Magnetic fields are everywhere around us, from the ones generated by small kitchen magnets to the Earth’s own field, which shields us from the solar wind. Although our understanding of terrestrial magnetic fields has greatly advanced over the years, if we look further in space a lot is still unclear. The Universe is intrinsically magnetized: galaxies have large-scale, ordered magnetic fields, and in more ‘exotic’ objects such as gamma-ray bursts — the brightest events known to occur in the universe — magnetic fields are prime suspects for unusual particle acceleration (Fig. 1). How these magnetic fields are initially generated and subsequently amplified to produce such extreme events is still an open question.

Now, as they report in Nature Physics, Channing Huntington and colleagues have found solid experimental evidence of laboratory magnetic fields self-generated through a process known as the Weibel instability.

In theoretical work published more than 50 years ago, Erich Weibel postulated that a magnetic field could be generated in a plasma — a ‘hot soup’ of free ions and electrons — without the need for an initial magnetic field. For this to occur, the charged particles in the plasma must have an anisotropic velocity distribution that causes them to bunch up and form current filaments, leading to the generation of strong magnetic fields. One way of maximizing this anisotropy is to use two plasma beams flowing in completely opposite directions. However, there is a ‘catch’: if the charged particles between the opposite plasma flows collide too often, their kinetic energy can dissipate through a shock wave and the Weibel instability won’t be seeded. Thus, the interaction has to be ideally ‘collisionless’.

The experiments performed by Huntington et al., involving two counter-streaming plasma flows, fulfil the necessary conditions. The plasmas were produced at the OMEGA laser facility, where a number of simultaneous short-pulse laser beams with durations of one nanosecond were focused onto two carbon-based foils oriented face-on, separated by a few millimetres. The extremely high laser intensities rapidly heated the foils and produced two opposite blow-off carbon plasmas. As carbon is a relatively light material, the plasmas can propagate very fast, with velocities of 1,000–2,000 km s⁻¹. These high flow speeds lead to a collisionless counter-streaming interaction, ideal for sparking the Weibel instability. Shortly after the moment when the plasmas interacted at the midpoint between the foils, a series of filaments, aligned with the direction of the flow of charged particles in the plasma, was observed — a clear indication of the formation of the Weibel instability.

But are these filaments due to self-generated magnetic fields? Imaging and measuring magnetic fields is difficult as they cannot be observed directly, but, in a way similar to electric fields, they do affect charged particles. To visualize the experimentally obtained magnetic structures, the authors used a technique known as proton radiography: a beam of energetic protons (with energies on the order of several MeV) are sent through the plasma and their deflection due to magnetic fields is recorded at the other end. The proton beam is produced with intense lasers that implode a tiny deuterium-filled capsule, and the protons are a by-product of fusion reactions. The proton beam can be produced with sub-nanosecond accuracy, enabling measurements of the growth of the magnetic structures and their characteristic.

Figure 1 | Composite X-ray (blue and green), infrared (yellow and orange) and radio (pink) image of supernova remnant W49B, which is believed to be the result of a gamma-ray burst that took place a few thousand years ago in the Milky Way. A possible explanation for the occurrence of cosmic gamma-ray bursts involves the Weibel instability, leading to the self-generation and subsequent amplification of magnetic fields within a plasma. Huntington et al. have now succeeded in generating a Weibel instability in a laboratory laser-generated plasma.

PLASMA PHYSICS

How to spark a field

The successful formation of self-generated magnetic fields in the lab using large-scale, high-power lasers opens the door to a better understanding of some of the most extreme astrophysical processes taking place in the Universe.

Francisco Suzuki-Vidal
wavelength in separate but reproducible experiments. It is worth pointing out that extracting physical parameters from the results of proton radiography presents an interesting challenge. As with other point-projection imaging techniques, the probe beam passes through an inherently three-dimensional object, which leads to a path-integrated measurement of a physical quantity. The deflection of protons due to Weibel-generated magnetic fields increases the level of complexity when interpreting the results, as the fields could be randomly distributed as a function of space. Measuring the separation between the Weibel-generated filaments could be thought of as inferring the spatial distribution of trees in a forest by watching light scattered through the trees. Nevertheless, the authors get around this problem by performing state-of-the-art numerical simulations that not only examine the interaction between the counter-streaming plasmas but also reproduce the interaction between the proton beam and the Weibel-generated magnetic fields, leading to a fully-simulated proton radiograph. The simulations and theoretical analyses of Huntington et al. are in excellent agreement with their experimental results.

The experimental observation of the Weibel instability is one of many ongoing efforts to study astrophysical phenomena in the laboratory. Laboratory experiments are becoming an essential part of what used to be a ‘members only’ club for observations and numerical simulations in astrophysics. Although the results of Huntington et al. are extremely promising, the formation of a fully-mediated, electromagnetic collisionless shock — one of the main challenges for laboratory astrophysics — has not been realized yet. This could possibly be achieved if the experiments are scaled up to a bigger laser such as the National Ignition Facility (NIF) — the largest high-power laser facility in the world (http://go.nature.com/WhrGwS).

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TEN YEARS OF NATURE PHYSICS

The monopole movement

The monopole picture for spin ice offers a natural description of a confounding class of materials. A 2009 paper in Nature Physics applied it to study the dynamical properties of these systems — sparking intense experimental and theoretical efforts in the years that followed.

Claudio Castelnovo

The rich and complex behaviour of strongly correlated many-body systems is often best interpreted in terms of effective degrees of freedom that abstract from the microscopic constituents of the model. Once identified, these degrees of freedom can provide a natural framework for understanding the principal characteristics of the specific system under investigation.

Spin ice is a case in point. Coined as an analogy with water ice, the term proved to be an appealing and intuitive means for understanding the geometric origin of the low-temperature thermodynamic properties of rare-earth pyrochlore magnets such as Ho₂Ti₂O₇ and Dy₂Ti₂O₇ (Fig. 1), most notably their residual entropy. However, the extent to which the analogy worked seemed to involve an almost miraculous degree of fine-tuning. The holmium and dysprosium magnetic moments have non-collinear easy axes and long-range, anisotropic dipolar interactions — a rather complex scenario as far as classical spin systems go. Indeed, it took almost a decade until the monopole excitations. This breakthrough made it possible to connect the physics of spin ice with models and techniques from seemingly unrelated areas of research, such as Coulomb liquids and random walks. It also set off a hunt to prove that emergent monopoles were real and not just convenient bookkeeping concepts.

It is against this backdrop that, writing in Nature Physics in 2009, Ludovic Jaubert and Peter Holdsworth focused their attention on the dynamical properties of spin ice, which at the time were poorly understood. They incorporated Coulomb interactions between monopoles into a pre-existing theory of non-interacting dynamics. They devised an efficient computational scheme that combines the energetics of dilute magnetic monopoles with the entropies of bulk spin ice, permitting detailed studies of remarkably large systems. They were thus able to show that magnetic relaxation measurements in Dy₂Ti₂O₇ (ref. 10) can be described in terms of the diffusive motion of monopoles in the presence of long range Coulomb interactions and an underlying network of ‘Dirac strings’.

Figure 1 | Crystals of Ho₂Ti₂O₇ and Dy₂Ti₂O₇, spin ice.

mechanism for this apparent fine-tuning was explained mathematically.

Even so, it was not until much later that the ‘natural’ degrees of freedom for describing this behaviour were identified: at low temperature, spin ice can be viewed as a vacuum that hosts emergent magnetic