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 ones[7], 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 masses[4]. 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 still[2]. 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 explosion[5] — 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 theory[8] 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 proposing[8] 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 work[9], as well as observations[10], 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 Figer[1] 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

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Figure 1 **Clash of giants — the colliding Antennae galaxies, observed with the Hubble Space Telescope[12]. The patchwork of blue knots are star bursts, where tens of thousands of massive stars are forming. The existence of possibly hundreds of supermassive stars drives the highly violent events associated with star bursts. To fully understand such observations, we need to know the maximum possible mass of a star. This image conveys events similar to those that shaped our present-day galaxies shortly after the birth of the Universe.**

highly significant, the uncertain age of the cluster leaves some room for arguing that it could be old enough for more massive stars to have already exploded as supernovae. However, the absence of hot, expanding gas bubbles does not support this scenario. In addition, observations in the similarly young and massive R136 cluster located in a neighbouring galaxy — the heavy-element-deficient Large Magellanic Cloud — support Figer's analysis, as here also no stars more massive than about 150 solar masses were found[11].

These results suggest that the upper limit for the mass of a star may be unrelated to the heavy-element content of the star-forming gas. This could in turn imply that radiation pressure is not the physical mechanism that limits how massive stars can become. Environments that are rich in heavy elements are dusty, and radiation pressure is particularly efficient at blocking the infall of dusty gas, so we might have expected the heavy-element-poor environment of the Large Magellanic Cloud to have allowed stars with higher mass to form through accretion.

Whereas the physics of faint, low-mass stars transcending into brown dwarfs is well understood[4], there is no clear explanation for why stellar masses should be limited to near 150 solar masses. And a nagging uncertainty remains: the details of supernova mechanisms are not fully understood, and it may be that stars more massive than 150 solar masses did exist, but have already imploded to black holes in the Arches and R136 clusters, leaving little trace except a hole in space-time accompanied by a brief burst of neutrinos and gravitational waves. ■

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NATURE

100 YEARS AGO

Prof. A. H. R. Buller, writing from the University of Manitoba, describes some striking electrical effects due to the dryness of the atmosphere at Winnipeg… When the thermometer is low, ranging as it often does for a week or more at a time from 0° to −40° F., very little friction, such as, for instance, as may be produced by walking along a carpet, causes a person to become charged with sufficient electricity to produce a visible and audible spark on touching an iron bedpost, the radiator, the gas-tap, or any other conductor. It is a favourite amusement of some children to take sparks from each other's noses after running about a carpeted room… Many ladies have considerable difficulty in combing their hair; for during the process it becomes so charged with electricity that it stands out in the most astonishing manner… It is quite easy to light the gas with a spark from the finger when matches are not handy by merely shuffling a few paces over the carpet and then holding a finger to the burner.
From *Nature* 9 March 1905.

50 YEARS AGO

"Scientific Progress and Security Regulations." … Dr. Hildebrand insists that positive achievement and progress, not the negative policy of restriction and security, provide the only firm basis of security… Security-screening programmes are a means to an end, not an end in themselves. Their role in defence policy is negative rather than positive. They may deprive a potential enemy, at any rate temporarily, of information about armed forces or the development of new weapons; but they create no new weapons themselves… What has now to be recognized is that, with the essential dependence to-day of military strength upon science, the security practices used in the past to safeguard military information are no longer fully valid. Scientific knowledge cannot be kept secret by such means. Progress in science is a cumulative process in which each scientist builds upon what is known, and national boundaries and security systems cannot contain this process of extending knowledge without so discouraging the spirit of inquiry that the state of learning and of technology as well as the rate of scientific progress are adversely affected. At best, among advanced nations, security measures can provide an advantage of time: there is no such thing as a permanent scientific secret.
From *Nature* 12 March 1955.