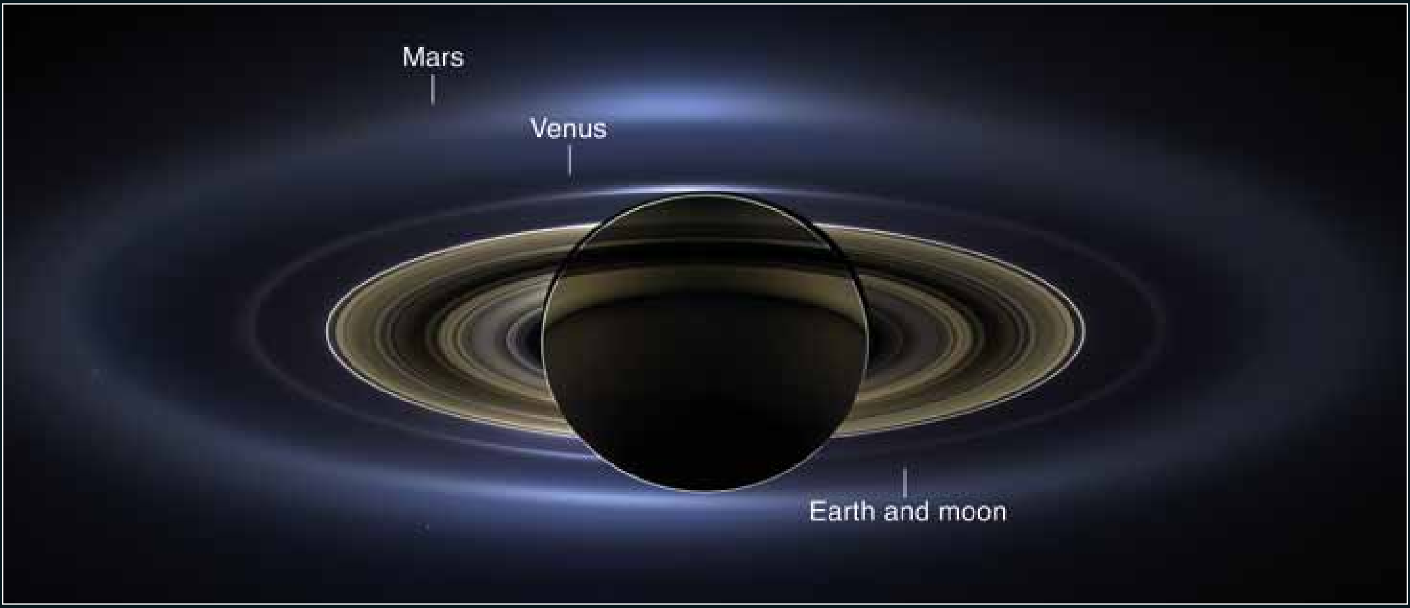
Cassini–Huygens: Saturn, rings and moons

With the Cassini–Huygens mission now in its Grand Finale phase, **Andrew Coates** reviews the impact of one of humankind's most spectacular voyages of exploration, in the first of four articles in this issue.



1 (Left): Artist's impression of Cassini during its Grand Finale orbits inside the rings. (NASA/JPL-Caltech)
2 (Above): Solar eclipse image of Saturn from Cassini, emphasizing the ring structure. (NASA/JPL-Caltech/SSI)

Launched in 1997, and spending 13 years at Saturn, the Cassini orbiter began its Grand Finale in April 2017: a series of weekly dives between the planet and its rings (figure 1). It is due to expire on 15 September this year, when it will plunge into Saturn's atmosphere and burn up. Here I outline what we knew before the mission and highlight the main discoveries of the orbiter Cassini and the Titan lander Huygens. In the following papers in this issue you can read in detail about Saturn's atmosphere (p4.26), Titan (p4.31), and what Cassini's magnetometer uncovered (p4.36).

Until the discovery of Uranus in the 18th century, Saturn was the most distant planetary object known. Before the Cassini–Huygens mission, what we knew about Saturn and its glorious system came mainly from telescopes, including important discoveries by Cassini and Huygens themselves (see Coates 1997). In the space age, important new information was added from brief fly-bys by the Pioneer 11 and Voyager 1 and 2 spacecraft.

Pioneer 11 (September 1979) discovered an additional moon (Epimetheus, later found to be very close in its orbit to Janus, alternating as the nearest to Saturn every four years) and a new ring (the F ring), and it explored Saturn's magnetosphere and radiation belts. Pioneer 11 also found that Titan was too cold to sustain life.

Voyager 1 (November 1980) and 2 (August 1981) took many images of Saturn and its rings and moons, discovering three additional moons (Atlas, Prometheus and Pandora), Saturn's aurora and many other aspects of the planet, its atmosphere, rings, moons and magnetosphere. But Titan was veiled from view by an orange haze in Voyager's visible wavelength cameras, and Enceladus was just another relatively featureless icy moon.

Before Cassini–Huygens, we knew that Titan, orbiting Saturn at 20 Saturn radii, had an atmosphere like the early Earth's, composed of nitrogen (>90%) and methane (few percent), and the surface temperature (as determined from infrared measurements by Voyager 1) was 94–97 K (Samuelson *et al.* 1981), near to but just above the triple point of methane (91 K). The expectation was that there could be methane-driven weather systems and possibly lakes and oceans of methane, although the slightly higher temperature led some to consider that ethane would be more likely to be the dominant constituent of any surface liquid.

> **"The mission is a major example of successful international cooperation in space science"**

The best images of Titan from Voyager in the visible wavelengths showed orange smog and blue haze, tantalizingly hinting at chemical complexity in the atmosphere. Shortly before Cassini's launch, images and data from the Hubble Space Telescope showed that there were light and dark features on Titan's surface (Smith *et al.* 1996). One light region was named after the "lost continent" of Xanadu, in the hope that it might be a continent, surrounded perhaps by ethane–methane oceans.

Enceladus, on the other hand, orbiting at 4 Saturn radii, was proposed as the source of the E ring based on the brief Voyager measurements, but the images showed limited evidence for this.

Saturn itself is the second largest gas giant planet in our solar system after Jupiter. We knew that underneath the visible clouds is a complex circulation system of zones and belts with an equatorial speed five times faster than at Jupiter. As the pressure and temperature increase with depth, this gas giant is likely to have a core, including a metallic hydrogen layer powering the large magnetic field.

Scientific goals

The Cassini mission was proposed in the early 1980s and three of the main proponents were Toby Owen, Daniel Gautier and Wing Ip (Ip *et al.* 2004). A visit to the Saturn system with an orbiter and a Titan lander was selected by NASA (orbiter) and ESA (lander); instrument proposals were submitted in 1989 and selected by NASA and ESA jointly in 1990. The mission has involved thousands of engineers and scientists and is a major example of successful international cooperation in space science. The main scientific targets of the mission were to study Saturn and its rings, Titan, the icy satellites and the magnetosphere – all discussed below.

For those of us who had successfully proposed instruments on Cassini in 1989, the launch eight years later was a tense and exciting moment. The UK did extremely well in instrument selection for Cassini–Huygens, with involvements in six of the 12 instruments on the Cassini orbiter and two of the six instruments on the Huygens probe. We all breathed a sigh of relief as the powerful Titan 4 rocket emerged from the cloud it had lit up from behind, soon after the launch. The spacecraft spent the next seven years getting to Saturn, via Venus (twice), the Earth and Jupiter for gravity assists to increase its speed enough to reach Saturn. A crucial 96-minute burn slowed the spacecraft and took it into Saturn orbit successfully on 1 July 2004.

The 18 instruments of Cassini–Huygens

Huygens carried six instruments, Cassini had 12, many of them multi-function.

Huygens

Aerosol Collector and Pyrolyser (ACP) collected aerosols for chemical-composition analysis.
Descent Imager/Spectral Radiometer (DISR) took images and made spectral measurements using sensors covering a wide spectral range.
Doppler Wind Experiment (DWE) used radio signals to deduce atmospheric properties.
Gas Chromatograph and Mass Spectrometer (GCMS) was a gas chemical analyser designed to identify and quantify various atmospheric constituents.
Huygens Atmosphere Structure Instrument (HASI) comprised sensors for measuring the physical and electrical properties of the atmosphere and a microphone that sent back sounds.
Surface Science Package (SSP) was a suite of sensors to determine the physical properties of the surface at the impact site and to provide information about its composition.

Cassini

Optical remote sensing. Mounted on the remote sensing pallet, these instruments studied Saturn and its rings and moons in the electromagnetic spectrum: Composite Infrared Spectrometer (CIRS), Imaging Science Subsystem (ISS), Ultraviolet Imaging Spectrograph (UVIS), Visible and Infrared Mapping Spectrometer (VIMS).
Fields, particles and waves. These instruments studied the dust, plasma and magnetic fields around Saturn: Cassini Plasma Spectrometer (CAPS), Cosmic Dust Analyzer (CDA), Ion and Neutral Mass Spectrometer (INMS), Magnetometer (MAG), Magnetospheric Imaging Instrument (MIMI), Radio and Plasma Wave Science (RPWS).
Microwave remote sensing. Using radio waves, these instruments mapped atmospheres, determined the mass of moons, collected data on ring particle size, and unveiled the surface of Titan: Radar, Radio Science Subsystem (RSS).

3 Hurricane within the hexagon jet stream structure at Saturn's north pole, with colossal wind speeds up to 150 m s^{-1}. (NASA/JPL-Caltech/SSI)

Saturn

A favourite image from Cassini showing the Saturn system, as only a spacecraft could, is the remarkable eclipse image backlit by the distant Sun, showing Saturn and the ring system (figure 2). This is an iconic image which also shows the Earth–Moon system, Venus and Mars as pixels, both reminding us of the context of our own planet and giving a remarkable view of Saturn and the rings.

There have been some stunning discoveries about Saturn, its atmosphere and the features within it (see Dougherty *et al.* 2009). These are reviewed in an accompanying article (Fletcher 2017; this issue).

Cassini has been at Saturn almost half a Saturn year. At Cassini's arrival in 2004 it was southern summer with the rings illuminated from below, and Cassini has continued observations through the prime, equinox (during which the rings were edge-on to us) and now solstice (northern summer) mission phases in its 13-year tour of Saturn's system. A final set of discoveries will come at the end of the mission in September 2017, from gravity and magnetometer measurements, which should reveal more about Saturn's interior structure, and from INMS measurements which will "taste" Saturn's atmosphere for the first time.

> "The INMS instrument will 'taste' Saturn's atmosphere for the first time"

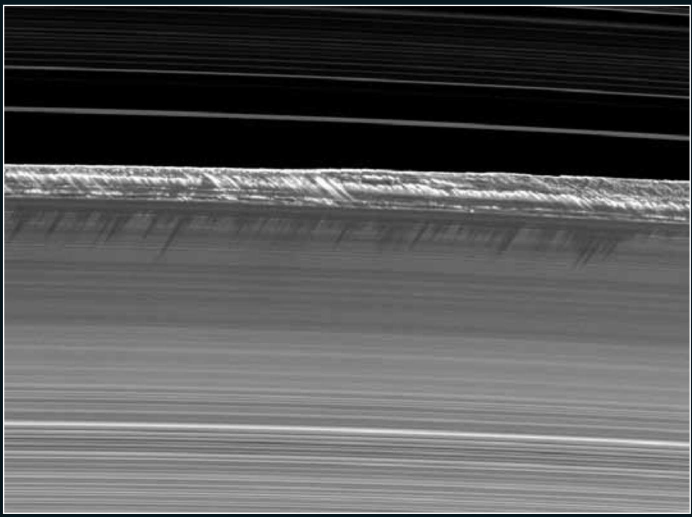
One of the puzzles from the data has been the length of the day on Saturn. The particle and field data all exhibit periodicities and features, including radio emission known as Saturn Kilometric Radiation (SKR). One of the interesting aspects has been that the northern and southern SKR periods are slightly different and in fact beat with each other (Gurnett *et al.* 2010). Identifying the source of this has been controversial, but the current favourite is circulations in Saturn's atmosphere leading to rotating current systems in each hemisphere, causing magnetic field perturbations (Jia *et al.* 2012).

One exciting observation during the Cassini mission was a long-lived storm in the atmosphere known as the Great White Spot, which started in 2010. It was originally identified by an amateur, but it engulfed the planet and was studied in detail by Cassini (e.g. Fletcher *et al.* 2011, Sánchez-Lavega *et al.* 2011, Sayanagi *et al.* 2013). These storms are seasonal, occurring once per Saturn year, and the Cassini observations are unique.

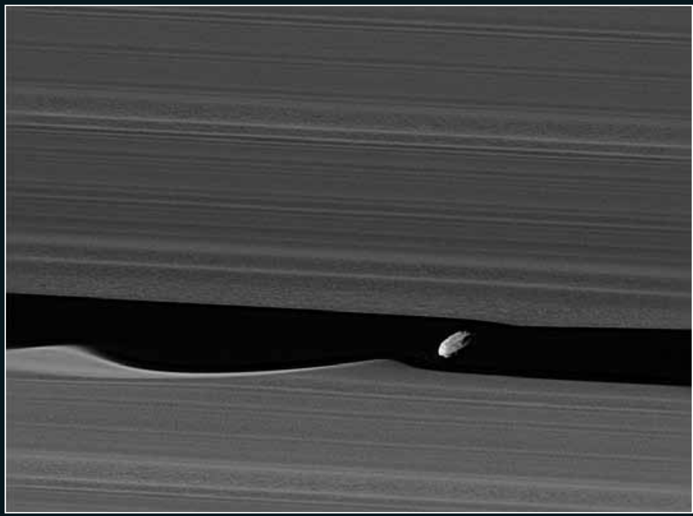
Another view of Saturn that is only possible from a spacecraft is that from above the pole – a vantage point unique to Cassini. Images have revealed a large hexagon structure at the north pole, caused by jet streams in the atmosphere (Fletcher *et al.* 2008). This has some similarities with Earth's Antarctic polar vortex around Earth's ozone hole, except that at Saturn the inside region has smaller and different haze particles, while outside the haze comes from larger particles. Figure 3 zooms into the hexagon and the hurricane at its heart (Baines *et al.* 2009). The hurricane is 20 times larger and four times the speed of terrestrial hurricanes. On Earth, hurricanes are driven by warm water – this is clearly not the case at Saturn.

The rings

Some of the first discoveries, made immediately after Saturn orbit insertion, were



4 Towering structures at the B ring edge, August 2009. (NASA/JPL/SSI)



5 Daphnis (5 by 8 km) in the 42 km wide Keeler gap. (NASA/JPL-Caltech/SSI)

that the rings have their own tenuous oxygen-rich atmosphere and ionosphere (Tokar *et al.* 2005, Coates *et al.* 2005). This is caused by energetic radiation belt particles hitting the icy ring particles and producing water; this then dissociates and the hydrogen freezes back onto the icy ring particles, leaving oxygen behind.

Some of the ring images have shown remarkable features. Figure 4 shows the outer edge of the B ring just before equinox in August 2009, illustrating that clumps of B-ring material extend above the ring plane up to 2.5 km above the 10–100 m thick rings, casting shadows onto the rings. This may be caused by moonlets up to a kilometre across (Spitale & Porco 2010).

The dark, rotating ring "spokes" also seen by Voyager appear to be highly seasonal and present near the equinox (Mitchell *et al.* 2013). The best explanation for these is related to dust particles that have become electrically charged, perhaps from impacts, which levitate above the ring plane. It was also suggested that these may be related to lightning in Saturn's atmosphere (Jones *et al.* 2006).

Figure 5, taken in January 2017, illustrates the interaction between small moons and rings. The moon in this case is Daphnis, measuring 5 km by 8 km and orbiting within the 42 km wide Keeler gap in the outer A ring. To the left of Daphnis is a tendril of material from the ring, which appears to be spreading out. Other features include propellers associated with hypothesized 100 m moonlets (Tiscareno *et al.* 2006), and waves and bands of ring material. New discoveries include the birth of a moon called Peggy (Murray *et al.* 2014) and interactions between the moon Prometheus and the rings, studied in detail by UK researcher Carl Murray and colleagues (Murray *et al.* 2005).

Titan

Titan has turned out to be even more exciting than expected (see papers in Brown *et al.* 2009). The early fly-bys by Cassini revealed a rich chemical complexity in the upper atmosphere from INMS and CAPS measurements, with unexpectedly complex neutral hydrocarbon and nitrile species (Waite *et al.* 2005, 2007), positive ions up to 1000 amu/q (Waite *et al.* 2007) and negative ions up to an incredible 13 800 amu/q (Coates *et al.* 2007). This implies that complex chemistry starts at the top of the atmosphere, producing tholins as anticipated, and these fall to the surface producing dune-like features and replenishing the lakes.

> "Titan is the only moon with a significant, and early Earth-like, atmosphere"

Multiwavelength imaging from Cassini significantly extended the wavelength range from Voyager to include infrared (VIMS, CIRS) and ultraviolet (UVIS) images and spectra. This revealed the detail of the surface, enabling full mapping of the lighter and darker surface features. Together with radar data, these show evidence for lakes of methane and ethane on the surface (Stofan *et al.* 2007; see figure 5 in Zarnecki 2017), and a whole new, inner planet-like world has come into view through the haze (see Brown *et al.* 2009).

The Huygens probe successfully landed on Titan in 2005 and showed remarkable features during its descent, such as river-like outflow channels carved by methane (Tomasco *et al.* 2005), a surface including chunks of ice with properties similar to wet clay, lightly packed snow and wet or dry sand (Zarnecki *et al.* 2005), suggesting a recently dried up methane lake bed (see figures 3 and 4, Zarnecki 2017 and references therein). The atmospheric composition at the surface included the anticipated species, and the local density of these rose when the relatively warm (compared to its surroundings) Huygens probe landed. In addition, more complex species such as benzene were also seen at the top of the atmosphere (Niemann *et al.* 2005).

One of the iconic Cassini images of Titan shows the glint of sunlight from a hydrocarbon lake (Stephan *et al.* 2010; see figure 6, Zarnecki 2017). This emphasizes Titan's importance as the only body beyond Earth where we have detected liquid on the surface. As well as lakes, some of them as large as great lakes on Earth and more than 100 m deep in places, there are dunes resembling terrestrial deserts such as the Namib desert (Lorenz *et al.* 2006), and river-like features seen in the Huygens and Cassini data currently replenish the lakes. Clouds and rainfall are found at times and the whole scenario has seasonable variability, completing the terrestrial planet-like environment. In addition, rotation (Lorenz *et al.* 2008) and gravity (Iess *et al.* 2012) measurements indicate a subsurface water ocean at Titan. Although the surface temperature is too cold for life at the moment, this result increases the likelihood of the future habitability of Titan, the only moon in the solar system with a significant, and early Earth-like, atmosphere.

Icy satellites

On the way towards closest approach, Cassini had already taken images of the moon Phoebe, confirming this retrograde-orbiting moon as a captured Kuiper belt object (Clark *et al.* 2005). Phoebe is an ice-rich body covered with a thin layer of darker material, visible in impact craters.

Another interesting result from the icy satellites has shown that an infrared image shaped like Pac-Man is seen on both Mimas (Howett *et al.* 2011) and Tethys (Howett *et al.* 2012), arising from a 15 K temperature gradient on each body (the warmest temperature is 95 K at

Mimas and 90 K on Tethys). The shape is explained by high-energy radiation belt electrons bombarding each staellite at low latitudes on the side of the moon that faces forward as it orbits Saturn, turning an initially fluffy surface into hard-packed ice. The altered surface does not heat as rapidly in the Sun or cool down as quickly at night as the rest of the surface.

At Iapetus, which despite its large distance from Saturn – 59 Saturn radii – is tidally locked to Saturn, the Voyager mission had discovered that one side was darker and the other lighter in colour. Cassini discovered that dark material, probably from Phoebe which orbits at 215 Saturn radii, is deposited onto the surface and is then "thermally segregated" – it warms in sunlight, is mobilized and then redeposited on colder areas (Tosi *et al.* 2010). Iapetus also has an equatorial ridge rising 10 km, with peaks up to 20 km, above the moon's surface (Porco *et al.* 2005), possibly from earlier rapid rotation or aggregation from a collapsed ring. Phoebe as a source is made more likely by the discovery using Spitzer Space Telescope data of a disc of material extending between at least 128 and 207 Saturn radii, associated with Phoebe (Verbiscer *et al.* 2009).

The icy satellites Rhea (Teolis *et al.* 2010) and Dione (Tokar *et al.* 2012) were found to have atmospheres, based on direct neutral and charged particle measurements. When neutral particles are ionized by sunlight they are initially accelerated by an electric field E provided from the flow of the surrounding plasma at velocity v in a magnetic field $\mathbf{B}$. This is found in the case of plasma rotating with Saturn from the Lorentz force and from assuming infinite conductivity, $E = -(v \times \mathbf{B})$. Having been accelerated by this electric field, the particles are "picked up" and gyrate around the magnetic field taking a cycloidal path. At Rhea, oxygen and carbon dioxide neutral particles were seen near the moon, while positive (before closest approach) and negative (after closest approach) ions were seen early in their gyration. This elegant measurement pinpointed their source as tenuous atmospheres at Rhea and Dione. The atmosphere is produced by energetic radiation belt particles hitting the icy surfaces; similar atmospheres are present at Europa, Ganymede and Callisto in the Jupiter system, and similar processes occur at comets.

The star of the icy satellites is Enceladus. In 2005, deflections in the magnetometer data initially showed that something interesting was happening (Dougherty *et al.* 2006), so Cassini took a closer look. Imaging showed that there were "tiger stripes" near the south pole (Porco *et al.* 2006, figure 11), and VIMS showed that these were warmer than the surface nearby (Brown *et al.* 2006). Imaging and other data also found that Enceladus was emitting plumes (e.g. Porco *et al.* 2006, Hansen *et al.* 2006), and further effects were shown in the plasma, dust and neutral particle data (described below). In particular, Enceladus was identified as definitely the source of Saturn's E ring.

The spectacular plumes of Enceladus were not known before Cassini's arrival. Now it is clear that Enceladus is the major source of neutral species and plasma near Saturn, more prolific as a source than Saturn's rings and the other moons, even including Titan (see also Coates 2012). Also, the plumes are a key indication, confirmed by gravity measurements, of a global subsurface ocean below an icy crust perhaps 30 km thick, but thinner near the tiger stripes. Subsequent results have found negative water ion clusters (Coates *et al.* 2010), charged dust grains (Jones *et al.* 2009), sodium in the dust showing that the ocean is salty (Postberg *et al.* 2009), silicate in the dust indicating possible hydrothermal vent activity at the bottom of the ocean (Hsu *et al.* 2015) and, most recently, hydrogen in the plume which may indicate that the ocean is habitable (Waite *et al.* 2017).

"Enceladus moves towards the top of the list of potential solar system habitats"

Taken together, these results propel Enceladus towards the top of the list of potential solar system habitats, joining Mars and Europa as the top three candidates for past or present life; Titan is a potential fourth location.

Magnetosphere

Saturn's magnetosphere is about 18 times the size of Earth's. Earth's magnetosphere is dominated by reconnection driven by the solar wind in a "Dungey cycle" with reconnection at the magnetopause and in the tail. At Saturn it was expected that the rapid rotation of the planet (period 10 hours 40 minutes) would dominate as it does at Jupiter's even larger corotating magnetosphere, leading to a larger scale "Vasyliunas cycle" with a reconnection line in the tail. Cassini sees a mixture of these (see e.g. Masters *et al.* 2011, Thomsen *et al.* 2015, McAndrews *et al.* 2008, Jasinski *et al.* 2016, Jackman *et al.* 2011).

Cassini showed that corotation is almost true in the inner magnetosphere, out to about double the orbit of Enceladus (Thomsen *et al.* 2010, Arridge *et al.* 2011). Cassini also found that the solar wind, as well as corotation, can affect Saturn's aurora (e.g. Badman *et al.* 2015 and references therein). This was the case while Cassini was approaching Saturn before orbit insertion (Crary *et al.* 2005), and has been confirmed in later results as well. The aurora provides an important diagnostic on the interaction between Saturn's ionosphere and magnetosphere and remarkable images were taken by Cassini VIMS (Stallard *et al.* 2008) (see figure 6).

One of the early *in situ* findings was that the magnetosphere is dominated by water group ions (Young *et al.* 2005), mainly from ionization of neutral particles originating at Enceladus with some from the rings and other moons. The neutral particle density is about two orders of magnitude higher than the plasma density, however, making Saturn's watery magnetosphere unique in the solar system.

Studying the magnetosphere and radiation belts, and their interaction with the rings, moons and neutral particles, has been one of the major areas of study for Cassini scientists. One finding has been that of long-term reconnection in the tail (Arridge *et al.* 2016), confirmation of the Vasyliunas cycle, plasmoids in the tail taking products from Enceladus away from the Saturn system (Hill *et al.* 2008, Jackman *et al.* 2014), observation of a "polar wind" like Earth's (Felici *et al.* 2016), new radiation belts unknown before Cassini arrived (Krimigis *et al.* 2005), and charging of the surface at Hyperion (Nordheim *et al.* 2014) and other moons.

Future missions

Following Cassini's intriguing discoveries about Enceladus and Titan in particular, it is not surprising that there have been several proposals for future missions from both sides of the Atlantic. Past proposals have arguably suffered from the Cassini mission still being underway, but as we approach the end of the mission it is certainly timely to be considering a return to the Saturn system – with Enceladus, Titan and Saturn's atmosphere the current proposed targets.

At ESA, proposals have included TandEM (Titan and Enceladus Mission, Coustenis *et al.* 2009), a large class mission candidate which was ranked equal in science with the subsequently selected JUICE mission (Grasset *et al.* 2013), but judged to have slightly more challenging technology readiness. Its predecessor was the ESA–NASA TSSM (Titan Saturn System Mission), which would have been similarly ambitious but with strong international collaboration following from Cassini–Huygens. TandEM would have consisted of two elements: an orbiter that would make several Enceladus flybys and deliver penetrators to the surface before going into orbit around Titan; and a Titan *in situ* component, i.e. a hot-air

6 Saturn's southern lights: infrared aurora 1000 km above the cloud tops from VIMS data on 1 November 2008. Aurora in green, reflected sunlight from the rings in blue (2–3 µm) and Saturn's emission in red (5 µm) are shown. (NASA/JPL/ASI/Univ. Arizona/Univ. Leicester)

balloon (Montgolfière) and possibly landing probes. Currently, missions are being evaluated in ESA's M5 (medium mission 5) call and the Hera Saturn Entry Probe Mission is one of the candidates (Mousis *et al.* 2014, 2016). Results are expected in a few months.

At NASA, proposals have included a Titan Mare Explorer (TiME), a finalist in the NASA Discovery mission line but not selected, which would have delivered a floating laboratory to perform *in situ* analysis floating on one of the northern Titan lakes, Ligeia Mare, similar in size to Lake Superior. Other proposed mission concepts include: ELF (Enceladus Life Finder), which would have flown a high-resolution mass spectrometer through the Enceladus plumes; and LIFE (Life Investigation For Enceladus), which would have brought Enceladus plume samples back to Earth for analysis. Currently, NASA's New Frontiers competition is underway, with 12 proposed missions. Two of the six mission themes for this opportunity are Ocean Worlds (Titan and/or Enceladus) and a Saturn Probe, so we may expect proposals in these targeted areas. It will be a few months before the outcome of the competition is known.

Cassini–Huygens has left a fantastic legacy of data that will be analysed for many years. The pioneering *in situ* discoveries and implications for the rest of the solar system are only beginning to be realized. But as Cassini approaches its Grand Finale in September 2017, it is clear that, one day, we must return to the Saturn system to follow up on the legacy left by Cassini and Huygens. Who knows what key answers to age-old questions – such as, are we alone in the universe? – may be lurking there. ●

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