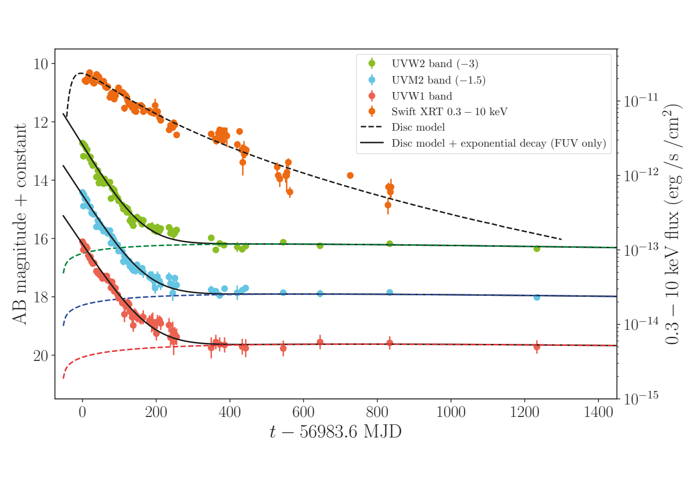

Fig. 1

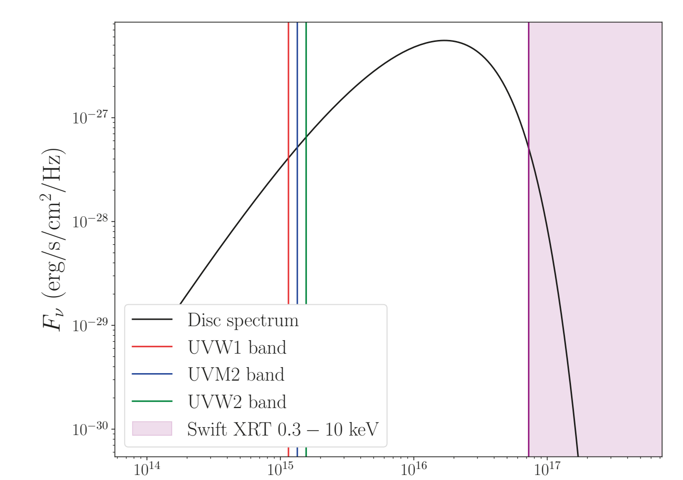

Fig. 2

spectrum and deduce the hole's mass and angular momentum. We have noted that the physics of the accretion process must be very well-understood if this scheme is to work, and such a crude uncertainty as not knowing the proper ISCO boundary condition renders this hope all but futile. So theorists found themselves constantly arguing about the ISCO stress.

Is it possible to deduce the ISCO stress from the disc spectrum? While in principle the answer is yes, for steady accretion this turns out to be very challenging to do, because its spectral influence is small. However, in an evolving disc, such as one might expect to find in a TDE, the answer that my student Andrew Mummery and I have found is much more interesting. We derived and solved the general relativistic equation for the evolution of a disc in Kerr geometry. As in the original Rees 1988 model, the total luminosity follows a power law time dependence at late times, $L \sim t^{-n}$. But now, the value of n turns out to have a bimodal behaviour. If the ISCO stress vanishes, $n>1$. If the ISCO stress is finite, $n<1$. Very convenient!

In 2017, a comprehensive study by K Auchettl, J Guillochon, and E Ramirez-Ruiz distilled, from a long list of candidates, four 'confirmed' TDE events based on a list of strict criteria, including a bullseye association with a galactic centre. Every one of their four candidates has power law X-ray luminosities with an index $n<1$. This is very strong evidence, not only for a disc to source the TDE emission, but one with a finite ISCO stress.

Emboldened by this success, Andrew has calculated detailed disc spectra based on both the narrow (far ultra-violet, or FUV) and broad (X-ray) band passes of the *Swift* X-ray satellite for the source known as ASSASN-14li. The acronym comes from the All Sky Survey of Automated Supernovae, a programme that is also well-suited to finding transient TDEs. ASSASN-14li has been observed over an extended period after its initial 2014 flare-up, and there are high-quality X-ray and FUV data. These are shown in fig. 1, along with fits to a single disc model.

The narrow FUV bands are observed to be very flat with time. This is completely consistent with a disc model. A disc spectrum is a superposition of local blackbodies. A readily identifiable Rayleigh-Jeans tail, peak, and Wien-like exponential cut-off are all present (see fig. 2). As a disc evolves and cools, the emission peak moves downwards in frequency. At a given observed frequency, just before the peak, the emission would therefore rise as the hump passed through, like a wave. But counteracting this rise at all frequencies is a general decline from cooling. For an extended time period, the rise and decline turn out to nearly balance one another. This is precisely what the FUV data show, in all three bands.

The X-rays tell a different story. Here, the emission comes from the Wien-like portion of the spectrum, and as time evolves, there is exponential decline with a power law coefficient. This combination fits the data beautifully as well. Both the FUV and the X-rays are reproduced by a single disc model. One of the by-products of the analysis of particular observational interest is an explicit, yet very general, mathematical prediction of the form that the decline in high energy X-ray luminosity should follow: neither a power law, nor pure exponential, but a simple product of the two, which mimics a power law over a restricted sampling interval.

CONCLUSION

LIGO and its sister observatories have made black hole gravitational radiation studies an indispensable component of the toolbox of modern astronomy. The astrophysical origin of the merging black hole binaries that form the bulk of gravitational wave sources is a stimulating puzzle for astronomers. The formalism for theoretical accretion disc studies, developed to help the early search for black holes, has meanwhile taken on a life of its own. Andrew Mummery and I have pushed the development of disc theory a step further, developing mathematical tools to study novel astrophysical events: the tidal destruction of a star passing close to a supermassive black hole. We are able to account for the disc emission spectrum of the one well-observed source, ASSASN14-li, in the process showing that this truly is a disc source with a *finite* ISCO stress (the strongest observational argument for this thus far advanced), and tightly constraining the mass of the black hole (just shy of two million solar masses). With most of the richest observations yet to come, the study of the tidal disruption of stars by supermassive black holes promises to remain lively and exciting for the foreseeable future.

Fig. 1: The top curve shows a theoretical fit to the light curve of the integrated X-ray spectrum of the Swift satellite, from 0.3 keV to 10 keV. It is well fit by the product of a declining power law and exponential cut-off in time. The three curves below are narrow FUV bands, fit without changing the X-ray inferred disc parameters. The FUV emission is quite flat with time.

Fig. 2: A typical disc spectrum at one point in time. It is broader than a single temperature blackbody, but has an identifiable low frequency (Rayleigh-Jeans), mid frequency (power law), and high frequency (Wien) regimes. The narrow FUV bands are shown as coloured lines; the broad Swift X-ray bandpass is shaded.

DISCOVERY OF MAGNETIC MONOPOLE NOISE

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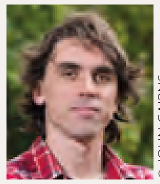
The nineteenth century saw teams of explorers from around the world take to the ices in search of the poles. The twenty-first century has again seen teams pulling together to find the poles – but this time, the task is to isolate the individual poles of a magnet. It is not the icy expanses of the tundra which we search, but insulating crystals known as 'spin ice'...



Dr Felix Flicker

Prof Stephen J Blundell

Prof Séamus Davis

Right: Fig. 1: Schematic of a fundamental Dirac monopole traversing the SQUID input coil. The magnetic-flux threading of the SQUID changes in total by $\Phi_0 = h/e$.

Bottom: Fig. 2: A line of bar magnets (top panel) ordered with north poles on the left and south poles on the right. Flipping one of them (middle panel) costs energy because you have two adjacent poles of the same type. Further magnet flips (bottom panel) cost little energy but separate the monopoles.

THE ELUSIVE MAGNETIC MONOPOLE

Our unified understanding of electricity and magnetism is encapsulated in Maxwell's equations. These describe the effects of point-like electric charges (electric monopoles) on the statics and dynamics of the electric and magnetic fields. One of Maxwell's equations can be stated in words: 'there is no such thing as magnetic charge' because no sources or sinks of magnetic field (magnetic monopoles) are described in the theory. But Maxwell's equation merely quantifies the experimental observation that we've never seen a magnetic monopole. If we detected magnetic monopoles, the law would have to be updated.

There are reasons to think such an observation may be possible. Some implications of the existence of magnetic monopoles in a quantum theory were discussed by Paul Dirac as early as 1931. Dirac noted that the existence of even a single magnetic monopole in our observable Universe would explain why all electric charge is quantised. Dirac's description also made clear that, in order to avoid the quantum phase of the electron becoming observable, there must exist an unobservable ('gauge-dependent') line of magnetic flux tethering any monopole to an anti-monopole. We now term this a 'Dirac String'. Moreover, magnetic monopoles are predicted by modern theories of physics 'beyond the standard model', including string theories and various theories of quantum gravity.

Particle physics searches for fundamental magnetic monopoles have been ongoing since the 1970s. Such a magnetic charge can, in principle, be detected by the quantised jump in magnetic flux Φ it generates upon passing through the loop of a superconducting quantum interference device (SQUID). Fig. 1 shows a schematic of such a SQUID-based magnetic monopole detector.

Using this classic technique, a single apparent observation of a fundamental magnetic monopole on 14 February 1982 (the St Valentine's Day Monopole) was never duplicated, and subsequent searches have proven negative.

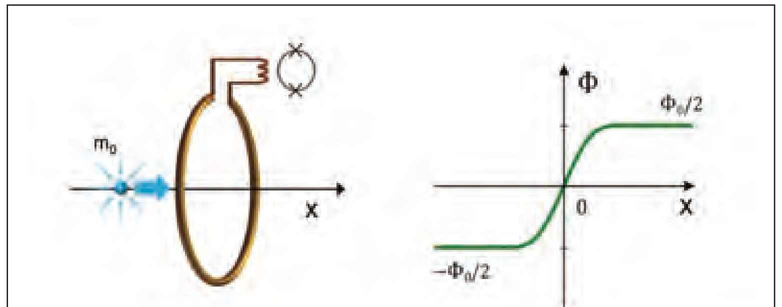


Fig. 1

A SOLUTION EMERGES

All is not lost, however, because condensed matter physics can come to the rescue. Condensed matter physics, while not concerned with fundamental particles, allows the appearance of quasiparticles with emergent properties. We live in a Universe which is filled with quantum fields and we regard particles as excitations of those fields. However, inside a solid there is a periodic arrangement of atoms with mobile electrons that can be so strongly interacting as to generate their own very exotic quantum fields. The net result of these interactions is that new particles can then emerge as excitations of the quantum fields in the low-energy sector of the Hamiltonian of the solid. This means that each type of condensed quantum matter that we study is a new Universe, with a different set of rules, and a different set of emergent particles. Can we therefore find a material in which the emergent particles are monopoles?

Let's build things up slowly. If we start thinking about building a periodic material in one-dimension, we can imagine a one-dimensional chain of magnets, each one lying with its north pole next to its neighbour's south pole. This is a stable situation and we simply have a line of dipoles. But we can imagine reversing one of these magnets. This creates two adjacent north poles and two adjacent south poles, not an energetically favourable situation. By flipping further magnets, we can move

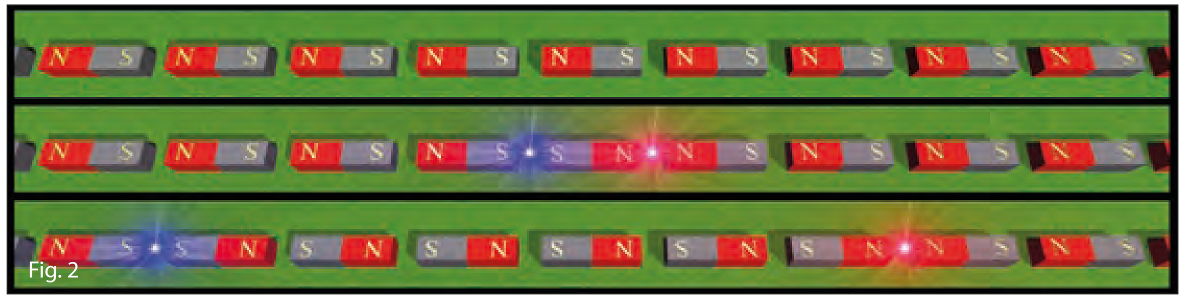


Fig. 2

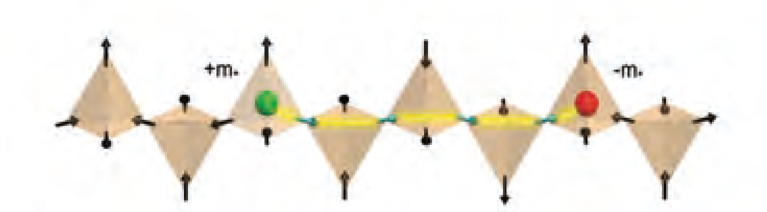


Fig. 3

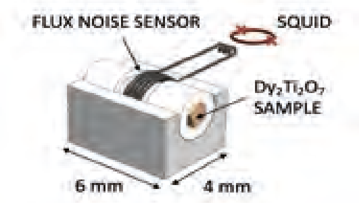


Fig. 4

Fig. 3: Schematic representation of the spin ice excited state in which two magnetic charges are generated by a spin flip and propagated through the material.

Fig. 4: Schematic of the Spin Noise Spectrometer.

the double-north and the double-south apart without much extra energetic cost. You can see that where we started with one flipped dipole, we now have two objects that behave like independent particles that can travel along the chain. Breaking a magnetic dipole in two, we have made two independent magnetic monopoles. In the jargon, our original excitation (the flipped magnet) has been fractionalised. The line of flipped spins between these emergent monopoles plays the role of the Dirac string.

THE ROUTE: SPIN ICE

The challenge in finding emergent magnetic monopoles, then, is to find a real material which performs this feat in three dimensions. Enter the spin ices (Fig. 3). The highly magnetic Dysprosium or Holmium ions in these materials live on a lattice of corner-sharing tetrahedra. The lowest-energy state of the system has the magnetic moments of two ions – their spins – pointing in, and two out, of each tetrahedron. This unusual property, discovered in crystals of dysprosium and holmium titanate by Steve Bramwell (UCL, DPhil Oxford) and Mark Harris (RAL, and later a Chaplain at Oriel College), led to these materials being called spin ices, by analogy with the proton configurations in water ice. The prediction of magnetic monopoles in this material, specifically because the two-in two-out configuration allows a chain of spin flips to occur during which an emergent magnetic monopole with magnetic charge +m* and anti-monopole with charge –m* can separate (Fig. 3), was made about ten years ago by Claudio Castelnovo and Roderich Moessner (both then at Oxford) along with Shivaji Sondhi of Princeton. Most of the world's supply of spin ices is grown in Oxford by Dharmalingham Prabhakaran.

THE EXPEDITION

The Oxford expedition in search of the poles began with a theoretical proposal to harness recent developments in nanoscale magnetometry[1]. The key realisation was that, while emergent magnetic monopoles would be confined within the spin ices, their magnetic fields could still be felt outside the sample. These fields feature a distinctive inverse-square law decay, as opposed to the inverse-cube law decay of the field from a magnetic dipole. The original proposal was that a sufficiently sensitive nanoscale detector of magnetic fields could, in principle, detect these magnetic fields at the surface of a spin ice sample. But very large numbers of emergent magnetic monopoles are expected to be moving around at random within the crystal, so that the magnetic fields should be wildly fluctuating. In this context, DPhil student Fran Kirschner, in collaboration with Felix Flicker in work led by Stephen Blundell, carried out numerical simulations of the magnitude and frequency dependence of the magnetic field noise that should be generated by a fluctuating fluid of magnetic monopoles.

Looking for a signature in fluctuations is an interesting approach, since physicists usually regard noise as the thing which has to be separated from the signal. But here the noise *is* the signal! In fact, it has been known for many years that the character of noise yields numerous clues explaining its origin. Noise has colour: white noise has a uniform power spectrum S, with equal intensity across all frequencies f: $S(f)\approx$const. Pink noise, on the other hand, has a power spectrum which falls off in inverse proportion to the frequency: $S(f) \propto 1/f$ (hence its other moniker, $1/f$ noise). Simulations showed that while the movement of the monopoles is random, it is also constrained by the presence of the Dirac strings. It turns out these constraints should also be revealed in the noise, which is predicted to fall off as $S(f) \propto 1/f^b$ with b between one and two (somewhere between pink and red), and varying characteristically with temperature.

Then in 2018, Séamus Davis and his group, intrigued by the ingenious proposal to find the poles using their magnetic noise, joined the expedition. In work conducted by DPhil student Ritika Dusad, they proposed to detect the predicted magnetic monopole noise by using the classic magnetic monopole detector – the input loop of a SQUID. Ritika developed a flux-noise spectrometer using a six-turn superconducting pickup coil (Fig. 4) connected to a SQUID, and optimised it for the predicted magnetic noise signal of $Dy_2Ti_2O_7$ spin ice. This is the condensed matter physics version of the classic magnetic monopole search apparatus shown in Fig. 1.

This set-up allowed the study of the magnetic-flux noise not just at the surface, but throughout the bulk of the crystal. They used it to determine the flux noise spectral density of the $Dy_2Ti_2O_7$ spin ice samples over a frequency range $1\text{Hz}<f<2.5\text{kHz}$ in the temperature range $1.2\text{K}\leq T\leq 7\text{K}$, both predicted to be optimal for detection of most intense magnetic noise spectra from the millimetre-scale $Dy_2Ti_2O_7$ crystal. The experiments were successful, revealing that mm-scale $Dy_2Ti_2O_7$ crystals spontaneously generate magnetic-field noise of magnitude 10^{-12} Tesla and below. They found that the magnetic-flux noise spectral density of $Dy_2Ti_2O_7$ is constant for frequencies from near 1Hz up to an angular frequency $\omega(T)\sim 1/\tau(T)$, above which it falls off as ω^{-b} where b spans a range between 1.2 and 1.5. They also observed the strange fact that had been predicted by the simulations, that the magnetic noise should increase rapidly with falling temperature proportional to $\tau(T)$. Thus, the SQUID-based flux-noise spectrometry experiments had detected (Fig. 5A) virtually all the features of the magnetic noise predicted for a dense fluid of magnetic monopoles (Fig. 5B). The team had found the poles[2].

There was also a striking bonus effect. As scientists, we are used to studying data plotted on graphs and we spend a lot of time looking at our data in lots of different ways to try to understand what is going on. Visualisation techniques are therefore key in physics. However, much less common is the opportunity to listen to our data. Extraordinarily, because this magnetic monopole noise occurs in the frequency range below 20 kHz, when amplified by the SQUID it is actually audible to humans.

AS SCIENTISTS, WE ARE USED TO STUDYING DATA PLOTTED ON GRAPHS AND WE SPEND A LOT OF TIME LOOKING AT OUR DATA IN LOTS OF DIFFERENT WAYS TO TRY TO UNDERSTAND WHAT IS GOING ON. MUCH LESS COMMON IS THE OPPORTUNITY TO LISTEN TO OUR DATA. LUCKILY THIS MAGNETIC MONOPOLE NOISE OCCURS IN THE FREQUENCY RANGE THAT IS AUDIBLE TO HUMANS.

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Fig. 5. Left: simulated noise spectral density S(w, T) in temperature range 4K to ~1K which one might expect to achieve by cooling $Dy_2Ti_2O_7$.

Right: measured noise spectral density from $Dy_2Ti_2O_7$ samples in the range 1.2K≤T≤4K. Red axes indicate spectra scaled for B-fields, blue axes (matching scales) spectra scaled for magnetic flux.

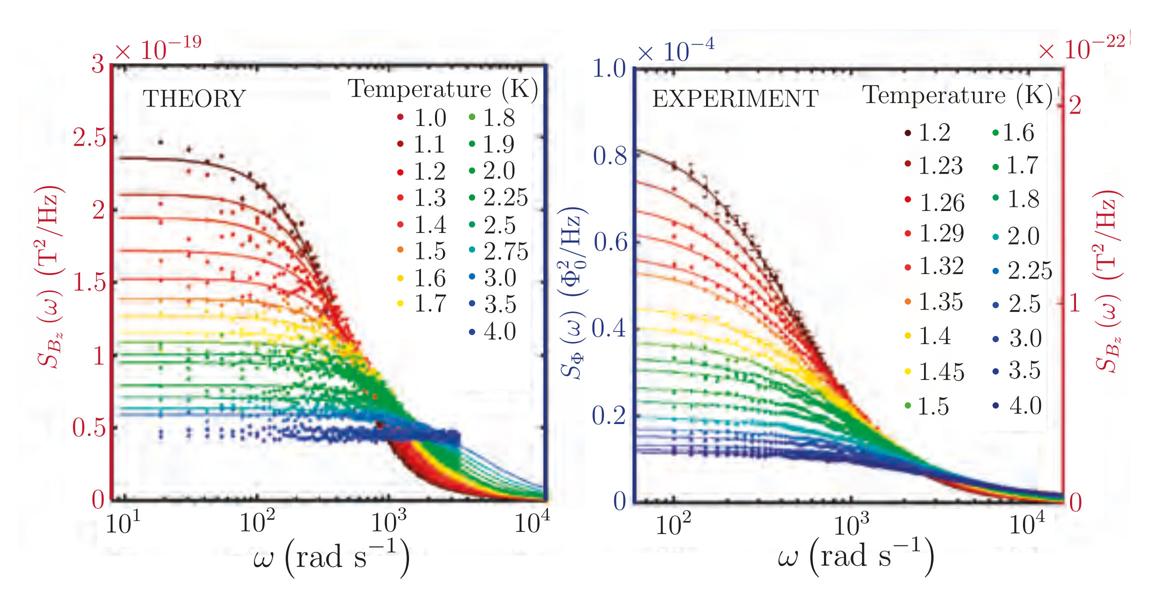

Fig. 5

NEW FRONTIERS

Returned from such an expedition, the explorer's thought must surely be to the next challenge. Possible applications for magnetic monopoles in spin ices include the creation and manipulation of 'magnetricity', a magnetic version of electricity. But the detection of a single magnetic monopole is still a key goal for this team. Our SQUID-based detection technique had provided the first experimental evidence of magnetic monopoles which has a single-particle limit: while we heard the collective noise of many monopoles, the same basic approach at yet higher sensitivity could in principle be used to detect individual magnetic monopoles. So, our follow-up projects have begun, to better understand the monopoles' noise signatures in different contexts; to detect the individual emergent magnetic monopoles; and to apply the same measurement techniques to explore other exotic magnetic systems.

Are Maxwell's equations still correct? No physics needs to be unlearned yet, as the monopoles in spin ice are emergent (for those that can remember their electromagnetism, these monopoles are divergences in H and not in B) and Maxwell's equations remain unbroken. But these results demonstrate the power of using spin noise spectroscopy to study many different exotic magnetic systems which will contain numerous different species of emergent particles. Rather than wait for the Universe to deliver a rare, exotic magnetic particle to a detector, one can now explore the universes of quantum matter, studying such particles by the noise and eventually the signal they produce.

1 F K K Kirschner, F Flicker, A Yacoby, N Y Yao, and S J Blundell, Proposal for the detection of magnetic monopoles in spin ice via nanoscale magnetometry, *Physical Review* B 97, 140402 (Rapid Communications) (2018)

2 R Dusad, F K K Kirschner, J C Hoke, B R Roberts, A Eyal, F Flicker, G M Luke, S J Blundell and J C S Davis, Magnetic Monopole Noise, *Nature* 571, 234-239 (2019)

Below: An artist's impression of spin ice monopoles.