

are relatively old and metal-poor, the stars in Andromeda's halo appear to be very metal-rich⁶, as do the stars in the stream-like feature discovered by Ibata and colleagues. Astronomers use the term metal to mean any element heavier than helium, so metallicity is an indication of age because the early Universe was free of heavy elements — these were only produced later, inside stars. The authors propose that Andromeda's entire halo could have formed through the destruction of former companion galaxies, such as the current satellites M32 or NGC205 (the dwarf elliptical galaxies seen in Fig. 2).

This would explain the metal-rich nature of Andromeda's halo, but it still raises the question of why it should be so different from the Milky Way's halo, even though both are similar spiral galaxies. Perhaps the answer lies in understanding the satellite systems surrounding these galaxies. Or perhaps Andromeda and the Milky Way had different formation histories. Alternatively, what is believed to be a metal-rich halo in Andromeda could be an extended thick disk⁷, in which case the stream-like feature observed by Ibata *et al.* could be the result of M32 and NGC205 perturbing this thick disk. There is growing evidence of extreme warps in the main stellar disk of Andromeda, possibly related to the strong perturbations produced by these dwarf galaxies⁸.

To unravel the true nature of the feature described by Ibata *et al.* would require measurements of the stars' spectra to determine their motion, as well as to confirm their metallicity. Knowing how the stars are moving can tell us whether the observed structure is indeed a stream. In that case the stellar motions would also be useful for determining the current orbit of the halo material and its possible history. It remains to be seen whether models can be built to reproduce its characteristics, and in particular whether the dwarf galaxies M32 or NGC205 could be responsible for this unusual stream of material, as the authors suggest.

The sort of detailed analysis of the outer regions of nearby galaxies carried out by Ibata *et al.* complements studies of very distant galaxies. Continuing this work will require detailed images of nearby galaxy halos, as well as analysis of large samples of stars, such as those provided by the Sloan Digital Sky Survey. The analysis of this particular database is presently uncovering the rich structure of our own Galaxy⁴ to an extent unimaginable 15 years ago. In the long run, several satellite missions will accurately measure the motion of thousands to millions of stars in our Galaxy and in our nearest neighbours.

These are exciting times because we are starting to converge on a theory that describes the formation of galaxies from first principles. Observations of the early Universe, of very distant galaxies and now

of our immediate neighbourhood all appear to favour hierarchical formation. Indeed, both Andromeda and the Milky Way — the only two galaxies to be studied in great detail — have revealed a rich substructure in their halos. Today, the main unanswered question is about the nature of the unseen dark matter that keeps satellite galaxies orbiting their parent galaxies, and families of galaxies bound together in a cluster. Studies like those of Ibata *et al.* may be particularly helpful, because streams of debris can be used to map the distribution of both the luminous and the dark matter in a galaxy in unprecedented detail. Questions about the structure of that most elusive of all

galaxy components, the dark halo, may soon have answers. ■

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Biogeochemistry

The nitrogen fix

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At some time in life's history, microorganisms started to make metabolically usable nitrogen from N₂ in the atmosphere. A provocative proposal accounts for the 'why and when' of that event.

To what extent is biological evolution driven by environmental evolution? This is one of the big questions for both evolutionary biologists and geoscientists. On page 61 of this issue, Navarro-González and colleagues¹ describe their investigation into a central innovation in the evolution of life. This was the invention of biological nitrogen fixation, by which life could create biologically usable forms of nitrogen instead of depending on abiotic sources. The authors propose that it was triggered by a change in environmental circumstances — a steep fall in the rate of abiotic nitrogen fixation by lightning at some point during the Archaean era, the first half of Earth's history.

Production of nitric oxide (NO) by lightning is a source of fixed nitrogen today, accounting for 10¹²–10¹³ g of nitrogen per year. But the rate of biological nitrogen fixation is much higher, at least 2 × 10¹³ g N yr⁻¹ and perhaps much more². This process is carried out by certain microorganisms, which ultimately make nitrogen available to all of the rest of life. No organism can do without nitrogen — it is, for instance, a component of all amino acids.

In today's oxygen-rich atmosphere, NO is oxidized to NO₂ and exists in the ocean in the form of nitrate ions, NO₃⁻. Today's atmosphere contains 21% O₂ and 78% N₂. So NO is produced by the efficient (at high temperatures) reaction N₂ + O₂ → 2NO. The Archaean atmosphere is thought to have contained similar amounts of N₂, but little or no O₂. However, NO could still have been produced using oxygen atoms obtained by splitting of CO₂ and H₂O. In the anaerobic Archaean ocean, this NO should have dis-



Figure 1 Lightning in the lab — the type of experimental vessel used by Navarro-González *et al.*¹ in their laser simulations of nitrogen fixation in the atmosphere of the early Earth.

proportionated to form N₂O (nitrous oxide), NO₂⁻ (nitrite) and NO₃⁻ (ref. 3). Organisms can use both nitrate and nitrite as a source of nitrogen.

Navarro-González *et al.*¹ have studied the rate of NO production in the laboratory, using lasers to simulate the effect of lightning. They carried out pulsed-laser experiments in reaction vessels (Fig. 1) containing 'atmospheres' with various proportions of N₂, CO₂ and H₂O. This in itself is a useful advance on previous theoretical treatments, most of which assumed that thermodynamic equilibrium is maintained down to some critical 'freeze-out' temperature. In reality, reaction kinetics must be taken into account, as shown by the fact that different results are obtained from mixtures of gases with the same overall

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elemental composition but different distributions of chemical species⁴. In the absence of detailed kinetic information, experiments such as those of Navarro-González *et al.* are clearly a better way to proceed.

The authors' thesis is as follows. On the early Earth, concentrations of CO₂ in the atmosphere were high — because of oxidation of CO produced by impacts of extraterrestrial bodies⁵ and only slow removal of CO₂ by weathering (the continents were smaller at this time⁶, meaning that a smaller area of minerals was exposed for weathering). With these CO₂ conditions, the authors estimate that the initial production rate of NO was about 3×10^{11} g N yr⁻¹. Atmospheric CO₂ levels declined with time, however, as the impact rate dropped and the continents grew. A rise in atmospheric CH₄ produced by methanogenic — methane-generating — bacteria may have warmed the Archaean Earth and speeded the removal of CO₂ by silicate weathering⁷. As this happened, the production rate of NO by lightning dropped to below 3×10^9 g N yr⁻¹ because of the reduced availability of oxygen atoms from the splitting of CO₂ and H₂O. The resulting crisis in the availability of fixed nitrogen for organisms triggered the evolution of biological nitrogen fixation about 2.2 billion years ago.

This hypothesis is attractive but, like many good ideas, difficult to confirm. As the authors point out, genetic studies of the enzyme involved (nitrogenase) indicate that biological nitrogen fixation is an ancient metabolic pathway. If anything, one might imagine that it was invented during the early Archaean, before 3 billion years ago, rather than later on. But then, the crisis in abiotic nitrogen fixation could have occurred very early as well. One model⁸, which emphasizes rapid weathering of fragments from impacts and efficient sequestration of carbon in the Earth's mantle, proposes that concentrations of atmospheric CO₂ were low from the very beginning of Earth's history and that the Archaean climate was warmed almost exclusively by CH₄. In that case, the availability of fixed nitrogen could have been a problem almost as soon as life originated, around 3.5 billion years ago.

The hypothesis also has a couple of wrinkles, the first of which is discussed in the paper. Photochemical models⁹ predict that nitrogen can also be fixed as HCN (hydrogen cyanide) in atmospheres containing N₂ and CH₄. HCN is hydrolysed in solution to form NH₄⁺ (ammonium), which is also a biologically useful form of nitrogen. The rate of HCN production in an anoxic atmosphere is uncertain, but it could have approached the modern rate of abiotic NO production¹. Whether or not this process actually occurred in the postulated manner is unclear, as the relevant photochemical reactions have not been well studied. This deficiency should

be remedied once the importance of the reactions is realized.

The other problem is that HCN might have been involved in a different way. The ancestral counterpart of nitrogenase may have originally been a detoxyase¹⁰, used to protect organisms against triple-bonded compounds — such as C₂H₂ (acetylene) and HCN — that are formed in anoxic atmospheres. So biological nitrogen fixation may have evolved because too much HCN was being produced, rather than too little. In either case, however, the role of the environment in triggering the evolution of nitrogen-fixing metabolism is clear.

The issues might be clarified by comparing the evolutionary histories of biological nitrogen fixation and methanogenesis. The Archaean climate was probably warm, so the atmosphere must have contained large amounts of either CO₂ or CH₄. Navarro-González and colleagues' argument requires that methanogenesis preceded biological nitrogen fixation. On the face of it, this seems unlikely because the ability to fix nitrogen is widespread among prokaryotes (Bacteria and Archaea), whereas methanogenesis is restricted to a single group within the Archaea.

Parsimony would dictate that the more ubiquitous metabolic process came first. However, if the ability to fix nitrogen was spread by rampant gene transfer between organisms, then methanogenesis could conceivably have evolved first and the premise of Navarro-González *et al.* could hold. This

question might be resolved by comparing the phylogenies of various nitrogenase-related (*nif*) genes with those derived from ribosomal RNA. If the phylogenies of *nif* genes are in accord with those from ribosomal RNA, then nitrogen fixation can be assumed to have been vertically inherited, and so be an anciently derived character. The phylogeny of one component of nitrogenase (*nifH* gene)¹¹ is in partial agreement with that of ribosomal RNA, but still does not constitute conclusive evidence for either vertical or horizontal descent of nitrogen-fixing genes. Analyses of other *nif* genes might allow us to distinguish between these alternatives. ■

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Apoptosis

DNA destroyers

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Proteins with quite mundane functions in healthy cells often behave very differently during cell suicide. One protein normally involved in copying mitochondrial DNA actually degrades nuclear DNA in dying cells.

The degradation of DNA is one of the hallmarks of programmed cell death (apoptosis)¹. When forced to commit suicide, apoptotic cells — like good secret agents — grimly destroy their 'instruction book', chewing up their genomic DNA into tiny morsels. Until now, only two DNA-destroying enzymes (nucleases) with a clear role in cell death were known, one in mammals² and one in the nematode worm *Caenorhabditis elegans*³. But, on pages 90–99 of this issue, Li and colleagues⁴ and Parrish and co-workers⁵ show that another nuclease, endonuclease G (endoG), also contributes to the carnage, and might even influence the likelihood that a cell will live or die.

Li *et al.*⁴ encountered endoG while searching for new cell-death-inducing factors that are released from mitochondria — the energy-generating organelles — in

mammalian cells that are primed to die. The authors exposed isolated mitochondria to the truncated, apoptosis-inducing version of the protein Bid. The mitochondria then released a nuclease activity into the medium; this activity could, when incubated with isolated nuclei, generate the pattern of DNA fragments that is characteristic of apoptotic cells. The nuclease activity was distinct from that of the known mammalian nuclease, CAD (also known as DFF40)². Li *et al.* purified the new apoptotic nuclease, and identified it as endoG — a previously described mitochondrial enzyme with a proposed role in the replication of mitochondrial DNA⁶.

Why would a cell need more than one nuclease to digest its DNA? One hint might come from the different ways in which CAD and endoG are regulated. In living cells, CAD is sequestered in an inactive complex, bound