Exploring Planetary Atmospheric Processes from Terrestrial Worlds to Giant Planets

RAS Specialist Meeting Discussion Report

Hannah Joyce and Blair McGinness report on the RAS Specialist Discussion Meeting – 'Exploring Planetary Atmospheric Processes from Terrestrial Worlds to Giant Planets'.

After a prolonged period of virtual meetings, on 11th November 2022 we were able to meet in person at the Royal Astronomical Society at Burlington House in London. Though labelled as a continuation of the Planetary Atmospheres meeting in February 2020, many of us attending were not part of this community two and a half years ago – I was taking a break from academia after achieving my Masters in 2019 and working in a supermarket, for instance. Additionally, there are some of us no longer in academia, whether that being due to graduating from their studies, or other reasons. As such, the meeting was opened with a short tribute to Fred Taylor, an atmospheric physicist and planetary scientist who passed away in December 2021.

Many of us present in the room were anxious and excited to be here. For some, this was their first in person meeting since lockdown, and for others this was their first time standing up and presenting in front of this community. The reason for our gathering was that we were all interested atmospheres, some of us terrestrial planets and some of us those further out in our solar system, and even comets. Regardless of which planet held our personal interests, we were all here to discuss processes not necessarily unique to a single planet. From dust storms on Mars to identifying clouds on Jupiter to infrared observations of Neptune, we were all eager to share our accumulated knowledge to an interested gathering of people whom we could see rather than looking at our own image on a computer screen.

A planetary atmosphere refers to the envelope of gases that surrounds a planet. This atmosphere has layers, typically defined by pressure levels, with its own specific traits. Four of these are part of the neutral atmosphere, which is defined as atmosphere consisting of neutral gasses. The first of these is the troposphere. Closest to the planet, the troposphere is typically where clouds are found and has temperatures decreasing with height. Above this is the stratosphere, which is composed of stratified temperature layers and contains a higher concentration of a species which absorbs radiation from the space above. Not all planets, such as Mars, have stratospheres and instead transitions directly to the mesosphere, which typically sits above the stratosphere. Similarly, to the case of stratospheres, not all planets have a mesosphere, Jupiter being an example. A mesosphere is the coldest region of a planetary atmosphere, acting as a cooling agent that radiates heat into space. The top layer is the thermosphere, a region in which temperature increases with altitude. This region is usually governed by heating from ultraviolet (UV) radiation and heating resulting from auroral processes. There is also a fifth layer, known as the ionosphere. This 'layer' is embedded within the neutral atmosphere, usually the upper section, and exists due to extreme ultraviolet (EUV) and x-ray solar radiation penetrating the atmosphere of the planet and ionising atoms and molecules. This region consists of mostly ions and free electrons and can be variable in time and location.

Planetary atmospheres are a vital part of planetary science and understanding them is key to understanding a planet and its relationship to the space around it. The UK planetary atmospheres community does not have any regular meetings, but it felt timely to convene a meeting given the upcoming research opportunities present by the launch of the James Webb Space Telescope (JWST), to capitalise on data from ongoing missions such as ExoMars and Juno and to discuss paving the way for future investigations on Venus and the Ice Giants (Uranus and Neptune), the latter of which we have very little information on.

So, after some tea, coffee, and biscuits, we sat down to listen to a wide variety of talks on the atmospheres of the various celestial bodies in our solar system. The talks in this meeting will cover a vast range of atmospheric topics, and in this summary article we aim to summarise all of these topics with the aim in provide a background subject of the talk as well as covering the information presented in the talk itself.

Terrestrial Worlds

The first session of the day focused on the terrestrial planets in our solar system. The talks in this session focused on the atmosphere of at least one of the 3 inner planets in possession of a considerable atmosphere - Venus, the Earth, and Mars - with Mercury's tenuous atmosphere sadly neglected.

To open the day's presentations, Will Seviour (University of Exeter) talked about translating Earth science to the field of planetary atmospheres, particularly via the study of polar vortices. Seviour noted that there are many similarities between the Earth atmospheric science of a few decades ago, and the terrestrial planetary atmospheric science of today. The focus of this talk was on comparing the study of polar vortices on Earth, Mars, and Titan, however it was noted that similar comparisons between Earth and planetary science could be made for other aspects of the atmosphere. A polar vortex is a planetary scale flow of wind, circling the pole, in the same direction as the planetary rotation. Potential Vorticity (PV) is a useful diagnostic for studying the polar vortices, since a map of PV can show the structure of the polar vortex. In Earth's polar vortex, this PV has a maximum near the pole, however on Mars, the vortex has an annular shape, with a maximum in PV away from the pole. Will noted that this annular shape would typically be unstable, and that using atmospheric modelling it is possible to search for conditions which could allow the annular shape to appear, such as additional heating at the poles. In addition, Will investigated the mixing across the polar vortex, and showed that on Titan there are strong links between hydrocarbon concentration and PV maps.

Following this, Blair McGinness (University of Reading) discussed some evidence found for a global electric circuit on Venus, using data from the Venera 13 & 14 landers. On Earth, the global atmospheric electric circuit is a planetary-scale system, connecting regions of disturbed and fair weather, through the conducting ionosphere and surface. Since the global circuit distributes electric charge across the atmosphere, it leads to electrical effects being of global importance, rather than being confined to the charge generation regions. It is unknown whether such a circuit exists in Venus' atmosphere. Previous electrical data recorded by the Venera 13 & 14 landers hinted at some structure existing in the lower atmosphere of Venus, with proposals of charged haze layers beneath the expansive cloud layers. In order to investigate the Venusian electrical environment, an electrical model of Venus' atmosphere was produced, allowing the concentration of ions and atmospheric conductivity to be determined. This model was then used to attempt to explain the data recorded by the "point discharge" sensors onboard the Venera 13 & 14 landers, while assuming the presence of haze layers in the lower atmosphere. It was found that model reproductions of the Venera data matched observations significantly better if the presence of a global electric circuit was included in the model, suggesting that such a circuit may be present in Venus' atmosphere.

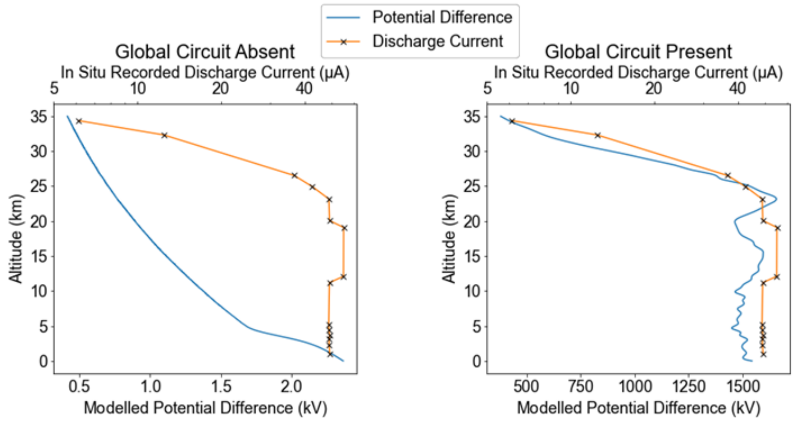

Figure 1: Plots showing the agreement between discharge currents measured by Venera 13 and potential difference values estimated from modelling. (Blair McGinness (University of

Next, moving from Venus onto Mars, Catherine Regan (University College London) gave a virtual talk, on investigating a Martian global dust storm, using the Mars express mission. During Mars' dust season, it is possible for several storms to merge into one, creating a global dust storm which may last for several months. These storms can have a huge impact on the atmosphere - including the upper atmosphere as dust can be lofted up to an altitude of 80 km. Since Mars has no intrinsic magnetic field, the Mars magnetosphere is very different to Earth's. Regan has investigated the times where the Mars Express mission crosses over several boundaries in Mars' magnetosphere - notably the bowshock and the induced magnetospheric boundary - during the 2007 global dust storm. Initially, a 3D model of the magnetospheric surfaces was used. When considering this 3D model, it was found that there was a large amount of variance in the location of the boundaries, and there was a high dependence on the solar zenith angle. Next, a 2D model was used, which showed that the boundaries were more stable than in the 3D case. It was found that each of these models brought both advantages and disadvantages, so in order to have a full picture both models needed to be used together.

Staying on Mars, Michael Battalio (Yale University) discussed the investigation of planetary waves on Mars, using data from the Mars Science Laboratory (MSL) and

Mars 2020. As planetary scale phenomena, "Rossby" or planetary waves have been studied far more extensively on Earth than on Mars. On Mars, these waves disrupt the annular structure of the polar vortices, and have been found to be associated with dust storms, so improving the understanding of these waves may prove very useful. These planetary waves are predominant in the fall and spring on both hemispheres, and can last for periods of 2-10 sols. A number of spacecraft have previously observed these waves, including the Viking missions, however the concurrent detections offered by the MSL and Mars 2020 offer new possibilities for lead-lag analysis to be performed as a wave travels between the two detection sites. In order to view the transient signals in Pressure data, it was important to remove the effects of seasonal and diurnal signals. From comparing the resultant data from the MSL and Mars 2020 sites, it was possible to identify information about the type of wave being observed, along with the hemisphere of origin of this wave.

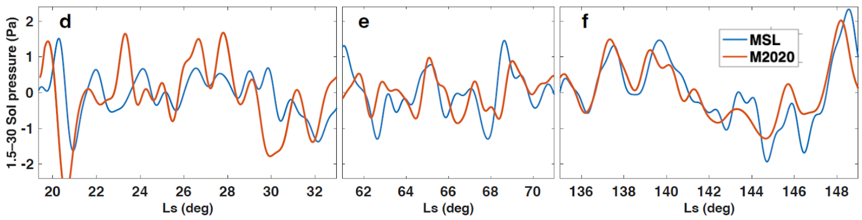

Figure 2: Several planetary waves as detected by Mars Science Laboratory (blue) and Mars 2020 (red). (Michael Battalio (Yale University))

Following this talk was the "poster pops"; The presenters for this days poster presentations were given 1 minute each to introduce their poster. There was a wide range of poster topics discussed, spanning from the terrestrial planets, to the gas and ice giants, to the Saturnian moon Titan.

Now, on a more experimental note, David Reid (University of Bristol) discussed their work investigating the electric and magnetic fields present inside Martian dust storms. In Terrestrial dust storms, magnetic and electric fields are generated from the movement of charged particles; Electric fields arise from the separation of positive and negative particles, and magnetic fields arise as charged particles follow spiral paths - akin to the current flowing in a solenoid. In order to experimentally reproduce the environment of a dust storm, a large, insulated tank was constructed, which allowed spiral airflows to be generated. The tank was insulated against magnetic and electric signals, to allow the fields generated by the storm to be measured in isolation. Measurements of these fields were taken while charged polystyrene balls were dropped vertically in the tank. For these vertical drops, it would be expected that a jump in electric field was measured, with minimal magnetic field detections. Although the electric fields matched what was expected, the magnetic measurements showed a strong signal at 50 Hz implying that some background signals were still able to penetrate through the insulation. In addition, when a motor is used to provide rotation within the tank, additional magnetic signals from the motor were observed. These results have necessitated the revisions to be made to the insulation of the tank.

Next, we moved from experimental work to the use of data assimilation. James Holmes (Open University) discussed the use of this method to investigate the Martian water cycle. On Mars, water can be lofted into the upper atmosphere where it may be lost. Several Mars-based spacecraft are able to observe the water vapour in Mars' atmosphere, and the loss of this water from Mars' upper atmosphere. In addition, Global Circulation Models of Mars are able to simulate the evolution of its atmosphere. By combining these observations and models, via data assimilation, a number of benefits are cultivated. For example, this data assimilation allows global mapping to be performed, as well as short term forecasts. Using the OpenMARS global reanalysis dataset, Holmes estimated the water loss during a regional dust storm, for a period where there are gaps in the observations. It was found that a peak in water loss occurred during this dust storm, and that it was important to include the effects of the dust storm on the water escape rate. For long term extrapolations of the water escape in Mars, including the effects of these dust storms will have an important impact on the result.

Also using data assimilation, Kylash Rajendran (Open University) discussed the climatology of Mars' superrotation using 12 years of reanalysis data. The total angular momentum of a planet is made up of the angular momentum of the atmosphere, and the angular momentum of the solid body. If the atmosphere's angular momentum is in excess of that of the solid body, then the planet is in a state of super rotation. This state can be measured using the global super rotation index S, where $S>0$ describes this state of super rotation. The OpenMARS reanalysis dataset allows this super rotation to be investigated. It was found that annual changes in the super rotation index were caused by the seasonal changes in the mid-latitude jets, while inter-annual changes were caused by changes to the tropical jet. For global dust storms occurring near the equinox, it was found that the super rotation index was particularly enhanced. For dust storms occurring near the solstice, however, this was not the case - the tropical jets were weakened with comparison to the equinoctial storms, leading to a lower enhancement of the super rotation index.

Following this, the chemical composition of Mars' atmosphere was discussed, as Juan Alday (Open University) talked about the photochemical fractionation of Carbon isotopes in the Martian atmosphere. An isotopic ratio is the ratio of the abundances of two isotopes of the same element. These ratios can provide important constraints to planetary atmospheres. On the long term, studying these ratios can provide information about the relevance that atmospheric escape has to changes in the planet's climate. On the short term, these ratios can provide information on chemical and physical processes present in the atmosphere. The atmospheric chemistry suite (ACS) aboard the ExoMars Trace Gas Orbiter is able to yield volume mixing ratios of several isotopes as a function of both altitude and time in Mars' atmosphere. It was found that the ratio of C-13/C-12 was depleted compared with the expected ratio. This was further confirmed by studying the ratio C-13O-16 / C-12O-18, and finding a similar depletion. Following this discovery, two important reactions for C-13 were identified and included into the LMD Mars Global circulation model. This model was initialised using in-situ measurements of isotopic ratios, as recorded by the curiosity rover. It was found that the depletion of C-13 measured from the ACS was able to be reproduced from this photochemical model. The model results also suggested that it was expected that the carbon isotope ratios would be more affected than the oxygen isotopes, which is also consistent with observations.

For the final talk of this session, Paul Streeter (Open University) returned to Mars' polar vortices, to discuss interannual similarities and differences in Mars' northern polar vortex. As discussed before, Mars' polar vortex has an annular shape. In order to study the polar vortices, the Open University's Mars global circulation model was used to perform data assimilation. The reanalysis data used spanned for a duration of 8 Martian years (~16 Earth years) and included two global dust storms in its period. It was found that global dust storms can impact the shape of the polar vortices, reducing their area. It was additionally found that global dust storms substantially reduced the potential vorticity in the southern vortex, although the intensity of the northern vortex remained similar. Looking at the seasonal behaviour of the northern vortex, it was found that there was a clear seasonal pattern in the PV with a visible annular structure, with the exception of times where large regional storms or global dust storms were present. In addition, it was found that storms of similar size had drastically different impacts on the polar vortex, depending on their timing. It was found that the timing of a storm affects its impact to a far greater degree than the storm's strength, with storms closer to the solstice appearing to affect the PV to a greater degree.

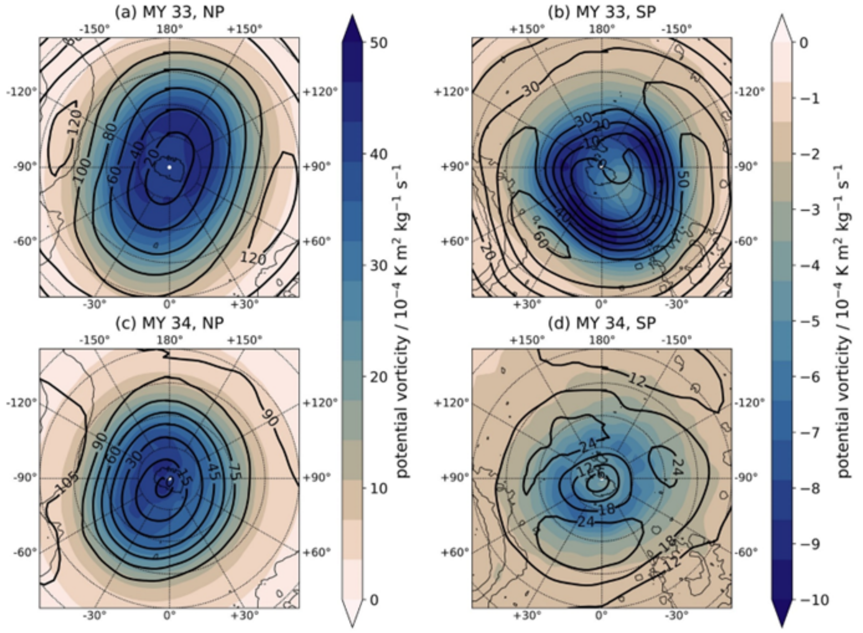

Figure 3: Demonstration of the effects that global dust storms can have on the polar vortices of mars. (a) and (b) showcase the north and south vortices respectively when there is no global dust storm, and (c) and (d) when there is a dust storm. (Michael Battalio (Yale University))

David L Clements (Imperial) opened the afternoon virtually, with our final talk on Venus, discussing several anomalies in Venus' atmosphere and how we can use the James Clerk Maxwell Telescope (JCMT) to monitor the atmosphere at millimetre wavelengths.

JCMT-Venus is a long-term programme designed to study the molecular content of the atmosphere of Venus at mm wavelengths due to the unexpected discovery of phosphine (PH_3) in the cloud layers of the planet by the Pioneer Venus Orbiter. The origin of the phosphine is currently unknown. It has been concluded that it cannot come from chemical processes, which include volcanism (Bains, 2021). Phosphine is not the only anomalous species in Venus' atmosphere, with an unknown UV absorber and O_2 also present. One of the aims of the mission is to see how phosphine interacts within the atmosphere, as well as identify its origin. It is hoped that the U'u receiver on JMCT will be helpful for this as it allows for wideband observation, meaning several lines can be observed simultaneously, and is intended to cover several molecular lines of interest, including PH_3, SO_2 and HDO (water with one H replaced by deuterium). The increased stability and sensitivity of the receiver are especially important as the telescope will be looking at weak absorption against the relatively bright source of Venus. So far, absorption lines of PH_3 SO_2 and HDO have been clearly detected in the preliminary analysis. Interestingly, there is less PH_3 after the surface of Venus has been exposed to sunlight for a while.

Commented [JH(R1]: Of what?

Atmosphere-Magnetosphere Interconnections

The second of the two topics discussed at the meeting moved away from the inner planets and towards the other bodies in our solar system. All the bodies discussed in this session have an ionosphere, a conducting layer of ions and free electrons that is embedded within the neutral atmosphere. Many of these systems also have a magnetosphere, a region carved out of interplanetary space where the dynamics are dominated by the magnetic field generated by the body. These two regions are intrinsically coupled.

The afternoon session's invited speaker, Luke Moore (Boston University), also presented remotely, with a fascinating review talk about the coupling between planetary atmospheres and the space around them.

Moore begins by speaking about the upper atmosphere, namely the thermosphere and ionosphere, and how it is a key transition region between the atmosphere of the planet and the space that surrounds it. It is where atmospheric escape occurs and where energy sources from outside of the planet initially interact with the atmosphere. There is evidence of space-atmosphere coupling from both above and below. The former is evidenced by solar photons and energetic particles providing heating, ionisation, and photochemical reactions in the atmosphere. The latter is shown through wave-driven modifications due to near-surface disturbances, such as gravity waves and acoustic waves. The existence of these waves has been known for decades but remains poorly understood. At Earth, an example of this process would be the Tonga volcano, an underwater volcano located off the coast of South America. When this volcano erupted, it affected the upper atmosphere through generated pressure waves and a resulting tsunami that induced extreme winds and had an impact on the temperature and electron density, respectively. Knowledge gained from the Earth can be applied to other planets in the solar system, such as Jupiter, where gravity wave characteristics can be seen in temperature data from the Galileo probe. Wave heating could potentially explain the high temperatures recorded at the giant planets, whose atmospheres were expected to be cold due to their distance from the Sun. Gravity waves have been detected at Saturn by Cassini, and the vertical structure seen in the electron density profiles of the giant planets can be explained by the presence of these waves. Wave heating, however, is intermittent and cannot heat the giant planets on its own.

In terms of coupling from above, the lower atmosphere is largely insulated from energetic particles such as solar extreme ultra-violet (EUV) radiation and soft X-rays, but some penetrate deeper. There are auroral-related hotspots in Jupiter's lower atmosphere, likely related to the precipitation of auroral particles or related current systems. It is also probable that this heating explains complex hydrocarbon formation at Saturn (Moses et al, 2017). The bulk of giant planet heating is thought to come from the equatorward transport of auroral energy from the auroral regions. Winds of unknown origin have been measured at Jupiter below the auroral region, and Moore suggests auroral ionospheric currents coupled to the magnetosphere could carry the neutral atmosphere along via ion-neutral collisions. Another example of coupling from above is given as the infalling ring particles and 'ring rain' at Saturn, where charged particles flow along magnetic field lines, modifying plasma chemistry. Additionally, Cassini detected an equatorial ring influx of greater than 1000 kg s^{-1} (Perry et al, 2018), which is caused by atmospheric drag on ring particles.
Moore summarises by saying that both forms of coupling are significant in terms of modifications of the local plasma conditions and that remotely measuring giant planet ionospheres is an excellent way to study the processes that drive this atmospheric region.

We then moved onto several talks focusing on Jupiter. The first Jovian speaker was Hannah Joyce (Lancaster) who presented results from the ISORRS model showing the effects of varying ionospheric conditions on ionospheric outflow at Jupiter.
Ionospheric Outflow is the process in which ions are accelerated out of the ionosphere and into the magnetosphere. Ionospheric Outflow is an important mass source for the Earth's magnetosphere, especially during times of quiet interaction with the solar wind. It is well understood at Earth, but less so at Jupiter, where the driver for this process and its importance within the system remains unknown. However, Juno has measured H^+ of planetary origin (Valek et al 2019) and outflow is expected to provide the magnetosphere with a source of H_3^+ as well.

Joyce uses the IonoSpheric Outflow in Rapidly Rotating Systems (ISORRS) model to look at ionospheric outflow above the main auroral emission at Jupiter. The main emission of Jupiter is omnipresent; However, asymmetries exist due to local time and planetary longitude variations. Therefore, the auroral ionosphere is an excellent test case to explore how varying atmospheric conditions affect outflow. Firstly, Joyce verified that widening the latitudinal extent of auroral region increases the total outflow rate. The effects of atmospheric temperature and field-aligned current density were next investigated as H_3^+ emissions of the auroral region suggest a non-uniform temperature (Johnson et al, 2018) across the underlying atmosphere. Additionally, magnetosphere-ionosphere (MI) coupling models predict local time asymmetries in current density magnitude. Results from the ISORRS model suggest that a hotter ionosphere is associated with a larger rate of outflow. Interestingly, field-aligned current strength has a negligible effect on the outflow due to the light mass of the constituents in contrast to outflow at Earth.

Next up was Deborah Bardet (Leicester), who discussed the thermal contrast between Jupiter's belts, zones and polar vortices using the VLT spectrometer.

Due to ground and space-based remote sensing, it is known that Jupiter has circulation cells located in its troposphere region. These cells may function similarly to Ferrel cells at the Earth; they occur at mid-latitudes and involve air converging at low altitudes to rise upward along the boundaries between the warmer sub-tropical air and the cold polar air. Using infrared (IR) data from the VISIR instrument on the Very Large Telescope (VLT), Bardet shows results from 4 ground based observing nights, with pole-to-pole coverage and planetary-scale wave tracking over time of Jupiter. Global multispectral maps with 13 narrow-band filters were used to sense stratospheric temperature, tropospheric temperature, aerosol opacity and the distribution of ammonia. Using this data with the NEMESIS tool (Irwin et al, 2008), the temperature and chemical structure of the planet can be derived.

As seen in Figure 1, a cross-section of the planet shows that there is warming present over the North Equatorial Belt (NEB) and South Equatorial Belt (SEB), cooling over the equatorial zone (EZ), North Tropical Zone (NTropZ) and South Tropical Zone (STropZ) and a cold polar vortex poleward of 70°. This represents a pattern of cool anti-cyclonic zones and warm cyclonic belts throughout the mid-latitudes up until the polar boundary. Comparing with perijove 13 (PJ13) data from Juno, a large region of cooling is identified co-located with aerosols observed in methane and ethylene-band imaging by Juno. This suggests aerosols may be important in terms of radiative cooling in the polar regions, with this cooling extending from the troposphere to the stratosphere. Evidence is also seen of heating in the high latitudes due to auroral precipitation. Additionally, brightness temperature perturbations highlight stratospheric planetary-scale wave patterns, but spectral analysis is needed to determine the nature of these waves.

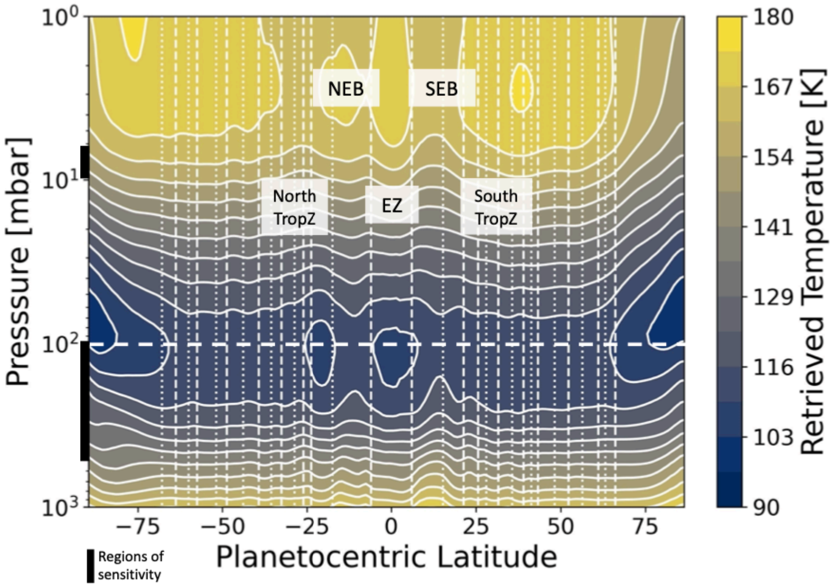

Figure 1 – An estimation of zonal-mean retrieved temperature mapped onto a grid representing pressure and latitudinal location using the NEMESIS tool for radiative transfer (Deborah Bardet (Leicester))

Charlotte Alexander (Oxford) then took to the stage to discuss the degeneracy of cloud properties on Jupiter and how predetermining atmospheric parameters can help simplify cloud structure.

Jupiter is quite well known in the solar system for its colourful clouds. Varying from white to red to brown, their composition and the distribution of chromophores i.e. the part of a molecule that determines the colouration, within the atmosphere is unknown. Current models of Jupiter's atmosphere typically use a 3-cloud model with varying methods of chromophore distribution with a main cloud layer and haze. There are huge variations in these models due to the unknowns, which creates a large degeneracy. Using the two-angle viewing method of Perez-Hoyos et al (2020) Alexander showed that the model of Braude et al (2020) was inefficient. Thus, Alexander wanted to produce a model able to fit the two-angle spectra comparatively or better and one that is derived in such a way that the number of unknown variables is reduced before the retrieval.

Able to constrain the main cloud pressure and thickness using techniques from Irwin et al (2008), Alexander employed small wavelength range retrievals from ground-based observations from the Very Large Telescope (VLT) and the Multi Unit Spectroscopic Explorer

(MUSE) instrument to acquire data. From this, the full spectrum in the visible and IR range were reconstructed using the Minnaert approximation at each latitude band (Minneart, 1941). Fitting this approximation allows for reconstructed spectra to be extracted for any viewing angle. Alexander also showed the results of a 'bracket' and 'snippet' analysis (Irwin et al, 2020), shown in Figure 2, for a single cloud layer at 1.4 bar pressure. A full model for all latitude regions still needs to be developed, as currently the uniform main cloud pressure can only be informed for latitudes between 50° south and 50° north.

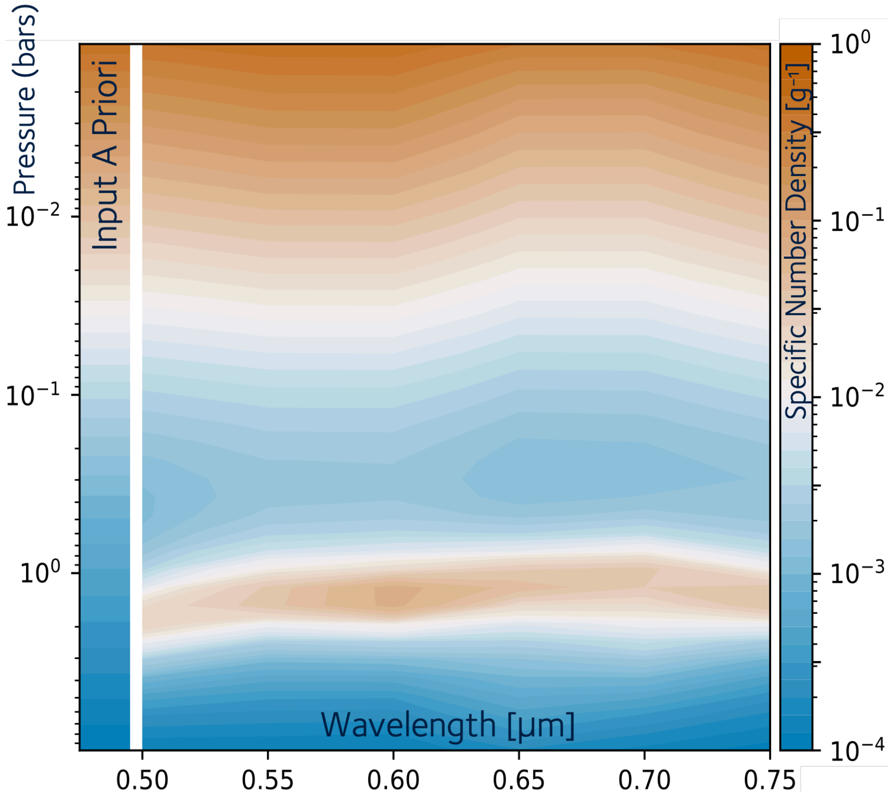

Figure 2 - Results of a 'bracket' and 'snippet' analysis of a reconstructed spectra of Jupiter showing the prescence of a single cloud layer at 1.4 bars (Charlotte Alexander (Oxford))

Jake Harkett (Leicester) presented preliminary results from James Webb showing mid-infrared observations of Jupiter's Great Red Spot.

At over 200 years old, the Great Red Spot (GRS) of Jupiter is an enormous anticyclone with many unanswered questions. It is the largest anticyclone in the solar system and is currently observed to be shrinking and becoming more saturated in terms of its red colouration. The driving mechanism for the storm and how long it has been present on Jupiter are currently unknown. James Webb Space Telescope (JWST) is ideal for observing the GRS as it can obtain an uninterrupted spectrum using the Mid-Infrared Instrument (MIRI) instrumentation, whilst the mid infrared (IR) wavelengths are absorbed by the Earth's atmosphere, meaning ground-based observations are unhelpful. There are still complications, however, as the field of view of the telescope is so small that a mosaic of 3 tiles needs to be used to view the GRS and Jupiter's rapid rotation results in observing geometry that was consistently changing.

Though JWST has not been in operation for long, preliminary data has been retrieved, showing a cold anticyclone located beneath the tropopause with a warm 'cyclonic' heat of the GRS deep in the troposphere. In figure 3, Harkett showed a surprisingly complex stratospheric structure with temperature patterns that appear to shift with depth. Phosphine (PH_3) was shown to be elevated throughout the GRS, which Harkett suggests could be due to aerosols shielding the particle from the ultraviolet (UV) rays that normally photolyse and remove the molecule from the upper troposphere. NH_3 is also observed to be north-south asymmetric, with the maximum located in the northern GRS. This latter observation was not unexpected, as the GRS is known to tilt in the north-south direction, possibly due to the upwelling in the north and subsidence in the south caused by a high-pressure region located under the northern edge. This work is still ongoing, and these observations are part of a wider programme of upcoming observations involving the outer planets.

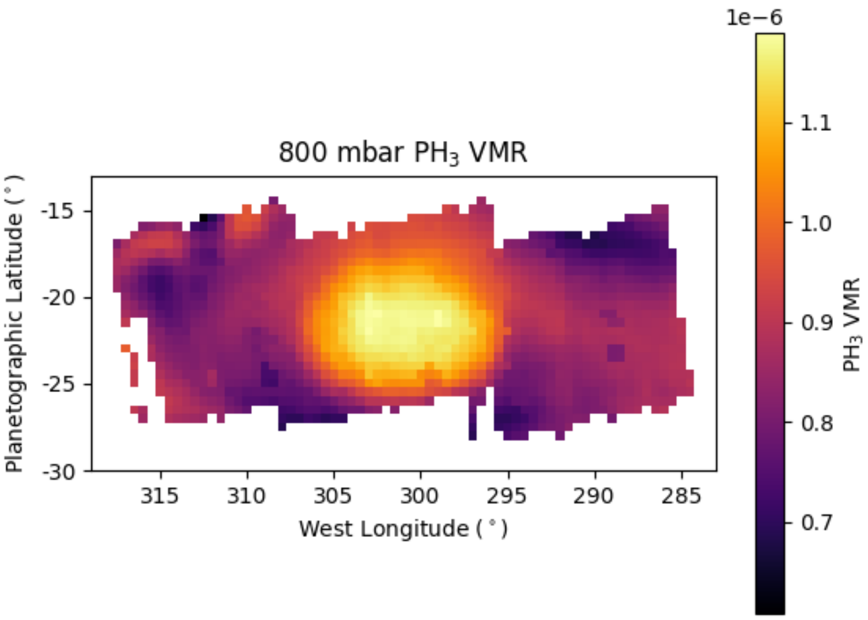

Figure 3 – An infrared (IR) image of Jupiter, showing elevated levels of phosphine shown to match the latitudinal and longitudinal location of the Great Red Spot (Jake Harkett (Leicester))

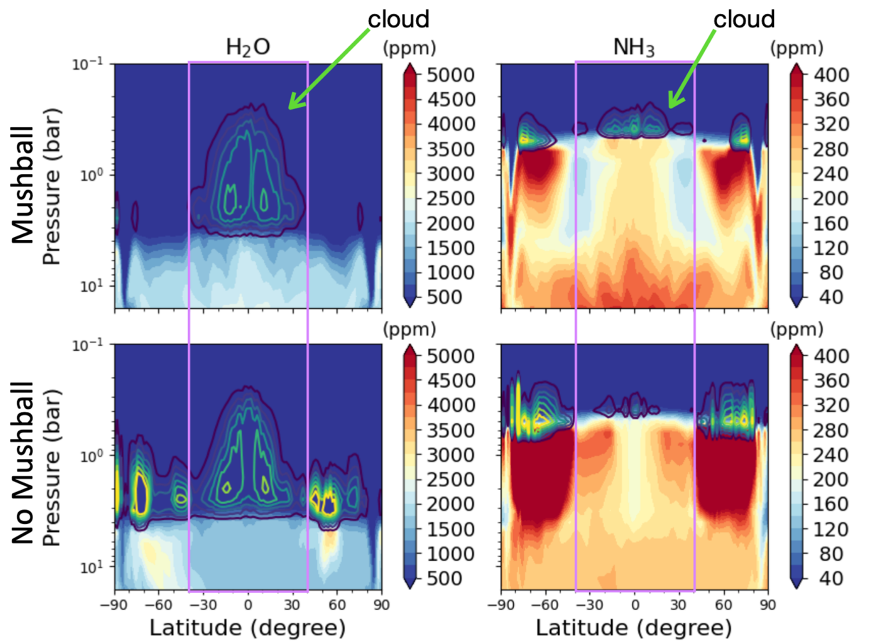

Figure 4 – Preliminary results showing the concentration of water and ammonia depending on pressure and latitudinal location with or without the presence of mushballs (Xinmiao Hu (Oxford))

For the final Jupiter, talk, Xinmiao Hu (Oxford) discussed the hailstones composed of a mixture of water and ammonia known as 'Mushballs' and how they developed a simple parameterisation scheme for them in general convection models.
Recent observations from Juno in microwave wavelengths have revealed some unexpected features in the ammonia distribution in Jupiter's atmosphere. One of these features is a layer with low concentrations of ammonia outside of the equatorial region to ±40° latitude (Li et al, 2017). Guillot et al (2020a) showed that ammonia vapour can dissolve into water (ice) within storms, forming 'mushballs', which are ammonia (NH_3) rich hail; this leads to the transportation of ammonia to the deeper atmosphere, hence the depletion at mid-to-high latitudes. This mechanism has, however, not yet been tested in numerical simulations, nor has the depletion of ammonia been factored into general circulation models for Jupiter. Knowing that mushball formation is triggered by moist convection as well as a sufficient source of ammonia, Hu aimed to develop a parametrisation scheme and study its interaction with atmospheric dynamics in a general circulation model. Adapting the 5-layer model of Guillot et al (2020b), the parameters used are the ratio of NH_3 to H_2O, formation efficiency and the evaporation and detrainment profile of the downward current of air (downdraft). This scheme is implemented using the general circulation model based on the MITgcm (Young et al, 2019a, b) that includes a simple cloud microphysics model for water and ammonia and a convection scheme that advects ammonia as a passive tracer as well as a dry convective scheme and a two-stream radiative transfer scheme. Preliminary results, seen in Figure 4, show a strong ammonia depletion in the ±20 - 40° latitude range, extending below the water cloud deck, with less depletion near the equator. Also seen is the

depletion of the water clouds. This is all consistent with Juno observations. Additionally, Hu shows that the formation of the mushballs can only occur near 1 bar pressure.

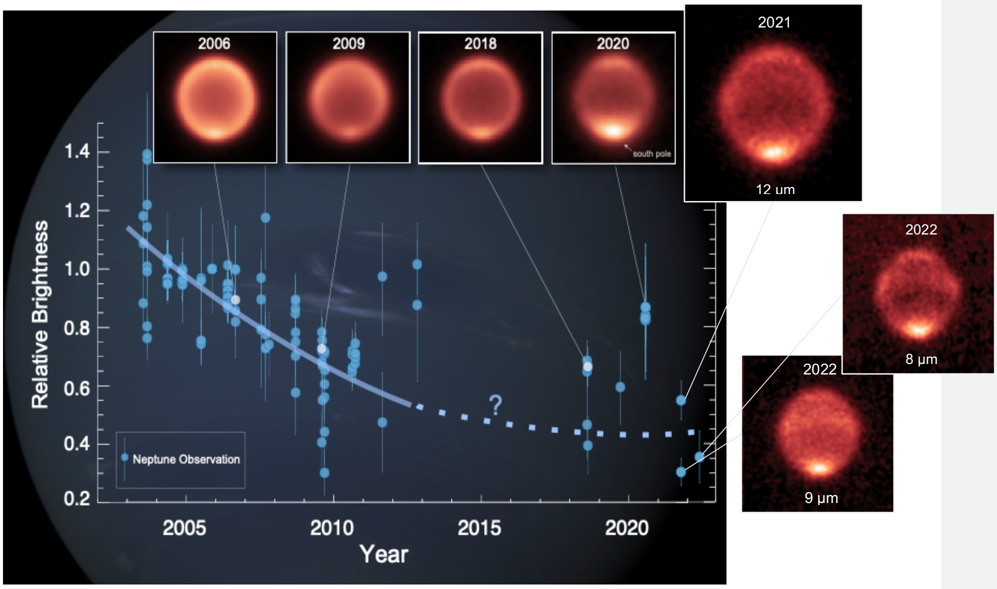

Figure 5 - IR images of Neptune showing the trend of cooling, as inferred from the relative brightness, that the planet has undergone since 2003 (Michael T. Roman (Leicester))

Michael T. Roman (Leicester) then took us further away from the Sun and to the Ice Giants, discussing mid-infrared observations of Uranus and Neptune and how our limited information on them may be changed by James Webb.

The furthest planets away from the Sun, Uranus and Neptune remain the least explored planets in the solar system. Despite also being known as 'giant planets' alongside Jupiter and Saturn, they are known to be quite different from the two gas giants. They are planets of extremes, with the strongest winds, coldest temperatures, and longest seasons. They are similar to each other in size and composition, and thus potentially representative of a distinct class of planet. However, due to their cold temperature and their distance from the Sun, they make for difficult targets for infrared observations (IR). Yet, observations are improving. Using the VISIR instrument on the Very Large Telescope (VLT), upper tropospheric temperatures, stratospheric temperatures and chemistry has been viewed. The troposphere appears to be quite similar for both planets, with warmer temperatures equatorward and toward the poles, suggesting the presence of a large-scale circulatory system.

In contrast, the stratospheres of Uranus and Neptune appear to be vastly different, possibly the due to the difference in seasonal sunlight. Looking at Neptune in particular, the stratosphere shows a surprising amount of variability on the timescale of sub-seasons, and a

trend in decreasing temperature since 2003 as shown in figure 5; this is unexpected as during this time Neptune was in its summer season. Recent observations (2020) do show an increase in brightness however, but this increase is mostly localised to the poles and an emerging band in the equatorial region. Viewing the whole planet, it appears the trend of cooling is continuing.
For Uranus, much less data is available, so conclusions cannot be drawn – the differences between the tropospheric and stratospheric temperature could be due to stratospheric circulation, but whether that is an adiabatic process or a chemical process cannot currently be determined. It is likely these problems will be able to be better investigated soon, however, as the James Webb Space Telescope (JWST) will be able to view both Uranus and Neptune in the mid-IR wavelengths with unprecedented sensitivity. This should provide a huge advancement in understanding for both planets, especially Uranus. By measuring across the disk, JWST observations should allow to differentiate between chemical and temperature processes to answer the question of what is going on in Uranus' stratosphere. It should also be able to assist in characterising the rapid warming of Neptune's south pole and evaluate whether the chemistry has also been changing.

Zoe Lewis (Imperial) had the final talk of the day, moving away from planets and discussing the ionospheric composition of comet 67P near perihelion with multi-instrument Rosetta datasets.
In 2004, the European Space Agency (ESA) launched the Rosetta mission, the 'comet-chaser'. Arriving in 2014, Rosetta orbited the comet 67P, also known as 'Churyumov-Gerasimenko', for 17 months as it travelled along its orbit around the Sun. Rosetta witnessed the comet evolve between 3.8 AU to 1.2 AU, witnessing it change from a low-activity body of ice to a dynamic object with large-scale plasma structures and rich chemistry. One of these plasma structures is the diamagnetic cavity. Though the comet does not have enough gravity to hold its own atmosphere, interactions with solar extreme ultra-violet photons and the neutral coma of H_2O results in an induced ionosphere, where the neutral coma is formed via the sublimation of ice. This mass loading of ions prevents the solar wind and interplanetary magnetic field (IMF) within it from penetrating the nebulous envelope surrounding the comet (the coma), creating a region free of magnetic field around the comet.

Lewis focuses on the changing role of chemistry during Rosetta's mission, in particular the compound NH_4^+. The only way to produce this compound is protonation, a process in which NH_3 'steals' a proton from H_3O^+, the latter of which would form from interactions with the ionised H_2O and the neutral coma. Lewis showed that there was an increase in NH_4^+ detections as the comet reaches its perihelion, suggesting a higher rate of outgassing, a process that involves the release of gas that was trapped in a material, including sublimation and evaporation. A higher rate of outgassing means that the coma around the comet would be denser, and there would therefore be more ion-neutral collisions. A link has also been observed between the higher rate of outgassing and the presence of the diamagnetic cavity, with higher concentrations of NH_4^+ inside the cavity, suggesting that the transport of material is more significant as a loss process outside the cavity and plasma dynamics are important in terms of the ion composition of the coma.

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