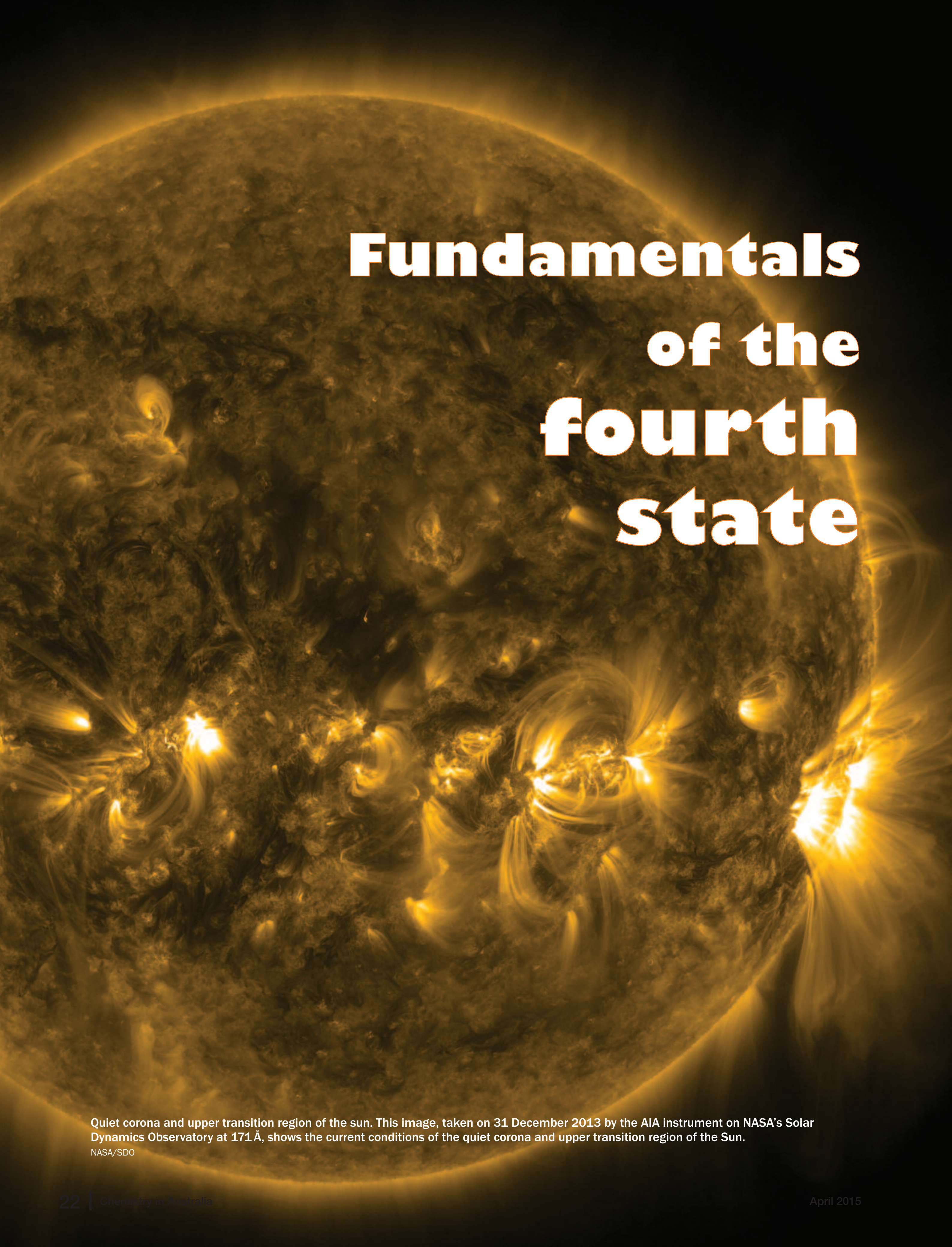
Fundamentals of the fourth state



Quiet corona and upper transition region of the sun. This image, taken on 31 December 2013 by the AIA instrument on NASA's Solar Dynamics Observatory at 171 Å, shows the current conditions of the quiet corona and upper transition region of the Sun.

NASA/SDO

Tiny particles do extraordinary things at incredible temperatures, discovers **DAVE SAMMUT** as he looks on the sunny side.

Most of us will encounter only three states of matter: solid, liquid and gas. We know the chemistry and behaviours in these states quite intimately. But the sun offers us a look at the fourth state – plasma – and matter(s) get interesting.

Being a complete novice in this area, I've been reading. Particular among these, Golub and Pasachoff have produced a readily accessible work in *Nearest star: the surprising science of our sun* (Cambridge University Press, 2014).

Let's start at the corona. What an astounding region this is. So very hot that the temperature can only be estimated spectrally, at something around one million kelvin. So dilute that on average it is barely more than vacuum, yet it is subject to movements of vast quantities of matter, all of which twists and turns at enormous velocities under the influence of unimaginable magnetic fields.

At coronal temperatures, the energy of its matter is so great that a portion of it is able to escape the sun's gravity as a solar wind. Each second, the sun ejects approximately 1.5 million tonnes of matter and emits 3.8×10^{20} MJ of energy into space, vastly more energy in a second than is produced in all of the world's power plants in a year.

The corona is so hot that the photons are shifted mostly beyond the visible spectrum into the violet, ultraviolet and higher-energy short-wavelength regions. The earliest studies of coronal spectra were actually misled by these extraordinary energy conditions. While the 'D3' line, first seen in 1868, was correctly used to identify the new light element helium (named for *Helios*, the sun, and in 1895 identified in uranium materials on Earth), a strong green coronal emission line was attributed to a new element called 'coronium' in 1869.

Due to its presence in the corona, it was assumed that coronium must be lighter than hydrogen. But this was a problem, particularly in light of Mendeleev's breakthrough work on the periodic table of the elements. It wasn't until 1939 that spectrologists Bengt Edlen and Ira Bowen at Caltech and Walter Grotrian in Potsdam, Germany, correlated the green coronium emission to spark discharge spectra in Grotrian's laboratory, and it was found to be Fe^{XIII}. That's 13 lost electrons of only 26.

Strangely, the corona is two to three orders of magnitude hotter than the surface of the sun itself, which is 'only' 6000 K (calculated by taking the total power emitted by the sun and dividing by its surface area). Yet we aren't sure why this should be. Why would it be cooler in closer, and why does the temperature spike so rapidly with distance? One of many theories is that magnetism carries energy from the inner layers of the sun directly to the corona, but there is as yet no agreement on the topic and it remains a key mystery.

But how do we even define the surface of the sun? It is a ball of gas, yet it appears to the naked eye to have a distinct edge. Here's two fascinating facts: first, light is being constantly emitted, adsorbed and re-emitted at every level of the sun from the surface to the core, everywhere that nuclear fusion is taking place. Yet with the constant adsorption and re-emission, it takes light produced at the core 100 000 years to reach the surface.

At coronal temperatures, the energy of its matter is so great that a portion of it is able to escape the sun's gravity as a solar wind.

Second, the sun's gas is itself opaque. Measuring 'opacity' (effectively the opposite of transparency) on a logarithmic scale, zero is completely transparent while we can see only murkily at 1, and by 5 a gas is completely opaque. Most of the light that we see from the sun is from a level at which the opacity is 0.67, and that is the point that we generally use to define the surface of the sun. Although the photosphere is several thousand kilometres thick, from our distance* that thickness yields less than a minute of arc, much too small to be resolved by the human eye.

---

*Approximately 150 million kilometres, give or take, with a nod to 400 years of researchers who worked hard to determine that particular datum, including Captain James Cook.

The truly unique aspect of a star is fusion itself – the forge of the elements. Chemist Carolyn Ruth put it pretty succinctly for the American Chemical Society in *ChemMatters* (October 2009, pp. 6–8): 'In stars less massive than the sun, the reaction converting hydrogen into helium is the only one that takes place. In stars more massive than the sun but less massive than about eight solar masses, further reactions that convert helium to carbon and oxygen take place in successive stages before such stars explode. Only in very massive stars (that are more massive than eight solar masses), the chain reaction continues to produce elements up to iron.'

Different stars go through different fusion processes. Stars like our own undergo the proton–proton chain described below, while more massive stars undergo the C–N–O (carbon–nitrogen–oxygen) process, which is a multistep cycle starting and finishing with carbon, also transforming hydrogen to helium. Mature stars rich in helium undergo helium fusion by the triple-alpha process, via beryllium to carbon.

That gets us just one element up the periodic table. The reactions just keep getting more complex and layered, and although the detail is way too much for this article, it is absolutely fascinating.

The proton–proton chain

^{1}H (proton) + ^{1}H (proton) → ^{2}H (deuterium) + e^{+} (positron) + ν_e (electron neutrino)
^{2}H (deuterium) + ^{1}H (proton) → ^{3}He (helium isotope) + γ (gamma radiation)
^{3}He + ^{3}He → ^{4}He (helium) + $2\,^{1}H$ (protons)

Ocean floor dust gives new insight into supernovae

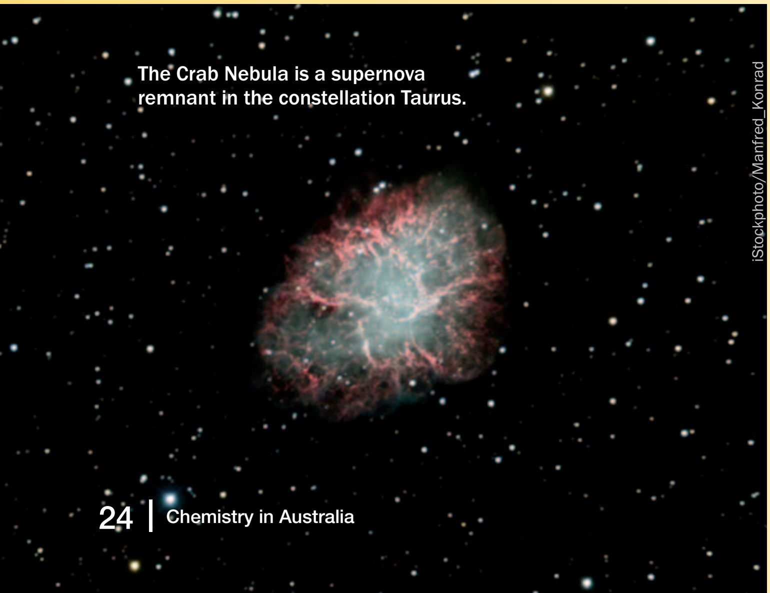
Scientists plumbing the depths of the ocean have made a surprise finding that could change the way we understand supernovae, exploding stars way beyond our solar system.

They have analysed extraterrestrial dust thought to be from supernovae, which has settled on ocean floors, to determine the amount of heavy elements created by the massive explosions.

'Small amounts of debris from these distant explosions fall on the Earth as it travels through the galaxy,' said lead researcher Dr Anton Wallner, from the Research School of Physics and Engineering at the Australian National University.

'We've analysed galactic dust from the last 25 million years that has settled on the ocean and found there is much less of the heavy elements such as plutonium and uranium than we expected.'

The findings are at odds with current theories of supernovae, in which some of the materials essential for human life, such as iron, potassium and iodine are created and distributed throughout space.



The Crab Nebula is a supernova remnant in the constellation Taurus.

iStockphoto/Manfred_Konrad

Supernovae also create lead, silver and gold, and heavier radioactive elements such as uranium and plutonium.

Wallner's team studied plutonium-244, which serves as a radioactive clock by the nature of its radioactive decay, with a half-life of 81 million years.

'Any plutonium-244 that existed when the Earth formed from intergalactic gas and dust over four billion years ago has long since decayed,' Wallner said.

'So any plutonium-244 that we find on Earth must have been created in explosive events that have occurred more recently, in the last few hundred million years.'

The team analysed a 10-centimetre thick sample of the Earth's crust, representing 25 million years of accretion, as well as deep-sea sediments collected from a very stable area at the bottom of the Pacific Ocean.

'We found 100 times less plutonium-244 than we expected,' Wallner said.

'It seems that these heaviest elements may not be formed in standard supernovae after all. It may require rarer and more explosive events such as the merging of two neutron stars to make them.'

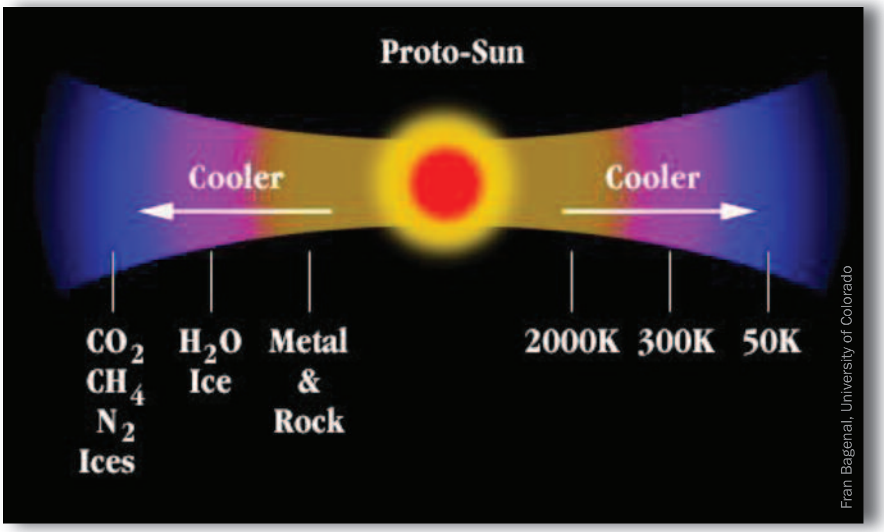
The fact that heavy elements such as plutonium were present, and uranium and thorium are still present on Earth, suggests that such an explosive event must have happened close to the Earth around the time it formed, said Wallner.

'Radioactive elements in our planet such as uranium and thorium provide much of the heat that drives continental movement; perhaps other planets don't have the same heat engine inside them,' he said.

The research is published in *Nature Communications*.

AUSTRALIAN NATIONAL UNIVERSITY

Neutron by neutron, elements larger than helium are created within these stars and flung off into the empty vastness of ever-increasing space, slowly or with cataclysmic force.



Fran Bagenal, University of Colorado

Separation of refractory and non-refractory materials during formation of our solar system (Laboratory for Atmospheric and Space Physics, University of Colorado Boulder, http://lasp.colorado.edu/home).

Here's where I leave the dry commentary. I cannot say how inspired I am to think that the substances that we work with every day as chemists, the very materials of our own bodies and minds, are quite literally stardust.

From the infernal maelstrom of the Big Bang, in a matter of just minutes, are born the hydrogen and helium isotopes that underlie our entire universe. Some 100–300 million years later, in these roiling clouds, massive, fast-burning stars form, ejecting huge quantities of matter into space before exploding spectacularly. Over literally billions of years, generations of stars are born in galaxies in the densest areas of the ever-expanding, churning clouds of matter. Neutron by neutron, elements larger than helium are created within these stars and flung off into the empty vastness of ever-increasing space, slowly or with cataclysmic force.

And somewhere, in some far-flung and remote cloud of matter, a ripple passes. Pushed together, gravity takes hold of the particles and a new system begins to form. As the cloud of hydrogen, helium, various molecules and dust contracts, it spins faster, conserving angular momentum. The various elements and compounds separate – lighter materials such as water, methane, carbon monoxide and nitrogen on the outer, heavier elements towards the centre. In the hot, dense bulb at the centre, a proto-sun flares.

Critically, our own planet forms in one of the sub-ripples. Again, condensation and accretion separate the materials, iron and heavier elements mostly to the proto-Earth's core, lighter silica and alumina outer. Perhaps some of the lighter materials came back to Earth later in the form of planetissimals or comets, and the like.

Of course, the whole process would have been incredibly complex, and our understanding is still limited. But that's not the point. The point is that by whatever variation in the mechanisms of formation, our planet came together from the various material of the stars.

Whether chemically formed or falling in from space, the various chemicals of life collected on this one little planet – methane, ammonia, carbon dioxide and more. Warmed by a sun to temperatures between freezing and boiling, at some point life began.

So here we are, each of us part of a global effort to advance our knowledge of the universe and our place within it. Daily, we work in theory and practice with physical materials born uncountable millennia ago, each day in the hope of making our world a better place to exist. And daily, whether shining directly or clouded by a bit of water vapour, our sun continues its inexorable processes. How can we feel anything but optimistic?

Dave Sammut FRACI CChem is principal of DCS Technical, a boutique scientific consultancy, providing services to the Australian and international minerals, waste recycling and general scientific industries.