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MEETING OF THE ROYAL ASTRONOMICAL SOCIETY

Friday 2023 November 10 at $16^h\ 00^m$
in the Geological Society Lecture Theatre, Burlington House

MARK LESTER, *Senior Secretary*
in the Chair

The Chair. Firstly, I have apologies from the President who is unavoidably delayed by floods somewhere between here and the Principality, so unfortunately you have myself, the Senior Secretary, to chair the evening session. This is a hybrid meeting; questions can be asked at the end of the lecture, but you will be muted, so please use the chat facility. Your questions will be read out by Dr. Pamela Rowden, RAS Editorial Assistant.

The first talk will be given by Dr. Beatriz Sanchez Cano from the University of Leicester who was the recipient of the Fowler Award for 2021. Dr. Sanchez Cano is an STFC/Ernest Rutherford Fellow and Lecturer at the University of Leicester working mainly on planetary–solar-wind interactions. Beatriz did her PhD in Spain at the Universidad Complutense in Madrid. She has spent several long research stays at the European Research and Technical Centre (ESTEC) of ESA in the Netherlands and at the Abdus Salam Centre for Theoretical Physics in Italy. She moved to Leicester in 2014 as a PDRA where she became an academic member in 2021. The title of her talk is 'Mars' ionosphere — from our current knowledge to the future of Mars exploration'.

Dr. Beatriz Sanchez Cano. The Martian space environment is a complex system in which strong couplings occur between the solar wind, magnetosphere, ionosphere, and atmosphere. For planets such as Mars without a global intrinsic magnetic field, the ionosphere is the conducting layer embedded within the thermosphere and exosphere that is mostly the result of solar extreme-ultraviolet (EUV) photoionization. Furthermore, it is also the layer that connects the neutral atmosphere with space and acts as the main obstacle to the solar wind. The solar wind interaction with the ionosphere is, therefore, a critical factor for understanding atmospheric evolution of unmagnetized or nearly unmagnetized planets.

This talk focusses on our current knowledge of the Martian ionosphere, how it is affected by space-weather activity, and how it compares to other planets. Mars is special in the sense that it has interaction with the solar wind because it possesses crustal magnetization in its surface that directly interacts with the solar wind. Moreover, orbital eccentricity, together with the 11-year solar cycle, are the dominant long-term factors that model the behaviour of the system, which is strongly affected by sudden inputs of energy from solar transient events, such as coronal mass ejections, which are known to affect space. Some of the most obvious effects are displayed in the form of Martian aurorae, of which four different types are currently known: a discrete aurora over crustal-field regions, a sinuous aurora, which is similar to the discrete aurora but often far away from crustal fields, a diffuse aurora that occurs after space-weather activity, and a proton aurora in the day-side produced by solar-proton impacts in the atmosphere. However, other phenomena also occur during space-weather activity that are allowing us to advance in the understanding of the ionospheric reaction to different space-weather events during different phases of the solar cycle, both from the data analysis and ionospheric-modelling perspectives. This is the case of radio blackouts observed at Mars by the current two radars in operation, which stop receiving signals from the surface of Mars during those events. These are direct space-weather effects, which are produced by radio-signal absorption in the lower ionosphere of Mars (~ 70 km) and are the result of new ions found there (where typically there are not many) produced by the space-weather event. This is key research at the moment since it has strong implications for planetary exploration as it affects current technology deployed on the planet.

Our knowledge of Mars as a coupled system comes from near three decades of continuous exploration, which has opened the door to the understanding of the Martian space environment as never before for any other planet than Earth. However, this knowledge is very limited as it comes from isolated observations of different parts of the system taken with different instrumentation. The future of Mars exploration needs to have a full scientific characterization of the plasma environment, which is essential to understand the radiation reaching the surface of Mars, and that can only be done with simultaneous and co-ordinated observations of the different regions of the planet. This is why the community, led by myself, is proposing a mission to Mars named *M-MATISSE* (*Mars Magnetosphere ATmosphere Ionosphere and Space weather SciencE*) to the European Space Agency in its so-called Medium class (M7), which is currently in Phase-A of the competition.

Understanding the fate of the ionosphere, as a natural sink of both internal (*i.e.*, atmospheric cycles) and external (*i.e.*, solar wind) energy inputs, is the key for a successful future systematic exploration of Mars.

The Chair. Speaking as someone who is directly interested in this mission, you can't bring it forward, can you?

Professor Marina Galand. Thank you very much for a very interesting talk. Can you say more about the mission, what kind of plasma and particle instruments you have? Is there also any instrument covering the UV, for example?

Dr. Sanchez Cano. It is a full plasma mission. It is actually based on experience from NASA's *Mars Atmosphere and Volatile EvolutioN* (*MAVEN*) mission but the problem with *MAVEN* is that it is just one satellite. At the moment it is not sampling the solar wind so it is extremely difficult to do the science that we wanted to do. That is the motivation for our mission. We start out with exactly the same instrumentation; we have six instruments and two of them actually have sub-instruments. They cover the neutral atmosphere from the surface up to space and also cover the ionized part of the atmosphere from the lower part of the ionosphere at about 70 km up towards space. For the first time we have an electric-field sensor, and it will be amazing to understand the currents at the planet which we couldn't have done before. Unfortunately there is not an IERS instrument, but there is an all-round camera in visible light and there are also instruments for all energies of ions and electrons. I believe we have covered all of the energies for the key types of particles as well as the fields and also we have a camera for dust. This will allow us to do meteorological studies in the future if people are interested in that.

The Chair. Any other questions in the room?

Mr. Horace Regnart. If anyone were foolish enough to suggest that tax cuts were a better option than funding your research, would you point out to them the costs and benefits of understanding the risk to telecommunications that follow from not understanding the sort of work that you and your colleagues are doing.

Dr. Sanchez Cano. This is a question which comes up quite often. It may sound like a lot of money to invest but it is not when considering the amount of benefit that we get. In the technology sector, the medical sector, even in the human sector, we can learn a lot about the human body by trying to protect cells in an environment such as this one. For me it is a full benefit for society, and I hope that everyone can see that.

Professor Kathy Whaler. I wonder if there are lessons for the terrestrial environment as the field strength here is weakening, particularly over the South Atlantic; does the fact that we have such a dense atmosphere compared to that of Mars make the comparisons not so useful?

Dr. Sanchez Cano. Venus has a similar interaction to that of Mars but the atmosphere of Venus is much, much denser than that of Earth. It has the same interactions as Mars, the same atmospheric escape, even if it is not as dense. The magnetic field of Earth is getting weaker because it is in the process of inversion so there will be a point when the magnetic field will reach a point similar to that of Mars. We know that in the past Mars had a field like Earth — we see the magnetization at the surface which came from a dipole which formed thousands of years ago, but something happened to the planet possibly as the result of a meteorite impact which stopped the dynamo inside the planet. We don't know what will happen to Earth but it is good to learn how the bodies close to Earth have evolved in the inner Solar System so we can apply the lessons to Earth. If the magnetic-field strength reduces to the level of that of Mars, at least we know what we are going to find. We have an excellent laboratory in the Solar System and we should do all we can to exploit it.

The Chair. Nothing online? In that case can we thank Beatriz again? [Applause.]

Our next presentation is to be given by Dr. Elizabeth Watkins from the University of Manchester. She received her PhD in astronomy at Cardiff studying the impact of stellar feedback in the star-forming molecular clouds in the Milky Way. She continued studying stellar feedback during her first postdoctoral position at the University of Heidelberg. While there she moved on to studying feedback on much larger scales in nearby galaxies, focussing on observing and identifying super-bubble regions of hot gas. She currently works at the University of Manchester where she is comparing simulations of stellar feedback with observations, to understand better how feedback benefits molecular clouds and the star formation within galaxies. The title of her talk is 'Characterizing (super) bubbles in nearby galaxies'.

Dr. Elizabeth Watkins. Without the light that stars produce, we are unable to understand the Universe around us. Therefore investigating how stars form from the interstellar medium (ISM) within galaxies, and the processes that regulate this star formation, is an important field of astronomical research. Super-bubbles are hot, expanding regions of ionized gas that sweep up the surrounding ISM into a shell and are driven by the winds and supernovae (*i.e.*, stellar feedback) from young stars. Studying these bubbles is therefore one way we can chart the interaction between stellar feedback and the ISM, and the larger galactic flows needed to regulate star-formation processes globally. The first *JWST* observations of nearby galaxies (<30 Mpc) unveiled a brand new (and breathtaking) view of galactic structures rich with bubbles in exquisite detail. These bubbles finally showed the extent to which young stars shape their galaxies. *JWST* and *ALMA* are providing novel constraints on bubble populations and stellar-feedback physics, which has an impact on the clouds and molecular gas from which stars form.

Using *JWST* data observed for a *JWST*-Cycle-1 Treasury Programme, I presented the first extensive extragalactic catalogue of these bubbles in NGC 628 at high resolution (12 pc) and statistically evaluated their characteristics. The catalogue contains 1694 bubbles with radii between 6–550 pc. Of these, 31% contain at least one smaller bubble at their edge, indicating that previous generations of star formation have a local impact on where new stars form. With 1694 bubbles found in a single galaxy, we can expect to find up to 500 000 bubbles in total from *JWST*-Cycle-1 and now Cycle-2 Treasury Programmes that will cover 90 galaxies. To find these bubbles, future plans include the development of automated algorithms, machine-learning techniques, and citizen-science projects. This work has been published in the *Astrophysical Journal Letters* as part of a *JWST* special edition in 2023.

To quantify the feedback energetics on the star-forming gas, we have created the largest molecular super-bubble catalogue found to date within nearby galaxies using ^{12}CO (2–1) observations. Since stars form from molecular gas, using it to find super-bubbles allows us to trace the exact impact stellar feedback has on star formation. However, molecular gas, such as ^{12}CO, is quickly destroyed by young stars, and so molecular super-bubbles do not get very big before they are no longer detectable in ^{12}CO. This means we need high resolutions and large mapping areas to investigate a statistically significant sample of molecular super-bubbles. With 90 galaxies observed in ^{12}CO at about 100-pc resolution as part of the 'Physics at High Angular resolution in Nearby Galaxies' (PHANGS)-*ALMA* large programme, we finally have the means to undertake such a study. Focussing on 18 *ALMA* galaxies with co-spatial *HST* and *MUSE-VLT* observations, I catalogued 325 super-bubbles with radii between 30–330 pc and expansion velocities of about 10 km s^{-1}. By focussing on a subset of these that have clear super-bubble signatures (unbroken shells, *etc.*), we can leverage the kinematic information available with ^{12}CO along with the stellar information available with *HST* to constrain the feedback processes driving the super-bubbles. The two datasets together show that most molecular super-bubbles are driven by the kinetic push from supernovae, and rather than dispersing and destroying molecular gas, I find that the gas is swept up into a shell that grows over time. Therefore, molecular super-bubbles can potentially form stars in their shells rather than inhibiting star formation, matching what I observed in the higher-resolution *JWST* observations for the NGC 628 bubble catalogue. This work has been published in *Astronomy and Astrophysics* in 2023.

The Chair. Any questions from the audience?

Dr. Quentin Stanley. It must be very exciting to see all those images, as you say. Can you say how you manage to spot those bubbles manually — there still seem to be a lot of areas that are still dark?

Dr. Watkins. I use a combination of three wavebands. It is basically an *RGB* image. I use red from *JWST*, and it needs to be co-spatial with H-alpha which shows that ionized gas is powering the bubble. I also have to check if there is any blue light which is tracing the young stars in the centre. If I had all three of these co-spatial — that is how I found the bubbles. They tend to be quite round and obvious to the eye. It is subjective, but we did get other people to do this and we found that even if we had slightly different bubbles, we got the same results.

Professor Steven Searjeant. Really nice talk. Finding all of those bubbles is an heroic effort.

Dr. Watkins. No, it wasn't really. I enjoyed it — I love monotony! [Laughter]. It was so much more relaxing than writing applications for telescope time.

Professor Searjeant. There are numerical simulations of spiral discs. I guess they are of similar quality to this, so have you eyeballed simulated data to see if this overlap of bubbles is what is going on?

Dr. Watkins. It's funny that you should ask that. We are trying to do citizen-science projects like Zooniverse to find bubbles. We do have some simulated galaxies and some of them do look quite similar to NGC 628, the Phantom Galaxy, and we are going to put a couple of them in to test. The problem with simulations is how the energy is injected — it's totally different. They inject it at different scales and if they do it like a single super-bubble they model it with those different models that I was talking about, but not all of them follow that model. They are simulations, but how they work is a bit different.

Dr. Pamela Rowden. This question comes from Ki-sha Kwok. "May I ask how the public can find these data too?"

Dr. Watkins. You have to go to the Mikulski Archive for Space Telescopes (MAST); typically they have their own reduction. The reduction we have done is much better and we will be making our reduction public. I know that you can definitely get the raw data from MAST at the Space Telescope Science Institute (STScI). If you can't find it please feel free to e-mail me or people in PHANGS — you can even e-mail the STScI and they will help you.

Dr. Rowden. This is a question from Julian Sylvester-Summer. "Would machine learning be a promising approach to finding bubbles in galaxies, instead of eyeballing?"

Dr. Wilkins. There are a few things being done right now. One team wants to get the citizens involved, another team has been writing algorithms to find bubbles automatically. Machine learning is great but what I did is not scaleable to 90 galaxies, but because this is a new field, it had to be done by a human first. To do machine learning we would have to find more bubbles than this to get a good sample so that when we have more galaxy data we can feed that in. Machine learning is one of those things that we will use because there are potentially 500 000 bubbles.

A Fellow. I have to ask the physics-uncertainty question which is how sure are you that there are not 1695 bubbles?

Dr. Watkins. I could have kept going. When we got other people to do this work we had to get them to check that what I did is not based on human bias, so two other people bravely volunteered and they each found only 800 bubbles. They did not go to such small scales as me. Below 30 pc they are not complete. For all the large bubbles, we all found the same bubbles. There will be bubbles that I perhaps got wrong or missed, but it doesn't matter as we have enough statistically.

The Fellow. It would be interesting to see what AI did.

The Chair. I know that this is a very interesting topic but I'm afraid that we are going to have to call it a day on the questions. One more on-line. I'm glad that *Hubble* is still involved. All I would say is that it gives a whole new meaning to the term 'Hubble bubble' [laughter].

Dr. Watkins. HST is still being used and is still oversubscribed. It has been vital for the work that we do.

Dr. Rowden. John Alderson is asking how does bubble size and number correlate with star formation in terms of mass per year?

Dr. Watkins. The size of the bubble is a mixture of the pressure pushing out to the galaxy pressure holding it in. The pressure pushing it out is related to the star-forming (SF) rate. A higher SF rate leads to more bubbles and those bubbles can have a different size distribution. How we find the theoretical number of bubbles is a mixture of how long we can physically see the bubble, the average mass of the cluster, and then the SF rate. All of that gives you the prediction, so SF is a key number when working out how many bubbles to expect.

The Chair. Thank you, Elizabeth [applause].

Now we have the James Dungey Lecture and I'm delighted to say that here to present it is Marina Galand, Professor in Planetary Science at Imperial College London. Her principal research interest is the study of planetary atmospheres and cometary comae. She has investigated the deposition of solar and auroral energy in atmospheres throughout the Solar System and beyond, using sophisticated, state-of-the-art kinetic and fluid models that she has developed and adapted to new environments. She has undertaken this modelling activity in close links with space missions such as *Cassini*, *Rosetta*, *Ariel*, and *JUICE* and is leading the magnetometer on probe *B2* in the *Comet Interceptor* mission. She has been awarded the Ferdinand Holweck Medal and Prize of the Institute of Physics (IoP) and the Société Française de Physique (SFP) for her research and is actively involved in outreach to stimulate the public's interest in space science and to inspire the next generation.

Professor Marina Galand. I would like to thank the RAS very much. I was extremely grateful to have been awarded the James Dungey Lecture. The first one was ten years ago to celebrate Jim's 90th birthday. He is no longer with us, but this year we celebrate his centenary.

Jim Dungey was an amazing scientist. He pioneered many fundamental concepts in space physics, and more especially in the solar-terrestrial coupling, and he had the idea of the open magnetosphere to describe the interaction of the solar wind with the Earth, with reconnection on the day-side and night-side of the Earth — the so-called Dungey cycle. He was first to recognize that the Earth's radiation belt has an external source. He was a modeller and followed space missions closely. He also highlighted the importance of the ionosphere about which I am going to talk today.

Today I will be focussing on the energy deposition yielding the formation of the ionosphere. Consider a neutral species in the atmosphere — say N_2; then solar extreme UV (EUV) photons and energetic electrons can ionize the atmosphere leading to the formation of ions and electrons, hence a plasma that we call the ionosphere. This layer is critical in linking the atmosphere to the space environment of the Solar System body considered. This plasma can interact with dust or macroparticles and in the case of Titan it can lead to a complex organic factory. This ultimately leads to prebiotic chemistry on the surface of Saturn's moon.

To probe the ionosphere we can send rockets (100–1000-km altitude) and planetary probes but it can also be probed remotely. The energy sources which lead to the creation of the ionosphere can also excite the neutral species. Eventually there has to be de-excitation which can occur through radiation decay which leads to the production of a photon. The emitted radiation can be analyzed spectroscopically in order to learn about the source process and these atmospheric regions. I have been developing and applying models throughout the Solar System to assess how the energy is deposited and redistributed in the atmosphere and how the ionosphere is formed, transported, and lost, using a kinetic and fluid approach. I have combined data from different types of instrument from a given space mission with physics-based models in order to enhance the science return.

I would first like to concentrate on the magnetosphere–ionosphere coupling, as Jim Dungey was the first to highlight its importance in solar/terrestrial coupling. One of the consequences of this coupling is auroral emission by which Jim Dungey was fascinated.

The ionosphere is a layer of plasma in the atmosphere. How does magnetospheric/ionospheric coupling at Earth compare to the one at Ganymede? Ganymede, one of the Jovian moons discovered by Galileo, is the largest moon in the Solar System, larger than Mercury. It has an icy crust — on the day-side the atmosphere is formed from thermal sublimation and in the polar regions there are bombardments by energetic particles which lead to sputtering of the moon's surface. The sputtering leads to the release of water, O_2, and H_2. Solar radiation can then ionize the neutral species in the thin atmosphere which leads to the formation of the ionosphere. How does this differ from Earth? Compare the profile of the electron density with altitude: at Earth the ionosphere is typically above 80 km, whilst at Ganymede it extends down to the surface because the underlying neutral atmosphere is very thin. A similarity is the presence of an internal magnetic field — Ganymede is the only known satellite in the Solar System to generate one. It seems that the core is liquid metal which is producing the field through dynamo action. Whilst the ionosphere on Earth is the inward boundary of the magnetosphere, at Ganymede the ionosphere is produced within the magnetosphere and these two regions are intrinsically coupled. Whilst Earth is immersed in a super-magnetosonic solar wind, Ganymede is located in the magnetosphere of Jupiter which is sub-magnetosonic. At Earth the super-magnetosonic flow leads to a bow shock whilst at Ganymede the interaction of a subsonic magnetospheric flow with magnetic-field lines leads to Alfvén wings. A surprise on Ganymede is that most likely 100 km below the icy crust there is an ocean. This ocean experiences a changing of Jupiter's magnetic field; this produces a current which in turn gives rise to a magnetic field and it is this induced magnetic field that the magnetometer onboard *JUICE* will try and detect in order to characterize the subsurface ocean.

To summarize, the magnetosphere around Ganymede is quite complex. There are closed magnetic-field lines going from footprint to footprint on Ganymede whilst at high latitude you have open magnetic-field lines with a footprint on Ganymede and the other end at Jupiter. The co-rotating plasma with Jupiter goes much faster than the moon; the magnetospheric tail is in front of the moon.

There are only two close fly-bys of Ganymede by the *Galileo* spacecraft to provide data on the ionized layer below 2000-km altitude. Recently *Juno* did two fly-bys of Ganymede, one of which was close, but *Juno* will not be able to return to Ganymede. To study Ganymede's plasma layer we need to use modelling, so one of my PhD students, Gianluca Carnielli, developed the first 3-D model of

Ganymede's ionosphere. Solar EUV and energetic electrons ionize the neutrals leading to the production of electrons and ions. The modelling simulates the transport of ions through the electric and magnetic fields once the ions are produced by ionization. The ions can also undergo charge exchange with atmospheric neutrals. Inside the magnetosphere of Ganymede, the ionospheric plasma dominates over the Jovian plasma. How realistic is the modelled atmosphere?

We compared the simulation with the observations using the few data we had, particularly from *Galileo*. Among others, we looked at the total electron density *versus* time along the trajectory of *Galileo* which flew by Ganymede. We needed to increase the neutral-density factor by ten to have agreement between the observed and simulated electron densities. The number density of neutrals at Ganymede is not very well known. More recently a new model to explain some recent *HST* observations was published which includes the fact that more water and H_2 needs to be added to explain those observations. A closer agreement in terms of electron density is reached when the simulation is using this updated background neutral atmosphere.

What we learn from the modelling is that not only are the Jovian particles penetrating the polar regions and sputtering the surface but now, having actually modelled the ionospheric ions, they are accelerated with enough energy to sputter the surface themselves and to contribute to the production of the neutral atmosphere. If you are interested, there is a book on Ganymede which is due in 2024 May from CUP.

One of the consequences of magnetosphere/ionosphere coupling is auroral emission. To produce an aurora we need energetic electrons or ions originating from outside the atmosphere. An aurora is the photo-manifestation of the interaction of energetic extra-atmospheric particles with an atmosphere; the key thing is that the source of energy comes from outside the atmosphere.

On Earth we have aurorae, including one in the UK last Sunday. The green glow is produced by oxygen emission and it forms an oval around the magnetic poles. These ovals are also present at Ganymede and have been observed with *HST*. Atomic oxygen lines at 1304Å and 1356Å observed at Ganymede are the same lines that have been observed at Comet 67P.

At Ganymede the source of the O I emission lines is energetic electrons which dissociate O_2 and excite one of the produced oxygen atoms. At Comet 67P, is dissociative excitation of neutral species (H_2O, O_2) by energetic electrons the only process that generates the far ultraviolet (FUV) O I lines? If so, what is the source of these energetic electrons? To address the first question, we focus on FUV emissions observed at nadir (*Rosetta*–comet radial direction) [*Rosetta* escorted 67P for over two years] on a part of the surface which was in shadow to minimize scattered sunlight. Using measurements of energetic electrons and of the neutrals from *Rosetta* we simulated the brightness and compared with the observations from the UV spectrograph on-board *Rosetta*. Not only is there very good agreement between observations and the simulations but also, when the model predicts no emission, the spectrograph detected no emission either, showing that the dissociative excitation by energetic electrons is the main process of generating aurorae at Comet 67P. Now that we have confirmed the process yielding the auroral emissions, what is the source of the energetic electrons — are they coming from solar radiation or elsewhere? This time we used FUV observations from limb viewing (direction 'above' the cometary nucleus). We used the measured electron flux at *Rosetta* and the observed the column of atmosphere along the line of sight to estimate the brightness and then we compared this estimation with the observation of the emission which was produced far from *Rosetta*. This time we used hydrogen Lyman-β data produced through the same process as O I lines. Not only is there very good agreement in brightness, between observations and calculations, but there were also sharp changes which were captured in both. The electrons responsible for the emissions are not local; they were solar-wind electrons accelerated in the environment of the comet which then dissociate H_2O molecules. Through the observation of the O I 1356-Å line we can assess the variability of solar-wind electrons, so it has space-weather implications.

After this tour at Ganymede and Comet 67P, what is next? Ganymede is the main target of the *Jupiter Icy Moons Explorer* (*JUICE*). I was fortunate enough to be present at the launch from French Guyana on 2023 Apr 14. *JUICE* is now on its way, ultimately reaching Jupiter. It will make three fly-bys of the Earth–Moon system for gravitational assist and another past Venus. The magnetometer was built at Imperial College London, led by Professor Michele Dougherty. I am also associated with the radio plasma-wave instrument and the UV spectrograph. Four out of five of the stated aims of *JUICE* are concerned with Ganymede: why is Ganymede unique, what are water worlds like, what is the nature of the complex relationship of Ganymede with Jupiter, and is there life in the Jupiter system? In 2031 *JUICE* will be orbiting Jupiter with some fly-bys of the moons, and ultimately it will enter orbit around Ganymede with closest circular orbits of 200-km altitude.

What is happening on the cometary front? After *Giotto* and *Rosetta*, the next ESA mission to visit a comet is the *Comet Interceptor* mission originally proposed by Geraint Jones, the lead, from UCL, and Colin Snodgrass, the deputy lead from the University of Edinburgh. I joined the proposal at the start. The goal is to target a dynamically-new comet — a comet which reaches the inner Solar System for the first time, as we would like to study a body which is as pristine as possible. Comets were formed at the same time as the Solar System but unlike planets and moons they do not evolve for most of their lives until they reach the inner Solar System. They are time capsules. Another originality of *Comet Interceptor* is that it offers a multi-point capability.

In 1966 Jim Dungey already proposed a cluster mission to ESA. This ultimately led to *Cluster* with four spacecraft which was launched in 2000 and is still orbiting the Earth. *Comet Interceptor* is composed of three spacecraft, the mother spacecraft *A* and two probes *B1* (from JAXA) and *B2*. It was selected by ESA in 2019 and adopted in 2022 which means that we can go ahead with building the instrument. We have to deliver the instruments by the end of October 2025/early 2026 with launch in 2029. When the dynamically-new comet is detected we need to be ready to reach it. The spacecraft will be waiting at the Lagrange point L2. I am interested in the interaction between the solar wind and cometary plasma, especially plasma and field boundaries and regions.

We have engagement events for the public every month at Imperial College London. For December the topic was 'Space'. It is important to share our passion for space physics and science in general and inspire future generations. All the work I have described has been possible thanks to collaborations with colleagues in the UK, Europe, and the USA, and above all, with my team at Imperial College London.

Dr. Sanchez Cano. I have a question on the last slide that you showed of the cometary environment where the solar wind was accelerated. Can you explain the process at play?

Professor Galand. What happens is that the solar radiation ionizes the cometary neutral gas which leads to the set-up of an ambipolar electric field and a potential well. The solar-wind electrons fall into the potential well, are accelerated, and are able to ionize and excite the neutral gas. You have the energy of a solar-wind electron which is colour-coded in energy on the figure with blue as low energy and red as higher energy; as the electrons fall into the potential well they are accelerated. If they don't undergo collision then they get out of the potential well. If not they will deposit energy by ionizing and exciting the cometary gas; that is the source of the cometary aurora.

Mr. Steven Cockcroft. I love the idea of picking up a pristine comet. How do you know that it is pristine, and that it didn't pass 100 years ago and we just didn't spot it?

Professor Galand. Modelling the dynamical history we can look back at the evolution of comet orbits. Nearby stars, or massive planets such as Jupiter, can alter the cometary trajectory. For 67P, in the 19th Century and also in the 1920s and late 1950s, its orbit was perturbed which brought it ultimately into the inner Solar System where it has outgassed more significantly. There is an hemispherical asymmetry in the composition of the neutral gas in 67P and that may be due to evolutionary changes. For *Comet Interceptor*, we really want to have as pristine a comet as possible. When new candidates are detected, the dynamical history has to be modelled.

The Chair. A quick question about *Comet Interceptor*. You are at L2 waiting for your pristine comet to appear. How long can you wait and will you be operating your instruments there?

Professor Galand. *Comet Interceptor* can wait up to four years at the Lagrange point L2. It's a function of the amount of propellant. Currently ESA is not planning to allow science operation for L2 but let's see. There is already a Target Identification Working Group as part of *Comet Interceptor* and we have already started to look at candidates, in order to assess how many dynamically-new comets per year we could discover and are suitable candidates. We also have back-up candidates just in case. It will take between six months to three years to reach the comet; if you wait longer at L2 it will not be possible to go as far. Let's hope to find a very good target fast enough not to have to wait at L2 too long.

The Chair. Can I thank you again, Marina? [Applause.]

I'd like to remind you about the drinks reception after this meeting in the RAS Council Room and I give notice that the next A & G Highlights meeting will be on Friday, December 8th.

LATE-VICTORIAN LANCASHIRE ASTRONOMERS AND THE RAS 1871–1901

By Steven Phillipps

Astrophysics Group, University of Bristol

A previous paper[1] outlined the contribution of Lancashire astronomers to the Royal Astronomical Society in the fifty years to 1870. For most of this time the RAS and its journals