for full contact with the differential equations that describe reconnection. One of the four spacecraft is placed in the desired orbit and the other three are maneuvered relative to it, using periodic thruster firings. Position is measured by a navigator system that is the first to use the global positioning system (GPS) from outside the GPS constellation. The MMS orbits are coordinated with those of the NASA THEMIS (Time History of Events and Macroscale Interactions during Substorms) mission, which currently measures conditions on the opposite side of the magnetosphere with a more extended constellation of three spacecraft.

Each MMS spacecraft carries an identical instrument complement that includes suites for plasmas, energetic particles and fields, as well as two active spacecraft potential control devices and a central instrument data processor. The control devices neutralize the electrical potential of the spacecraft, which not only allows measurement of low-energy ions and electrons but also eliminates spurious electric fields that can contaminate double-probe measurements. The data processor provides the interface between the instruments and the spacecraft command and data handling subsystem, which implements a mass memory module and burst data system with storage sufficient for 4–5 days of data. Only a fraction of the full-resolution data can be telemetered. The high-resolution data is first reduced to survey data products that are sent from the four spacecraft to the ground. Then events of interest are identified, and finally the spacecraft are told which full-resolution data should be sent. The download, processing and upload process includes automated steps that can be overridden or modified by ground personnel.

The MMS mission is a significant step towards understanding when, where and how explosively magnetic reconnection occurs. Every bit of experience and skill gained in previous missions has been integrated into the MMS science payload, and we expect to learn a huge amount about this universal process as the mission begins to operate in September. At the time of writing, a smooth launch has placed the spacecraft in the specified orbits, nearly all of the instruments have been activated, checked out, and are being commissioned and inter-calibrated. All systems are working well as we enter a few weeks of eclipse season, during which commissioning will stand down, followed by several more weeks of activations, inter-calibrations and preparations of the ground system for full operation and arrival of the MMS constellation in the dayside region of interest for its first reconnection studies. ❐

Thomas Earle Moore is at NASA's Goddard Space Flight Center, Greenbelt, Maryland 20771, USA. James L Burch is at Southwest Research Institute, San Antonio, Texas 78238, USA. Roy B. Torbert is at the University of New Hampshire, Durham, New Hampshire 03824, USA.
e-mail: thomas.e.moore@nasa.gov

References

1. Priest, E. & Forbes, T. *Magnetic Reconnection: MHD Theory and Applications* (Cambridge Univ. Press, 2000).
2. Burch, J. L. & Drake, J. F. *Am. Sci.* **97,** 392 (2009).
3. Daughton, W. *et al. Nature Phys.* **7,** 539–542 (2011).
4. Moore, T. E. *et al. J. Atmos. Solar. Terr. Phys.* **99,** 32–40 (2013).
5. Burch, J. L. *et al. Space Sci. Revs.* http://doi.org/6c4 (2015).
6. Fuselier, S. A. *et al. Space Sci. Revs.* http://doi.org/5pw (2014).

Acknowledgements

This work was supported by the NASA Magnetospheric MultiScale mission and its partners.

LISA and its pathfinder

Karsten Danzmann for the LISA Pathfinder Team and the eLISA Consortium

On astronomical scales, gravity is the engine of the Universe. The launch of LISA Pathfinder this year to prepare the technology to detect gravitational waves will help us 'listen' to the whole Universe.

The past century has seen enormous progress in our understanding of the Universe. We know the life cycles of stars and the structure of galaxies, have seen the remnants of the Big Bang, and have a general understanding of how the Universe evolved. We have gone remarkably far using electromagnetic radiation as our observational tool. However, gravity is the engine behind many of the processes in the Universe, and much of its action is dark. Opening a gravitational window on the Universe will let us go further than any alternative. Gravity has its own messenger: gravitational waves, ripples in the fabric of spacetime. They travel essentially undisturbed and let us peer deep into the formation of the first seed black holes, exploring redshifts as large as $z \sim 20$, prior to the epoch of cosmic re-ionization. Exquisite and unprecedented measurements of black hole masses and spins will make it possible to trace the history of massive black holes across all stages of galaxy evolution, and at the same time constrain any deviation from the Kerr metric of general relativity.

Making it happen

The European Space Agency (ESA) recently selected 'The Gravitational Universe' as the science theme for its third large space mission, L3, with a foreseen launch date in 2034. The reference mission for this theme is a large space-based laser-interferometric gravitational wave observatory, known as the Laser Interferometer Space Antenna, or LISA. It has been under intense study for the past two decades both by the ESA and the US space agency NASA. Since 2011, the ESA has been proceeding alone, with studies that are continuing under the name eLISA (evolving LISA)[1,2], but it is expected that NASA will be back in the boat soon.

In this Commentary, I use the name LISA as the trademark for an observatory of low-frequency gravitational waves using laser interferometry between free-flying test masses shielded by drag-free spacecraft at the corners of an equilateral triangle with million-kilometre arm lengths in heliocentric orbit some ten million kilometres from the Earth.

The fantastic science

LISA will be the first ever mission to allow the study of the entire Universe with gravitational waves. LISA is an all-sky monitor and will offer a wide view of a dynamic cosmos using gravitational waves as unique messengers. It will give us the closest ever view of the early processes at TeV energies, provide observations of guaranteed sources in the form of verification binaries in the Milky Way, and enable us to probe the entire Universe, from its smallest scales around singularities and black holes, all the way to cosmological dimensions.

Box 1 | LISA Pathfinder mission facts.

Objective. Demonstrate the most important LISA technologies in space and validate a complete noise model.

Method. Drag-free operation at Lagrange point L1, featuring laser interferometry between two free-flying test masses in one satellite.

Launch. End of 2015.

Duration. Six months for nominal mission.

Orbit. Halo orbit around Earth–Sun Lagrange point L1.

Instrument suite. Laser interferometer, free-flying test masses, gravitational reference sensor, drag-free operation and micro-Newton thrusters.

Team. ESA, France, Germany, Italy, NASA, Netherlands, Spain, Switzerland and the UK.

Scientific landscape of 2030

Naturally, science is not predictable, and the most interesting discoveries between now and 2030 will be the ones we cannot predict! But planned projects already hint at where the frontiers of science will be when LISA operates. For example, massive progress can be expected in transient astronomy. Telescopes like the Large Synoptic Survey Telescope (LSST)[3] and the Square Kilometre Array (SKA)[4] are likely to identify new systems that flare up irregularly or only once, and there is a good chance that some of these will be associated with gravitational wave signals. As another example, extremely large telescopes — the European Extremely Large Telescope (EELT), Thirty Meter Telescope (TMT) and Giant Magellan Telescope (GMT) — and large space telescopes — the James Webb Space Telescope and Athena — will be observing (proto-)galaxies at unprecedentedly high redshifts, at which LISA will simultaneously observe individual merging black hole systems.

Gravitational wave science by 2030

By 2030, gravitational wave astronomy will be well established through ground-based observations operating at 10 Hz and above, and pulsar timing arrays (PTAs) at nHz frequencies. The huge frequency gap between them will be completely unexplored until LISA is launched.

The ground-based network of advanced interferometric detectors — three LIGO detectors, VIRGO[5] and the Kamioka Gravitational Wave Detector (KAGRA)[6] — will have observed in-spiralling binaries up to around 100 solar masses ($M_\odot$) and measured the population statistics. It is possible that the third-generation Einstein Telescope will have come into operation by 2030[7], further extending the volume of space in which these signals can be detected. At the other end of the mass spectrum, PTAs[8] will have detected a stochastic background due to many overlapping signals from supermassive black hole binaries with masses over $10^9\ M_\odot$, and they may have identified a few individual merger events. The background will help determine the mass function of supermassive black holes at the high-mass end, but it will not constrain the mass function for the much more common $10^6\ M_\odot$ black holes that inhabit the centres of typical galaxies and that are accessible through LISA observations. Besides making high-sensitivity observations of individual systems, LISA will give us the chance to characterize the population statistics of black holes in the centres of galaxies, of intermediate-mass black holes and of the early black holes that eventually grew into the supermassive holes we see today.

© ESA/ASTRIUM UK

Figure 1 | LISA Pathfinder. The image shows the LISA Pathfinder satellite in preparation. The payload is now completed and we expect that by July integration will be finished and final environmental tests will be underway in preparation for shipment to the launch site in Kourou, French Guiana, for a launch at the end of 2015.

LISA and fundamental science in 2030

One of the signature goals of the LISA mission is to test gravitation theory, and it seems unlikely that any other method will achieve the sensitivity of LISA to deviations of strong-field gravity by 2030. Unlike ground-based instruments, LISA will have sufficient sensitivity to allow us to detect small deviations from the general theory of relativity, and possibly to recognize unexpected signals that could indicate new phenomena.

By observing the long-duration waveforms from extreme mass ratio inspiral (EMRI) events, LISA will allow us to map with exquisite accuracy the geometry of supermassive black holes, and will detect or limit extra scalar gravity-type fields. X-ray and other electromagnetic observatories may measure the spins of a number of black holes, but LISA's ability to follow EMRI events and merge signals through to the formation of the final horizon will not have been duplicated, nor will its ability to identify naked singularities or other exotic objects (such as boson stars or gravastars), if they exist.

By 2030 we will know much more about the large-scale Universe: in particular, about the nature of dark energy from the upcoming optical/infrared surveys dedicated to probing large-scale structure. However, only detections of gravitational waves can probe the period in the evolution of the Universe ranging from reheating after inflation until Big Bang nucleosynthesis. LISA can thus gather information about the state of the Universe at much earlier epochs than those directly probed by any other cosmological observation.

The information contained in gravitational waves from the early Universe is complementary to that accessible by particle accelerators. The presence of a first-order phase transition at the TeV scale, the presence of cosmic (super-)strings in the Universe, the properties of low-energy inflationary reheating, even the nature of the quantum vacuum state before inflation began, are some of the fundamental issues that will still be open in 2030, and to which the LISA mission might provide some answers.

LISA and cosmology in 2030

By 2030 observations may well have constrained the supermassive black hole mass spectrum from a few times $10^{10}\ M_\odot$, or even higher, down to around $10^{7}\ M_\odot$, but probably not into the main LISA range of 10^4–$10^6\ M_\odot$, especially at $z > 2$. LISA observations will fill this gap and also provide a check on selection effects and other systematics of the electromagnetic observations. By being able to measure the masses and spins of massive black holes as a function of redshift out to $z = 20$, LISA will allow us to greatly improve models of how supermassive black holes grow so quickly, so as to be in place at $z \sim 7$.

LISA and massive black holes in 2030

LISA has extraordinary sensitivity to massive black holes in the mass-range of most galactic-core black holes. Gravitational wave detectors like LISA are inherently all-sky monitors: always on and having a nearly 4π field of view. They naturally complement other surveys and monitoring instruments operating at the same time, like LSST, SKA, neutrino detectors, gamma-ray and X-ray monitors. The massive black hole mergers detected by LISA out to modest redshifts ($z = 5$–10) could well be visible to SKA and LSST as transients in the same region of the sky. The identification of 5 to 10 counterparts during a two-year LISA mission would not be surprising. These might then be followed up by large-collection-area telescopes like TMT, GMT and EELT, providing an unprecedented view of the conditions around two merging massive black holes.

Technology status

All critical technologies for LISA have been under intense development for more than 15 years, and today all are available in Europe and almost all in the US. The interferometry with million-kilometre arms cannot be directly tested on the ground, but it is being studied through scaled experiments and simulations. All other technologies are being tested on the precursor mission LISA Pathfinder, to be launched at the end of 2015 (Box 1). The LISA Pathfinder satellite (Fig. 1) carries the LISA Technology package (LTP) provided by European member states. The LTP is a complete system resembling a LISA arm shortened to 38 cm, it employs two gravitational reference sensors containing the free-falling test masses, an optical metrology system for laser interferometry between the test masses, a discharge system, a diagnostic package, and a drag-free and attitude control system (DFACS). Two different micro-propulsion systems will be carried on board the LISA Pathfinder: a set of cold-gas thrusters provided by ESA and a set of colloid thrusters provided by NASA. The latter is part of the ST7 DRS (disturbance reduction system) payload, which will provide an independent test of DFACS using the European LTP as the reference sensor.

The 2015 LISA Pathfinder flight provides a final verification and in-orbit commissioning of these systems and most of the LISA metrology capability. After a successful LISA Pathfinder flight, the worldwide scientific community will be poised to begin this revolutionary new science. ❒

Karsten Danzmann is at Leibniz Universität Hannover and the Max Planck Institute for Gravitational Physics, Callinstr. 38, D-30167 Hannover, Germany. The complete list of authors and contributors is available at http://elisascience.org/authors and http://elisascience.org/contributors.
e-mail: danzmann@aei.mpg.de

References

1. Jennrich, O. *et al. NGO: Revealing a Hidden Universe: Opening a New Chapter of Discovery* (ESA, 2012); http://sci.esa.int/cosmic-vision/NGO_YB.pdf
2. Amaro-Seoane, P. *et al. Doing Science with eLISA: Astrophysics and Cosmology in the Millihertz Regime* (eLISA, 2012); http://elisascience.org/whitepaper
3. Merloni, A. *et al.* Preprint at http://arxiv.org/abs/1209.3114 (2012).
4. Aharonian, F. *et al.* Preprint at http://arxiv.org/abs/1301.4124 (2013).
5. Aasi, J. *et al.* Preprint at http://arxiv.org/abs/1304.0670 (2013).
6. Somiya, K. *Class. Quantum Grav.* **29,** 124007 (2012).
7. Punturo, M. *et al. Class. Quantum Grav.* **27,** 194002 (2010).
8. Hobbs, G. *et al. Class. Quantum Grav.* **27,** 084013 (2010).

Ψ in the sky

Kai Bongs, Michael Holynski and Yeshpal Singh

Quantum technologies, including quantum sensors, quantum communication and quantum metrology, represent a growing industry. Out in space, such technologies can revolutionize the way we communicate and observe our planet.

Most of modern technology — primarily transistors and lasers — is based on our understanding of the quantum rules governing energy levels and electronic transport in conductors and semiconductors. This ‘Quantum 1.0’ technology relies on many-body quantum effects without the need for control at the single-particle level. We are now on the verge of a Quantum 2.0 revolution, where single-particle control enables us to harness more advanced aspects of quantum mechanics, such as superposition and entanglement. The new quantum technologies include quantum communication, quantum computing, quantum imaging, quantum metrology, quantum sensors and quantum simulation. Extrapolating from the economic impact of Quantum 1.0, expectations are high, driving an estimated global research budget of €1.5 billion with over 7,000 active researchers in this area worldwide. A particular push towards technology is the UK Quantum Technologies Program investment of €370 million over 2014–2019 as a first step in implementing a pioneering Quantum Technologies Strategy (http://go.nature.com/sZafBA).

Some Quantum 2.0 developments already offer substantial benefits over

Correction

In the Commentary 'LISA and its pathfinder' (*Nature Physics* **11,** 613–615; 2015), in Box 1 Italy and Spain were mistakenly omitted from the list of mission team members. This error has been corrected in the online versions 20 August 2015.