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MEETING OF THE ROYAL ASTRONOMICAL SOCIETY

Friday 2024 October 11 at $16^h 00^m$
in the Geological Society Lecture Theatre, Burlington House

Mike Lockwood, *President*

Mark Lester, *Senior Secretary*
in the Chair

The President. Good afternoon, everybody. I'm not going to crack any jokes because I have a cracked rib and making myself laugh is a very painful experience. I am not going to chair most of this meeting because getting in and out of one of these seats is going to be awful. Mark Lester has kindly agreed to chair most of the meeting. This is a hybrid meeting and if you are on Zoom you will be muted. At the end of the talks please put any questions you may have in the Q and A and they will be read out by Dr. Pam Rowden. I am now going to depart so I will hand over to Mark Lester.

The Senior Secretary. Thanks, Mike. The first speaker this afternoon is Professor Roberto Orosei from IRA/INAF in Bologna. He is on-line today. He has a long history in space experiments including being a science-team member of *Rosetta* and *JUICE* as well as *Cassini*, *Mars Reconnaissance Orbiter*, *Dawn*, and *JUNO*. He is currently the principal investigator in the *MARSIS* radar on ESA's *Mars Express* spacecraft which provided evidence of the presence of liquid water beneath the surface of the south polar cap on Mars, and Roberto is going to speak about 'Unveiling the interior of the Martian polar caps with radar'.

Professor Roberto Orosei. Mars is a cold desert where temperatures rise above the freezing point of water for only a few hours a day at the equator. The atmosphere is mainly CO_2 and is very thin, with a surface pressure that is less than 1% that of the Earth. As a consequence, the surface is bathed in ultraviolet radiation and cosmic particles that would be deadly for life as we know it. There is ample evidence that things were different in the past, however, as images acquired since the 1970s by probes at Mars show landforms that are obviously related to the erosive action of water, such as rivers and lakes. Scientists studying Mars concluded that there had to be liquid water flowing on its surface in the past, as this would be impossible under the present climate. It has been thus postulated that Mars used to be a much warmer planet, and that water, given the ample evidence of its presence, must have been much more abundant than it is today. This suggested that life could have been possible on Mars, at least in principle.

Determining if life ever arose on Mars, given that its early conditions appear to have been similar to those of the Earth, is the fundamental goal of Mars exploration. Achieving this goal requires an understanding of the history of water, a large fraction of which is thought to have been lost in space over billions of years because of the weak Martian gravity. The lack of a global magnetic field and the resulting erosion by the solar wind further accelerated the loss of the atmosphere, which was probably much denser and capable of warming the planet through a greenhouse effect. If life ever arose on Mars, could it have survived somehow? Where could it be found today? Probably life could survive under current Martian conditions only in the subsurface. Because Mars is a terrestrial planet similar to the Earth, its interior is still warm and heat flowing from it heats the upper layers of the crust. The increase of temperature with depth eventually reaches the point where liquid water might persist in spite of the freezing cold at the surface.

How do we find this water, which would be the starting point for looking for habitats on Mars? A radar instrument, called *MARSIS*, was proposed for the first European mission to Mars, *Mars Express*, at the end of the last century. Radar waves are capable of propagating through solid materials, and this is the reason why we are able to use cell phones in a closed room, for example. The lower the frequency, the greater the thickness of the material that can be passed through by an electromagnetic wave. This technique is routinely employed on Earth for tasks ranging from finding buried pipes to detecting subglacial lakes, such as those discovered under Antarctica's and Greenland's ice sheets. A low-frequency radar orbiting around Mars was deemed capable of detecting water, which is a strongly reflective material at these wavelengths, down to depths of a few kilometres. After *MARSIS*, which is still in operation today, a second radar, called *SHARAD*, was launched a few years later on NASA's *Mars Reconnaissance Orbiter*.

Water on the Martian surface is frozen, and most of it is contained in the two polar caps. The northern one, called Planum Boreum, consists mainly of a geological unit called the North Polar Layer Deposits, or NPLD for short. Layers within the NPLD are made of a mixture of dust and ice in variable proportions. Contrary to what happens on Earth, where polar caps are almost exclusively made of water ice, Planum Boreum is thought to contain a percentage of dust comprised between 5% and 10%. Beneath the NPLD lies another geological unit called the basal unit, which could be the remnant of older, more ancient, and dustier icy deposits. The internal structure of the NPLD, shown in great detail in radar sections, is thought to result from climate cycles determined in turn by the oscillation of the spin axis of the planet. On Mars, in the absence of a large moon, the inclination of the axis of rotation can reach up to 45 degrees. This produces extreme variations of climate and causes changes in the composition of the material accumulating in the polar caps. During periods of high obliquity, the polar caps are exposed to sunlight for extended periods of time and are in fact sublimating, leaving behind a lag deposit of dust. The South Polar Layered Deposits, constituting much of the southern polar cap, have a similar structure but a greater dust content.

Early attempts at identifying liquid water with *MARSIS* were based on the search for very strong radar echoes from the sub-surface, as water is highly reflective at radar frequencies. These first efforts were unsuccessful, however, as alternative explanations for the origin of bright sub-surface reflections could be convincingly presented. After almost a decade of attempts, liquid water was finally identified at a depth of about one-and-a-half kilometres beneath the

South Polar Layered Deposits. Success came only after enabling data downlink without on-board processing, which we could do with great technical difficulty and for very short observations.

Sub-surface liquid water at the poles is difficult to explain, as the mean surface temperature is around 160 K. Even if this value increases with depth thanks to the heat flux from the interior of the planet, it is difficult to imagine that it can go up by more than a few tens of K over one-and-a-half kilometres. There are two factors that can explain the presence of liquid water, however. One is the presence of salts, ubiquitous on the surface of Mars, which can lower the freezing temperature by more than 60 degrees C. The other is a thermally insulating layer in the polar cap. The surface of the south polar cap is covered by dust that could be several metres thick, and we know that a loose dust layer possesses low thermal conductivity.

There is evidence in radar sections that liquid water is also affecting the evolution of the internal structure of the South Polar Layered Deposits, causing deformations in the stratigraphy due to differential ice sliding over dry and wet basal surfaces. Images also reveal morphologies on the surface of the south polar cap that have been interpreted as listric faults, and could again be indicative of differential ice sliding. Such indirect geological evidence for basal liquid water is found also in areas where no strong sub-surface echoes were detected. This could be explained by a change in sub-surface conditions over time, which would have profound implications for the survivability of habitats in the sub-surface of Mars. Although no conclusions can be drawn at this time, this evidence is suggestive of the important role that liquid water played in the evolution of the polar caps, and is begging for further investigation.

The Senior Secretary. Are there any questions in the room, please? We have one on-line at least.

Dr. Pamela Rowden. The question is from someone called P. "Is the pulse-repetition frequency tuneable, for instance, to resolve interference between reflections from different materials and depth layers? Then there is a supplementary question: is it possible to derive the temperature of the ice?"

Professor Orosei. In reply to the second question, the answer is that it is not easy to do from radar data alone. We can only put constraints on the maximum temperature of ice by exploiting the different electromagnetic properties of the materials constituting the Martian polar caps. The polar deposits are a mixture of ices and dust. Water ice, which is by far the dominant component, is very transparent to radio waves below about 220 K, while it becomes increasingly attenuating as temperature approaches the melting point. Another characteristic of water ice is that attenuation is independent of frequency. Attenuation caused by dust, on the contrary, is independent of temperature but increases with frequency. Thus, in a dust–ice mixture, attenuation will be dominated by dust, and thus frequency-dependent, at low temperatures, while it will be frequency-independent when temperature increases above 220 K and water ice becomes the primary factor in determining radar penetration. As *MARSIS* can operate at different frequencies, we have been able to determine that attenuation increases with frequency, allowing us to infer that temperature in this part of the Martian southern polar cap should not exceed 220 K.

The first question is technically an interesting one. It's about the pulse-repetition frequency, PRF in short, and the problem of interferences, which were probably noticeable in some radar sections. Unfortunately the PRF is not tuneable, and thus we can only perform a post-processing similar to the one used in ground-penetrating radar and called migration. In airborne radars the corresponding method is called Synthetic Aperture Radar (SAR) processing, which we are experimenting with on raw *MARSIS* data. We are also working on integrated processing of multiple observations to obtain three-dimensional views of the interior of the polar caps, and perhaps there could be a possibility in the future even to merge data acquired at different frequencies to try and achieve greater resolution.

The Senior Secretary. Thank you, Roberto [applause].

Our next speaker is Dr. Dmitrii Kolotkov from the Centre for Fusion, Space and Astrophysics at the University of Warwick. His research interests span solar and stellar magnetohydrodynamics, non-linear dynamical systems, to helio- and asteroseismology as well as modern techniques for data analysis. He has recently been working on the use of MHD waves and oscillations for advanced seismological diagnostics of a plasma in the atmosphere of our Sun and in the atmospheres of other stars as potential hosts of habitable worlds. The title of his talk is 'What makes waves in the Sun's corona wavy?'

Dr. Dmitrii Kolotkov. Imagine a pond where a stone has just been tossed — ripples spread across the water, revealing the underlying properties of the pond's surface; or a violin string bowed steadily, producing acoustic tones at specific frequencies, which propagate through the air. These are well-known, nice and regular waves, resulting from initially aperiodic perturbations. But what exactly makes such initially aperiodic perturbations (*e.g.*, a stone tossed in a pond or a bow moving steadily across the violin string) to develop into an oscillatory pattern? It turns out that the Sun's corona, the glowing halo visible during total solar eclipses, also behaves much like an elastic and compressible material, responding to initially aperiodic impulsive or steady disturbances with a range of oscillatory motions.

The Sun's corona is more than just a stunning sight during solar eclipses — it is a window into the complex dynamics of the solar atmosphere made of the fourth state of matter, the plasma. Plasma makes up most of the visible Universe, and the Sun's corona is one of the most accessible places to study this state of matter. However, understanding the corona is not straightforward. This outer layer, extending millions of kilometres from the Sun's surface, is home to extreme physical conditions: temperatures above one-million Kelvin, and a very low density, dominated by the magnetic field. It is a natural laboratory where scientists can explore a broad variety of fundamental plasma-physics problems and observe the evolution of plasma and its dynamics almost in a live format. This research also goes beyond academic curiosity; it helps us understand the mechanisms behind solar flares, the most powerful explosions in the Solar System, and their potential impact on space weather, which can affect satellites, power grids, and even astronauts.

The plasma in the Sun's outer atmosphere is highly non-uniform, characterized by a wide range of structures — from coronal loops anchored to the solar surface, massive prominences suspended above the surface, thin current sheets triggering magnetic reconnection and large-scale eruptions, to coronal holes with the magnetic field extending towards the heliosphere. The presence of such plasma structures in the Sun's corona creates conditions ripe for hosting various oscillations and waves — they act as effective waveguides and/or resonators, providing a physical ground for an external perturbation to develop into a periodic or quasi-periodic wave structure self-consistently, *i.e.*, without the involvement of a periodic driver. Waves detected in the corona behave similarly to traditional water or sound waves, but with an important twist — the intricate interaction between the dynamics of electrically conducting gas (the coronal plasma) and electromagnetic fields, described by magnetohydrodynamic (MHD) theory. Notably, the striking similarity between MHD waves guided by coronal plasma structures and dispersive waveforms used in geodynamics and oceanography further exemplifies the effective transfer of knowledge across disciplines and the inherently cross-disciplinary nature of this research.

The study of coronal waves has dramatically evolved with the advent of space-borne observatories that capture detailed images of the solar corona in extreme-ultraviolet light (EUV) with unprecedented clarity and resolution. Since the launch of such space missions as the *Transition Region and Coronal Explorer* (*TRACE*) in 1998, the *Solar Dynamics Observatory* (*SDO*) in 2010, and the more recent *Solar Orbiter* (*SolO*) in 2020, our observational capabilities have improved significantly — from approximately 360 km per pixel every 75 seconds up to about 100 km per pixel every 2 seconds. For instance, the new-generation EUV imager on-board the *Solar Orbiter* mission can discern features in the Sun's corona as small as about 100–200 km (relative to the solar radius of about 700 000 km) every few seconds. Given that the characteristic spatiotemporal scales of coronal waves range typically from a thousand kilometres (a megametre, Mm, traditionally used in solar physics) to a few hundred thousand kilometres (hundreds of Mm) and from a few seconds to several tens of minutes, these waves can perhaps be regarded as the longest electromagnetic waves in the Universe that are fully resolved both in space and in time. Specific data-analysis techniques such as the time–distance analysis allow researchers not only to reveal the presence of waves but also to track their evolution over time as they propagate through the corona, measure characteristic parameters such as the oscillation period, damping time, apparent propagation speed and direction, *etc.* By comparing these observed wave parameters to theoretical models, scientists can better understand the physical conditions of the Sun's atmosphere, perform remote sensing of the coronal plasma, which is known as the original method of MHD coronal seismology — much like how seismic waves are used to probe the Earth's interior.

The phenomenon of quasi-periodic pulsations (QPPs) in solar and stellar flares represents another, indirect manifestation of waves and oscillations in coronal active regions, when observations with advanced spatial resolution are not available or are highly limited (which is especially relevant for stellar observations). QPPs are seen as patterns of repeated fluctuations in solar-flare radiation, usually short-lived, that hint at the presence of waves, although the exact QPP-formation mechanisms are yet to be revealed. Detected in the majority of flare events on the Sun, QPPs offer a way to probe the extreme physical conditions in flares, acting like a cosmic stethoscope that listens to the solar atmosphere's heartbeat. Their presence has even been detected in flares on other stars, suggesting that similar physical processes might be at work across the Universe, offering a potential bridge between solar and stellar studies. This connection between the Sun and other stars has far-reaching implications. For instance, understanding the dynamic processes in stellar flares through the prism of QPP and, more importantly, decoding the unique seismological information about stellar-flare plasma, carried by QPPs, could shed light on how these stars influence their surrounding planets. Such research is crucial for exploring exoplanets, especially those orbiting stars with intense flare activity that might affect habitability.

In conclusion, the waves in the Sun's corona are not just an interesting quirk of solar physics — they are key to understanding the fundamental physical problems of our Sun. From ripples on a pond and violin-string oscillations to electromagnetic waves in space, the universality of the wave theory as an overarching principle in physics, combined with careful observations and advanced theoretical modelling, help scientists unlock the secrets of solar activity and use it as a test-ground extending to other stars and the broader Universe.

The Senior Secretary. Thank you, Dmitrii. Are there any questions?

Dr. Ziri Younsi. One thing I couldn't help but notice was the mathematical form of your density solution. Those videos which show your simulations look awfully like solitons where there is a beautiful balance between non-linearity and dispersion. I wonder if you think that they are just solitary waves where the scale height of the medium shrinks over time?

Dr. Kolotkov. The wave phenomena discussed in this talk are mostly linear, and the generalized symmetric Epstein profile (determined by sech^2 indeed) is used for modelling the initial equilibrium density profile only. Similar waveguide profiles are used for modelling wave propagation in optical fibres, for example. For fast-mode MHD waves in solar coronal waveguides, the development of non-linearity is generally suppressed by strong geometric dispersion. However, large-amplitude standing kink oscillations of loops may manifest non-linear effects *via* Kelvin-Helmholtz instability (*e.g.*, formation of vortices and smaller scales). For slow-mode waves, the waveguide dispersion is less pronounced, which, in general, can result in steepening, but waves dissipate faster usually. The non-linear Schrödinger equation and Burger's equation are usually used for describing the propagation of weakly non-linear MHD waves in the corona.

Dr. Younsi. That solution is actually an analytic solution for the Korteweg–de Vries equation. If you did a non-linear analysis do you think that the density perturbations would be a solution of that?

Dr. Kolotkov. This is an equilibrium form. We did a non-linear analysis but it does not result in solitary solutions. Sometimes we model this in terms of Burger's equation where we observe the steepening of the wave. The beauty of solar physics is that it allows for the direct comparison of the analytical solution with observations.

Professor Eric Priest. What do you think is the nature of the quasi-periodic pulsations that you mentioned?

Dr. Kolotkov. In short, these are indirect signatures of waves and oscillations discussed today in flare-hosting active regions. We currently consider over a dozen specific mechanisms of how those oscillatory processes can modulate the flare electromagnetic emission (in different bands) and result in QPP, the detailed discussion of which would require a dedicated lecture.

The Senior Secretary. Thank you again [applause].

The final speaker this afternoon is Dr. Jan Röder who started his journey in physics and astronomy at Goethe University in Frankfurt where he worked on neutron stars and numerical simulations of radiative transport in exotic black-hole space-times. Afterwards he moved to the Max Planck Institute for Radioastronomy in Bonn, becoming a radio astronomer, and he recently completed his PhD. Congratulations! His interests are in the theory and radio observations of relativistic jets in AGN from event-horizon scales to extended jets. His talk is entitled 'A multi-frequency study of sub-parsec jets with the *Event Horizon Telescope*'.

Dr. Jan Röder. [Active galactic nuclei (AGN) are among the most powerful sources of energy in the Universe. In the direct vicinity of the supermassive black holes at their centres, hot plasma forms an accretion disc, from which highly collimated outflows are launched — relativistic jets. Moving with close to the speed of light, they can extend hundreds, or even thousands of light years into interstellar space. They have been subjects of active research for decades, and our understanding of the inner workings of AGN and jets has since been gradually advancing. With the *Event Horizon Telescope*, a global network of radio telescopes, we are able to study AGN jets at micro-arcsecond spatial resolution, close to the central black hole. In combination with observations at lower frequencies, we can test the established models of jets from the extended kilo-parsec structure, down to sub-parsec scales near the launching region.] [It is expected that a full summary of this talk will appear in *Astronomy & Geophysics*. — Ed.]

The Senior Secretary. Thank you, Jan. Questions?

Reverend Garth Barber. Many jets are just single and often that is because the opposite jet is hidden in some sense. Would you say that the jets are always in pairs, going either way?

Dr. Röder. Yes. The reason we see one side of the jets is because they are beamed. One side gets Doppler-boosted away from us — it gets Doppler-boosted so much that we just don't see it at most viewing angles. When you compare the geometry of a given jet across a range of scales you could, for example, see a one-sided jet at large scales and as you zoom in, you might have some change in viewing angle. You may then have a twin-jet system appear. Intrinsically, however, jets are always launched both ways from the black-hole accretion-disc system.

Professor Phil Charles. That was a great description of VLBI and how it all works but one thing you didn't mention is that there is an inherent assumption in there that the structure of your source remains constant during the time that you are compiling the data for the image. We know that Sgr A* does frequently have significant variations over a much shorter timescale so would you like to comment on that? Surely you are looking at an average process?

Dr. Röder. First, Sgr A* was not in this sample: we looked at AGN, and Sgr A* is Galactic. As for the variability, some sources do indeed vary more than others and the big surveys taken in single epochs may not reflect the typical state of a given source. On top of that, the higher you go in frequency the higher the variability in source geometry (typically). This is why we try to focus on the property of the cores, because this is something that over a larger time period remains robust. You are completely correct that many jets can undergo big variations over a matter of weeks, and we are prone to a systematic uncertainty based on source variability. It is discussed in more detail in the paper.

Professor Mike Cruise. The orange doughnut has become iconic. Could you say something about the pixel size on that picture of the orange doughnut and the resolution of the whole telescope array?

Dr. Röder. I'll take the last question first. There is a famous analogy that we have the resolution to see an orange on the Moon — that is about 20 μas on the sky. As for the pixel, that depends on the algorithm used to reconstruct the image from the data, so one sets the pixel size in many methods you use. The *EHT* images are about 200 μas in size. I believe they use 128 and 256 pixels per image. I was not yet in the collaboration when the first image was published. Ziri — do you know what was used initially for the reconstruction?

Dr. Younsi. Sixty-four to 128.

Professor Cruise. I thought I had read in the original paper that the image of the doughnut was a simulation not a reconstruction. Have I got that wrong?

Dr. Röder. It was surely a reconstruction from real data, from different algorithms. The theory component that came with the first few papers compared the images that were created to simulations, in order to extract physics from them. The doughnut is real — it exists.

Professor Mike Edmunds. You were telling us about the Blandford chemical model with $1/r$ and $1/r^2$ for tangential and parallel components. If you have an accelerating flow what would it do? Presumably people have modelled it since 1977?

Dr. Röder. That is true but I couldn't say off the top of my head.

Professor Edmunds. We can work it out. If the thing is accelerating then you are going to lower densities essentially; does the magnetic field just go with the density?

Dr. Röder. I would assume that it is not necessarily tied to the particle number density; if everything stretches out then it will also dissipate faster, I would guess.

Professor Edmunds. I'm just surprised that there isn't a modelling that has done that.

The Senior Secretary. Are there any other questions? Thank you very much again for an excellent talk [applause]. It just leaves me to give notice that the next A & G Highlights meeting of the Society will be Friday, November 8th at 4 pm and I believe it will be here. Finally there is a small drinks reception in the Council Room immediately after we finish and you are all welcome to attend. Thanks very much again to all our speakers and questioners.

REDISCUSSION OF ECLIPSING BINARIES. PAPER 23: THE F-TYPE TWIN SYSTEM RZ CHAMAELEONTIS

By John Southworth

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RZ Cha is a detached eclipsing binary containing two slightly evolved F5 stars in a circular orbit of period 2·832 d. We use new light-curves from the *Transiting Exoplanet Survey Satellite* (*TESS*) and spectroscopic orbits from *Gaia* DR3 to measure the physical properties of the component stars. We obtain masses of $1{\cdot}488 \pm 0{\cdot}011\ M_\odot$ and $1{\cdot}482 \pm 0{\cdot}011\ M_\odot$, and radii of $2{\cdot}150 \pm 0{\cdot}006\ R_\odot$ and $2{\cdot}271 \pm 0{\cdot}006\ R_\odot$. An orbital ephemeris from the *TESS* data does not match published times of mid-eclipse from the 1970s, suggesting the period is not constant. We measure a distance to the system of $176{\cdot}7 \pm 3{\cdot}7$ pc, which agrees with the *Gaia* DR3 value. A comparison with theoretical models finds agreement for metal abundances of $Z = 0{\cdot}014$ and $Z = 0{\cdot}017$ and an age of 2·3 Gyr. No evidence for pulsations was found in the light-curves. Future data from *TESS* and *Gaia* will provide more precise masses and constraints on any changes in orbital period.