

Turning over a new leaf

Paul Kenrick

A model based on biophysical principles of plant physiology, and drawing on fossil and environmental data, indicates that the origin of leaves was triggered by falling levels of atmospheric CO₂.

The early evolution of plant life on land was as much a conquest of the air as a subjugation of soil and rock. Leaves were one of the first innovations, and they have been such a success that it is difficult to imagine a world without them. Yet there is an enormous gulf of time between the origin of land plants and the evolution of leaves with a substantial lamina (flat blade) — for at least the first 40 million years of their existence, land plants were leafless or had only small spine-like appendages.

On page 352 of this issue, Beerling *et al.*¹ propose a novel explanation for this long delay. They use a model based on biophysical principles worked out from living plants, involving details of water use, and heat and gas exchange, and draw on anatomical and environmental data from the fossil record. They conclude that leaves with a broad lamina evolved in response to a massive drop in atmospheric CO₂ during the Devonian period, some 410–363 million years ago.

Plants with vascular systems — that is, with water- and food-conducting systems — have leaves of two main types. The microphyll is usually a short spine-like leaf and is characteristic of clubmosses; the megaphyll is generally bigger, and has a substantial lamina and a complex pattern of veins like the leaves of ferns and flowering plants². Almost all living plants have megaphylls or their derivatives, and it is this leaf type that principally concerns Beerling *et al.*

The gap between the earliest fossil evidence of vascular plants and the advent of megaphylls is puzzling. Megaphylls are ubiquitous today, and their photosynthetic proficiency makes their evolution seem inevitable. The structural framework necessary to assemble the primitive leaf (meristem, vasculature, cuticle and epidermis) was in place by the Early Devonian, some 410 million years ago. The fossil record shows that megaphylls evolved from the photosynthetic branching systems of early vascular plants that became flattened and later webbed to produce a broad lamina in several groups by the end of the Devonian³ (Fig. 1). Furthermore, the transformation of branch to leaf does not seem to require any major innovations in body plan. In the absence of obvious structural limitations, Beerling *et al.* turn to the environment for an explanation.

Certain aspects of plant structure change in response to fluctuations in atmospheric

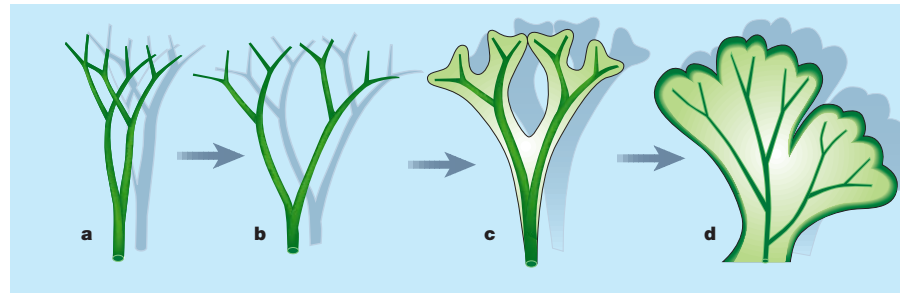


Figure 1 The advent of megaphylls — leaves with a broad lamina (flat blade), as opposed to the spine-like photosynthetic appendages of clubmosses. Fossil evidence shows that megaphylls evolved from simple, leafless photosynthetic branching systems in early land plants (a, b) to dissected (c) and laminate (d) leaves over a period of at least 40 million years. From Beerling and colleagues' biophysical model¹, which simulates gas exchange rates and energy budgets, it seems that these transformations were governed by falling concentrations of atmospheric CO₂ during the Devonian period, some 410–363 million years ago. In the high-CO₂ atmosphere that prevailed during the early phases of plant life on land, leaves with a broad lamina (c, d) and a low density of stomata would have been prone to overheating. Hence the absence of leaves with substantial blades during this time. Only with falling CO₂ in the atmosphere could megaphylls make their appearance, with their photosynthetic efficiency coming into its own.

gases, particularly CO₂. The density of stomata — the microscopic epidermal pores that regulate gas exchange and water transport — is one such variable⁴. Plants in a high-CO₂ environment need fewer stomata to supply their photosynthetic needs. But reduced stomatal density comes at a price: fewer stomata means that, at high light intensities, leaves with a broad lamina are more likely to suffer heat stress because less heat is lost through evaporation.

One response by plants to heat stress is to alter leaf shape, specifically the amount of dissection — the degree to which the margin of the leaf is lobed. Highly dissected leaves have deep, finger-like lobing and a greater cooling capacity than leaves with an unlobed blade. So, other things being equal, stomatal density decreases and leaf dissection increases with increasing levels of CO₂ (ref. 5). These variable traits can be seen in fossils, providing us with a kind of palaeontological barometer. Beerling *et al.* turn this approach on its head by using atmospheric CO₂ concentration to explain the development of megaphylls from photosynthetic branching systems, which are the functional equivalent of highly dissected leaves.

The evolution of megaphylls coincides with a drop of around 90% in atmospheric CO₂ concentration⁶. Working backwards, Beerling *et al.* use computer models to simulate gas exchange rates and energy budgets to

assess the likely costs and benefits of evolving leaves with a broad lamina under the high-CO₂ conditions that prevailed during the early phases of life on land. The model shows that a hypothetical megaphyll would overheat in such an atmosphere, reaching lethal temperature at low latitude and near-lethal temperature at high latitude. Furthermore, the rates of photosynthesis in branching systems exceed those of modelled high-latitude leaves, so having megaphylls at this early stage would not have been advantageous. In short, megaphylls would have made life too hot for the earliest plants.

The results of modelling systems that are so remote from the modern world have to be treated with scepticism. How can one be confident in a result for which so many parameters have to be estimated? This is a genuine concern, but Beerling and colleagues' calculations are based on independent biochemical, palaeobotanical and geochemical evidence, and seem reasonable. Enzyme kinetics can be estimated from living species; remarkable details of stem anatomy and stomatal distribution can be seen in the fossil record⁷; and the broad outline of atmospheric evolution in the Palaeozoic, although not written in stone, has withstood some independent tests⁸.

So there are good reasons to take Beerling and colleagues' proposal seriously. But it does require further scrutiny. For example, leaves

with a broad lamina would be expected to develop first at high latitudes, because here plants intercept less solar energy and are less likely to overheat. And one would expect high stomatal densities in early megaphylls because this would contribute to leaf cooling. Also, if fossils with megaphylls were found that dated to before around 386 million years ago, this would undermine the correlation between decreasing CO₂ and leaf lamination. Fossils with apparent leaf-like structures (protomegaphylls), such as *Eophyllophyton bellum* from 390-million-year-old deposits in China⁹, are of interest in this context.

Finally, if Beerling *et al.* are right, and leaf evolution was driven by a large fall in atmospheric CO₂, what then drove that fall in CO₂? Remarkably, the answer appears to be plants. The evolution of a land flora, and in particular the advent of large plants, had a major impact on the carbon cycle by drawing CO₂ out of the atmosphere and locking it up in trunks and leaves. Perhaps even more signifi-

cant, though, was the evolution of roots. The physical and chemical effects of root systems on rocks and soils increase rates of weathering, which is thought to have been responsible for removing enormous quantities of CO₂ from the Devonian atmosphere¹⁰. So roots may have played a key role in the evolution of leaves by way of the carbon cycle. ■

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1. Beerling, D. J., Osborne, C. P. & Chaloner, W. G. *Nature* **410**, 352–354 (2001).
2. Stewart, W. N. & Rothwell, G. W. *Paleobotany and the Evolution of Plants* (Cambridge Univ. Press, 1993).
3. Kenrick, P. & Crane, P. R. *Nature* **389**, 33–39 (1997).
4. McElwain, J. C. & Chaloner, W. G. *Ann. Bot.* **76**, 389–395 (1995).
5. McElwain, J. C., Beerling, D. J. & Woodward, F. I. *Science* **285**, 1386–1390 (1999).
6. Berner, R. A. *Am. J. Sci.* **294**, 56–91 (1994).
7. Edwards, D. *Phil. Trans. R. Soc. Lond. B* **353**, 141–157 (1998).
8. Mora, C. I., Driese, S. G. & Colarusso, L. A. *Science* **271**, 1105–1107 (1996).
9. Hao, S.-G. & Beck, C. B. *Palaeontographica B* **230**, 27–41 (1993).
10. Berner, R. A. *Phil. Trans. R. Soc. Lond. B* **353**, 75–82 (1998).

Astronomy

Brown dwarf is a radio star

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Brown dwarfs are sometimes referred to as failed stars because they emit extremely little radiation. Astronomers have now found a brown dwarf that ‘whistles’ strongly at radio wavelengths.

Brown dwarfs are hard to find. They are small, cool objects, somewhere in size between the smallest stars and largest planets, and give off a dim, reddish optical glow. Their existence was confirmed only five years ago¹. Perhaps they would have been spotted earlier if they all emitted strong radio waves like brown dwarf LP944-20, described on page 338 of this issue by Berger and colleagues². This nearby brown dwarf (some 15 light years away) appears to be emitting a constant background of radio waves at a wavelength of 3.6 cm. These occasionally flare up for a few hours, growing in strength by more than an order of magnitude.

This is the first time that radio emission has been recorded from a bona fide brown dwarf. These objects are too small to burn hydrogen so they do not shine like regular stars, but they differ from giant planets because they can fuse deuterium in their centres. A brown dwarf has to be at least 12 times the mass of Jupiter to be able to burn some deuterium. This can only happen when it is young, in the first 10 million years or so. But at the ripe old age of 500 million years, LP944-20 is far beyond that stage and has no such heat source in its centre. So what might be producing its unusually strong radio emission?

Some of the smallest and coolest stars, like rapidly rotating type M and K stars, are known to be strong radio emitters at a

wavelength of 3.6 cm. A gaseous planet like Jupiter, on the other hand, emits appreciable radio waves only at wavelengths of ten metres and longer. So as far as radio emission is concerned, LP944-20 behaves more like a star than a planet.

In 1999, an X-ray flare was detected from LP944-20 for the first time³. To date, this is the only brown dwarf from which both X-ray and radio flares have been recorded. Active cool stars have a clear linear relationship between

their background radio and X-ray emission⁴ (Fig. 1). The relationship also holds for flares over many orders of magnitude⁵, from so-called nanoflares on the Sun to stellar superflares. To understand this relationship we have to know a little bit about how both types of radiation are created.

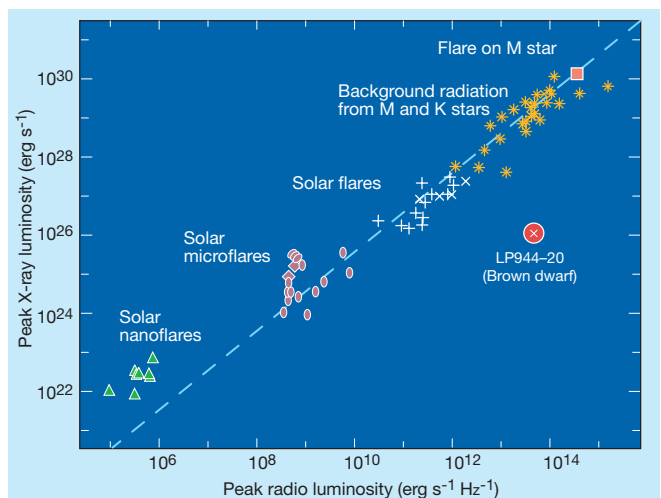
Cool stars have a surface temperature of just a few thousand degrees, but are surrounded by a much hotter atmosphere of ionized gases (plasma), known as the corona. Despite plasma temperatures reaching a few million degrees, the corona’s low density means it yields relatively little thermal radiation. Nonetheless, the corona is responsible for most of the radio and X-ray emissions from these cool stars.

The hot gases in the corona emit thermal radiation as X-rays, which reach a peak during flares. Radio waves, on the other hand, are not produced by thermal radiation but through interactions between electrons and magnetic fields in the coronal plasma. The radio waves come from synchrotron radiation, which is emitted when energetic electrons spiral in the strong magnetic fields in the corona. By following the magnetic field lines, the electrons eventually hit the cool dense layer below the corona, where they heat it up to X-ray-emitting temperatures, resulting in flares.

The conditions for electron acceleration, propagation and energy deposition appear to be quite similar for various types of stars, resulting in the general relationship seen in Fig. 1. But deviations from this expected behaviour have been reported for very young stars⁶, and for some nanoflares deep in the Sun’s corona⁷. In both cases, the radio emission was more than an order of magnitude lower than expected.

The observed radio emission of LP944-20 was more than three orders of magnitude stronger than expected, which is why it was detected. What makes this brown dwarf so different from cool stars? The observed rela-

Figure 1 Peak fluxes of X-ray and radio emissions from solar and stellar flares at centimetre wavelengths⁶. The relationship between radio and X-ray emission is consistent across a wide range of stars, from the coolest M and K types, to ordinary G stars like our Sun. The background emission from cool M and K stars that are more active than the Sun may just be the product of many small flares. Berger *et al.*¹ have



now discovered surprisingly strong radio emission from a brown dwarf, LP944-20, which is smaller than the coolest stars, so is not expected to shine brightly at any wavelength.