maintains a steady functionality despite the animal's continuously increasing body size.

Next, the researchers investigated the dynamics of radial-muscle contraction and relaxation around tens of thousands of chromatophores. They discovered co-variations in muscle movements at many spatial scales, indicating that chromatophores are regulated by modules of motor neurons that function in synchrony, and that operate on skin patches of different sizes. The smallest modules consisted of fewer than ten adjacent chromatophores of the same colour. By contrast, larger modules, when contracted in synchrony, displayed more-complex shapes, such as rings, rectangles or disjointed structures resembling eye spots. These results pave the way to investigating how the geometry of these modules gives rise to the camouflage motifs seen in cuttlefish in their natural environment.

Finally, the authors studied chromatophore responses to changes in the cephalopod's visual environment, for instance when an investigator passed a hand above the animal, causing its skin pattern to change. They found that chromatophores display a highly coordinated choreography over time — reminiscent of the choreography of neuronal-population activity during movement[5]. Strikingly, chromatophores went through the same sequence of contractions and relaxations each time the test was repeated. This indicates a remarkable level of fine control by motor neurons, and highlights the potential of cuttlefish studies to deepen our understanding of complex motor systems.

Reiter *et al.* have achieved a breakthrough that will allow researchers to study this motor system in much more detail than was previously possible. The next challenge will be to determine how cuttlefish change the 3D texture of their skin for camouflage on sand, algae or corals. This process involves sets of muscles called papillae that create bumps and lumps. To gain a complete understanding of the animal's display system, chromatophores and papillae should be studied together.

The authors' advance also has implications for visual perception and motor control more generally. For instance, we should now be able to gain a better understanding of texture perception in both cephalopods and their vertebrate predators, by investigating which visual features in the cuttlefish environment drive skin-pattern choices. Given that we can read the perceptual state of cuttlefish on their skin, it might also become easier to investigate the brain activity that translates visual perceptions into motor outputs.

Furthermore, because cuttlefish coordinate millions of muscles simultaneously, they could provide insights into the principles underlying motor coordination. The authors' findings suggest a hierarchical organization of motor-neuron modules, in which higher-level modules control complex, global skin patterns and lower-level modules control simple, local motifs. Such a hierarchy of motor controllers has long been thought to be a key principle underlying behaviour in most animals, including humans[6]. However, recording the activity of every muscle in a human is currently impossible. The simple readout provided by the skin-display system of cuttlefish could well lead us to a greater understanding of motor control. ■

Adrien Jouary *and* **Christian K. Machens** *are in the Champalimaud Neuroscience Programme, Champalimaud Centre for the Unknown, 1400-038 Lisbon, Portugal.*
e-mails: adrien.jouary@neuro.fchampalimaud.org; christian.machens@neuro.fchampalimaud.org

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QUANTUM PHYSICS

Exploring the Universe with matter waves

An exotic ultracold gas known as a Bose–Einstein condensate has been produced and studied in space. Such gases could be used to build quantum sensors that probe the properties of the Universe with extreme precision. SEE LETTER P.391

LIANG LIU

Many great discoveries in modern physics depend on the invention of sensors based on new principles. For example, in 1887, an optical interferometer — a sensor based on wave interference — was used to disprove the existence of luminiferous aether, a universal medium through which light waves were thought to propagate[1]. In 1968, radio telescopes were used to discover extreme astronomical objects known as pulsars[2]. And in 2016, a laser interferometer was used to detect gravitational waves[3]. On page 391, Becker *et al.*[4] demonstrate how space-borne sensors based on an exotic state of matter called a Bose–Einstein condensate might provide the next big discovery.

A fundamental principle of quantum physics is wave–particle duality, which describes elementary particles in terms of quantum-mechanical waves (de Broglie

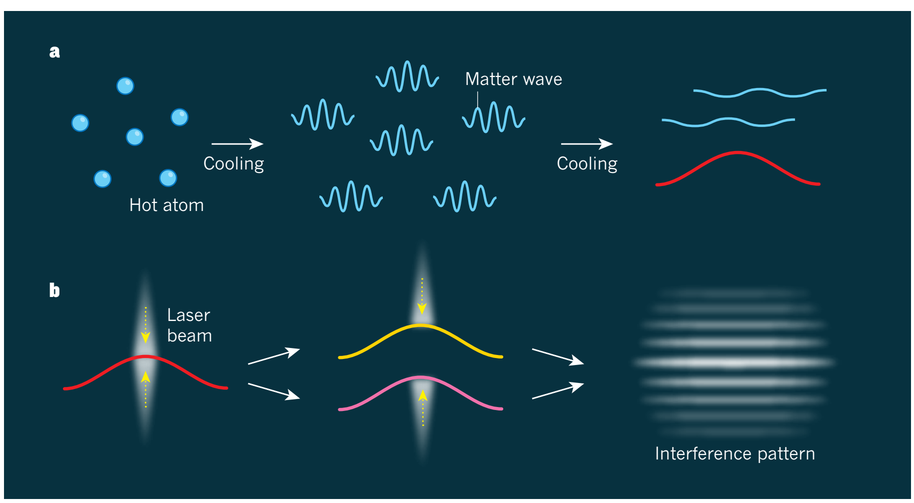

Figure 1 | Production and application of a Bose–Einstein condensate. a, In quantum physics, matter can behave like a wave that has a particular wavelength. For a cloud of hot atoms, these wavelengths are so short that each atom can be regarded as an individual object. If the atoms are cooled, the wavelengths become longer. And if the atoms are cooled to a critical temperature, the wavelengths are large enough to cover the extent of the atomic cloud. Most of the atoms condense into a state known as a Bose–Einstein condensate (BEC), in which they can be regarded as a single matter wave (red). Becker *et al.*[4] have produced and analysed a BEC in space. **b,** BECs can be used in sensors known as atom interferometers, in which laser beams cause a matter wave to split into two and then recombine to generate an interference pattern that is sensitive to external perturbations.

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. ■

Liang Liu *is in the Key Laboratory of Quantum Optics, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China.*
e-mail: liang.liu@siom.ac.cn

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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