waves). The higher the velocity of a particle, the shorter the wavelength of the de Broglie wave. For a cloud of hot atoms, the de Broglie wavelengths are so short that each atom can be considered as an individual object (Fig. 1a).

If these atoms are cooled, the de Broglie wavelengths become longer. And if the atoms are cooled to a critical temperature (typically several hundred nanokelvin), the wavelengths become large enough to cover the whole atomic cloud. In this scenario, most of the atoms condense into a state in which they all behave in the same manner, and can be regarded as a single matter wave. Such a state is known as a Bose–Einstein condensate (BEC).

Producing a BEC is not easy. Even though the concept was proposed[5,6] in 1924–1925, a BEC was not realized[7,8] until 1995, after two types of cooling (laser and evaporative) had been invented. Since then, the matter waves associated with BECs have been widely used in atom interferometry (Fig. 1b). Atom interferometers use laser beams to split up matter waves and then recombine them to produce interference patterns. These patterns are sensitive to vibrations, changes in temperature and other disturbances.

Sensors based on matter waves differ from those based on light because atoms have a mass and an internal structure. The mass means that matter-wave sensors are extremely sensitive to gravity. They are therefore more suited to work in space, where gravity is extremely weak (a condition known as microgravity), than they are to work on the ground. Moreover, the internal structure of atoms means that there are more ways to control the properties of matter-wave sensors than those of optical sensors.

Becker and colleagues developed a BEC set-up for a rocket, which was launched to a height of 243 kilometres before returning to the ground. The BEC was produced while the rocket was in space, which is a milestone on the path towards building space-borne matter-wave sensors. During the launch phase and the 6 minutes of space flight, an astonishing 110 BEC-related experiments were carried out. The BEC set-up was only slightly bigger than the average human, withstood the vibrations and shocks during the launch of the rocket, and automatically conducted all of the experiments. Such a set-up represents a technical marvel in modern atomic physics.

The authors compared the formation of the BEC in space with that of one on the ground. They found that there were more atoms in the space-based BEC than in the ground-based one, although the fraction of atoms in the atomic cloud that were condensed was lower in space than on the ground. In an atom interferometer, a greater number of condensed atoms can give rise to a stronger interference signal, whereas a larger condensation fraction increases the signal-to-noise ratio. As a result, precision interferometry requires both a large number of condensed atoms and a high condensation fraction. The authors should therefore try to improve the condensation fraction for their space-borne BEC.

Becker *et al.* demonstrated transport of the BEC away from the surface of the chip on which it was formed — a key step towards realizing more-complex motion. Such motion, combined with further manipulation, would enable the natural expansion of the BEC to be precisely controlled, maximizing the time that the atomic cloud could be used in an interferometer. The transport of the BEC from the chip caused complex oscillations in the shape of the atomic cloud. These oscillations reveal valuable details about the hydrodynamic behaviour of the BEC, but their impact on interferometry performance needs further investigation.

On the ground, microgravity can be achieved for only a few seconds. But in space, it can be supported for essentially an infinite length of time, offering new opportunities for studying cold-atom physics. For example, a BEC in microgravity could reach temperatures as low as picokelvin (equal to 10^{-12} K) or even femtokelvin (10^{-15} K) ranges, compared with nanokelvin on the ground. Gases at such low temperatures are an ideal platform for probing fundamental physics, and the authors' space-borne BEC is the first step towards this goal.

Becker and colleagues' work paves the way for quantum sensors in space that could be used to conduct experiments that are not possible on Earth. Examples include detecting gravitational waves in a frequency range that is not usually accessible, sensing possible ultralight dark-matter particles and observing subtle effects associated with Einstein's general theory of relativity. Who knows what mysteries of the Universe could be revealed by space-borne quantum sensors. ■

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CELLULAR EVOLUTION

The eukaryotic ancestor shapes up

Asgard archaea are the closest known relatives of nucleus-bearing organisms called eukaryotes. A study indicates that these archaea have a dynamic network of actin protein — a trait thought of as eukaryote-specific. **SEE LETTER P.439**

LAURA EME & THIJS J. G. ETTEMA

Eukaryotic cells, which carry their DNA in a nucleus, are thought to have evolved from a merger between two other organisms — an archaeal host cell[1–3] and a bacterium from which eukaryotic organelles called mitochondria emerged[4]. Some insights into the biological properties of the host have come from the closest known archaeal relatives of eukaryotes, the Asgard superphylum[5,6]. The genomes of organisms belonging to this archaeal group encode a suite of proteins typically involved in functions or processes thought to be eukaryote-specific. The functions of these 'eukaryotic genes' in Asgard archaea have been elusive, but on page 439, Akıl and Robinson[7] provide evidence that some of them encode proteins that are structurally and functionally similar to their eukaryotic counterparts.

Apart from their nucleus and energy-producing mitochondria, eukaryotic cells are characterized by a complex internal system of membrane-bound compartments (the endomembrane system), and by a dynamic network of proteins such as actin, called the cytoskeleton. The latter gives the cells their shape and structure, but is also involved in a variety of cellular processes specific to eukaryotes[8]. These features are thought to have been present in the last common ancestor of all eukaryotes, which lived about 1.8 billion years ago[9], but no life forms have been found that represent an intermediate between eukaryotes and their bacterial and archaeal ancestors. The seemingly sudden emergence of cellular complexity in the eukaryotic lineage is a conundrum for evolutionary biologists.

Several of the proteins produced by Asgard archaea are evolutionarily related to proteins that in eukaryotes modulate complex cellular processes[5,6]. The identification of these proteins raised the question of whether Asgard archaea have some primitive versions of

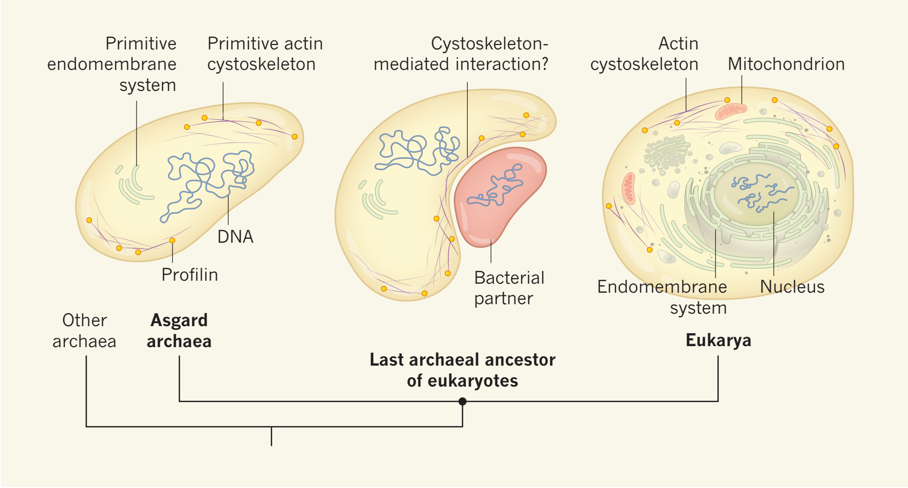

Figure 1 | Cellular complexity along the tree of life. The Eukarya (organisms whose cells harbour DNA in a nucleus) are thought to have arisen from a merger between their last archaeal ancestor and a bacterium. In addition to a nucleus, eukaryotes have several characteristics that are thought to separate them from archaea, including: a complex internal system of membranes called endomembranes; a structural feature called the actin cytoskeleton, the dynamics of which are regulated by the protein profilin; and energy-producing organelles called mitochondria, which arose from the bacterial partner. But Akıl and Robinson[7] provide evidence that members of the Asgard superphylum — an extant group of archaea thought to be related to eukaryotes — harbour a primitive profilin-regulated actin cytoskeleton. If the last archaeal ancestor of eukaryotes had this feature, it might have enabled the cell to wrap around its presumed bacterial partner. In addition, it is possible that Asgard archaea and the last archaeal ancestor of eukaryotes carry primitive endomembrane systems. (Cells and cellular features are not drawn to scale.)

certain eukaryotic properties. If they do, it would suggest that the last archaeal ancestor of eukaryotes already displayed a certain — albeit probably limited — degree of cellular complexity reminiscent of eukaryotes.

Experiments to support such ideas are complicated by the fact that evidence for the existence of the four known Asgard lineages (Lokiarchaeota, Odinarchaeota, Thorarchaeota and Heimdallarchaeota)[5,6] is based solely on metagenomics analyses. The cells have yet to be observed under a microscope, and have not been cultured *in vitro*. Nevertheless, Akıl and Robinson were determined to gain insight into the properties of Asgard proteins related to the eukaryotic proteins actin and profilin. In eukaryotes, profilin regulates the polymerization of actin into filaments of the cytoskeleton. These filaments have pivotal roles in processes that include vesicle and organelle movement, cell-shape formation and phagocytosis[8], in which cells ingest foreign particles or other cells.

To produce Asgard profilins, Akıl and Robinson expressed these proteins in the bacterium *Escherichia coli* using a circular DNA molecule called a plasmid that harboured the profilin-encoding genes. They then purified the proteins and studied their structures using X-ray crystallography. Asgard profilins share limited amino-acid sequence identity with their eukaryotic counterparts. Nonetheless, the authors found that the structure of lokiarchaeal profilin is topologically similar to that of human profilin, although some structural divergences could be observed. This confirms that Asgard and eukaryotic profilins are indeed evolutionarily related, albeit distantly.

Next, the researchers set out to investigate whether Asgard profilins could interact with Asgard actins. Unfortunately, despite considerable efforts, they were unable to produce functional Asgard actin. As an alternative, they therefore carried out *in vitro* and co-crystallization experiments to test whether Asgard profilins could interact with eukaryotic actins. Remarkably, despite being separated by 2 billion to 3 billion years of evolution[9], several of the Asgard profilins bound to mammalian actin and regulated its polymerization kinetics. Asgard and mammalian profilins seem to have similar effects on mammalian actin, although the Asgard proteins act less efficiently. These results suggest that Asgard archaea harbour a profilin-regulated actin cytoskeleton — a cellular feature generally regarded as a defining characteristic of eukaryotic cells (Fig. 1).

> ***"The inference of a primitive dynamic actin cytoskeleton in Asgard archaea sheds light on the biological properties of the ancestor of eukaryotes."***

The inference of a primitive dynamic actin cytoskeleton in Asgard archaea sheds light on the biological properties of the ancestor of eukaryotes. In eukaryotic cells, the energy required to dynamically regulate actin is mainly provided by mitochondria[10]. Although the energetic and metabolic properties of Asgard archaea are currently unknown, they certainly lack the firepower that mitochondria provide. A profilin-regulated actin cytoskeleton in the archaeal ancestor of eukaryotes is therefore unlikely to sustain energy-consuming processes such as phagocytosis.

But was the energy provided by mitochondria necessarily the ultimate driving force for the emergence of complex cellular features in eukaryotes? Archaea such as *Ignicoccus hospitalis*, along with several types of bacterium, have independently evolved endomembrane systems[11]. Because these lineages lack mitochondria, energetic constraints can be ruled out as a limiting factor in the emergence of such a system. It is therefore feasible that Asgard archaeal cells produce sufficient energy to harbour both a primitive endomembrane system and undergo actin-driven membrane and cell-shape deformation. Perhaps the latter ability could have facilitated the symbiotic interaction between the Asgard-related host cell and the bacterial ancestor of mitochondria, for example by optimizing the membrane surface area for metabolic exchange between the two cells. Once mitochondria became an intrinsic part of eukaryotic cells, their capacity for energy production could have conferred selective advantages on their host. However, the exact contribution of these organelles to the emergence of the complex features of eukaryotic cells remains unresolved.

Future efforts to elucidate the biological and physiological properties of Asgard archaea will be essential to increase our understanding of the emergence of eukaryotes. Although biochemical and structural studies of individual Asgard proteins, such as those by Akıl and Robinson, are likely to provide piecemeal insights, it is the ability to grow Asgard archaeal lineages *in vitro* that will ultimately unravel their obscure biology. ■

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