**Meeting Report** Weather on other planets: Measurement and Interpretation

The idea for this meeting was generated by the Royal Meteorological Society's *Special Interest Group on Meteorological Observing Systems* and organised by Ian Strangeways jointly with Colin Wilson of the Atmospheric, Oceanic and Planetary Physics Group of Oxford University, with additional support from Giovanna Tinetti of UCL. It was held as a combined meeting between the Royal Meteorological Society and the Royal Astronomical Society who scheduled it as their first *Specialist Discussion Meeting* of the 2015 season on 9 October at The Geological Society Lecture Theatre, Burlington House, Piccadilly. The joint-organisation of the meeting between the two Societies and the Oxford Physics Group reflected its wide interdisciplinary nature, combining meteorology, astronomy and planetary instrumentation, generating a lot of general interest.

The meeting was an opportunity for planetary scientists to survey the state of a field that is rapidly developing and driven by advances in complex technology, and was set up by the RMetS who are interested in how other planets' weather differs from Earth's and in particular how they are measured. Most of the talks took a review angle, while also looking to the near future in terms of planned spacecraft missions and telescopes. All of the planets and moons with substantial atmospheres were represented in the line-up of talks, along with extra-solar planets and solar weather.

The day started and ended with talks on the broad range of atmospheres being revealed through extra-solar planets. *Ray Pierrehumbert* (University of Oxford) began with an introductory talk covering several general principles that govern what we can observe in planetary atmospheres, how they behave, and in particular what physical parameters can be varied to get different types of planet. He identified critical properties as the thermal inertia of the atmosphere and ocean, the degree of orbital eccentricity, whether the planet orbits close to its parent star, and the amount of latent heat and condensable substances in the atmosphere.

The first talk covering specific planets was by *John Rogers* (University of Cambridge, British Astronomical Association Jupiter section Director), who discussed impressive observations of the planets being made by amateur astronomers. More and more amateurs worldwide have been regularly taking high quality images of Jupiter in particular, as quality telescopes have become more affordable to the general public. He highlighted some observations that can only come from amateur observers, such as the JUPOS database, which catalogues spot positions on Jupiter, and now has some 50,000 measurements added each year. Amateurs also observe the start of dramatic meteorological events and monitor long climatic cycles, neither of which are done by professional astronomers.

*Leigh Fletcher* (University of Leicester) turned to the professional side of giant planet observations, outlining how spacecraft are currently studying the climate and weather of Jupiter and Saturn. He focused on the various length scales of interest, going from large scale (e.g. Saturn's seasonal cycle and the evolution of vortices at its poles over a year), via medium scale (e.g. belt and zone structure on both giant planets, and multiple levels of clouds driving multiple convective cell systems), to small scales (e.g. convective plumes, injection of energy into storms, and coupling between troposphere and stratosphere). Both the Juno (arriving at Jupiter in 2016) and JUICE (not arriving at Jupiter until 2030) missions will advance our knowledge of Jupiter considerably.

Moving further out, *Chris Arridge* (Lancaster University) tackled the problem of observing the ice giants Uranus and Neptune. Since Voyager 2, observations of the ice giants have been taken solely by ground- and space-based telescopes. Uranus has developed from a very bland appearance into a more active planet as it has approached equinox. Neptune has always been active, however, with cloud features changing rapidly. Linking back to John's earlier talk, he reported that amateur observations are beginning to resolve cloud features on Uranus such as the 2015 bright storm. The challenges for observing the ice giants are the spatial resolution due to distance, the low albedo of the planets themselves, the difficulty of distinguishing weather from seasonal behaviour over a long period (these planets have only completed 1-2 orbits around the Sun since their discovery), and the problem of getting enough data back at such low radio power at that distance. The need to understand these bodies is high, however, as exoplanet observations suggest this class of planets is very common.

The last talks before lunch came back to the centre of the Solar System, with *Andrew Coates* (UCL) and *Manuel Grande* (Aberystwyth University) discussing planetary space weather – how the space environment varies due to changing conditions on the Sun and in atmospheres. The interaction between the solar wind and magnetised atmospheres (all but Venus, Mars, and Pluto) is extremely complicated, with a need for space weather forecasts to predict the effects on radio propagation, radiation belt conditions, solar monitoring of coronal mass ejections, and to support planetary space missions and Earth monitoring satellites. The COSPAR/ILWS roadmap prioritizes advances that can be made on short, intermediate, and decadal time scales with relevance to people's daily lives, such as electrical systems, navigation, communications, and aerospace. Currently the highest priority research areas are to quantify magnetic structure, and to understand the global solar coronal field and radiation belts. Also highlighted was the Planetary Space Weather Service, which aims to make prototype planetary event and space weather prediction operational in Europe.

During lunchtime several posters were displayed, covering energy cycles on Mars and other planets (*Peter Read*, *Fachreddin Tabataba-Vakili*), the DREAMS experiment on ExoMars (*Colin Wilson*), microlander concepts for Mars (*Michael Johnson*), space weather at the Met Office (*Suzy Bingham*), analysis and visualisation tools (*Charles Roberts*), and Jupiter atmosphere modelling (*Roland Young*).

After lunch the focus turned to terrestrial planets. First were two talks on Mars, the first given by *Manish Patel* (Open University). He summarised Mars's atmospheric structure, particularly highlighting how the meridional circulation is similar to that found on Earth, but is exaggerated due to lower thermal inertia in a lower temperature and pressure environment. During most of the year a single Hadley cell exists, covering most of the planet. Water ice clouds and atmosphere dust are both critical to the thermal state of the atmosphere, with dust devils considerably larger than those observed on Earth. The near future promises new meteorological data, both from ESA's Schiaparelli ExoMars 2016 lander, which carries a small meteorological package, and NASA's InSight seismic station, which will include an extremely accurate atmospheric pressure sensor.

*Stephen Lewis* (Open University) focused on the meteorological observations that can be made during a spacecraft's entry, descent, and landing. The Schiaparelli lander will include instruments to measure atmospheric pressure, density, winds, and temperature during its descent. He presented numerical simulations predicting the atmospheric conditions during the Curiosity rover landing at Gale Crater in 2012. A mesoscale weather model was nested inside a global scale climate model and observations from orbiting spacecraft were assimilated into the model to generate high-resolution simulations of the Curiosity landing site and a predictive weather forecast for Gale Crater during the landing itself, to inform the team operating the lander. The surface pressure was successfully forecast two years ahead of time using this method. Schiaparelli will land during a time of year with much higher dust variability, however, which may be harder to predict.

The topic then turned to Venus. *Colin Wilson* (University of Oxford) reviewed the Venusian weather and climate, along with spacecraft observations. Venus has an extreme environment below the main cloud decks but the atmospheric profile from 1 bar pressure to space is similar to that of Earth (with different composition). Information about the lower atmosphere has come from orbiters (most recently Venus Express), balloons (Vega), and 11 descent profiles (Pioneer Venus, Vega, and Venera). These found a convective cloud layer between 50 and 80 km altitude with stable layers above, episodic injections of $SO_2$ into the mesosphere, and complex cloud chemistry in addition to the predominant $H_2SO_4$. Surface probes have measured winds around 0-1 m/s, while cloud top winds are around 100 m/s. Future missions of all three kinds are either in progress or proposed. Akatsuki will orbit the planet from 6 December 2015, Venera-D will measure descent profiles of temperature and pressure, and proposed balloons would circumnavigate the planet in about a week.

*Ingo Muller-Wodarg* (Imperial College London) described Titan as *a terrestrial planet lost in the outer Solar System*, as he described its weather, in particular the observations made by the Ion Neutral Mass Spectrometer (INMS) on NASA's Cassini spacecraft. Titan and Earth are similar in terms of vertical structure, and both have active weather systems with liquids on the surface. In the upper atmosphere, $CH_x$ and $N_x^+$ species react to form large and heavy hydrocarbon haze molecules. The INMS has made density measurements down to 950km altitude during 36 flybys, showing considerable structure and variability that do not correlate with expected energy sources. This has been modelled using a thermospheric general circulation model, with a lower boundary in the stratosphere. Small variations near the bottom of the model cause large variations higher up. Upwards-propagating waves generate variability in the thermosphere consistent with observations, and accelerate Titan's background winds. Atmospheric waves are key to understanding the upper layers of any atmosphere, but are poorly understood.

Finally, the Solar System was put into a broader context by *Giovanna Tinetti* (UCL), who discussed the rapidly growing field of extra-solar planet atmospheres. Some 2000 planets beyond the Solar System have been confirmed in the last 20 years. From this wide range of planets we expect interesting and varied weather that will be challenging to simulate and understand. The atmospheres of these planets are critical to understand as only they can give information about many chemical, physical, and potential biological processes present. Telescopes use a wide range of techniques to probe many different properties of these atmospheres. The most promising technique is to measure the planet's electromagnetic spectrum during transit or by direct imaging, which measures atmospheric composition, temperature structure, and even atmospheric dynamics. Two future mission concepts were highlighted: Twinkle is a UK/SSTL spacecraft using a spectrograph to measure transit spectra for 100 exoplanets around bright stars in the near-infrared wavelength range. ARIEL is a 1m class near-infrared space telescope to look at 500 transiting, hot exoplanet atmospheres. The exoplanet field has moved from a focus on discovery to a point where understanding how planets form and evolve is the major aim.

One came away from the meeting with a sense that there are a lot of good ideas for improving our understanding of these planets in the next decade or so. The focus seems to be primarily on Mars, Jupiter, and extra-solar planets during the near future, while new data from other targets such as Venus and the ice giants will take longer to obtain. The breadth of topics presented was a very good overview of the current state of the field.

Roland Young
roland.young@physics.ox.ac.uk