Refining the Theories of **Planet Formation**

Dr Melissa A. Morris

Scientia

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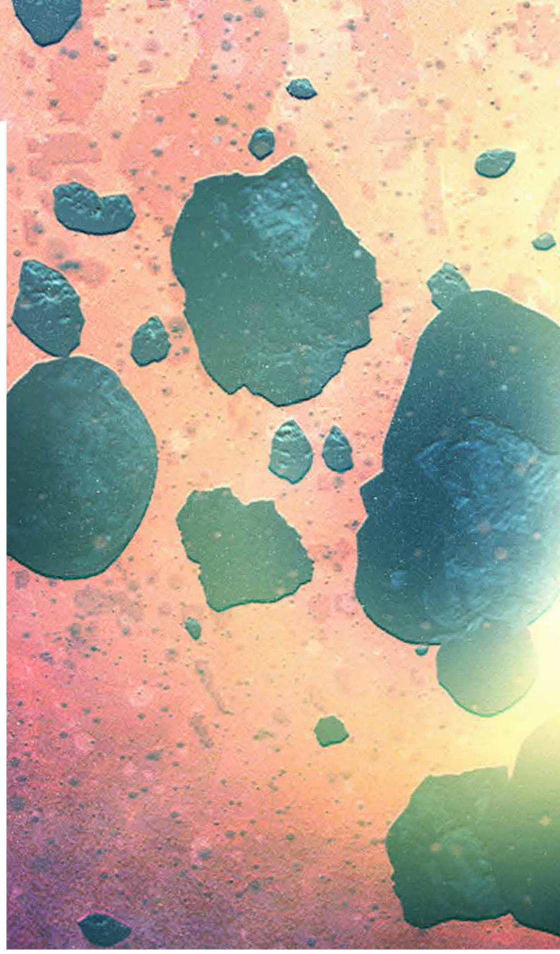
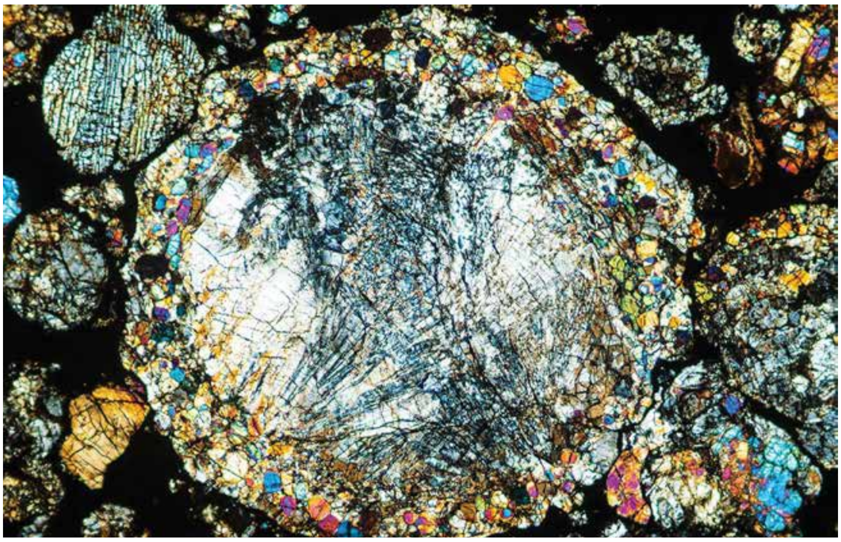


Science and philosophy are two of the most important pillars of human civilisation. But when it comes to the important questions, is there really much difference between them? Where do we come from? What is the meaning of life? Answers to such philosophical questions can often be scientific in nature, as shown by the work of **Dr Melissa Morris,** who is probing the early stages of how solar systems form.



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The Universe and Everything in It

Around 13.7 billion years ago, our Universe burst into being in a titanic event – the very space that we occupy came into existence in a 'flash' of extremely high energy and tremendous heat, before rapidly expanding outwards like an immense balloon. We call this event 'the Big Bang' and we owe our knowledge of it, in part, to Edwin Hubble. In 1929, Hubble discovered that the entire Universe was in a state of expansion and, when we run this process in reverse, the building blocks of every single thing that exists coalesces at a single point in space and time. From its outset, the Big Bang Theory was a controversial one. Many astronomers believed in an opposing idea – that of a 'steady state Universe' – and it wasn't until the accidental discovery of the Cosmic Microwave Background (CMB) radiation, that the Big Bang became widely accepted.

A large proportion of what we know about the beginning of the Universe is based on astronomical observation. Scientists consider what we know – such as the universal expansion discovered by Hubble – and try to fit their theories to these 'constraints'. When a theory can fit all of the known constraints of a system, it is accepted as the most likely explanation. That is, until a new constraint is discovered, or a better theory comes along. The discovery of the CMB radiation provided an additional constraint to the observed universal expansion – one which had been predicted by the Big Bang Theory – and signalled the end of the steady state idea that had been accepted for decades. It is in this manner that scientists build up models of all physical systems.

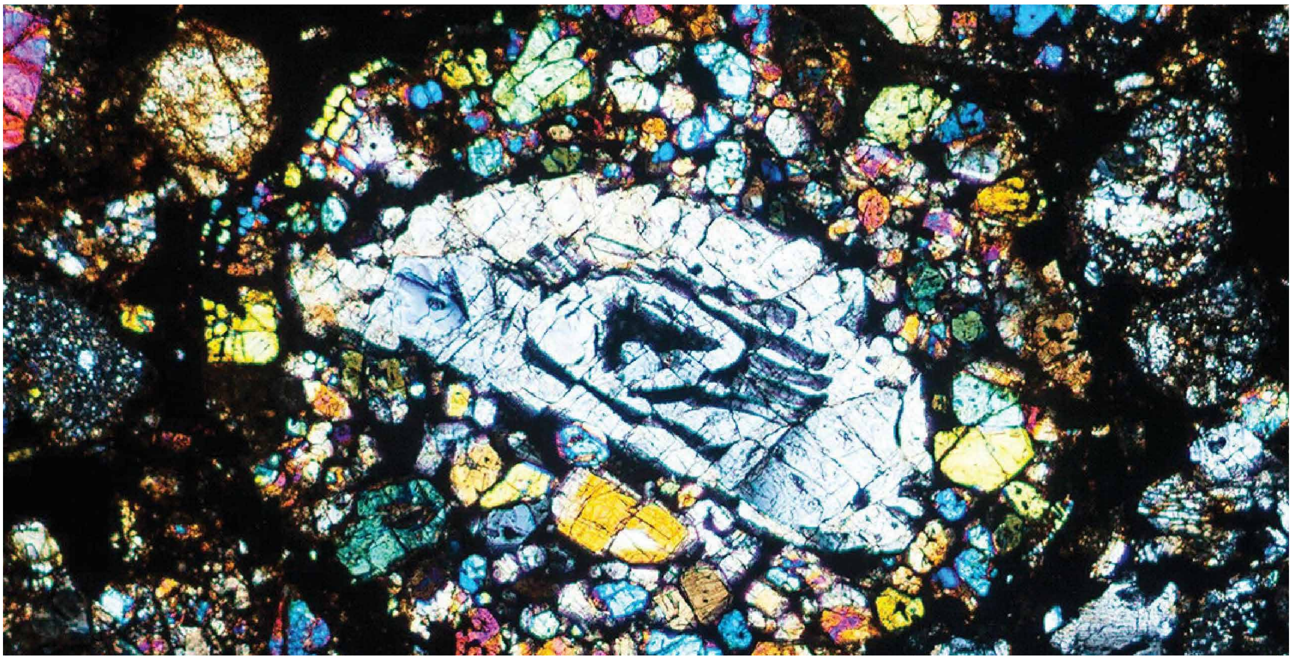
Although information from the early stages of the Universe is scarce, astronomers have managed to provide an account of the circumstances that eventually led to the formation of solar systems like our own. After rapidly expanding into space, the constituent particles of matter slowly began to clump together and form areas of higher density than the surrounding space. Due to the attractive effects of gravity, these higher-density areas pulled in more and more particles, forming large disks of gas and dust that rotated around a central axis. These enormous rotating disks, many of which are hundreds of thousands of light years across, are what we call galaxies today.

Within these galaxies, such as our own Milky Way, vast molecular clouds called nebulae started to collapse under the influence of their own gravity, ultimately leading to the formation of stars, such as our Sun. In the same manner that campers might rub sticks together to start a fire, the friction caused by atoms and dust rubbing together at the core of these rotating collapsed clouds kick-started a process known as thermonuclear fusion, giving rise to a star. The resulting disk of gas and dust rotating around this infant star is known to astronomers as a protoplanetary disk, and it is here that Dr Melissa Morris and her research team are focusing their expertise.

Protoplanetary Disks and Planet Formation

It is well-known amongst astronomers that protoplanetary disks are an integral part of planet formation – many systems that we can view with an optical telescope are currently in this stage and, using techniques such as spectroscopy, we can tell their molecular makeup. Spectroscopy is a method of

'I try to figure out how planetary systems form – in particular, systems with planets that could support life.'



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analysing materials by shining light on, or through them, and measuring what light is reflected back or passes through. It's impossible to shine light on gas and dust clouds located hundreds of lightyears away, so astronomers typically measure the light from the infant star, or another celestial source, after it passes through the protoplanetary disk.

Each chemical element interacts with light in a unique way based on its atomic structure – absorbing only certain frequencies (colours) of light. As many specific frequencies of light aren't absorbed by a particular element, we end up with a 'spectrum' of light that shows weaker signals at the absorption frequencies, and stronger signals where light isn't absorbed by the element. Each element in the periodic table has its own 'optical fingerprint' and spectroscopy is an extremely useful technique for distinguishing different types of matter throughout the Universe.

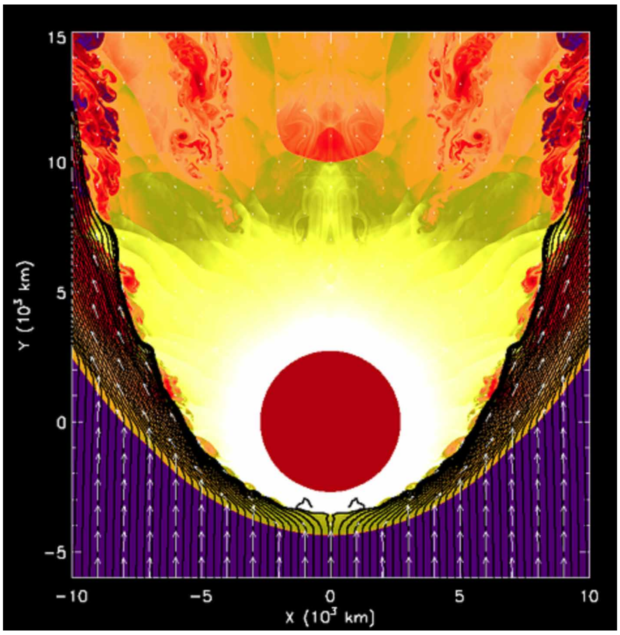
After a few hundred thousand years after the formation of a protoplanetary disk, it begins to change and larger bodies, such as asteroids, protoplanets, and planets, start to form from the dust and gas contained within the disk. This is a problem for astronomers, as techniques like spectroscopy are less effective when the composition of the disk changes from an evenly distributed gas and dust cloud, to a sparser dust cloud containing large solid formations, or 'planetesimals'. In this situation, the use of spectroscopy as a constraint when modelling the system becomes ineffective – we no longer have enough information to model the system accurately. Our entire understanding of the formation of planets – and their growth – is dependent on our knowledge of the total mass of gas contained within a protoplanetary disk and how it develops over time. During the early stage described here, these quantities are poorly defined and, as a result, current models describing the development of our Solar System have large uncertainties. In order to better understand this stage in our history, astronomers seek out different constraints.

Digging into Meteorites for a Deeper Understanding

Chondrules are submillimetre-sized spheres of silicate rock that are found in large quantities in meteorites known as chondrites. Understanding how they form could help clear up some of the uncertainties that arise during the early protoplanetary disk stage in our Solar System. One explanation comes from the so-called 'bow shock model'. Consider a ship sailing across a dark blue sea, or a rock sitting stubbornly in a stream. That apparently unchanging wave that forms on the boundary between ship and sea, rock and water, is a bow wave. Bow waves appear when the fast-moving water particles of the stream, or ocean, have to abruptly slow down when they encounter the front-facing surface of the rock, or ship. In a similar way, when a planetesimal moves through the protoplanetary disk, a shock wave forms at the front-facing surface. This is known as a 'bow shock'.

The bow shock model demonstrates that chondrules can form under certain circumstances in the bow shock of a planetesimal, moving through its protoplanetary disk, as the relatively free particles of gas and dust bunch-up against its front face. Not only does this cause the particles to slow down relative to the planetesimal, it also causes a dramatic increase in the temperature of the material within the bow shock region. It is thought that this increase in temperature is what causes chondrules to form, by melting the dusty chondrule precursors as they pass the shock front. Until recently, models that simulate the formation of chondrules in this way indicated a cooling rate of around 10 thousand degrees Celsius per hour – far in excess of that needed to match the constraints on chondrule formation.

In her 2010 paper, *Thermal Histories of Chondrules in Solar Nebula Shocks*, Dr Morris updated the large-scale shock model – another shock model used to describe how



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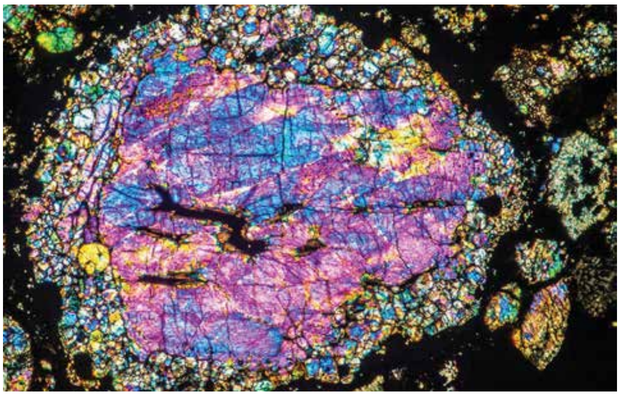

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chondrules might have formed through shocks caused by gravitational instabilities in the disk – by adding a further constraint: the inclusion of molecular line cooling due to water molecules. Molecular line cooling is similar to spectroscopy in that molecular transitions follow the same physical process as atomic transitions to emit or absorb radiation in the form of light, or heat. This transfer of radiation can contribute to cooling the gas, and as a result, can affect how fast newly-formed chondrules cool.

This apparently simple constraint added by Dr Morris and her team, based on extremely complicated mathematics, demonstrates that chondrule formation is, in fact, consistent with observational constraints. In their updated shock model, the team found that the cooling rates needed for chondrules to form was somewhere between 10 and 1000 degrees Celsius per hour, which is in line with what has been indicated by experimental reproduction of chondrules.

In 2011, another research team added a further constraint to the model of chondrule formation. They demonstrated that large planetesimals (around half the size of Earth) were present at the time that chondrules formed. Using this new information, Dr Morris and her team were able to model chondrule formation caused by the passage of protoplanetary disk matter in the bow shocks created by these large planetesimals. They demonstrated that, in principle, a small number of planetesimals could be responsible for producing all of the observed chondrules, without breaking any of the known constraints.

Until recently, all models describing the formation of chondrules made a simplified assumption – all chondrule precursors are the same size. Dr Morris and her team changed this with their paper, *The effect of multiple particle sizes on cooling rates of chondrules produced in large-scale shocks in the solar nebula*, where they demonstrated that if multiple different chondrule precursor sizes are taken into account, heating and cooling rates could be obtained that were in line with observational evidence.

Using samples of the metal-rich Isheyevo meteorite in their 2015 study, *New Insight into the Solar System's Transition Disk Phase provided by the Metal-rich Carbonaceous Chondrite Isheyevo*, Dr Morris' team went on to provide the first evidence of our own Solar System's transition phase. Found in a field in Russia in 2003, the Isheyevo meteorite has unique sedimentary layers of material, implying that it formed through some type of sedimentation process. By modelling this process, Dr Morris and her colleagues were able to show that the gas densities required to produce meteorites such as Isheyevo are consistent with those observed in transition disks, meaning that the studied samples provide the first physical evidence of our Solar System's own transition phase, when the disk went from one composed of mainly gas and fine-grained dust, to one with little gas (but some!) and larger solids.

Life by Proxy: The Search for Extra-Solar Water

In contrast to chondrules, phyllosilicates are minerals that form from the interaction of rock and water. It is a widely held belief in astronomy that where there's water, there might be life. It is, after all, one of the few constraints we have on our only example of a life-bearing planet – Earth.

In one of their earlier studies, Dr Morris and her colleagues showed that, due to the dust ejected from asteroid-asteroid collisions, phyllosilicates should be detectable in other solar systems if liquid water was present at some time. This provides astronomers with the tools for detecting water in solar systems other than our own, and could help focus our search for extra-terrestrial life.

What's Next?

'The logical next steps for my work are to continue to add more relevant physics and chemistry into my models to further constrain important processes in forming planetary systems, including our own,' says Dr Morris. In 2013, Dr Morris received funding from NASA for a project to investigate the possibility of chondrule formation in impact plumes – high-energy ejection of matter that occurs when two planetesimals or protoplanets collide. Another NASA-funded project she is involved with hopes to model the formation of 'igneous rims' around chondrules – a feature assumed to be the result of a second heating event in Solar System formation. Through this future work, Dr Morris and her team will provide yet more insight into the formation of our Solar System and, by analogy, other systems capable of sustaining life.

Our ability to query our own origin is what sets our species apart from all other known life. By pinning down the circumstances that led to the formation of our Solar System, Dr Morris and her team contribute greatly to our understanding of where we come from and what leads to the development of life. But whether we can ever fully comprehend our Universe in all its brilliance and beauty, remains a question for philosophers amongst us.

Meet the researcher

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Dr Melissa A. Morris received her BSc in physics, with a minor in astronomy, from Missouri State University in 2003. She then moved on to Arizona State University to complete a MSc (2007) in physics and a PhD (2009) in astrophysics. Currently at the Physics Department of the State University of New York at Cortland, her research interests include studying the formation of stars and planets by modelling extrasolar protoplanetary systems and the formation of early Solar System materials – such as those found in meteorites. Recently, her work has focused on chondrules – millimetre-sized spheres of igneous silicate which are found in large quantities throughout rocky meteorites known as chondrites. By modelling how these chondrules form, Dr Morris and her team have contributed multiple new insights into the formation of our Solar System. She has extensive experience teaching physics and astrophysics at a variety of universities and has been awarded multiple awards, including Excellence in Research, Scholarship and Outreach in 2015.

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