The Animal Star Compass

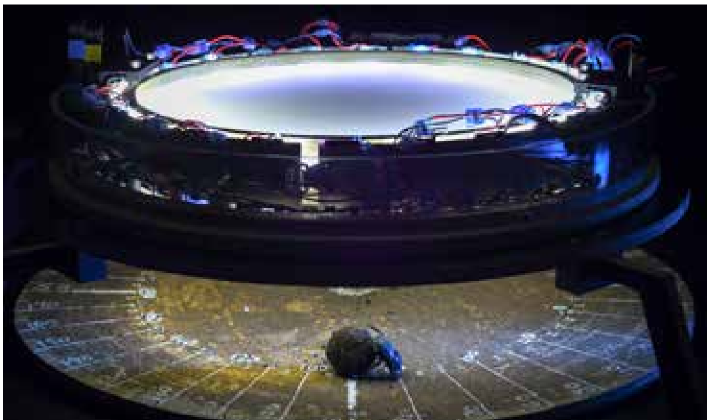
James Foster of Lund University, Sweden, explores how animals navigate using celestial clues.

Across the length of human history, the stars have followed a consistent and reliable pattern, often in stark contrast to the unstable and rapidly changing nature of earthbound objects. Indeed, in the ancient world a clear distinction was drawn between the unpredictable movement of all things terrestrial and the smooth motion of celestial bodies. This apparent perfection made the deviations of stars from their predicted movements all the more troubling to ancient astronomers, and the history of science may be told in part from the perspective of ever increasing accuracy in humankind's ability to predict astronomical events and describe the motion of celestial bodies.

For animals, celestial cues also present a reliable pattern, quite distinct from ephemeral earthbound landmarks, and many animal species have been shown to use the sun as a point of reference to direct their behaviour. In the sun's absence, the moon can also play similar role for several nocturnal species. As the sun and moon set, the stars come to dominate the sky, though these dimmer celestial bodies follow a different schedule and require more sensitive eyes and more sophisticated interpretation. Animals must adapt from relying on a single, bright point of light, to a broad pattern of points, nearly all of which are smaller than the region illuminating a single light sensitive cell in the eye of any animal. For animals with camera eyes, i.e. eyes for which the whole field of view is resolved by a single lens, it is the spaces between stars, rather than the region occupied by each star, that shapes the image of the night sky that is so familiar to humans. In this image, the positions of a few bright stars are easily discriminated from the fainter background made up of countless dimmer stars.

To compound eyes made up of many facets, such as those of insects, the night sky is most likely a more impressionist scene, in which individual facets receive light from multiple stars simultaneously, causing stars separated by small distances to appear to overlap. For both types of eye, signals from neighbouring image pixels are often also combined to boost sensitivity under these dark conditions, which may convert a clear night sky to a Van-Gogh-like starry night, with stars that blur and swirl together from the point of view of many nocturnal animals.

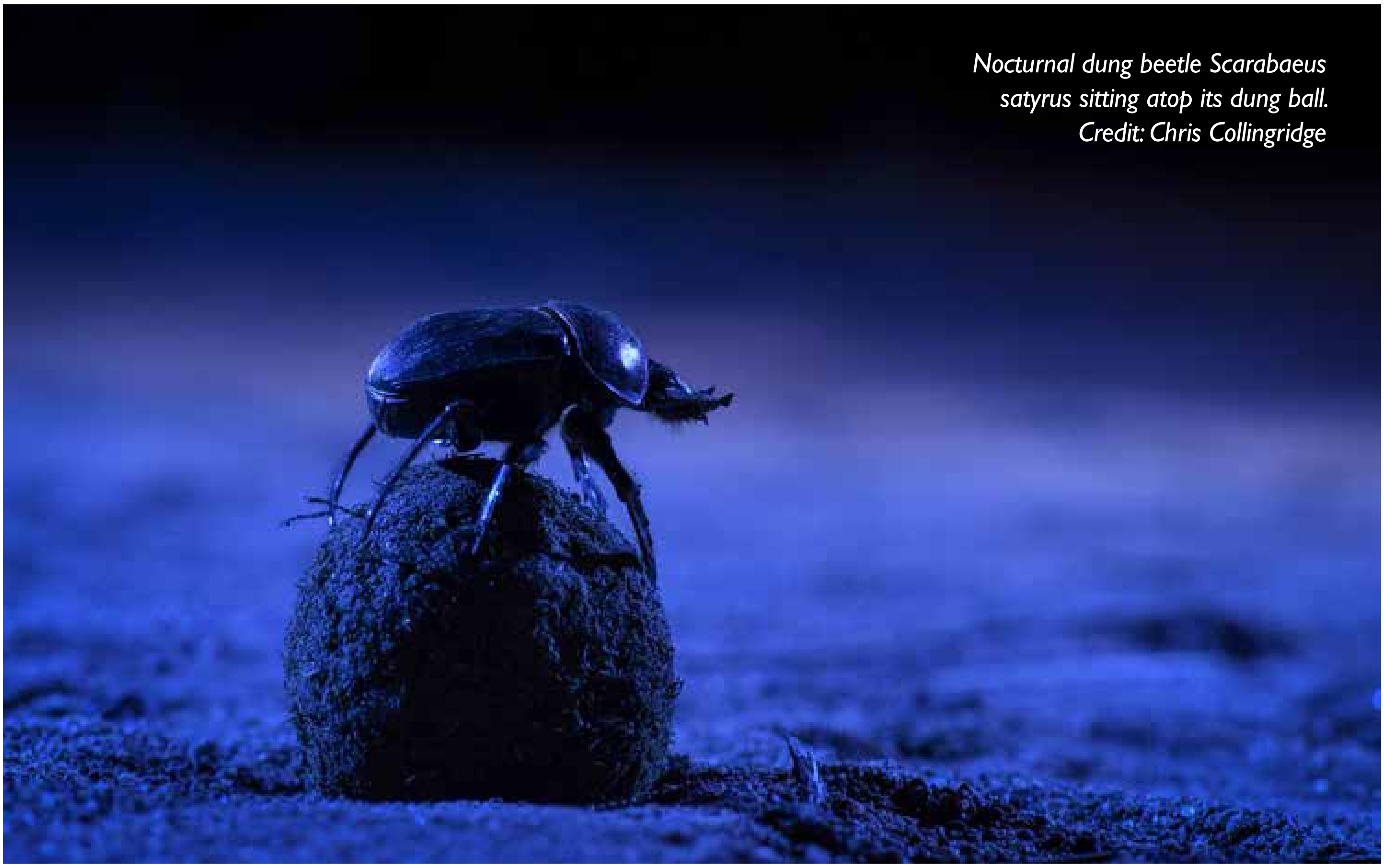
So how then do animals interpret this froth of tiny points or blurry orbs into something they can use to hold their course? To answer this question, we need first to address the goals of orienting animals and then to observe how well they achieve these goals under controlled conditions. Directed behaviour in animals comes in many forms, from migrations that circumnavigate the globe from pole-to-pole, to basic straight-line travel.



A lab-based artificial sky experiment Credit: Chris Collingridge

Early experiments to investigate star orientation focussed on the performance of migratory birds in planetaria, in particular indigo buntings, a species that migrates between North- and Central America with the changing seasons. The birds remained well oriented in the planetarium throughout the night, and birds tested in spring and autumn headed in opposing and season-appropriate directions. To hold such a stable course, the birds must overcome the effects of celestial rotation. As stars sink below the horizon and new ones rise to take their place, they come to form different patterns at different times of night and year, and at different locations on the globe. So how did these birds know which direction to travel at different times of night? It seems that they can learn to identify the group of stars around the sky's centre of rotation, the stars directly above the earth's poles that do not move below the horizon. As more and more of the stars outside of this "centre of celestial rotation" were experimentally removed from view, it became clear that indigo buntings require only a small group of bright stars within 30° of Polaris to choose an appropriate heading. In further experiments, birds raised in a planetarium that rotated around Betelgeuse rather than Polaris learned to recognise the stars in this region as indicators of true north, and oriented themselves away from Betelgeuse when attempting to migrate south. This suggests that the centre of celestial rotation of a starry sky is not hard-wired in the brains of migratory birds, but rather must be learned as the bird matures. This is a reasonable requirement: while over the lifetime of a single bird the same stars appear fixed above the poles, the centre of the starry sky does move, over the course of thousands of years, as a result of the wobbling spinning motion of the earth, in a process known as the precession of the equinoxes. Since each new generation of birds learns to identify the centre of rotation afresh, they develop a well calibrated star compass that can be adapted to any real or artificial starry sky, provided it rotates while they learn its configuration.

Whereas the star compass employed by migratory birds is accurate and robust to changes across long time periods and travel across great distances, it relies on a sophisticated memory and advanced pattern-recognition abilities. Animals with humbler travel ambitions may not have the time or resources to invest in learning the stars that sit at the centre of the sky's rotation. The nocturnal dung beetles of the savannahs of southern Africa are just such animals. They take to the air each summer's night with no intention of traversing a continent, but instead aiming to find a dung pat from which they can sculpt a ball of dung that they will bury and consume nearby. They are not alone; others of the same species are bound to find the same odorous dung pile and may choose to sidestep the effort of constructing a dung ball by stealing a ready-made one from its sculptor. To avoid the influx of would-be thieves and find a safe place to bury and consume their dung ball, these beetles must roll in a straight line away from the dung pat. While their diurnal relatives hold their course steady using the sun and its associated patterns of skylight, nocturnal beetles must rely on the moon, and, in its absence, the stars. Dung beetles spend their early life underground and so, on emerging from the ground in search of the first meal of their adult lives, are faced with a starry sky that they have never encountered before. The broadly-spaced



Nocturnal dung beetle Scarabaeus satyrus sitting atop its dung ball. Credit: Chris Collingridge facets of their compound eyes help to collect as much light as possible from this dark and unfamiliar scene, but also cause stars to blur together, producing an image that is ill-suited to identifying patterns of individual stars. Indeed, when scientists tested these beetles in a planetarium displaying bright stars of the type used by birds to identify the centre of celestial rotation, they performed dismally, orienting little faster than when the planetarium's projector was switched off altogether. Nonetheless, when shown a complete starry sky these beetles oriented well, and performed comparably when the brighter stars were removed from the scene, or when only the dim streak of the Milky Way was presented. This type of Milky-Way-reliant orientation suggested an entirely different form of star compass.

What, then, makes the Milky Way's streak an appropriate orientation cue for dung beetles when the bright stars, so important to the bird star compass, are insufficient? How do they manage when the Milky Way passes close to the zenith, forming a near symmetrical band crossing the sky and making it hard to distinguish north from south? To answer these questions, we created an artificial Milky Way in which we could control the brightness and configuration of the (limited) component parts. Beetles were presented with either a pattern of stars within this artificial Milky Way, balanced in brightness between the two halves of the synthetic sky, or a range of artificial Milky Ways in which there was a difference in brightness between the two halves of the sky, but no configurational information from the spacing of the lights. Were beetles learning the spacing of stars within the Milky Way streak or did they rely instead on broader patterns of brightness? Our results suggested the latter: patterns of bright stars, either within or outside of the Milky Way streak, are less important to orienting dung beetles than broad-scale differences in brightness, which their eyes are well adapted to detect. Our own measurements, performed on clear nights in South Africa, suggest that the high density of stars around the galactic centre in the southern part of the sky drives a consistent contrast between the southern and northern halves of the sky, aiding this robust, though unsophisticated, star compass. This form of star orientation is better-suited to dung beetles than to migratory birds, because of the fundamental differences in their goals: while beetles must travel as fast as possible over the course of a few minutes without returning to their point of origin, they do not need to maintain a steady course towards a specific location across many nights, while stars rotate, rise and set. This strategy may be unsuitable for long distance migration, with its poor robustness to celestial rotation, but could prove to be the star compass employed by many nocturnal animals that perform short journeys.

In comparison to the star compasses of migratory birds and dung beetles, those of other nocturnal animals remain more of a mystery, and future work may further expand the ranks of known animal star navigators. The night-time journeys of many animals are somewhat intermediate between those of night-migrating birds and nocturnal dung beetles. Radio-tracking data show that harbour seals undertake long foraging trips over the course of several days, retracing their steps to return to their preferred resting beach, all while travelling through the visually-sparse environment of the open ocean. In a set of experiments that involved the construction of a floating planetarium, two seals were successfully trained to swim towards the bright star Sirius, demonstrating a capacity to remember patterns of projected stars. Several species of moth undertake large scale migrations, flying at night under clear starry skies. Bogong moths are one example, traversing eastern Australia to escape the hot summer months for cool mountain caves, returning to their breeding sites the following autumn. Experiments similar to those performed with dung beetles are currently underway to determine whether these moths also employ a star compass, and if so, whether their star orientation strategy relies more on patterns of stars, as migratory birds do, broad-scale brightness differences, as dung beetles do, or indeed something else entirely.

As we learn more about the star compasses developed by animals over millennia, the night sky is changing at an unprecedented pace around the globe. Light pollution, emanating from streetlights, buildings and ornamental lights, is growing at a rate of 2% per year, and in many metropolitan regions already obscures the Milky Way and dimmer stars from view. Knowing which animals rely on the stars, and how they do so, may help guide policies to mitigate light pollution's most damaging effects, safeguarding the ability of animals to follow the stars for generations to come.

Marie Dacke and James Foster of Lund University, performing behavioural experiments with nocturnal dung beetles.
Credit: Chris Collingridge