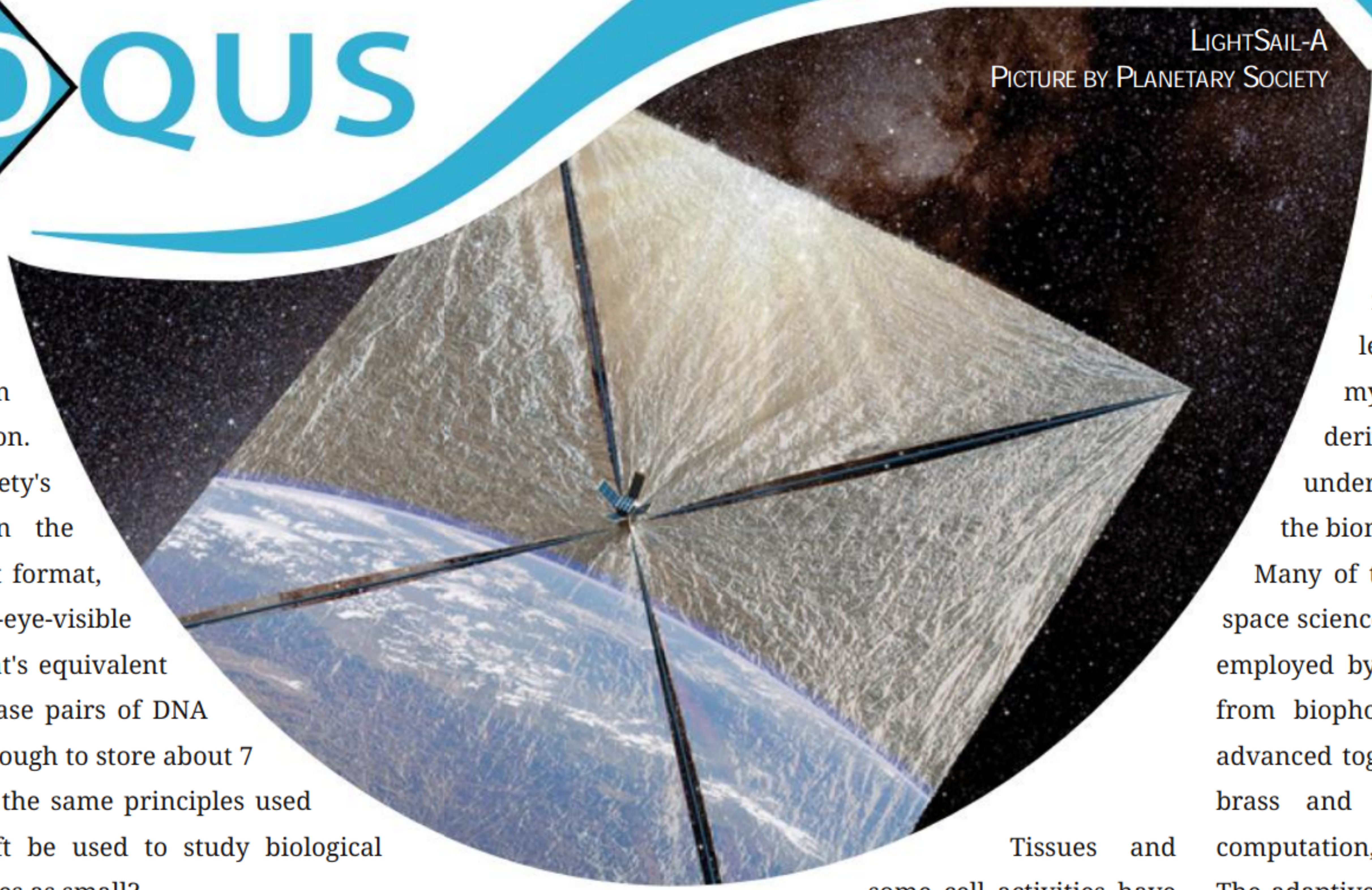
To Space and Back With Biophotonics

Carl Sagan inspired a wave of minds young and old to curiosity, scepticism and enquiry throughout his career. He was among the first to see the value of escaping the ivory tower and encouraging scientific literacy in a public audience, and in 1976 Carl Sagan went on the Johnny Carson show to describe the concept of solar sailing, a bizarre idea that dares to propel a spacecraft on a current of light. The strangeness defies intuition until the realisation of a simple photonic quirk of nature: photons of light, despite having zero invariant mass, possess momentum.

I'll invoke the most famous equation in the world to convince my readers. Energy is equivalent to mass multiplied by the square of the speed of light ($E = mc^2$). One can verify from experience that light has energy: we can feel our skin temperature increase in sunlight. Thanks to Einstein, we know that it therefore must have inertial mass, and thus momentum, as well. This is why light is effected by gravity (allowing us to observe the mysterious influence of dark matter in the universe), and why a spacecraft can conceivably push itself along by reflecting photons. The latest effort to bring this science fiction closer to engineering practicality was the launch of LightSail-A by Carl Sagan's own Planetary Society. The craft tested sail deployment mechanisms, and subsequent versions of the craft will test solar sailing as a means of increasing orbital speed, and thus improve the practicality of light-based sail propulsion.

The reader may be beginning to wonder what all this whimsical sailing has to do with biology. We have briefly discussed a fundamental concept in photonics, the momentum of light, but we're missing at least one prefix to bring us back to focus. A solar sail craft must have an enormous wingspan to eke out an appreciable acceleration. The Planetary Society's LightSail-A, based on the shoebox-sized CubeSat format, unfurled to a naked-eye-visible 32 square meters. That's equivalent to almost 24 billion base pairs of DNA in a straight line, or enough to store about 7 human genomes. Can the same principles used to propel a spacecraft be used to study biological molecules a billion times as small?


LIGHTSAIL-A
PICTURE BY PLANETARY SOCIETY

The same physics apply, although we sometimes have to treat them slightly differently, at a scale of billions and billions, where we would like to send spacecraft, down to a scale of billionths and billionths where we find proteins. It is not typically necessary to brace ourselves against a strong gust of sunshine at the macroscopic human scale, we have more pressing forces to worry about. However, at the level of proteins and cells the magnitude of forces driving the essential activities of life is within the range of forces we can impart by redirecting a bit of laser light. This is the point at which we add a 'bio' prefix to make 'biophotonics', the study of life with light and vice-versa.

Several PHOQUS projects are built on the practice of redirecting light momentum to impart and measure minuscule forces to biological material, a group of techniques grouped under the term "optical tweezers." Typically we use micron-scale plastic beads to act like tiny lenses, redirecting light and receiving a corresponding push. By tracking the position of the bead when it is influenced by fluidic or biomolecular forces, we can precisely infer or deliver the forces involved in fundamental processes. Tissues and some cell activities have conventionally been just above the strength of forces we can influence and measure with optical tweezers, especially as, for biological materials, at some point increasing laser power will cook the sample. PHOQUS fellow **Valentina Ferro** develops anti-reflection coatings and high refractive index microbeads to overcome this historical hurtle. High strength microbeads are expected to enable experiments in tissue dynamics and cell motility previously unavailable to the advantages of optical tweezers.

My own work aims to directly measure the momentum change of light affected by microbeads to study protein conformation and activity associated with cell division. Genetics and molecular biology have provided a high-level blueprint of the parts involved, and my enquiry with optical tweezers aims to derive an engineer's mechanistic understanding of one simple protein piece of the biomolecular machine.

Many of the techniques are heavily influenced by space science, or alternatively, many of the techniques employed by scientists studying space are borrowed from biophotonics. Microscopy and telescopy have advanced together from a beginning in hand-wrought brass and glass to the modern application of computation, deformable mirrors, and liquid crystals. The adaptive optics I use to arbitrarily control optical tweezers are descended from systems first employed to counteract atmospheric turbulence in ground-based astronomy. It is unsurprising that a cohort of PHOQUS fellows are closely involved in collaborative outreach at the Mills Observatory in Dundee, highlighting seeing-based scientific enquiry in a project titled "Outer Space/Inner Space" (Or "Inner Space/Outer Space", as fits your inclination). Looking inward or outward, the same fundamental technologies are enabling our enquiries.

ARTICLE BY Q. TYRELL DAVIS (PHOQUS FELLOW NO. 6)

SPIM-FLIM-FLAMMING!

Investigating cellular nuclear dynamics using single photons

The human body is an amazingly complex system with numerous different networks working together to create one functioning object, you! You are a number of organ systems, consisting of individual organs functioning in unison. These individual organs are made up of different tissues which themselves are composed of individual cells-the basic biological unit that provides structure and function to all living beings. But these individual cells are composed of minute objects, organelles, macromolecules, molecules and even down to single atoms.

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