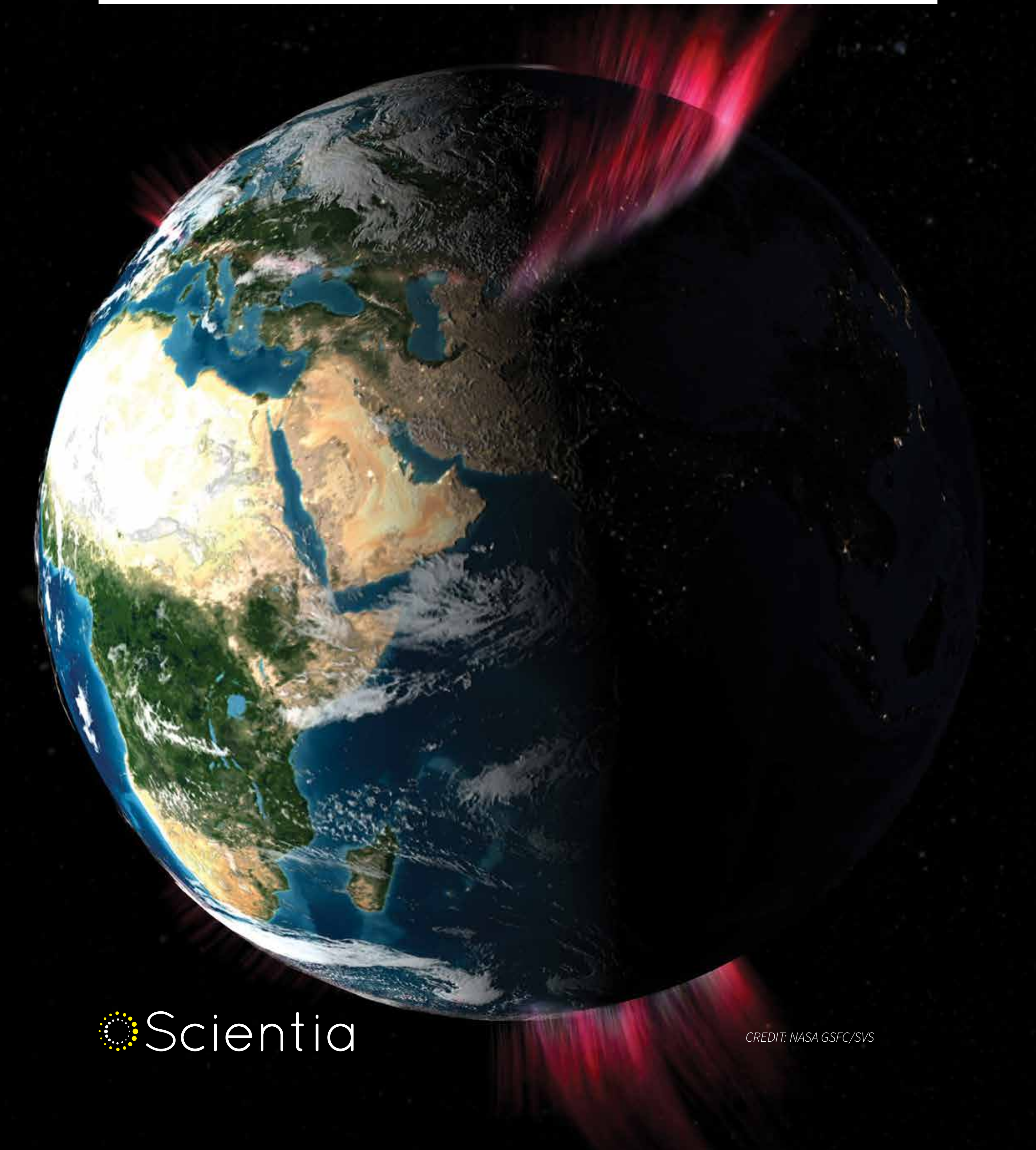
From THEMIS to ELFIN: Exploring Near Earth Space

Professor Vassilis Angelopoulos



CREDIT: NASA GSFC/SVS

Scientia

FROM THEMIS TO ELFIN: EXPLORING NEAR EARTH SPACE

Dr Vassilis Angelopoulos and his colleagues at the UCLA Earth Planetary and Space Sciences Department in California study the interaction of solar radiation with the Earth's magnetosphere using multiple NASA research satellites. Their aim is to protect our modern technology from being ravaged by solar storms while educating the next generation.

Too Much of a Good Thing

The Sun is ultimately the engine of all life on Earth. The radiation from our Sun powers our atmosphere, provides our food and supports the Earth's entire biosphere. Without energy from the Sun, all life would end and the Earth would eventually become a cold, dark planet. But on occasion, the Sun puts out a little too much energy in the form of solar flares.

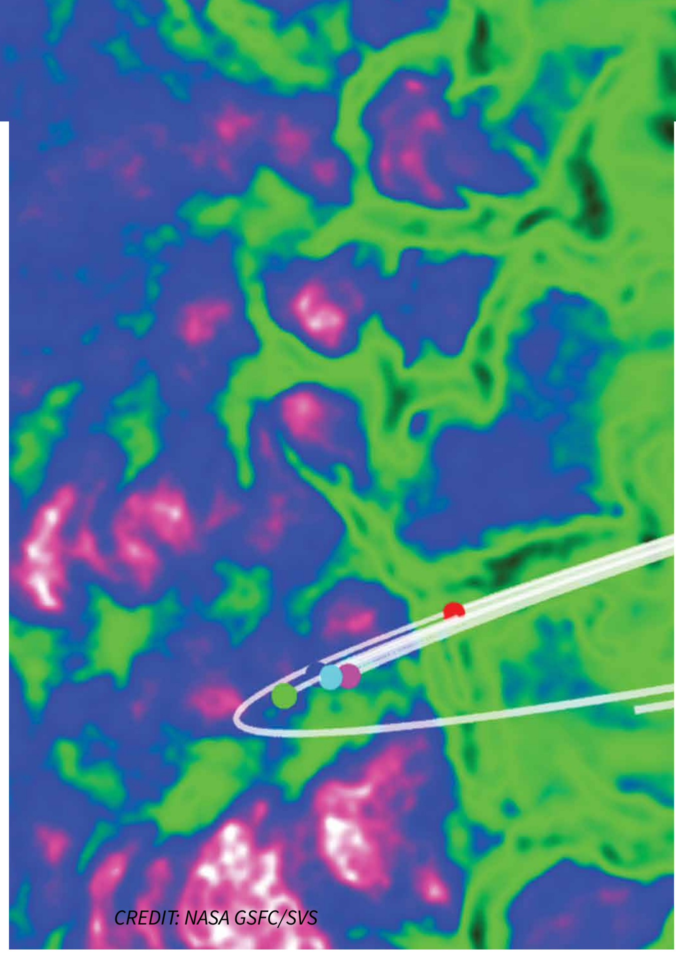
First described back in 1859 by the amateur astronomers Richard C. Carrington and Richard Hodgson, a solar flare is a sudden and massive release of magnetic energy – on the order of millions of hydrogen bombs – that travels outward into the solar system, interacting with objects in its path. In particular, ionised particles and magnetic fields released from solar flares, in the form of coronal mass ejections, interact with Earth's magnetic field, and can cause huge damage to electrically sensitive equipment. This is important for us on Earth, since our civilisation has become increasingly dependent upon complex electronics.

Solar storms and solar flares can disable satellites, threaten orbiting astronauts and overload electric transformers on Earth. In fact, former US President Obama warned that such phenomena could 'significantly degrade critical infrastructure – could disable large portions of the electrical power grid, resulting in cascading failures that would affect key services such as water supply, healthcare, and transportation.' In other words, solar storms might cause system wide power failures that don't just turn off the lights. They could also lead to a massive human toll when food, water and other necessities cannot be distributed, leading to disease, famine and even death on a global scale.

This is exactly the scenario Dr Angelopoulos and his colleagues are interested in forecasting and preventing from happening. He tells *Scientia* that he and his team have been 'studying space weather, and in particular one aspect in greater detail: how does solar energy become converted into the harmful radiation that zaps satellites, threatens astronauts and creates space electrical currents which can fry transformers of the power grid on the ground?' This energy conversion, which powers damaging magnetic storms, is not easy to figure out, but by using advanced satellites orbiting the Earth and the Moon, Dr Angelopoulos and his team are making some headway.

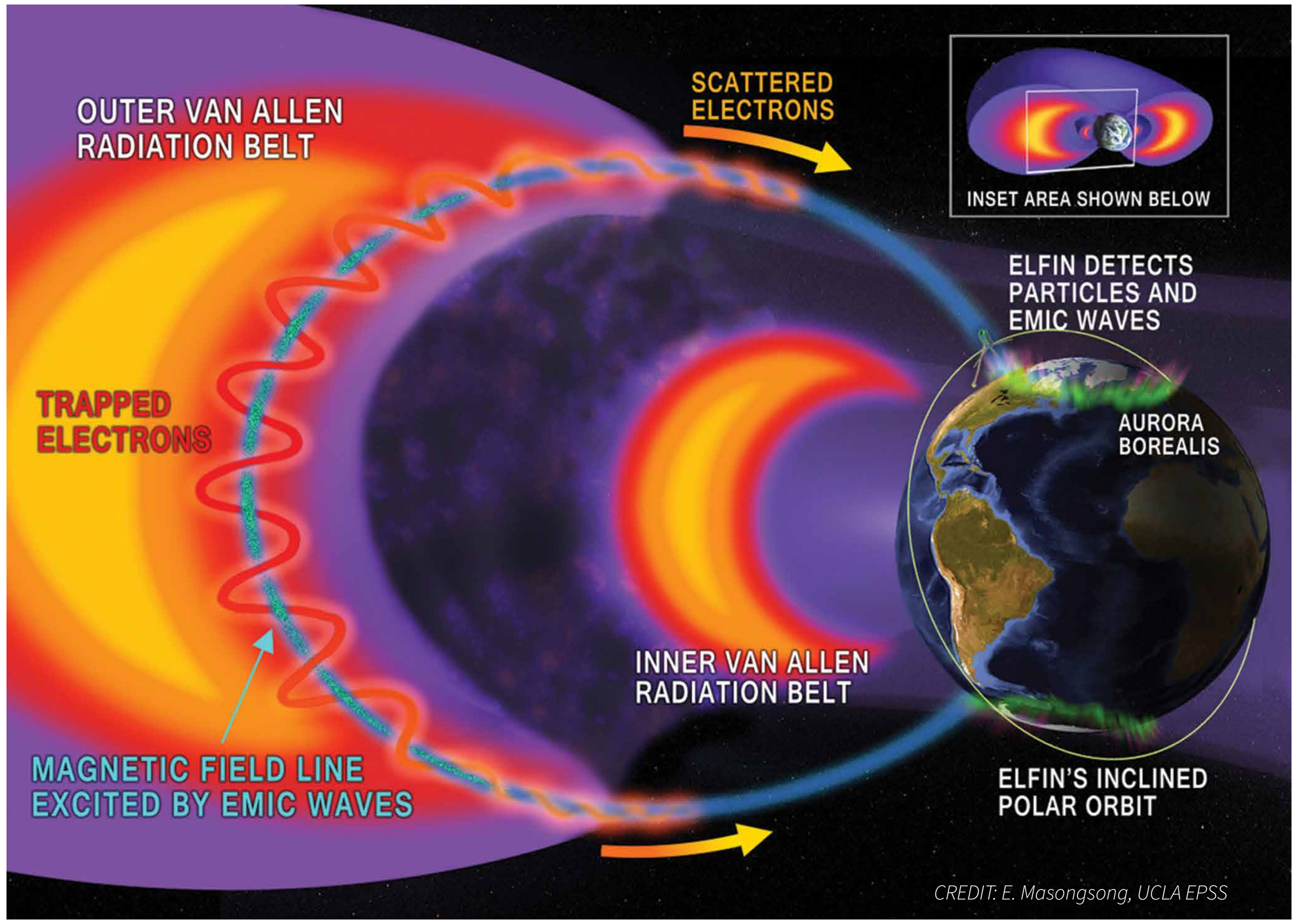
Probing Energies in Near Earth Space

As the energy released from the Sun – called the solar wind – flows past the Earth, it interacts with the Earth's magnetosphere. The solar wind is composed primarily of high-energy plasma – matter that is so energised that it becomes ionised, with electrons being ripped from atoms and molecules. Since plasma is ionised and therefore magnetic, it interacts with magnetic fields, like the magnetic field of the Earth. The Earth, with its spinning metallic core, is after all a large magnet, with a north pole and a south pole. The resultant magnetic field surrounding the Earth – the magnetosphere – deforms the solar wind and diverts its flow, while the solar wind deforms the magnetosphere as well. On the dayside of the Earth, which faces towards the Sun, the pressure of the solar wind compresses the magnetosphere closer to the Earth. On the night side of the Earth facing away from the Sun, the solar wind drags the magnetosphere out over great distances, forming a tail similar to that of a comet. The interaction between the magnetosphere and solar wind causes massive bursts of energy that can often be seen from the Earth's surface as aurorae – dramatic light shows especially at higher latitudes. In the northern hemisphere, aurorae are termed the aurora borealis, while in the southern hemisphere, it's the aurora australis. Up until a decade ago, the mechanism by which aurorae and other solar wind phenomena were generated were not well understood. However, since 2007, satellite probes have been exploring the regions of space where the solar wind and the Earth's magnetosphere interact, sending back information to explain what's going on in our neighbourhood. These probes are the result of a major effort by Dr Angelopoulos and his colleagues at UCLA. Under the mission names of THEMIS and ARTEMIS, the probes have been exploring the physical processes occurring between the magnetic field and solar wind, to understand the causes of the aurorae and magnetic storms in the Earth's magnetosphere. Here we discuss the team's ground-breaking discoveries to date, along with their plans to launch a new mission – called ELFIN – which aims to investigate electrons in the hazardous radiation belts around earth.



CREDIT: NASA GSFC/SVS

CREDIT: NASA GSFC/SVS



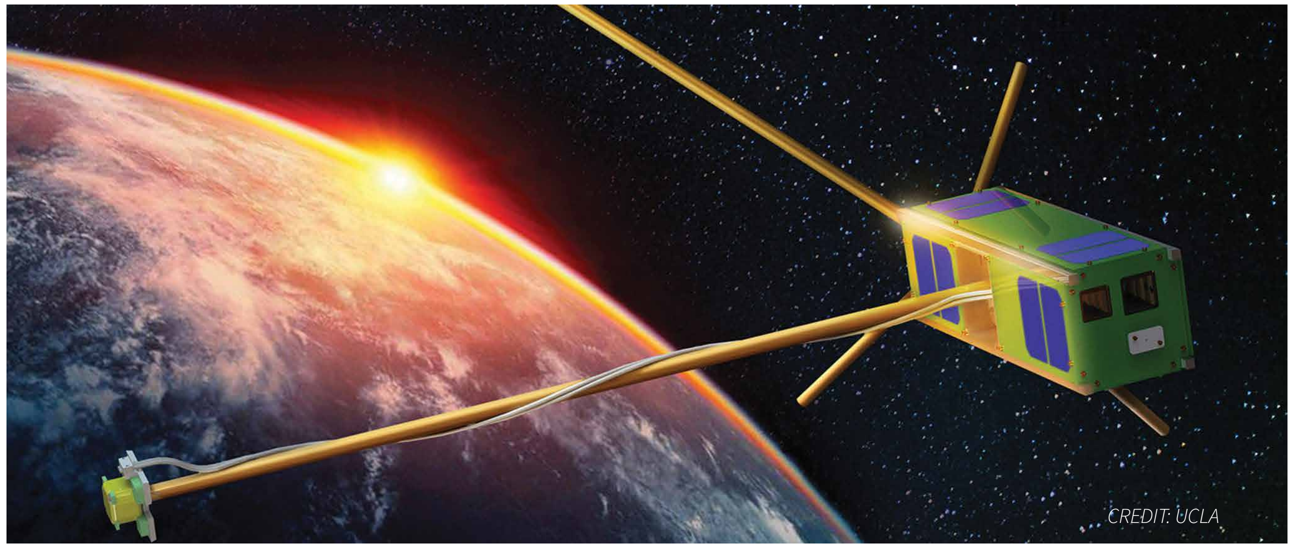
CREDIT: E. Masongsong, UCLA EPSS

THEMIS: Looking for Answers from The Gods

Formally, the THEMIS project is entitled the 'Time History of Events and Macroscale Interactions during Substorms'. But a double entendre points the name to Themis, the Greek goddess of justice, wisdom and good counsel. The daughter of the sky god Uranus and the Earth goddess Gaia, Themis is the perfect patroness of scientists studying the auroras and other manifestations of the Earth's interaction with the solar wind in the sky.
Dr Angelopoulos' group and NASA designed the THEMIS mission to determine where and when the energy exchange occurs between the solar wind and the magnetosphere relative to the ground. According to Dr Angelopoulos, they did this by lining up the five THEMIS probes and tracking the flow of energy to determine its origin with sufficient time resolution. In other words, they mapped the flow of energy as it moved from the solar wind plasma through the magnetosphere. Their findings were published in the journal *Science*.

'We found that the trigger of the energy release is magnetic reconnection, a process whereby magnetic field lines – visualised as stretched rubber bands – are broken and then re-connected to form two loops that are allowed to contract,' Dr Angelopoulos explains. 'The field line contraction results in transferring energy released by reconnection towards the Earth, which then accelerates particles to high energies and creates the space currents.' The energy is thus transformed from magnetic flux to kinetic energy, thermal energy and acceleration of particles. This is how aurorae are formed from the deformations of the magnetosphere by the solar wind. But it was still not clear exactly how the energy was actually converted. One thing they noticed was that the energy release was only in a small location in space, usually about 25 Earth radii away from Earth at the night side. But the Earth's magnetosphere's tail is very large, stretching much further than that. So why is this energy release so localised?

To figure this out, Dr Angelopoulos and his team tallied the total energy in the system, measuring where that energy is converted and estimating whether that energy conversion is sufficient to give the results they actually saw. But the total energy coming from the solar wind was difficult to measure without a spacecraft far enough from Earth where good estimates of the magnetosphere tail size could be made, say greater than 30 Earth radii. Since the radius of the Earth is about 6400 km, that means over 192000 km – about half way to the Moon. The scientists realised that they could not coordinate the furthest THEMIS probes from Earth well with the closest ones because their orbits were significantly interfered with by the moon. So, in Dr Angelopoulos' words, 'rather than trying to beat the moon, we decided to join it.'



CREDIT: UCLA

ARTEMIS: Getting the Most Out of What You've Got

In a strategy that enabled NASA to extend the THEMIS probes' mission and save millions of dollars, the team used the remaining fuel on two of the THEMIS probes to raise their orbits and enter Moon orbit, about 60 Earth radii from home. This new mission was called ARTEMIS – 'Acceleration, Reconnection, Turbulence and Electrodynamics of the Moon's Interaction with the Sun'. The objectives of this new mission were to study the lunar space environment and to get into the Earth's magnetosphere's tail and make estimates of the total magnetic energy content. The repurposed probes could also be better aligned with the remaining three THEMIS probes to determine where the energy conversion was occurring. In a paper published in Science, Dr Angelopoulos and his group reported that the energy conversion occurs within extremely thin sheets of electrical currents in space. At only about 10 km thick, these current sheets or magnetic fronts can convert all the available energy from magnetic energy into particle energy.

So first of all, the kinetic energy of the solar wind is converted into magnetic energy in the Earth's magnetospheric tail. This magnetic energy is then converted back into particle energy when the magnetic fields reconnect. It is the conversion of that energy back into particle energy that ultimately powers the aurorae. This conversion also heats up the magnetospheric plasma and energises the Van Allen radiation belts – areas on the inner part of the magnetosphere that sequester energised particles. In other words, the 'weather' in space around our Earth is in large part determined by the solar wind blasting away at the Earth's magnetosphere. This causes storms, substorms and other phenomena, and just like our terrestrial weather, we would like to be able to predict our space weather. Dr Angelopoulos and his team are up for that.

Into the Future – ELFIN

In order to develop quantitative models of space weather, you have to understand the correlation and self-organisation of the energy conversion regions into one large magnetic storm. Dr Angelopoulos believes that this will require multiple small satellites that can make multi-point measurements over broad areas in space with sufficient spatial resolution. So, he and his team have now embarked on a miniaturisation effort with the potential to radically change how they conduct space research. 'Rather than using classical spacecraft, we would be using flotillas of space buoys,' he explains. 'There is a trend to capitalise on CubeSat technology to help advance space instrumentation. We are looking to do that for energetic particle detectors.'

A CubeSat – also called a U-class spacecraft – is a miniaturised, cubic satellite made primarily with off-the-shelf electronics. Relatively cheap and small, CubeSats are used extensively with the International Space Station and its scientific projects. Dr Angelopoulos' team are now in the process of building a CubeSat that can be used in fleets launched in the magnetosphere. Their proposed mission is called ELFIN – Electron Losses and Fields Investigation.

Designed and built by UCLA undergraduates, ELFIN's goal is to investigate high-energy electrons that travel at relativistic speeds in Earth's radiation belt, and to understand how they become knocked out of their cyclical orbits by low frequency electromagnetic waves. This process scatters the electrons that are then guided by the Earth's magnetic field and fall into the atmosphere. Then, at an altitude of about 100 km above the poles, these electrons finally lose their harmful energy, generating auroral displays in the process. This effective emptying of the radiation belts moderates increases in electron fluxes caused by solar events. 'We need to understand these loss processes to assemble the full picture of how space radiation is driven by solar particles,' Dr Angelopoulos explains.

But that's not the only expected benefit of ELFIN. There is already a great reward being reaped at UCLA – ELFIN and its CubeSats are at the forefront of higher education. Dr Angelopoulos proudly tells *Scientia* that the project provides opportunities for students to work in a professional environment and develop critical thinking and problem solving abilities that are much needed in research and industry. Dr Angelopoulos' vision is that innovation and discovery come from transcending disciplinary boundaries and approaching problems holistically. His students are exposed to a fast-paced research environment with realistic goals and obstacles. Furthermore, with information readily available through Internet resources, teaching students how to critically and effectively process information towards generating new knowledge or products becomes the new role of academia. Dr Angelopoulos' ELFIN project is more than just checking space weather around the Earth. With ELFIN he's trailblasing a new way of teaching science at the university level.

CREDIT: E. Masongsong, UCLA EPSS

Meet the researcher

Professor Vassilis Angelopoulos
Department of Earth, Planetary and Space Sciences
University of California, Los Angeles
Los Angeles, California
USA

Dr Vassilis Angelopoulos received his PhD from the University of California at Los Angeles in 1993, for a thesis on Space Plasma Physics. After receiving his doctorate, he worked as a post-doctoral researcher at the Applied Physics Laboratory at Johns Hopkins University. After working as a research physicist at the University of California at Berkeley, Dr Angelopoulos joined the faculty at UCLA in 2007 where he is now Professor of Space Physics.
Dr Angelopoulos' primary interest is the study of how particles are accelerated by and in the Earth's magnetosphere, and how the upper atmosphere, the ionosphere and the lunar environment respond to space currents driven by the solar wind. Dr Angelopoulos is the Principal Investigator of the ELFIN Cubesat nanosatellite mission, supported by grants from NASA and NSF. He is also Principal Investigator of THEMIS – a five satellite and 20 ground based observatory mission proposed and managed by the UC-Berkeley's Space Science Laboratory – and Principal Investigator of the ARTEMIS project – a two satellite lunar mission. Dr Angelopoulos has authored or co-authored more than 500 articles published in peer-reviewed journals and other professional proceedings.

CONTACT

T: (+1) 310 794 7090
E: vassilis@ucla.edu
W: http://esp.epss.ucla.edu

FUNDING

NASA
NSF
US Air Force Research Laboratory

REFERENCES

V Angelopoulos, *et al.*, Electromagnetic Energy Conversion at Reconnection Fronts, Science, 2013, 341, 1478–1482. DOI: 10.1126/science.1236992

VA Sergeev, V Angelopoulos and R Nakamura, Recent advances in understanding substorm dynamics, Geophysical Research Letters, 2012, 39, L05101. DOI: 10.1029/2012GL050859

V Angelopoulos, The ARTEMIS Mission, Space Science Reviews, 2010. DOI: 10.1007/s11214-010-9687-2

V Angelopoulos, *et al.*, Tail Reconnection Triggering Substorm Onset, Science, 2008, 321, 931.

V Angelopoulos, The THEMIS Mission, Space Science Reviews, 2008. DOI: 10.1007/s 11214-008-9336-1

THEMIS ARTEMIS ELFIN