the strahl in the northern polar cap shows which of Earth's field lines are open. Satellites flying over the polar caps saw pairs of field-aligned currents that, at first sight, appeared to be the normal response to magnetospheric reconnection with the IMF. However, we would expect these to be on closed field lines and, although this was true for the currents near dawn in both hemispheres, near dusk in the Northern Hemisphere they were on open field lines. This can be explained by an extreme rotation of the low-altitude signatures of the reconnection site X_S (see Fig. 1a) from noon to dusk[4]. This is consistent with the solar-wind proton precipitation seen at dusk. Small shifts of this 'cusp' in local time had been predicted, but the magnitude of the shift in this case was a surprise, and may have arisen because the magnetic field in the outer regions of the enlarged magnetosphere was weak.

The field-aligned currents at dusk were found to be strong in the Northern Hemisphere, but entirely absent from the south[4]. It seems that this asymmetry cannot be due to the lack of sunlight in the winter (southern) polar cap because the dawn currents were not similarly suppressed. The IMF orientation observed, with components away from the Sun and northward, favours the Northern Hemisphere for a second type of reconnection at a higher-latitude site such as X_{LN} in Fig. 1b (ref. 5). There is no signature of this in the southern polar cap, which offers an alternative explanation of the hemispheric asymmetry. The surprise is that both types of reconnection appear to have taken place simultaneously for an extended period[6,7]. This may have been possible because the reconnection at X_S that generates the new open flux was shifted to the dusk flank, whereas the reconnection of already open flux at X_{LN} may have taken place nearer noon.

Comparison of the two models proposed in Fig. 1 may be reminiscent of a spot-the-difference competition; however, understanding how the relative importance of these two types of reconnection varies has practical implications. For example, spacecraft can be destroyed by energetic electrons produced in the inner magnetosphere using the energy extracted from the solar wind and stored in the magnetic field of the magnetospheric tail. This stored energy drops when the tail expands because of reduced thermal pressure of the solar wind. Only reconnection that generates new open flux (as in Fig. 1a but not in Fig. 1b) increases the stored energy, and during this event the harmful electrons decayed away to very low fluxes and took longer than expected to recover to normal values.

The rarity of such solar-wind events, and the solar conditions that give rise to them, are discussed in the other papers in the special issue. The papers published so far have some promising proposals, but they add up to neither a coherent nor a comprehensive picture of the day the solar wind almost died. But they do suggest that this event may well help to answer unresolved questions about solar–terrestrial relations. ■

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1. Tenuous solar wind. *Geophys. Res. Lett.* **27,** 3761–3792 (2000).
2. Farrugia, C. J. *et al. Geophys. Res. Lett.* **27,** 3773–3776 (2000).
3. Fairfield, D. & Scudder, J. A. *J. Geophys. Res.* **90,** 4055–4067 (1985).
4. Ohtani, S., Newell, P. T. & Takhashi, K. *Geophys. Res. Lett.* **27,** 3777–3780 (2000).
5. Lockwood, M. & Moen, J. *Ann. Geophys.* **17,** 996–1011 (1999).
6. Papitashvili, V. O. *et al. Geophys. Res. Lett.* **27,** 3785–3788 (2000).
7. Rostoker, G. *Geophys. Res. Lett.* **27,** 3789–3792 (2000).

Developmental biology

A macho way to make muscles

Olivier Pourquié

The 'mosaic' theory of development applies, to different degrees, to most animals. It owes its existence in part to a group of obscure marine invertebrates, which now take centre stage in the molecular age.

The development of many animal species — from insects to vertebrates — relies in part on material deposited in specific places in the egg by the mother. The first evidence for such localized 'maternal determinants' was provided in 1905 from classical studies[1] of muscle development in ascidians, a group of marine invertebrates. But the molecular identity of the muscle determinant remained elusive. On page 724 of this issue[2], Nishida and Sawada describe a likely candidate — a messenger RNA molecule that they call macho-1. Ascidians are back in the limelight, with a good chance of staying there.

During the seventeenth century, the popular 'preformationist' theory suggested that development consists simply of the growth of tiny but fully formed embryos contained in the sperm or egg. Preformationism did not survive the invention of microscopy in the eighteenth century and subsequent observations of developing embryos. But a more sophisticated version of the theory — the concept of mosaic development — was proposed in the nineteenth century[3] and is still around today. According to this theory, the egg contains, not a fully formed embryo, but rather a mosaic pattern of determinants that control the development of the particular embryonic cells that inherit them.

This concept, too, took a battering, in the late nineteenth century from experiments in which the cells (called 'blastomeres' at this early stage of development) of a four-cell sea-urchin embryo were separated from one another[4]. In contrast to the predictions of the mosaic theory, these separated cells developed into four larvae, instead of four partial embryos. So, like the fertilized egg, early embryonic cells exhibit 'totipotency' — the ability to give rise to all the different cells that make up an organism. Around the same time, however, similar studies showed that ascidian embryos behave as predicted by the mosaic theory: separation of ascidian blastomeres led to the development of just the embryonic parts normally fated to be formed by those cells[5]. Soon afterwards, evidence for localized maternal determinants in ascidians was provided[1].

Ascidians are marine invertebrate chordates. They develop as a tadpole with a body plan similar to that of vertebrates — a noto-