spins and acquire a Berry phase. This phase then acts as an effective electromagnetic field, termed an emergent field[3].

For instance, an emergent magnetic field arises when electrons flow through what are known as topological non-collinear spin structures, those with a particular topology that makes them robust against small distortions or perturbations. The generated magnetic field leads to an extra signal in voltage measurements — known as Hall measurements — that is induced by a physical phenomenon called the topological Hall effect[4,5]. Given the complex nature of such spin structures, this voltage signal offers a convenient way to explore topological magnetic states in a wide range of materials[6,7].

By contrast, an emergent electric field arises from the dynamics of non-collinear spin structures. For example, such a field is generated when a magnetic field drives the motion of domain walls[8] — the boundaries between domains that have different magnetization orientations in magnetic materials. In 2019, it was shown theoretically that an emergent electric field could also be produced by the current-driven dynamics of non-collinear spin structures[9]. More spectacularly, it was predicted that this field would generate an inductance that is proportional to the rate of change of the current density. Because this density would be inversely proportional to the cross-sectional area of the device, the emergent inductance would increase with decreasing area, in sharp contrast to the situation in ordinary inductors (Fig. 1).

Yokouchi and colleagues exploited this idea using a micrometre-scale magnet made of $Gd_3Ru_4Al_{12}$ (Gd, gadolinium; Ru, ruthenium; Al, aluminium) that contains various non-collinear spin structures, such as helical, conical and fan-shaped structures. They selected this material because it has a weak magnetic anisotropy (directional dependence of magnetic properties), and because its spin structures have a short pitch (spatial periodicity). Spins can move relatively freely under a weak magnetic anisotropy, and the emergent inductance is inversely proportional to the pitch length[9].

The authors investigated the emergent inductance of their inductor using a technique called lock-in detection. They controlled the spin-structure state of the device by altering the temperature and strength of an applied magnetic field, and carried out measurements on different states. They also varied the length, width and thickness of the device, to confirm reproducibility and exclude the possibility that the observed signal was caused by external factors, such as the presence of contact electrodes.

Most strikingly, Yokouchi *et al.* observed a large emergent inductance (approximately −400 nanohenries), comparable to that of a conventional inductor, for a device of about one-millionth the volume of such an inductor. By changing the spin-structure state of the device, the authors clarified the correspondence between the emergent inductance and the non-collinearity and dynamics of the spin structures. This correspondence is well explained by the previously mentioned mechanism for emergent inductance.

For example, Yokouchi and colleagues discovered that the current-driven dynamics of the helical spin structures are responsible for the large emergent inductance. By contrast, the fan-shaped structures yield a much lower inductance because their local angular variations are much smaller than are those of the other structures. Moreover, the authors found that the sign of the emergent inductance can be switched between positive and negative by controlling the direction of spin-structure motion, also in striking contrast to ordinary inductors.

Yokouchi and colleagues' work is important for several reasons. First, it offers a scalable approach for developing miniaturized high-inductance inductors, which could be used in many micro- or nanoscale electronic devices and integrated circuits. Such inductors would also be much simpler in design than are conventional inductors, because a coil and a core would not be needed. Second, the work opens up exciting opportunities for constructing highly efficient hybrid spin–electronic circuits and systems. And third, it serves as proof that a fundamental concept in quantum mechanics — a Berry phase — can lead to real-world applications.

However, practical uses of such emergent inductors will need further breakthroughs. One major challenge is to develop inductors that act at room temperature, rather than at the current temperatures of about 10 kelvin. Overcoming this limitation will require extensive exploration of potential materials, especially to find a magnet in which short-pitch non-collinear spin structures can be readily stabilized and manipulated at room temperature. Developing a scheme for adding these inductors to integrated circuits will also be essential for applications. Nevertheless, Yokouchi *et al.* have made a key discovery that could lead to future engineering efforts in electronic devices, circuits and systems, while establishing an inspiring bridge between the world of quantum mechanics and modern electronics.

Seonghoon Woo is at the IBM Thomas J. Watson Research Center, Yorktown Heights, New York 10598, USA.
e-mail: shwoo@ibm.com

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Neurodevelopment

Maternal microbes support fetal brain wiring

Katherine R. Meckel & Drew D. Kiraly

Resident bacteria in the maternal gut are important for normal fetal brain development in mice. It emerges that this effect is driven by bacterially produced metabolite molecules that signal to the fetal brain. **See p.281**

The population of resident gut microorganisms, which are often referred to as the gut microbiota, are crucial for health throughout life. Many studies in animals indicate that the microbiota has a key role in ensuring proper fetal development in the face of environmental stressors. However, what contributions maternal microbes might make to embryo development in the absence of such stressors remain poorly understood. Vuong *et al.*[1] report on page 281 that, in pregnant mice, specific maternal gut bacteria produce molecules as metabolic by-products that influence the neural development of certain sensory pathways in the fetus, leading to lasting behavioural changes in offspring.

Over the past decade, animal studies have demonstrated that the gut microbiota can have marked effects on the development of the central nervous system and on an individual's subsequent behaviour. In mice, the maternal gut microbiota is necessary for maintaining normal fetal development after maternal inflammation[2], and changes in the

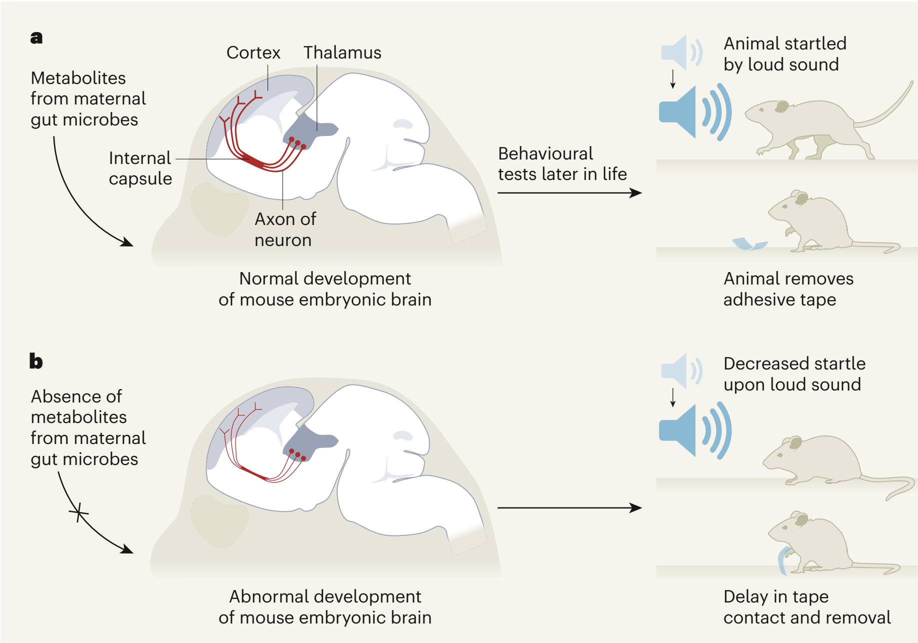

Figure 1 | Molecules from maternal gut microbes affect mouse embryonic brain development. While developing *in utero*, mouse embryos receive metabolites from maternal gut microorganisms. Vuong *et al.*[1] report that these metabolites aid normal wiring by neuronal projections called axons that connect brain regions called the thalamus and the cortex. Such connections are needed for sensory processing. **a**, During normal development, these axons form a thick bundle at a structure called the internal capsule. When these mice became young adults, they responded normally to behavioural tests, 'startling' and moving in response to a sudden increase in sound loudness, and quickly touching and then removing adhesive tape attached to their paws. **b**, If pregnant mice lacked their usual gut microbes and their fetus did not receive maternal microbial metabolites, then neurons forming thalamocortical projections had axonal defects, including thinner-than-normal axons. These animals displayed behavioural abnormalities when tested.

maternal microbiota due to a high-fat diet lead to neurobehavioural abnormalities in offspring[3]. However, it is not clear whether these effects of the maternal microbiota are restricted to events during gestation, or whether they occur mainly postnatally, as a result of maternal transmission of microbes to offspring[4].

Vuong and colleagues provide insight into the role of the maternal microbiota in prenatal development under non-stressed conditions. The authors report that brain structure in the embryos of pregnant mice that were germ-free (animals living in sterile conditions and lacking a microbiota), or whose microbiota had been depleted by antibiotic treatment, was different from that of embryos whose mothers had a normal microbiota. These changes in brain structure were relatively specific to circuits involved in sensory processing. Thus, in mid-gestation-stage embryos of microbiota-deficient mothers, the neuronal projections (axons) connecting a region called the thalamus to another region, the cortex, were smaller and shorter, and the axon bundles in an axonal grouping called the internal capsule were thinner, than were those of embryos from mothers with a normal microbiota (Fig. 1). The authors also observed marked differences in gene expression, including for genes linked to axon formation, in brain cells from the two types of embryo.

The thalamus is a major 'relay station' in the brain, directing sensory and motor information received from the environment to the appropriate cortical targets to mediate a suitable behavioural response. These thalamocortical projections, which are established by migration processes that occur during embryonic development, create lasting connections to cortical regions involved in auditory, visual, somatosensory (relating to the perception of sensations such as pain or pressure) and motor responses. To determine whether the effects observed were due to the deficient maternal microbiota, Vuong *et al.* used a co-culture system of neurons taken from embryos and grown *in vitro*. This revealed that the impaired growth of embryonic axons from microbiota-deficient mothers could not be corrected by adding growth factors produced by embryos of mothers with an intact microbiota.

Realizing that the microbiota was necessary for the development of these thalamocortical projections, Vuong and colleagues investigated whether the disrupted thalamocortical neuroanatomy had lasting consequences in offspring. The authors examined the offspring of germ-free and antibiotic-treated mothers in adulthood, using a range of behavioural tests to look for any sensorimotor deficits. They found that mice born to mothers with a deficient microbiota had impaired responses to heat, sound and pressure compared with animals whose mothers had a normal microbiota (Fig. 1). The authors observed no problems in visual or motor-coordination tests.

To determine which bacteria in the maternal microbiota were responsible for the positive effects on offspring neurodevelopment and behaviour, Vuong and colleagues performed a series of experiments in which previously germ-free mice were inoculated with specific bacterial groups. When spore-forming *Clostridium* species of bacteria were used, the abnormalities in offspring brain development and behaviour did not occur, suggesting that these bacteria normally aid neurodevelopment.

Although there is strong evidence for a connection between gut microbes and the brain, uncovering the underlying mechanism can be difficult. One possible means of transmission between these distant sites is by metabolite molecules that are produced by gut microbes and absorbed into the bloodstream[5,6]. During pregnancy, these metabolites, along with other nutrients from the maternal circulation, are transported by way of the placenta to the fetus. Vuong and colleagues hypothesized that the maternal microbiota might be the source of these metabolites for the fetus. Using an approach called discovery metabolomics, the authors found that the maternal microbiota affected the levels of many metabolites in maternal blood and fetal brain tissue.

Testing microbiota-derived metabolites, Vuong *et al.* found that maternal supplementation of certain metabolites could rescue the effects of a deficient microbiota on axon growth *in vitro*. Excitingly, such supplementation in microbiota-deficient pregnant mice also prevented the behavioural deficits that would otherwise have occurred in their offspring.

This work not only contributes to the growing field of research on how the gut microbiota affects the developing brain, but also sets the stage for future work. At present, the details of how these microbiota-derived metabolites affect developing neurons are unclear. Nor do we fully understand why the effects are at least somewhat specific to neurons in the thalamocortical sensory-relay pathways, particularly in neurons mediating heat, sound and pressure detection. Further research should help to clarify the molecular mechanisms underlying this phenomenon.

Finally, although these findings are from mice, this work might be relevant to human health in medical settings in the future. Understanding the composition of the maternal microbiota and the metabolites that reach the fetus presents a clear potential pathway for the development of clinical interventions.

One such possibility is characterization of the levels of maternally provided molecules that could be used as 'biomarkers' to monitor development for signs of abnormalities. If it turns out that the level of specific metabolites can be supplemented to help fetal brain development, in the way that folic acid supplements are given during pregnancy to prevent neural-tube defects, the implications for reducing neurodevelopmental disorders and promoting healthy brain development could be enormous. Much work would still need to be done before any clinical trials assessing such an approach could begin. Nevertheless, Vuong and colleagues' work provides a necessary foundation for understanding how the maternal microbiota affects normal brain development.

Katherine R. Meckel and **Drew D. Kiraly** are in the Nash Family Department of Neuroscience and the Department of Psychiatry, Icahn School of Medicine at Mount Sinai, New York, New York 10029, USA.
e-mail: drew.kiraly@mssm.edu

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Astronomy

The early onset of planet formation

Patrick Sheehan

Narrow rings and gaps have been seen in a particularly young disk of dust and gas around a nascent star, using the world's most powerful radio telescope. The finding provides a potential glimpse of the earliest stages of planet formation. **See p.228**

Young stars are typically surrounded by rotating disks of gas and dust, called protoplanetary, or protostellar, disks. These structures are, crucially, the reservoirs of material that go on to form planets, but when the planet-forming process begins is a major open question. On page 228, Segura-Cox *et al.*[1] cast light on this mystery by reporting a series of rings and gaps in a protostellar disk that is so young that its birth cloud is still collapsing to form the star and disk. Such features are frequently attributed to planets carving lanes through the disk. Given that this is perhaps the youngest disk observed to have such features, the findings help to set the timescale for the emergence of planets and place key constraints on theories of how planets assemble.

Planet formation is a complex process that involves tiny dust particles (less than one micrometre in size) accumulating until they become Earth-sized bodies, or even larger. The most popular theory that has been proposed to explain this process is core accretion[2], in which the steady accrual of small particles produces pebbles, rocks, boulders and eventually planets. One potential problem with this scenario is that planet formation can be slow, which seems to be at odds with the observation that protostellar disks older than about one million years do not seem to have enough material in them to form planets[3]. Updates to the theory have been proposed to remedy this[4,5], but, ultimately, the only way to refine models of core accretion is to determine how long it takes for planets to actually form. Naturally, the best way of doing this is to find baby planets in young disks.

One approach for detecting baby planets is to find evidence of their influence on the structure of the disk in which they are embedded. In the past five years, the Atacama Large Millimeter/submillimeter Array (ALMA) observatory in Chile has provided a wealth of high-resolution imagery of protostellar disks older than one million years. An abundance of interesting 'substructures' has indeed been found[6].

Most common are the narrow bright and dark rings that might be signs of a planet carving out gaps in the disk as it circles the star – although other features, such as spirals or large asymmetries in the distribution of material in the disk, have also been observed. One striking result is that these substructures, which might be related to planet formation, seem to exist in almost every protostellar disk that has been imaged with sufficiently high resolution to detect them[7]. The 'planets carving gaps' scenario would imply that planets can be formed in about one million years.

The frequency with which planets have been detected in disks that are more than one million years old raises questions about the earliest time at which planets, or at least disk substructures, can form. A few examples of younger disks (500,000–1,000,000 years old) with substructures have been found[8], but these are not much younger than the substructured systems that were observed before them.

Segura-Cox and colleagues' work pushes past this age limit, finding the first clear evidence of narrow bright and dark

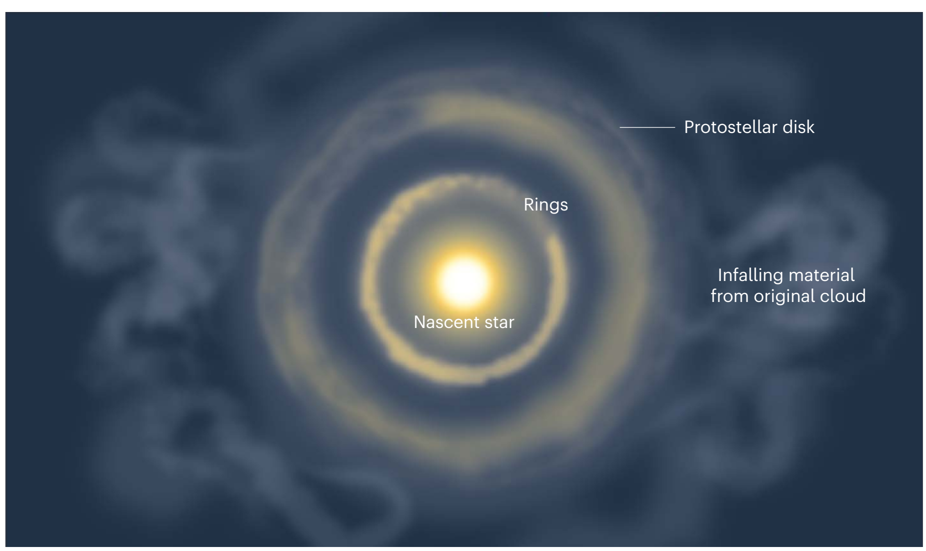

Figure 1 | Rings in a young protostellar disk. Stars form when a cloud of dust and gas collapses to produce a denser disk of material, known as a protostellar disk. The star forms at the centre of the disk, whereas planets can form from the disk material. Segura-Cox *et al.*[1] report observations of a protostellar disk that is so young (less than 500,000 years old) that the disk is still surrounded by an envelope of material from the original cloud. Rings visible in the disk could be signs of planetary formation; the rings in the actual system are very faint (see Fig. 1 of the paper[1]), but are shown more prominently here, for clarity. The findings cast light on the earliest time at which planets can form in protostellar disks.