stead, its presence has to be inferred from trace constituents with abundances at most 10^{-4} that of H_2. The most widely used tracer is CO because it is the easiest to observe, but estimating H_2 masses from CO observations is like estimating the weight of a dog from the number of hairs on its tail. To make matters worse, CO is an optically thick molecule; the strength of its radio-spectral lines is more closely related to the temperature of the gas cloud than to how many molecules are radiating.

Two significant discoveries in the mid-1970s emphasize the importance of obtaining accurate H_2 masses from the CO observations. The first is the ubiquity of CO in the plane of the Milky Way, implying that a significant fraction, perhaps most, of the interstellar gas is H_2 and not atomic hydrogen (H I), which previously had been thought to be the reservoir of the star-forming gas. The second is that essentially all present-day star formation takes place in giant molecular clouds, which have masses of about 10^5 solar mases and are composed almost entirely of H_2 (but detected by radio observations of CO). Therefore, the question of star formation on a galactic scale was reduced to the question of how giant molecular clouds form. Do they, for example, condense from the atomic gas, or do they form from the collisional accretion of small molecular clouds without the mediation of an atomic phase? Important clues were to be found in the relative amounts of H_2 and H I. (Ultimately the answers can be applied to studies of other spiral galaxies. The evolution of the disk of a galaxy is essentially its star-formation history, which in turn is largely the history of the giant molecular clouds.) The results of the first CO surveys of the galactic plane implied that between the galactic centre and the position of the Sun, which is about half-way out, the interstellar gas is overwhelmingly molecular. One study suggested it contained ten times as much H_2 as H I, which in turn implied that atomic gas is largely irrelevant to the formation of giant molecular clouds, but these conclusions were quickly challenged by several groups who argued that the molecular phases are about equal in abundance inside the solar distance. In that case, instabilities in the atomic component are likely to play an important role in the formation of the giant molecular clouds.

The different estimations have been largely the result of using different ratios to convert CO line strengths to H_2 column densities, and also to the importance of temperature and heavy-element abundance variations in the Milky Way. New light has been shed on this subject by gamma-ray astronomy. It was established in the 1970s that diffuse high-energy gamma-rays (> 50 MeV) come primarily from the interaction of cosmic rays with the interstellar gas. If the gamma-ray emissivity of the gas can be determined, the number of hydrogen nuclei in a column along a given line of sight can be obtained from measurments of the gamma-ray intensity. The contribution to this intensity from atomic hydrogen is known from 21-cm line observations; the remaining contribution must therefore be from molecular hydrogen (corrections due to helium and other trace constituents are straightforward). In principle, this approach is the most accurate way to determine the H_2 from CO, because the gammas rays directly trace the dominant component of the gas — hydrogen — independently of excitation and abundance variations in the CO.

Interpretation of the gamma-ray results has not been without its problems, however. Initially, the results from the US SAS-2 satellite and the European COS-B satellite were not in agreement — a large and difficult to determine instrumental background for COS-B seems to have been the culprit — and other technical problems with the data analysis have only recently been solved. Nevertheless, the quantity of molecular hydrogen in the Milky Way reported by the Durham group on page 511 of this issue is still half that derived by the Caravane collaboration, which launched COS-B. The groups agree, however, that the gamma-ray data unequivocally imply that the H_2 does not dominate the H I inside the solar distance.

More H_2 would simply produce more gamma rays than are observed. The work of the Durham group implies that nowhere in the Milky Way does the H_2 surface density dominate that of the H I. In the published work of the Caravane collaboration, H_2 may dominate weakly within a small range of distance from the galactic centre. The residual difference between the two groups probably results from systematic uncertainties that increase the formal erros assigned to the data by Bhat *et al.* A new sophisticated analysis by the Caravane collaboration using the most extensive available data sets is forthcoming and should shed additional light on this nagging astrophysical controversy. ☐

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100 years ago

THE way in which a bird builds its nest, seemingly without instruction, has been brought forward as a proof of blind instinct governing it in its task. A remarkable instance, however, of a changed mode of nest-building has been brought to my notice by Mr W. Burton. His brother took to New Zealand some young chaffinches. Some of the birds have built a nest, and the structure shows very little of that neatness of fabrication for which the bird is noted in England. The cup of the nest is small, loosely put together, and the walls of the structure are prolonged for about eighteen inches, and hang loosely down the side of the supporting branch. Clearly these New Zealand chaffinches were at a loss for design when fabricating their nest.

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Evolution

Interpretations of mass extinction

from Michael J. Benton

IT IS becoming clear that the history of life has been punctuated by a series of events during which, typically, an apparently random selection of organisms died out. These mass extinction events can be seen to have 're-set' the evolutionary clock: they wiped out whole families or orders of plants and animals, irrespective of the darwinian fitness of the individual organisms or of the species involved, and created opportunities for the survivors to radiate out into the 'empty' ecospace that was left. The recent suggestion that mass extinctions might be cyclical in occurrence is important because it raises the possibility of identifying one kind of explanation for all mass extinctions through time, whether or not the events have a regular periodicity and whether the ultimate causes are terrestrial or extra-terrestrial. These ideas have important implications for evolutionary biology and for historical geology.

The most important recent impetus to the discussion of the causes of mass extinctions has been the suggestion of Raup and Sepkoski[1], from their analysis of the fossil record of marine animals, of a regular periodicity of about 26 Myr to mass extinctions over the past 250 Myr. Hallam[2] has pointed out how uncertainties in dating of mass extinctions, especially before the late Cretaceous, weaken the claim of regular periodicity, but the suggestion remains a very important one and is having a considerable influence on the ways in which we may interpret a cyclical pattern of mass extinctions.

Four interpretations of the cyclicity are possible and worth considering. The first two are deterministic and the other two stochastic viewpoints: (1) each extinction event was triggered by the same external impulse, acting directly; (2) the cyclical pattern of extinction events correlates with some physical phenomenon that follows the same cycles (for example, fluctuations in temperature or sea level), and these are controlled by a third external variable; (3) the events are caused by a variety of factors that relate to the internal dynamics of the biological system; (4) the apparent cyclicity is an artefact of the patchiness of the fossil record.

The first interpretation is favoured by Raup and Sepkoski and their followers, who suggest an extraterrestrial cause for the periodic mass extinctions. Three main schools of thought have sprung up. The first is that a hypothetical companion star of the Sun (called Nemesis) disturbs the Oort cloud and sends a shower of comets hurtling towards Earth every 30 Myr[3,4]. The second is that the whole of the Solar System oscillates through the galactic plane with a semi-period of 30 Myr and periodically scatters Oort cloud comets into the terrestrial zone[5-7]. The third idea is that the unknown Planet X, located beyond the orbit of Pluto, follows an eccentric path which causes it to disturb a comet belt beyond Neptune and precipitate a shower of comets, some of which would eventually reach the Earth, every 28 Myr[8]. These astronomical theories are still highly speculative and controversial (see *News and Views* 7 March p.17).

The second interpretation, that cycles of mass extinction correlate with cycles in terrestrial phenomena, has been the generally held view for some time. Fischer suggested that the Earth has passed through cycles of different orders of magnitude[9,10], the largest of which each lasted about 300 Myr and began with rapid convection in the mantle. This led to the break-up of Pangaea-like supercontinents, elevated sea levels and marine transgressions, intense vulcanism, release of CO_2 to the atmosphere and the development of a greenhouse climate, resulting in worldwide warm conditions and warm seas. Such episodes occurred from late Cambrian to late Devonian and early Jurassic to late Eocene.

The second phase of each 300-Myr supercycle was characterized by low mantle convection, continental accretion, low sea level and regression, reduced atmospheric CO_2 and the development of an icehouse state. This gave high latitudinal climatic gradients, cold dry polar regions and cold oxygenated ocean waters. These conditions characterized the latest Precambrian to early Cambrian, the late Palaeozoic to Triassic and the latter half of the Cenozoic, in which we still live. The crossovers from greenhouse to icehouse correspond to mass extinctions in the late Cambrian (500 Myr), the late Devonian (355 Myr), the late Triassic (192 Myr) and the late Eocene (40 Myr). These crossovers are about 150-Myr apart, giving a span of 300 Myr for the full cycle. This model does not explain the terminal Permian and the terminal Cretaceous extinction events.

Fischer also described two classes of shorter-range cycles in tectonic activity and world climate[9,11], one set occuring every 30 Myr and the other consisting of smaller climatic cycles in the range 20,000–400,000 years, which are induced by orbital pertubations. The 30-Myr cycles are reflected in temperature fluctuations, variations in carbon isotope ratios and in the fossil record of planktonic and nektonic taxa.

Newell[12,13] and Hallam[14,15] have argued that sea-level changes are the most important prime cause of mass extinctions, thus laying the main emphasis on one segment of the Fischer theory. Sea-level changes have exhibited a cyclicity on several scales through the Phanerozoic and many of the well-known mass extinctions correlate well with worldwide episodes of regression. In general terms this usually coincides with a reduction in the area of diversity of continental shelf habitats, and in some cases (for example, the end-Pliensbachian, end-Cenomanian and possibly the end-Triassic, late Devonian and end-Ordovician events) with periods of oceanic anoxia, as recorded by extensive black shale deposits.

The other kind of terrestrial explanation, which modifies part of Fischer's thesis and relegates sea-level changes to a minor role, emphasizes changes in temperature. This has been championed recently by Stanley[16-18]. He notes evidence of global episodes of cooling that coincide with mass extinctions in the late Eocene and the Plio-Pleistocene and hints at evidence for temperature changes linked to earlier mass extinction events (it becomes harder to pin down temperature changes the further back in time one goes). Stanley supports this thesis with the fact that mass extinctions have frequently been concentrated in the tropics, which became a refrigerated trap into which high-altitude forms migrated and were then wiped out. He also argues that the long periods of time that characterize most mass extinctions accord more with a gradual change in temperature than with a catastrophic change brought about by an exterrestrial agent.

If, however, cyclicities in geological processes should turn out to have regular periodicities, an extraterrestrial cause will have to be considered. Has the time come with the discovery by Rampino and Stothers[19] of two dominant periodicities, of about 33 and 260 Myr, in a time-series analysis of various geological phenomena (sea-level fluctuations, sea-floor spreading discontinuities, tectonic activity, geomagnetic reversals)? These correspond to the two major orders of cyclicity identified by Fischer, Rampino and Stothers suggest they were caused by periodic comet impacts. The issue at stake is clearly the evidence for regular periodicity in geological processes, which has been questioned (see *News and Views*, 7 March p.17).

There are important philosophical consequences if we accept some or all of these aspects of regular cyclicity in mantle, plate-tectonic, eustatic, atmospheric and climatic processes and their concomitant effects on the history of life. Periodicities of these kinds would form a part of Charles Lyell's interpretation of Uniformitarianism which has generally been abandoned[20]. Lyell believed that there were constant changes on the Earth, but that these cycled endlessly and with no direction. He would not accept the idea of progressionism in the history of life, believing instead that any life form could exist at any time if the conditions were right: thus he expected to find Silurian mammals, or dinosaurs, at some future time. This anti-progressionist stance was ignored or abandoned by most other scientists during Lyell's lifetime, and the idea of uniformity of conditions has also not found favour. Now it must be reconsidered if we accept that most major processes on the Earth have followed, and continue to follow, long-term cyclical patterns.

The third interpretation of cyclical mass extinctions — that they arise from the internal dynamics of the biological system — has recently received support from Kitchell and Pena[21]. Attempting to fit different time-series models to the extinction curve of Raup and Sepkoski, they find that the best statistical fit is a stochastic time-series model that shows 'pseudocycles' every 31 Myr. This model takes account of the observed spacing and the relative magnitude of each peak of mass extinction. Kitchell and Pena conclude that each extinction event should be investigated on its merits; it may be incorrect to seek an overall controlling pattern or an ultimate cause that explains all mass extinctions.

The fourth explanation, which is that the apparent regular pattern is an artefact, has also received support. Re-analysing Raup and Sepkoski's data, Hoffman and Ghiold find that they correspond just as well to a neutral model, in which origination and extinction rates vary independently and randomly through time, as they do to the deterministic periodic model[22]. Episodes of high origination and high extinction rates usually correspond with highly fossilferous geological units. The apparent periodicity of 26 Myr in mass extinctions could be an artefact of the average length of stratigraphic stages, the basic time units used in the calculations.

We are left with all four explanations for mass extinction cycles. Arguments for and against each view will continue. But more detailed analyses of the fossil data, and refinements in dating events in the geological past, will be necessary before we can decide which view is correct. □

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