The Butterfly and the Sun

The adage **natura non facit saltus** (Nature does not make jumps) appears repeatedly in the text of Charles Darwin's *Origin of Species*. He uses it to support the notion that the evolution of organs, entire organisms and instincts is gradual and continuous, and, by implication, that the record appears patchy simply because it is incomplete. The maxim was previously used by Carl Linnaeus in his *Philosophia Botanica* of 1751 to underpin the notion that all taxa have relations on every side and that there are no gaps in the botanical panorama. Alfred Marshall later made it the motto of his *Principles of Economics.* The fact that it was in Latin may account for the respect accorded to such a sweeping claim.

At all events you might think that the slogan could hardly survive after 1900, the year when Planck proposed that energy is composed of packets or quanta and when Mendel's work on particulate inheritance was validated. But at least since the days of Aristotle humanity has been familiar with a natural phenomenon characterised by dramatic jumps: metamorphosis, the sequence of distinct episodes by which an insect egg produces a caterpillar, which eventually turns into a pupa, which in due course becomes a butterfly. Darwin interpreted metamorphosis as the development of different body forms of a single organism in response to changing selective pressures; modern workers appear to be more interested in the processes at issue. Advances in genetics, biochemistry and microscopy highlight the role of hormones in triggering or halting the changes in tissue and cell differentiation that are genetically programmed but if anything they highlight the jumps (Ryan 2011).

There are many unsolved problems which could perhaps profit from explanations that are boldly discontinuous. The case study outlined here comes from solar physics. The corona's elevated temperature – 1-2 million K compared with a mere 4400 K at the photosphere – has been known for the best part of a century (Edlén 1942; Miyamoto 1943). The explanatory models currently most in favour invoke heating primarily by waves or by solar flares, and although they recognise such features as the Transition Region, where temperature jumps from 10^4 K to 10^6 K (Sakurai 2017), and may identify magnetic structures (Ruderman 2006), they implicitly view the solar atmosphere as a physical unit.

A recent study (Vita-Finzi 2021) suggests that the threefold structure of the solar atmosphere – namely chromosphere, transition region and corona – is the outcome of differential heating rather than its cause. Ohmic heating raises the temperature of the chromosphere to about 30,000 K. The transitional region, as noted earlier, then swiftly attains a temperature of a million K, and that of the corona perhaps one of 2 million K. There are parallels with insect metamorphosis in that three successive steps, which depend on distinct processes, are triggered and sometimes delayed by a local control mechanism.

The pink chromosphere, briefly glimpsed during eclipses, owes its hue to the ionisation of hydrogen to H alpha. The energy needed for this transformation is due to induction (or ohmic) heating generated by rotating magnetic fields beneath the photosphere. These fields arise from spinning columns whose summits can be seen making up the network on imagery of the solar surface, a pattern made familiar on the Web by the Swedish telescope on La Palma and more recently transmitted by the Inouye telescope in Hawaii.

Why the chromosphere should be confined to the relatively shallow zone of the Sun's atmosphere finds an explanation in research on nuclear fusion and in particular a version that exploits tokamaks, one of a class of experimental reactors called stellarators. Tokamaks generally run on deuterium-tritium. Ohmic heating of this mix is self-limiting and can bring temperatures in the reactor up to a maximum of about 20 million K. On the Sun 4.5 aeons of nuclear fusion saw hydrogen changed into helium, and the mass balance released as energy. For the resulting hydrogen

+ helium mix the maximum temperature attained by Ohmic heating is about 20,000 K, a limit set mainly set by the loss of power to radiation.

The loss is compensated by a remarkable decrease in cooling efficiency by six orders of magnitude, that is 1,000,000 x, which characterises the plasma at high temperatures. The corollary is uninhibited heating by the prevailing source. There is some debate about the source. One possibility is the inverse of a mechanism discovered in 1852 by James Joule and William Thomson (later Lord Kelvin) which is widely exploited in refrigeration, where a gas cools on expanding. The three gases which are exceptions to the J/T mechanism include hydrogen and helium, the major constituents of the solar plasma, and under lab conditions they heat up rather than cool on expanding. An alternative, perhaps complementary, mechanism for dramatic heating of the TR is extreme ultraviolet (EUV) radiation, which was detected at the top of the chromosphere from Skylab, the earliest manned US space station, in 1973-4. By whichever route, temperatures in this part of the solar atmosphere shoot up to 250,000 K.

We now encounter yet another source of heating: that due to expansion of a plasma into the almost perfect vacuum of space, bringing temperatures to 1-2 million K. It was the combination of hot, rarefied gases and good heat conduction hereabouts that led Eugene Parker, against much opposition, to postulate the existence of a supersonic solar wind blowing spacewards at the coronal margins.

In short, the onset of the distinctive temperature range of the three major subdivisions of the solar atmosphere is triggered by the preceding unit. But, unlike the butterfly, our product is constantly being assembled, a trotskyite (constant revolution) version of metamorphosis or perhaps better a kavkaesque vision of Gaia.

Acknowledgment

I thank Tim Oleson for his comments on an early draft of this note

References cited

Edlén B (1942) Die Deutung der Emissionslinien im Spektrum der Sonnenkorona. Z. Astrophys. 22, 30–64

Miyamoto S (1949) Ionization theory of solar corona. Publ. Astron. Soc. Jpn.1, 10–13.

Parker E N (1958) Dynamics of the interplanetary gas and magnetic fields. Astrophys J 128: 664-676

Ruderman MS (2006) Nonlinear waves in the solar atmosphere. Phil Trans Roy Soc Lond A364:485-504

Ryan F (2011) The mystery of metamorphosis. Chelsea Green, White River Junction, VT

Sakurai T (2017) Heating mechanisms of the solar corona. Proc Jpn Acad Ser B Phys Biol Sci 93: 87-97

Samir U et al (1983) The expansion of the plasma into a vacuum. Rev Geophys Space Phys 21:1631-1646

Truman JW, Riddiford LM (2019) The evolution of insect metamorphosis: a developmental and endocrine view. Phil Trans Roy Soc Lond B 374:20190070

Vita-Finzi C (2021) Core to solar wind: a stepwise model for heating the solar corona. arXiv:2101.08251[astro-ph.SR]