By working together, GRAIL's two probes will map the gravity of both the near and far sides of the Moon.

LUNAR SCIENCE

Twins to probe Moon's heart

NASA mission will survey lunar gravity to map the dense rock beneath the surface.

BY ERIC HAND

The Moon's face is an open book, but its deeper nature is still a mystery. Probes from Europe, Japan, India, China and the United States have imaged the lunar surface in exquisite detail, mapped its minerals, looked for evidence of water and scouted for potential landing sites. Now Maria Zuber, principal investigator for NASA's Gravity Recovery and Interior Laboratory (GRAIL) mission, which is set to launch on 8 September, wants to reveal the Moon's hidden history.

"I think we're going to find something quite surprising," says Zuber, a geophysicist at the Massachusetts Institute of Technology in Cambridge. Her confidence stems from the maps of lunar gravity that GRAIL is set to provide — orders of magnitude better than any before. The density variations they aim to reveal in the subsurface rock should shed light on the Moon's tumultuous and geologically active past, help to determine whether it has a liquid core and yield clues to the underlying structure of its giant impact basins, the lunar 'maria'.

The GRAIL mission consists of twin spacecraft that are near replicas of the Gravity Recovery and Climate Experiment (GRACE),

a pair of satellites that have orbited Earth since 2002, mapping the planet's gravity field so finely that they could see shifts in groundwater aquifers and ocean currents. Adapting that flight-tested technology helped to keep the cost of GRAIL to US\$496 million. Another saving came in mission design: instead of blasting straight to the Moon, the spacecraft will ease into a lunar polar orbit after a three-and-a-half month journey, and only a modest amount of fuel will be needed for slowing down.

Apart from four cameras on each spacecraft, which will capture images for public outreach, GRAIL carries only one instrument — and it isn't even pointed at the Moon. As the two spacecraft coast 55 kilometres above the lunar surface, and 60–225 kilometres apart, a high-frequency radio link will measure the exact distance between them. As one probe approaches a high-density object — for example, a mountain — it will feel a slightly stronger gravitational force and will momentarily speed up, changing the separation from its companion. For GRAIL to deliver on its promise, such movements will need to be measured to a fraction of a micrometre. Such precision

will require taking into account the gravitational influence of distant planets, the movement of tectonic plates under tracking stations on Earth and even the pressure of sunlight on the spacecrafts' solar panels, says Zuber.

The Moon's gravity has already been mapped less precisely, by measuring, from Earth, the shifts in the speed of a single lunar orbiter — but this is impossible when the orbiter goes behind the Moon. SELENE (Kaguya), a Japanese mission launched in 2007, mapped gravity on the far side with the help of a relay satellite that orbited at a higher altitude, within radio-sight of both Earth and SELENE. But Zuber says that GRAIL's maps will be far more precise — even better than GRACE's maps of Earth, because the effects of Earth's atmospheric drag mean that the GRACE spacecraft have to orbit at altitudes ten times higher than GRAIL will.

One science target will be the Moon's deep structure. By bouncing lasers off reflectors left by the Apollo astronauts, researchers have picked up hints of a subtle wobbling, suggesting the presence of a soft core. Zuber says GRAIL should be able to confirm those hints, and might also find surprising additions to the core — for instance, by discerning whether compounds such as titanium oxide crystallized and sank into the core when the Moon was initially a ball of magma.

The overall findings could illuminate how planets in the inner Solar System cooled into layered structures. "It transcends just knowing about the Moon," says geologist Brad Jolliff of Washington University in St Louis, Missouri. "It helps us to understand how other rocky bodies differentiate." By probing the rocks around impact basins, Zuber says, GRAIL should also help modellers to understand the dynamics of giant impacts.

NASA's plans for exploring the Moon after GRAIL's 90-day mission are uncertain, says Chip Shearer, a planetary geologist at the University of New Mexico in Albuquerque and chair of NASA's Lunar Exploration Analysis Group. A wave of missions designed to support NASA's now-defunct Constellation programme, which envisioned returning humans to the Moon by 2020, is tapering off (see 'Moon rush'). The last of these, the Lunar Atmosphere and Dust Environment Explorer (LADEE), a mission to measure the effects of the Moon's fine dust, is due to launch in 2013. But two lunar science priorities aren't being addressed. A proposed mission, led by Jolliff, to return samples from the Moon's largest impact basin, near the south pole, lost out to a mission to return an asteroid sample. And advocates for the International Lunar Network, once a NASA-led endeavour to set up seismic detectors on the Moon's surface, have been told that they will have to compete for NASA's support with everybody else's Solar System proposals.

"We know what, in terms of lunar science, should come next," says Shearer. "But we don't know what will come next." ■

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NASA

MOON RUSH

The wealth of lunar missions in the past two decades is not set to last.

1994

NASA's Clementine hints at existence of water at lunar south pole (pictured).

1998

NASA's Lunar Prospector allows gravity map of the Moon's near side.

2004

United States unveils 'vision' to return astronauts to the Moon.

SMART-1, Europe's first lunar orbiter, launched.

2007

Japan's SELENE (Kaguya) produces gravity map of the far side.

Launch of Chang'e, China's first lunar orbiter.

Google supports US\$30-million Lunar X Prize for first private team to put a rover on the Moon.

2008

India's Chandrayaan-1 finds evidence of watery minerals.

2009

NASA's Lunar Reconnaissance Orbiter finds water in shadowed polar craters.

2010

Chang'e 2 launches.

NASA human space policy revised to target asteroids before the Moon.

2011

GRAIL due to launch.

2013

NASA's Lunar Atmosphere and Dust Environment Explorer (pictured, below) is scheduled to launch.

NASA/AMES

COLLABORATION

Red tape puts chill on Siberian research

High-profile carbon project to proceed, but with a proviso.

BY QUIRIN SCHIERMEIER

One of Russia's most prominent international science projects has fallen foul of cold-war-era concerns. An expedition to study carbon transport around Siberia's Yenisey River has been postponed for a year after officials blocked the use of sampling equipment and put some sites off-limits. The episode highlights the tension between Russia's bureaucracy and its growing ambition to develop wider research collaborations — part of a strategy to revitalize domestic science.

In July, Ernst-Detlef Schulze, a carbon-cycle researcher and founding director of the Max Planck Institute for Biogeochemistry in Jena, Germany, and 35 scientists from Germany, the Netherlands, France and Russia, had their bags packed for the journey to Siberia.

Then they received a letter from the Russian Federal Security Service prohibiting them from using any Western equipment on the trip. Schulze, who last year received a 150-million-ruble (US\$5-million) grant from the Russian government to do research in Siberia, was aghast. "When I first saw the letter I just couldn't believe what I read," he says. "I was so disappointed and furious I went to my own forest and lumbered trees until I was exhausted."

Western scientists participating in the 12-billion-ruble 'mega-grant' programme that funds Schulze (see *Nature* 473, 428–429; 2011) have previously complained about excessive bureaucracy and frequent problems with export control and customs, and have received support from the Russian science minister, Andrei Fursenko (see *Nature* 465, 858; 2010).

So Schulze and his co-workers at the Siberian Federal University in Krasnoyarsk used diplomatic channels to try to reverse the ruling. Equipment worth €600,000 (US\$865,000) was already in Siberia, ready to be used to calculate the carbon budget of the Yenisey's huge catchment area (see map). Siberia's soils and forests serve as one of Earth's largest carbon sinks, but the carbon flux between ecosystems there has never been studied in detail.

At a hastily arranged meeting in Moscow on 4 August, Fursenko said that he regretted the situation and promised to try to find a solution. A week later, the expedition was given clearance to begin on 1 September — but with restrictions that Schulze found unacceptable. Sampling tools, for instance, could be handled only by

D. SCHULZE

Russian staff — most of whom are not trained to use the geochemical analysis equipment, says Schulze. The Russian Federal Services for Technology and Export Control also refused to approve the purchase of equipment in the West, such as a freeze-dryer to preserve samples.

"This is not the way to do science," says Han Dolman, an environmental scientist at the VU University Amsterdam. Dolman had planned to study how carbon is transported from soils into the Yenisey River, and how much of the organic carbon dissolved in the river becomes carbon dioxide. Unlike on land, carbon exchange in aquatic systems is poorly understood.

On 12 August, Schulze threatened to cancel the expedition, but further negotiations yielded a compromise: the trip will take place next year, with the only restriction being a ban on taking samples from a roughly 20,000-square-kilometre area around Krasnoyarsk, where Russia operates a nuclear-reprocessing facility.

The saga shows that scientists do not yet have enough freedom in their research in Russia, says Schulze. "There's an absurdly opaque and often arbitrary bureaucracy at work. Thankfully, Fursenko was always clearly on our side." ■

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