A&G

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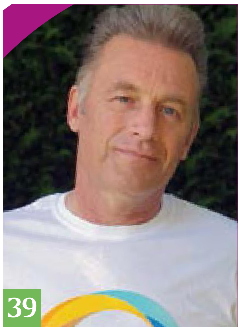
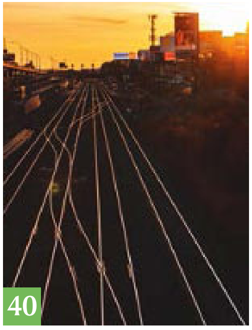
Royal Astronomical Society

What's going on with Betelgeuse?

Autumn MIST *Back together again*
Railway risk *Brace for 'space weather on the line'*
Fragile skies *Showing the impact of space junk*

A&G





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Astronomy & Geophysics publishes news, reviews and comment on topics of interest to astronomers and geophysicists. See academic.oup.com/astrogeo for more details or contact the editor:

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Contents

Is it a runaway star? Yes. **Did it form in a merger?** Maybe. **Why did its brightness drop by half in 2019 and 2020?** Look, we don't really know, OK? Perhaps it was a particularly vigorous twinkle.

We're talking, of course, about **Betelgeuse**. Big enough and near enough for some surface features to be seen, this seething, red supergiant in a cloud of gas and dust many times the size of the solar system is an **excellent testbed** for ideas about **star formation**, **evolution** and **death**. And we'll tell you this: when it explodes, it will be a billion times brighter than the Sun, and will appear about a quarter the brightness of the Moon in the skies of Earth. We hope that will be in about 100 000 years.

On the cover

It's the recognisably red bright spot on Orion's shoulder, clear even under city skies. In 2019-20 it subjected us to the Great Dimming, and we don't know why. Meet Betelgeuse.

Royal Astronomical Society

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News

Editorial
Going deep

Sue Bowler, Editor

There's something a little different about this issue of *A&G*. The cover feature is much longer than usual, offering an in-depth snapshot of research in one field. Betelgeuse is well worth it: it's both a big star and an object with a big research footprint, from its colour and surface features to its changing brightness. This is a chance to find out what astrophysics is going on, from the team behind The Betelgeuse Project. I plan to include similar in-depth articles in future issues. There are some areas in astronomy, planetary sciences, solar-terrestrial and solid Earth geophysics where rapid progress is changing the research landscape, or where efforts to tackle outstanding questions reveal new unknowns. We want to get into the complexities of our sciences now and again, so if there's a review you are burning to write, but can't fit in our shorter word limits, then get in touch and we'll discuss it. Also, if there's a topic you'd like to read about in more depth, tell me and we'll try to find a great writer to cover it. But most of all, tell me if you love or hate this type of extended review. It's your magazine, after all.

sbowler@ras.ac.uk

Prof. Gillian Wright with the Caroline Herschel Medal and citation and the host of the ceremony, Ambassador Miguel Berger

Caroline Herschel Medal award ceremony

The first UK winner of the new Caroline Herschel Medal received the award in a ceremony held at the residence of the German Ambassador, Miguel Berger, on 13 April 2023.

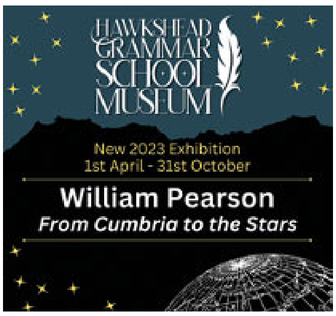
Prof. Gillian Wright, Director of the UK Astronomy Technology Centre, received the award for her outstanding work in developing instrumentation, notably in infrared astronomy, and most recently leading the international consortium that built the Mid-Infrared Instrument, MIRI, for the James Webb Space Telescope.

At the ceremony, Prof. Wright received the medal and award from Professor Stefanie Walch-Gassner, incoming President of the Astronomische Gesellschaft, then gave a very well-received address on the power of technology to reveal the hidden infrared universe. She shared with the audience her first-hand account of the design and development of the Webb telescope, stressing the unique contribution that MIRI is already making to our understanding of the universe.

The Caroline Herschel Medal is a new award funded by the UK government to recognise outstanding women astrophysicists in the UK and Germany. It is administered jointly by the Royal Astronomical Society and the Astronomische Gesellschaft, with the medal awarded in the UK and Germany in alternate years. **bit.ly/3oPo7Xn**

Pearson in Hawkshead

From 1 April to 31 October 2023 Hawkshead Grammar School Museum is hosting an exhibition about former pupil William Pearson. Pearson was a Cumbrian farm boy who was one of the founders of the Royal Astronomical Society and invented his own scientific instruments. He developed his passion for maths and geometry at Hawkshead Grammar School and worked there as an assistant master before embarking on his 'stellar' career. Visit the museum to see the book he donated to the school, along with a celestial globe and much more besides.



Prizewinning posters

The winners of the RAS poster competition for students studying GCSE Astronomy have been announced at the Ordinary Meeting of the RAS in March. Congratulations to Maya Charman from Parkstone Grammar School, Poole, who won first prize for a poster titled 'How to find exoplanets: the search for hidden worlds'. Abbott Bai, from Marlborough College, Wiltshire, won second prize for 'Can we throw satellites into space?'

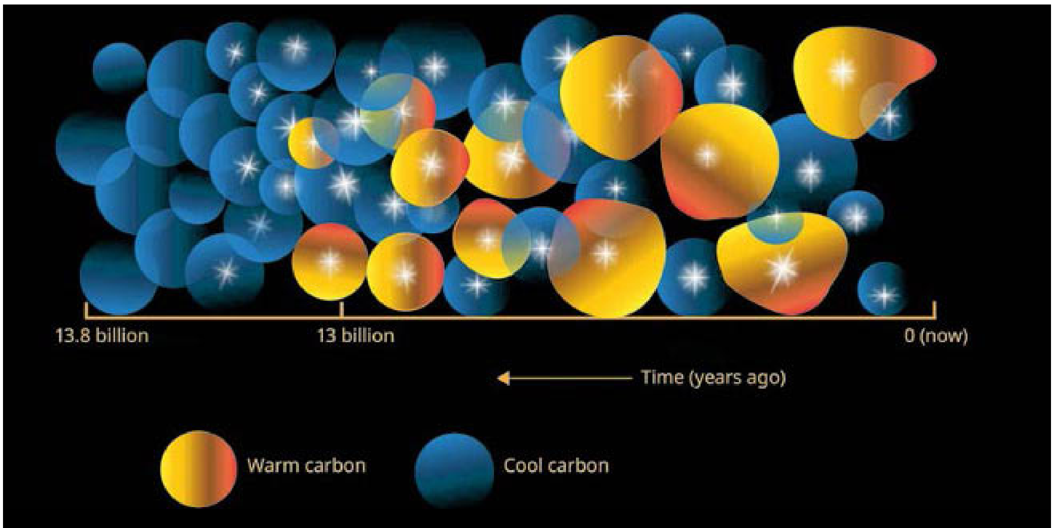
This annual competition, intended for students to showcase their astronomy knowledge, is sponsored by Winton, and offers book tokens as prizes. Congratulations to our winners, and thank you to everyone who entered. **bit.ly/3oGTC5K**

A valued gift

The RAS is pleased to acknowledge a legacy from long-term Fellow John Murrell. John died in June 2022, aged 69. He left the Society £10000, which will be used for grants funding, to support the organisation of scientific meetings, trips for observation and for travel to scientific conferences. "We are very grateful to be able to use the legacy to support us in our charitable objectives," said Executive Director Philip Diamond.

John spent most of his career working as an engineer for Transport for London. He was an avid amateur astronomer, and became a Fellow of RAS in 1998. He was well thought of at the London Amateur Astrophysics Group, with white dwarfs a particular interest.

If you are considering leaving a legacy to the Society, please consult the RAS website or contact the Treasurer (treasurer@ras.ac.uk). **bit.ly/3NfFeMa**



Warm carbon from reionisation?

The amount of warm carbon in the early universe suddenly increased by a factor of five over a period of only 300 million years. That's the conclusion of a study by Rebecca Davies (Swinburne University of Technology) and colleagues appearing in *Monthly Notices of the Royal Astronomical Society.* The authors suggest that light from the epoch of reionisation may have led to rapid heating of the gas, causing the rise. While more carbon might have come about as stars produced more heavy elements, the Swinburne team noted that the amount of cool carbon did not increase in the same way. **bit.ly/3oOS4a7** (R. Davies)

General relativity passes next test

A statistical analysis of 1.2 million galaxy observations has quantitatively characterised the extent to which the orientation of distant galaxies is aligned. These alignments, reported by Teppei Okumura (Academia Sinica Institute of Astronomy & Astrophysics) and Atsushi Taruya (Kyoto University), in *The Astrophysical Journal Letters*, are primarily produced by interactions with nearby objects. The results of the model agreed with theoretical calculations, giving evidence that the orientations of these galaxies are related, strengthening the case for General Relativity on a cosmological scale. **bit.ly/3HsrJ8c**

JUICE journey started

The European Space Agency's JUICE (JUpiter ICy moons Explorer) has begun its journey from Kourou, French Guiana. On 14 April the spacecraft separated from the Ariane 5 rocket and within hours had unfurled its solar panels. Orbital insertion at Jupiter is expected in July 2031. Its eight-year cruise will include slingshot flybys of Earth and Venus.

Dark matter map

A team of astronomers have used the Atacama Cosmology Telescope (ACT) to study how the gravitational pull of massive dark matter structures can warp the CMB on its 14-billion-year journey to Earth. The resulting map shows directly the invisible cosmic web of dark matter that surrounds and connects galaxies. Remarkably, it provides measurements that show that both the 'lumpiness' of the universe, and the rate at which it is growing after 14 billion years of evolution, are in complete agreement with the standard model of cosmology. A series of papers will appear in *The Astrophysical Journal*. **bit.ly/3neSBBD**

Booming baby galaxy

Astronomers have found a very small galaxy dating from about 500 million years after the Big Bang – one of the smallest yet discovered at this distance. The researchers, led by Hayley Williams of the University of Minnesota, found that the galaxy's volume is roughly a millionth that of the Milky Way. Despite that, it is still forming stars at the same rate as our home galaxy. A paper appears in *Science*. **bit.ly/3HmNxSK**

(ESA/Webb, NASA & CSA, P. Kelly)

Out-of-place baby star

Researchers have discovered a very young star in its formation phase near the supermassive black hole Sgr A* at the centre of the Milky Way. The 15 solar-mass star, X3a, is only a few tens of thousands of years old and should not be able to exist so close to the SMBH. Researchers believe it may have formed in a dust cloud orbiting Sgr A* sank to its current orbit only after it had formed. Powerful winds are distorting the star's envelope. A paper by Florian Peißker and colleagues appears in *The Astrophysical Journal* (University of Cologne). **bit.ly/3LCsePh**

Metal-poor stars more hospitable

A new study looks at how the metallicity of a star is connected to the ability of its exoplanets to create an ozone layer. Metal-poor stars emit more UV radiation than their metal-rich counterparts. But the ratio of ozone-generating UV-C radiation to ozone-destroying UV-B radiation also depends on metallicity. In metal-poor stars, UV-C radiation allows a dense ozone layer to form. For metal-rich stars, the predominant UV-B radiation means this layer is sparser. So, metal-poor stars should provide more favourable conditions for the emergence of life. A paper by Anna Shapiro (Max Planck Institute for Solar System Research) and colleagues appears in *Nature Communications*. **bit.ly/3AKk69s**

Secondary supernova source

Planets may face other dangers from supernovae than intense radiation and energetic particles. If a supernova's blast wave strikes dense surrounding gas, it can produce a secondary large dose of X-rays that arrives years after the explosion and last for decades. This could be lethal within 160 light-years of the explosion. The issue is covered in *The Astrophysical Journal* by Ian Brunton (University of Illinois Urbana-Champaign) and colleagues. **s.si.edu/3LjiZlT**

One down, one to go!

The RAS patchwork quilt – inspired by Ellen Baker's 1876 quilt now in the Smithsonian Museum – is finally complete, after three and a half years. And the Society is looking for help to complete a second quilt, at sketching and stitching workshops to be held this summer.

The completed quilt will be on display at Burlington House during events this year. "The 100 patchwork squares were stitched together to form the top of the quilt," said Annie Hogan, the former RAS Membership Officer who led this project to celebrate the RAS bicentenary. "The top, batting and backing were quilted together thanks to the help of our amazing volunteers. Lastly, the binding around the edge was stitched in place."

The second quilt will show an embroidered map of the solar system. "Our talented volunteer embroiderers are making excellent progress on the Sun and Jupiter", said Hogan. "We're also in the process of planning summer workshops for anyone who's keen to add their stitches to our homage of Ellen Baker's 1876 masterpiece." One such workshop will take place during the Royal Society Summer Exhibition Lates – look out for notices on the Royal Society website. **bit.ly/40QRAgO**

Welcome Gracecook and Maryblagg

The latest batch of International Astronomical Union minor planet namings includes two English women, Alice Grace Cook (1877-1958) and Mary Adela Blagg (1858-1944), writes Bill Barton, deputy director, British Astronomical Association Historical Section, and Society for the History of Astronomy County Coordinator for Suffolk.

Cook lived in Stowmarket, Suffolk while Blagg lived in Cheadle, Staffordshire; they were among the first women fellows elected to the RAS in January 1916.

Miss Cook's planet was previously known as 2000 EY156, or 50739, and is now named Gracecook. The citation reads "After joining the British Astronomical Association, she observed the 1914 Mercury transit from her own observatory, and was elected a Fellow of the Royal Astronomical Society in 1916. Known for meteor and auroral observations, she received the E C Pickering Fellowship in 1920."

Miss Blagg's planet was previously known as 2000 EO177, or 50753, and is now known as Maryblagg. The citation reads: "After joining the British Astronomical Association, she helped develop a uniform system of lunar nomenclature and was later elected as a Fellow of the Royal Astronomical Society. She joined the Lunar Commission of the IAU in 1920, standardizing lunar nomenclature in Named Lunar Formations."

Both planets are solar system objects orbiting the Sun within the main asteroid belt. Gracecook is 4.75km across and orbits with a semi-major axis of 2.56au. Maryblagg is a little further out, at 2.7au, and is slightly smaller at 3.49km in diameter. Both orbits are inclined to the ecliptic at more than 10°.

go.nasa.gov/3nhxIWj
go.nasa.gov/41K5OkJ
bit.ly/3Ay3CRH

Asteroid tail forms from impact debris

Jian-Yang Li (Planetary Science Institute) and colleagues, writing in *Nature*, have confirmed that debris excavated by an asteroid impact can form a tail. Observations of NASA's Double Asteroid Redirection Test (DART) impact with Dimorphos on 26 September 2022 revealed the complex ejecta evolution in the first two and a half weeks under the influence of the gravity of Didymos and the pressure of sunlight. Although not all asteroid tails are necessarily from impacts, the DART observations demonstrate that a tail can originate this way. **bit.ly/3LjHsY8**

How green is your model?

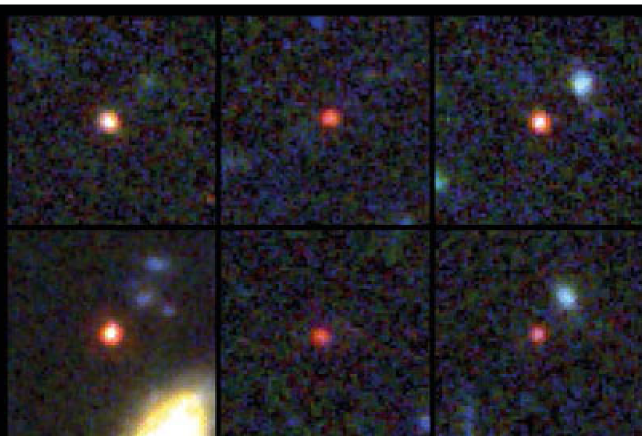
Computing costs in time and money are often part of research planning. Now there's a website where you can assess the carbon impact of your work as well and find ways to make your work more sustainable. The Green Algorithms project includes calculators for different types of computational projects, training resources and tools to find out, for example, the carbon intensity of electricity supply in different places. **bit.ly/3AAq5NZ**

Plate tectonics underway early

Wriju Chowdhury (University of Rochester) and colleagues have used small zircon crystals to unlock information about magmas and plate tectonic activity on the early Earth. The research provides chemical evidence that plate tectonics was most likely occurring more than 4.2 billion years ago when life is thought to have first formed. The research appears in *Nature Communications*. **bit.ly/44fctoM**

Ultramassive black hole?

Astronomers have used gravitational lensing to reveal one of the biggest black holes ever found. The team ran hundreds of thousands simulations to try to match the features of an HST image of Abell 1201. The results favoured a black hole in the foreground galaxy with a mass over 30 billion solar masses. This is on the upper limit of how large astronomers believe black holes can grow. The study, led by James Nightingale (Durham University) appears in *The Monthly Notices of the Royal Astronomical Society*. **bit.ly/414MLkl**



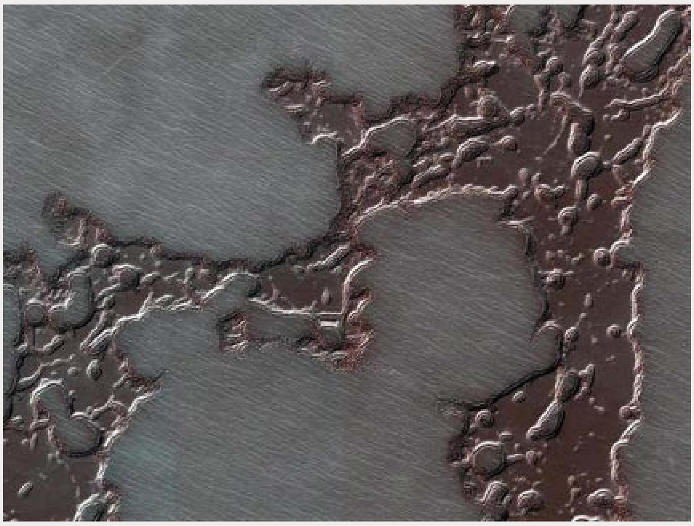
Cosmology challenge

Mike Boylan-Kolchin (University of Texas) has observed six galaxies from between 500 and 700 million years after the Big Bang that appear to be more than 10 billion solar masses. This would require an unlikely 100% conversion rate of gas into stars and contradicts the prevailing ΛCDM cosmological model. Either these galaxies look more massive or older than they really are, or the universe was expanding faster shortly after the Big Bang than the model predicts. The results are presented in *Nature Astronomy*. **bit.ly/3AFGaSs** (NASA/ESA/CSA/I Labbe)

Snowball Mars?

Astronomers have discovered a relict glacier near the equator of Mars. Located in Eastern Noctis Labyrinthus, this finding is significant as it implies the presence of water ice at the surface of Mars in recent times, even close to the equator. This discovery raises the possibility that ice may still exist at shallow depths in the area, which could have significant implications for any future human exploration. The study was reported by lead investigator Pascal Lee (SETI Institute) at the 54th Lunar and Planetary Science Conference in Texas, USA. **bit.ly/3LyVPct** (NASA MRO HiRISE and CRISM false colour composite. Lee et al. 2023)

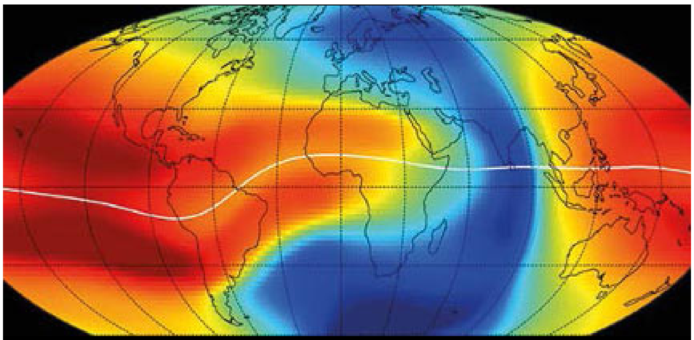
Water wobbles



A new study has linked the global movement of water on Mars over half a million years to the tilt of its spin axis. Peter B Buhler (Planetary Science Institute, Arizona) and colleagues analysed the H_2O ice layer formation in the massive martian south polar CO_2 ice deposit, which represents a 510000-year climate record. The slow variation of the spin axis tilt causes water ice to move from warmer to colder regions, driving Mars' basic long-term water cycle. The image shows pitted dry ice overlying the topmost layer of smooth water ice. The results of the study appear in *Geophysical Research Letters*. **bit.ly/3oVkTSl** (NASA/JPL-Caltech/University of Arizona)

History of water

Observations of the isotope composition of a protostar called V883 Ori have helped scientists to find a probable link between the water in the interstellar medium and the water in the solar system. Using ALMA, the research team led by John Tobin (NRAO) found that the isotopic composition of water remains relatively unchanged between each stage of planetary system formation: protostar, protoplanetary disk, and comets. Water in the disc of V883 Ori had a HDO:H_2O ratio of $2.26\pm0.63\times10^{-3}$, comparable to that found in protostellar envelopes and comets. The ratio is significantly higher than that found in Earth's oceans. A paper appears in *Nature*. **bit.ly/3HmGNnC**



New ionosphere

Researchers led by Artem Smirnov and Yuri Shprits (GFZ German Research Centre for Geosciences) have presented a new model of the ionosphere, published *Nature Scientific Reports*, developed on the basis of neural networks and satellite measurement data from the past 19 years. In particular, the new model can reconstruct the topside ionosphere, the upper, electron-rich part of the ionosphere much more precisely; high electron density is shown here in red, low in blue. **bit.ly/3HKoGZh** (CCBY 4.0 Smirnov et al. (2023))

Gruber Prize for benign iconoclast

The 2023 Gruber Prize in Cosmology is awarded to Prof. Richard Ellis of University College London for his innovative work that has reimagined cosmology in fundamental ways; his observations have pushed back the cosmic horizon and the instruments he conceived have transformed astronomical methodologies. Ellis will receive the $500000 prize and gold laureate pin at a ceremony to be held in in July at the Laboratoire d'Astrophysique of Marseille, France. **bit.ly/41E5y6Z**

Oh Canada...

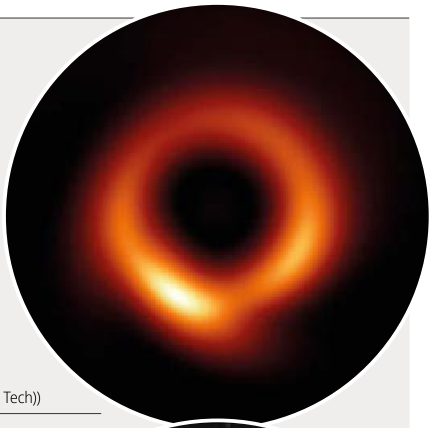
The Editor wishes to apologise for the misspelling of the name of Canada's capital city – Ottawa – in the April issue of *A&G*. This marred the otherwise excellent article by Cameron Patterson about his planned train journey from Ottawa to San Francisco, and was not his fault. This was entirely our mistake and we can only apologise, both to Cameron and to the inhabitants of Canada, especially Ottawa.

Jules Janssen Prize 2022 awarded

Prof. Dame Jocelyn Bell Burnell has been awarded the 2022 Jules Janssen Prize by the French Astronomical Society. She accepted the award at a ceremony in March this year, before which she had planted an apple tree in the grounds of the Camille Flammarion at Juvisy, France. "I am delighted that our former President Dame Jocelyn Bell Burnell has been the awarded the Jules Janssen prize," said current President Prof. Mike Edmunds. "It honours a lifetime of dedicated work in science – including her well-known and crucial role in the discovery of pulsars and her passion in advancing the cause that science is for all in society." **bit.ly/3LCtXnL**

M87 at full resolution

Lia Medeiros (Institute for Advanced Study) and colleagues have developed a technique to enhance the fidelity of the 2017 EHT image of M87's central black hole. It is based on a branch of machine learning known as 'dictionary learning' and produces the full resolution of the EHT. The authors, writing in *The Astrophysical Journal Letters*, say the image shows the full extent of the object's dark central region and the surprisingly narrow outer ring. The width of the ring in the image is now smaller by about a factor of two, which will likely be a powerful constraint for theoretical models and tests of gravity. **bit.ly/421vUQ2** (L. Medeiros (Institute for Advanced Study), D. Psaltis (Georgia Tech), T. Lauer (NSF's NOIRLab), and F. Ozel (Georgia Tech))

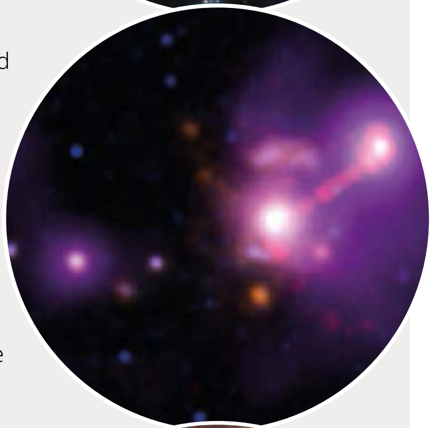


Gassy baby cluster

Astronomers have witnessed the birth of a very distant cluster of galaxies in the early universe. A research team used ALMA to observe the Spiderweb protocluster, located at an epoch when the Universe was only three billion years old. The results show that the protocluster contains a vast reservoir of hot gas (shown in blue) indicating that the system is on its way to becoming a proper, long-lasting galaxy cluster rather than dispersing. The work, by Luca Mascolo (University of Trieste) and colleagues was published in *Nature*. **bit.ly/3LCTT2B** (ESO/Di Mascolo et al.; HST: H. Ford)

Lonely galaxy

Astronomers have revealed a galaxy that seems to have swallowed a cluster. The environment of 3C 297 appears to have the key features of a galaxy cluster, yet stands alone. The researchers, headed by Valentina Missaglia (University of Torino), suggest the gravitational pull of the one large galaxy, combined with interactions between the galaxies, caused them to merge, making 3C 297 a 'fossil group'. There is abundant hot gas (shown in pink), together with a bent jet, suggesting interaction with its surroundings and a bright spot where the jet has energised the gas. It is challenging to explain how the universe can create this system only 4.6 billion years after the Big Bang. The research appears in *The Astrophysical Journal*. **s.si.edu/44nye66**
(X-ray: NASA/CXC/Univ. of Torino/V. Missaglia et al.; Optical: NASA/ESA/STScI & International Gemini Observatory/NOIRLab/NSF/AURA; Infrared: NASA/ESA/STScI; Radio: NRAO/AUI/NSF.)



Faux holes

New research by Pierre Heidmann (Johns Hopkins University) and team shows how a 'topological soliton' distorts space in exactly the same way as a black hole – but behaves unlike a black hole as it scrambles and releases weak light rays that would not escape a true black hole. Simulations published in *Physical Review D* show an object looking like a blurry image of a black hole from afar but like something else entirely up close. In other words, if it looks like a black hole and bends light like a black hole, it doesn't mean it is a black hole. **bit.ly/3Hrh6m1** (Pierre Heidmann/Johns Hopkins University)

Exoplanet magnetism?

Radio emissions originating from star YZ Ceti could come from an exoplanet's magnetic field. That's the conclusion of a study by Sebastian Pineda (University of Colorado Boulder) and Jackie Villadsen (Bucknell University), now appearing in *Nature Astronomy*. The pair observed a repeating radio signal emanating from YZ Ceti using the Karl G. Jansky Very Large Array (VLA). They theorise that the stellar radio waves are generated by the interactions between the magnetic field of an Earth-sized exoplanet, YZ Ceti b, and the star it orbits. **bit.ly/44fG2GX**

Cepheid calibration

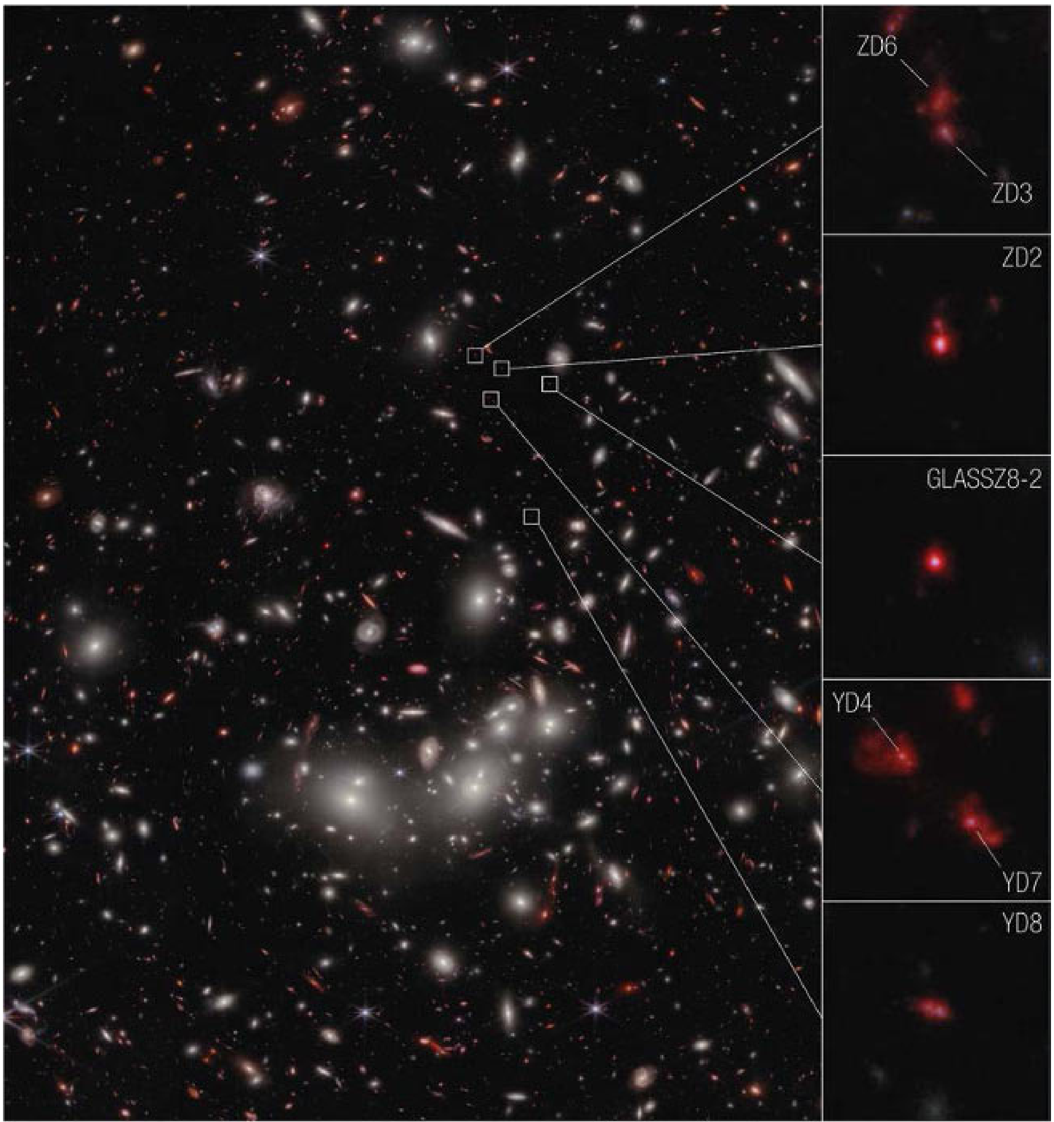
A study by Mauricio Cruz Reyes and Richard I Anderson (Institute of Physics, Swiss Federal Institute of Technology, Lausanne), based on data collected by ESA's Gaia mission, has achieved the most accurate calibration of Cepheid variables to date. Using co-moving stars within clusters, the researchers pushed the accuracy of Gaia parallaxes to their limit. The resulting calibration, published in *Astronomy & Astrophysics*, provides distances to within ± 0.9% accuracy, and also confirms the 73.0km/s/Mpc expansion rate measured from supernova studies. **bit.ly/3Vd6uNi**

Ill-placed planet would eject Earth

A terrestrial planet orbiting between Mars and Jupiter could have pushed the Earth out of the solar system, according to a new study. Stephen Kane (UC Riverside), reporting in *The Planetary Science Journal*, ran computer simulations of a planet between Mars and Jupiter with a range of different masses. The fictional planet gives a nudge to Jupiter that is just enough to destabilise everything else. The worst-case scenario saw Earth, Mercury, Venus, Uranus and Neptune all ejected from the solar system. **bit.ly/3navrfL**

Melted meteorite idea blown out of the water

Where did Earth's water come from? Not melted meteorites, according to a new study. Researchers have analysed 4.5-billion-year-old meteorites and found that they have extremely low water content – in fact, they were among the driest extraterrestrial materials ever measured. This led the researchers to conclude that water was likely delivered to Earth via unmelted, or 'chondritic', meteorites. Megan Newcombe (University of Maryland) and colleagues present their results in *Nature*. **go.umd.edu/3VhhE3p**



Cluster prequel

NASA's JWST has discovered a protocluster of seven galaxies at a redshift of 7.9, or a mere 650 million years after the Big Bang. Based on the data collected, Takahiro Morishita (IPAC-CalTech) and colleagues calculated the nascent cluster's future development, finding that it is likely to grow in size and mass to resemble the Coma Cluster, a behemoth of the modern universe. The study is published in *The Astrophysical Journal Letters*. **go.nasa.gov/3VmgeF6**

(NASA, ESA, CSA, Takahiro Morishita (IPAC)/Alyssa Pagan (STScI))

Ryugu biochemicals

Researchers analysing pristine samples of asteroid Ryugu collected by the Japanese Space Agency's Hayabusa2 spacecraft have found traces of the chemical 'uracil' – one of the informational units that make up ribonucleic acid, or RNA. Nicotinic acid, also known as Vitamin B3 or niacin, which is an important cofactor for metabolism in living organisms, was also detected in the samples.
The team, led by Yasuhiro Oba (Hokkaido University), hypothesised that the nitrogen-containing compounds were, at least in part, formed from simpler molecules such as ammonia, formaldehyde and hydrogen cyanide. While these species were not detected in the Ryugu samples, they are known to be present in cometary ice – and Ryugu could have come from a comet or a parent body in cold conditions. The research appears in *Nature Communications*. **bit.ly/3VjhcBP**

More cosmic discrepancy

A research team have measured the amplitude of matter fluctuations or 'clumpiness' of dark matter and found a value of 0.776. The new result used sophisticated computer simulations and a weak lensing survey of 25 million galaxies using the 8.2-metre Subaru telescope. Unfortunately, the value does not agree with the value of 0.83 derived from studies of the Cosmic Microwave Background (CMB). This appears to exacerbate the problems with the standard cosmological model because the expansion rate of the universe has also been shown to have an early/late discrepancy. A series of five papers on these results will appear in *Physical Review D*. **bit.ly/40POQAc**

The Library
New books

The RAS Library and Archives are currently open from Tuesday to Friday, and you can check https://ras.ac.uk/library/opening-times for the latest updates on opening hours.

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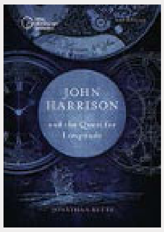

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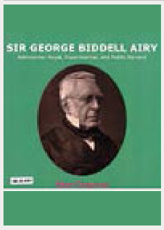

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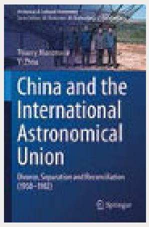

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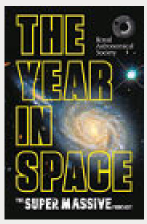

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Neptune's red Trojans

Asteroids sharing their orbits with Neptune seem to consist of two populations. In a study of 18 neptunian Trojans, Bryce Bolin (NASA GSFC) and team found that several of the asteroids were much redder than most asteroids, and other asteroids in this group. The redness implies that they contain a higher proportion of more volatile ices such as ammonia and methanol and probably formed further out in the solar system before being captured into the orbit of Neptune. **bit.ly/3oNYPJ0**

Structure traced in universal chaos

Researchers have used a novel tool to uncover the spatial distribution of galaxies in the universe. The new study applied a 'pair-connectedness function', a technique commonly found in materials science. When applied to questions of spatial relationships between galaxies, the tools underscored a kind of correlated disorder – a complex structural property that is definitely not random. A paper, by Oliver HE Philcox and Salvatore Torquato (Princeton University) appears in *Physical Review X*. **bit.ly/3LG302M**

Jet executes a sharp turn

It is not often that an astronomical object changes classification. But that is exactly what has happened to a radio galaxy called PBC J2333.9-2343, located 657 million light years away, because of its odd blazar jet. It contains an AGN with a jet directed towards the Earth, which defines a blazar. But the jet has changed its direction drastically, by as much as 90°, switching from perpendicular to our line of sight (making it a radio galaxy), to pointing directly towards us: it's a radio galaxy plus blazar now. The research team, led by Lorena Hernández-García (Millennium Institute of Astrophysics), speculate that the change of direction could have been driven by a merger, or a strong burst of activity in the galactic nucleus after a dormant period. A paper appears in *Monthly Notices of The Royal Astronomical Society*. **bit.ly/3oZ7A2W**

Would Europa move?

If the silicate core of Jupiter's moon Europa gave rise to quakes, how big would they have to be to be detectable on the icy surface? The best estimate of researchers led by AG Marusiak of NASA's Jet Propulsion Laboratory, USA, is that a magnitude of at least M_W=5 would be needed to be detectable by a seismometer on the surface of Europa using current technology. Such quakes would provide valuable data about the internal structure of the moon, as earthquakes do, but the signal would be attenuated by a liquid ocean under the outer ice shell, and by the – so far unknown – thickness of the shell itself. Marusiak and colleagues published their work in *Earth and Space Science*.

Looking for life in earthly dust

Evidence for life on another world may exist right here on Earth. Following enormous collisions such as asteroid impacts, some material from an impacted world may be ejected into space. This material can travel vast distances over extremely long periods of time. In theory this material could contain direct or indirect signs of life from the host world, such as fossils of alien microorganisms. And this material could be detectable. Tomonori Totani (University of Tokyo) discusses the suggestion in the *International Journal of Astrobiology*. **bit.ly/3NovgYN**

AI finds first star families

Tilman Hartwig (University of Tokyo) and colleagues have used artificial intelligence to analyse elemental abundances in more than 450 extremely metal-poor stars. Based on the newly developed supervised machine learning algorithm, trained on theoretical supernova nucleosynthesis models, they found that 68% of the observed extremely metal-poor stars have a chemical fingerprint consistent with enrichment by multiple previous supernovae. The finding strongly suggests that the first stars were not born alone, but instead formed as a part of star clusters or multiple star systems. The study appears in *The Astrophysical Journal*. **bit.ly/3HpdfWm**

Up, up and oh dear...

The first integrated test flight of the SpaceX Starship ended in detonation of the combined launcher and spacecraft; not all of the 33 engines on the Super Heavy booster appeared to fire during the launch before what SpaceX described as a "rapid unscheduled disassembly". The US Federal Aviation Authority is investigating the launch failure, which damaged the launch pad despite clearing the launch tower during its brief flight. **bit.ly/428cwkG**

Down, down and oh dear...

The Hakuto-R Mission 1 Lunar Lander, part of the commercial ispace mission to the Moon, appears to have been lost during landing on 26 April. It seems the spacecraft ran out of thruster propellant at the last stage of landing; Hakuto was vertical on its final approach when the descent speed increased rapidly. "What is important is to feed this knowledge and learning back to Mission 2 and beyond so that we can make the most of this experience," said Takeshi Hakamada, Founder and CEO of ispace. **bit.ly/3LMRB1f**

Not bad for a girl!

A community project to promote gender equality in the science workplace was once again at the European Geoscience Union meeting in Vienna, highlighting sexist behaviour in the workplace and the unconscious bias beneath it by means of cartoons. Each strip is based on a report sent to the website didthisreallyhappen.net and presented anonymously, without comment. It's not just a funny story, though; the team has identified six patterns of behaviour that disadvantage women in science (Bocher *et al.* 2020 ADGEO, 53, 15–31) **bit.ly/44nsdX4** (Images from https://didthisreallyhappen.net/)

1 *Schematic showing the scale of the red supergiant Betelgeuse and its circumstellar medium compared to that of the Solar System.* (Art by L. Calçada, by permission of the European Southern Observatory (ESO))

Betelgeuse: *a review*

Was Betelgeuse once in a binary star system? What causes it to vary over a vast range of timescales? Why did it dim dramatically in 2020? When and how will it explode? **J. Craig Wheeler** and **Manos Chatzopoulos** present a host of challenges to both observers and theorists.

Betelgeuse has fascinated people since ancient times. Here we present a contemporary summary of the observations and theory that lead to the current understanding of Betelgeuse as a massive red supergiant doomed to eventual collapse and explosion, probably ~100 000 years from now. Although it lies only ~200 parsecs from Earth, and hence can be spatially resolved with appropriate instrumentation, uncertainties in its distance remain a critical impediment to deeper understanding.

The surface of Betelgeuse is rent with a complex structure as deep convective eddies arise to the surface affecting the photosphere, chromosphere, mass loss, the formation of dust and molecules, and the surface magnetic field structure. The global effective temperature has some irreducible uncertainty because of associated temperature variations in the atmosphere. The surface gravity is not precisely known, leading to further uncertainties in the current mass. Determination of the equatorial rotation velocity is critical since some current estimates indicate that Betelgeuse is rotating anomalously rapidly, near rotational breakup, a property that cannot be explained by basic single-star evolutionary models. Betelgeuse is also moving through space at high, though not unprecedented, velocity that indicates that it received a boost, perhaps through collective interaction with other stars in its birth cluster, though disruption of an original binary system has been suggested. A bow shock and other structure in the direction of the motion of Betelgeuse suggests that it has affected the organisation of the distant circumstellar and interstellar medium. Betelgeuse varies in brightness on a variety of time scales with ~200 days, ~400 days and ~5000 days being prominent. Models of this variability may be in conflict with historical records suggesting that Betelgeuse was yellow in colour, not red, only two millennia ago.

Betelgeuse is also subject to a rich variety of theoretical studies that attempt to understand its observational properties and current evolutionary state. Betelgeuse is statistically likely to have been born in a binary system, and the high space velocity and apparent rotation have been related to binary star evolution. One possibility is that Betelgeuse has been subject to common envelope evolution in which a companion star plunges into the primary and becomes tidally disrupted as it nears the core of the primary. This interaction is complex in three dimensions and not sufficiently well understood. Such merger models have been invoked to account for the apparently anomalous rotation velocity.

Betelgeuse underwent a Great Dimming in 2020 that caught the attention of astronomers and the general public worldwide. Explanations have focused on large cool spots on the surface and the expulsion of a cloud of dust that obscured the surface.

Betelgeuse

Betelgeuse (α Orionis) is a nearby, massive red supergiant (RSG) that is most likely destined to explode as a classic Type II-P supernova (SN II-P) and leave behind a neutron star. Study of Betelgeuse thus promises insight into a broad range of issues of the structure, evolution, rotation, magnetic fields, mass loss, stellar winds, circumstellar medium, dust formation, atmospheres, chromospheres, radiative transfer, nucleosynthesis, and, eventually, the explosion of massive stars. Betelgeuse is special because its propinquity allows its image to spatially be resolved. Betelgeuse also has properties such as its runaway kinematics that may be special to it. Most massive stars arise in binary systems and there are hints this may have been true for Betelgeuse despite its current apparently solo state, which seems typical of SN II-P. Betelgeuse shows a 420-day period that is most likely a first overtone radial pulsation mode and variance on timescales of 2000 days that is associated with overturn of convective plumes. Then, just to keep us guessing, Betelgeuse staged the Great Dimming of 2019/20, the detailed origin of which is still debated. Figure 1 gives some sense of the scale of Betelgeuse.

Despite the relatively small distance from Earth, and in some sense because of it, it has been difficult to obtain tight constraints on the distance, luminosity, radius, current and Zero Age Main Sequence (ZAMS) masses, and information about the internal rotational state and associated mixing and hence on the evolutionary state of Betelgeuse and when it might explode. The best current guess is that Betelgeuse is in core helium burning and will not explode for about 100000 years, but it will be a tremendous spectacle from Earth when it does.

Observations

Valuable summaries of basic observational properties of Betelgeuse are given by Dolan *et al.* (2016) and Joyce *et al.* (2020). Here we summarise some key aspects.

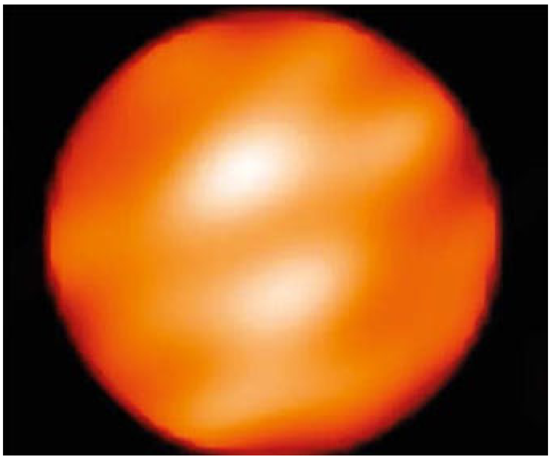
Distance

Even recently the distance to Betelgeuse has been known to only 20% ($D \approx 197 \pm 45$ pc; Harper *et al.* 2008; 2017), a situation that was not improved by the Gaia mission that provides accurate parallaxes, but which saturates on such a bright star. Key properties such as radius and luminosity were thus significantly uncertain, *R* to within 20% and *L* to only 40%. Estimates of mass that determine the evolution depend sensitively on *L* and *R,* and thus also remained uncertain. The effective temperature that can be determined independent of distance has its own intrinsic uncertainties. Dolan *et al.* (2016) estimated $T_{eff} = 3500 \pm 350$ K. Within these uncertainties, models of contemporary Betelgeuse could be brought into agreement with observations of *L*, *R*, and T_{eff} all the way from the minimum-luminosity base of the giant branch to the tip of the red supergiant branch (RSB) (Wheeler *et al.* 2017). Recent work has proposed ways to reduce the uncertainty in distance, but with conflicting solutions converging on either the base or the tip of the RSB.

Spatial Resolution

A special characteristic of Betelgeuse is that its relatively small distance allows its surface to be spatially resolved with appropriate instrumentation as shown in figure 2. The photosphere of Betelgeuse subtends an angle of ~30 milliarcseconds that can be resolved with ground-based interferometry in the optical and infrared (Haubois *et al.* 2009; Montargès *et al.* 2016; López Ariste *et al.* 2022) and submillimetre (O'Gorman *et al.* 2017; Kervella *et al.* 2018; Haubois *et al.* 2019) or from space with the Hubble Space Telescope (HST) (Gilliland & Dupree 1996; Uitenbroek *et al.* 1998).

Gilliland & Dupree (1996) resolved Betelgeuse spatially by obtaining images with the HST Faint Object Camera in 10 resolution elements across the surface. They found the ultraviolet diameter of Betelgeuse to be 108 ± 4 mas, a factor of 2.2 larger than the optical diameter, suggesting an extended chromosphere in analogy to the hot temperature inversion in the Sun. A single bright, unresolved area was 200 K hotter than the mean value. Gilliland & Dupree (1996) suggested this surface inhomogeneity might be



2 *Spatially-resolved H band image of Betelgeuse. From Haubois et al. (2009)* (by permission of X. Haubois, ESO/Observatoire de Paris, and A&A.)

due to magnetic activity, atmospheric convection, or global pulsations that produce shock structures that heat the chromosphere. Spatially resolved spectroscopy with the Goddard High Resolution Spectrograph suggested the complicated dynamics of outflowing material in the chromosphere.

Haubios *et al.* (2009) undertook H-band interferometry with the Infrared-Optical Telescope Array (IOTA) at the Whipple Observatory to measure the diameter (44.28 ± 0.15 mas), effective temperature (3600 ± 66 K), limb darkening, and bright or dark patches in the photosphere and surroundings.

Montargès *et al.* (2016) did H-band interferometry on the VLT to explore mass loss driven by strong convective motions by mapping the shape of the envelope and following the structure of the wind from the photosphere out through the nearby circumstellar medium and into the interstellar medium. They detected a hot spot on the photosphere comparable in size to the radius of the star.

O'Gorman *et al.* (2017) used submillimetre observations with the Atacama Large Millimeter Array (ALMA) to study the free-free emission in the extended atmosphere of Betelgeuse. They found that the mean temperature at 1.3 stellar radii was 2760 K, a value that is less than both the photospheric temperature they gave as T_{eff} = 3690 K and the temperatures at 2 solar radii, implying an inversion of the mean temperature in the atmosphere. The emission showed evidence for inhomogeneous localised heating in the atmosphere of Betelgeuse, perhaps related to magnetic activity generated by large-scale convection.

Convection and Plumes

The extended outer envelope of Betelgeuse engenders appreciable superadiabatic temperature gradients that lead to strong convection (Schwarzschild 1975). Both direct observations (Gilliland & Dupreee 1996; Uitenbroek *et al.* 1998; Haubois *et al.* 2009; Montargès *et al.* 2016; O'Gorman *et al.* 2017; Kervella *et al.* 2018; Haubois *et al.* 2019; López Ariste *et al.* 2022) and models (Chiavassa *et al.* 2010; Goldberg *et al.* 2022) indicate that the convective structure of the envelope of Betelgeuse is characterised by large plumes of upwardly rising hot material and inwardly cascading cooler material. The plumes in turn lead to hot and cold patches on the surface that are substantially large compared to the radius of the star (Montargès *et al.* 2016). This leads to complications in determining basic quantities like the global effective temperature (Levesque & Massey 2020).

Atmosphere, Photosphere, Chromosphere

Driven by the irregular convective plumes, the outer layers of Betelgeuse reveal a complex atmospheric structure as the optically-thick convective envelope yields to a wavelength-dependent and position-dependent photosphere and chromosphere (Bernat & Lambert 1976; Lim *et al.* 1998, *Nature*, 392, 575; Plez & Lambert 2002; Montargès *et al.* 2016; O'Gorman *et al.* 2017; López Ariste *et al.* 2022). O'Gorman *et al.* (2017) established a temperature inversion between the photosphere and chromosphere.

Mass and Mass Loss

The ZAMS mass is a fundamental property that determines the evolution of a star. In the case of Betelgeuse, the uncertainty in distance and other factors yields intrinsic uncertainty in the ZAMS mass. Betelgeuse qualifies as a massive star, but estimates of the ZAMS mass vary from 10 to 25 $M_\odot$. In recent estimates, Dolan *et al.* (2016) gave 17–25 $M_\odot$ whereas Joyce *et al.* (2020) found 18–21 $M_\odot$. This mass range destines Betelgeuse to succumb to iron core collapse and a likely catastrophic explosion. Direct collapse to a black hole is a remote possibility (see 'Evolutionary Models').

The subsequent evolution of Betelgeuse is not determined solely by its ZAMS mass, but also depends on abundances, rotation, stellar winds, the presence of a binary companion and the possibility of a merger.

Mass loss on the main sequence is estimated to be less than 0.1 $M_\odot$, a small effect compared to other uncertainties. Harper *et al.* (2001) and Le Bertre *et al.* (2012) determined the current mass loss rate to be ~1–4 × 10^{-6} $M_\odot\,yr^{-1}$. Dolan *et al.* (2016) adopted 2 × 10^{-6} $M_\odot\,yr^{-1}$. Estimates of the current wind velocity of Betelgeuse range from 3 to 14 km s^{-1}. Dolan *et al.* (2016) adopted a range of 9 ± 6 km s^{-1}. The wind accelerates, so a single wind velocity may not be appropriate.

As for other RSGs, mass loss from Betelgeuse in its current configuration is episodic (Decin *et al.* 2012; Massey *et al.* 2023), a factor often neglected in prescriptions for mass loss rates. This variability is probably linked to the sporadic convective plumes and to the intrinsic pulsational properties. Magnetic fields may play a role (see 'Magnetic Fields').

López Ariste *et al.* (2022) sought to understand convection and the mechanisms that trigger mass loss by using linear spectropolarimetry of the atomic lines to provide velocity and hence depth information in addition to spatial distribution. The result was images of the photosphere of Betelgeuse that provide information about the 3D distribution of brightness in the atmosphere. The data revealed the velocity of vertical convective flows at different heights in the photosphere that showed that non-gravitational forces are present in the photosphere of Betelgeuse that allow plasma to reach velocities close to the escape velocity. These forces may trigger mass loss and sustain large stellar winds.

Humphreys & Jones (2022) argue that Betelgeuse gives evidence for discrete, directed clumpy outflows that are related to magnetic fields and surface activity. They argue that this clumpy outflow analogous to solar coronal mass ejections is a major contributor to mass loss from RSGs, including Betelgeuse.

Molecules and Dust

Plasma recombining to gas continues to cool as it is ejected from the surface of Betelgeuse. If it gets sufficiently cool, the gas can form molecules through complex non-equilibrium chemistry. The molecules can then serve as nucleation sites where inorganic dust can form. Dust grain surfaces in turn provide an environment to form yet other molecules.

Jennings & Sada (1998) discovered water in the atmosphere of Betelgeuse. Tsuji (2000) confirmed the presence of water in data taken 35 years previously with the balloon-borne telescope Stratoscope II (Woolf *et al.* 1964). He proposed a molecular shell, a 'MOLsphere', in the atmosphere of Betelgeuse. Perrin *et al.* (2007) subsequently identified a geometrically thin shell between 1.31 and 1.43 R_{star} with a typical temperature of 1550 K that contained H_2O, SiO, and Al_2O_3. Ohnaka *et al.* (2009; 2011) spatially resolved the macro-turbulent gas motion in the photosphere and MOLsphere of Betelgeuse for the first time.

Models presented by Harper *et al.* (2001) suggested that dust formed at about 33 R_{star} at a temperature of ~360 K. Kervella *et al.* (2018) argued that convective cells lead specifically to the production of molecular plumes and dusty knots in the north polar region of Betelgeuse. Related notions came to the fore during the Great Dimming of 2019/20 (See 'The Great Dimming').

Haubois *et al.* (2019) did near-IR interferometry to explore the connection between dust formation and mass loss from Betelgeuse. They found a halo of fosterite (Mg_2SiO_4) dust beginning about 0.5 R_{star} above the photosphere, much lower than suggested by the models of Harper *et al.* (2001). The height of molecule and dust formation may vary inhomogeneously over the surface of Betelgeuse.

Surface Gravity

The gravitational acceleration at the surface of Betelgeuse, the surface gravity, $g = G\,M/R^2$, provides an independent constraint on the ratio R/M. This quantity is determined from the analysis of line structure in the photosphere and is typically presented as the logarithm in base 10 of *g* measured in the cgs system. Lambert *et al.* (1984) observed forbidden O I lines, vibration-rotation bands of second-overtone CO near 1.6 micron, NH bands between 3 and 4 microns, OH fundamental bands near 3 microns, and CN red lines near 8000 Å and 2 microns, and employed sophisticated model atmospheres designed for supergiant stars. For Betelgeuse, Lambert *et al.* (1984) adopted $\log g = 0.0 \pm 0.3$. Lobel & Dupree (2000) used near-UV, optical, and near-IR high-dispersion spectra analysed with non-LTE radiative transfer calculations to obtained $\log g = -0.5$ that is somewhat less, even given the nominal uncertainties. Neither Lambert *et al.* (1984) nor Lobel & Dupree (2000) considered the plume structure of the envelope and departures from spherical symmetry.

Neilson *et al.* (2011) employed limb-darkening laws and grids of spherical model stellar atmospheres to determine $R/M = 82^{+13}_{-12}\ R_\odot/M_\odot$. From their best-fitted models, Dolan *et al.* (2016) obtained $R/M = 40\ R_\odot/M_\odot$, substantially less than Neilson *et al.* (2011), and $\log g = -0.05$ for their Eggleton-based code and $\log g = -0.10$ with the stellar evolution code Modules for Experiments in Stellar Astrophysics (MESA; Paxton *et al.* 2011; 2013; 2015; 2018). The latter estimates for $\log g$ are roughly consistent with Lambert *et al.* (1984) but appreciably larger than found by Lobel & Dupree (2000).

In principle, the effective gravity at the surface of a star is reduced by the centrifugal effects of rotation that is substantial in Betelgeuse (see 'Rotational Velocity'). For a 20 $M_\odot$ model rotating at velocities typical of Betelgeuse, Wheeler *et al.* (2017) found $\log g = +0.42$ at the luminosity minimum at the base of the RSG branch and $\log g = -0.48$ during carbon burning when the model had slowed due to envelope expansion. The former is somewhat beyond the upper limit set by Lambert *et al.* (1984) and the latter in close agreement with the determination of Lobel & Dupree (2000). For their models with a 16 $M_\odot$ primary merging with a 4 $M_\odot$ secondary, Chatzopoulos *et al.* (2020) found post-merger surface gravity for models merging at 300 and 250 $R_\odot$ to be 4.67–6.65 cm s^{-2}, corresponding to $\log g = 0.67$–0.82.

There are thus significant uncertainties in both observations and models of $\log g$ for Betelgeuse. Constraints on $\log g$ come into play in considering pulsational properties (see 'Pulsation Periods') and the possibility of a recent colour change in Betelgeuse (see 'Recent Change in Colour?').

Rotational Velocity

The rotation of Betelgeuse at the surface and at depth has implications for estimates of the current age, the current mass, the ZAMS mass, the current evolutionary state, and the time to explosion.

Betelgeuse appears to have an anomalously large rotational velocity. Long-slit spectroscopy across the minimally resolved disk of Betelgeuse obtained with the HST yielded an estimated surface rotational velocity $v_{rot} \sin(i) \sim 5$ km s^{-1} at an inclination of $i \approx 20°$ (Dupree *et al.* 1987; Gilliland & Dupree 1996; Uitenbroek *et al.* 1998; Kervella *et al.* 2009). These data imply an equatorial rotational velocity of ~15 km s^{-1}. The uncertainty in this quantity is itself uncertain.

More recent observations appear to further support this result even within the uncertainties imposed by large-scale convective motions on the star's surface. Kervella *et al.* (2018) used ALMA to resolve the surface velocity and determined that Betelgeuse rotates with a projected equatorial velocity of $v_{eq} \sin(i) = 5.47 \pm 0.25$ km s^{-1} with an estimated rotation period of 36 ± 8 years. They confirmed that the chromosphere is co-rotating with the star up to a radius of 1.5 times the continuum radius. They found that the position angle of the polar axis of Betelgeuse coincided with a hot spot in the ALMA data, suggesting that focused mass loss was currently taking place in the polar region. They proposed that a particularly strong convection cell was driving a focused molecular plume that could subsequently condense into dust at a few stellar radii thus contributing to anisotropic mass loss.

> *"Recent observations proposed that a particularly strong convection cell was driving a focused molecular plume that could subsequently condense into dust at a few stellar radii thus contributing to anisotropic mass loss"*

High rotation during the supergiant phase is not found in stellar evolution calculations of single massive stars (see 'Single Star Models') – including those that are rapid rotators at the Zero Age Main Sequence (ZAMS) – nor expected by simple arguments of angular momentum conservation (Wheeler *et al.* 2017).

Single massive stars lose a fraction of their mass and angular momentum through winds already during the main sequence (MS) phase. O stars with initial rotation velocities of ~200 km s^{-1} evolve through rapid mass and angular momentum losses to become much slower rotating B stars with $v \sin(i) \lesssim 50$ km s^{-1} (Maeder & Meynet 2000; Higgins & Vink 2019 and references therein). Simple analytic arguments (Chatzopoulos *et al.* 2020) and stellar evolution calculations (Claret & Gimenez 1989) suggest that a star rotating at ~200 km s^{-1} at the ZAMS is likely to decrease to $\lesssim 50$ km s^{-1} at the Terminal Age Main Sequence (TAMS). Similar estimates and detailed simulations of the evolution of massive stars, including mass and angular momentum losses from the ZAMS to the supergiant stage typically yield an upper limit to the equatorial rotational velocity of $v_{eq} < 1$ km s^{-1} on the RSB (Ekström *et al.* 2008, 2012; Brott *et al.* 2011a,b). Measurements of giant and supergiant star rotation rates support this argument (Ceillier *et al.* 2017). Wheeler *et al.* (2017) and Chatzopoulos *et al.* (2020) found a velocity of ~0.1 km s^{-1} high on the RSB.

Kepler observations of low-mass giant stars ($< 3 M_\odot$) showed 17 with rotational speeds up to ~18 times that of the Sun (Costa *et al.* 2015). It is possible that a yet unknown mechanism, perhaps transfer of angular momentum from inner regions by g-mode acoustic waves (see 'Asteroseismology'), could account for this rapid rotation (Fuller *et al.* 2014; Townsend *et al.* 2018), but it is not clear that even such mechanisms can account for the rotation of a massive RSG like Betelgeuse.

Taken at face value, Betelgeuse is thus rotating too rapidly by a factor ~15 and perhaps as much as 150 compared to basic single-star models high on the RSB (Wheeler *et al.* 2017; Chatzopoulos *et al.* 2020; Joyce *et al.* 2020). Models of Betelgeuse on the RSB give a critical Keplerian velocity of ~65 km s^{-1} (Wheeler *et al.* 2017); the observed rotational velocity is thus a substantial fraction of the escape velocity. Such a rotation may cause measureable oblateness that could complicate interpretation of the observations (Tatebe *et al.* 2007; Haubois *et al.* 2009).

There are concerns that the deduced rotational velocity is not correct, perhaps confused by the complex large-scale convective flows at the photosphere. Gray (2001) found a macroturbulence Gaussian dispersion ~15 km s^{-1} with a FWFM of ~ ±50 km s^{-1} consistent with many convection cells appearing on the stellar disk but with no evidence for giant convection cells. More recently, López Ariste *et al.* (2018) found characteristic upflow and downflow speeds of 22 and 10 km s^{-1}, respectively. Jadlovský *et al.* (2023) argued that the projected rotational velocity v_{rot} sin(i) is not trustworthy, as both edges of Betelgeuse seem to be moving towards Earth at a similar velocity.

An accurate measurement of the equatorial rotational velocity of Betelgeuse is important in order to constrain models. Single-star rotating models give v_{rot} ~15 km s^{-1} only in a brief phase near the base of the RSB that would last for a few thousand years at most. It is conceivable that Betelgeuse might currently reside in this portion of the Hertzsprung-Russell Diagram (HRD) by appropriately pushing 3σ error bars on R, L, and T_{eff} (Wheeler *et al.* 2017). The historical colour changes of Betelgeuse characterised by Neuhäuser *et al.* (2022) may demand that Betelgeuse is currently in this lower portion of the HRD where massive stars can change T_{eff} on timescales of 1000 years (see 'Recent change in colour?'). This conclusion conflicts with the results from the careful study of the pulsation period given by Joyce *et al.* (2020) that places Betelgeuse higher on the RSB (see 'Pulsation Periods').

One possibility to account for the high rotation velocity is that Betelgeuse has undergone a merger as it expanded and evolved up the RSB (see 'Merger Models'). Another pathway to form a rapidly-rotating supergiant is presented in de Mink *et al.* (2013). They propose that Case A Roche lobe overflow mass transfer from a ~20 $M_\odot$ primary is enough to spin up a ~15 $M_\odot$ secondary to high rotational velocity if the transfer occurs right after the TAMS before the ascent up the RSB. This possibility requires considerable fine-tuning of the binary evolution parameters and the timing of the onset of mass transfer.

Both the merger model and the Case A transfer model should be examined for testable observational consequences.

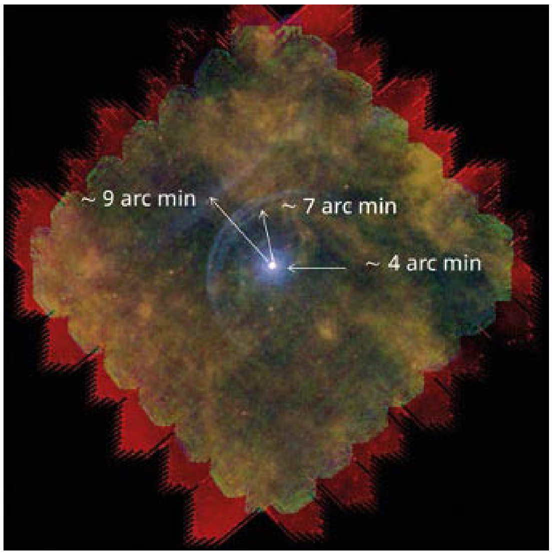
Observed Abundances

Photospheric abundances are yet another clue to the evolutionary history and state of Betelgeuse. The measured N/C (nitrogen to carbon) and N/O (nitrogen to oxygen) surface abundance ratios for Betelgeuse are 2.9 and 0.6, respectively, compared to solar values of N/C = 0.3 and N/O = 0.1 and the ratio $^{12}C/^{13}C$ is much lower than solar (Lambert *et al.* 1984). These ratios vary as massive stars burning hydrogen on the CNO cycle settle into CNO equilibrium, with N being produced at the expense of C and O. CN-equilibrium is achieved before an inhibiting gradient in mean molecular weight is established between the core and the envelope, so the excess N can quickly be transported to the stellar surface thus producing large N/C ratios. Full CNO-equilibrium is achieved only after significant hydrogen burning, so surface O depletion only occurs later.

The observation of enhanced nitrogen at the surface of Betelgeuse may be indicative of enhanced mixing, perhaps triggered by rotation (Meynet *et al.* 2013). The effects of rotational mixing are more pronounced at lower metallicity, higher ZAMS mass, and higher rotational velocity (Brott *et al.* 2011a). Rotational mixing may need to be supplemented by other effects such as binary evolution and magnetic fields to understand the abundance distributions in evolved massive stars (Brott *et al.* 2011b).

Luo *et al.* (2022) have used surface abundances to constrain the nature of Betelgeuse in terms of initial mass, rotation, and overshoot. They find the acceptable range of ZAMS masses is slightly larger for rotating models than non-rotating models, 12–25 $M_\odot$ versus 15–24 $M_\odot$, respectively. They find that the initial rotation on the ZAMS must be restricted to 0.3 of the Keplerian velocity in order to fit the surface abundances of Betelgeuse as an RSG and find that some of their models could be in the phase of carbon burning or beyond.

The observed abundances in Betelgeuse are consistent with material that has been mixed to the surface in the first dredge-up phase when the convective hydrogen envelope penetrates the helium core (Lambert *et al.* 1984; Dolan *et al.* 2016). This constrains Betelgeuse to have passed the base of the RSB and to be ascending the RSB, consistent with the results of Joyce *et al.* (2020) but perhaps in contradiction with the conclusions of Neuhäuser *et al.* (2022).



3 *Structure in the large scale CSM surrounding Betelgeuse observed by the Herschel mission. Note the prominent bow shock at 7 arcmin that is in the direction of the spatial velocity of Betelgeuse.* (From Decin et al. (2012). Adapted by permission of L. Decin and A&A.)

Kinematics, Nearby CSM, ISM, Bowshocks

In addition to perhaps being a rapid rotator, Betelgeuse is also a known runaway star with a measured space velocity of ~30 km s^{-1} and a kinematic age of ~7–11 Myr (Harper *et al.* 2008; 2017).

As shown in figure 3, the flight of Betelgeuse through the interstellar medium is also illustrated by HST and Herschel observations of a bow shock forming a swept-up shell of material of ~0.14 $M_\odot$ at a radius of ~6–7 arcmin corresponding to a physical distance of ~0.8 pc using a distance to Betelgeuse of ~400 pc (Noriega-Crespo *et al.* 1997; Decin *et al.* 2012) (current estimates of the distance are less by a factor of two or three). The prominent bow shock is in the same direction as the kinematic motion, indicating a peculiar velocity with respect to the local standard of rest of $v \approx 25$ km s^{-1} (Harper *et al.* 2008) or perhaps as much as 35 km s^{-1} (van Loon 2013). The morphology of this structure is attributed to wind from the star sweeping up interstellar medium in the direction of motion (Mohamed *et al.* 2012; Decin *et al.* 2012; Mackey *et al.* 2014). The observations also show a smaller ring of material with a diameter of about 4 arcmin (Le Bertre *et al.* 2012). One explanation is that this is wind mass that is radiation-impeded by external radiation (Mackey *et al.* 2014). There is also an odd, very linear feature about 9 arcmin away, beyond the bow shock, that remains unexplained (Noriega-Crespo *et al.* 1997; Decin *et al.* 2012). Wheeler *et al.* (2017) noted that a merger event might have some relation with the interstellar shells of higher density in the vicinity of Betelgeuse. The strangely linear feature at 9 arcmin might be related to the square axisymmetric circumstellar nebula recently discovered around the B9 Ia star HD93795 by Gvaramadze *et al.* (2020). Such a connection might in turn suggest that Betelgeuse had undergone some previous mass expulsion.

Proposals to account for the high space velocity of Betelgeuse include multi-body stellar interactions in its birth cluster and the possibility that a binary companion underwent a supernova explosion (Blaauw 1961; van Loon 2013). In a study of the 30 Doradus region of the Large Magellanic Cloud, Sana *et al.* (2022) conclude there are two different populations of massive run-away Main Sequence O stars: a population of rapidly spinning (v_{eq} sin(i) > 200 km s^{-1}) but slowly moving (v = 25–60 km s^{-1}) runaway stars and a population of slowly rotating (v_{eq} sin(i) < 200 km s^{-1}) rapidly moving (v > 60 km s^{-1}) stars. They found no rapidly spinning, rapidly moving stars in their sample. Sana *et al.* (2022) argue that slowly-moving, rapidly-spinning stars result from binary ejections, while rapidly-moving, slowly-spinning stars result from dynamical ejections, with slowly-moving, rapidly-spinning stars and hence binary evolution dominating the current massive runaway star population in 30 Doradus. Betelgeuse nominally belongs in the slowly-moving, rapidly-spinning runaway category.

Backwards extrapolation of the current trajectory of Betelgeuse has led some to suggest that its possible birthplace is the Orion OB1a association (Briceño *et al.* 2005). Others have argued that a backward extrapolation of its known space velocity does not appear to bring Betelgeuse close to any plausible sub-association of OB1 as its birth place (Bally 2008). Bally (2008) suggests a two-step process: a dynamical ejection of a binary within the first few million years after the formation of Betelgeuse's birth cluster; and a subsequent merger of the binary or a supernova explosion of the more massive component, releasing the surviving, now single, Betelgeuse at some post MS stage of its evolution.

Work on the kinematic effects of supernovae in massive star binary systems tends to discourage the conjecture of the previous explosion of a companion to Betelgeuse. Renzo *et al.* (2019) confirm that of order 20–50% of massive star binaries merge rather than undergoing disruption. They also find that by far the largest fraction of binaries disrupted by the collapse and explosion of the primary result in 'walkaway' rather than 'runaway' stars. The velocity distribution of the ejected companion peaks at about 6 km s^{-1}. For secondaries more massive than 15 $M_\odot$, as likely applies to Betelgeuse, only ~0.5% have velocities of 30 km s^{-1} and above, as appropriate to Betelgeuse.

These results suggest that, while non-zero, the likelihood that the space motion of Betelgeuse resulted from the previous explosion of a companion is small. The results depend on assumptions about primordial binaries, among other things, but the general result is that it is easier to generate walkaway stars than runaway stars. A runaway binary is likely to be rare, but is not precluded.

As discussed above, a reasonable alternative is that the proper motion of Betelgeuse arises from stellar dynamics in its natal cluster (Poveda *et al.* 1967; Oh & Kroupa 2016; Schoettler *et al.* 2019). Early ejection as a single star either by the disruption of a cluster binary or dynamical escape from a cluster are unlikely to yield a rapid rotator in the present supergiant stage. Even if spun up on the ZAMS, its rotation on the RSB would be slow. If a previous binary companion exploded, then it clearly could not have merged with the current Betelgeuse as discussed in 'Merger Models'.

The origin of the space motion of Betelgeuse is thus one more fascinating open question about this tantalising star. Whether Betelgeuse attained its proper motion from the explosion of a companion or from cluster dynamics, if it emerged as a single star then the apparent observed equatorial velocity remains an issue.

"Whether Betelgeuse attained its proper motion from the explosion of a companion or from cluster dynamics, if it emerged as a single star then the apparent observed equatorial velocity remains an issue"

One possible way to account for both the space motion and the equatorial velocity would be to provide the space motion by cluster dynamics and ejection of a binary, of which the star we currently observe as Betelgeuse was the primary, and a subsequent merger along the RSB. This is, admittedly, an improbable string of events. Oh & Kroupa (2016) find that a majority of ejected massive binaries have a period shorter than 105 days. Supergiant branch merger models have a typical presumed orbital period of about 30 years or 10^4 days (Wheeler *et al.* 2017). Having a rather massive companion might increase the likelihood that the binary remains intact upon ejection from the natal cluster. Current results allow for that possibility.

We note that while Betelgeuse may have moved hundreds of pc during its main sequence lifetime, it is expected to have moved only ~2 pc during the 100 000 years or so it has been in core helium burning as a RSG.

Magnetic Fields

The atmosphere of Betelgeuse is observed to harbour magnetic fields of ~1 G as measured by circular polarisation (Mathias *et al.* 2018) and as inferred from the Zeeman effect (Aurière *et al.* 2010). These fields are thought to originate from local low-scale convective activity and associated non-linear dynamo action in Betelgeuse or perhaps from giant convective cells on its surface (Dorch 2004).

We have noted earlier that magnetic fields may play a role in localised hot spots on the surface of Betelgeuse, in the formation of the chromosphere, and in clumpy mass loss. Thirumalai & Heyl (2012) addressed the effects of magnetic fields on winds, dust, and the structure of the photosphere and chromosphere of Betelgeuse.

Pulsation Periods

We noted in 'Surface Gravity' that measurement of the surface gravity provides a constraint on R/M, given an independent measurement of R. Stellar pulsation modes also depend on gravity, giving yet another constraint on R/M. Betelgeuse displays a range of periodic behaviour.

Studies of Betelgeuse have long revealed a variety of pulsation modes. Of particular value is the record of optical photometry compiled by amateurs and professionals for nearly 100 years and recorded by the American Association of Variable Star Observers (AAVSO). These data reveal at least two different timescales, ~388 days and a 'long secondary period' (LSP) of ~2050 days (5.6 years) (Kiss *et al.* 2006; Chatys *et al.* 2019). The LSP might be related to the rotation, but the rotation period is apparently significantly longer (see 'Rotational Velocity').

Joyce *et al.* (2020) analysed the most recent ~40 years of data from the AAVSO complemented with data incidentally produced by Solar Magnetic Ejection Imager (SMEI) observations. They find periods of 185 ± 13.5 days, 416 ± 24 days, and 2365 ± 10 days, cautioning that these periods could evolve with time. U-band observations are relatively rare. Ogane *et al.* (2022) presented 23 years of UBVRI data obtained at the private Ogane Hikari Observatory and found periods of around 405 days and 2160 days. Jadlovský *et al.* (2023) presented an analysis of spectroscopic and photometric variability in the UV and optical, finding photometric periods of 417 ± 17 d and 2190 ± 270 d and radial velocity periods from spectroscopy of 415 ± 11 days and 2510 ± 440 days. The radial velocity determined from ultraviolet spectra show longer periods of variability that may be related to the outflowing wind.

Models of RSGs show that pressure-mode or p-mode radial pulsations can be driven by the opacity or κ-mechanism in the hydrogen ionisation zone. In this mechanism, the opacity varies out of phase with the luminosity, being lower when the star is compressed and hot, releasing radiant energy and allowing more compression, and higher when the star expands and cools thus blocking radiant energy and driving more expansion. Simulations yield mass-dependent periods of the fundamental of years in both linear and nonlinear models (Li & Gong 1994; Heger *et al.* 1997; Yoon & Cantiello 2010; Paxton *et al.* 2013; Dolan *et al.* 2016; Goldberg *et al.* 2022). Modelling pulsation processes may require 3D, time-dependent convection, or otherwise more sophisticated physical formalisms that are beyond the scope of typical 1D stellar evolution programs, but 1D analyses already provide useful insights.

Joyce *et al.* (2020) used 1D hydrodynamical models and the GYRE pulsation module of MESA to analyse the pulsations and provide new constraints on *R/M* for Betelgeuse. They deduced that the 416 day period represents oscillation in the fundamental mode, driven by the opacity mechanism, and that the 186 day period represents the frequency of the first overtone of radial pulsations. Joyce *et al.* (2020) also used the period information to provide a tighter constraint on the radius of Betelgeuse, $R = 750^{+62}_{-30}\,R_\odot$ (3σ), compared to the previous estimate of 887 $R_\odot$. Surprisingly, this led to a tighter constraint on the distance and parallax than previous methods, $D = 165^{-16}_{-8}$ pc with <10% uncertainty compared to the previous estimate of 197 pc with 20% uncertainty, and tighter constraint on the ZAMS mass, 18–21 $M_\odot$ and the current mass, 16.5–19 $M_\odot$. Joyce *et al.* (2020) do not give a surface gravity to compare with atmospheric observations (see 'Surface Gravity'). They give an extensive discussion of model degeneracies that make estimates of *L* and T_{eff} uncertain.

With the new constraints, Joyce *et al.* (2020) concluded that Betelgeuse is in core helium burning, with ~100 000 years to go before explosion.

Recent Change in Colour?

Another approach to determining the mass, luminosity, radius, distance, effective temperature, age and current evolutionary state of Betelgeuse is to study the colour evolution from the historical record. In a recent rigorous analysis of extensive multi-cultural historical literature including Tycho Brahe's comparison of Betelgeuse to his supernova of 1572 and to Aldebaran, Neuhäuser *et al.* (2022) argue that Betelgeuse has significantly changed colour over the last two millennia.

Contemporary Betelgeuse is, as can be verified by casual naked eye observation, red, with a formal colour of B–V = 1.78 ± 0.05 mag. Neuhäuser *et al.* (2022) argue that 2000 years ago Hyginus in Rome reported Betelgeuse to have a colour similar to Saturn that is equivalent to B–V = 1.09 ± 0.16 mag and that Sima Qian in China independently reported Betelgeuse to be 'yellow', a condition that Neuhäuser *et al.* (2022) quantify to be B–V = 0.95 ± 0.35 mag. Neuhäuser *et al.* (2022) estimate that these historical estimates of colour differ from the contemporary colour by 5.1σ. In contrast, Antares has always been reported as red for over 3000 years.

Taken at face value, this colour change of Betelgeuse represents a strong constraint on evolutionary models. Neuhäuser *et al.* (2022) compare their estimates of historical and contemporary colours of Betelgeuse to the MESA Isochrones and Stellar Tracks (MIST) of Choi *et al.* (2016). They deduce that Betelgeuse is likely to be near the cool end of the Hertzsprung Gap and less than 1000 years past the minimum of the RSB when relatively rapid changes in colour are expected. Neuhäuser *et al.* (2022) specifically argue that the colour evolution and location in the colour-magnitude diagram constrain the ZAMS mass to be ~14 $M_\odot$ with a current age of ~14 Myr. This deduction is in distinct contrast with the location in the Hertzsprung-Russell Diagram, the ZAMS mass (18–21 $M_\odot$), and the evolutionary state deduced by Joyce *et al.* (2020).

In their study of the rotation of Betelgeuse, Wheeler *et al.* (2017) noted that the radius increases and the surface velocity plummets as models proceed across the Hertzsprung Gap and up the RSB. The only position in the Hertzsprung-Russell Diagram for which single star models could plausibly give the observed equatorial rotation of ~15 km s^{-1} is when the models first approach the base of the red supergiant branch (RSB), having crossed the Hertzsprung Gap but not yet having ascended the RSB. This condition is similar to that deduced by Neuhäuser *et al.* (2022). Wheeler *et al.* (2017) argued that because that phase is so short (~100 years), that possibility is highly unlikely. Rather, they suggested, Betelgeuse may have been in a binary system that merged, producing the observed rotation near the upper tip of the RSB, the condition deduced by Joyce *et al.* (2020). If Neuhäuser *et al.* (2022) are correct in their interpretation of the historical data, their results are a challenge to models, including merger models, that attempt to place contemporary Betelgeuse in the upper reaches of the RSB.

At this writing, the conflict between Joyce *et al.* (2020) and Neuhäuser *et al.* (2022) is unresolved. Wheeler *et al.* (2017) noted that a solution near the base of the RGB, as advocated by Neuhäuser *et al.* (2022), would yield an excessively large surface gravity, log $g \approx +0.42$ (see 'Surface Gravity'). This may mitigate against the solution of Neuhäuser *et al.* (2022), but a proper resolution would involve identifying a flaw in either the analysis of Joyce *et al.* (2020) or that of Neuhäuser *et al.* (2022).

Once again, an important factor is the distance. Neuhäuser *et al.* (2022) favour a distance of 151.5 ± 19 pc as determined from *Hipparchos* data (van Leeuwen 2007) rather than greater distance of 197 ± 45 pc determined by Harper *et al.* (2008), for which they consider the ALMA distance less certain. With the larger distance, Neuhäuser *et al.* (2022) find a ZAMS mass of 17 or 18 $M_\odot$, closer to the result of Joyce *et al.* (2020). On the other hand, Joyce *et al.* (2020) favor a distance of ~165 pc, closer to the preferred value of Neuhäuser *et al.* (2020) despite their other disagreements. More accurate determinations of the surface gravity by spectral analysis and modelling would also be useful.

Given the uncertainties, it is possible that Neuhäuser *et al.* (2022) and Joyce *et al.* (2020) could be brought into agreement in terms of ZAMS mass, *L*, and T_{eff} but still disagree on the corresponding evolutionary state, near the end of the Hertzsprung Gap, or substantially up the RSB. Another possibility is that other surface activity analogous to the recent Great Dimming may have caused colour changes. It would be interesting if such a possibility could be ruled out.

Asteroseismology

The 'Pulsation Periods' section dealt with the fundamental global pulsation properties. There could, in principle, be other temporal signals coming from the depths of Betelgeuse that give yet more evidence of the inner structure and evolution, perhaps of unorthodox evolution such as a merger.

Over the last two decades there has been tremendous progress in using the technique of asteroseismology to explore the depths of stars from the Sun to evolved giants. High-precision μ-magnitude space-based photometry from the CoRoT and Kepler missions showed complex but interpretable variations due to acoustic signals arising from deep within stars that is analogous to exploring the core of the Earth with seismic signals (Aerts *et al.* 2010). Study of these signals revealed the inner rotation of the Sun and understanding of the structure, rotation, and inner magnetic field distribution of thousands of stars from the ZAMS to the red giant branch, especially those of low mass that are technically easier to analyse.

The question then arises as to whether such asteroseismology techniques can be applied to Betelgeuse and other RSB stars. The potential is great. The inner structure of evolved massive stars is suspected to yield complex convective regions that will generate acoustic signals in the form of pressure modes and gravity waves. These should get especially intense late in the evolution near core collapse when the convective timescales become comparable to the nuclear burning timescales (Arnett & Meakin 2011; Couch *et al.* 2015; Chatzopoulos *et al.* 2016). Convective regions should hammer on the inside of the star with increasing violence and decreasing timescale as the star nears core collapse. In practice, it is difficult to do asteroseismology of RSB stars because typical oscillation periods are long and because the oscillations are affected by complex processes in the atmosphere and wind that affect the boundary conditions employed in the analysis but that are not well understood (Aerts 2015). In addition, Betelgeuse is too bright to study with traditional telescopes on the ground or in space due to instrument saturation.

In principle, asteroseismology could be used to determine the evolutionary stage of Betelgeuse since interior acoustic activity should get more intense with time and carry signals specific to certain stages of evolution, especially oxygen and silicon burning in the years or days before core collapse. The added mass and angular momentum and associated plumes and mixing might give evidence of a merger. The key question is whether some of that acoustic power reaches the surface. Could one see small perturbations on the surface of Betelgeuse given the extensive convective envelope?

The potential of asteroseismology to glean an understanding of the interior structure of Betelgeuse in particular and RSG in general has been explored theoretically. Following Shiode & Quataert (2014), detailed stellar models can be used to estimate characteristic acoustic frequencies driven by inner convection as $\omega = v_{conv}/H_p$, where v_{conv} is a convective velocity and Hp is an appropriate scale height associated with a given convective region. The outer extended convective envelope has a characteristic cutoff frequency, $\omega_{cut} = c_s/H_p$, where c_s is the sound speed, below which any acoustic signal cannot effectively propagate.

Typical signals from late in the evolution are potentially observable, but the envelope cutoff, propagation efficiency, wave effervescence, damping, and shock dissipation probably muffle all the inner convective noise (Fuller 2017; Ro & Matzner 2017; Nance *et al.* 2018). The largest envelope pressure waves may arise from wave heating during core neon burning and a third carbon shell burning phase a few years before core collapse because later, more intense waves associated with oxygen and silicon burning do not have time to reach the surface before core collapse (Fuller 2017). The shock dissipation of the acoustic luminosity generated in the very late stages of burning may eject some mass into the CSM (Fuller 2017; Ro & Matzner 2017; Morozova *et al.* 2020).

Most of the work on the issues described here have been done with spherically-symmetric codes, albeit ones that can treat angular momentum and its transport. Some work has been done in 2D (Leung & Fuller 2020), but a more complete understanding probably requires 3D studies (Tsang *et al.* 2022). Beside effects on late-time ejection of mass from the extended envelope, effective 3D porosity of the envelope may mitigate some of the wave damping effects and allow some asteroseismological signals to percolate to the surface causing diagnostic brightness variations even at earlier evolutionary phases.

Evolutionary models

Single Star Models

The evolution of single massive stars, both non-rotating and rotating, has been discussed extensively in the literature (Brott *et al.* 2011a,b; Ekström *et al.* 2012; Branch & Wheeler 2017; Wheeler *et al.* 2017; Sukhbold *et al.* 2018; Chatzopoulos *et al.* 2020). Models of these stars show that hydrogen is burned on the CNO cycle in a convective core yielding a helium core of about one-third of the original ZAMS mass. The helium core contracts and heats, and a thin hydrogen-burning shells forms at its surface. The shell sits at a node in the structure such that as the core contracts, the outer envelope expands becoming large in radius and convective.

Helium eventually ignites in the centre, forming a core of carbon and oxygen. Contraction of this core results first in carbon burning and then the burning of heavier elements as the inner core contracts and heats. Shells form burning helium, carbon and other elements. Convection in these shells is expected to produce intense acoustic waves (see 'Asteroseismology').

Near the end of the star's lifetime, a core of silicon forms. Burning of silicon yields a core of iron. Iron is endothermic in terms of its thermonuclear properties. Within days of the formation of the iron core, it will absorb thermal energy from the star, reduce the pressure, and trigger catastrophic dynamical collapse to form a neutron star, or perhaps a black hole.

For the case of a neutron star, most likely for Betelgeuse, most of the kinetic energy of collapse will be lost to neutrinos but of order 1% will be deposited in the inner regions, sufficient to cause a violent explosion of the star, ejecting the outer layers, and leaving behind the neutron star (See 'The Explosion to Come').

Common Envelope Evolution

It has been well established that a majority of O and B stars are in binary systems (Sana *et al.* 2012; de Mink *et al.* 2014; Dunstall *et al.* 2015; Costa *et al.* 2015; Renzo *et al.* 2019; Zapartas *et al.* 2019), so it is *a priori* likely that Betelgeuse began as a binary system. The implication is that many RSG – including Betelgeuse – that appear to be single now have undergone mergers.

An important implication of the potential that Betelgeuse arose in a binary system is that Betelgeuse may have undergone common envelope evolution (CEE) sometime during its history. CEE is expected when the two stars in a binary are sufficiently close they interact as the more massive star evolves, expands, fills its Roche Lobe, and transfers mass to its lower-mass companion. In some circumstances, the companion cannot ingest the transferred material as rapidly as the primary loses it, and the excess mass forms a red giant like envelope surrounding the secondary and the evolving core of the primary. The secondary orbiting within the common envelope (CE) will undergo drag and spiral inward toward the evolved core. While the details are complex, there is then a potential for the secondary to merge with the core of the primary (see 'Merger Models'). The result could appear to be a single star, but with an inner structure rather different than would be expected of a single star of the same luminosity, radius, and T_{eff}.

CEE can result in several types of anomalous mixing within the core and between the core and the surface of the star. The inspiral phase leads to increased equatorial rotation and thus chemical mixing via rotational mechanisms. Plume mixing and nucleosynthesis occur during the moment of the final tidal disruption of the secondary, and merger with the core of the primary will affect the structure of the material inside and around the core of the primary. Details depend on whether the plume mixing is strong enough to rejuvenate hydrogen burning in the core. On longer timescales, rotational mixing can dredge some α-enhanced material from the inner regions to the surface (see *Observed Abundances*).

Ivanova & Nandez (2016) (see also Morris & Podsiadlowski 2007; Taam & Ricker 2010; Ivanova *et al.* 2013, 2015; MacLeod *et al.* 2018; Chatzopoulos *et al.* 2020; Roepke & De Marco 2022) describe the basic phases of CEE and the mechanisms for treating it in 3D and 1D. There are three stages to the process, each with associated loss of mass and angular momentum: a precursor phase when the stars begin to interact and corotation is lost; a plunge-in phase with a large rate of change of orbital separation and a timescale close to dynamical, at the end of which most of the mass of the CE is beyond the orbit of the companion; and a self-regulated slow inspiral of the companion. There are two basic endpoints to CEE: formation of a compact binary system and merger. For mergers, Ivanova & Podsiadlowski (2003) differentiate three outcomes: a quiet merger, a moderate merger, and an explosive merger. Only the former leaves behind an RSG and hence is pertinent to Betelgeuse.

An important aspect of the problem is the deposition of the mass and orbital angular momentum of the secondary. In 3D simulations most of the initial angular momentum of the secondary is deposited in the outer layers of the primary envelope. Mass and angular momentum are lost by dynamical interaction, outflow driven by recombination, and shrinking of the orbit. The surface layers are 'shock heated' and quickly ejected prior to the plunge-in (Zhao & Fuller 2020). The slow inspiral often begins with an envelope that is significantly reduced in mass and angular momentum. In some cases, recombination outflow can eject nearly all the envelope during the slow inspiral. The exception to these cases of extreme mass loss is when the primary is substantially more massive than the secondary. For small secondary masses, the fraction of mass lost in the precursor phase and the plunge-in phase is of order q, the mass ratio of secondary to primary.

In their treatment of a red giant of modest mass ($1.8\,M_\odot$), Ivanova & Nandez (2016) find that companions of mass less than $0.10\,M_\odot$, corresponding to about 5% of the primary mass, undergo merger. The time to merger is about 1000 days, long compared to the dynamical

"An important implication of the potential that Betelgeuse arose in a binary system is that Betelgeuse may have undergone common envelope evolution sometime during its history"

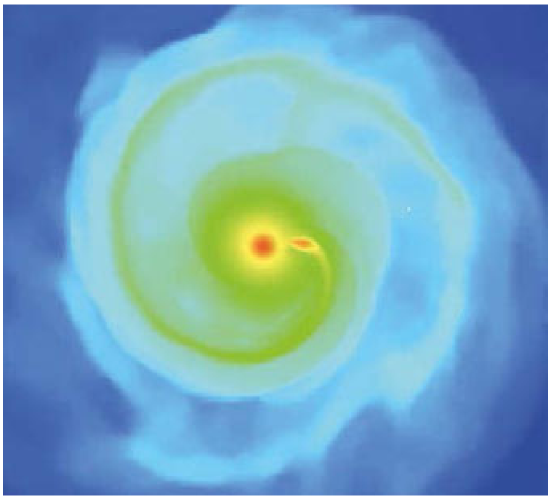
time of the CE but short compared to the thermal or evolutionary time of the primary. While these results do not necessarily scale with mass, this suggests that for many cases of interest here, a companion of about $1\,M_\odot$ undergoing CEE with a primary of about $20\,M_\odot$ is likely to quickly undergo merger while sustaining a substantial envelope, as Betelgeuse is observed to have.

The plunge-in phase is expected to induce very asymmetric structures and the slow inspiral to yield appreciable departures from spherical symmetry that can be simulated in 3D but are beyond the capacity of 1D models. In 3D there is a significant density inversion in the vicinity of the companion and rather little material near the centre of mass of the binary. On the other hand, the 3D simulations often treat the companion star and the red giant core as point sources. In 1D, the primary core, at least, can be modelled in more detail. A 1D code like MESA conserves energy and angular momentum within expected numerical accuracy. MESA also automatically handles energy released by recombination as the envelope expands and the angular momentum is lost in winds. In some 1D simulations of CEE, the companion is treated in a 'thin shell' approximation.

Chatzopoulos *et al.* (2020) argue that for massive primaries with mass ratios $q < q_{blue}$ (where $0.25 < q_{blue} < 0.33$) and initial period, P_i, greater than a few tens of days, mass transfer starts in early Case B mass transfer. This situation arises when hydrogen is exhausted in the primary, so the primary has evolved off the main-sequence but not yet ignited helium, and while the secondary is still on the main-sequence. This mass transfer is rapid and results in the primary envelope engulfing the much-lower mass secondary. The secondary spirals inward producing a merger.

In this scenario, the helium core of the primary is surrounded by a H-burning shell. When the secondary reaches the critical tidal disruption distance from the core of the primary, a tidal stream will form that transports fresh H fuel toward the core (Ivanova 2002; Ivanova *et al.* 2002; Ivanova & Podsiadlowski 2003) as shown in figure 4. Mixing can thus happen if the mass transfer stream can penetrate the core. The depth of penetration of the stream into the core depends on the direction, entropy, width, and angular momentum of the stream, the rotation, orientation, and mass of the secondary, on the density structure and relative rotation of the core, and on fluid instabilities.

The penetration depth of the stream into the core of the primary determines the extent of its rejuvenation; if fresh fuel reaches the core then core H-burning will be reignited and the star may evolve toward the blue supergiant (BSG) phase. If, on the contrary, the stream does not penetrate deeply into the core but



4 *Density profile from a 2D simulation of a $16\,M_\odot + 1\,M_\odot$ merger occurring at an initial separation of $12\,R_\odot$ showing the formation of the tidal stream (teardrop shape to the right of centre) within the common envelope (outer green and blue green) as the secondary fills its Roche Lobe and is disrupted by the core of the primary (large red dot in the centre).* (From Chatzopoulos et al. (2020))

rather converges with the H-burning shell, then the star will continue to evolve toward the RSG stage. Chatzopoulos *et al.* (2020) confirm, by using the arguments presented in Ivanova *et al.* (2002), that none of the models they explored (secondaries in the range 1–4 $M_\odot$ merging with primaries in the range 15–17 $M_\odot$) undergo stream-core penetration.

These results suggest that the 'quiet merger' described above is more relevant to the case of Betelgeuse. In that case, the amount of orbital angular momentum depends mostly on the binary separation when the primary overflows its Roche lobe. The total angular momentum deposited in the envelope of the primary depends on the radius of the primary when it engulfs the secondary during its crossing of the Hertzsprung Gap.

Merger Models

Of primary interest for Betelgeuse is how and under what circumstances a merged system could end up rotating at ~23% of the critical velocity, as observations suggest. Merger models provide a reasonable 'natural' explanation for why Betelgeuse has a large, but sub-Keplerian equatorial velocity (Wheeler *et al.* 2017; Chatzopoulos *et al.* 2020; Sullivan *et al.* 2020). These results do not prove, but do allow that Betelgeuse might have merged with a lower mass companion. Betelgeuse might look substantially the same whether it merged with a 1 or 10 $M_\odot$ companion. Joyce *et al.* (2020) concluded that Betelgeuse merged prior to the later carbon-burning phases, but see Luo *et al.* (2022).

"Of primary interest for Betelgeuse is how and under what circumstances a merged system could end up rotating at around 23% of the critical velocity"

While the hypothesis that Betelgeuse might have merged with a companion is credible and consistent with the *a priori* estimate that Betelgeuse has a probability of ~20% of being born in a binary system (de Mink *et al.* 2014), it raises a number of interesting issues involving CEE, the fate of the companion and its angular momentum, and effect on the post-merger structure of the primary.

The luminosity of an evolved massive star is typically a function of the mass of the helium core and rather independent of the mass of the envelope. If a companion merged with the core of Betelgeuse, then the current luminosity may be a measure of the core mass (~5 to 6 $M_\odot$), but the mass of the envelope would be rather unconstrained and probably smaller than the estimates given based on single-star models that attempt to reproduce the luminosity, radius and effective temperature. If there were a coalescence, there would be some mass ejected.

The mass lost from the system during the merger may be substantial. The 3D 16 $M_\odot$ + 4 $M_\odot$ merger model of Chatzopoulos *et al.* (2020) lost 0.5 $M_\odot$. This model accounted for rotation, but not radiative effects nor recombination. Sullivan *et al.* (2020) found up to 5 $M_\odot$ lost. The mass loss is a combination of the loss of mass accreted from the secondary plus loss of mass from the primary itself. The latter is due to winds prior to the accretion event and then the rotationally-induced mass loss after the accretion.

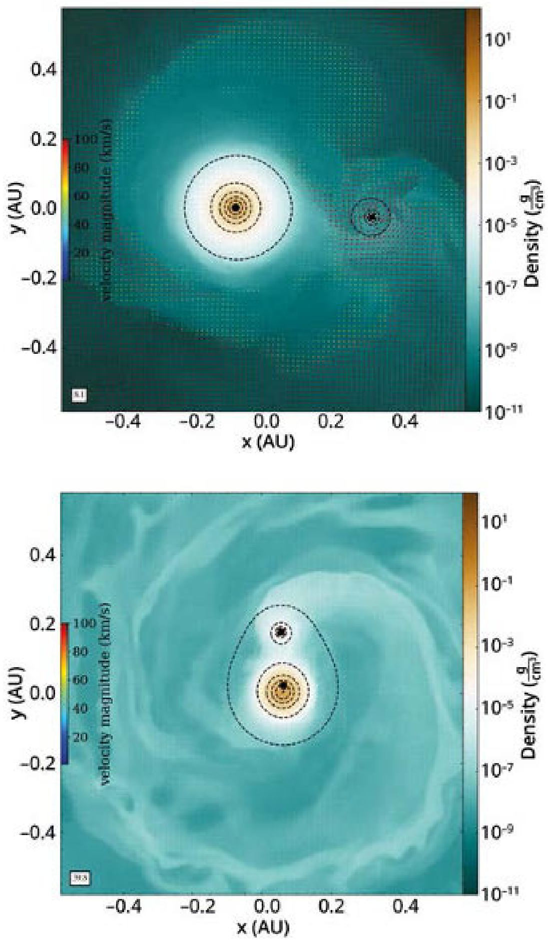
A main sequence companion of about a solar mass would have a mean density of about 1 g cm^{-3}. That density is characteristic of the base of the hydrogen envelope in the RSG models, implying that a companion might not be dissolved until it reaches the edge of the helium core (see discussion of CEE and plume penetration in the previous section). If the companion merged with the core, the evolution of the primary might be severely altered by anomalous burning and mixing effects, and surface abundances might be affected.

Sullivan *et al.* (2020) used the MESA code to study the merger problem in a rudimentary way that nevertheless gave some insights to the relevant physical processes. They did not attempt to treat the companion as a corporeal entity, but allowed for its effects by adding the relevant mass and associated angular momentum to the outer envelope of the primary, a computational process identified as 'accretion' to distinguish it from the more complex behaviour of a true merger. The HRD of all the models of Sullivan *et al.* (2020) were qualitatively similar. The accretion events resulted in irregular transient loci before settling down to a rather normal evolution up the RSB to the point of collapse of the models. The models suggest that the rotation of Betelgeuse could be consistent with a primary of ZAMS mass somewhat less than 15 $M_\odot$ accreting between 1 and 10 $M_\odot$ in the core helium burning and core carbon burning epochs. The observed equatorial velocity might also be attained by accreting a broad range of masses onto a primary of ZAMS mass somewhat more than 20 $M_\odot$ in the later carbon shell burning epoch.

Chatzopoulos *et al.* (2020) used the MESA code to compute the 1D rotating post-merger evolution of systems with mass ratio $0.06 < q < 0.25$ that suffer an early Case B merger. In this case, unstable mass transfer occurs during the crossing of the Hertzsprung Gap. A 'stellar engineering' approach was adopted by incorporating a perturbation term that captures the effects on the specific angular momentum and entropy. This term was used to readjust the post-merger structure of the envelope of the primary star during the inspiral prior to the dynamic disruption of the secondary around the He core of the primary. The magnitude of the perturbation applied is proportional to q and the structure of the primary. In their MESA simulations, the mass of the secondary was added to the core plus hydrogen-burning shell. The composition was not adjusted as done by Menon & Heger (2017) in their models of SN 1987A (See 'Lessons from SN 1987A'). Post-merger profiles were computed for different primary radii corresponding to the time when the envelope of the primary engulfed the secondary (200–700 $R_\odot$). The initial primary radii represented initial separations corresponding to binding energies that enabled the binary progenitor system to survive a possible past ejection from its birth cluster, to be consistent with the borderline 'runaway' nature of Betelgeuse. The resulting models were used to investigate the rotation rate of the post-merger object.

The models explored by Chatzopoulos *et al.* (2020) were able to reproduce the overall observed properties of Betelgeuse, including its position in the HRD, its surface rotation rate, and its surface abundances, especially the observed overabundance of nitrogen. Their 16 $M_\odot$ + 4 $M_\odot$ merger occurring at ~200–300 $R_\odot$ yielded the best fit. These models had a sustained high equatorial rotation for a few hundred thousand years after the merger.

Chatzopoulos *et al.* (2020) also presented a 3D simulation of the merger between a 16 $M_\odot$ primary and a 1 $M_\odot$ secondary that occurred when the primary reached a radius of ~12 $R_\odot$, right after the end of its TAMS. The simulation was performed with the 3D OctoTiger Adaptive Mesh Refinement (AMR) hydrodynamics code developed by the LSU Center for Computation and Technology (CCT) (Marcello *et al.* 2021). Post-processing of the 3D internal structure of the post-merger object confirmed



5 *The initial (upper panel) and final (immediately prior to the merger of the secondary with the core of the primary) (lower panel) density structure of a $15\,M_\odot + 4\,M_\odot$ system with an initial core/secondary separation of $50\,R_\odot$ simulated with the 3D AMR OctoTiger code. The core of the primary and the secondary are treated as point masses. The colour bar on the right represents density in g cm^{-3}. Dashed lines represent equipotential surfaces. In the upper panel, arrows with length proportional to magnitude represent the velocity field. Velocities beyond the primary core and secondary are typically 50 km s^{-1}. The numbers 8.1 and 39.8 in the lower left corners represent the 'orbit number' that was used in OctoTiger (even after the merger) to represent the time/phase of the simulation.* (From Chatzopoulos et al. 2023, in preparation.)

that the envelope of the primary was spun-up by a significant amount during the inspiral phase.

The degree of envelope spin-up is, however, proportional to the primary's radius at the onset of the merger. Three-dimensional simulations of mergers occurring at larger primary radii are needed to compute post-merger structures that evolve to become rapidly-rotating supergiants. The limitation in simulating the CEE evolution of such systems in 3D is purely of computational nature; the inspiral timescale for a $15\,M_\odot + 1\,M_\odot$ merger occurring at ~$300\,R_\odot$ is ~1000 years, requiring a very long simulation time. In addition, the density contrast between the compact secondary and the low-density outer regions of the envelope of the primary as well as the large simulation box that would be required to include the entire system makes it difficult to adequately resolve the full structure of the secondary, its tidal disruption plume, and the dense core of the primary, requiring billions of zones rendering such calculations prohibitively expensive.

Despite these computational challenges, there are ongoing efforts involving the use of point masses to represent the secondary and the core of the primary. The merger can be accelerated by the removal of a constant, yet small, amount of angular momentum per orbit. This allows the long-term evolutionary calculation of post-merger angular momentum profiles for the primary.

An example of such a simulation involving the merger between a $15\,M_\odot$ primary and a $4\,M_\odot$ secondary initiated with a separation between the secondary and the core of the primary of $50\,R_\odot$ is shown in figure 5. This model lost ~$0.4\,M_\odot$ in the 'mergeburst' (Soker & Tylenda 2006) phase right after the merger when the surface equatorial velocity was ~60 km s^{-1}. The simulation focused on the angular momentum of the remaining bound object and did not quantify the amount of angular momentum lost.

The spherical, mass-weighted, angle-averaged profiles for internal energy, density, and temperature and the cylindrical mass-weighted profile for specific angular momentum of the post-merger object resulting from this simulation are shown in figure 6. Note that the x-axis is q, the normalised mass-coordinate variable. The specific angular momentum, j, decreases with q, but increases in radius, so the bulk of the structure is dynamically stable. A minor decrease/instability develops in the very outer regions that contain very little mass. That behaviour is in agreement with Ivanova & Nandez (2016).

This simulation was long and expensive. It used a sufficiently large box to follow the unbound material after the merger for as long as possible in order to characterise the mergeburst transient and also with sufficient zones to resolve enough of the secondary structure and the primary core such that they are dynamically stable in the grid. This balance did not allow sufficient resolution to resolve the stream-core interaction in detail but such simulations will be done in the future. These proposed simulations will allow a comparison to the 3D models of Ivanova & Nandez (2016) for lower mass systems. For related work on the effect of radiation pressure and recombination energy in the ejection of mass in the CEE of an RSG star see Lau *et al.* (2022).

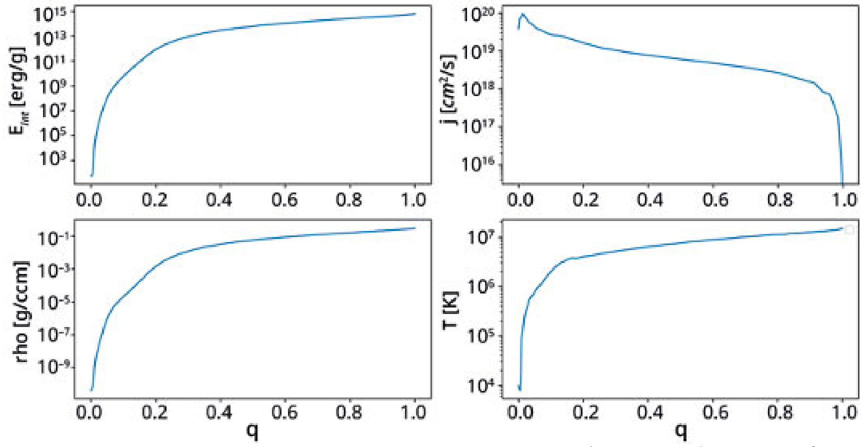
Insensitivity of Final Equatorial Velocity to Accreted Mass

The original motivation of Wheeler *et al.* (2017) for hypothesising that Betelgeuse might have merged with a companion was the difficulty of accounting for the nominal currently-observed equatorial rotation velocity, ~15 km s^{-1}, allowing for inclination. A companion mass of ~$1\,M_\odot$ was estimated from simple arguments based on conservation of angular momentum. Subsequent work showed that, broadly, the final rotational velocities of the models were rather independent of the companion mass accreted.

Although the treatment of the post-merger system by Sullivan *et al.* (2020) and by Chatzopoulos *et al.* (2020) is rather different, the results for the final equatorial rotational velocity are very similar. This gives confidence that this quantity is somewhat robust against the details of the merger process and depends primarily on a global quantity such as the pre-merger orbital angular momentum.

If a merger occurred in Betelgeuse, the product must have settled into a state for which the rotation is sub-Keplerian. This global criterion is independent of the masses of the primary and secondary involved in the merger. The implication is that the loss of mass and angular momentum must adjust to meet this criterion rather independently of the masses involved and the epoch of accretion. This also serves to constrain the final rotation of the envelope to potentially large, but finite values.

For these studies to have any relevance to Betelgeuse, it is important that the structure remain that of an RSG after the proposed merger. As mentioned in 'Common Envelope Evolution', a 'quiet merger' can leave behind an RSG, depending on pre-merger conditions. Ivanova & Podsiadlowski (2003) suggest that this condition favours secondary masses $>2\,M_\odot$ and a primary close to carbon ignition so that strong gradients inhibit core/envelope mixing. Ivanova & Nandez (2016) note that during a slow spiral-in, the angular velocity becomes constant in most of the CE and the value of the angular velocity is significantly smaller than the local Keplerian velocity in the envelope, so the approximation of spherical symmetry is reasonable.



6 *Energy density, specific angular momentum, density, and temperature profiles of the post-merger object following the merger of a 15 $M_{\odot}$ + 4 $M_{\odot}$ system occurring at 50 $R_{\odot}$. The original 3D profiles have been mass-weighted and angle-averaged. From Chatzopoulos et al. 2023, in preparation.*

Angular Momentum

During the merger and redistribution of density, angular momentum, and composition, some angular momentum is lost to the surroundings in the rotation-enhanced wind, and some is retained to propagate inward toward the primary core. In the 1D 'accretion' models explored by Sullivan *et al.* (2020), the angular momentum that is retained is redistributed by an inward diffusive wave of angular momentum. The profiles of the specific angular momentum and angular velocity quickly evolve to stable forms delineated by an inward propagating front with the specific angular momentum increasing outward beyond the front and the angular velocity being nearly constant.

A few years after accretion, the ingoing wave of angular momentum propagated to the boundary between the outer envelope and the H/He shell. The wave of angular momentum was halted at the composition boundary at the edge of the helium core leaving behind an envelope of constant angular velocity and a monotonically rising angular momentum per unit mass. By the epoch of collapse, the angular momentum distribution in the outer envelope had scarcely changed. The wave of angular momentum swept through the H/He shell, but was halted at the outer boundary of the He shell at 7 $M_{\odot}$ for both the 20 $M_{\odot}$ + 1 $M_{\odot}$ and the 20 $M_{\odot}$ + 10 $M_{\odot}$ models. The composition distribution remained virtually unchanged.

All the final models of Sullivan *et al.* (2020) have inner regions of negative gradient in *j* in regions of sharp composition gradients. These must be stabilised against the Rayleigh instability by the associated composition gradients. This condition has not been investigated in detail.

Ivanova & Nandez (2016) presented a model of a primary of 1.8 $M_{\odot}$ and secondary of 0.1 $M_{\odot}$ (model M10). While the mass scale is smaller than considered by Sullivan *et al.* (2020) and Chatzopoulos *et al.* (2020), the mass ratio, ~0.05, is about the same as for their 20 $M_{\odot}$ + 1 $M_{\odot}$ models. The angular velocity as a function of mass for model M10 50 days after the plunge-in is basically flat throughout the model. The value of the angular velocity, ~3×10^{-7} rad s^{-1}, is close to that of Sullivan *et al.* (2020), perhaps fortuitously, but the peak value of the angular momentum per unit mass for model M10 is about a factor of 30 less than found by Sullivan *et al.* (2020). The flat angular velocity profile in the 3D simulations seems to arise naturally in MESA simulations.

Significant departures in behaviour between Ivanova & Nandez (2016) and Sullivan *et al.* (2020) are found in the innermost and the outermost regions. Ivanova & Nandez (2016) do not consider the inner core, so they do not explore the distribution of angular momentum in the core. On the other hand, Ivanova & Nandez (2016) and the upper right panel of figure 6 find a distinct decrease in both the specific angular momentum and the angular velocity in the outer 10% of the mass of the envelope that the models of Sullivan *et al.* (2020) do not reveal. This difference probably arises in the loss of mass and angular momentum in the dynamical plunge-in phase that Sullivan *et al.* (2020) do not treat accurately.

Composition

In their 1D calculation with a fully-resolved primary core, Sullivan *et al.* (2020) found the composition distribution of the inner core to be only slightly affected even by the accretion of a companion of large mass. Thus while the inner structure might be somewhat perturbed by accretion of substantial mass, there may be rather little effect on the outside to indicate that the accretion occurred. The implication is that the inner composition structure of Betelgeuse could be rather different depending on the mass accreted with basically no indication reflected in the outer, directly observable structure.

Evidence of internal mixing due to a merger (or other effects) can be revealed by anomalous surface abundances. Chatzopoulos *et al.* (2020) were able to reproduce surface abundances of Betelgeuse, especially the observed overabundance of nitrogen (Lambert *et al.* 1984). Brott *et al.* (2011a,b) and Ekström *et al.* (2012) find N/C surface enhancements that are similar to those found in the merger simulations of Chatzopoulos *et al.* (2020) due to the enhanced rotation from the spiralling-in phase.

Entropy

Ivanova & Nandez (2016) give an extensive discussion of the treatment of entropy in CEE. They argue that the evolution of the entropy of the common envelope material differs between 3D and 1D simulations. In 1D, the entropy is generated because the energy is added as heat. Since the radius at which the recombination energy release overcomes the potential well depends on the entropy of the material, the entropy generation observed in 1D codes will likely predict different outcomes than 3D CE evolution. Ivanova & Nandez (2016) argue that 1D stellar codes should add the energy as mechanical energy rather than 'heat' that moves the material to a higher adiabat.

Chatzopoulos *et al.* (2020) find relatively little heating effects in their 3D merger simulation of Betelgeuse. We note, however, that heating during merger can lead to non-linear envelope pulsations and to potentially large mass loss (Clayton *et al.* 2017).

Recombination

The role of hydrogen and helium recombination in abetting CE mass loss is discussed by Ivanova *et al.* (2015), Ivanova & Nandez (2016), and Lau *et al.* (2022). These reservoirs of energy can help to trigger envelope instability depending on where and when the recombination energy is released. The time-scale of recombination runaway can be up to several hundred days and gets longer as the mass of the companion decreases. In such cases, radiative losses can become important so that 3D simulations that lack radiative transfer are no longer appropriate. For all their limitations, 1D stellar evolution codes like MESA can handle this aspect of the physics.

Magnetic Fields

As noted, Betelgeuse displays various effects of magnetic fields. The magnetic properties are often omitted in CEE simulations. Sullivan *et al.* (2020) and Chatzopoulos *et al.* (2020) included magnetic effects as treated by the MESA Spruit/Tayler algorithm in some cases, but did not include magnetic effects of the magneto-rotational instability (Wheeler *et al.* 2015; Moyano *et al.* 2023). The omission of the latter will undoubtedly alter the quantitative, if not qualitative results. The Spruit/Tayler mechanism gives results that typically weight the radial component, B_r, orders of magnitude less than the toroidal component, B_ϕ. The magneto-rotational instability tends to give the radial component about 20% of the toroidal component. Another important caveat is that MESA computes the magnetic field structure based on the instantaneous structure of the model. In reality, the field only decays on a dissipation timescale that might in some circumstances be long compared to the evolutionary timescales. This would lead to fossil magnetic field in a region that made a transition from being unstable to stable to the Spruit/Tayler instability. MESA has no means to treat the existence and decay of such fossil fields. The magnetic structure computed by Sullivan *et al.* (2020) is thus interesting, but should not be given any quantitative weight.

Sullivan *et al.* (2020) found that accretion has little effect on the production of magnetic fields by the Spruit/Tayler mechanism. Their models show a more substantial field in the outer part of the helium shell, reaching up to the base of the hydrogen envelope. The peak fields are of order 1 G and 1000 G for the radial and toroidal fields, respectively, with considerable variation with radius that is likely to be affected by issues of numerical resolution. Below an inward gap where the fields are very small the fields become large, but variable, in the innermost layers of the oxygen core. The radial fields peak at ~1000 G and the toroidal fields at ~10^6 to 10^7 G. In the models, the fields peak off centre and the toroidal field declines to about 1 G in the centre. The accretion appears to have a quantitative, but not qualitative, effect on the field strength and distribution just prior to collapse. Subsequent core collapse by a factor of ~100 in radius would amplify the field by compression alone by a factor of ~10^4. The resulting field of ~10^{11} G would not be dynamically significant, but would give ample seed field for growth of the field in the proto-neutron star by the MRI (Akiyama *et al.* 2003; Obergaulinger *et al.* 2009; Mösta *et al.* 2018).

Lessons from SN~1987A

To account for the circumstellar nebular rings, many studies of the mergers of massive stars have focused on the prospect that the progenitor of SN 1987A may have undergone a merger (Morris & Podsiadlowski 2007). Merger models can also account for why the progenitor was a blue rather than red supergiant by invoking mixing of helium from the core into the outer envelope (Menon & Heger 2017).

In the case of Betelgeuse, a contrasting conclusion applies. While some discuss the possibility that Betelgeuse will explode as a blue supergiant (van Loon 2013), Betelgeuse is still a red supergiant. If one accepts the basic *ansatz* that a merger is required to account for the observed rotational velocity of Betelgeuse, then it follows that a merger did not produce a compact blue envelope and thus, by the arguments of Ivanova *et al.* (2002) and Menon & Heger (2017), little to no helium could have been mixed outward from the core, consistent with the simulations of Sullivan *et al.* (2020) and Chatzopoulos *et al.* (2020).

The modelling of a putative Betelgeuse merger by Chatzopoulos *et al.* (2020) concluded that the plume from the disrupted secondary would not penetrate the helium core and induce substantial helium mixing according to the prescription of Ivanova *et al.* (2002). Mixing may be more likely for more massive secondaries, so the results of Sullivan *et al.* (2020) and Chatzopoulos *et al.* (2020) may be less reliable for larger mass secondaries. Plume mixing is a complex hydrodynamical problem that deserves more study if we are to understand both Betelgeuse and SN 1987A as products of massive star mergers.

The Great Dimming

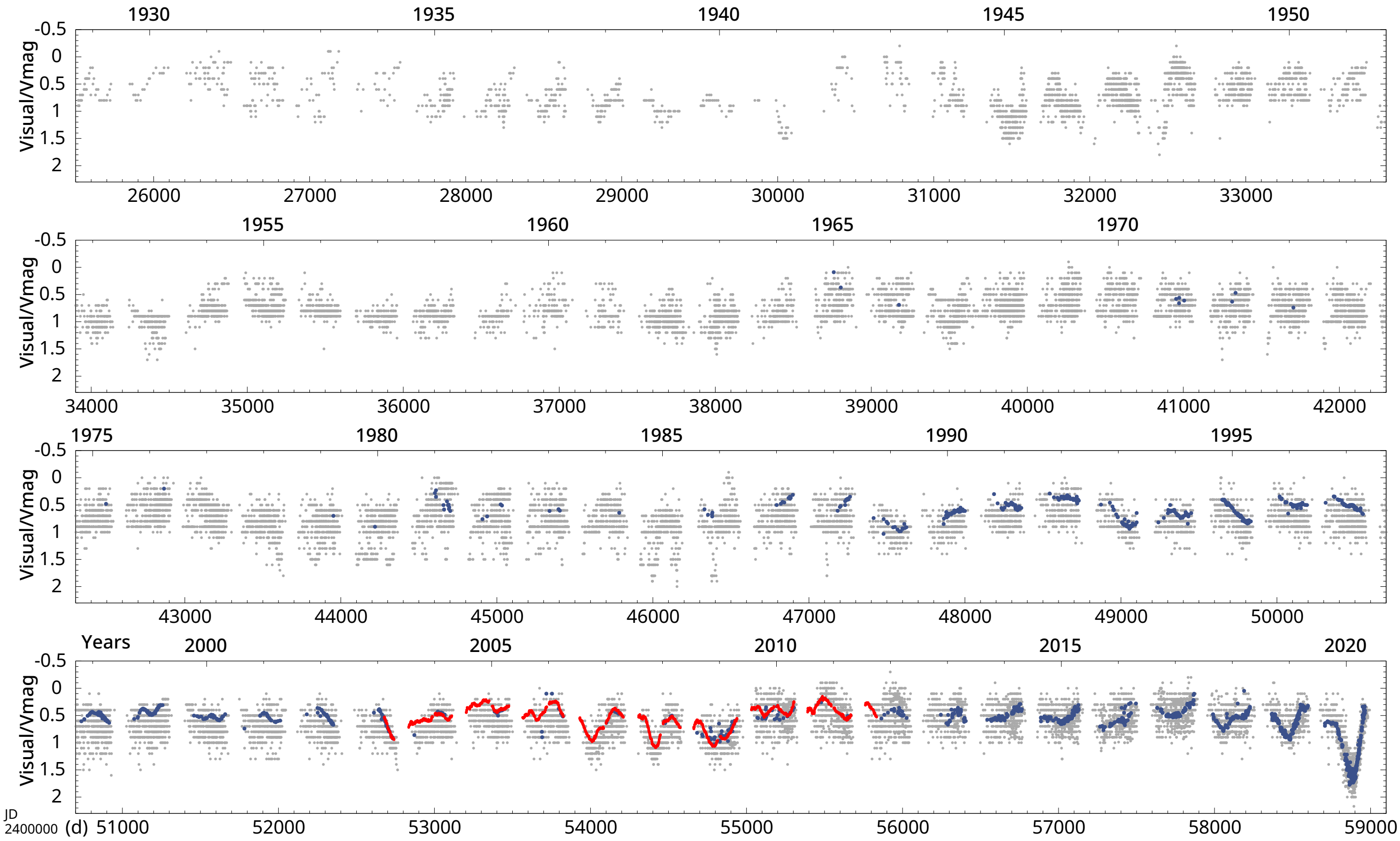
Betelgeuse surprised the astronomical community and fascinated people worldwide when it went through a phase of anomalously low optical luminosity beginning in October 2019 and lasting through March 2020. This became known as the 'Great Dimming'. The brightness decreased by over a factor of two and was easily noticed by even casual observers of the night sky. Twitter alit with rampant speculation that Betelgeuse was about to explode, thus requiring some effort by supernova experts to tamp that particular hyped fever.

The Great Dimming was dramatic enough on its own (Guinan *et al.* 2020; Levesque & Massey 2020; Harper *et al.* 2020a; Dupree *et al.* 2020; Dharmawardena *et al.* 2020; Harper *et al.* 2020b; Safonov *et al.* 2020; Montargès *et al.* 2021; Levesque 2021; Harper *et al.* 2021; Alexeeva *et al.* 2021; Kravchenko *et al.* 2021; Dupree *et al.* 2022; Mittag *et al.* 2023; Matthews & Dupree 2022; Taniguchi *et al.* 2022; Cannon *et al.* 2023). Both professionals and amateurs had monitored the brightness of Betelgeuse for about a century. Much of that data is stored in the valuable records of the American Association of Variable Star Observers (AAVSO) (figure 7). These studies had established that Betelgeuse was a variable star with regular pulsations on a variety of time scales. The decrease in V band amplitude corresponding to the ~400 day pulsation is typically 0.3–0.5 mag. In the Great Dimming, the decrease was over 1 mag.

There is some suggestion in the AAVSO records that Betelgeuse underwent other periods of anomalously large dimming, perhaps in the early 1950s and the late 1980s (Joyce *et al.* 2020). Dimming with a period of about 30–40 years might be related to the rotation period of Betelgeuse, but uncertainties in the early photometry and in the radius and rotational velocity and hence the period of Betelgeuse make that difficult to determine. There is also some concern that individual AAVSO observers in the 1950s and 1980s showed a tendency to report anomalously faint data that might have biased the mean AAVSO values and produced a false impression of minima (T. Calderwood, private communication, 2023).

There was no missing the Great Dimming of 2019/20. Attention may have been amplified by an initiative of Andrea Dupree of the Center for Astrophysics who convened many of world experts to participate in April 2018's Month of Betelgeuse (MOB), an intense global, multi-instrument, multi-wavelength coordinated study, when Betelgeuse was especially well-situated for studies with the HST. Some 44 astronomers joined the MOB. A month was not, of course, sufficient to address all the mysteries, but because of the MOB activity, attention to Betelgeuse was still focused as the Great Dimming got underway. Dupree *et al.* (2020) witnessed a bright UV flare on 6 October 2019 with HST that may have been a precursor event to the Great Dimming prior to any substantial decrease in brightness.

Ed Guinan of Villanova had been doing careful photometry and other studies of Betelgeuse for over 25 years. Guinan *et al.* (2019) reported V-band, Wing TiO-band, and NIR photometry on 7 December 2019. They presented one of the first interpretations of



7 *Century-long record of the visual and V-band brightness of Betelgeuse compiled by the American Association of Variable Star Observers supplemented by data from the Solar Magnetic Ejection Imager (SMEI). The final large dip is the Great Dimming of 2020 (See The Great Dimming).* (From Joyce et al. (2020) by permission of Meridith Joyce, László Molnár, and ApJ.)

8 *Resolved images of Betelgeuse through the Great Dimming. January 2019 was prior to the dimming; December 2019 was somewhat after the onset of the dimming; January 2020 was near the minimum of the dimming; and March 2020 was after the maximum dimming.* (From Montargès et al. (2021) by permission of M. Montargès and ESO.)

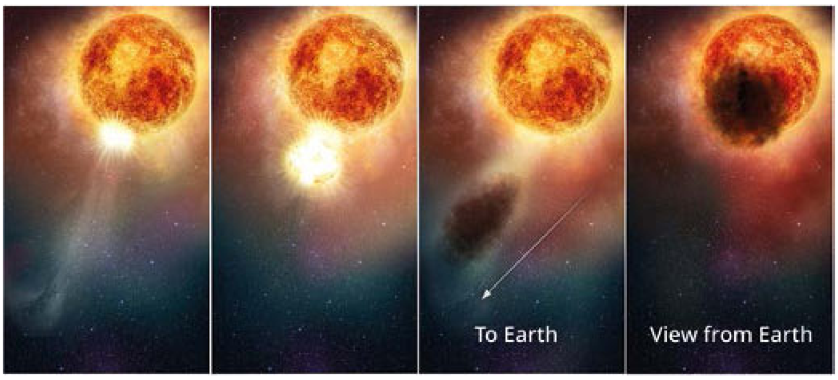
9 *Schematic of gigantic cool dim patches on the surface of Betelgeuse that were proposed as contributing to the Great Dimming.* (By permission of T. Dharmawardena and Max Planck Institute for Astrophysics, Heidelberg. Credit: Judith Neidel, MPIA graphics department.)

the Great Dimming, noting that "the light variations are complicated and arise from pulsations as well from the waxing and waning of large super-granules on the star's convective surface". They predicted a minimum on 21 February 2020 ± a week, based on the assumption that a 420-day period was in a fortuitous concatenation with longer-term (5–6 years) and shorter term (100–180 days) brightness changes and perhaps a super-granule upwelling of a cool plume. This estimate turned out to be remarkably close to the observed light minimum of 1.614 ± 0.008 mag during 7–13 February 2020 (Guinan *et al.* 2020).

Levesque & Massey (2020) reported optical spectroscopy on 15 February 2020. They also examined the TiO bands and reported a T_{eff} of 3600 K compared to a typical value ~3660 K. They argued that the small change in T_{eff} was not commensurate with the large change in V-band luminosity and that a temporary cool period on the surface of Betelgeuse due to convective turnover was likely not the primary cause of the Great Dimming. Rather, they proposed an increase in large-grain gray dust.

Guinan *et al.* (2020) and Levesque & Massey (2020) thus framed the extremes of the possible explanations of the Great Dimming that continues to be debated. Early discussions of T_{eff} during the Great Dimming assumed spherical symmetry. Subsequent consideration of spots, super-granules, and circumstellar dust call that assumption into question. The question of how accurately a global value of T_{eff} can be determined if T_{eff} varies over the surface of the star remains to be determined.

Montargès *et al.* (2021) illustrated this conundrum by producing dramatic spatially-resolved interferometric images of Betelgeuse obtained with the SPHERE instrument on the VLT in December 2019 and January 2020 that showed that the southern half of the star had become markedly fainter than in January 2019, indicating that a major change has occurred in, or near, the photosphere (figure 8). Montargès *et al.* (2021) attributed this dark patch to 'a dusty veil'.



10 *Schematic of model of the Great Dimming in which a blob of gas is ejected, cools to form dust, and passes through the line of sight to cause the Great Dimming.* (Courtesy Ray Villard, STScI and NASA, art by E. Wheatley, STScI.)

Harper *et al.* (2020b) reported Wing three-filter (A, B, and C band) TiO and near-IR photometry that showed that portions of the photosphere had a mean T_{eff} significantly lower than that found by Levesque & Massey (2020). They interpreted the image of Montargès *et al.* (2021) to be a large patch in the photosphere that could be 250K cooler than surroundings. They concluded that no new dust was required and emphasised the interpretation of Guinan *et al.* (2019) that the Great Dimming resulted from a coincidence of the 430-day and 5.8-year periods of Betelgeuse. They suggested that the cooling of a large portion of the surface was produced dynamically by photospheric motions due to pulsation and large-scale convective motions (figure 9).

Dharmawardena *et al.* (2020) reported 13 years of submillimetre observations of Betelgeuse including the epoch of the Great Dimming obtained with the James Clerk Maxwell Telescope and the Atacama Pathfinder Experiment. These long-wavelength observations were were not expected to be obscured by dust as the observations could be. Dharmawardena *et al.* (2020) found that Betelgeuse had also dimmed by ~20% at these longer wavelengths during the optical minimum. They concluded that the dimming was due to changes in the photospheric luminosity as opposed to obscuration by surrounding dust. See also Matthews & Dupree (2022) for 1.3cm and 7mm observations with the VLA on 2 August 2019, just prior to the onset of the optical dimming and Harper *et al.* (2021) for observations of circumstellar [O I] 63.2 μm and [C II] 157.7 μm emission profiles and [O I] 63.2 μm, [O I] 145.5 μm, and [C II] 157.7 μm fluxes obtained shortly after the Great Dimming with SOFIA.

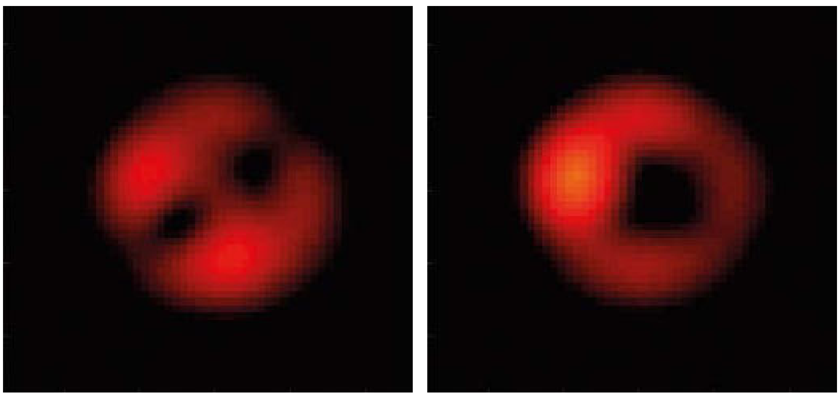
Dupree *et al.* (2022) presented a synthesis of observations and an interpretation of the Great Dimming that was a variation on the picture first presented by Kervella *et al.* (2018). Dupree *et al.* (2022) outlined a scenario in which the UV burst reported by Dupree *et al.* (2020) represented a surface activity perhaps catalysed by an upwelling that ejected a blob of matter. That matter cooled as it expanded away from the surface allowing dust to form. The resulting clump of dust crossed the line of sight to Betelgeuse resulting in the dim patch observed by Montargès *et al.* (2021) and the resulting Great Dimming (figure 10).

Alexeeva *et al.* (2021) presented high-resolution high-S/N ratio near-infrared spectra obtained at Weihai Observatory on four epochs in 2020 during and after the Great Dimming. They argued that a decrease in the overall mean T_{eff} by at least 170K on 31 January 2020 could be attributed to the emergence of a large dark spot on the surface of Betelgeuse. Levesque (2021) argued for a synthesis in which the dark patch of Montargès *et al.* (2021) and the Great Dimming were caused by dust forming over a cold patch in the southern hemisphere. Cannon *et al.* (2023) presented VLTI Multi AperTure mid-Infrared SpectroScopic Experiment (MA-TISSE) observations in the N-band (8–13 μm) near brightness minimum. They explored a model invoking multiple clumps of dust close to the star and another considering a large cool spot on the stellar surface with no dust. They found that both the dust clump and the cool spot models are compatible with the data, noting that the extinction and emission of a localised dust clump in the line of sight compensate each other making the clump undetectable. They concluded that the lack of infrared brightening during the Great Dimming (Dharmawardena *et al.* 2020) does not exclude extinction due to a dust clump as one of the possible mechanisms.

Spectropolarimetry provides another tool to explore the geometry of the surface of Betelgeuse (López Ariste *et al.* 2018; Haubois *et al.* 2019; Cotton *et al.* 2020). Safonov *et al.* (2020) argued that to address the challenges of the Great Dimming it was important to employ methods to resolve an inhomogeneous stellar atmosphere. They presented a set of differential speckle polarimetric observations of Betelgeuse obtained at the 2.5m telescope of the Caucasian Mountain Observatory operated by the Sternberg Astronomical Institute of Moscow State University. Observations on 17 days at wavelengths 465, 550, 625 and 880nm spanned the Great Dimming event. The envelope was found to be highly inhomogeneous but correlated, with features varying on a timescale of two or three months (figure 11). An animation captured the dramatic variability registered in the polarisation. The net polarised brightness of the envelope remained constant as the V-band flux approached its minimum. After the minimum, the polarised flux of the envelope rose a factor of two as the optical flux was restored. Safonov *et al.* (2020) concluded that the Great Dimming was caused by the formation of a dust cloud located on the line of sight.

Kravchenko *et al.* (2021) used high-resolution spectroscopy to do a tomographic study of the structure during the Great Dimming. This suggested that two shocks propagated in the upper atmosphere, one in February 2018 and one in January 2019 with the second amplifying the effects of the first. Kravchenko *et al.* (2021) suggest that this shock structure modified by underlying convection or outward gas motion altered the molecular opacity in the line of sight.

Mittag *et al.* (2023) have engaged in long-term studies of the chromosphere of Betelgeuse since 2013, including the epoch of the Great Dimming when they determined the absolute and normalised excess flux of the CaII H&K lines. They found behaviour similar to that during a previous decrease in the visual brightness of Betelgeuse in 1984 and 1985. The chromospheric emission of Betelgeuse did not change significantly between November 2019 and February 2020, but did vary after the Great Dimming. Mittag *et al.* (2023) argue that this delay of the chromospheric reaction suggests that the cause for the Great Dimming is located in the photosphere.



11 *Speckle polarimetry of the surface of Betelgeuse on 27 October 2019 at the very beginning of the Great Dimming (left panel) and on 5 February 2020 at the extreme of the dimming (right panel).* (From Safonov et al. (2020) by permission of B. Safonov, Caucasian Mountain Observatory, and the Sternberg Astronomical Institute of Moscow State University.)

Himawari-8 is a Japanese geostationary meteorological satellite orbiting 35786km above the equator at 140.74°E. Several bright stars, including Betelgeuse, occasionally fortuitously appear in the images. Taniguchi *et al.* (2022) used the 16-band photometry from 0.45 to 13.5 μm from Himawari-8 to construct a light curve of Betelgeuse spanning 4.5 years from 2017 to 2021 with a sampling that averaged once per 1.72 days. Taniguchi *et al.* (2022) used the infrared optical depth in contrast to variations in the visual extinction, A(V), to directly trace the amount of circumstellar dust. The IR optical depth increased during the Great Dimming with a small delay between the peak in IR optical depth and the extinction in the visual. Taniguchi *et al.* (2022) argue that their data suggest that a clump of gas produced dust that obscured the photosphere of Betelgeuse and contributed to the Great Dimming and that the enhancements of visual extinction and IR optical depth during the Great Dimming may have occurred very close to the photosphere. They conclude that their results support a scenario in which the Great Dimming was caused by a combination of a decrease in T_{eff} and an increase in A(V) in roughly equal amounts consistent with the change in polarisation reported by Cotton *et al.* (2020) and Safonov *et al.* (2020).

The Great Dimming was clearly a complex phenomenon. It seems unlikely that its alignment with the phase of the ~400 days pulsation period was a coincidence, but that alone cannot account for the magnitude and spatial inhomogeneity of the obscuration. There seems to be solid evidence that dust with an inhomogeneous spatial distribution played a role. A decrease in T_{eff} occurred, perhaps in the form of large, cooler patches. Such patchy structure in surface temperature calls into question the meaning of a global T_{eff} and at least sets upper limits on the precision with which a global T_{eff} can be determined.

The explosion to come

In an epilogue, after the Great Dimming, Betelgeuse has shown repeated minima at an interval of ~200d and has steadily increased in mean brightness to reach an historic maximum of V ~0 in April, 2023 (M. Montargès, private communication, 2023). Betelgeuse will eventually explode, probably still as a red supergiant, thus producing a Type II supernova (Branch & Wheeler 2017). The details will be affected by the intense convection in the late shell-burning phases less than a year before explosion that may also produce significant outward acoustic flux and mass loss. The convection seeds turbulence in the collapsing material that is expected to enhance the subsequent explosion (Arnett & Meakin 2011; Couch *et al.* 2015; Chatzopoulos *et al.* 2016).

At the expected iron-core collapse, 10^{53} ergs of neutrinos will be produced that emerge from the envelope about an hour after collapse and flood into space. About 600 years later, detection of those neutrinos will give any humans on Earth their first hint of the events to come, i.e. ~100 trillion neutrinos, vastly less than a lethal dose of radiation.

The shock wave generated by the explosion carrying ~10^{51} erg of kinetic energy will take about a day to reach the surface. A blast of UV lasting about an hour will then occur. The resulting UV flux will be less than the flux of the Sun at Earth but perhaps sufficient to cause some disruption of atmospheric chemistry.

In two weeks, the explosion will be producing a billion times the solar luminosity. At the Earth, Betelgeuse will appear as a pinpoint about as bright as a quarter Moon lasting for around three months. The explosion will then fade, but remain visible at the Earth for many years and to scientific instruments for centuries. The explosion of Betelgeuse is likely to produce a pulsar that will also be visible for a million years or more.

The supernova blast wave will propagate out through the surrounding CSM and ISM and interact with any mass lost in the next 100000 years and eventually with the complex CSM illustrated in figure 3. The shock wave will propagate at ~5000 kms^{-1} and hence collide with the bow shock in about 60 years and the odd linear structure about 20 years later, assuming a distance to Betelgeuse of 165 pc (Joyce *et al.* 2020).

By the time the supernova shock reaches the Earth more than 100000 years after the explosion, the solar magnetosphere should easily deflect it. The Earth, immersed within the supernova remnant, may witness an increase in cosmic ray flux.

Summary, conclusions and future

Betelgeuse still presents a host of outstanding issues. Its irregular surface; the manner in which it ejects matter to form a chromosphere, wind, dust, and molecules; how it came to move through space and spin so rapidly; the nature of its variability and magnetic fields; and the possibility that it underwent a significant change in colour within historical times. Statistics suggest that it was likely to have been born in a binary system and undergone complex common envelope evolution. Are the distant circumstellar structures related to the interaction of winds with the interstellar medium or the products of the dramatic turmoil of a merger?

A pertinent question is the condition of Betelgeuse as we see it today, gracing Orion. While uncertainties in the distance remain troubling, Betelgeuse is most likely near the tip of the RSB. Since core helium burning is far longer than subsequent burning phases, Betelgeuse is most likely in core helium burning. The pulsation period likely constrains the radius and distance and the evolutionary state to core helium burning (Joyce *et al.* 2020), but there are arguments to the contrary (Neuhäuser *et al.* 2022; Lau *et al.* 2022).

Estimates of the surface gravity of Betelgeuse span a large range. The inclination angle is uncertain. A more accurate measurement of log *g*, radius, and distance could yield new constraints on the current total mass. Comparison to the luminosity that most directly measures the core mass could reveal hints of the current mass of the outer hydrogen envelope, past mass loss, and the current evolutionary state. Continued exploration of atomic, isotopic and molecular abundances may yield more information on internal mixing processes.

The notion that Betelgeuse may have undergone a merger remains viable. The extra angular momentum may have come from merger with a companion in the red supergiant phase, nearly independent of the mass of the secondary. Once a transient phase of merging has settled down and substantial mass and angular momentum have been ejected, there is rather little external difference in models in late core helium burning and subsequent phases. This frustrates attempts to determine the internal structure and state of the star. How can we prove Betelgeuse has undergone a merger?

There remain challenges in understanding the associated physical processes if Betelgeuse underwent a merger. These must be explored with extensive, highly-resolved 3D studies of the formation and evolution of tidal plumes as any secondary is disrupted near the core of the primary. How deeply does the plume penetrate? What abundances are mixed to the surface? What is the level of envelope enrichment

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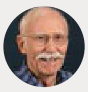
Software: MESA (Paxton *et al.* 2011, 2013, 2015, 2018); OctoTiger Adaptive Mesh Refinement (AMR) hydrodynamics code developed by the LSU Center for Computation and Technology (CCT) (Marcello *et al.* 2021).

AUTHORS



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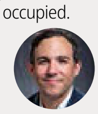

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with helium that may determine whether the star remains red or moves back to the blue? What is the expected structure of the inner core as it evolves, rapidly rotating, beyond core helium burning?

The Great Dimming of 2019/20 did not portend imminent explosion. The origin of the dimming might have been related to a resonance of pulsation periods, expulsion of a dust cloud, and extra-large star spots.

How can we test the current evolutionary state of Betelgeuse with observations of pulsations and surface irregularities? Are there faint signals from acoustic waves generated internally that carry information about the core structure that would prove or disprove the hypothesis of a merger?

What are the clues to imminent collapse that might pertain now, or in the far future, if Betelgeuse is in core helium burning now? Models predict extensive mass loss shortly before collapse driven by rapid convection in the inner burning shells and there are hints of such pre-collapse mass loss in Type II supernovae that are thought to arise in red supergiants like Betelgeuse.

Mysteries abound! ●

Our Fragile Space

Max Alexander has designed an exhibition and science communication project aimed at protecting the near-space environment

With the exponential growth of satellites orbiting just a few hundred kilometres above our heads, I wanted to make a contribution to the understanding of what is happening in the near-space environment, including the impact on optical and radio astronomy, and the loss of the night sky for humanity. I felt I needed to tell the wider story of how space is intertwined in our everyday lives and society. Much of modern life is governed by its use and many of the benefits we gain go unnoticed. I set out to highlight the measures that are being taken to protect this fragile environment, including solutions, mitigation and the emerging field of space sustainability, to show the whole picture in one photography-led project.

A year in the making, my photography for 'Our Fragile Space: Protecting the Near-Space Environment' took me to the top of volcanoes in the Pacific and Atlantic Oceans, clean rooms across Europe, mega-constellation launches on both coasts of the United States, and a farm in England. It also took me on a journey through the space sector: space agencies, government, military, regulation, insurance market, astronomy and space sustainability enterprises.

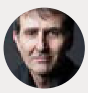
The project takes a human perspective, from the ground looking up, connecting the Earth to the near-space environment. I chose this everyday approach to make the issues more tangible because space debris is just up there, part of Earth's environment.

Human activity over hundreds of years has led to global changes on the land, in the oceans, in the atmosphere, and now in space with debris. We are only 65 years into the Space Age so we have an opportunity to not repeat the same behaviour. The sustainability imperative is becoming embedded within us; protecting the near-space environment is in everyone's interests.

The exhibition was launched in October 2022 at Lloyd's of London, who showed amazing support.

Clockwise from bottom right: *Lloyds of London hosted the exhibition's launch in October 2022; Amelia Bayo, Spanish ESO Faculty member, contemplates the Milky Way in the Atacama Desert, Chile; Starlink satellite train after launch passes overhead in the pre-dawn sky in London; Haleakalā Observatory, Hawai'i, on the island of Maui. On the left are the astronomical instruments, on the right is the Maui Space Surveillance Complex operated by the US Air Force.* (Photographs by Max Alexander; except Lloyd's of London).

AUTHOR



Max Alexander is a photographer and Fellow of the RAS, known for his public engagement in astronomy **maxalexander.com**

Some 150 people attended from across multiple sectors including the worlds of insurance, finance and regulation. It was opened by John Neal, CEO of Lloyd's, Ian Annett, UK Space Agency Deputy CEO, and British ESA astronaut Tim Peake, who set the scene by giving the perspective from space. Writer and project collaborator Dr Stuart Clark ran the evening including moderating a panel discussion with leading space lawyer Prof. Joanne Wheeler, who concurrently announced her space sustainability standards initiatives. Dr Robert Massey of the RAS was in attendance, with his portrait appearing in the exhibition.

Lloyd's was the perfect place to launch the exhibition, with the ever-increasing risk to satellites, the potential loss of certain orbits and the need for responsible behaviour. Several months later UK Science Minster George Freeman hosted a round-table discussion at Lloyd's, initiated by Joanne Wheeler, and Lloyd's now include space in their Purpose Statement – both tremendous project outcomes.

The exhibition is now on tour over the next two years. It has been to The Eden Project and Spaceport Cornwall. It spent 6–21 May at The Ruins, Coventry Cathedral, under an open sky, in collaboration with Warwick University, through Professor Don Pollacco and the Centre for Space Domain Awareness (CSDA).

'Our Fragile Space' will be hosted by the United Nations Office of Outer Space Affairs (UNOOSA) in Vienna, during the Committee on the Peaceful Uses of Outer Space (COPUOS), from 31 May to 9 June. This is supported by the European Astronomy Society through Professor Roger Davies, with their organisation's concerns about the impact on professional astronomy. There is also support from NOIRLab and SKAO, who are also directly supporting the exhibition at Jodrell Bank, running from 12 June to September. Many other locations are in the works. ●

MIST reunited

Emma Woodfield, Andy Smith and colleagues outline the research presented and discussed at the Autumn MIST meeting in November 2022

The first in-person Autumn MIST since the start of the Covid-19 pandemic was held in the Geological Society on 18 November 2022. It was a very successful hybrid meeting with 89 people attending in person and 24 online. The meeting was split into three oral sessions: planetary, solar and Earth-based presentations alongside two poster sessions to accommodate the very large number of abstract submissions to this thriving meeting.

The first session of the day collected a selection of planetary presentations. **Mark Lester** (University of Leicester) began the day by presenting Mars radar data from the MARSIS instrument on the MAVEN spacecraft during solar energetic particle (SEP) events. Using radar blackouts from MARSIS in the AIS mode (when it is a topside ionospheric sounder which also receives reflections from the surface) in conjunction with the MAVEN SEP particle instrument, Mark demonstrated the presence of a highly variable ionisation layer in the low-altitude atmosphere of Mars.

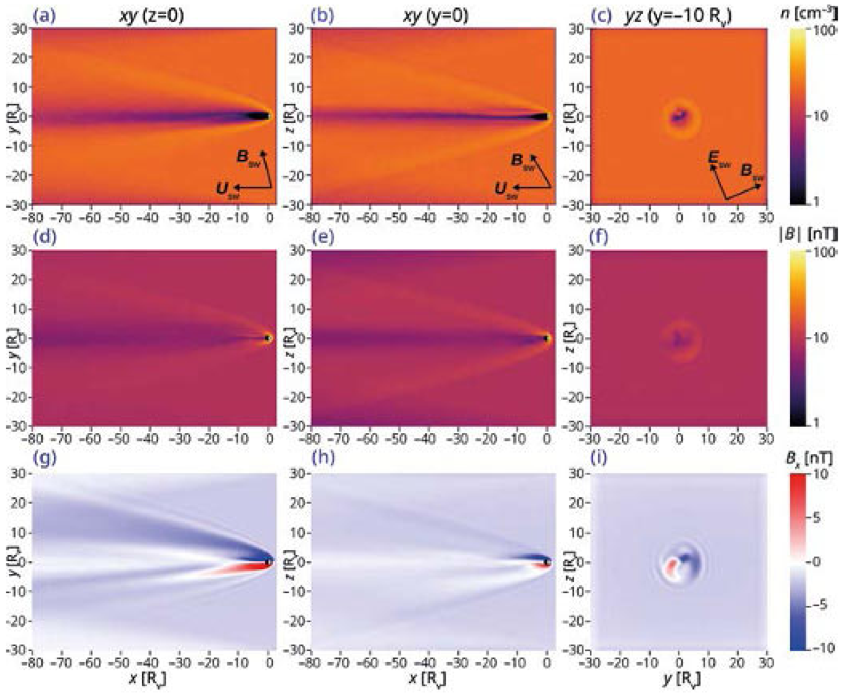
Katerina Stergiopoulou (University of Leicester) presented an investigation of the induced magnetotail at Venus using data from two flybys of the planet by ESA's Solar Orbiter spacecraft. Taking electron density and magnetic field measurements, Katerina compared these to hybrid simulations of Venus' magnetosphere using a model by Jarvinen and Kallio from Aalto University in Finland (figure 1). The comparison revealed times when the observed magnetic field vector was rotated away from the modelled vector and possible evidence of escaping plasma.

Charlotte Goertz (Northumbria University) took us on a tour of the diamagnetic cavity that occurs within the plasma environment around comets. Charlotte showed that these cavities, where the magnetic field strength is zero and no solar wind is observed, rather surprisingly sometimes contain protons, as shown by the Rosetta measurements of comet 67P/Churyumov-Gerasimenko. Having ruled out several other possibilities, Charlotte proposed that these protons can enter the cavity when the interplanetary magnetic field is parallel to the solar wind velocity.

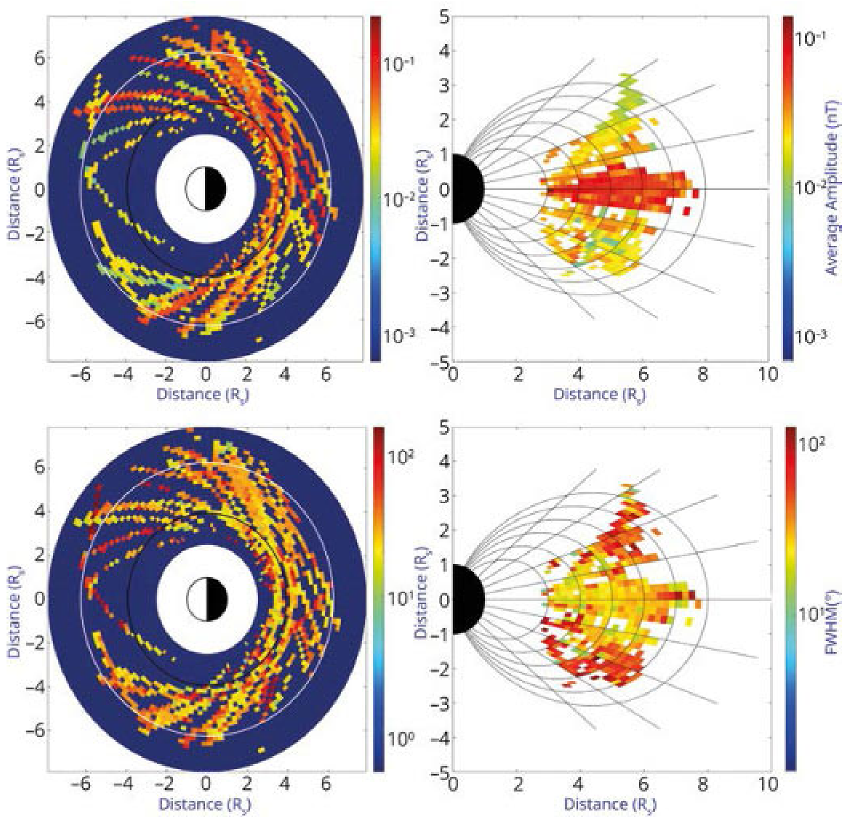
To finish the planetary session, **Cristian Radulescu** (University College London) presented findings on the distributions of pick-up ions at Saturn from Cassini data. These ions were recently neutral particles ejected by the moon Enceladus and have been 'picked up' by the fast-moving plasma in Saturn's magnetosphere. The evolution of the velocity distribution of these ions is related to the production of ion cyclotron waves. Analysing data between 4 and 6 Saturn radii (R_S) from the centre of the planet, Cristian found that the region of most intense ion cyclotron waves (centred on the equator) is co-located with the region of narrower ion pitch angle distributions and vice versa (figure 2).

Solar wind studies

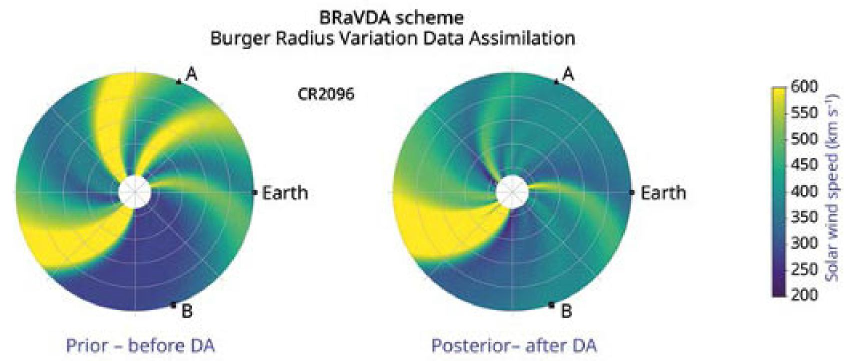
The second session began with **Harriet Turner** (University of Reading) looking at the use of real-time data in solar wind data assimilation. Noting the



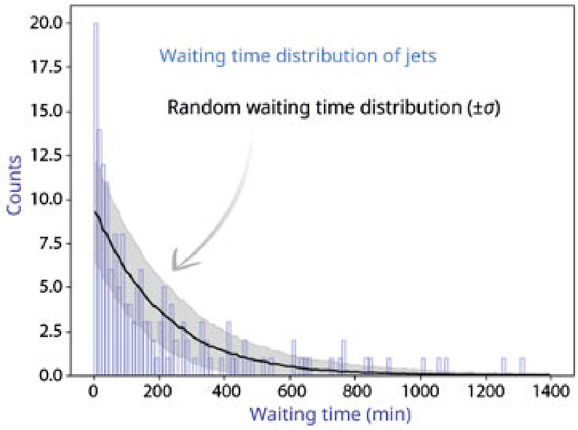
1 *Simulation results of the solar wind-Venus interaction from the global hybrid simulation RHybrid developed by Jarvinen and Sandroos at the Finnish Meteorological Institute (FMI). Solar wind density in XY, XZ and YZ VSO planes in (a)–(c), magnetic field magnitude in (d)–(f) and the X component of the magnetic field, BX, in (g)–(i).* (Reproduced from Figure 4 of Stergiopoulou et al., 2023, JGR, 128, 2)



2 *Cassini observations of ion cyclotron waves at Saturn showing the average amplitude (top row) and the full width at half maximum of the water group pick-up ion pitch angle distributions (bottom row).*



3 *Solar wind solution from the BRaVDA model using the simplified solar wind model HUX, initialised on 22/04/2010 for Carrington Rotation 2096 (22/04/2010 to 19/05/2010). The prior state (left) is that before the in situ data assimilation has taken place and the posterior state (right) is after the data assimilation. Indicated on both panels is the location of STEREO-A (A), Earth and STEREO-B (B) on 22/04/2010.* (Reproduced from Figure 1 of Turner et al. 2022, Space Weather, 20, 8)



4 *The waiting time distribution of reconnection exhaust jets in the solar wind (Preliminary data shown here, the updated version is in Fargette et al. 2023,* Astron. Astrophys.*, accepted)*

difference in the data between real-time and the cleaned-up science level data which appears some time later, Harriet showed that using the BRaVDA scheme (Burger Radius Variational Data Assimilation) with real-time data did not significantly worsen forecasts of the solar wind (figure 3). Harriet also showed that a future mission pairing of both an L5 and L1 monitor would improve forecasts of solar wind speed.

Next up, **Naïs Fargette** (Imperial College, London) described his work on the clustering of reconnection exhausts in the solar wind. Past observations have shown many reconnection jets at 1au but very few at 0.1au. Using Solar Orbiter data, Naïs set up an automatic detection algorithm and found 163 jets in a span of 24 days at 0.7au. Upon analysing the time in between jets, there was evidence of jets clustering together in time with the jets typically of short duration and low shear (figure 4).

Alina Bendt (Centre for Fusion, Space and Astrophysics, University of Warwick) investigated the use of wavelet decomposition on Solar Orbiter data to investigate turbulence in the solar wind. With non-gaussian probability distribution functions confirming turbulence, Alina found the scaling component was close to 3/2 but not fully in the inertial range. Fractal behaviour was evident in the kinetic range and multi-fractal behaviour in the inertial range.

In the penultimate talk of the session **Abid Razavi** (Mullard Space Science Laboratory) presented studies of interplanetary shocks. Abid showed examples of flat-top shock distributions, so named from their shape in the phase space density versus energy, from Solar Orbiter data. The shape of the distributions has implications for the energy dissipation at a shock. These case studies are the start of a larger statistical investigation.

In the final talk of the session, **Domenico Trotta** (Imperial College, London) presented analysis of particle acceleration at interplanetary shocks, focusing on upstream steep structures known as shocklets. A multi-spacecraft case study of a strong shock using observations from Solar Orbiter, Wind, THEMIS, DISCOVR and ACE shows the broad spatial extent of these phenomena upstream from the shock front.

Earth-based science

The final session of the day hosted talks focused on Earth-centred science from the MIST community. **Ciaran Beggan** (British Geological Survey, BGS) started the session by providing a description of how the BGS are increasing the number of locations at which observations of the magnetic field are made in the UK. Three new sites are being added to the current network of four existing magnetometers to dramatically improve the spatial coverage available. These stations now return high-quality magnetic variation data through the 4G network in near-real time, and improve our ability to monitor space weather.

Next, **Harley Kelly** (Imperial College, London) discussed how current understanding of the Kelvin-Helmholtz instability is based on simplified and unrealistic assumptions, partly because of the difficulty of measuring these data with spacecraft. Harley then described using GORGON MHD (MagnetoHydroDynamic) simulations to probe Kelvin-Helmholtz votices in global-scale 3D simulations. They located the structures by searching for pressure minima, and found more Kelvin-Helmholtz structures on the magnetopause, where they form tubular structures, than in the magnetotail.

Nonetheless, a complex series of phenomena occur in the Earth's magnetotail. Some of these are linked to magnetospheric substorms, which are a global cycle of energy storage and release that can be monitored in different data sets, using a range of techniques. **Christian Lao** (University College London) presented work comparing and contrasting the different databases of substorms that identify substorms through distinct methods. None of these competing catalogues agreed entirely with another, yet the time differences between them (when they agreed) was equal to the shortest time tested – suggesting that the events are near-simultaneous when the same event was recorded.

Gemma Bower (University of Leicester) then presented work investigating the formation and evolution of a type of auroral configuration known as 'Horse Collar Aurora'. This kind of auroral event was shown to occur during northward IMF (interplanetary magnetic field) conditions, with 11 events (out of 650) showing sufficient data to examine the auroral forms in more detail. In all cases the formation and motion of the aurora appeared to be governed by the sign of the IMF B_y component, as predicted by the Milan *et al.* (2020) model.

Following this, **Thomas Daggitt** (British Antarctic Survey, BAS) described their work exploring how the radiation belts – and the charged particles therein – interact with the ever-changing location of the magnetopause. When the magnetopause is compressed the radiation belts lose particles when and where they intersect. Thomas showed how existing analytical models of the magnetic field can predict this process on a large scale, but fail to do so during short-lived events where the magnetopause is compressed to within geosynchronous orbit. Further, there is a strong dependence on the magnetic local time of the observations, with satellites in similar but offset orbits encountering very different flux profiles (Daggitt *et al.* 2022).

Gareth Dorrian (University of Birmingham) then moved the focus of the session down to the Earth's ionosphere, discussing a new way to monitor ionospheric disturbances using the LOFAR (LOw Frequency ARray) radio telescope. This pan-European telescope is designed for radio astronomy, but by monitoring natural, consistent radio sources Gareth used it to understand the changing ionosphere through which received radio waves must travel. By monitoring different astrophysical sources it was possible to map where ionospheric disturbances existed and how they moved, results that were consistent with maps derived independently using GPS observations (figure 5).

The next talk returned to the radiation belts: **Shannon Killey** (Northumbria University) presented work using machine learning to diagnose the behaviour of relativistic electrons within the radiation belts. Shannon used a series of advanced methods to group similar types of radiation belt observations, allowing the isolation of when and where certain conditions manifest (figure 6). During the seven years of observations, five types of plasma conditions are found to dominate. One type, the 'butterfly'-shaped distribution is mainly seen at the edges of the belts, and is thought to represent regions where waves and particles are interacting, exchanging energy. Meanwhile during dynamic geomagnetic storms the type of conditions changes over time.

For the final talk of the session, **Ingrid Cnossen** (BAS) brought us to the upper atmosphere of the Earth, discussing predictions of the impact of climate change on the upper atmosphere and its consequences for space debris. Ingrid's simulations run from the present day through to 2070 and include the effects of solar and geomagnetic variability, along with changing trace gas (e.g. CO_2) emissions. These simulations show a long-term decrease in density of the upper atmosphere, with the knock-on effect that space debris will last for longer before burning up in the atmosphere. This amounts to 15% more debris by 2070 and indicates that there will be more frequent catastrophic collisions.

The success of the meeting means the MIST community has weathered the storms of the past few years. MIST council would like to thank the Geological Society for hosting us, and the Royal Astronomical Society for the continued support. Furthermore, we thank all attendees and presenters for contributing to an engaging and enjoyable meeting. ●

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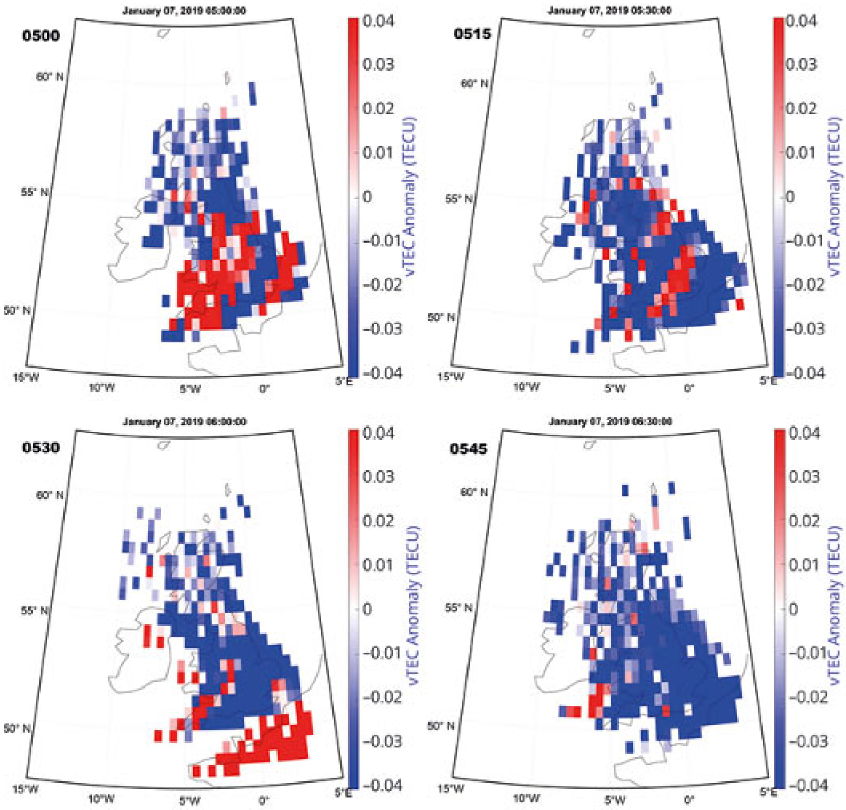
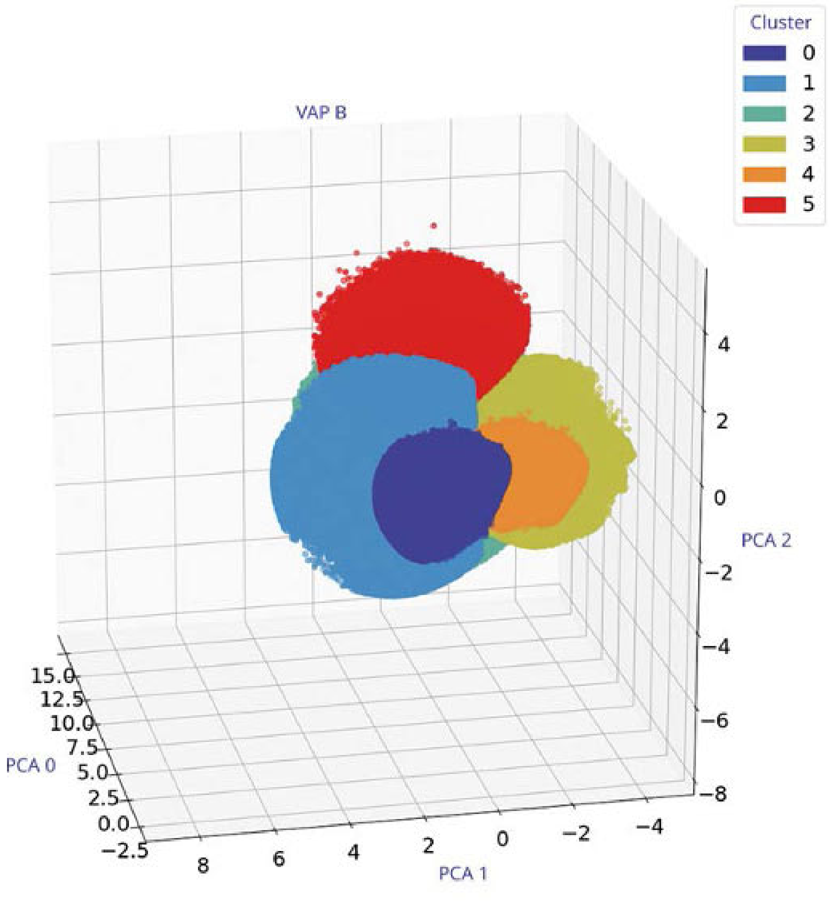


5 *Global Navigation Satellite System Total Electron Content anomaly data, averaged to 30-min* (adapted from Figure 10 of Dorrian, G. et al., 2023, Space Weather, 21, e2022SW003198, with credit to David Themens, University of Birmingham).



6 *Seven years of Van Allen probe REPT data processed using an autoencoder neural network followed by principal component analysis to reduce the dimensionality of the data. This figure shows the clusters of similar plasma conditions that emerge from using K-means clustering on the reduced dimension data.*

Poster Presentations

In addition to the excellent oral presentations we had 37 outstanding posters shown across two sessions.

Joel Baby Abraham	Mullard Space Science Laboratory	*Radial Evolution and Energy Budget of Thermal and Suprathermal Electron Populations in the Slow Solar Wind from 0.13 to 0.5AU: Parker Solar Probe observations.*
Anasuya Aruliah	University College London	*Are thermospheric models overestimating mass density?*
Sarah Bentley	Northumbria University	*Radial Diffusion Benchmarking: Initial Conditions*
Shahbaz Chaudhry	University of Warwick	*Global dynamic network response of Pc2 waves to the 2015 St Patrick's day storm using SuperMAG and Intermagnet ground based magnetometers*
Joseph Eggington	Imperial College London	*Global Magnetospheric Modelling with Gorgon*
Omar El-Amiri	University of Warwick	*PIC Simulations of Electromagnetic Ion Beam Instabilities in Earth's Foreshock*
Amy Fleetham	University of Leicester	*AMPERE, GICs and the Electric Current of Geomagnetic Storms*
Colin Forsyth	Mullard Space Science Laboratory	*Potential observations from nanosatellites in ESA's D3S programme*
Laura Fryer	University of Southampton	*Global magnetotail configurations of simulated pressure pulses during northward IMF conditions.*
Imogen Gingell	University of Southampton	*Simulations of the decay of reconnected structures downstream of Earth's bow shock*
Sarah Glauert	British Antarctic Survey	*Theoretical loss timescales and pitch angle distributions for the radiation belts*
Adrian Grocott	Lancaster University	*SuperDARN observations of the two component model of ionospheric convection*
Rosie Hodnett	University of Leicester	*Harmonic Frequency Separation of Ionospheric Alfvén Resonances Observed at Eskdalemuir*
Lauren James	University of Reading	*Sensitivity of Model Estimates of CME Propagation and Arrival Time to Inner Boundary Conditions when Constrained by Spacecraft Data.*
Simon Joyce	University of Leicester	*Update on the Mars Express Active Ionospheric Sounder data processing*
Andrew Kavanagh	British Antarctic Survey	*DRivers and Impacts of Ionospheric Variability with EISCAT_3D (DRIIVE)*
Adrian LaMoury	Imperial College London	*Magnetopause reconnection and dynamics following the impact of magnetosheath jets*
Andrea Larosa	Queen Mary, University of London	*The interplay between magnetic switchbacks and solar wind turbulence in the inner heliosphere*
Harry Lewis	Imperial College London	*Generalised Ohm's Law in the Magnetosheath: Relative Contributions to Turbulent Electric Fields as Modified by Plasma Conditions*
Subir Mandal	British Antarctic Survey	*Understanding the Gravity Wave Activity in the Scandinavian Mesospheric Region as part of the MesoS2d Project*
Jack McIntyre	Queen Mary, University of London	*Parameters underlying the evolution of the magnetic field spectral index in the solar wind*
Tracy Moffat-Griffin	British Antarctic Survey	*MesoS2D:Mesospheric sub-seasonal to decadal predictability*
Michaela Mooney	University of Leicester	*Evaluating Auroral Forecasts Against Satellite Observations*
James Plank	University of Southampton	*Measures of Correlation Length at Quasi-Parallel and Quasi Perpendicular Shocks*
Catherine Regan	Mullard Space Science Laboratory	*Investigating the 2007 Global Dust Storm at Mars with Mars Express*
Jade Reidy	British Antarctic Survey	*Preliminary analysis of low altitude electron density measurements from EISCAT*
Sam Rennie	University of Leicester	*SuperDARN Observations of High-m ULF Waves*
Jasmine Sandhu	Northumbria University	*Exploring the complex response of ULF waves to plasmaspheric plumes*
Md Goribullha Shah	Queen Mary, University of London	*Multiband Whistler Mode Waves in the Earth's Magnetosphere: MMS Observations and Two-Fluid Plasma Simulations*
Julia Stawarz	Imperial College London	*The Evolution of Intermittency in the Solar wind During a Radial Alignment Between Parker Solar Probe and Solar Orbiter*
Gabriel Suen	Mullard Space Science Laboratory	*Solar Orbiter Observations of Switchback Dissipation Through Magnetic Reconnection*
Maria-Theresia Walach	Lancaster University	*Dusk-Dawn Asymmetries in SuperDARN Convection Maps*
Xueyi Wang	University of Warwick	*Wavelet analysis determination of scaling exponents and ranges in the magnetohydrodynamic range of solar wind turbulence seen by Parker Solar Probe*
James Waters	University of Southampton	*A Perspective on Substorm Dynamics Using 10 Years of Auroral Kilometric Radiation Observations from Wind*
Cara L. Waters	Imperial College London	*Calibration and Attitude Determination of the Inboard Magnetometer on the RadCube CubeSat*
Emma Woodfield	British Antarctic Survey	*The effect of Z-mode waves on the electron radiation belt at Jupiter.*
Sophia Zomerdijk-Russell	Imperial College London	*Assessing how BepiColombo will use Solar Wind Variability to Probe Mercury's Interior*

Future UK solar system science

A new Roadmap for Solar System Research in the UK has been published, and the Solar System Advisory Panel report on the processes involved in updating the previous iteration

Solar system research in the UK is booming, with an active, growing community of researchers. Yet this is also a critical time, with demand and new opportunities outstripping available resource.

In the last few years, one of the biggest tasks for the Solar System Advisory Panel (SSAP) has been preparing an updated version of its Roadmap for Solar System Research. The new version was issued in December 2022, and is available online (De Moortel *et al.* 2022).

The idea of the roadmap is that it guides the STFC Science Board as to where the community is, where it thinks it is going and what the main impediments and opportunities are. As the Astronomy Grants Panel (AGP) is totally independent of SSAP (see box 'Routes to funding'), the Solar System Roadmap is not a charter that directly drives future funding awards. Instead, it reassures the Science Board that there is a strong, vital, UK-based community, achieving fundamental and important advances, aligned with the opportunities provided by various space agencies, for example the UK Space Agency (UKSA), as well as NASA, the European Space Agency (ESA), the Japanese Space Agency (JAXA), the Canadian Space Agency (CSA) and so on. It should also persuade the Science Board that the key technologies and computing breakthroughs that are necessary for a healthy future are being advanced.

The previous version of this roadmap was issued in 2015 (Grady *et al.* 2015), and before that in 2012 (Grady *et al.* 2012). With a seven-year gap since the last version, a major reappraisal of the field was deemed appropriate; one of the key findings of the work is just how much the field has advanced in such a short period.

Consultation details

All members of SSAP contributed to this work, over a period of more than a year, holding regular online group meetings throughout the Covid-19 pandemic. From the beginning, the SSAP sought significant input from the wider community, via a variety of routes. A call for 'white papers' on areas of interest was issued in 2021. In response, 55 white papers were submitted, giving a substantial body of information to guide the panel's work and confidence that it accurately reflected the views and interests of the solar system community. This was followed by distribution of an online questionnaire in autumn 2021, asking for comments on the existing roadmap and any suggested changes, accompanied by a community survey on broad issues ranging from funding priorities to career development opportunities (79 responses). A second call for comments on the summaries of the white papers and questionnaire responses was distributed online in early 2022 (receiving 29 responses to the questionnaire, and written comments from eight people).

Members of SSAP read and extensively discussed the white papers, using their contents to guide their deliberations. Similarly, the questionnaire feedback and other inputs were carefully reviewed and all comments considered. The community response to the question of changes to the key scientific challenges was interesting. Around 95% of the 2021 questionnaire responses said none of the existing challenges should be removed, but 40% felt there was a need for revisions, and 34% suggested additions. Thus, the 2022 roadmap is an evolution of the previous one, recognising the continuing developments in the field.

One point that was repeatedly raised by the community throughout the consultation period was that the lack of funding was critical; almost every area of research and technical development offered significant opportunities that could be exploited with more funding. It was pointed out that both ESA and NASA are currently preparing for large future missions, and UK involvement needs appropriate funding levels. Further to this, about 63% of the respondents to the 2021 online questionnaire (and 60% in 2022), felt the issue of access to space missions was extremely important, and so the relationship between STFC and UKSA needed more attention.

As well as the science topics themselves, the community clearly felt strongly in several broader areas, namely: developing a more diverse, representative community of scientists equally accessible to all; ensuring proper career development in the early phases of a career; and sustainability.

As our draft roadmap progressed, incorporating this feedback, preliminary reports on progress were made in 2022 at the British Planetary Science Conference (BPSC), UK Solar Physics and Magnetosphere Ionosphere Solar Terrestrial community meetings and the National Astronomy Meeting (NAM).

Main roadmap findings

The roadmap provides a brief overview of UK interests in solar system research, and the recommendations made by SSAP are shown in Table 1. The roadmap grouped activities in three main themes: Solar variability and its impact on us; Planets and life; and Space plasma processes. Such divisions are to a degree arbitrary and cover a wide range of topics inside each theme. However, they do permit an ordering of material with some common interests. Indeed, taking a holistic view, scientific results from one area may have influence on questions in the other themes, but a degree of compartmentalisation is helpful in planning. This means that research in each theme is not totally separate; there will be overlap, for example, where a single space mission carries instruments for several purposes, thus contributing to more than one theme. In addition, crosscutting and underpinning support (e.g. high-performance computing) by its very nature often supports more than one theme.

In all the themes, SSAP found that significant progress was being made, with work advancing on emerging topics as well as on key issues identified in previous versions of the roadmap. The first theme, 'Solar variability and its impact on us', acknowledges the impact that the Sun has on both the Earth and the whole solar system. Understanding stellar processes that can influence the near space around a star (i.e. the solar system) is therefore a vital undertaking. Processes deep inside the Sun, variability of the surface and atmospheric magnetism, the solar

Table 1: Main recommendations from the Roadmap for Solar System Research 2022

This Roadmap highlights UK community strengths and areas of leadership but, given the fundamentally international nature of solar system science, SSAP does not recommend it should be the (sole) basis for any prioritisation exercise by STFC. SSAP recommends that STFC take note of the synergies between this Roadmap and relevant international exercises, to both illustrate the excellence of UK science and to understand strategic opportunities for international impact.

HPC is now a core requirement across solar system research and SSAP strongly urges STFC (and UKRI) to implement a long-term, sustainable HPC strategy. The investment in hardware must be accompanied by support for skills training for early-career researchers and STFC should recognise the long-term nature of code development and the requirement for support for highly skilled people on timescales beyond the three-year funding cycle.

SSAP recommends that STFC plays a clear role in the development of UKSA's Bilateral Programmes to ensure alignment with well-established UK scientific goals and priorities. SSAP notes the strong UK solar system community support for such a programme, provided it does not come at the expense of existing international activity.

The 'dual-key' funding approach between the UK Space Agency (UKSA) and the research councils continues to present challenges in ensuring that the funding process is agile, transparent, and effective. SSAP recommends reviewing the relevant advisory and governance structures to make sure opportunities are fully visible to both sides to maximise mutual benefit. The UKSA Aurora space exploration programme offers one successful model which has integrated instrumentation development and science exploitation.

That STFC maintains its support for ground-based and space-based telescope operations and instrumentation at a level that will enable the UK to maintain its high international profile in the relevant fields. This support should recognise and balance the competing claims of new developments versus extension of current instrumentation, such that UK scientists are able to access the range of facilities they require to meet their goals.

To promote a culture of open-data and maximise the long-term return of UK investment in missions and instrumentation, it is paramount that STFC fully supports data storage and curation both for individual scientific projects and missions and facilities.

SSAP recommends that STFC builds on the success of programmes such as SWIMMR to articulate the importance of UK solar system science within UKRI, and to continue to work with the UK solar system community to identify and secure long-term support outside of core Research Council budgets.

Increasing the exploitation funding line level (cash basis, not percentage of the programme) should be a top priority for STFC. Grants, fellowships and studentships have been chronically underfunded and are at a level where the community's international leadership position cannot be maintained. SSAP welcomes the recently announced uplift in the STFC grant line, but a further uplift will be required to return this to an internationally competitive level (particularly if association with Horizon Europe is not achieved).

That STFC maintains support for ground-based laboratory experimental, analytical, simulation, fieldwork activities and curation facilities, to enable the UK to maintain its high international profile in the relevant fields and play a leading role in forthcoming sample return missions.

SSAP recommends that STFC continues to support UKSA in its investment in ESA's Science, Human and Robotic Exploration, and Space Safety Programmes, recognising the value that this investment brings to supporting and sustaining the UK solar system community.

SSAP recommends that STFC further strengthens its efforts and commitments to ensuring that the solar system community reflects the diversity of the UK population and uses examples of best practice from the UK solar system community to influence more widely, within UKRI and beyond.

Fig 1 *NIRCam image of Jupiter* (JWST NASA/ESA/CSA/Schmidt)

Fig 2 *The Aurora Borealis over northern Canada, photographed by Tim Peake on the International Space Station, 20 January 2016* (ESA/NASA/Tim Peake)

wind, connections with planetary atmospheres and magnetospheres are all important. Recent observations at higher spatial and temporal cadence reveal activity at all scales and the importance of the chromosphere in the mass and energy cycle of the solar atmosphere. Figure 1 shows aurorae at the north and south poles of Jupiter, and figure 2 shows the Aurora Borealis on Earth, an illustration of the connection between solar activity and the planets (with strong and widespread aurora seen on Earth in early 2023 for example). Space weather (including short-term effects on the ever increasing satellite population as well as the technology here on Earth) is recognised by the Cabinet Office as a major risk and is included in the UK's National Risk Register.

The UK has internationally leading teams working on many aspects of the science of the Sun. There are strengths in involvement in current and future space missions and in ground-based observatories (including contributions to the Daniel K. Inouye Solar Telescope), development of new instrumentation, modelling of solar and terrestrial interactions, and advances in the theories and computational models behind many aspects of solar processes. This breadth in expertise means the UK community is well poised to take on leading roles in upcoming international missions.

As well as remote-sensing observations and *in-situ* measurements of the Sun and at the Earth, the UK community also plays leading roles in studying solar interactions with other planets. At Mercury and Venus, UK teams will play leading roles on BepiColombo and EnVISION respectively, which will significantly advance our understanding of these bodies over the next decade. For the outer solar system, there is world-leading expertise in, for example, coupled magnetosphere-ionosphere-thermosphere complexes at Jupiter and Saturn. UK expertise and leadership in these and other aspects of this theme is widely recognised internationally.

Under the second theme, 'Planets and Life', a major development in recent years has been the opening up of the whole solar system to more detailed research. The inner planets, the Moon, Mars, asteroids and comets, as well as the outer solar system are now all subject to ongoing or increasing exploration and study. This will continue, with key missions to all these regions. The Artemis programme for return to the Moon, for example, together with the scientific opportunities that new lunar landings and a lunar orbiting Gateway space station present, will be hugely significant. The giant planets and their moons will also return to sharp focus, with current, planned and proposed new missions such as JUICE and Europa Clipper to these bodies. By their nature, such missions are often expensive, requiring heavy launchers, and many years of planning, construction and flight time before they even reach their destinations, thus requiring an appropriately supportive eco-system for the scientists and engineers involved in such work. Indeed, even missions in the inner solar system usually last years. Stop-start support does not work well with such projects.

Moreover, it is not all in space. Sample return missions such as JAXA's Hayabusa1 and 2 and NASA's OSIRIS-REx asteroid missions, and Mars Sample Return (MSR) in 2032, are delivering pristine materials from known locations in the solar system. Increasingly, the study of extra-terrestrial samples will therefore be carried out here on Earth, requiring a network of well-equipped laboratories and sample handling and curatorial facilities. The first stages of MSR have started with the successful drilling into Jezero Crater by NASA's Perseverance Rover. The UK is well placed to contribute both technology (such as instrumentation for analysis within containment) and science advances from MSR. This extends the heritage and ongoing work investigating meteorites, Apollo-era lunar samples, cometary dust captured in space, and suchlike.

Fig 3: *Winchcombe meteorite.* Top: *Footage of the fireball enabled the pre-atmospheric orbit and strewn field of the Winchcombe meteorite to be calculated* (Richard Fleet / UK Meteor Network) Bottom: *A fragment of the pristine Winchcombe carbonaceous chondrite meteorite. The fragment is about 2cm across and has a small patch of brown/ red fusion crust* (Trustees of the Natural History Museum, London).

The strength of the UK in this field was illustrated by the nationwide response to the serendipitous fall of the Winchcombe meteorite in 2021; see figure 3 (King *et al.* 2022). The flight of this body across the UK skies was mapped by the UK's fireball camera networks, aiding not only its rapid recovery, but providing orbital information. Over 120 scientists from around 20 UK institutions then formed teams to study the recovered material, showing the UK's strength in depth in this area.

The third theme, 'Space Plasma Processes', recognises that plasma processes are widespread throughout the solar system and play a vital role in explaining a wide-range of solar system phenomena. Yet, plasmas are subtle in nature and complex to model. Key questions are emerging and being worked on. It is vital to understand how waves propagate in inhomogeneous plasmas, for example, and how turbulence affects plasmas is critical to fully model plasmas in many areas of the solar system. How individual plasma processes can combine is also still to be fully understood. Similarly, how plasmas accelerate charged particles to high, non-thermal energies awaits a fuller elucidation. Beyond plasmas, magnetic fields are of fundamental importance in understanding

Routes to funding

Support for research in this field comes from a variety of sources. In the UK, the STFC is a major source of funding for solar system research. STFC covers several other areas as well as the solar system (e.g. the rest of astronomy and also nuclear and particle physics) and to help its main advisory body (Science Board, **bit.ly/43OPelh**), it has dedicated advisory panels devoted to each area it covers. The advisory panel which covers solar system activities is called the Solar System Advisory Panel (SSAP, **bit.ly/41FbQ5W**). SSAP provides a link from Science Board to the broader community of users, and helps provide input on both general policy matters and specific issues that arise. One thing it does not do, however, is recommend the awards of grants from STFC – that is the remit of the separate Astronomy Grants Panel (AGP), which covers astronomy and all solar system related research. Membership of SSAP varies with time, but is drawn widely from across the UK, covering a range of fields from solar terrestrial physics to planetary science, with experts in analysis of data from space missions, modelling, laboratory experiments, instrument development, etc. STFC panels and committees have regular turnover (typically three-year terms), and new volunteers are regularly sought, and can indeed self-nominate; if you are interested in volunteering, watch out for the next call (for general details of the process, see **bit.ly/3N0uyRo**).

"These are exciting times, with many new space missions underway or planned, backed by laboratory research and computational modelling"

the evolution of many bodies, yet are also poorly understood. At the Sun, why some solar cycles are more dominant than others awaits explanation, with new data expected from the Solar Orbiter spacecraft as it moves to higher solar latitudes. In addition, where planetary magnetic fields exist, their generation and how they are sustained with time (or not in the case of Mars) is a challenge. As more data is obtained over the next decades from a variety of missions to the Sun and planets (in both the inner and outer solar system), there is a need for major advances in modelling of plasmas and magnetic phenomena. These are thus exciting and challenging times in this field.

In addition to the science in the various themes, SSAP also recognised the ever-increasing importance of the working environment. Whilst much of this is dependent upon the universities and research institutions that train PhDs and employ the technical staff, researchers and faculty members, the STFC and UKRI play a broader role in requiring and supporting developments in diversity and sustainability.

Wider context

Inside the UK, STFC is not the only significant player in solar system research. The UK Space Agency (UKSA) also plays an important role. UKSA is the government agency that coordinates UK efforts, industrial and public sector, in accessing and exploiting space. It organises UK space missions and related efforts, and liaises with international agencies. The relationship between STFC and UKSA is therefore of fundamental importance to the scientific community, and SSAP regards keeping this link strong as a major requirement for a healthy research environment.

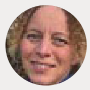
Furthermore, the UK is not a solo act with regard to solar system research. The UKSA negotiates the UK's role in ESA programmes and provides bilateral access to other agencies (e.g. NASA, JAXA, CSA, etc.). In addition to this, many researchers maintain individual relationships with overseas agencies, often holding formal or informal investigator status on space missions. These latter relationships are a testimony to the high international regard in which UK scientists are held, and provide welcome access to cutting-edge data from missions. For example, many UK scientists won access to samples of the Ryugu asteroid under the first general international (competitive) call JAXA held as part of the Hayabusa2 sample return mission. Similarly, there have been a large number of successful UK observing proposals for the Daniel K. Inouye Solar Telescope, with the UK making up 14% of recent successful proposals (the second largest national contribution behind the US). Having funding which can support such a broad-based university community is therefore vital to maintain a thriving, world-leading community.

Conclusions

In summary, the 2022 Roadmap for Solar System Science offers a snapshot of UK solar system research at a moment in time. A large community of researchers is active in the UK, recognised internationally for their excellence. Moreover, these are exciting times, with many new space missions underway or planned, backed by laboratory research and computational modelling. It is clear from the community feedback, and the widespread activities observed by the SSAP members during preparation of this roadmap, that many opportunities exist and are being grasped enthusiastically. There are issues, particularly with funding which is at the core of many of them. However, other issues vital to the health of the UK solar system research community include: how resources are allocated, the relationship between STFC and UKSA and STFC and other UKRI funding agencies, how key national priorities are set, broadening the community to be more representative, and ensuring a community with good morale where individuals can see a positive future and an equal career path. Meanwhile, for more details, read the roadmap itself (De Moortel *et al.* 2022). ●

AUTHORS

Ineke De Moortel (Chair until 31 December 2022; University of St Andrews, Scotland)



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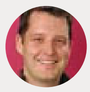
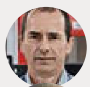


John Bridges (Deputy Chair, Leicester University)



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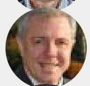

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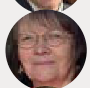
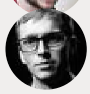


Suzie Imber (Leicester University)

Ashley King (Natural History Museum),

Richard Morton (University of Northumbria)



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SSAP gratefully acknowledges the input and support of the entire solar system community, without which this roadmap would not have been possible. The panel is also very grateful for the support of STFC, particularly Chris Woolford, Michelle Cooper and Colin Vincent in preparing the Roadmap. For the purpose of open access, the authors have applied a Creative Commons Attribution (CC- BY) licence to any Author Accepted Manuscript version arising.

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Improving events for autism

'Welcoming autistic people' is a new free guide, devised to educate and make astronomy events and activities more flexible and accommodating for people with autism. Sue Bowler takes a look.

While eleven of the RAS200 bicentenary outreach projects involve the RAS working with partner organisations on workshops, events and exhibitions, the twelfth project is a little different. The National Autistic Society (NAS) has focused on offering advice to the other RAS200 projects to make events and activities welcoming for autistic people. They have produced a booklet, 'Welcoming autistic people', which counts as a valuable resource for anyone running astronomy events as well as science centres and exhibitions.

"The NAS is here to create a society that works for autistic people, but with more than 700000 autistic people in the UK, we know that everyone needs to play their part," said the organisation's Tom Purser. "Accessibility is vital to make this happen and organisations, activities and venues need to feel confident about how they can be more autism-friendly. Our guide sets out some really practical, low-cost steps that anyone can take to make sure their service is open to autistic people and their families. We hope our guide continues the legacy of the RAS200 project and opens astronomy up to autistic people, now and into the future."

One of the rationales behind outreach is to foster interests that could lead on to satisfying careers; many people with autism have valuable skills, especially for science subjects, yet employment rates are low. This booklet aims to level up access to astronomy and geophysics outreach, with a combination of practical guidelines to help autistic people enjoy events and testimony from autistic people about their experience of the world.

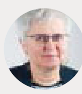
A lack of understanding of autism among the general public is perceived to be one of the greatest barriers to education, employment and enjoyment amongst autistic people. Autism can bring difficulties in communication and interaction, as well as sensitivity to the noise and bright lights that come almost as standard for the modern outreach event or exhibition. But people with autism are frequently well equipped to develop deep knowledge and understanding of specialist areas such as science and astronomy, and a barrier to those skills is a barrier for the sector as a whole.

"Ask autistic participants what they want to make the experience better. One of the most powerful messages you can send is that you are keen to listen, to make adjustments and to welcome autistic people."

It is clear from the examples and guidelines presented in the new booklet that a few simple steps can make our sciences much more accessible for this interested audience. Relaxed performances of planetarium shows, for example, that are easy to leave if need be, are now being provided at some venues. And online guides that focus on what to expect and where to expect it can be useful to manage anxiety before coming to a new venue. Most of all, it helps to make clear that the organisers are open to contact and ready and willing to welcome autistic people.

Overall, the takeaway message of this booklet is that people are individuals, autistic people included, and that the best way to find out what works is to ask people. "Every autistic person is different so there isn't always one single thing that ensures your event or venue is accessible," said Tom. "But I would encourage everyone, after reading our guide, to speak to your autistic visitors or participants and ask what they want to make their experience better. One of the most powerful messages you can send, by asking this question, is that you are keen to listen, to make adjustments and that you want to welcome autistic people." ●

AUTHOR



Sue Bowler is editor of *A&G* and looks forward to seeing these principles at work at RAS outreach events.

Pick up your free copy of 'Welcoming autistic people' from the RAS at Burlington House or contact Education and Outreach Officer Sheila Kanani. It is also available online on the RAS website at **bit.ly/3ULX9vt**

Space on the line

Cameron Patterson explains how, in these days of the complex interdependence of technologies, the Sun presents a decided threat to your train journey – and a great deal more besides

If you were dozing on a long train journey and heard an announcement that your train was delayed due to space weather, would you think that you were dreaming of a problem with the Red Planet Express to Olympus Mons? Or would you just shake your head and add it to the list of eye-rollable railway problems, alongside weather that is too hot, too cold or too wet, the wrong kind of snow, leaves on the line, and so on and so on?

Well, the truth is, space weather isn't some science fiction invented to hike your season ticket price: it affects railway systems around the globe, and I have been studying its effects on railway signalling systems in the UK.

Space weather refers to the physical conditions and phenomena that occur in the space environment, particularly near Earth, that can affect technological systems and human activity in space and on the ground. An important part of space weather is geomagnetic storms, which occur when emissions from the Sun, such as coronal mass ejections (CMEs), disrupt the Earth's magnetic field. These storms can cause power outages, disrupt satellite communications, and lead to misoperations in railway signalling.

The Carrington Event was a massive solar storm that occurred in September 1859. The event caused widespread disruption to telegraph systems, with some operators reporting sparks and fires, and others able to communicate with their power supplies turned off, purely by the currents that were being induced in the telegraph wires by the storm. Auroras were observed as far

Image: Brian Jones/Unsplash

"The electric field generated at ground level during geomagnetic storms can induce a current in the rails that either flow with or against the existing current in the track circuit"

south as the Caribbean; they were so bright that they sparked an argument among gold miners in the Rocky Mountains as to whether it was time for breakfast.

More recently, in March 1989, a powerful geomagnetic storm caused by a CME disrupted power grids in Quebec, Canada. The storm caused a power surge that triggered plant safety systems and over six million people lost power for several hours. While the Carrington event may not have been too damaging in the mid-1800s, today's society depends far more on technology and the risk that severe space weather poses has increased significantly. The potential risk to railway systems comes from electrical currents induced in the ground and in long conductors such as power lines, oil pipelines and railway lines, and the signals that control train movements.

Railway signalling

There are many types of railway signalling systems, but most follow the same basic setup: a train line is split up with insulated joints in the rails to form multiple smaller sections called 'blocks'. Only one train can occupy each block at any time, and various detection methods are employed to let train drivers know if the blocks in front of them are occupied or not. One widely used detection system is the 'track circuit', shown in figure 1. A power supply is placed at one end of the block and a relay is placed at the opposite end, so that currents travel through the rails from one to the other, contained in their block by the insulated rail joints. With no train occupying the block, the power supply energises the relay which displays a green signal to oncoming drivers; when a train enters the block, the conducting wheels and axles cause a short circuit, and the current from the power supply no longer reaches the relay and it de-energises, displaying a red signal. The reason that the default state of a track circuit is the energised state is to act as a failsafe. If there is a malfunction anywhere in the circuit, the relay will de-energise and show the block as occupied, avoiding potential collisions.

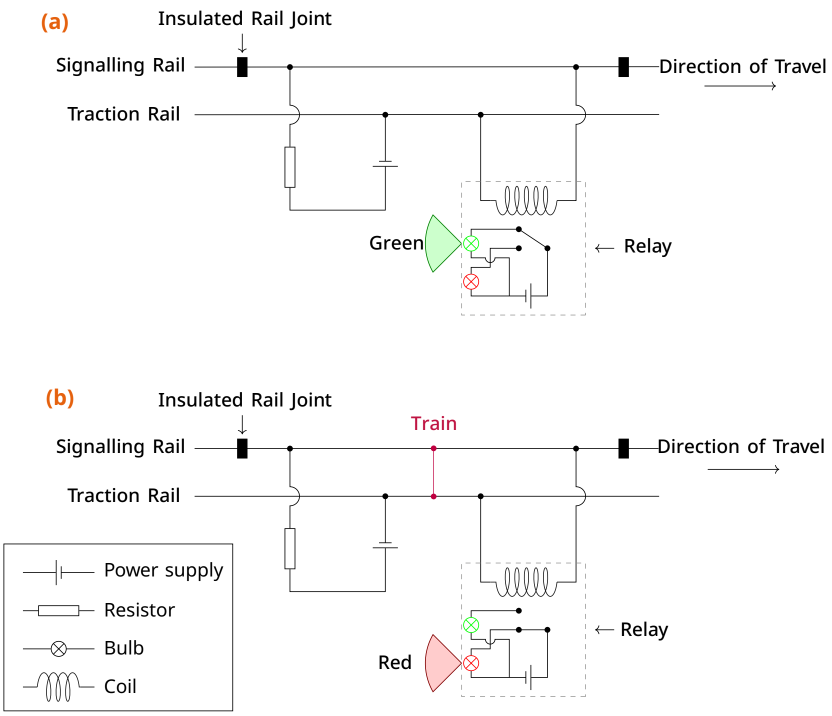
The UK has both unelectrified and electrified railway lines. In the unelectrified case, the insulated rail joints are usually located at symmetrical positions in both rails. This means that the currents induced in both rails from geomagnetic storms are equal, and no induced current will cross the relay, effectively making them immune to interference from space weather. However, in the case of electrified lines using alternating current, there needs to be a continuous path for the current from the overhead lines that power the train to return to the power grid. This is achieved by removing the insulated rail joints from one of the rails (the traction rail), allowing it to carry the current from the train back to the grid to complete the circuit.

This is where space weather enters the picture. The electric field generated at ground level during geomagnetic storms can induce a current in the rails that either flow with or against the existing current in the track circuit, interfering with normal relay operation. These additional currents can potentially de-energise an energised relay, making it seem like the block is occupied when it is not (a right-side failure), or energise a de-energised relay, making the block seem clear when there is a train occupying it (a wrong-side failure). Such failures are called misoperations.

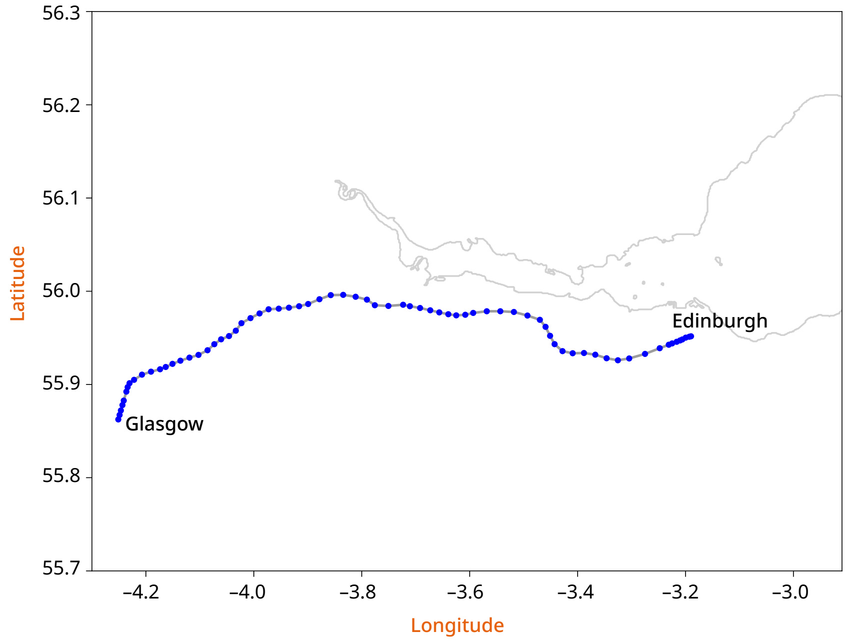
Making models

I have created realistic models of two railway lines in the UK: a north-south orientated portion of the West Coast Main Line between Preston and Lancaster, and the east-west orientated Glasgow to Edinburgh via Falkirk line. In this model, each rail is regarded as a transmission line consisting of series impedances and parallel admittances that correspond to the resistance of the rails and the leakages to the ground, respectively. Subsequently, the transmission line model for each rail is transformed into an equivalent-pi circuit, comprising admittances and current sources, as described by Boteler (2021). The resulting circuits for both rails are then combined with the track circuit relay components to establish a nodal admittance network. Data from Network Rail standards documents were used to ensure the model parameters were relevant to the UK.

In this article, I am only going to discuss the Glasgow to Edinburgh line, shown in figure 2.



1 *Diagram of a railway signalling track circuit.* (a) *shows an unoccupied block. The current from the power supply (left) reaches the relay (right) and energises it, causing a green signal. In* (b)*, the block is occupied. The train is causing a short circuit, current from the power supply no longer reaches the relay, causing it to be de-energised, displaying a red signal.*



2 *Map of the Glasgow to Edinburgh via Falkirk line. The line has been split into blocks, with the dots representing the boundaries of the track circuits.*

For simplicity, I am only considering right-side failures, the case where no trains are occupying any blocks, and the problem is the de-energisation of energised relays. Patterson *et al.* (2023) contains a more detailed explanation of the model and further results not discussed here.

Thresholds for misoperation

To understand what happens to the current through the relays during a geomagnetic storm, first consider the case where there is no geomagnetic activity. In the model, the external electric field was set to zero, so no currents are being induced in the rails; the only currents are those from the power supplies. Figure 3 shows the current through each of the relays along the line. The red (solid) line indicates the 'drop-out current', the value that the current through the relay must drop below to de-energise. The green (dashed) line shows the 'pick-up current', the value the current must go above to energise once again. Under these conditions, all track circuit blocks should be energised, which they are.

As an aside, the gap between the drop-out current and pick-up current is an important factor. If the induced currents in a track circuit force the relay to de-energise, it has to then go above the 'pick-up current' to re-energise. This means that once the relay misoperates, even if the induced currents responsible fall, the misoperation could persist.

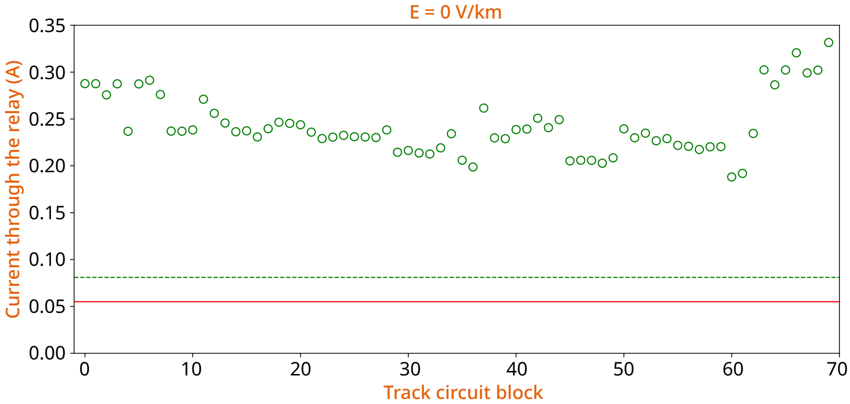
Raising the electric field by 0.1V/km at a time, we are able to pinpoint the threshold at which the first misoperation occurs. In this case, the first relay misoperates when the eastward electric field is reaches –2.8V/km, as shown in figure 4. Based on the results of Beggan *et al.* (2013), an event of this magnitude in the area of the Glasgow to Edinburgh line is expected to occur once every 30 years.

The electric field expected to arise from a 1-in-100-year extreme space weather event is estimated at around 5V/km for the UK. Let's take a look at the what the situation might be on the Glasgow to Edinburgh line under those conditions. Figure 5 shows that a geomagnetic storm of that magnitude would give rise to significant disruption, causing many of the signals across the line to misoperate.

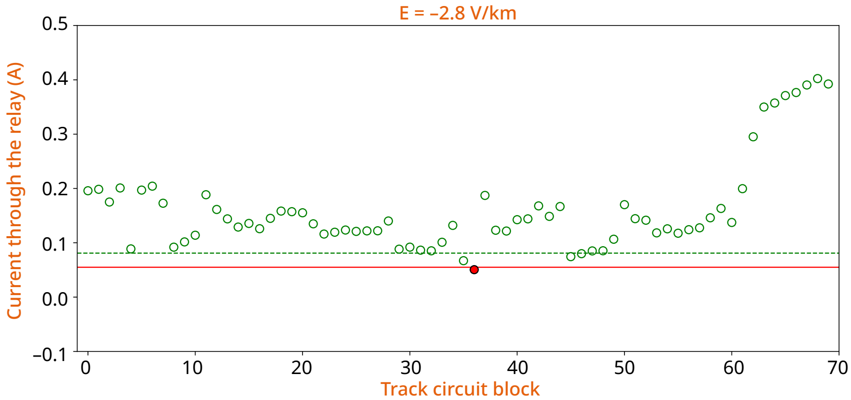
What does this mean for us?

Right-side failures have the potential to be disruptive, but not hazardous. Signal operators would notice the signals turning red without a train occupying the block. As de-energisation is the default failure mode of a track circuit relay, this would present a similar scenario to other faults unrelated to space weather. Trains may be asked to proceed more slowly through the blocks in question, resulting in delays. Passengers should note that space weather seems to affect railway signalling far less frequently than many of the other issues that railway operators face daily.

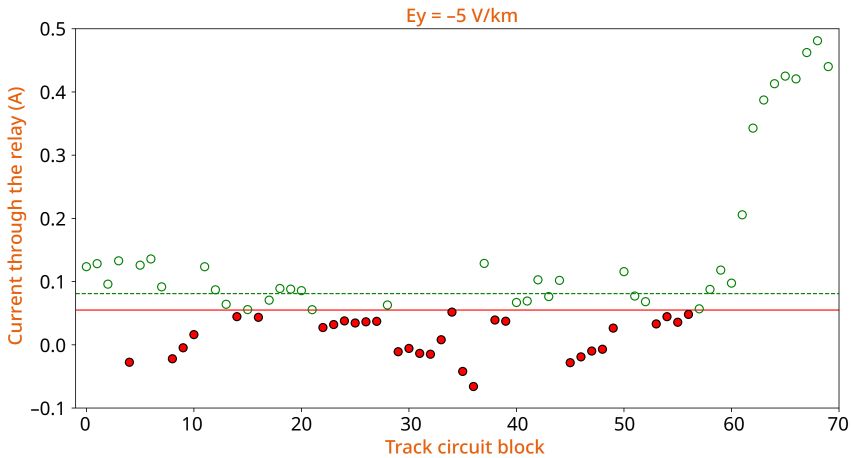
It is also worth noting here that signalling failures would not be the only problem in an extreme space weather event; it is more than likely that power grids, GPS satellites, and radio communication are all going to be affected simultaneously. We are no longer in the 1800s, where a failure in the telegraph system has little impact; the interdependency of the power, communications and transport systems is where the disruptive power of space weather lies. We must continue to research those areas, and ensure that we are prepared for the inevitable effects of space weather. ●



3 *The current through each of the track circuit relays between Glasgow to Edinburgh with no geoelectric field applied. In this and the following figures, green circles indicate the current of each relay, the red (solid) line shows the current value below which the track circuit would de-energise and display an incorrect signal, and the green (dashed) line shows the level that the current would need to rise above to re-energise if de-energised. An unfilled green circle means normal operation, so in this case, all signals show no misoperations.*



4 *The current through each of the track circuit relays between Glasgow to Edinburgh with a geoelectric field of –2.8V/km applied. A filled red circle indicates a misoperation. In this case, we see the first misoperation for the line, at block 36.*



5 *The current through each of the track circuit relays between Glasgow to Edinburgh with a 1-in-100-year geoelectric field estimate of –5V/km applied. In this case, the model shows many misoperations – red filled circles – all along the line.*

AUTHOR

Cameron Patterson is a research student at Lancaster University, UK, working on how space weather affects railway systems. and the Lancaster University Faculty of Science and Technology. This work, presented as a poster, was awarded the Rishbeth Prize at the 2022 National Astronomy Meeting.

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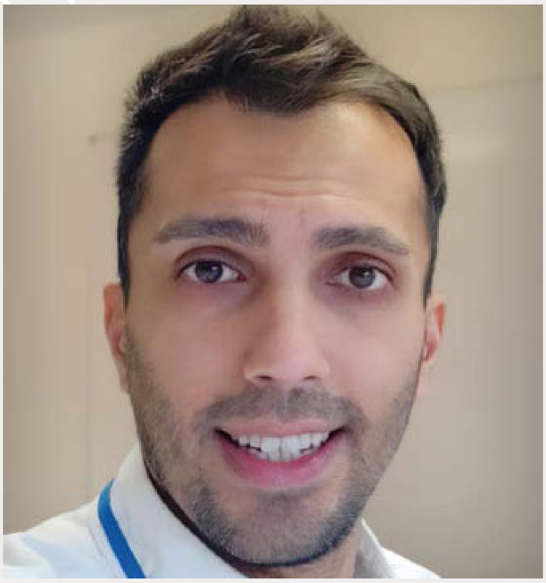
Q&A

Ravindra Desai winner, Winton Capital Award 2022

Sue Bowler talks to Ravindra Desai about the lure of solar physics, building a career and keeping safe on the Moon



Congratulations on receiving the Winton Capital Award 2022! Tell us a bit about your research.
I am an Assistant Professor in physics at the University of Warwick. My research interests span astrophysical plasma physics across the solar system and their intersection with our increasingly space-based society. Specifically, I look at coronal mass ejections and their evolution through the heliosphere and the impacts when they strike the Earth's magnetic field and influence the Earth's radiation belts. These events cause stunning auroral displays but can also damage satellites and knock out communications and power grids.

I love the dual nature of this research area. There are many fundamental questions governing how our star (the Sun) behaves and forms this giant cavity called our heliosphere, and how the Earth's magnetic field similarly forms a protective bubble around our planet that has allowed life to flourish. In studying these fundamental questions, we are however also having direct impact by contributing to the field of space weather forecasting through helping to predict and mitigate the dangers inherent to venturing out into space with our infrastructure and astronauts.

Your work was also recognised with the RAS Higher Education Award 2022.
Over four years at Imperial College London, I supervised over 30 undergraduate and masters student projects. I really enjoyed working with students and designing challenging research projects for them. Multiple students as a result published first author peer-reviewed papers, and went on to doctoral programmes at top institutions across the world. I also participated in the Nuffield research programme which gives students from under-represented backgrounds a chance to gain work experience in a university setting, which I feel is very important to diversifying science.

What got you started in science?
I have been fascinated by space and the vastness of it all since I was very young. In using data from space missions and modelling large-scale systems in space such as our magnetosphere and heliosphere, I feel like I am contributing to the exploration of the universe.

What are you working on now?
I am currently involved in the Lunar Gateway space station as part of the Artemis programme to return humans to the Moon and I am really excited to leverage our scientific understanding to help understand the radiation environment to protect astronauts returning to the Moon.

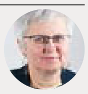
What do you see as the greatest step forward in science over the past century?
Flying satellites and humans into space and across the solar system is for me the biggest accomplishment as this follows on from great terrestrial explorers who first expanded our horizons. These missions further expand the boundaries of the 'world' that we live in and I am really excited to see (and be involved in) humans returning to the moon in the next decade to build a permanent base there.

What scientific question would you most like to see answered in the next century?
I would like to know if there is life elsewhere in our solar system, perhaps on Mars or Venus or within sub-surface oceans on Jupiter's or Saturn's moons. Hopefully in my lifetime we will be able to make significant progress in answering this question! I am hoping the advances we have seen in rocket technologies across the past years will translate into an increased number of scientific missions across the solar system.

What gets you out of bed in the morning?
My two small children are the reason I get up in the morning, and the day wouldn't feel quite right without spending time with them before heading to work. It is definitely a challenge balancing family and academic life but very worthwhile too. In my spare time, I also enjoy sports such as tennis and climbing.

What is the best thing about your work?
I enjoy the challenging nature of research and the opportunity to work with a diverse range of people, from undergraduate students through to professors and people across the world as space physics is a very international field.

And the worst?
Academia can be tough and requires many years of grafting before one can find job security. This I think results in a false emphasis on short-term results. I have recently acquired a permanent position here at Warwick and am very much excited by the foundation that this provides to plan a longer-term research programme. I now plan to scale my research through growing my own research group here. I have students starting this coming academic year and looking forward to the dynamics associated with leading a research team. ●

AUTHOR

Sue Bowler is editor of *A&G*
Ravindra Desai is an Assistant Professor in Physics at the University of Warwick