

Fossils make waves

James W. Kirchner and Anne Weil

A 62-million-year cycle in biodiversity emerges from scrutiny of a marine-fossil database, but its causes remain mysterious. Thus, this discovery is likely to provoke a flurry of theoretical speculation.

For decades, palaeobiologists have been finding large-scale cycles and patterns in fossil records, and one might assume that there was nothing substantial left to be discovered. Not by a country mile! On page 208 of this issue¹, Rohde and Muller demonstrate a 62-million-year cycle in fossil biodiversity during the Phanerozoic, the past 500-plus million years of life on Earth. This 62-million-year wave is surprisingly strong and — so far — there's no good explanation for it.

In some fields of science, particular data sets achieve iconic status, focusing the attention of whole communities of researchers as they try to understand the patterns they contain. For the past two decades, many palaeobiologists have been exploring the marine-fossil databases created by the late Jack Sepkoski^{2,3}. Sepkoski spent years combing through the palaeontological literature, compiling the first and last known occurrences of every animal genus in the marine-fossil record, more than 30,000 in all. He used genera because, being the taxonomic level above species, they are revised less often by palaeontologists and their numbers are more manageable. And he dealt exclusively with marine animals, because their fossil record is longer and better preserved than that of their terrestrial counterparts. Sepkoski's labours produced a detailed history of biodiversity through time, which in turn has generated a kaleidoscope of analyses⁴⁻⁹ aimed at both detecting its patterns and explaining them.

Over time, these analyses have explored increasingly subtle features of the fossil record (Box 1), but Rohde and Muller's discovery shows that there are still broad patterns left to be found. They have taken Sepkoski's fossil diversity curve — a graph of the total number of marine-fossil genera at each point in the past 542 million years — and subtracted a smooth mathematical function that accounts for the broadest trends of diversity through time. What is left is a diversity curve that rises and falls somewhat irregularly, but roughly in step with a 62-million-year cycle. Rohde and Muller use spectral analysis to show that these ups and downs oscillate much more rhythmically than one would expect by chance.

The 62-million-year wave is too big to ignore, with biodiversity growing and shrinking by several hundred genera between the peaks and the troughs. The cycle is visually obvious, and some palaeobiologists will wonder why they haven't seen it before. In fact, a similar long wave in diversity was suggested almost 30 years ago in the pages of this journal¹⁰, but only with the most recent refinements to the geological timescale can the cycle in fossil diversity be shown to be too regular to have arisen at random.

Rohde and Muller show that the 62-million-year cycle is particularly strong when one considers only short-lived genera, which

they define as those that survive less than 45 million years. This seems to make perfect sense; longer-lived genera are thought to survive longer because they are more diverse and more widespread, and thus more resistant to disturbance. But it is also almost true by definition, because it would be hard to construct a wave from components that endure for more than half the wavelength, and that would therefore bridge the peaks and troughs.

Two other aspects of Rohde and Muller's discovery may also attract sceptical attention. First, the 62-million-year cycle is largely absent from the past 150 million years, which is precisely the part of the fossil record that is most accurately known. Second, many will have nagging suspicions that the cycle is somehow a statistical fluke, because some apparent patterns in the fossil record have evaporated when subjected to statistical scrutiny. To their credit, Rohde and Muller have tested the 62-million-year cycle in several different ways, and in each case it seems to be statistically significant.

If the 62-million-year cycle is real, it demands an explanation, and the search for one will be interesting. Rohde and Muller are physicists, and they examined 14 possible geophysical and astronomical drivers for the cycle. Several of these are at best highly speculative, including a companion star to the Sun and a hypothesized large planet for which no evidence exists. But in any case, all of these

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Box 1 Explorations of the fossil record

Palaeontologists use compilations of fossil taxa (which may be species, genera, families or even larger groupings) to study not only taxon richness through time, but also extinction and evolutionary diversification, and the rates at which these processes occur. As documented by Miller¹¹, the earliest curve of Phanerozoic species richness was constructed in 1860, and ever since then palaeontologists have striven for increasingly more complete and accurate data compilations.

In 1860, statistics was in its infancy. But by 1982, when Sepkoski published his database of fossil marine families¹², he did so with every intention of applying statistical tests. The best-known finding from this work was the hotly debated 26-million-year periodicity of extinctions. Further findings characterized the taxonomic composition of Earth's oceans through time, and evolutionary patterns common to different families. Sepkoski's database of fossil marine genera³ could be

parsed more finely; studies based on it have included several spectral analyses, many estimates of speciation rates, and calculations of how such rates might be influenced by the way in which time intervals are defined in geological timescales.

Moreover, many hypothesized causes of large-scale patterns depend on processes at smaller scales, and global databases are often unsuitable for tests requiring nuanced comparisons. Workers thus use more-detailed databases, or break down the

larger ones by geographical region, by time period, by taxon (snails vs clams, for example), by ecological role (predator vs prey; specialist vs generalist), or by environment (terrestrial vs marine; deep vs shallow water). Such partitioning enables researchers to study, for instance, spatial and temporal scaling; variation in the speed, taxonomic composition and geography of recovery from mass extinctions; and patterns of morphological diversification within large groups. **J.W.K. & A.W.**

candidate driving mechanisms seem to be insufficient to cause the 62-million-year cycle.

As other disciplines enter the fray, the range of possible explanations will grow. Earth scientists and palaeontologists will point out that marine-fossil diversity depends on the diversity of marine habitats, and thus on the size and configuration of the continental shelves. They will therefore ask whether the 62-million-year cycle could potentially reflect changes in the continental margins through time, as sea level fluctuates and the continents rearrange themselves. Others will observe that this long wave in biodiversity is broadly consistent with the reported phase shift between fluctuations in the rate of extinction of existing organisms and the diversification of new ones⁷, and will search for a theory that unites these observations. Theoretical biologists will also note that global biodiversity is a tapestry that weaves itself, so the 62-million-year cycle in fossil diversity need not be generated by similar cycles in external driving factors. Instead, biodiversity could swing like a pendulum, with a rhythmic cycle that is governed by its own internal dynamics rather than by rhythmic external forcing.

But if the 62-million-year cycle is caused by a biological pendulum, it swings so slowly that it will be challenging to discern the underlying mechanisms. By any biological yardstick, 62 million years is a very long time; 62 million years ago last Tuesday, we mammals had only recently embarked on our striking morphological diversification following the mass extinction at the end of the Cretaceous. Clever modellers should have little difficulty creating biological models that exhibit very long oscillations in biodiversity. But the hard work will lie in showing that the premises behind these models are themselves accurate, or at least plausible.

It is often said that the best discoveries in science are those that raise more questions than they answer, and that is certainly the case here. Let the theorizing begin. ■

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Astronomy

Stellar mass limited

Pavel Kroupa

Is there an upper limit to the mass of a star? The answer to this long-standing question seems to be yes — and it has important consequences for our understanding of the evolution of galaxies.

Stars form from interstellar gas and synthesize elements heavier than helium in their cores. Carbon, oxygen, silicon and iron, which are crucial for the existence of planets — and for life — are produced mostly by stars that are more massive than the Sun. To understand how galaxies evolve and are enriched in these elements, we need to know exactly how massive stars can be. Using the Hubble Space Telescope, Donald Figer (page 192 of this issue)¹ has analysed the stellar content of the Arches cluster, a highly populous, nearby star cluster. He finds that there are no stars heavier than about 150 solar masses, providing direct evidence for the idea that the spectrum of stellar masses has an upper limit.

The most abundant stars in the Universe are faint and cool red dwarfs^{2,3}. These have smaller masses than that of the Sun, with a lower limit of 0.072 solar masses⁴. Below this limit, the dwarf stars weigh so little that their central densities and temperatures are insufficient to stabilize them through thermonuclear reactions — they become ‘brown dwarfs’, and cool indefinitely. Most of the stellar mass of galaxies is locked up in long-lived dwarf stars, which return hardly any of their mass back to the interstellar gas from which they were born.

Stars that are heavier than the Sun rarely weigh more than 20 solar masses — for every 1,000 dwarf stars we find just one star weighing 20 solar masses, and more massive stars are rarer still². Stellar luminosity increases rapidly with mass, and whereas dwarf stars contribute very little to the luminosity of galaxies, massive stars live expensively, radiating some 10,000 times more energy per second than the Sun. Not surprisingly, they have a short lifespan: the Sun will live for about 10,000 million years, but stars heavier than about 20 solar masses live only a few million years.

Once the central region of a massive star has exhausted its primary fuel — hydrogen — it contracts, thereby increasing its central density and temperature further so that carbon and consecutively higher elements can be synthesized. Dwarf stars of solar mass or less never reach the conditions for synthesizing significant amounts of elements as heavy as oxygen or iron.

Eventually, when the core of a massive star has become sufficiently enriched in iron, it cannot be stabilized by the fusion of higher elements, and it collapses. An object then

forms that has a high density of neutrons — a neutron star — or under more extreme conditions a black hole may form. A supernova explosion ensues as the rest of the star crashes into the core, driving a detonation shock-front outwards and tearing most of the star apart. A single explosion can inject large amounts of heavy elements back into the galaxy and thus into the cycle of stellar birth and death. Attempts to understand the details of these processes lie at the forefront of astrophysical research, but theoretical calculations cannot convincingly reproduce the observed events. They often result in a whole star disappearing from our horizon by imploding to a black hole without a supernova explosion⁵ — at least in computer simulations.

It was not clear until now whether stars as massive as 300 or even 1,000 solar masses could exist. Theoretical modelling of such stars^{6,7} is difficult because of the extreme conditions of their interiors and their highly dynamical evolution. One theory⁸ states that stars more massive than about ten solar masses cannot form because the pressure exerted by radiation is so high that it prevents any further matter accreting from its natal cloud. The existence of heavier stars was therefore explained by proposing⁸ that they form from colliding and coagulating protostars. These weigh up to ten solar masses and are found in dense, central regions of young star clusters. Other theoretical work⁹, as well as observations¹⁰, suggest that accretion from massive circumstellar disks may in fact overcome the radiation pressure exerted by protostars heavier than ten solar masses.

To determine whether there is a stellar mass maximum, astronomers need to study rich populations of young stars such as are found in interacting galaxies (Fig. 1). But these distant populations cannot be resolved into individual stars, even with today's best telescopes. The Arches cluster studied by Figer¹ seems a suitable alternative for the task, as it is only a few million years old and is relatively near. It is rich in heavy elements, but lies very close to the centre of our Galaxy, making it difficult to observe. Yet in this populous cluster, stars more massive than about 150 solar masses ought to be present in sufficient numbers to be detected. However, they are entirely absent from Figer's observations and thus he concludes that they are unable to form.

Although Figer's result is statistically