Using meteorite magnetism to elucidate early solar system history – MMESSH

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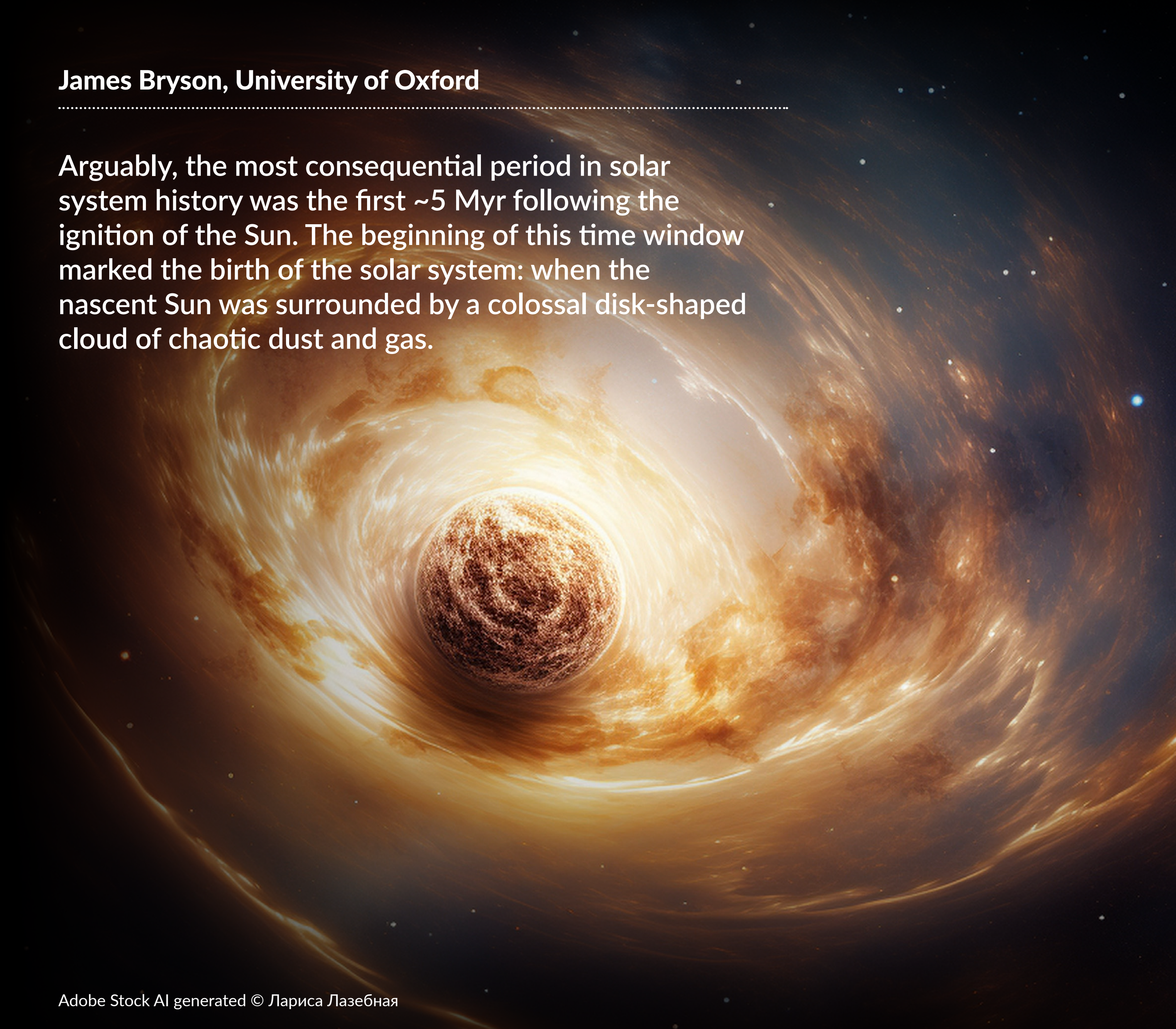
Arguably, the most consequential period in solar system history was the first ~5 Myr following the ignition of the Sun. The beginning of this time window marked the birth of the solar system: when the nascent Sun was surrounded by a colossal disk-shaped cloud of chaotic dust and gas.



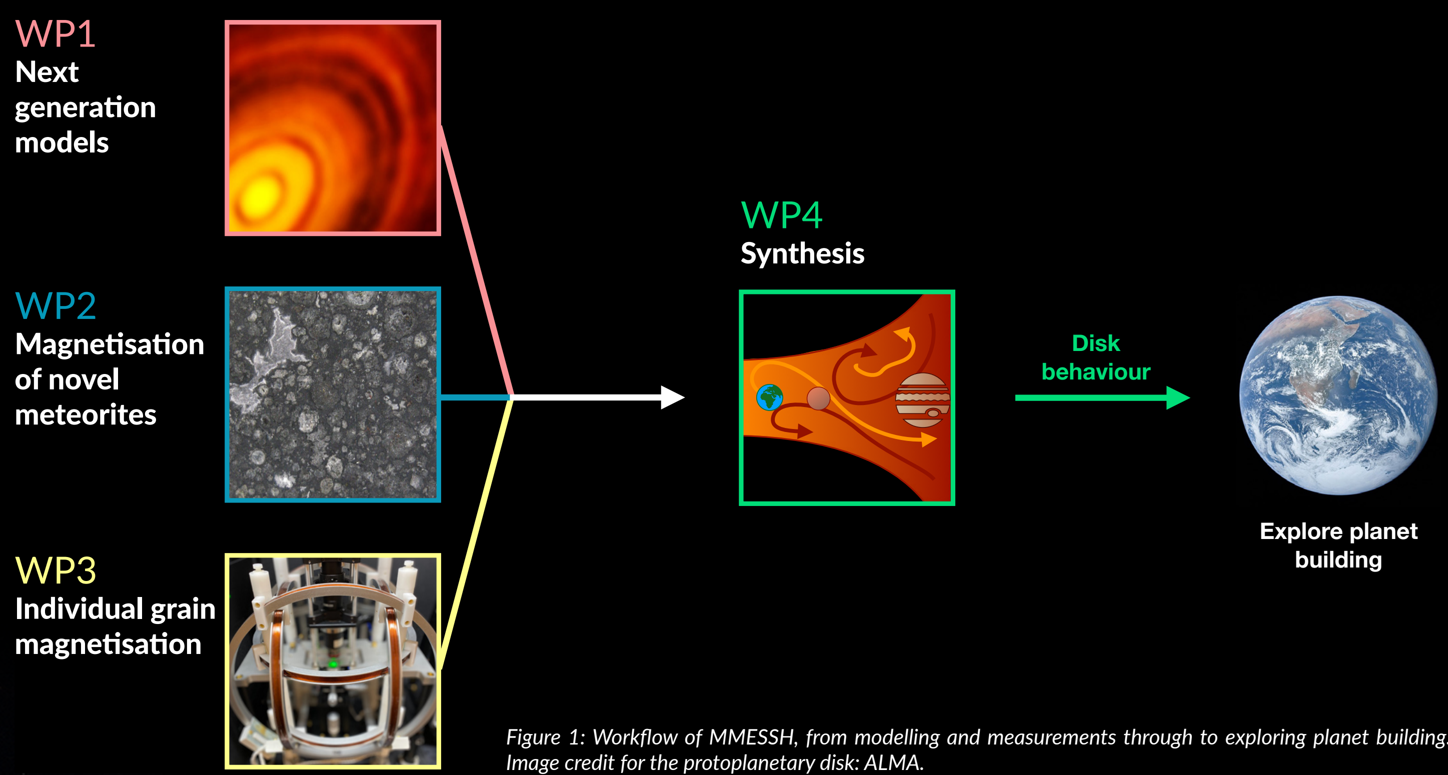


Figure 1: Workflow of MMESSH, from modelling and measurements through to exploring planet building. Image credit for the protoplanetary disk: ALMA.

By the end of this period, this protoplanetary disk had transformed into millions of asteroids, comets, planets and moons, each on its own determined orbit. This was, therefore, the pivotal period when the planets were born and their evolutionary pathways were set. How did the disk transform? What were the consequences of the disk's behaviour on the properties of the planets? Did the disk play a key role in planetary habitability? These questions, among others, are the focus of the MMESSH project, which will use ancient rocks that originate from throughout the solar system to illuminate the disk's behaviour and its role in planet building.

Magnetic rocks from space

Each year, ~16 million kilograms of extra-terrestrial material falls to Earth. This material encodes the evolution of our solar system and has yielded numerous invaluable insights, including the age of Earth, the inner workings of the Sun, and the history of comets. The vast majority of this material is tiny dust particles, but a small portion is meteorites—rocks that range from under 1 gram to more than 50 tonnes that are fragments of asteroids, the moon and Mars.

The aim of MMESSH is to utilise the magnetisation carried by meteorites to illuminate the behaviour of our disk and its influence on planet building. Like a hard drive, rocks can carry memories of the magnetic fields they experienced when they formed. Depending on the sample, this magnetic remanence can be stable for trillions of years. Fortunately, some meteorites that formed during the lifetime of the disk are examples of these very magnetically stable rocks. During this period, the particles of dust and gas that made up the disk were charged and in constant motion. As such, the whole disk generated a vast magnetic field via a process akin to the Earth, with the properties of this field reflecting the behaviour of the disk. These ancient meteorites can, therefore, have recorded magnetic remanences of this field, such that their magnetisations are unique archives of the disk's behaviour.

Thanks to several recent breakthroughs in instrumentation, modelling and meteorite characterisation, we are now on the cusp of reliably unlocking these archives. MMESSH will achieve this by measuring a variety of magnetisations carried by a suite of meteorites to recover the most complete magnetic history of the disk to date. The project will also build cutting-edge computational models of the disk to predict the most reliable properties of its magnetic field yet. By comparing these data and predictions, MMESSH aims to unlock several novel insights into the disk's behaviour and use these to elucidate the process of planet building.

Next-generation modelling of protoplanetary disks

The first work package will involve writing computational models of the protoplanetary disk. The intensity of the magnetic field created by the disk has been predicted previously by balancing forces in this cloud. These intensities agree broadly with existing measurements of the magnetisation of meteorites, giving confidence to this approach. However, these models are based on uniform disks, i.e. those with smoothly decreasing pressure profiles with increasing radial distance from the Sun. Over the last decade, the ALMA telescope has captured stunning, high-resolution images of distant disks, which show that these clouds contain rings and non-uniformities in their pressure profiles. Evidence for similar features in our own disk has also recently been inferred from the isotopic compositions of meteorites. These measurements indicate that our disk contained distinct regions, suggesting our disk was divided by at least one discontinuity. Together, these observations demonstrate that current models based on uniform disks do not accurately reflect the magnetic field that actually existed in our disk. As such, our ability to use models to translate observations from meteorites into the behaviour of our disk is currently limited.

Thankfully, several recent studies have derived the behaviour of rings and non-uniformities in protoplanetary disks. As such, we are now in a position to build these descriptions into magnetic field calculations of our disk and use these to predict the most realistic intensity profiles to date. Moreover, current models of the disk's magnetic field do not account for its evolution across the ~5 Myr lifespan of the disk. These new descriptions of non-uniformities include their temporal progression, so we are now also able to explore the time dependence of the disk's field for the first time. Work package one will construct these next-generation models of disks and run them for various scenarios to predict realistic profiles of the disk's magnetic field. Dr Jason Terry, who has joined MMESSH as a postdoctoral associate, will conduct this research.

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The magnetisation of novel meteorites

The second work package focuses on the bulk magnetisation of a fascinating subclass of meteorites. Meteorites are classified into various types based on their textures and compositions, with this work package focussing on a type called chondrites. These meteorites can be thought of as 'cosmic sedimentary rocks' because they are aggregates of the sub-millimetre solids that once floated freely through the protoplanetary disk. The first planetary bodies in the solar system—which were 10–500 kilometre-sized objects called planetesimals—formed through the agglomeration of trillions of these objects, and fragments of dozens of these bodies exist on Earth as meteorites.

Because planetesimals formed during the first 5 Myr of solar system history, the entirety of each of these bodies could feasibly have been magnetised by the disk's field. As such, chondrites can carry vital magnetic records. However, chondrites are notoriously complex rocks, which introduces several hurdles when studying their magnetisation. Firstly, the constituents of primitive chondrites are unstable magnetic recorders, likely preserving magnetic remanences for only ~10 000 years. As such, these meteorites cannot yield reliable records of the disk's ancient field. Secondly, the parent bodies of other chondrites incorporated appreciable amounts of ice, which melted to create water that reacted with the remaining components to produce a suite of secondary minerals. This suite includes magnetite, an iron oxide with a magnetisation that is routinely stable for trillions of years. Hence, unlike primitive chondrites, these evolved chondrites could feasibly preserve a magnetic record to the present day. However, this magnetite recorded its remanence during its formation reaction, which is a complex and poorly understood process. As such, our ability to reliably interpret the magnetisation of these chondrites is limited. Thirdly, rocks can record magnetisations as they cool from high temperatures, which, unlike chemical reactions, is a well-understood and well-studied mechanism. Unfortunately, most aqueously altered chondrites only ever reached low temperatures, so do not carry this well-understood type of remanence. Combined, these hurdles meant the meteorite record contained a conundrum: there were no chondrites that had the correct mineralogy and thermal history to yield reliable and well-understood bulk paleomagnetic remanences of the disk's field.

Thankfully, ahead of JAXA's Hayabusa2 and NASA's OSIRIS-REx missions, dozens of anomalous chondrites were studied in detail. These meteorites were found to be atypical because they experienced transient heating following the formation of magnetite, possibly due to a small impact on their parent body. As such, these meteorites exhibit the ideal combination of mineralogy and thermal history, so they uniquely overcome the difficulties that have hindered previous efforts to glean the disk field's intensity. This work package, performed by Dr Catherine Harrison, will first involve characterising the peak temperature reached by several anomalous chondrites. It will then involve a series of demagnetisation campaigns to recover the ancient field intensities recorded by these meteorites. Finally, these values will be used to identify the intensity of the disk's field at the times and locations at which planetesimals formed.

Individual grain magnetisation unlocked by cutting-edge microscopy

The third work package focusses on the magnetisation of one of the constituents of chondrites, called chondrules. These objects make up <5—80% of chondrites and are 0.1—1 mm sized spherules that were repeatedly melted when they were free floating in the disk (i.e. before they accreted onto a planetesimal). This thermal history means they recorded a well-understood magnetisation, and ~1–10% of chondrules house sub-micrometre beads of iron-nickel metal, which are a notably reliable paleomagnetic recorder. As such, these chondrules carry ideal records of the disk's field. However, their small sizes mean their magnetisations are simply too weak to be measured reliably using conventional magnetometers, preventing their vital records from being accessed.

Over the last decade, a new magnetometer—called a geo-quantum diamond microscope (geo-QDM)—has been pioneered, which can reliably, routinely and robustly measure the weak magnetisations of sub-millimetre scale samples. As such, it is now feasible that the magnetisation of hundreds of chondrules can be measured to unlock the intensity of the disk's field at the times and locations in which these spherules formed. These measurements will be conducted by Dr Evie Baker using the geo-QDM in the Oxford Paleomagnetism Laboratory, which is only the second such instrument in Europe.

What does it all mean?

Combined, work packages two and three will provide a thorough magnetic history of the protoplanetary disk, and work package one will produce models that predict this history for various behaviours. As part of the final work package, I will compare the measured data to the range of model predictions and identify the behaviour of the disk from the best matches. I will then feed this behaviour into planet formation models to explore how Earth and the other rocky planets were created. This will enable me to identify whether there is a unique feature in Earth's early history that potentially led to it being the single known planet that supports life.

Altogether, by utilising several recent breakthroughs in the magnetisation of the early solar system, MMESSH promises to recover the behaviour of our protoplanetary disk with unparalleled clarity. Because this behaviour underpinned planet building, this project has the potential to revolutionise our understanding of the origin and habitability of the Earth.

PROJECT NAME

Using Meteorite Magnetism to Elucidate Early Solar System History (MMESSH)

PROJECT SUMMARY

By utilising several recent breakthroughs in extraterrestrial magnetism, MMESSH aims to unlock pivotal insights into the protoplanetary disk of dust and gas that surrounded the young Sun. Because the behaviour of this disk underpinned the process of planet building, this project has the potential to revolutionise our understanding of the formation and habitability of the Earth.

PROJECT PARTNERS

MMESSH is working with researchers at the Natural History Museum (Prof Sara Russell & Dr Ashley King), the University of Manchester (Prof Jamie Gilmour), the University of Bristol (Prof Tim Elliott), Lawrence Livermore National Laboratory (Dr Greg Brennecka), the University of Chicago (Prof Fred Ciesla) and the Massachusetts Institute of Technology (Dr John Biersteker).

PROJECT LEAD PROFILE

Dr James Bryson was awarded a MSci and PhD from the University of Cambridge. He then conducted postdoctoral research at the Massachusetts Institute of Technology and the University of Cambridge, where he was a Research Fellow. He is now the Associate Professor of Mineralogy in the Department of Earth Sciences, University of Oxford, where he studies meteorites to elucidate the early solar system.

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