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In Retrospect

Method for studying dark matter turns 25

In 1993, two papers reported observations of an astronomical phenomenon called gravitational microlensing. The results showed that microlensing could be used to probe the elusive dark matter that is thought to pervade the Universe.

GRZEGORZ PIETRZYŃSKI

One of the biggest mysteries in astronomy is the nature of dark matter, which is thought to account for about 85% of the matter and 25% of the total energy in the Universe[1]. There are several strong pieces of evidence for dark matter[2]. In particular, spiral galaxies such as the Milky Way have flat rotation curves[3] — graphs that show the orbital speed of stars as a function of their distance from the galactic centre. This property indicates that spiral galaxies are surrounded by large quantities of unseen matter. Dark matter has not yet been detected directly, so its identity is still unknown. But 25 years ago, Alcock *et al.*[4] and Aubourg *et al.*[5] reported observations in *Nature* that paved the way to a better understanding of its properties.

In 1986, the Polish astronomer Bohdan Paczyński suggested an observational test[6] to determine whether dark matter present in the halo of our Galaxy is composed of astronomical bodies such as small stars, brown dwarfs, neutron stars or black holes. Such bodies are intrinsically faint and would therefore be difficult to see in the Galactic halo from Earth.

According to Einstein's general theory of relativity, these massive compact halo objects (MACHOs) could act as lenses, focusing light and amplifying the observed brightness of stars in nearby galaxies (Fig. 1). This phenomenon, called gravitational microlensing, is sensitive to even low-mass lenses. Paczyński therefore proposed that, by monitoring stars in nearby galaxies, astronomers could look for microlensing events and verify whether MACHOs can account for dark matter.

Conceptually, this test is simple. But in practice, it requires millions of stars to be monitored over a period of years. The reason is that the microlensing events have an extremely low probability of being detected, because the star, the MACHO and the observer all need to be aligned. At that time, it was a challenge to observe such a huge number of stars, accurately measure their brightness and analyse the resulting data.

In October 1993, Alcock *et al.* and Aubourg *et al.* independently announced the first candidates for microlensing events caused by dark objects in the Galactic halo. Alcock and colleagues used a dedicated 1.27-metre-diameter telescope. The telescope was equipped with two charge-coupled device (CCD) cameras that had a field of view of 0.5 square degrees, which was considered large at that time. The authors spent a year monitoring 1.8 million stars in a nearby galaxy known as the Large Magellanic Cloud, and discovered one microlensing candidate. By contrast, Aubourg and colleagues used photographic plates that had a field of view of about 25 square degrees. They monitored 3 million stars in the Large Magellanic Cloud for more than three years, and detected two microlensing candidates.

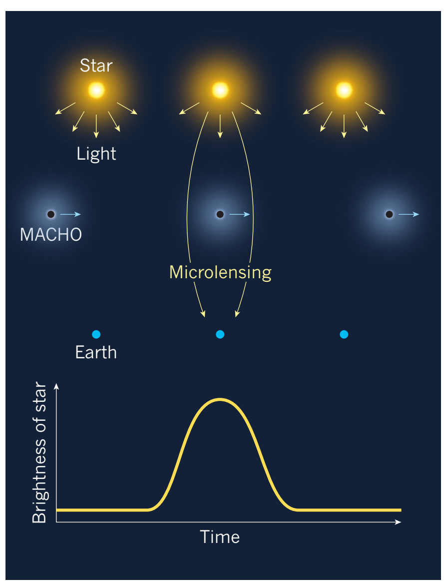

Figure 1 | Gravitational microlensing. In 1993, Alcock *et al.*[4] and Aubourg *et al.*[5] presented possible evidence for astronomical bodies called massive compact halo objects (MACHOs). Such bodies could account for dark matter — the 'missing' matter in the Universe. A MACHO can be detected when it passes in front of a star in a nearby galaxy. The MACHO bends light from the star towards Earth, which temporarily amplifies the star's observed brightness. This effect is known as gravitational microlensing.

The candidates all had fairly symmetrical light curves — plots that show the observed brightness of a star as a function of time (Fig. 1). Both teams obtained light curves in two different colours (blue and red) and found that the shapes of these plots were extremely similar. Such symmetrical and achromatic light curves are in agreement with what is expected for microlensing events.

However, the light curves of the two candidates obtained using photographic plates had a low signal-to-noise ratio. And for all three candidates, there was incomplete coverage of the brightening event, especially close to the peak brightness. Furthermore, although the frequency of the observed candidates was consistent with theoretical predictions, their low number prevented any firm confirmation that the light curves were products of microlensing — rather than light curves of a previously unseen class of astronomical object of varying brightness.

Despite these limitations, the potential discovery of microlensing by dark objects in the Galactic halo was spectacular. It demonstrated the feasibility of using microlensing to detect extremely faint stellar-mass or sub-stellar-mass bodies in the Galactic halo and, as a result, the feasibility of verifying whether dark matter in spiral galaxies is composed of such bodies. The microlensing surveys showed that it was possible to monitor millions of stars over years and to analyse the resulting enormous data sets, which was a breakthrough in observational astronomy.

Motivated by the work of Alcock *et al.* and Aubourg *et al.*, microlensing surveys improved enormously over the following 25 years, reaching capabilities to observe about 1 billion stars per night[7]. The huge data sets of high-quality light-curve data revolutionized many fields of astronomy — for example, the study of pulsating stars, extrasolar planets and star formation[8,9]. Moreover, millions of objects of varying brightness and thousands of microlensing events were detected, mostly in the direction of the Galactic bulge (a spherical structure near the centre of our Galaxy).

However, on the basis of observations of 35 million stars over eight years, only four microlensing events in the direction of the Large Magellanic Cloud were detected[10]. If these signals were caused by MACHOs, the contribution of these objects to the mass of the Galactic halo must be low (a few per cent). But the more likely explanation of these detections does not involve MACHOs at all, and relies on the lensing of stars in the Large Magellanic

Cloud by other objects in this galaxy.

Either way, MACHOs cannot account for all of the dark matter in spiral galaxies, and the identity of this mysterious matter remains unknown. The microlensing experiments ultimately gave a negative result. However, they have had a huge impact on many fields of modern astrophysics and have provided a lot of excitement and stimulation for the whole astronomical community. ■

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NEUROSCIENCE

A living display system

Pigmented cells in the skin of cuttlefish can contract or relax to produce different skin-colour patterns. Tracking the dynamics of these cells reveals how this display system develops, and how it is controlled. SEE ARTICLE P.361

ADRIEN JOUARY & CHRISTIAN K. MACHENS

Our thoughts are hidden from sight, buried deep in the brain. Although this is undoubtedly beneficial in daily life, it is a serious drawback for neuroscientists: because much brain activity does not translate directly into behaviour, its function is difficult to determine. On page 361, Reiter *et al.*[1] take a step towards circumventing this problem. The authors studied cuttlefish, which can change their appearance on the basis of their perception of the external world — in essence, they display some of their 'thoughts' on their skin. Using a range of state-of-the art techniques for computer vision, spectrometry and biomathematics, together with electrophysiology, the group exposes one of the most complex systems of motor coordination ever recorded.

Cuttlefish, like squid and octopuses, are cephalopods. They have one of the largest brains among invertebrates, and can memorize complex spatial relationships or episodic events — abilities conventionally associated with mammals and birds[2]. These brainy molluscs lack a protective shell, but have evolved a sophisticated display system that enables them to quickly transform the colour and patterning of their skin in response to a changing perception of the world around them, generating a broad range of patterns used for camouflage, deception of prey or sexual communication[3].

The cuttlefish skin contains millions of cells called chromatophores, which can produce tiny dots of colour (yellow, orange, red, brown or black). If the radial muscles that control a chromatophore are relaxed, the pigments are imperceptible. But muscle contraction produces a colourful pixel several tens of micrometres wide[4] (Fig. 1). When viewed at a distance, the millions of individual pixels form a complex image in the style of a pointillist painting, displayed on the animal's skin. This process is orchestrated by many motor neurons, which innervate the radial muscles of individual chromatophores to control their contraction.

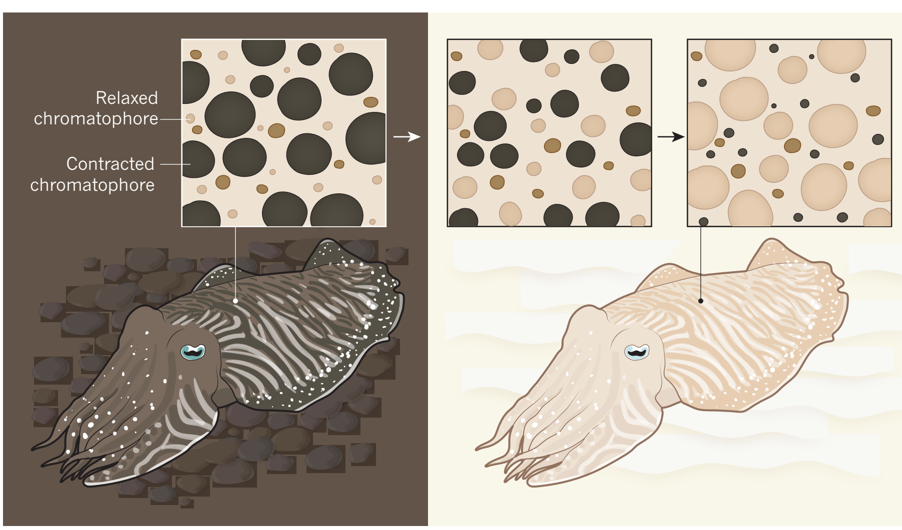

Figure 1 | Thoughts on display. Chromatophores are pigmented cells found on the skin of cuttlefish. Modulations in muscle contraction determine whether or not the cells' pigments are displayed, producing a changing patterning system that the animal uses for camouflage. Reiter *et al.*[1] used computer-vision tools to track tens of thousands of chromatophores. The authors' investigation reveals how skin pattern is controlled and how it varies over time. In response to changes in the cuttlefish's surroundings, the muscles that control groups of chromatophores contract or relax in unison, to produce a coordinated alteration in skin appearance.

Cuttlefish move rapidly, and because they are soft-bodied, frequently change shape. This constant flux presents a huge technical challenge for studies of individual chromatophores, because such analyses require imaging techniques that can keep track of individual cells between frames of video footage. Reiter *et al.* found that each chromatophore is surrounded by a unique arrangement of neighbouring chromatophores, akin to a fingerprint that could be picked out in a single frame, despite changes in skin pattern. By following the characteristic fingerprint of each chromatophore in the video footage, the researchers were able to simultaneously track tens of thousands of cells over time. This enabled them to study how the control of individual chromatophores produces the complex skin patterns formed by the cell population as a whole.

The authors first investigated the emergence of local skin motifs in which dark chromatophores are surrounded by more-colourful ones. Observations over several weeks led to a surprising discovery: the difference in colour reflects a difference in age. The pigment of every chromatophore starts as yellow before turning red, then brown, and ending up as black. New chromatophores are generated throughout the life of the cuttlefish, and the group found that the ratio of black to coloured chromatophores is maintained by keeping a tight balance between the birth rate of new cells and the time it takes them to mature to a black colour.

Reiter *et al.* showed that new chromatophores are generated in regions in which there are no existing ones, with a simple local-repulsion rule ensuring an even spread of the cells across the skin. The authors found that the same rule could explain the patterns of chromatophore formation seen in other species of cephalopod. These findings suggest that evolutionarily conserved molecular interactions govern chromatophore positioning — a proposal that should be investigated in the future. The rule also explains how the cuttlefish display system