Institution: University of Leicester

Unit of Assessment: 10 Mathematical Sciences

Title of case study: Mathematical modelling contributes to NASA space mission and inspires public interest in science

1. Summary of the impact

NASA's Cassini mission to Saturn's icy moon Enceladus in 2009-10 investigated the presence of explosive ice geysers towering over the south pole of the planet. The geysers consist of vapour and ice particles which rise up to 1,000 kilometres above Enceladus' surface. The source of these jets has been hotly contested. Cassini's mission was to fly as close as possible to the plumes to search for evidence of sub-surface water containing the building blocks of life.

Mathematical modelling, conducted at Leicester, allowed the mission designers to calculate the possibility of the Cassini Spacecraft colliding with dust from the Enceladus jets, with potentially catastrophic results, enabling the craft to be manoeuvred as close as safely possible to the moon's surface to capture the images it required.

The mission, with an estimated $3.26 billion cost, was successful – gathering evidence that the research team's hypothesis of a subterranean sea on Enceladus was correct – a revelation which has inspired public interest around the world.

2. Underpinning research

In 2008, Nikolay Brilliantov (University of Leicester since 2007, now Chair, Professor in Applied Mathematics) collaborated with Jurgen Schmidt and Frank Spahn (both Institute of Physics, University of Potsdam, Germany) publishing research in Planetary and Space Science [1]. The research analysed previously published qualitative models of the geysers of Enceladus and examined two hypotheses for the underlying cause of Enceladus' geysers already proposed by astronomers, in the light of data gathered by Cassini.

The first **'Cold Faithful hypothesis'** assumes an explosive boiling of subsurface liquid water, when pressure exerted by the ice crust is suddenly released due to an opening crack. In the second hypothesis, **'Frigid Faithful'**, the existence of a deep shell of clathrates below Enceladus' south pole is conjectured; clathrates can decompose explosively when exposed to vacuum through a fracture in the outer icy shell.

Development of a new hypothesis

Brilliantov elaborated mathematical models that quantified both hypotheses and his collaborators performed the numerical computations. It was found that, for the Cold Faithful model, the explosive boiling can't provide the velocities of icy particles observed in the plume. It also found that the low temperatures of the Frigid Faithful model implied a too dilute vapour to support the observed high particle fluxes in Enceladus' plume.

In the same year, the same team published a novel hypothesis [2], underpinned by the new mathematical model by Brilliantov, to explain the icy geysers. The explanation was a liquid water ocean with a large vapour reservoir below Enceladus' south pole. Smaller velocities for the geyser's grains than for the vapour had been difficult to understand. The gas and dust were too dilute in the plume to interact, so the difference had to arise below the surface. The team published a model for grain condensation and growth in channels of variable width showing that repeated wall collisions of grains, with re-acceleration by the gas, induced an effective friction, offering a natural explanation for the reduced grain velocity. The gas seemed to form near the triple point of water; gas densities corresponding to sublimation from ice are generally too low to support the measured particle fluxes. This in turn suggested liquid water ocean below Enceladus' south pole. This theory was in a quantitative agreement with data gathered so far by Cassini.

In 2009, Brilliantov elaborated a theory quantifying the sodium content in the icy geysers. He provided the mathematical modelling expertise , in a the team comprising colleagues from Potsdam, Heidelberg, Gottingen and Leicester, providing strong evidence [3] that supported the

theory that liquid water, rather than frozen water, below Enceladus' south pole was responsible for the icy geysers. After studying data from the Cosmic Dust Analyzer (CDA) on board the Cassini spacecraft and combining this data with laboratory experiments, the team reported the detection of sodium salts among the dust ejected in the Enceladus plume, hinting at the salty ocean deep below and thus confirming their theory. The results of the study imply that the concentration of sodium chloride in the ocean can be as high as that of Earth's oceans.

Brilliantov's mathematical model was combined with computational modelling of the grain sizes and laboratory experiments performed by the rest of the team. This explained the observed concentration of salt in icy grains, especially, for the part of grains with a low salt concentration. Their conclusion through analysis of the distribution of grain size, was that the type and speed of particles could only have been produced from liquid water, hence the hypothesis of the existence of a subterranean ocean and the conclusion that the grain sizes and speed were unlikely to damage Cassini.

This work enabled NASA to conclude that the risks were such that it deemed 'safe' for the mission to fly closer to the moon's surface and thus undertake the exploration leading to the subsequent important discoveries.

3. References to the research

1. N. Brilliantov, J.Schmidt and F. Spahn, Geysers of Enceladus: Quantitative analysis of Qualitative models, Planetary and Space Science, 56 (2008), pp. 1596-1606.

2. J. Schmidt, N. Brilliantov, F. Spahn, and S. Kempf, Slow dust in Enceladus' plume from condensation and wall collisions in tiger stripe fractures, Nature, 451 (2008), pp. 685-688.

3. F. Postberg, S. Kempf, J. Schmidt, N. Brilliantov, A. Beinsen, B. Abel, U. Buck & R. Srama, Sodium salts in E-ring ice grains from an ocean below the surface of Enceladus, Nature, 459 (2009) pp. 1098 -1101

4. Details of the impact

The Cassini Missions

Cassini–Huygens is a flagship-class NASA-ESA-ASI robotic spacecraft sent to the Saturn system. It has studied the planet and its many natural satellites since arriving there in 2004, also observing Jupiter, the Heliosphere, and testing the theory of relativity. Sixteen European countries and the United States make up the team responsible for designing, building, flying and collecting data from the Cassini orbiter and its Huygens probe. Cassini completed its initial four-year mission to explore the Saturn System in June 2008 and the first extended mission, called the Cassini Equinox Mission, in September 2010.

Cassini's discovery of an icy plume shooting from one of Saturn's moons, and subsequent observations of the spray containing complex organic chemicals have caused much debate and conjecture on the part of astronomers. Brilliantov's work has helped to identify warm, liquid water ocean encased beneath the surface of Enceladus' moon as being the most likely cause of the icy geysers.

Evaluation of flightpath

Brilliantov's work was used by NASA in the planning of the Cassini mission in 2009-2010 in an absolutely fundamental way. The contribution is summarised in a statement by one of the Principal Investigators of the Cassini Mission, Prof. L. Esposito, who wrote that:

"… the model of Schmidt et al 2008 (J. Schmidt, N. Brilliantov, F. Spahn, and S. Kempf, Nature, 451 (2008) 685) has been used to evaluate the planned flybys of the spacecraft of the Cassini mission in 2009-2010, allowing the mission designers to calculate the danger of the Cassini Spacecraft colliding with dust in the Enceladus plumes and jets. This has allowed NASA's Cassini Project to reduce the hazardous impacts of the probe with the ice grains within the Enceladus plume."

Economic impact

The total cost of the mission was about **$3.26 billion**, which was paid for by the US, the European and the Italian Space Agencies. Had the Cassini spacecraft collided with the plumes due to failure to take account of the research underpinning this impact case, this significant investment would have been largely lost.

Cultural impact

The team's research enabled the Cassini mission to carry out a very close sweep of the moon and capture unique data that provided further evidence of the presence of a subterranean sea and verification of the chemical composition of the moon's atmosphere.

The significance of the presence of the liquid water sea has implications for mankind. Tidal heating is keeping Enceladus warm and hotspots associated with the fountains have been pinpointed. With heat, organic chemicals and, potentially liquid water, Enceladus could be a place where primitive life forms might evolve. Questions surrounding Enceladus' "astrobiological potential" are at the heart of many investigations being conducted in the Solstice Mission. Because of its large astrobiological potential a forthcoming European mission "**Enceladus Explorer**" is planned including a base station on the Enceladus surface and ice drilling to examine the liquid ocean for any traces of microorganisms.

The mission has inspired extensive media and public interest on a global scale. The discovery of the underground ocean and potential life in outer space has, understandably, been the source of widespread media coverage reaching millions of people (e.g. New York Times articles reaching almost 2 million readers plus online hits).

Social media statistics also illustrate how inspiring this story is to the general population. As of June 2013 #Enceladus had almost 35,000 mentions (76% of which were retweets showing that the stories have gone viral) and Life on Saturn is searched for by 5,400 people a month on Google.

NASA has a comprehensive outreach programme and has disseminated the findings of the Cassini mission to millions of people including well used teaching materials in schools. One of the top documentary films of 2010 "**7 Wonders of the Solar System**" annotates "*The seven wonder of our solar system are discussed: Enceladus' geysers, Rings of Saturn, Jupiter's Great Red Spot, the Asteroid Belt, Mars' Olympus Mons, the Surface of the Sun, and planet Earth";* it has been watched by several hundred thousand people.

5. Sources to corroborate the impact

1. Factual statement from the Principal Investigator of the Cassini Ultraviolet Imaging Spectrograph (LASP, Boulder, USA).
2. Article from the New York Times, "Saturn Imitates Louis XIV", February 28, 2008: http://tierneylab.blogs.nytimes.com/2008/02/28/saturn-imitates-louis-xiv/
3. Report from the BBC on the underground sea on Enceladus on 25 June 2009: http://news.bbc.co.uk/1/hi/sci/tech/8115148.stm
4. Statement from the Co-Investigator of the Cosmic Dust Analyser on the Cassini Spacecraft.
5. Article in Sciencedaily http://www.sciencedaily.com/releases/2008/02/080222112324.htm
6. Article in Physorg http://www.physorg.com/news122898790.html
7. Report by The Cheers News Agency http://newsagency.thecheers.org/Science/news_12848_Scientists-unravel-secret-behind-Saturns-moons-mysterious-plumes-of-dust-and-water-vapour.html
8. Report in Thaindian News http://www.thaindian.com/newsportal/health/scientists-unravel-secret-behind-saturns-moons-mysterious-plumes-of-dust-and-water-vapour-2_10020607.html
9. JPL News Feature http://saturn.jpl.nasa.gov/news/cassinifeatures/

10. On Space.Com http://www.space.com/4935-mystery-saturn-watery-moon-solved.html

11. NASA report http://www.nasa.gov/mission_pages/cassini/whycassini/cassinif-20080207.html