Investigating Plasma Storms and Substorms in our Near-Earth Backyard

Dr Tony Lui

INVESTIGATING PLASMA STORMS AND SUBSTORMS IN OUR NEAR-EARTH BACKYARD

Space physicist **Dr Tony Lui** has spent four decades increasing our understanding of the mechanisms behind the magnetic disturbances and interactions of space plasma surrounding our home planet.

Plasma, a ubiquitous state of matter

In the calm and comfort of a classroom, we have all learned about atoms and molecules. We think of these tiny constituents of all matter as having a compact nucleus with a peaceful cloud of orbiting electrons. The positive charge of the nucleus and the negative charge of the electrons sum to zero and life is neutral and good. But what if those atoms and molecules exist in regions of space where temperatures are, well, *astronomically* high – hot enough to strip these electrons from their nucleus? Then we do not have the tame, neutral atoms and molecules we are familiar with on Earth – we have plasma.

Plasma – the so-called fourth state of matter, is a gas so hot that its atoms are split into a cloud of ions and electrons that move and flow independent of each other. Astronomically speaking, plasma is everywhere. Our sun and the stars are made of plasma, for example. The solar wind and the tails of comets contain plasma. Even in our everyday experience here on Earth, plasma can be found in such places as fluorescent and neon lights, lightning flashes, candle flames and the cores of nuclear reactors. Overall, roughly 99.9% of the matter in the Universe exists as plasma, rather than the solid, liquid or gas we know here on Earth. And because the particles that make up plasma are electrically charged, they can conduct electricity and are influenced by magnetic fields. This makes for fascinating electromagnetic interactions, some of which Dr Lui has studied for most of his professional life.

The Earth's Magnetosphere – a plasma playground

The Earth, because of its liquid outer core of molten iron, is surrounded by an intrinsic magnetic field. Thus, we describe the Earth as having a north 'pole' and south 'pole', just as we would a magnet. The space surrounding the Earth where its magnetic field significantly influences the plasma contained there is called the *magnetosphere.* Most of this plasma comes from the Sun in the form of the solar wind.

The Sun, or any star for that matter, gives off massive amounts of plasma in what is called a stellar wind. For our Sun, it's termed the *solar wind.* This hot, ionised gas travels out from the star and interacts with any objects it encounters, particularly those with magnetic fields. Thus, the Earth's magnetosphere interacts with the solar wind as does the magnetosphere of Jupiter or Mercury or any other planetary body with a magnetic field. On the impact side of the planet – the planet's 'day' side – there is a significant compression of the planet's magnetic field by the solar or stellar wind, especially at high altitudes. On the 'night' side of the planet – with the solar wind blowing on past – the plasma flow actually causes the magnetosphere to stretch out into a 'tail', conceptually similar to the tail of a comet.

Here on Earth we see some of the interaction between the solar wind and the Earth's magnetosphere, especially in the northern and southern latitudes. Most commonly, the interactions result in spectacular light shows called *aurorae.* In the northern hemisphere, this is called the *Aurora Borealis* – the Northern Lights, while in the south the same phenomenon is known as *Aurora Australis.* But all consideration of visual spectacle aside, the fact that high energy ionic particles are dancing around our near-Earth space interacting with the Earth's magnetosphere leads to a very practical question: what effect does all this have on our space objects, such as telecommunication satellites or the International Space Station? We know that solar flares, or sun spots, dramatically increase the solar wind at intervals, and may at times disrupt our communications. How can we predict that or prevent it? What about the effects on our orbiting electronics and people? We need to know how all this works so we can find answers to these important questions. And that is what Dr Lui has worked on for years, investigating the physical processes of near-Earth plasma disturbances to hopefully allow forecasting of space disturbances as we achieve a better understanding of their underlying causes.

'This research has potential applications in understanding the physical processes responsible for many explosive phenomena in the universe at large'

Let's start by watching the light show!

Dr Lui tells Scientia about what inspired him to dedicate his career to the study of space phenomena. 'The year I graduated with my physics degree from the University of Hong Kong was the year that the U.S. had the Apollo 11 lunar landing with Neil Armstrong as the first human stepping on the surface of the moon,' he explains. 'He left "the next giant leap imprint". I was attracted to space research by this exciting adventure.'

Soon after this, some of his early research which was published in 1973 in *Planetary Space Science* interpreted data from the Canadian satellite ISIS-2, one of a series of Canadian satellites launched to study the Earth's ionosphere. ISIS-2 was able to take images of the entire Aurora Borealis from above. Dr Lui analysed the resulting images and discovered that, unlike images taken from the ground, the big picture from above indicated that the aurora was not individual auroral arcs as depicted in popular photographs. There was actually a diffuse and uniform belt of aurora that contained some discrete arcs and bands encircling the poles. This was a significant leap in our understanding of auroras and considered a major achievement in our understanding of the solar-terrestrial relationship.

A few years later, while studying auroral images from Defence Meteorological Satellite Program satellites, Dr Lui described large-scale, saw-toothed undulations on the equatorward edge of the visible diffuse aurora during magnetic storms. He found that the amplitude of these waveforms was large, from about 40 to 400 km, which would explain why it had not been observed from the ground. This phenomenon could last for about 0.5 to 3.5 hours. In each of the four cases he observed, the undulation occurred during a geomagnetic storm interval near the peak development of the storm time ring current. This finding was exciting enough to be reported in the local newspaper and it was later published in the *Journal of Geophysical Research.*

As technology progressed, Dr Lui kept progressing as well, particularly since satellite auroral imagers were continuously being improved with each new satellite mission and global views of auroras became more abundantly available for investigation. This allowed researchers like Dr Lui to conduct large analyses on auroral images to examine the dynamic behaviour of auroral activities – hence also magnetospheric activities – in an unprecedented way.

Getting a bird's-eye view of solar storms

Early on, it was known that the worldwide depression of the geomagnetic field during magnetic storms was caused by the development of a ring current encircling the Earth. However, because of the lack of measurements covering the energies for the ring current, determination on the evolution of the ring current during a magnetic storm was lacking until the Active Magnetospheric Particle Tracer Explorers (AMPTE) mission was launched – three spacecraft designed to study the sources, transport, and acceleration of energetic magnetospheric ions. This was the first time that the evolution of the ring current during two magnetic storms was quantitatively investigated. Dr Lui calculated from the data that the ring current intensified initially at its outer edge and later evolved to cover over the entire radial range of the ring current. This was published in 1987 in the *Journal of Geophysical Research.*

Perhaps even more exciting, a new diagnostic tool for magnetospheric investigation was developed for looking at energetic neutral atom (ENA) emissions, produced by charge-exchange collisions between energetic magnetospheric ions and the cold neutral hydrogen atoms. ENA measurements were taken with the Geotail satellite, a joint Japan-USA endeavour to study the structure and dynamics of the tail region of the magnetosphere with a comprehensive set of scientific instruments. Prior to the Geotail mission, no composition information for ENA emissions was available. The first composition information of ENA was reported with measurements from the Energetic Particles and Ion Composition (EPIC) instrument on Geotail. Dr Lui published some of the first composite measurements of ENA in *Geophysical Review Letters.* Further, he combined ENA data of the global magnetospheric population with ground-based observations by the networks of radar to solve an ongoing controversy about the cause of storms – were they caused by smaller, substorms building to a crescendo and resulting in a full-sized storm, or was it an increase in the convection of plasma from the tail enhancing the current ringing the Earth that ultimately led to storm development? He found that solar storms basically had both causes, one from enhanced convection without smaller substorm activity and the other from substorm activity with even a decrease in convection. Therefore, Dr Lui resolved the controversy by showing that both causes can lead to storm development independently. This novel insight was published in *Geophysical Research Letters.* 'The research undertaken has implications on space weather forecasting that can affect space assets as well as societal functions such as high-altitude flights and power blackouts due to space disturbances,' Dr Lui tells Scientia. 'It also has potential applications in understanding the physical processes responsible for many explosive phenomena in the universe at large.'

Where is Dr Lui looking now? To the sky, of course

It helps to be connected, and Dr Tony Lui is that. As a recognised expert in near-Earth space physics, he has his fingers in many projects. Right now he has a number of irons in the fire to continue his search for the whys and wherefores of our magnetosphere.

He is still a principal investigator in the monitoring of the Energetic

Particles and Ion Composition (EPIC) instrument on the Japanese-NASA satellite Geotail in the International Solar-Terrestrial Physics Science Initiative (ISTP) program. It was launched in 1992 and the data is still flowing in. Dr Lui is also a co-investigator of the Research with Adaptive Particle Imaging Detectors (RAPID) instruments on European Space Agency's Cluster satellite mission, launched in 2000. The aim of that instrument was to record data to generate 3-dimensional distributions of high-energy electrons and ions in plasma.

'The evolution of electrical currents in space plasma can be revealed in future suitable satellite constellation, which will yield very illuminating clues on the nature of physical processes that produce explosive energetic phenomena and turbulence in space plasmas.'

In 2007, NASA launched a set of five satellites named THEMIS – Time History of Events and Macroscale Interactions during Substorms. The purpose of those satellites was to study substorms in the Earth's magnetosphere, especially where they intensify auroras near the poles. Three of the satellites remain in the magnetosphere, while two have been restationed near the Moon. Importantly, the satellites record their data from space and correlate it with ground-based imagers and magnetometers. Dr Lui is a co-investigator on the THEMIS project, as well as on the NASA Van Allen Probes, two satellites taking measurements of goings-on in the Van Allen radiation belt. Understanding activities of plasma in the Van Allen belt is important in understanding the behaviour of plasma elsewhere in the Universe.

Another ongoing satellite project Dr Lui with which is associated is the Fast Auroral Imager on the Canadian Space Agency's CASSIOPE satellite. The satellite carries a scientific experiment package called e-POP (enhanced Polar Outflow Probe) that gathers data on solar storm effects in the upper atmosphere that can interfere with GPS and other communications. This is precisely what Dr Lui's research is aimed at – understanding solar weather and eventually devising measures to mitigate its deleterious effects.

What's next for Dr Lui?

Dr Lui hopes that the next steps for his research would lead to additional understanding of the phenomena of magnetic storms and substorms and finding evidence for the underlying physical processes for these phenomena. In particular, explanation of the evolution of electrical currents in space plasma can be sought in future suitable satellite observations. 'This will yield very illuminating clues on the nature of physical processes that produce explosive energetic phenomena and turbulence in space plasmas' Dr Lui explains. In all, Dr Lui has enough work to keep him busy for a further four decades!

Meet the researcher

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Dr Tony Tat Yin Lui received his PhD in Space Physics in 1974 from the University of Calgary. In 1979, after undertaking postdoctoral fellowships in Physics at the University of Calgary and Geophysics at the University of Alaska, as well as a Research Associate stint at the Herzberg Institute of Astrophysics, NRC of Canada, Dr Lui joined the Space Department at The Johns Hopkins University Applied Physics Laboratory.

Currently Dr Lui is Principal Investigator or Co-Investigator of several on-going space missions, including the Japanese satellite GEOTAIL in the ISTP program, the European Cluster satellite mission, the NASA Explorer mission THEMIS (Time History of Events and Macroscale Interactions during Substorms), the NASA satellite mission Van Allen Probes, and the Canadian satellite e-POP. He has edited seven scientific books and published more than 360 scientific papers in refereed journals. One early publication was cited by the American Society of Physics as one of the twelve outstanding pieces of research in Physics for 1973. Another publication in the same year was highlighted in Moldwin's Timeline of Solar-Terrestrial Physics. Dr Lui has received several NASA and ESA Awards and was elected to be a Fellow of the American Geophysical Union in 2008.

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FUNDING

NATO
National Science Foundation
NASA

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