ALEX WILD/VISUALS UNLIMITED, INC./SPL

Figure 1 | Fire ants and queen. Wang and colleagues' genetic analysis[1] of the fire ant *Solenopsis invicta* has revealed a pair of 'social chromosomes' containing a non-recombining region that is expected to encode many of the behavioural traits that define these ants' social structures. The similarity between these chromosomes and sex chromosomes may help our understanding of how Y chromosomes evolve.

the X, halting recombination between them means that the Y stops recombining entirely, although recombination continues between pairs of X chromosomes in females. This causes all sorts of problems for the Y chromosome, such as gene-function decay and the accumulation of repetitive DNA.

However, even though sex chromosomes have been objects of scientific obsession for decades, we do not really understand how recombination between X and Y chromosomes is suppressed. There are theories, of course, the most accepted of which suggests that Y-chromosome inversions, in which a region is flipped end-to-end, are selected for when they encompass both the male sex-determining gene and a nearby gene with male-specific benefits[7]. Such beneficial changes ensure that these genes are transmitted as a single unit — a 'male' supergene — from father to son, as inversions cannot pair correctly during meiosis and therefore recombination is halted in the inverted region between the Y and X. Over time, a series of inversions could theoretically encompass the entire Y chromosome.

There is circumstantial evidence to support this model, namely, in the existence of 'strata' within sex chromosomes that seem to correspond to specific inversion events[8]. However, it has proved exceedingly difficult to identify alleles with sex-specific benefits and, without this, it is almost impossible to find direct evidence for the inversion theory of sex-chromosome evolution.

Enter the fire ants. It was previously recognized that their monogyne and polygyne social forms corresponded to their allele status at the *Gp-9* locus. But these social forms come with an assemblage of morphological and life-history differences, so it is probable that other genes are involved. This begs the question of how alleles at multiple genes can be transmitted as a single unit along with *Gp-9*. Wang and colleagues show that this is accomplished through at least one massive inversion on the chromosome that encompasses the *Gp-9* locus as well as most of the other genes that show expression differences between the social forms. This inversion has, in effect, created a pair of social chromosomes. The inversion prevents recombination between the *B* and *b* forms of the social chromosome, in much the same way as we think inversions might prevent recombination between X and Y chromosomes. It also allows for the transmission of a supergene that encodes the polygyne social structure, directly analogous to the male supergene on the Y chromosome.

The fact that *bb* ants do not survive long enough to reproduce means that the *b* social chromosome is always paired with the *B* chromosome, much like sex chromosomes. And, again just as in the X and Y chromosomes, when recombination is halted between the *B* and *b* chromosomes, the *b* chromosome stops recombining altogether within the inversion. Interestingly, the *b* chromosome exhibits several characteristics also observed on Y chromosomes, including the accumulation of repetitive elements and gene-function decay. So it seems that ant behaviour has a lot to tell us about sex-chromosome evolution after all. ■

Judith E. Mank *is in the Department of Genetics, Evolution and Environment, University College London, London WC1E 6BT, UK.*
e-mail: judith.mank@ucl.ac.uk

1. Wang, J. *et al. Nature* **493,** 664–668 (2013).
2. Ascunce, M. S. *et al. Science* **331,** 1066–1068 (2011).
3. Krieger, M. J. B. & Ross, K. G. *Science* **295,** 328–332 (2002).
4. Gotzek, D. & Ross, K. G. *Q. Rev. Biol.* **82,** 201–226 (2007).
5. Keller, L. & Ross, K. G. *Nature* **394,** 573–575 (1998).
6. Burt, A. & Trivers, R. *Genes in Conflict: The Biology of Selfish Genetic Elements* (Harvard Univ. Press, 2006).
7. Charlesworth, D., Charlesworth, B. & Marais, G. *Heredity* **95,** 118–128 (2005).
8. Lahn, B. T. & Page, D. C. *Science* **286,** 964–967 (1999).

SOLAR PHYSICS

The planetary hypothesis revived

The Sun's magnetic activity varies cyclically over a period of about 11 years. An analysis of a new, temporally extended proxy record of this activity hints at a possible planetary influence on the amplitude of the cycle.

PAUL CHARBONNEAU

Right to the end of his life, the Swiss astronomer Rudolf Wolf (1816–93) sought to establish a causal link between the 11-year cycle of the number of dark patches on the Sun (sunspots) and planetary motions. Through his relentless historical detective work, he reconstructed the time series of sunspot number all the way back to the seventeenth century. Taken quite seriously and quantitatively elaborated upon until the end of the nineteenth century, the idea rapidly fell into disfavour following George Ellery Hale's discovery of the magnetic nature of sunspots[1]. Since then, the origin of the sunspot cycle, or solar magnetic cycle, has been sought in the Sun's interior, where the flow of magnetized fluid can lead to self-sustained dynamo action. Rediscovered periodically ever since (pun intended), nowadays the 'planetary hypothesis' for the solar cycle is

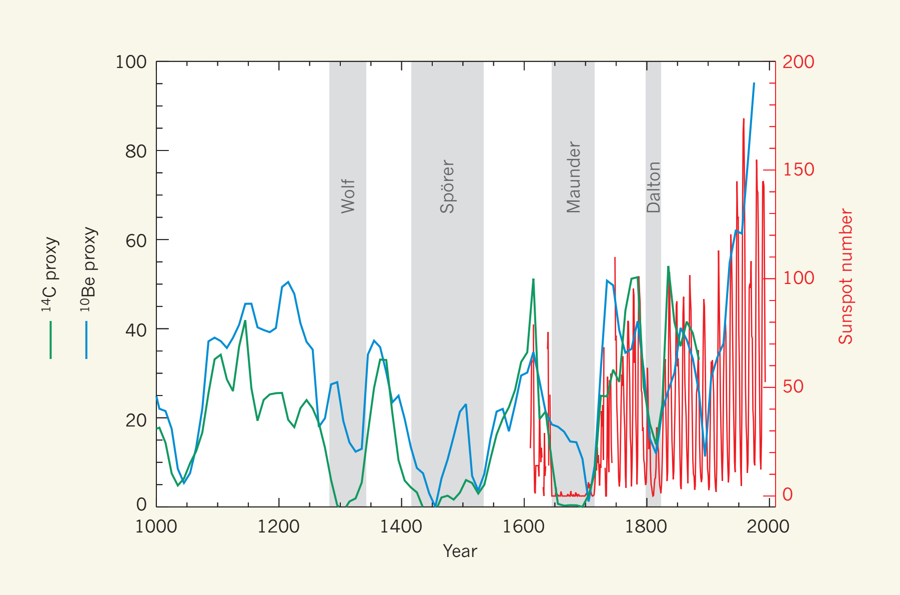

Figure 1 | The sunspot cycle. The graph shows the 11-year cyclical variation in the number of sunspots[11] and two proxy equivalents that are based on the production rate of the radioactive isotopes carbon-14 (^{14}C) and beryllium-10 (^{10}Be). The proxy data, which are averaged over periods of 10 years[12], quite closely follow the secular variation in the sunspot number during the 1600–2000 time interval. The shaded bands show the four intervals of suppressed sunspot activity (known as the Wolf, Spörer, Maunder and Dalton minima) that have occurred in the past millennium. Working with a much longer timespan than that shown here, Abreu *et al.*[2] find that amplitude variations in the sunspot cycle on long timescales exhibit periodicities essentially identical to those that characterize the angular-momentum vector of planetary orbital motions in the Solar System.

usually branded as astrology and summarily dismissed. But writing in *Astronomy & Astrophysics*, Abreu *et al.*[2] once again revive this hypothesis.

Abreu and colleagues do not question the idea that the magnetic cycle is powered by a hydromagnetic dynamo operating autonomously in the Sun's interior. In fact, they require such an internal dynamo process to provide the basic cycle. But they suggest that its operation is perturbed by the gravitational torque of orbiting planets of the Solar System. In this way, they seek to explain the many well-known centennial-scale quasiperiodicities in solar activity (Fig. 1). Now, generally speaking, such long-timescale modulation can also be produced by conventional dynamo models subjected to stochastic forcing[3], and stochastic perturbations certainly abound in the turbulent solar interior. So why bring planets into the picture at all?

If you propose an unorthodox explanation for a phenomenon already explained by orthodoxy, then the burden of proof is on you. You must do at least as well as orthodoxy at explaining what is already understood, and (it is hoped) succeed in explaining something that the orthodox line cannot. Raising the bar even higher, your novel explanation should be testable in some way within the context of orthodoxy. This adds up to a pretty tall order, but Abreu and colleagues' study meets all three of these requirements.

The authors' data are rock solid and their analysis techniques straightforward and entirely conventional. Working with a 9,400-year-long, high-quality time series for a well-known solar-activity proxy[4], namely, the production rate of the radioactive isotope beryllium-10 (^{10}Be) as determined from ice cores[5], they show that the proxy's time series exhibits many of the same long periodicities as those characterizing the temporal variations of the angular-momentum vector associated with planetary orbital motions. The match is almost perfect for five of the six most prominent periodicities longer than 50 years in the solar-activity record. No purely dynamo-based explanation that I am aware of yields anything remotely close to such an outstanding fit. By using a numerical method known as Monte Carlo simulation, Abreu *et al.* estimate the probability of coincidence for these long periodicities to be less than 1 in 10^6, although this is probably an underestimate, given the properties of the random signals used to test for coincidence between the time series of the ^{10}Be proxy and that of the planetary angular momentum.

Statistical considerations notwithstanding, for such an external torque to have any effect on the solar interior, it must act on an aspherical mass distribution. To explain this, Abreu *et al.* point to the base of the solar convection zone — the Sun's outer shell — where helioseismology studies have detected hints of asphericity[6]. They suggest that the planetary torque acting on the mildly aspherical mass distribution at this depth in the solar interior drives small structural changes that very slightly alter the magnetic-field strength threshold above which buoyant rise sets in and sunspots can form. This could then lead to a large modulation in the rate of sunspot emergence and of the interplanetary magnetic-field strength, in turn modulating the flux of cosmic rays reaching Earth's orbit, and thus the production rate of ^{10}Be.

So, small changes in the Sun's internal structure cause proportionally much larger changes in the amplitude of the solar magnetic cycle — have we now degenerated into astrological homeopathy? Not necessarily. The buoyant destabilization of sunspot-forming magnetic-field concentrations is definitely subjected to thresholds[7], and these are even incorporated in many extant dynamo models of the solar cycle[8–10]. In principle, it should then be a simple matter to carry out dynamo simulations that include a small multi-periodic variation in these thresholds, to assess whether they yield amplitude modulations of the solar magnetic cycle commensurate with those observed in sunspot and proxy data, such as those shown in Figure 1.

This is all pretty far-fetched, but the potential importance of Abreu and colleagues' proposal cannot be overstated. Should it be vindicated, a solid basis for long-term forecasting (and backcasting) of solar activity could then exist. This could greatly benefit current attempts to quantify the past and future long-term influence of solar activity on Earth's space environment, atmosphere and climate.

To sum up, what we have here is a fit to observations unmatched by any other extant explanatory framework, buttressed by a conjectural explanatory physical scenario that is testable at least at some level. It may all turn out to be wrong in the end, but this is definitely not astrology. This is science. ■

Paul Charbonneau *is in the Department of Physics, University of Montreal, Montreal, Quebec H3C3J7, Canada.*
e-mail: paulchar@astro.umontreal.ca

1. Charbonneau, P. *J. Hist. Astron.* **33,** 351–372 (2002).
2. Abreu, J. A., Beer, J., Ferriz-Mas, A., McCracken, K. G. & Steinhilber, F. *Astron. Astrophys.* **548,** A88 (2012).
3. Charbonneau, P. *Living Rev. Solar Phys.* **7,** 3 (2010).
4. Usoskin, I. G. *Living Rev. Solar Phys.* **5,** 3 (2008).
5. Steinhilber, F. *et al. Proc. Natl Acad. Sci. USA* **109,** 5967–5971 (2012).
6. Antia, H. M. & Basu, S. *Astrophys. J.* **735,** L45 (2011).
7. Fan, Y. *Living Rev. Solar Phys.* **6,** 4 (2009).
8. Ossendrijver, M. A. J. H. *Astron. Astrophys.* **359,** 364–372 (2000).
9. Nandy, D. & Choudhuri, A. R. *Astrophys. J.* **551,** 576–585 (2001).
10. Charbonneau, P., St-Jean, C. & Zacharias, P. *Astrophys. J.* **619,** 613–622 (2005).
11. Hoyt, D. V. & Schatten, K. H. *Solar Phys.* **179,** 189–219 (1998).
12. Usoskin, I. G., Solanki, S. K. & Kovaltsov, G. A. *Astron. Astrophys.* **471,** 301–309 (2007).