Zach Cano

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RESEARCH POSITIONS

CENTRE FOR ASTROPHYSICS AND COSMOLOGY (CAC), UNIVERSITY OF ICELAND | Postdoctoral Fellow
Since November 2012 | Reykjavík, Iceland

EDUCATION

ASTROPHYSICS RESEARCH INSTITUTE, JOHN MOORES UNIVERSITY LIVERPOOL | Doctor of Philosophy (PhD)
Oct 2008 – Oct 2011 | Liverpool, UK.

- Doctoral Thesis: *The Nature of Gamma-Ray Burst Supernovae*.
- Supervisor: Dr. David Bersier.

UNIVERSITY OF SUSSEX | Masters Degree in Physics Hons. (MPhys)
Oct 2000 – July 2007 | Brighton, UK.

- Masters Thesis: *Observing RR Lyrae Variable Stars*.
- Supervisor: Dr. Robert C. Smith.

IMBERHORNE VI FORM | A-Levels
Sept 1997 – July 1999 | East Grinstead, UK.

- Subjects: *Physics, Maths & Chemistry*.

POPULAR SCIENCE PUBLICATIONS

Science Writer CV & Portfolio

``A Matter of Cosmic Principle''
Astronomy Now, August 2013.

``The life of stars: Star Death''
The Sky at Night Magazine, June 2013.

``The Solar System in Chaos''
Astronomy Now, Feb. 2013.

``Expanding the View''
The Sky at Night Magazine, September 2012.

``Reflections'' (column)
Mercury Magazine, Spring 2010.

``Gamma Ray Bursts - Piecing Together a Cosmic Puzzle''
Mercury Magazine, Spring 2010.

``Phase Transitions and Exotic Relics''
Mercury Magazine, May - June 2005.

``Bloody Moon''
Amateur Astronomy Magazine, Issue 46, 2005.

``Turbulent Times in Pluto's Past''
Today's Science on File, March 2005.

``Hubble Lifts Fog on Early Universe''
Today's Science on File, December 2004.

A MATTER OF COSMIC PRINCIPLE

New cosmological results are confounding centuries of established astronomical ideology. Do we live in a special place in the Universe after all, asks **Zach Cano**?

▲ **Two cosmological philosophies face-off. Ptolemy argued for Earth being in a special location in the Universe, whereas Copernicus showed that Earth orbited the Sun just like the other planets, an ideology that led to the Cosmological Principle that there are no special locations or directions in the Universe. But how sure are we that this is true?**

Man's understanding of the Universe has evolved dramatically over the millennia. For fifteen centuries Ptolemy's geocentric model of the Universe was the accepted description of humanity's central role in the cosmos, where every other heavenly body orbited our sacred Earth. During the Renaissance, Ptolemy's model was usurped by Galileo, Copernicus, Newton and Kepler, who showed that the Sun did not revolve around the Earth, but instead the Earth revolved around the Sun. Such decrees were at odds with Christian theology, for so deeply woven was the thread from man to God that any observations which seemed contrary to the awesome wholeness and infallibility of God were regarded as being violently sacrilegious.

Since the Scientific Revolution sparked by Galileo, western science has revealed many clues about how the Universe operates. Newton's elegant theories of gravity persisted for over 200 years until they were ousted by the scientific genius of Einstein. Now a new upheaval of our understanding of the Universe is taking place; recent and independent observations made by the European Space Agency's Planck satellite, as well as maps of the distribution of galaxies and quasars in the early Universe, are showing that the fundamental assumptions that modern cosmology rests upon may not be entirely correct. Should it turn out that the foundations of modern cosmology are not as secure as once hoped, it could mean a profound change in our understanding of the true nature of the Universe.

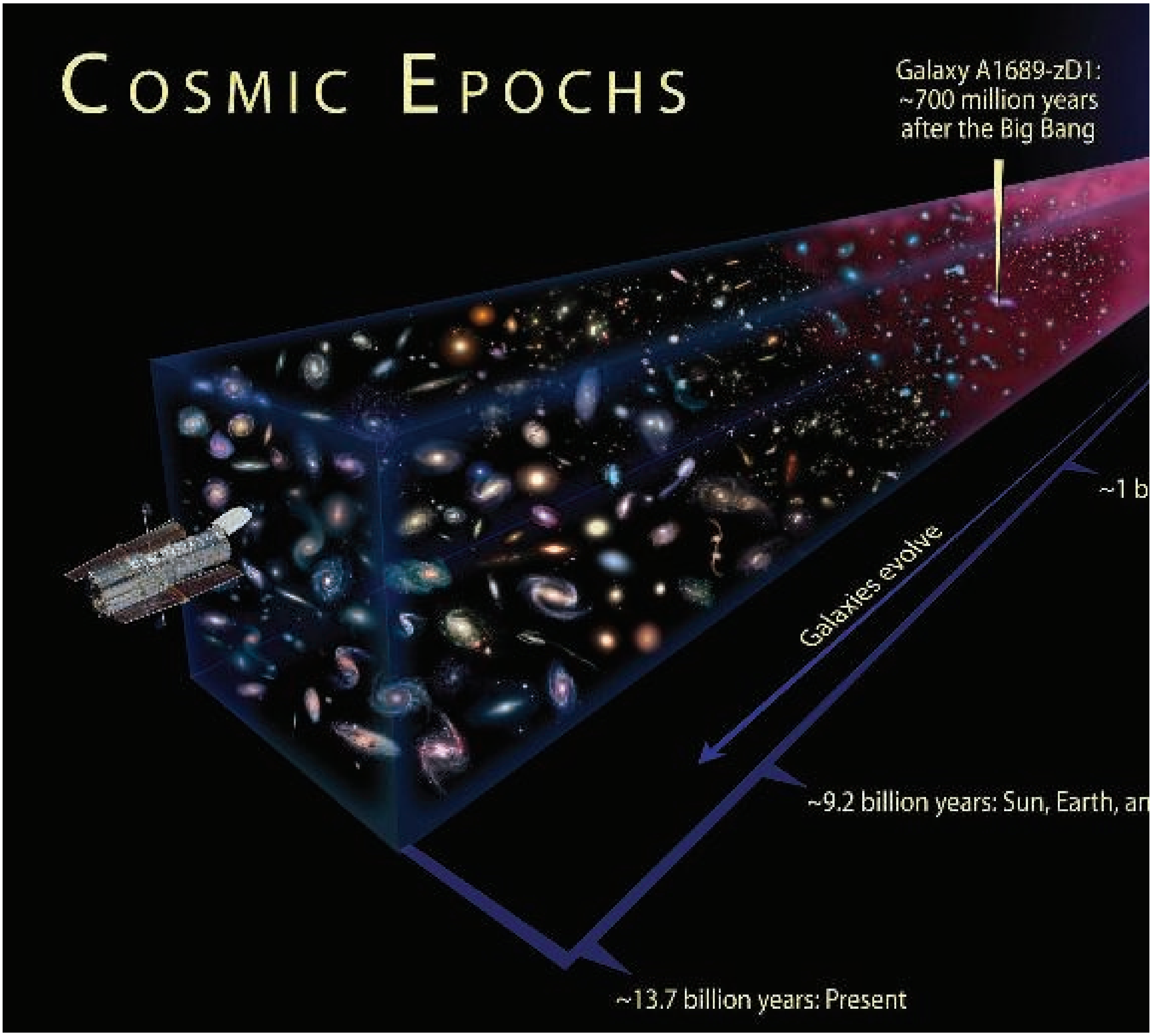
"IT COULD MEAN A PROFOUND CHANGE IN OUR UNDERSTANDING OF THE TRUE NATURE OF THE UNIVERSE"

Where it all began

The standard cosmological model, also referred to as 'concordance cosmology', is built upon two assumptions: that the Universe is isotropic and homogeneous. These assumptions are derived from the centuries-old Copernican Principle that states that the Earth is not in a central or specifically favoured position of the Universe. A generalisation of this statement is the Cosmological Principle, which says that there are no special places in the Universe (homogeneity), and there are no special directions in the Universe (isotropy). Therefore in whichever direction any observer in the Universe looks, the observer should not see any general difference in the structure within the Universe and that the average density of a large enough region of space is approximately the same everywhere.

These assumptions are expected to be valid on the very largest scales, on the order of billions of light years. It is obvious that the Universe isn't isotropic and homogeneous at all scales, for at smaller scales one sees planets and galaxies and clusters and superclusters of galaxies. However, when we look at structures and regions of the Universe at these very large scales, it is expected that the Universe is on average smooth (homogeneous) and each direction appears the same as all the others (isotropic). A study published in 2010 by Amit Yadav and a small team of theoretical cosmologists calculated that at scales larger than roughly 1.2 billion light years the Universe should appear smooth and isotropic.

Some observations appear to support the Cosmological Principle, including the recently completed WiggleZ Dark Energy survey at the Anglo–Australian Telescope. The survey, which looked at the distribution of over 200,000 galaxies, showed that at distances on the order of 325 million light years, matter is distributed smoothly and evenly.



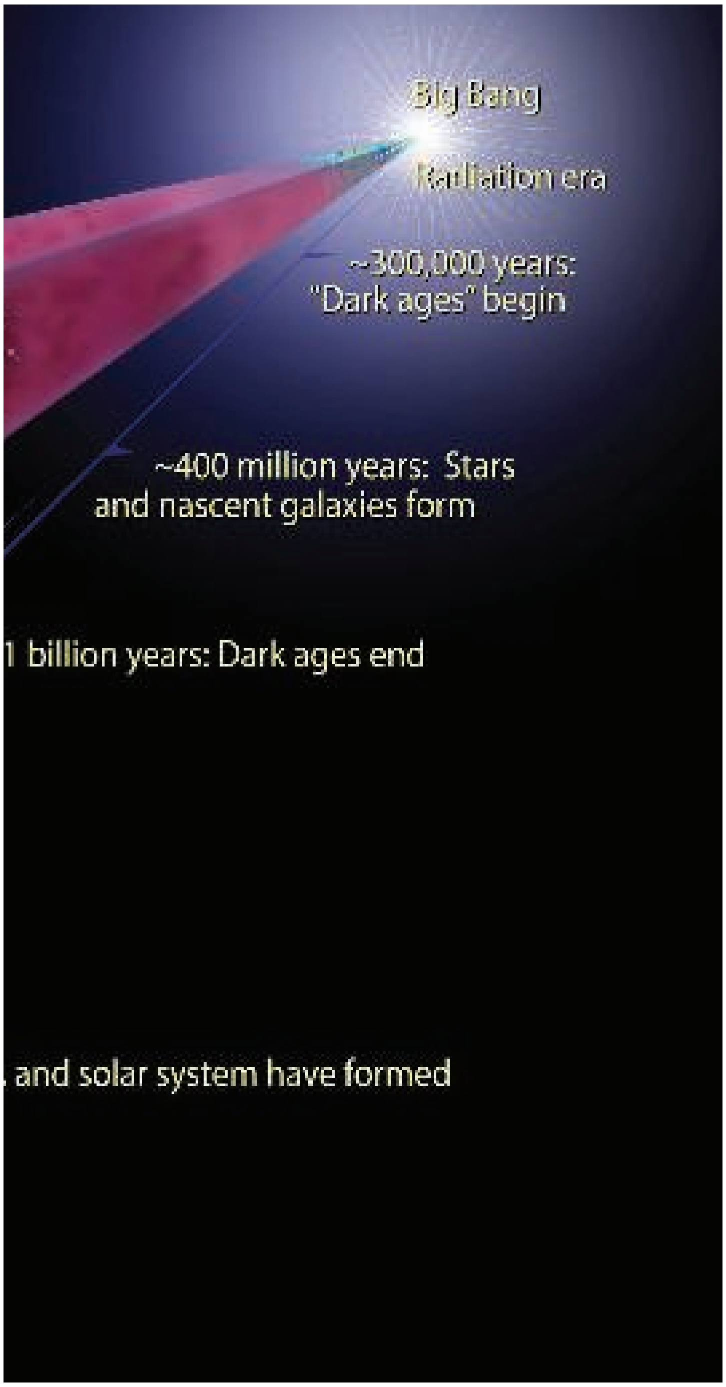
▲ **A slice of cosmic history, from the big bang and inflation to the cosmic microwave background radiation, the formation of the first stars and galaxies and their evolution to the present day. The Cosmological Principle says that this slice should look the same in any direction and from any point of view in the Universe. Image: NASA/ESA/A Feild (STScI).**

Where it started to go wrong

One of the first hints that the assumptions of isotropy and homogeneity may not be completely valid was revealed by the Cosmic Background Explorer (COBE) satellite in the early 1990s, which was followed up by the Wilkinson Microwave Anisotropy Probe (WMAP) in the 2000s. Both satellites were designed to detect and measure the cosmic microwave background (CMB) radiation, which has been around since nearly the birth of the Universe (see *The first 370,000 years*). These satellites measure small differences in the temperature of the microwave radiation, which in turn reveals very subtle clues about the conditions of the early Universe.

According to the concordance model, if the Universe is isotropic then no matter which part of the sky one inspects, the CMB should look on average the same, which no large variations from region to region. Surprisingly this does not appear to be the case, and instead an 'anisotropy' (the opposite of isotropy, where one direction does appear different) was observed in the CMB; there seems to be a 'preferred' direction in the way the temperature of the CMB varies. Cosmologists call this a 'hemispherical asymmetry,' which is an excess in temperature of one hemisphere in the sky with respect to its opposite hemisphere. This anisotropy was first spotted by COBE, and then by WMAP and, because of its peculiar alignment in the sky, was dubbed the 'Axis of Evil'.

Planck is a third-generation CMB satellite and the map it has recently produced is the most detailed and precise ever created. As well as determining the relative abundances of dark energy, dark matter and ordinary matter in the Universe (about 68, 27 and 5 percent respectively), the



The first 370,000 years

Most cosmologists believe that the Universe began with the big bang – all matter and energy arose from a singularity of infinite mass and density. Within the very tiniest fraction of a second the Universe inflated like a balloon, increasing its size by an unfathomable 10^{71} times! Tiny quantum fluctuations in the Universe were then magnified by this inflationary period and became the seeds for the growth of large-scale structure. Evidence of these seeds is seen in maps of the cosmic microwave background (CMB) radiation as tiny differences in temperature in the map.

The CMB arises from a time when the Universe was a writhing sea of hot plasma. After the big bang and the period of inflation, the Universe continued to expand and cool and, after roughly 380,000 years, radiation that was trapped in the plasma escaped into space and began its journey through the cosmos. It is this radiation, which now has an average temperature of only 2.73 degrees above absolute zero, that Planck has mapped.

Planck's CMB map, which is the most accurate and precise ever produced, provides hints that the Universe may deviate away from isotropy at different angular scales. The first is called a 'hemispherical asymmetry,' which is an excess in temperature of one hemisphere in the sky with respect to its opposite hemisphere. The other evidence is seen in the presence of cold spots, such as the one seen near the bottom right of the map, which indicates anisotropies at smaller angular scales.

power spectrum created with data obtained by Planck has shown that the theoretical models fit the data from scales of 180 degrees down to 0.1 degree exceptionally well. The agreement between observations and theory is remarkable and each one of the bumps and wiggles in the power spectrum, for which the data follows beautifully, is a further sign of how well cosmologists understand the contents, history and evolution of the Universe.

Planck's results are a marvel, although some anomalies have been found in the data. Planck has confirmed that the Axis of Evil anisotropy is real (or in more scientific terms, is statistically significant). Several cold spots are also seen in Planck's CMB map, the size and shape of which are not explainable within the concordance model. A quantity best measured by Planck is related to the typical size of spots in the CMBR map, which is roughly a degree. The cold spots are much bigger than this average size, roughly 5–10 degrees and their shape is not consistent with that predicted by the concordance model.

So precise are Planck's instruments and so sophisticated is its software that there are no doubts that the anisotropies are caused by a statistical fluctuation, as Paolo Natoli of the University of Ferrara, Italy explains. "The fact that Planck has made such a significant detection of these anomalies erases any doubts about their reality; it can no longer be said that they are artifacts of the measurements," he says. "They are real and we have to look for a credible explanation."

"BECAUSE OF ITS PECULIAR ALIGNMENT IN THE SKY IT WAS DUBBED THE 'AXIS OF EVIL'"

Clusters of quasars

In a completely independent study, Ashok Singal of the Physical Research Laboratory in Ahmedabad, India, has found additional evidence for an anisotropy in the distribution of quasars and radio galaxies in the early Universe. In his paper, Singal inspected a catalogue of quasars and radio galaxies to determine whether they are distributed randomly in the sky. The 3CRR (Third Cambridge, twice revised) radio catalogue contains all radio sources down to a certain detection limit and is one of the most reliable and thoroughly studied sample of radio sources ever compiled.

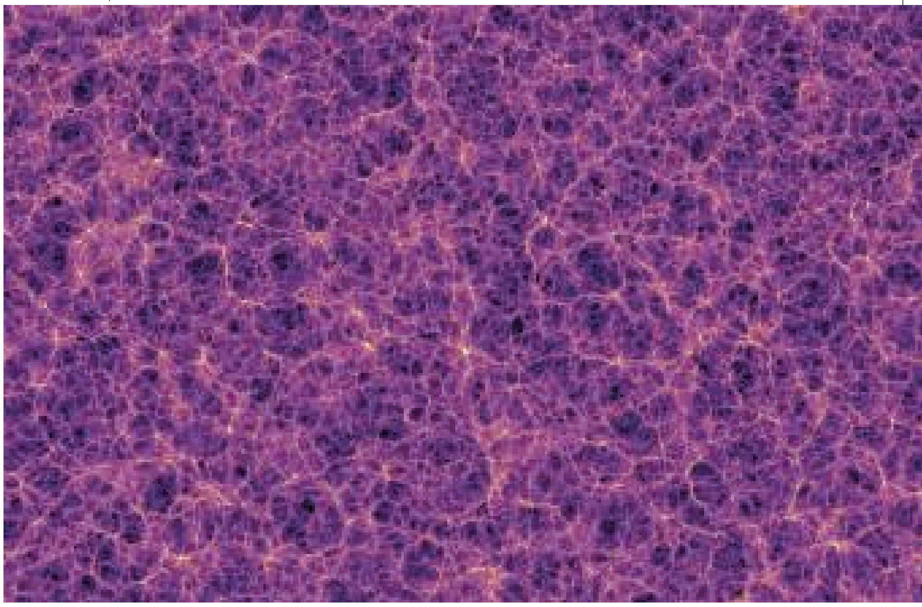
While inspecting the catalogue Singal noticed that, if he divided it into two regions separated by a line through the equinoxes and the northern celestial pole, an anisotropy in the distribution of quasars was seen with more than two-thirds of all of the quasars in the catalogue being found in one region. Such a large anisotropy in the distribution of the quasars, which are some of the most distant objects in the Universe, implies inhomogeneities at very large scales.

Singal also noted that some types of galaxies were uniformly distributed in the catalogue, while other galaxy types paradoxically appeared more often in the other region. When putting all of his results together he found that there was only a 0.005 percent chance that his result could be a statistical fluke.

"It is as if different parts of the Universe are more amenable to give rise to one type of radio galaxy than another," Singal muses. "What's more, these anisotropies could not be caused by the motion of the observer through the Universe as this would not give rise to different anisotropies for different kind of radio galaxies."

Another team, led by Roger Clowes of the University of Central Lancashire have also made observations of quasars in the early Universe and in doing so, have detected the largest structure ever observed. In their study they observed a large cluster of quasars, all at roughly the same distance away from us. What is so remarkable about this cluster is that it has a characteristic size of over 1.6 billion light years and a total length of over 3.9 billion light years!

The enormous size of the cluster is clearly at odds with the largest length allowable in concordance cosmology and, as Clowes explains, "While it is difficult to fathom the scale, we can say quite definitely it is the largest structure ever seen in the entire Universe. This is hugely exciting because it runs counter to our current understanding of the scale of the Universe and it challenges the Cosmological Principle, which has been widely accepted since Einstein."



▲ **The Millennium Simulation described the Universe in a computer model of ten billion particles, showing a cosmic web of matter and voids. On small scales of galaxies and galaxy clusters the Universe is lumpy, but on larger scales it appears smooth, with even distribution between matter and voids. Image: Virgo Consortium/Millennium Simulation.**

Is the model in ruins?

These results have stark implications for the concordance model. The studies, each with strong statistical support, imply that the assumptions of isotropy and homogeneity are not completely valid. So, should we expect angry hordes of scientists armed with torches and pitchforks demanding for these results to be stricken from the annuals of science, or maybe have them hidden in the bottom of a locked filing cabinet stuck in a disused lavatory with a sign on the door saying 'Beware of The Leopard'?

Perhaps not. In fact these results have had a lukewarm reception at best. "There is a lot of debate in the community now as to what significance to assign to these results, i.e. do we need to revise our assumptions?" says Jan Tauber, the Project Scientist for the Planck space mission. "There is great reluctance to go in this direction, because we do not have any theory that can satisfactorily explain the anomalies. So we would be moving into uncharted territory."

While some cosmologists seem reluctant to re-write the concordance model, others are questioning the validity of these studies. A recent paper by Seshadri Nadathur of the University of Bielefeld, Germany, has called into doubt the result of Clowes and his team. Nadathur first argues that the homogeneity scale is an average property of the Universe and is not necessarily affected by the discovery of a single large structure.

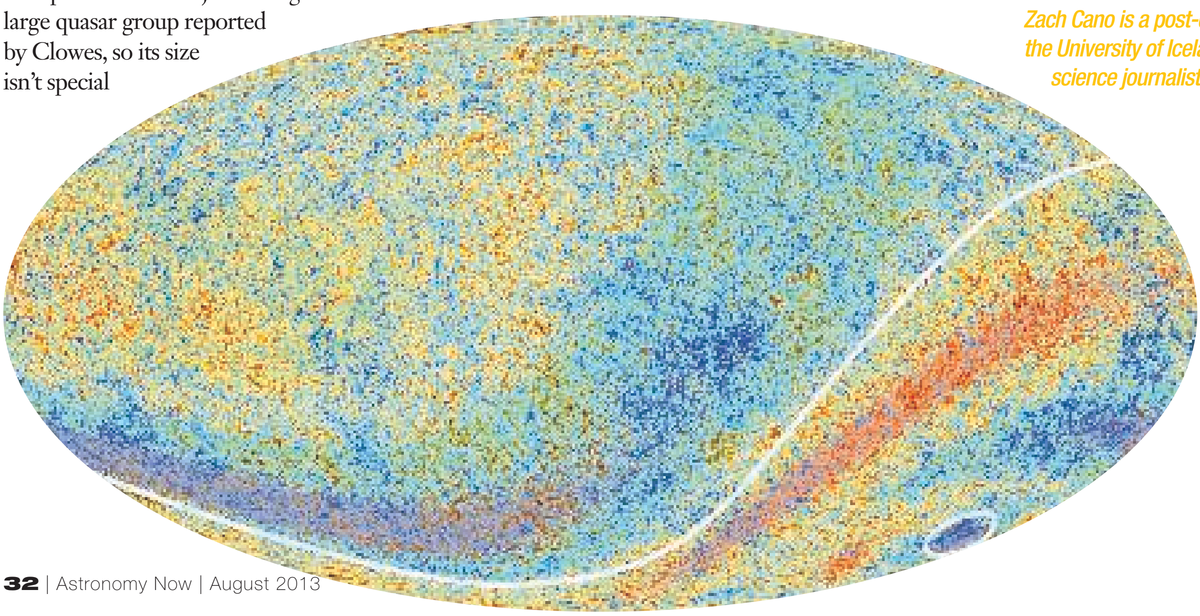
Then, when using the same search algorithm that Clowes used in his study, Nadathur discovered that it will regularly throw up false positive detections of 'structures' even in completely random distributions of points. "These false positives can be just as large as the large quasar group reported by Clowes, so its size isn't special after all," says Nadathur. "In fact it's completely consistent in all respects with what you would expect from random noise, so it could be argued that it shouldn't really be regarded as a structure at all."

Instead, Nadathur finds that the distribution of quasars in the Sloan Digital Sky Survey catalogue is in fact homogeneous at scales greater than approximately 600 million light years. This result is similar to that found by the WiggleZ survey, albeit with a larger homogeneity scale and both studies appear to support the cosmological principle.

No such reassurances are found when trying to interpret Planck's results however. Instead some very exotic physics have been suggested to explain the anisotropies and cold spots seen in Planck's CMB map. One idea is that of multiple, bubble universes that were created during the big bang. As the Universe inflated, collisions between these bubbles would cause different regions to inflate and expand at different rates. This would naturally explain the anisotropy seen in the CMB map because inflation would not have occurred uniformly in all directions. A possible explanation for the existence of the cold spots is that vast empty voids may exist between us and the primordial CMB photons. Intervening voids would then manifest themselves as cooler regions in the map. However, if such voids do exist, they would have to be more than a thousand times larger than any void yet observed.

With an entire theory at stake, there will be an ongoing debate as to whether the fundamental assumptions that the concordance model is built upon are valid and whether observations such as these support or refute them. These heated debates will inevitably push the boundaries of science to its very limits and, perhaps in doing so, another genius in the mold of Newton and Einstein may come along and reveal ever more subtle truths about the fundamental physics that rule our Universe.

Zach Cano is a post-doctoral researcher at the University of Iceland and is a freelance science journalist.



◀ **The cosmic microwave background radiation as seen by the Planck spacecraft. The temperature anisotropy between the two hemispheres is indicated by the white line, while a large cold spot is circled. Image: ESA/Planck Collaboration.**

STAR DEATH

Zach Cano explains how we are uncovering the inner workings of supernovae, the incredibly powerful explosions at the end of stars' lifetimes

Cassiopeia A is the remnant of a supernova explosion whose light first reached Earth 300 years ago

The end of a star's life is a dramatic event. Stars like our Sun expand to become red giants and then blow their outer shells into space to create a planetary nebula. But there are others that go out with a bang, ending their lives in a supernova. Among the most powerful and brightest explosions in the Universe, these events can outshine even the host galaxy in which they occur. Their mysterious and spectacular appearance has fascinated humankind for centuries – the first recorded example was documented by ancient Chinese astronomers in 185AD.

In subsequent centuries, astronomers could only record very luminous events that were visible to the naked eye: up to the 20th century, only seven supernovae were recorded. But in the past 113 years, 6,242 supernovae have been documented, and the vast majority (85 per cent) of these were recorded in the past 20 years, the total swelling as ever fainter events have been picked up – both by amateur astronomers and in automatic searches by professional telescopes.

The story so far

Despite the abundance of observations, there are still fundamental questions about what happens within a supernova, which supercomputer simulations are bringing us closer to answering. This much we do know: supernovae occur when certain stars explode violently, in the process ejecting a large amount of material into space in a brilliant and energetic display.

Supernovae are classified into two types, depending on whether hydrogen can be detected in their spectrum: Type I has hydrogen, Type II does not. There's another level of classification for Type I outbursts – into Type Ia, Ib and Ic – that's applied by analysing the spectrum further. Type Ia ▸

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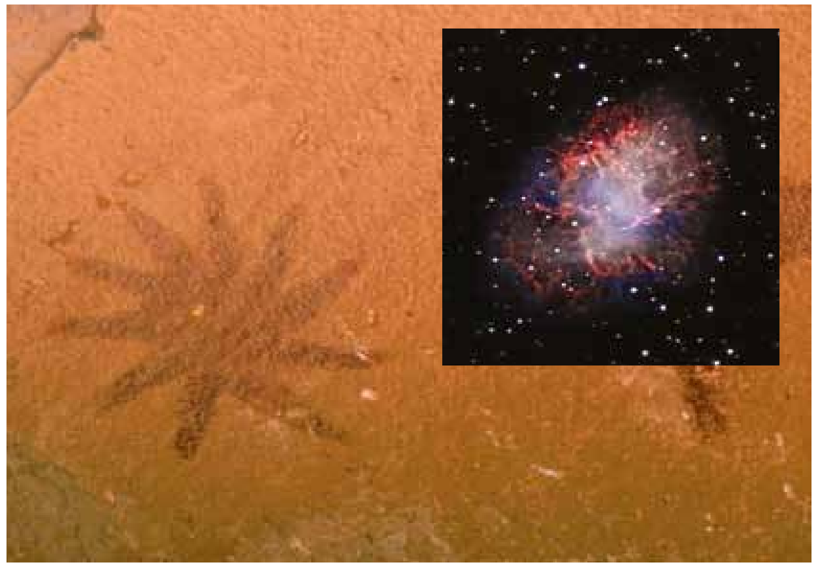


▲ An Anasazi Indian petroglyph at Penasco Blanco in New Mexico, of a supernova observed in 1054. We see the remains of this supernova today as the Crab Nebula, inset

▸ supernovae are thought to occur in two rather spectacular ways. The first scenario is when a white dwarf star in a binary system explodes after reaching a critical mass limit by pulling in too much material from its companion star. The second is when two white dwarf stars violently merge. These are also called thermonuclear supernovae.

In terms of what we think causes them, Type Ib and Ic supernovae are closer to Type II supernovae than Type Ia. The former three are all thought to occur when a massive star comes to the end of its life and explodes violently, its core collapsing. In Types Ib and Ic, the core is thought to collapse after the star has burnt off its outer layer of hydrogen. In a Type II supernova, the core collapses when the star's nuclear fuel is exhausted, while the hydrogen layer still surrounds the star. Without the energy produced by consuming its fuel, the star is no longer able to counterbalance the force of gravity, and so it collapses under its own weight, eventually leading to a gargantuan explosion.

Throughout its life, a star's energy source arises from nuclear fusion. When a star is born, it is made mostly of hydrogen. In the stellar core, the temperature and pressure is so high that hydrogen fuses to form helium, as well as releasing a large amount of energy. The rate at which the hydrogen fuel is consumed depends on how massive the star is – very massive stars will burn through their nuclear fuel in a few million years, while smaller stars can take over 10 billion years.

The beginning of the end

Once the hydrogen in the core has been exhausted, nuclear reactions cease. Throughout the star's life, the only force that has stopped the star from collapsing under gravity has been the counter-balancing energy produced through nuclear fusion. When the hydrogen runs out, the star's core contracts under the influence of gravity until the temperatures and pressures are so great that helium is fused into carbon.

It is here that a star's mass comes into play. For a star of relatively modest mass such as our own Sun, the contraction of the core will also cause the outer layers to expand and the star will enter a red giant phase. Eventually the helium will be entirely burned into carbon, resulting in a carbon core surrounded by an envelope of material that the star has blown off into space. The carbon core is known as a white dwarf star, while the glowing shell of gas that surrounds it is called a planetary nebula.

But in more massive stars the cycle of fusion continues, burning heavier and heavier elements until it forms an iron core with shells of different elements surrounding it like the layers of an onion. Once the iron core is formed, nuclear fusion ceases and the core contracts irrevocably. The collapse occurs very rapidly and so forcefully that electrons are smashed into protons to form neutrons, ultimately leading to the formation of an incredibly dense ball of neutrons known as a neutron star.

The formation of the neutron star halts the core collapse, and the layers that once surrounded the core slam into it. The collision creates a shockwave that rebounds through the star and ejects the stellar material out into space.

The trigger for a Type Ia supernova is also thought to be carbon burning within the star's core, but it comes about in a different way. Here one model has a white dwarf star's carbon core reigniting after it accretes material from its companion star in a binary system, eventually triggering a thermonuclear explosion. It is the consistency of this explosion's light curve that makes Type Ia supernovae useful in measuring distances to their host galaxies. The second model for Type Ia's also involves a binary system of two white dwarfs. Here the supernova is triggered when the stars violently collide and merge together.

Unanswered questions

These current models may give the impression that astronomers have this area sewn up, but fundamental questions still remain. During a core-collapse supernova, quite how the shockwave ejects material from the star into space is a matter of debate, and it's unclear what initially triggers the thermonuclear explosion of a Type Ia supernovae. While some astronomers are building bigger and more powerful telescopes to study supernovae, others are set on recreating them in a lab using ▸

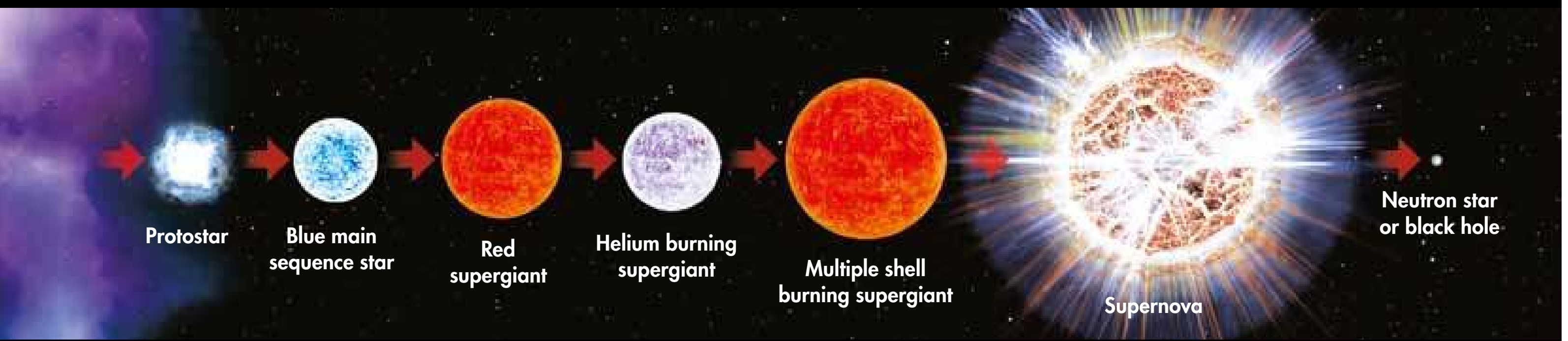
CORE-COLLAPSE SUPERNOVA

Stars that are more than eight times the mass of the Sun live short, bright lives – only a few million years, compared to the expected 10-billion-year lifespan of the smaller Sun.

When it is born, a massive star burns hydrogen in its core, where the temperatures and pressures are so high that the hydrogen is fused into helium. The massive star then burns heavier and heavier elements in its core, from hydrogen to helium to carbon – all the way up to iron. Once a particular fuel has been consumed, the core contracts until it is hot and dense enough to burn the next heaviest element, while a shell of material forms around it. Over time, the star develops an onion-like structure.

Eventually, when the star's core is made up of iron and other heavier elements that can't be burnt, the nuclear reactions within the star cease. At this point, there's no more pressure holding off the gravity of the outer layers, which subsequently begin to implode.

Once this happens, the pressures in the core become so high that protons and electrons combine to form neutrons, and a neutron star is created. The remainder of the imploding material rebounds off this neutron star in the form of a catastrophic supernova explosion.

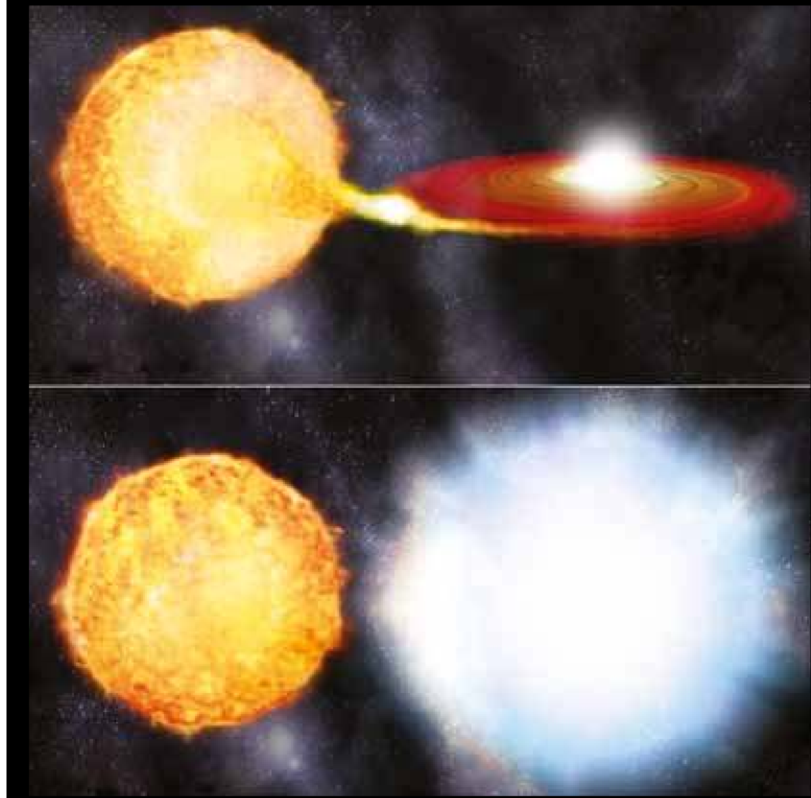


▲ The life cycle of a star more than eight times the mass of the Sun, ending in a supernova that leaves a neutron star or a black hole behind

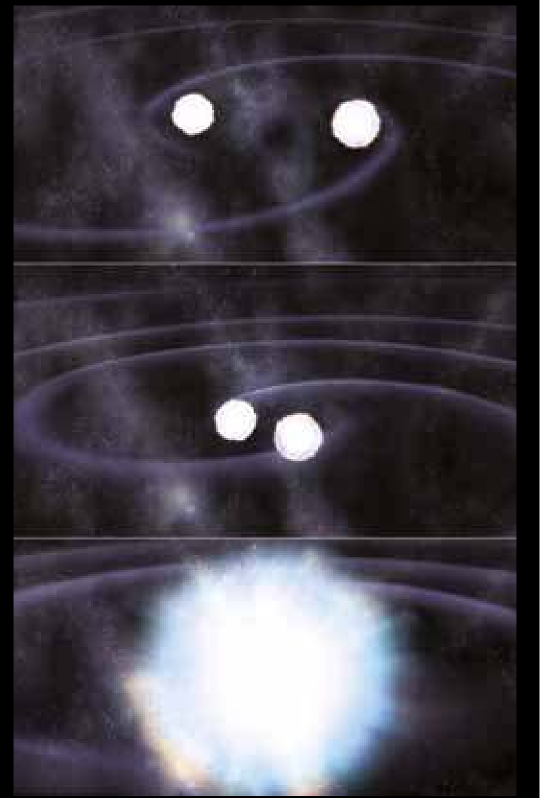
THERMONUCLEAR SUPERNOVA

There are two possible triggers for a Type Ia supernova, both of which involve a binary star system. In the first scenario it is thought that a white dwarf slowly draws material from a larger companion star. Eventually the white dwarf accretes so much material, and its mass grows so large, that it starts burning carbon in its core. From this carbon burning grow the seeds of the star's eventual demise. Eventually a thermonuclear explosion leads to the total destruction of the star and the expulsion of its ashes into space.

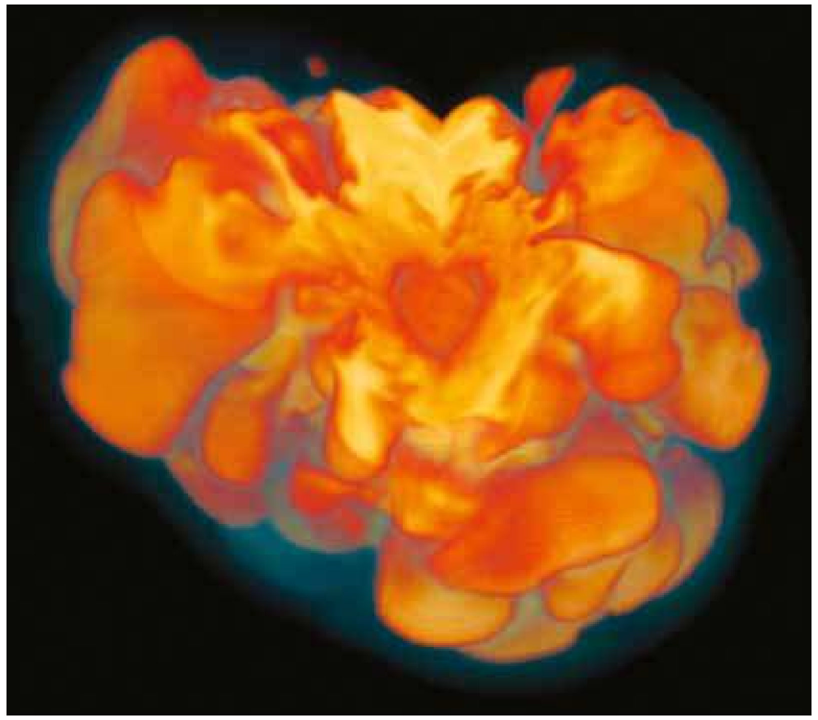
The second scenario thought to be behind Type Ia supernovae is when two white dwarf stars merge. Here, stars that once existed in a binary system gradually twirl together over time until they collide violently. In this scenario, the accretion of material is thought to happen very rapidly, but the outcome is the same – the total obliteration of both stars, with their remains scattered into space.



▲ Type Ia supernovae occur when a star accretes matter from its binary partner…



▲ …or when the two stars collide



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▲ **A simulated supernova, 300 milliseconds after core collapse; the turbulence is caused by unseen neutrinos**

▸ advanced computer simulations. The only problem is that, after more than 50 years of trying, no-one has been able to successfully recreate a supernova in a simulation.

From the 1960s to the 1980s, the computer simulations that could be carried out were very basic. Due to the limitations in available technology, many assumptions had to be made. Simulations were run in only a single dimension and, for reasons of simplicity, astronomers were limited to geometric models of the explosion that were spherically symmetric. In the 1990s, advances in numerical codes meant that it was possible to include two spatial dimensions, and more sophisticated models meant that scientists could simulate the elements of a star in motion during the explosions – so-called hydrodynamical mixing.

This led to new insights. Core-collapse models showed that acoustic vibrations within the star, reinforced by turbulent mixing in the material flowing out, could play a key role in adding energy to the shockwave at vital moments. Another factor highlighted by these simulations was the energy contained in the huge outflow of neutrinos (energetic subatomic particles) created during the core collapse as electrons and protons are forced together.

At the same time, improved computer technology allowed more and more physical processes to be included in the simulations. Teams of astronomers were finally able to use the world's fastest supercomputers to run their simulations and model the explosions in ever more realistic conditions.

Modelling supernovae

One such group has been led by theoretical astrophysicists Dr Hans-Thomas Janka at the Max Planck Institute for Astrophysics in Germany. They used a series of supercomputers in one of the first successful simulations of a core-collapse supernova. By working advanced models of the outflow of neutrinos from the stellar core into their two-dimensional simulations, they reproduced how the neutrinos interacted with matter within a dying star. The results supported theories that the explosions of stars with 11 to 15 times the mass of the Sun receive a crucial boost in energy through hydrodynamic instabilities: the star's layers were being heated, by neutrinos, into a bubbling mix.

Similar developments have been made in simulations of Type Ia supernovae. A team of astrophysicists in the US has successfully modelled the stages before a thermonuclear explosion in the first three-dimensional simulation to incorporate complex hydrodynamics. Their results not only confirmed the results of earlier, less sophisticated attempts, but also revealed that the behaviour inside the white dwarf just before detonation is more complex than expected.

The lead author of the study, Dr Michael Zingale of Stony Brook University, explains: "We focused on the early stages of the Type Ia explosion, trying to understand how the convective stage preceding the explosion ignites the initial burning front. Our results indicate that the ignition of the burning front is likely off-centre, which may lead to asymmetric explosions." Dr Zingale's simulations were performed on the supercomputers at the National Energy Research Scientific Computing Center in Oakland, California. Despite their huge power, each simulation still took over a million hours of processing time to complete.

Research and simulations into supernovae are still ongoing. "We will need a couple of years before we solve the problem of supernova explosions," says Dr Janke. Modelling a supernova is a grand computational challenge requiring very complicated simulations that incorporate many aspects of fundamental physics. With current technology, a single simulation that includes all three spatial dimensions and all of the key physical principles can take several weeks to run on a supercomputer; on a normal desktop computer they would take literally thousands of years to complete.

Adding even greater optimism are developments in observing technology. When future supernovae occur, astronomers will be able to observe them at all wavelengths, as well as any change in neutrinos and maybe even gravitational waves. These observations will help us to further uncover the mechanisms and the structure of these enigmatic exploding stars. Ⓢ

▲ **SN 1987A was visible to the naked eye. When future supernovae occur, astronomers will be able to study them in greater detail than ever before**

SUPERNOVA **SIMULATORS**

▲ **Mira's 3D simulation of a core-collapse supernova; the 'bubble' is the shock wave**

The computer simulations being used by astrophysicists today are vastly superior to those used only a decade ago. The greatest computational challenge is the successful reproduction of a supernova – a challenge that has not been adequately overcome in over 50 years of attempts.

One of the key challenges is including very complicated yet fundamental physics in the simulations to make them as real as possible. Today, simulations need to reproduce the explosion in three dimensions, as well as accurately model the complex behaviour of the material in the explosion.

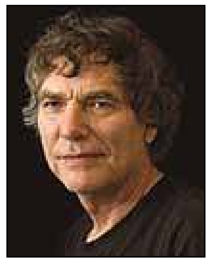
To do this, simulations have to recreate dynamic movement within the star with hydrodynamical codes, as well as accurately describe the way neutrinos are generated during the explosion.

This is the challenge for today's next-generation supercomputers; machines like Mira at the Argonne National Laboratory in the US, which can operate at 10 petaflops – meaning it can carry out 10 quadrillion (10 million billion) operations a second, and has 768 terabytes of memory. In comparison, the average desktop computer operates at a few gigaflops (handling a few billion operations a second), and may have only 6-8GB of memory.

▲ **The Mira supercomputer, built by IBM and housed at the Argonne National Laboratory**

THE EXPERT

Dr Stan Woosley, professor of astronomy and astrophysics at the University of California, Santa Cruz, uses computer simulations to simulate the deaths of massive stars



What have been the key developments in simulating core-collapse supernovae over the past decade?
I believe that it is a growing realisation that magnetic fields and rotation must be important in the deaths of some massive stars, which is based upon the connection of supernovae with gamma-ray bursts. Also key has been developing computer codes of increased realism and complexity to run on the exponentially advancing computer technology.

Why is it so difficult to explode a massive star in a simulation?
The difficulty is that the simulations are very complex and the explosion itself is only a small fraction – about a thousandth – of the total energy being tracked. It is also hard because it is necessary to model the explosion in three dimensions and include many different aspects of fundamental physics including general relativity, rotation, and complicated equations of state.

What does the future hold for our ability to simulate supernovae?
In general I am optimistic about the future. The good news is that we've most likely pinned down the important basic physics, while computers and our codes are becoming equal to the challenge, and progress is being made. The calculations being done today could only have been dreamed about 10 years ago.

More problematic are the codes needed to use those machines effectively. Certainly people are making advances, but no-one has yet produced a simulation that includes all of the necessary physics. They will, though.

The real challenge may not be in just getting the right answer, but in convincing the community of people working on the problem that the answer, once it's been found, is indeed correct and robust.

ABOUT THE WRITER

Zach Cano is a post-doctoral research fellow investigating core-collapse supernovae and gamma-ray bursts at the University of Iceland's Centre for Astrophysics and Cosmology.

The Solar System in chaos

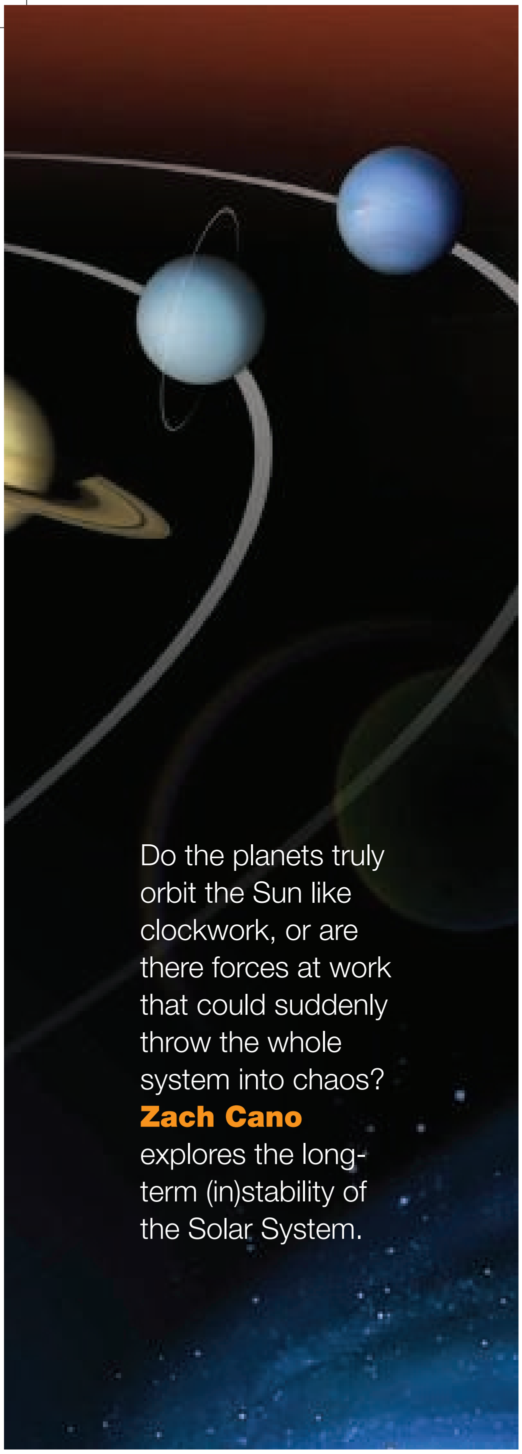
▲ The planets in their orbits (not to scale!). The odds are that they will remain in this orderly fashion – but there's a chance they won't. Image: NASA/JPL–Caltech.

Since evolution gifted man with the ability to think abstractly, and from a perspective other than his own, a cascade of existential thoughts have bombarded him: Who am I? Where do I come from? Where am I going? How will I die? Tied to the last question is not only a meditation into the demise of a single human, but that also of all mankind and all life on Earth. Will all life end through the folly of an overzealous political leader? Perhaps something more natural such as a comet colliding with Earth? Such concepts have been sensationalised in Hollywood movies, though the reality of a violent end to our beloved planet through a collision with another planet is more real than you might expect.

Five billion years from now the Sun will have exhausted all of the hydrogen in its core, thus running out of its main source of nuclear fuel. The stellar core will then contract under the immense force of gravity, creating temperatures and pressures great enough to fuse helium into carbon. As the core contracts the outer layers will expand and the Sun will enter a red giant phase. At this time Mercury and Venus will be swallowed by the Sun, and so too may the Earth. However, this scenario depends on one thing: that the planets remain in the same orbits that they currently occupy. As many astronomers and mathematicians have found out over the centuries, this is far from a certainty.

Soon after Isaac Newton formulated his law of universal gravitation, fundamental questions arose surrounding the dynamical stability of the Solar System. Is the Solar System currently stable? Will it be stable in the future? Will the Earth ever collide with another planet? Such questions are relevant today; from metaphysical musings of apocalyptic scenarios to technological developments in modern space travel.

Dating back to eighteenth century France, Joseph-Louis Lagrange and Pierre-Simon Laplace were members of an elite group of mathematicians and astronomers trying to deduce the order of the Universe. While observing the Solar System, Laplace and Lagrange developed a theory to describe the planetary orbits, which was later enhanced by Urbain Le Verrier and Simon Newcomb. The theory was a very good approximation of planetary motion over relatively short periods of time and indeed, such was the success

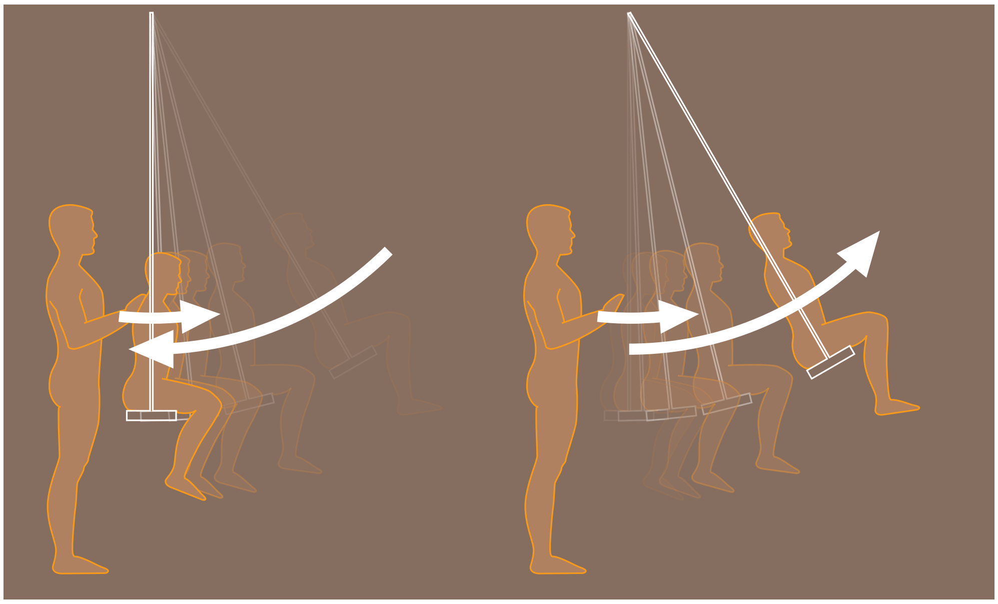


Do the planets truly orbit the Sun like clockwork, or are there forces at work that could suddenly throw the whole system into chaos? **Zach Cano** explores the long-term (in)stability of the Solar System.

enjoyed by Laplace when explaining the secular motions (i.e. deviations in a planet's elliptical orbit caused by the gravitational influence of other planets) of Jupiter and Saturn, that he was able to establish the philosophical concept of Laplacian Determinism – the idea that if we know all present conditions, as well as the laws that govern the Universe, then it is possible to predict all future events.

However, Laplace's bubble was burst in the late nineteenth century when Henri Poincare demonstrated that it is impossible to formulate an exact analytical solution for the motion of more than one planet. While conducting research into a three-body system, Poincare discovered that when he included gravity and the positions of three bodies in space, he was able to accurately calculate the positions of the three bodies at any future time, thus showing that the system is deterministic. More importantly, he also found that the evolution of such a system is chaotic in the sense that a slightly different starting position of one or more of the bodies leads to dramatically different outcomes. Thus, if the exact starting positions of all the known bodies are not known exactly, then it is impossible to precisely predict the outcome to the system. Poincare's research laid the foundations for the idea of chaotic systems and non-linear dynamics.

▼ The phenomena of resonance can be a powerful force between Solar System bodies. A down to Earth analogy is a swing – when the child gets a shove at the appropriate point in the swing's arc it amplifies the swing at the resonance frequency (right). If the shove takes place at the wrong point, for example in the opposite direction to the motion of the swing, the effect is to dampen the swing rather than amplify it (left). AN graphic by Greg Smye–Rumsby.



"AS MANY ASTRONOMERS HAVE FOUND OUT OVER THE CENTURIES, IT IS FAR FROM CERTAIN THAT THE PLANETS WILL REMAIN IN THE SAME ORBITS THAT THEY CURRENTLY OCCUPY"

Chaos

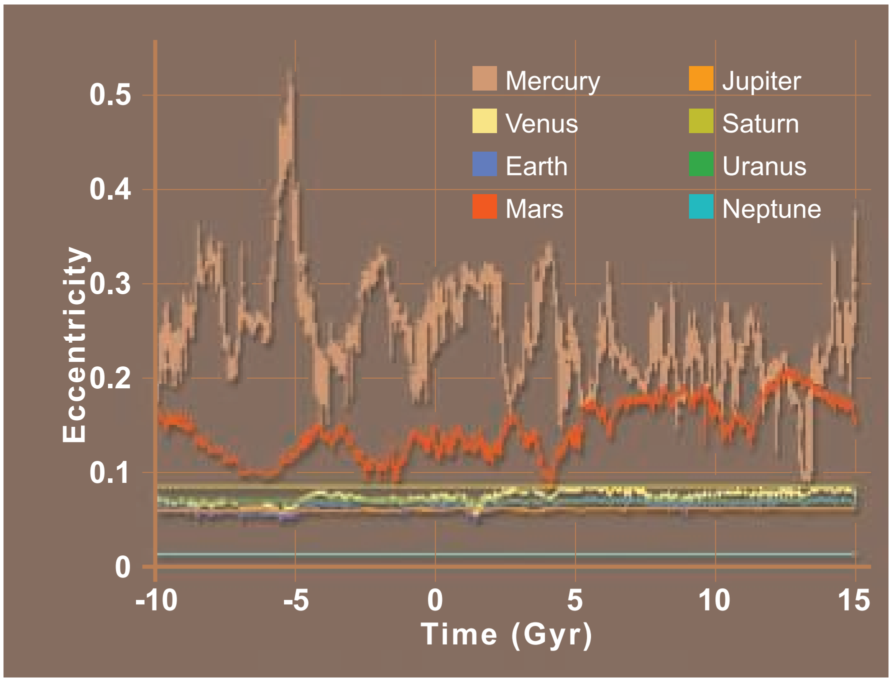
So what is chaos? It is a common enough concept and most associate it with the slight fluttering of elegantly-winged insects. But before we can develop an understanding of chaos and chaotic systems, we must first understand the different kinds of dynamical systems that exist.

What we mean by a dynamical system is how one state develops into another over time, such as describing how a snooker ball may travel across a table once it has been struck. If we know its mass, its starting position and its velocity, we can use the equations of motion to describe its movement over time. In this analogy, the solitary snooker ball is a regular dynamical system; its movement is well behaved and highly predictable. Small differences in its position grow linearly and can be easily calculated.

The other type of dynamical system is a chaotic system, where the behaviour of the components of the system are erratic and difficult to predict. In chaotic systems, small dynamical differences grow exponentially (i.e. in a non-linear manner), although on short time-scales they may appear linear and therefore non-chaotic. A clear example of such a chaotic system is the Solar System. On short time-scales planetary motion appears to be regular and like clockwork. However, if we try to calculate the positions of planets in the far future, it is found to be simply impossible.

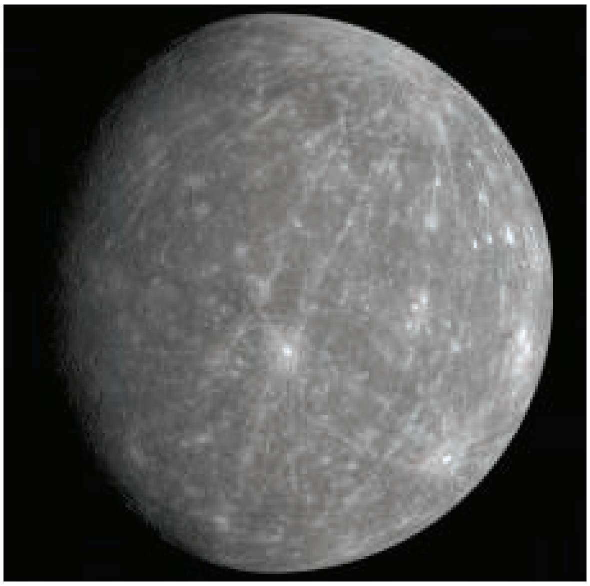
In the Solar System chaos arises because of resonance and a familiar example can be found in playgrounds. Imagine a young child on a swing – the parent will push the child at regular intervals to keep the child swinging at a constant amplitude. The parent doesn't push randomly but rather in the same direction as the swing's velocity and by doing so the parent can easily maintain or even increase the amplitude of the swing. This is the phenomenon called resonance and it happens when any two periods have a simple numerical ratio.

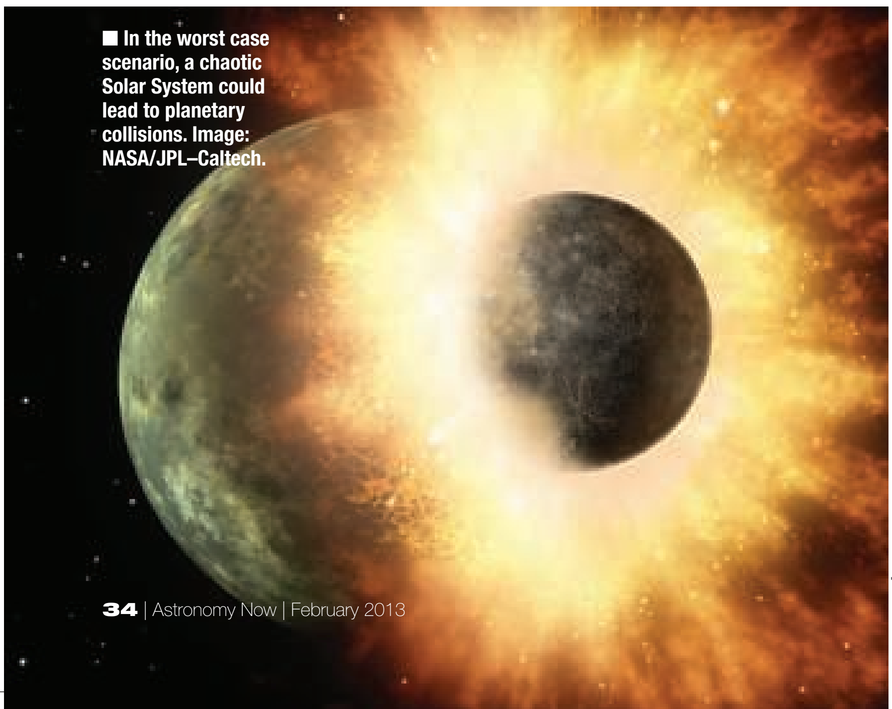
There are a two types of resonance in the Solar System and both involve the orbital motions of the eight major planets and their various satellites. The first is spin-orbit resonance, where the rotational period (its 'day') and orbital revolution (its 'year') are a simple ratio. Earth's Moon demonstrates an example of spin-orbit resonance, where the rate at which the Moon orbits the Earth is the same as its rate of rotation, which



▲ The orbital eccentricities of all the planets in the Solar System over timespans of billions of years (Gyrs). The eccentricities (i.e. how elliptical they become) of most of the planets remain stable. However, orbital resonances with Jupiter have the potential to make Mercury and Mars' orbits highly eccentric over long time periods. AN graphic by Greg Smye–Rumsby based on data from Laskar et al.

▼ Mercury is at the mercy of gravitational perturbations. Image: NASA/JHUAPL/Carnegie Institution.





■ In the worst case scenario, a chaotic Solar System could lead to planetary collisions. Image: NASA/JPL–Caltech.

is a 1:1 ratio (this is also referred to as synchronous rotation) and explains why we only ever see the same side of the Moon.

The other type is secular, or orbital, resonance where the precession of the orbits of two bodies is synchronised. Here, a small body in orbital resonance with a larger body will precess at the same rate as the larger, which will ultimately change the eccentricity (i.e. the amount that an orbiting body's orbit deviates away from a perfect circle) and inclination of the smaller body's orbit. A clear example of orbital resonance is the orbits of Jupiter's moons Europa and Io. The former has an orbital period of 3.55 days, while the latter is 1.77 days, which gives an orbital resonance between Europa and Io of 2:1.

Another example of orbital resonance may exist between Mercury and Jupiter in the future. Despite Jupiter being, on average, some 778 million kilometres distant from the Sun, the innermost planet is still susceptible to Jupiter's gravitational influence. Mercury's perihelion (the closest point to the Sun in its orbit) precesses at a rate that is similar to, albeit a bit faster, than that of Jupiter's perihelion. Should the two rates ever have the same value, constant tugs on Mercury's orbit from Jupiter's gravity will accumulate over many thousands and millions of years, eventually elongating Mercury's orbit (i.e. increase its eccentricity) to a point that it collides with Venus or the Earth, or is ejected from the Solar System.

What are the odds?

It is the accumulation of resonances within the Solar System that makes calculating the exact fate of the planets many billions of years into the future an ultimately fruitless task. However, this has not stopped many astronomers, including Jacques Laskar of the Astronomie et Systèmes Dynamiques at the Observatoire de Paris, from trying to gain some understanding of the ultimate fate of the Solar System.

It has been over 25 years since Laskar's research first descended into chaos. In the late 1980s he published a landmark paper showing that the Solar System really is a chaotic place and that this chaos inhibits the ability to accurately predict the precise future positions of the planets on time-scales spanning millions of years or more. Over the years Laskar has refined his method and has produced results that, as well as being repeatedly verified independently by other researchers, have shocking implications to life on Earth in the far future.

Laskar has used numerical integrations of averaged equations of motions to calculate the orbital positions of the Solar System's planets some five billions years in the future. The Sun is 4.64 billion years old with an expected lifetime of some 10 billion years and, by projecting his models so far into the future, Laskar seeks to understand the likely configurationof the planets as the Sun approaches its death. In his model, Laskar has tried to reproduce reality to the highest degree of accuracy possible by including the latest observations and measurements of the masses of the planets (including Pluto) and moons, as well as including Einstein's relativistic model of gravity.

While Poincare showed that it is not possible to calculate the exact outcome to any system with more two orbiting bodies, Laskar has determined the probability of various fates of the Solar System by running his simulation more than 2,500 times. The results of his work have very stark implications for Earth's ultimate fate.

Planet pinball

One to two percent of the solutions show that Mercury's orbit will reach eccentricities larger than 0.6, which is large enough to cross the orbital path of Venus and thus increase the rate of interactions between the other inner planets. Within these outcomes, the inner Solar System is sent into disarray and Mercury is either ejected into space or collides with the Sun or Venus. Furthermore, in some of the possible outcomes, increased interactions in the inner Solar System cause Venus to crash into the Earth, while others see the ejection of Mars into deep space. Another outcome saw a close encounter between Earth and Mars of only 800 kilometres, which is about the distance between Liverpool and Paris. Such a close approach would devastate all life on Earth and tidally disrupt Mars, leading to multiple impacts upon the Earth's surface.

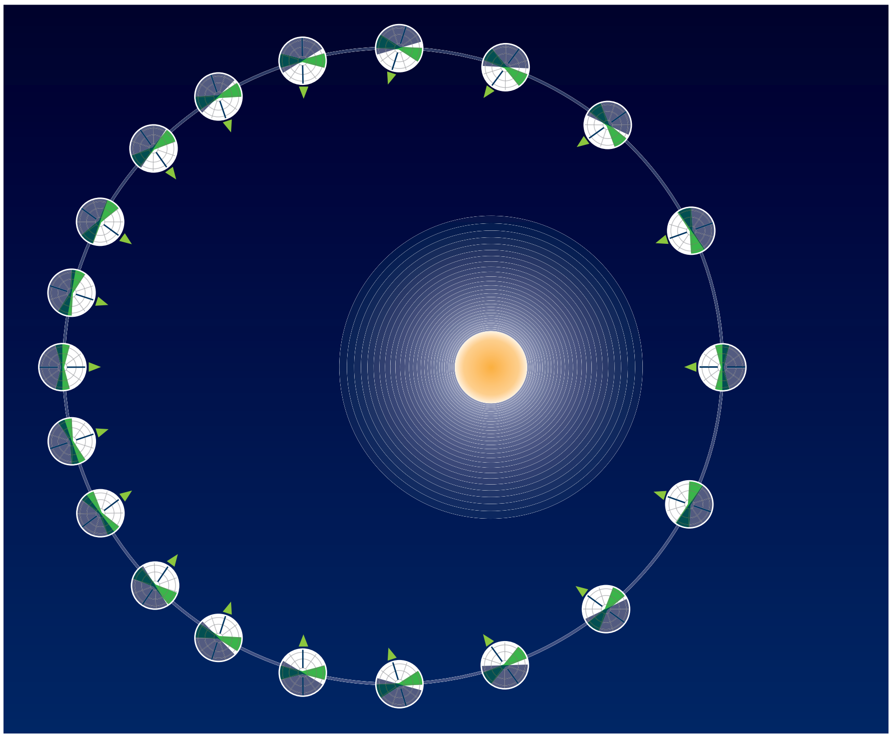
Similar results have been calculated by other groups, including Gregory Laughlin and Konstantin Batygin of the University of California in Santa Cruz. In their simulations (as well as Laskar's) the trigger for the collisional trajectories of Mars and Venus with the Earth is the increase in Mercury's eccentricity. Because Mercury and Mars possess smaller masses than Venus and Earth, they are thrown about much easier and thus more likely to collide with another planet or be ejected out into space.

> "THE INNER SOLAR SYSTEM IS SENT INTO DISARRAY AND MERCURY IS EITHER EJECTED INTO SPACE OR COLLIDES WITH THE SUN OR VENUS"

Both groups have found that in 98–99 percent of outcomes, the Solar System remains stable more than five billion years in the future. However there is still a small, yet non-negligible, chance that Earth may encounter a very violent end. Such odds are small but not impossible, nor improbable, especially when you compare the odds with other rare and bizarre events. For example, the odds of being hit by lightning are 576,000:1, while catching a foul ball at a baseball game is about 563:1. Indeed, the future odds of Earth colliding with Venus and being blown to a billion little pieces are almost a thousand times higher than you ever dating a supermodel (odds are 88,000:1)!

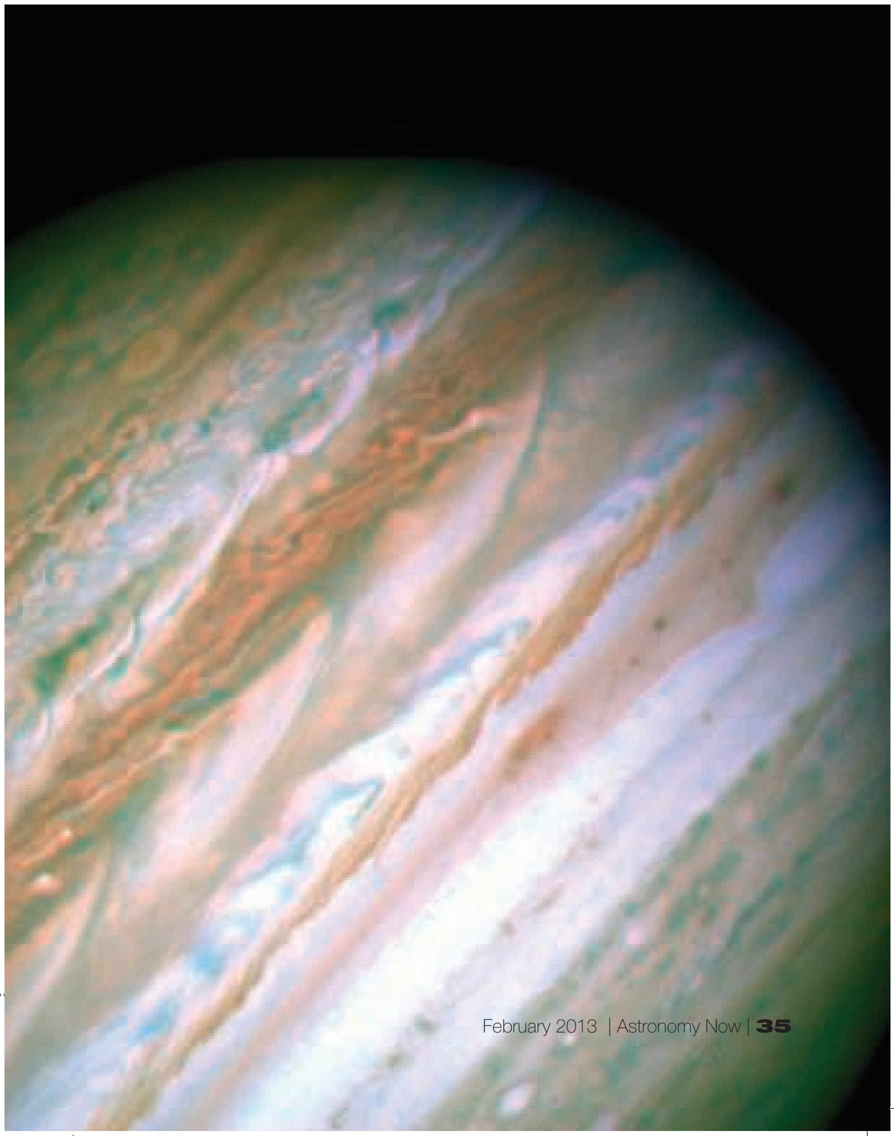
So, the ultimate fate of the Earth and indeed the planets will always have a degree of uncertainty. Because of the chaotic nature of the seemingly simple arrangement of the Solar System, all we can ever hope to know is the probability of a certain fate. The odds are that the Solar System is quite stable and that the Earth will still be orbiting the Sun much like it is now by the time the Sun expires. However, this is not a certainty and there is a small, but not insignificant chance that the Earth may collide with another planet, maybe Venus or Mars, in an event that would be utterly catastrophic for any life still clinging to existence at that time.

Zach Cano is a post-doctoral researcher at the University of Iceland and is a freelance science journalist.



▲ A schematic of synchronous rotation. Notice how the axial rotation of the planet (signified by the arrow) matches the orbital period of the planet (give or take the effects of libration caused by the elliptical orbit). This is a product of the spin-orbit resonance. AN graphic by Greg Smye–Rumsby.

▼ As the largest planet in the Solar System by far, Jupiter's gravity reigns as far as little Mercury and is the chief agitator when it comes to planetary instability. Image: NASA/ESA.



EXPANDING THE view

One of the biggest galaxy surveys ever carried out has brought us closer to understanding the enigma of dark energy. We look at what it has revealed and what is still to be uncovered

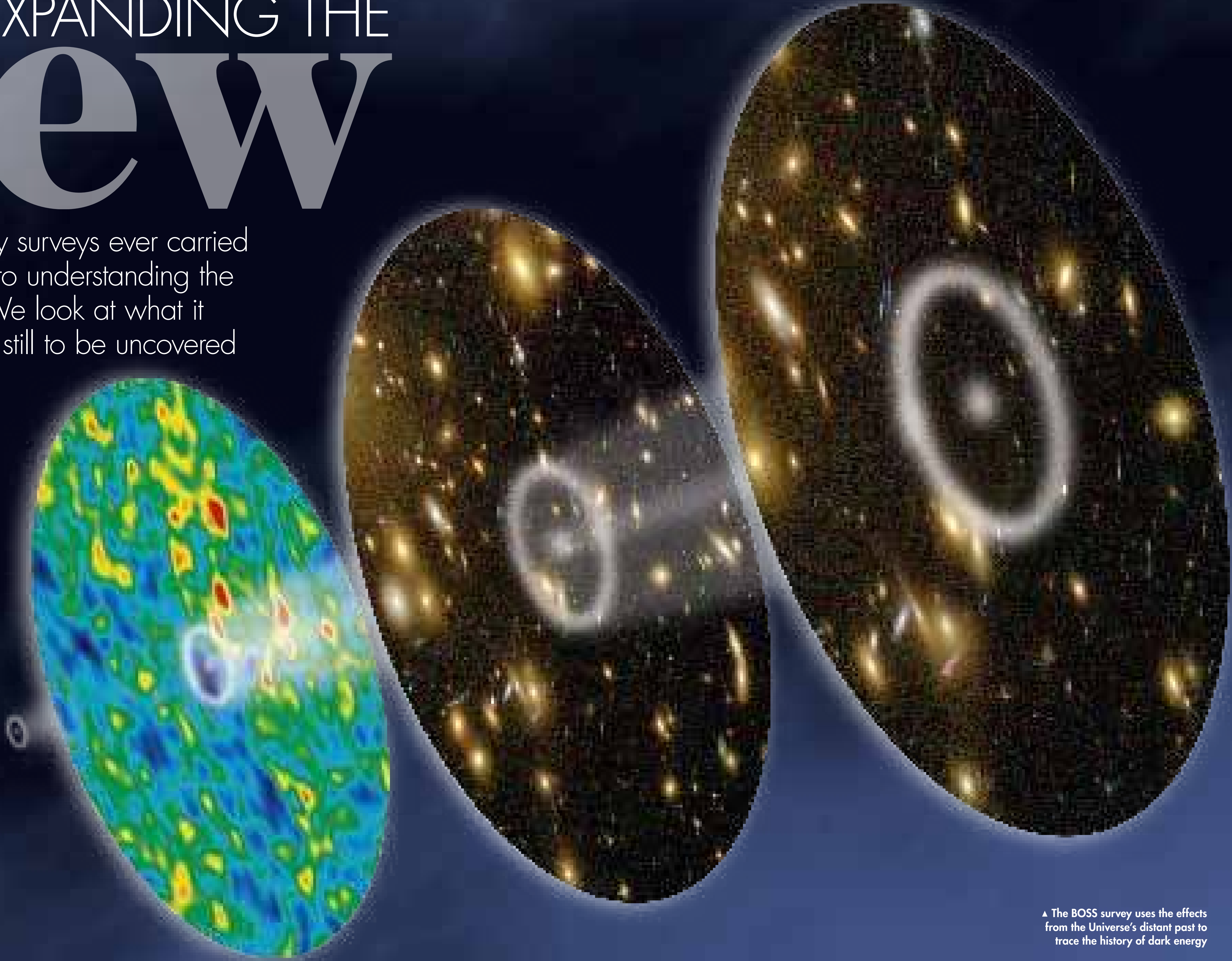
WORDS: ZACH CANO

NASA/WMAP SCIENCE TEAM, NASA/N. BENITEZ (JHU) T. BROADHURST (RACAH INSTITUTE OF PHYSICS/THE HEBREW UNIVERSITY) H. FORD (JHU), M. CLAMPIN (STSCI) G. HARTIG (STSCI) G. ILLINGWORTH (UCO/LICK OBSERVATORY) THE ACS SCIENCE TEAM AND ESA

Dark energy is one of the most baffling puzzles in modern cosmology. The Universe is thought to be more than 75 per cent dark energy, but scientists have yet to define it. Crucial questions about its nature still need to be answered. Why is there so much of it? Is there more now than in the past? Where does it come from? Now a team of astrophysicists have taken a definitive step forward in understanding how dark energy has shaped our past and how it may shape our future.

The modern cosmological model is built on our understanding of gravity and quantum mechanics, which has been confirmed by many crucial observations. One of the most important of these was made by the Cosmic Background Explorer (COBE) satellite, which observed tiny temperature fluctuations in the cosmic microwave background. These fluctuations were predicted by the Standard Model – the best accepted explanation of how elementary particles interact – and are expected to be the basis upon which all structure in the Universe is derived.

Another important observation was made by two teams led by American astrophysicists Adam Riess and Saul Perlmutter in 1997; they showed that not only is the Universe expanding, but that it ▸



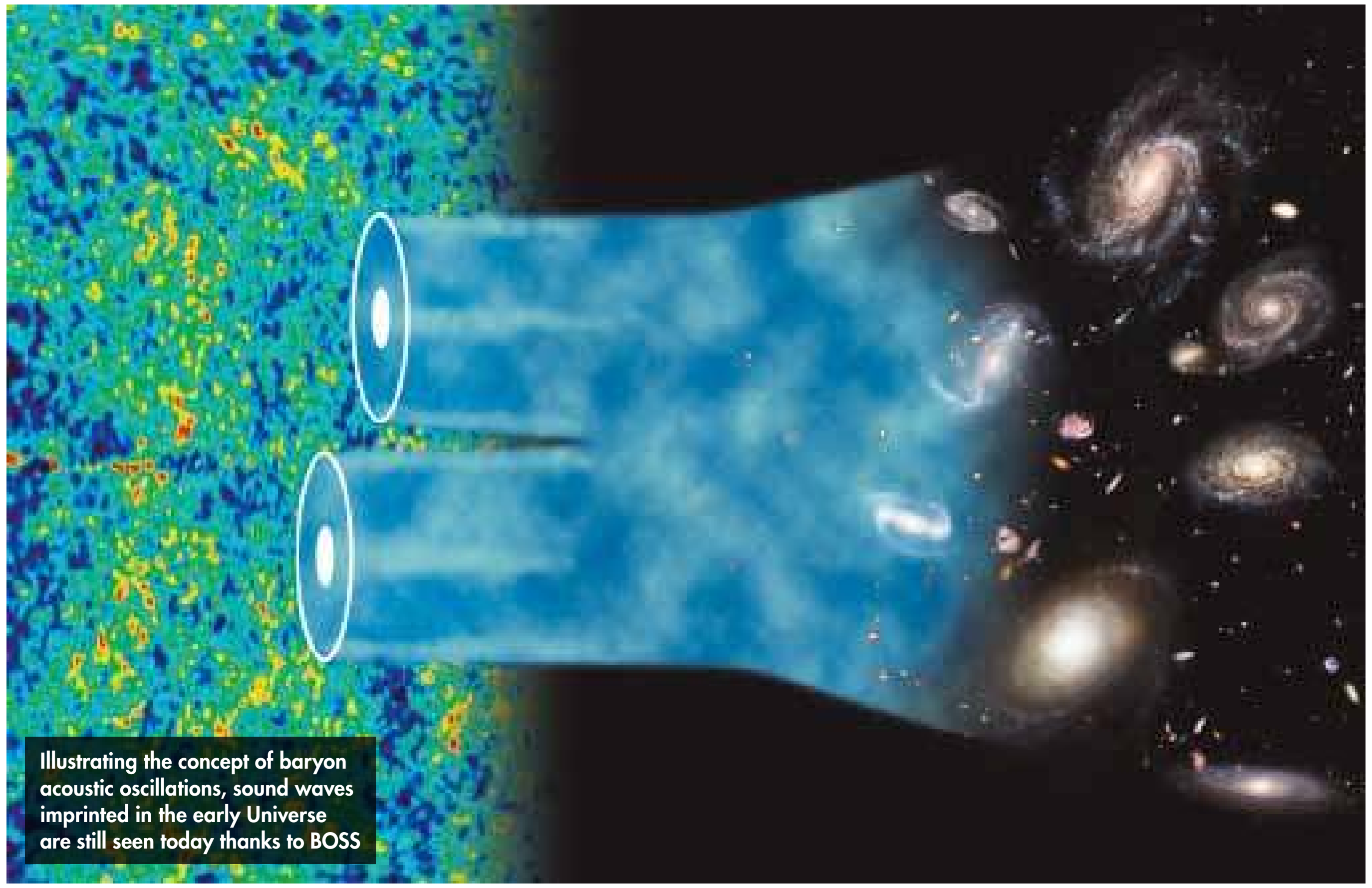
▲ The BOSS survey uses the effects from the Universe's distant past to trace the history of dark energy

WHAT ARE BARYON ACOUSTIC OSCILLATIONS?

In the early Universe, normal ('baryonic') matter existed in a hot plasma that trapped all photons within it. The Universe was also very smooth, with only small density differences existing from place to place.

Over time, denser regions gravitationally attracted matter towards them, but the gravitational force was counteracted by a pressure force from the hot plasma. This made the matter oscillate: first it was pulled towards the denser regions and overshot them, only to be pulled back again. This oscillation produced acoustic sound waves, which astronomers call baryon acoustic oscillations.

Around 400,000 years after the Big Bang, the Universe cooled enough to allow protons and electrons in normal matter to escape the plasma and form hydrogen. The distance that the baryon acoustic oscillations travelled was limited by the amount that the Universe had expanded up to this point, and details of this limit were imprinted on the trapped photons before they escaped out into space. So the signatures of the oscillations allow us to glimpse the end of an early chapter of the Universe, when it was still opaque and light couldn't travel freely, as it has done ever since.

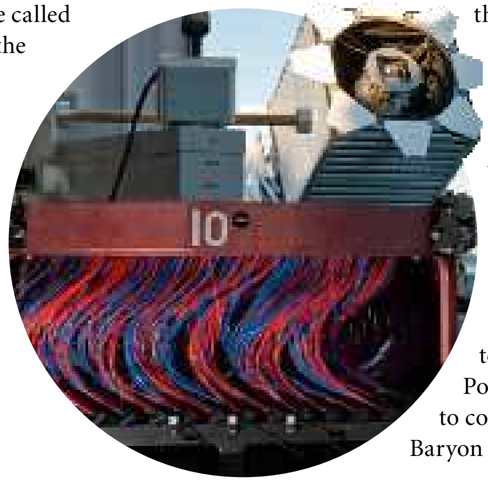


Illustrating the concept of baryon acoustic oscillations, sound waves imprinted in the early Universe are still seen today thanks to BOSS

▸ is doing so at an accelerated rate. This work relied on a particular kind of supernova, Type Ia, the fatal explosion of a white dwarf star. These supernovae behave in almost the same way every time they occur. Because they're so predictable, they're called 'standard candles' and are used to measure the distances to objects across the Universe.

A new riddle

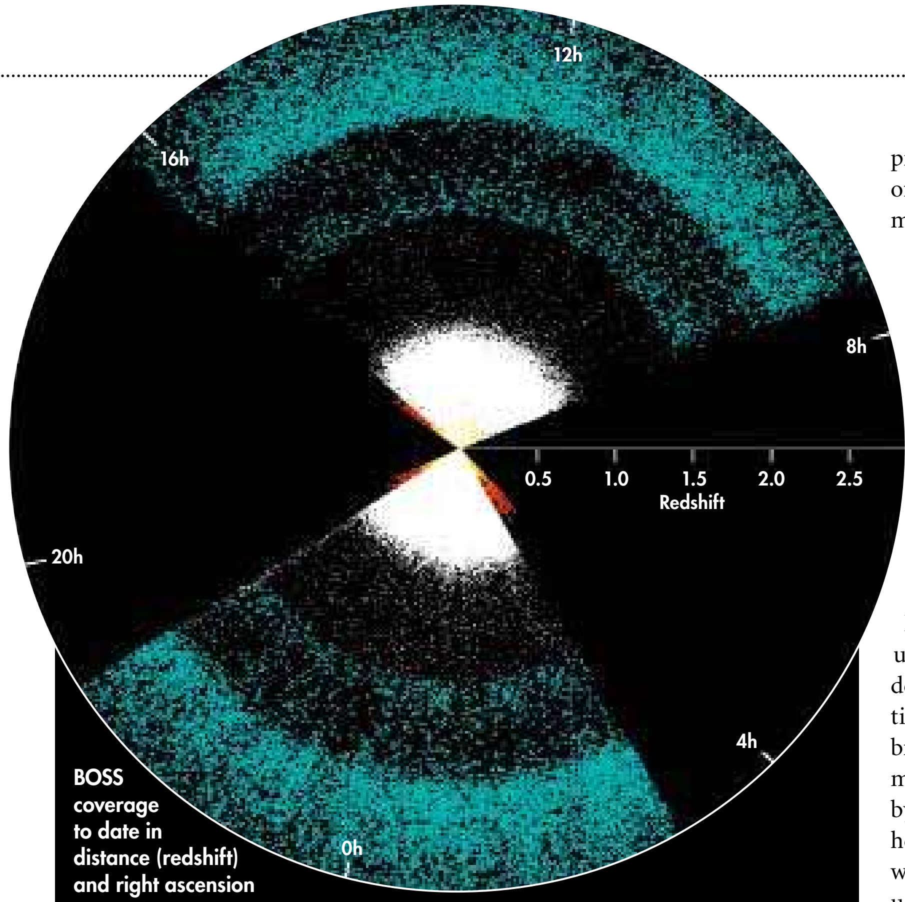
Riess and Perlmutter observed that the Type Ia supernovae that occurred in distant galaxies were fainter than expected. They concluded that the expansion of space during the time it took light to travel from the supernova to Earth was much greater than could be accounted for by a constant expansion rate, and so the idea of an unknown force driving the acceleration of this expansion – dark energy – was born.



▾ The Sloan Telescope at the Apache Point Observatory is one of BOSS's eyes on the sky

Additional clues to dark energy come in the form of the geometrical shapes of the vast swathes of galaxy clusters. The rate at which these large-scale structures grow is directly related to the amount of dark energy there is in the Universe. Therefore, if you can precisely map a large portion of the night sky, you can use the map to narrow down how much dark energy there was at different times in the Universe's past.

This is exactly what a team led by David Schlegel of the Lawrence Berkeley National Laboratory in California is currently doing. His team used the 2.5m Sloan Digital Sky Survey-III telescopes and spectrometers at Apache Point Observatory in New Mexico, US, to conduct a vast galaxy study called the Baryon Acoustic Oscillation Spectroscopic



BOSS coverage to date in distance (redshift) and right ascension

THE UNIVERSE SURVEYOR

So far, BOSS has measured the redshifts of 327,349 galaxies over a region of 3,275 square degrees. The final survey, expected in 2014, will map the positions of over 1.5 million galaxies and cover more than 10,000 square degrees – a quarter of the total area of the night sky. In doing so it will look back to a time just six billion years after the Big Bang.

BOSS's map shows that galaxies and clusters of galaxies are clumped together into walls and filaments, with vast voids between them. These structures grew out of minute variations in density that existed in the early Universe and bear the imprint of baryon acoustic oscillations in their structure. Using this map, astronomers can plot the number of galaxy pairs against separation distance to measure the most likely separation of all of the galaxy pairs. It's this value that gives an indication of the amount of dark energy present in the Universe when it was only half its present age.

Survey (BOSS). It is the most accurate map yet of galaxies in the farthest reaches of space. Using this map, Schlegel's team hopes to understand the behaviour of dark energy throughout the history of the Universe.

Rewinding the cosmic videotape back to 400,000 years after the Big Bang puts this BOSS research in context. Conditions in the early Universe were much hotter and denser than they are today. Energetic protons and electrons filled space in a hot plasma, trapping light inside it, so that photons ricocheted off the energetic subatomic particles in an eternal game of cosmic pinball. As the Universe expanded over time it also cooled and, after almost 400,000 years, the protons and electrons combined to form neutral hydrogen atoms, allowing light to escape out into space. This primeval radiation still exists today in the form of cool microwaves. We refer to it as the cosmic microwave background.

> "The rate at which large-scale structures grow is related to the amount of dark energy there is in the Universe"

The photons that escaped were measured by the COBE mission in the 1990s and more recently by the Wilkinson Microwave Anisotropy Probe (WMAP). They reveal that the early Universe was incredibly smooth, with density differences of only one part in 1,000. This is drastically different to how the Universe appears today, with vast voids and massive clusters of galaxies that are one million times denser than the mean cosmic density.

Blots on the soundscape

But how does a very smooth Universe end up so clumpy? It all has to do with the subtle density differences in the early Universe. The tiny overdensities that existed before the photons broke free gravitationally attracted surrounding matter. But this gravitational force was offset by a pressure imbalance from the photons and heat trapped in the hot plasma. This pressure was so great that the overdensities did not grow under gravity but instead oscillated to produce acoustic sound waves, which astronomers call baryon acoustic oscillations (see box, page 42).

Over time, these regions are far more likely to be sites where galaxies have formed. Overdense regions formed all over the Universe and many spherical, acoustic waves overlapped. It's like throwing a pebble into a pond – it will cause a ripple that spreads outwards. In the case of the Universe, there are billions of pebbles causing ripples everywhere.

Like a cosmic bagpipe, the Universe produced a cacophony of these sound waves. But the plasma (and the sound waves) disappeared when neutral hydrogen formed 400,000 years after the Big Bang, so there is only a finite distance that the sound waves could have travelled in that time. This is called the 'sound horizon scale length'. When the Universe cooled and the photons escaped out into space, they retained an imprint of this distance.

So how big was the Universe back then? One of the most accurate measurements was determined using observations made by WMAP, which found the scale length to be about 150 megaparsecs – equivalent to 489 million lightyears. This gave a ruler similar to standard candles, which has been useful when making measurements of galaxy distributions.

Armed with this standard ruler, Schlegel and his team are using the BOSS map as a geometric probe to trace out the history of the Universe's expansion, producing a graph that plots the number of galaxy pairs against the distance between them. This ▸

▲ The BOSS results will give a realistic view of the Universe's large-scale structures, illustrated here

► shows that there is a most likely distance that galaxy pairs will be separated, which depends on the amount of dark energy in the Universe. And how precisely one can measure this separation depends on accurately knowing the distances to the galaxies in the first place.

"BOSS's first major cosmological results establish the accurate three-dimensional positions of 327,349 massive galaxies across 3,275 square degrees of the sky – the largest sample of the Universe ever surveyed at this high density," says Martin White of the University of California, Berkeley, and chair of the BOSS science survey teams.

Schlegel adds: "We've made precision measurements of the large-scale structure of the Universe five to seven billion years ago. We're pushing out to the distances when dark energy turned on, where we can start to do experiments to find out what's causing accelerated expansion."

In this early epoch, gravity was the dominant force and all the baryonic matter – in other words, ordinary matter – in the Universe held back the repulsive force of dark energy. Six billion years ago, the Universe underwent a very fundamental change: as it continued to expand, matter was forced farther apart to the point that dark energy became the dominant force. It still dominates the Universe today, causing the fabric of space-time between galaxies to expand at an ever-increasing rate.

Enduring enigma

While the history of dark energy is being pieced together and much more detail is being uncovered about its effects, the question of what it is still remains. Some of the leading contenders include Albert Einstein's cosmological constant, quintessence and extra dimensions of space.

Einstein famously called the cosmological constant his greatest blunder. He originally included it in his general theory of relativity as a way of explaining a static Universe. In his theory, the gravitational effect of matter caused an acceleration, something he did not want. So he introduced a constant to counteract this acceleration.

The cosmological constant is attributed to energy that exists in the vacuum of space. It is constant everywhere in the Universe and has negative pressure. But when scientists calculated the amount of vacuum energy using quantum mechanics, they found that there was at least 10^{120} times too much, so it was quickly dismissed as a candidate for dark energy.

The expert

Dr Richard Battye of the Jodrell Bank Centre for Astrophysics plans to use the capabilities of the Square Kilometre Array (SKA) to further investigate dark energy

How will your research into dark energy be helped by the SKA?

My research is focused on trying to probe fundamental physics using astronomical observations. Until recently this has largely involved using observations of the cosmic microwave background to investigate theories of structure formation and the fundamental parameters of the Universe.

I have worked on theoretical models for dark energy for some time. Probing models of dark energy using observations is a hot topic in cosmology and many instruments are being designed to do this, including Euclid and the SKA. I am becoming involved in these projects, although both are years from completion.

What's the SKA's current state of development?

The SKA board recently made the decision to split the site over the two competing locations in Australia and South Africa. Both countries are building precursor instruments, called ASKAP and MeerKAT respectively, and the first phase of construction will involve extensions to these instruments. We're likely to be getting the first substantial results for cosmology approximately 10 years from now.

What science will the SKA be involved with?

I am part of the wider community hoping to benefit from the surveys the SKA will perform. There are many possible ways this data could be used for cosmological research, but two main ones. Firstly, to measure baryon acoustic oscillations in order to constrain dark energy; the SKA will use the 21cm spectral line, the wavelength of radiation given off when hydrogen atoms change energy levels, to do this. Secondly, the SKA will use weak gravitational lensing, the distortion of background galaxies by the invisible mass of dark matter and dark energy that's between the source and observers on Earth. This is done by measuring the shapes of many galaxy images, which allows us to measure the amount of dark matter and energy along the line of sight between us and the galaxies. We're going to practice this by performing a survey using the e-MERLIN radio telescope array in the UK. This will start in the autumn.

MARK GARLICK/SCIENCE PHOTO LIBRARY, SKA ORGANISATION/TDP/DRAO/SWINBURNE ASTRONOMY PRODUCTIONS, DR RICHARD BATTYE

▲ The Square Kilometre Array will start producing cosmologically substantial results in around 10 years

Could it be quintessence then? According to this theory, dark energy is a scalar field that exists everywhere in the Universe – a scalar field being a region where every point has a particular value, the same way that every point in a room has a particular temperature. In the case of the Universe, this implies that different values of dark energy may exist in different regions. A more dynamic explanation for dark energy would be easier to digest by many astronomers, but more research is needed to understand if a quintessence-like dark energy is compatible with other elements of the Big Bang theory.

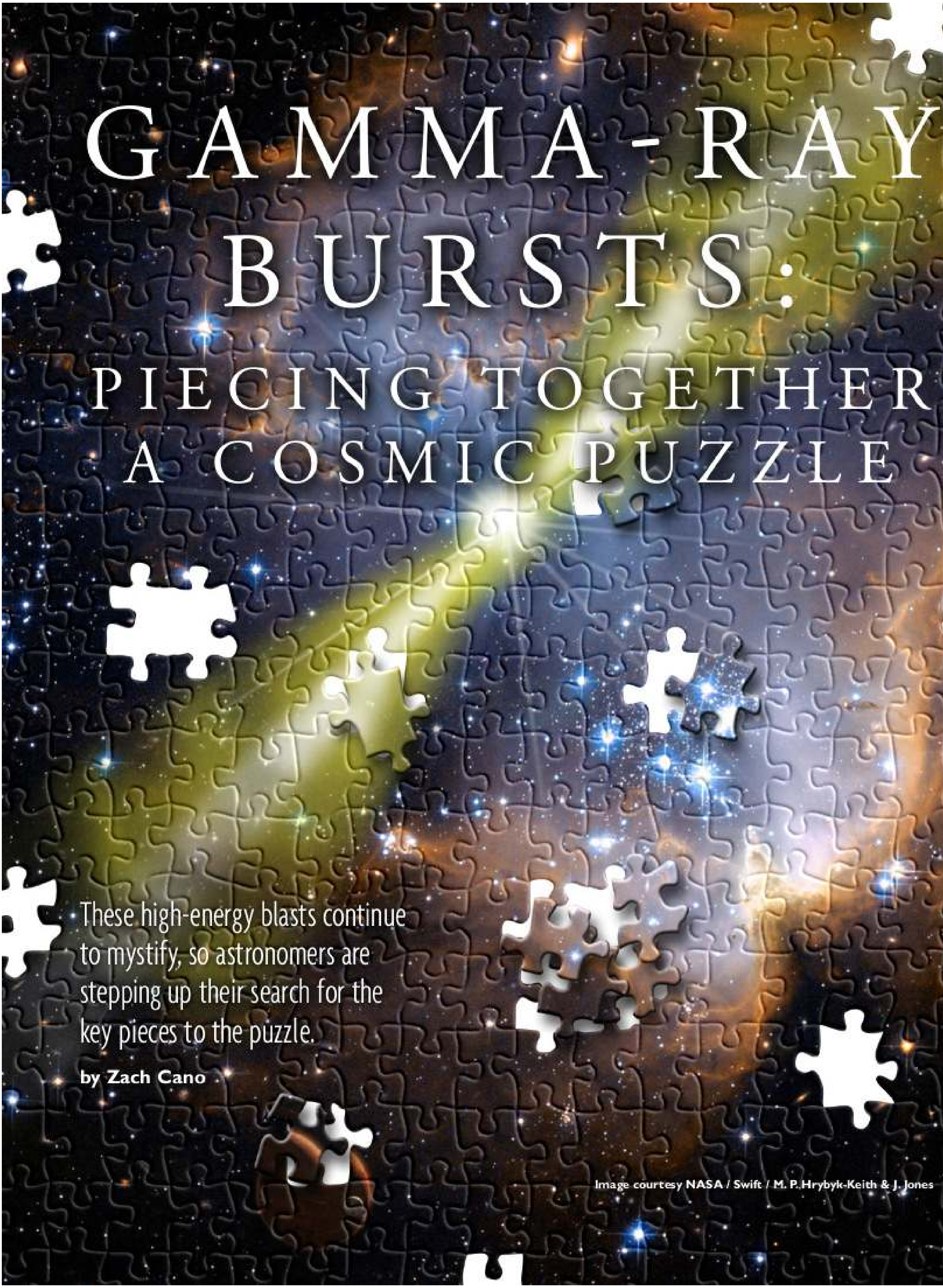
Another, more exotic theory for what dark energy is comes from string theory. While quantum mechanics overestimates the cosmological constant, the calculation made using string theory comes up with a value much closer to what is observed. It has been suggested that quantum fluctuations, which give the vacuum itself an energy, are confined to extremely small extra dimensions other than the three we're used to. These extra dimensions are so small that they restrict the strings, allowing them to vibrate only at certain frequencies, which reduces the amount of energy they possess.

> "While the history of dark energy is being pieced together, the question of what it is still remains"

Never has research into dark energy been so exciting. While Schlegel and his team are expecting to finish their survey in 2014, future missions are also being planned. One such mission is Euclid, which will study both dark matter and dark energy with high precision, tracing its distribution and evolution throughout the Universe. Euclid will map the three-dimensional distribution of up to two billion galaxies with the aim of plotting the evolution of large-scale structures in the Universe and the role of dark energy in their formation.

Also planned is the Square Kilometre Array, which will be built in South Africa and Australia. This massive radio telescope will survey the sky to look for the signature of dark energy in the structure of the Universe. These missions, coupled with the remaining two-thirds of BOSS that's yet to be completed, will take us a step closer to deciphering the enigma of dark energy.

GAMMA-RAY BURSTS: PIECING TOGETHER A COSMIC PUZZLE



These high-energy blasts continue to mystify, so astronomers are stepping up their search for the key pieces to the puzzle.

by Zach Cano

Image courtesy NASA / Swift / M. P. Hrybyk-Keith & J. Jones

Our journey begins on San Servolo Island, Venice, Italy. It's the middle of September 2009 — a beautiful, sunshine-filled day. You're seated inside a medium-sized conference room, far enough from a window that the allure of the golden-brown trees and soft, green grass isn't a distraction.

Instead you and the other participants are fixated upon the speaker at the front of the room who is challenging the audience to agree upon a foundation of physical processes that can lead to the creation of a gamma-ray burst (GRB).

A learned member of the crowd mentions idea after idea, and another equally learned participant rebukes them one by one. The debate rages on, and after 20 minutes you, like many of the audience, feel more than a little confused. Indeed, by the end of the debate, only one fundamental aspect of the physics required for the formation of a GRB could be agreed upon: relativistic motion is involved in the creation of a gamma-ray burst. Almost a half-century of research, and only one point of agreement! The realization is staggering.

What's a GRB?

Since the serendipitous discovery of GRBs by US spy satellites in the 1960s, thousands of papers have put forward numerous ideas and models to explain the occurrence of the brief flashes of highly energetic gamma rays. But our lack of understanding is not as dire as perhaps it first seems, for key observations during the last 20 years have allowed astronomers to piece together at least part of the puzzle surrounding the GRB phenomenon. Even more exciting, the questions resulting from these observations provide all of astrophysics with the mouth-watering prospect of revealing new physical processes that will not only decipher the long-standing GRB puzzle, but will also increase our understanding of fundamental astrophysics in general.

The first pieces of the puzzle consist of decades-long attempts to put GRBs into a theoretical framework. As the name suggests, a GRB is a brief burst of gamma rays lasting from one thousandth of a second to several tens of seconds. In the context of the electromagnetic spectrum, gamma rays are the most energetic type of radiation. The energy that is needed to create a GRB is enormous, implying that more energy than is generated by a normal supernova (SN) is needed to create a GRB.

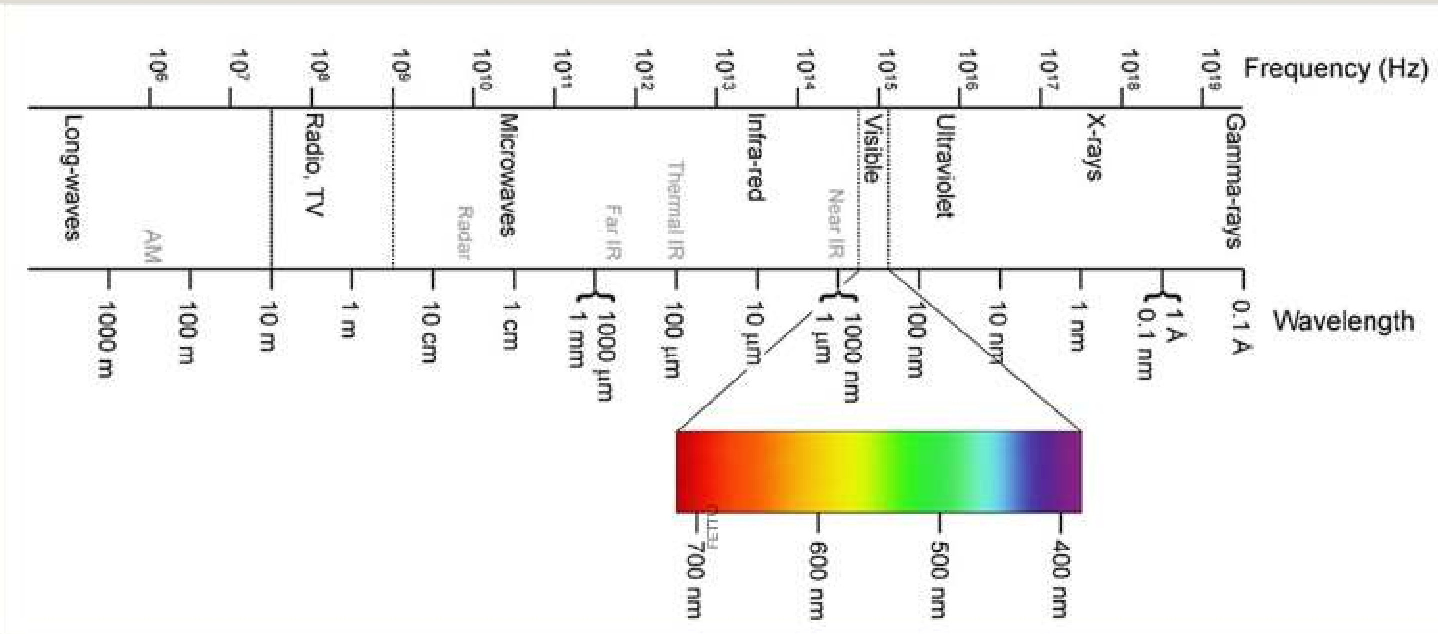
Astronomer's understanding of GRBs is exclusively due to their detection by spacecraft (see the sidebar). The first satellite to study GRBs was the Compton Gamma-Ray Observatory. With it, astronomers (in the 1990s) discovered that GRBs occur uniformly in all directions, implying they are located at cosmological distances (i.e. millions and billions of light-years away). This result was later vindicated by the measurement of GRB 970508's redshift ($z = 0.85$; a distance of at least six billion light-years) in 1997.

Compton also revealed that GRBs can be classified according to the burst duration: short GRBs lasting two seconds or less (to as short as about 300 milliseconds), and long GRBs from two seconds up to several minutes. The intervening years since this discovery have led to the realisation that these two groups (probably) have different progenitors.

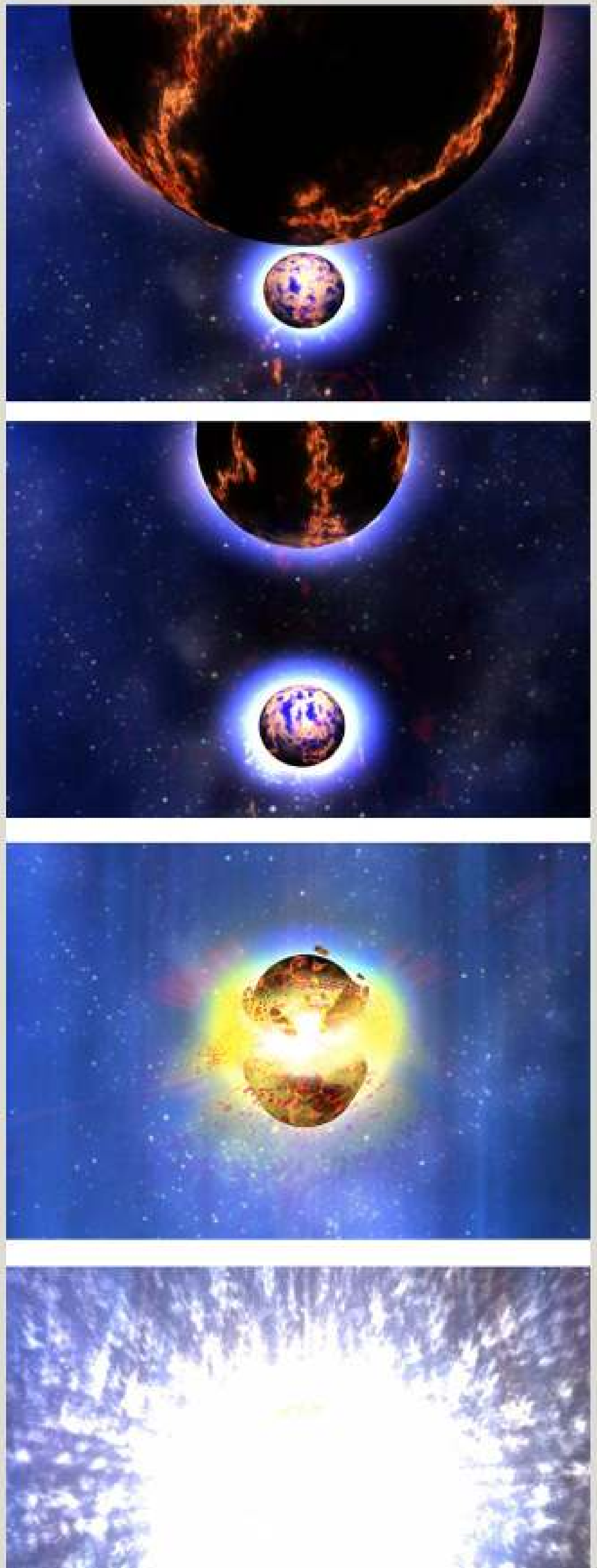
GRBs: the Long and the Short of It

Of the two, we know most about the long GRBs. The "standard model" astronomers use to describe a long-duration GRB has been developed during the past couple of decades. It's generally accepted that long GRBs are created during the collapse of a star, at least 20 times more massive than the Sun, into a black hole. The collapse of such a massive star causes a hypernova, a very energetic type of supernova.

Although the exact details are still a matter of great discussion, it's believed that during the collapse, blobs of star stuff are ejected, at relativistic speeds, into a collimated jet along the star's rotational axis. More than one blob is ejected along the axis, and eventually a

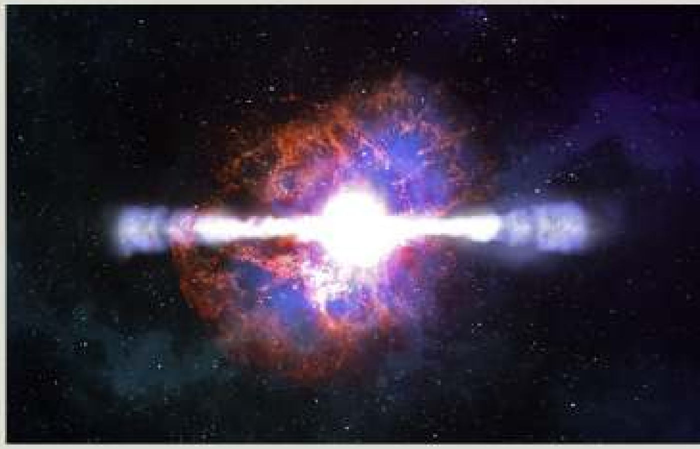


Gamma rays are short-wavelength, high-energy waves at the opposite end of the spectrum from long-wavelength, low-energy radio waves.



NASA / Dana Berry

Nobody knows how the short gamma-ray burst GRB 070714B was triggered, but a leading possibility is the inward spiral and merger of two neutron stars, depicted in this artist's rendition in the four panels above.



NASA / GSFC / Dana Berry

When a massive star runs out of fuel (above), the core collapses and forms a black hole. Shockwaves bounce out and obliterate the outer shells of the star. According to Swift observations, it appears that a newborn black hole in the core somehow re-energizes the explosion again and again, creating multiple bursts all within a few minutes.

faster blob catches up with a slower moving one. As the blobs collide, a shock wave is generated that accelerates electrons in the jet. The accelerated electrons quickly lose energy by emitting synchrotron radiation (radiation from electrons accelerated in a magnetic field) in the form of a burst of gamma rays that astronomers term the *prompt emission*.

As the blobs continue to speed away from the progenitor star, they eventually collide with gas and dust surrounding the star. The collision creates more shocks that result in the production of more synchrotron radiation at X-ray, optical, and radio wavelengths. This radiation is long lasting, emitted for days or weeks after the initial burst, and is referred to as the *afterglow*.

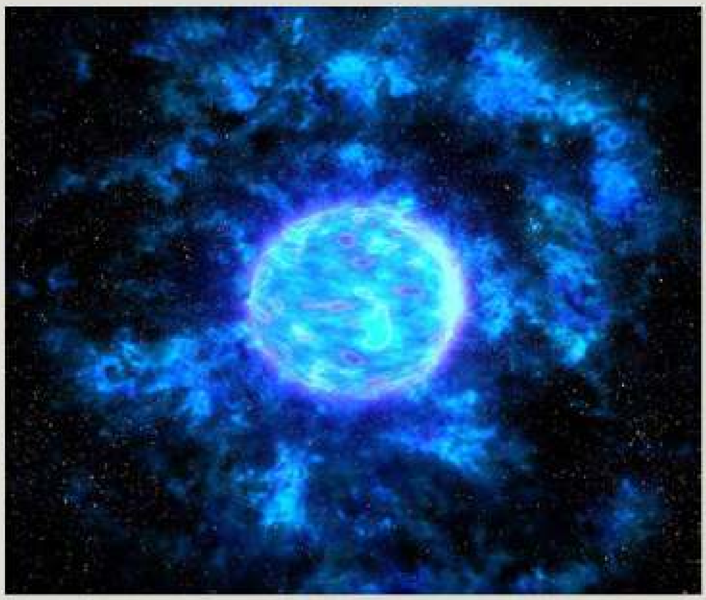
Less is known about short GRBs, mainly because very few have been detected at optical wavelengths. The currently accepted model describes a situation where a neutron star merges with a neutron star or black hole (or a black hole merges with another black hole). In similar fashion to a long-duration GRB, blobs of material are ejected along the rotational axis of the two-body system in a jet, which eventually leads to the formation of a short burst of gamma rays with a peak energy higher than that of a long-duration GRB.

The GRB-SN Connection

So far we have collected a few pieces of our puzzle. GRBs, both short and long, are located at cosmological distances. The detected emission is due to blobs of material launched into a jet at relativistic velocities, interacting with each other, and creating shocks that ultimately lead to the observed radiation at various wavelengths. In the case of long GRBs, the formation of the burst is associated with the collapse of a massive star and its explosion as a supernova.

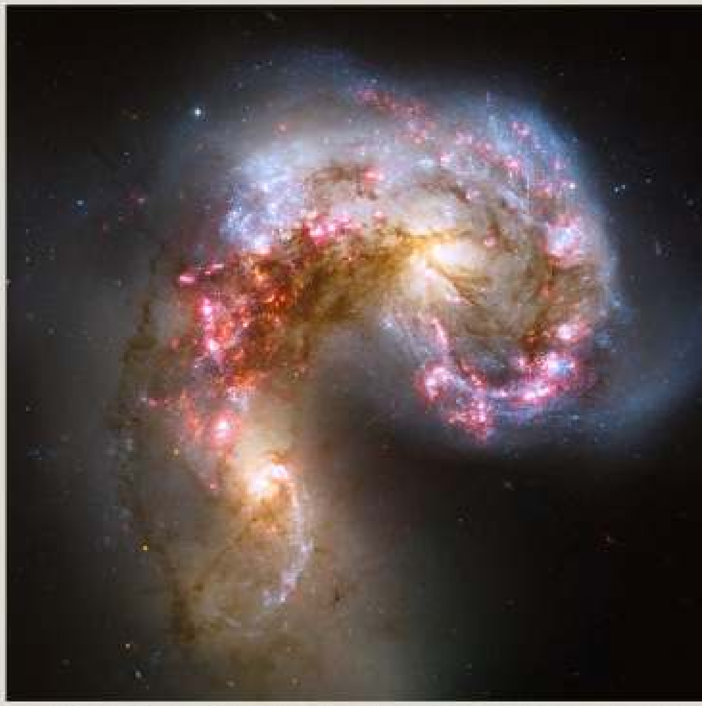
The first observational clue of a connection between a long GRB (hereafter referred to simply as a GRB) and a supernova was in 1998, when a special type of supernova was detected at the same time, and in the same host galaxy, as a GRB. The SN was a Type Ic — a core-collapse supernova that doesn't display hydrogen or helium lines in its spectra. The supernova detected in 1998 was dubbed 1998bw, and it remains to this day the archetype GRB-producing supernova.

There was, however, much debate surrounding this detection, because many astronomers were not satisfied that the two events (the gamma-ray burst and supernova) were actually physically connected. This controversy persisted for six years until GRB 030329



NASA

An artist's impression of a Wolf-Rayet star.

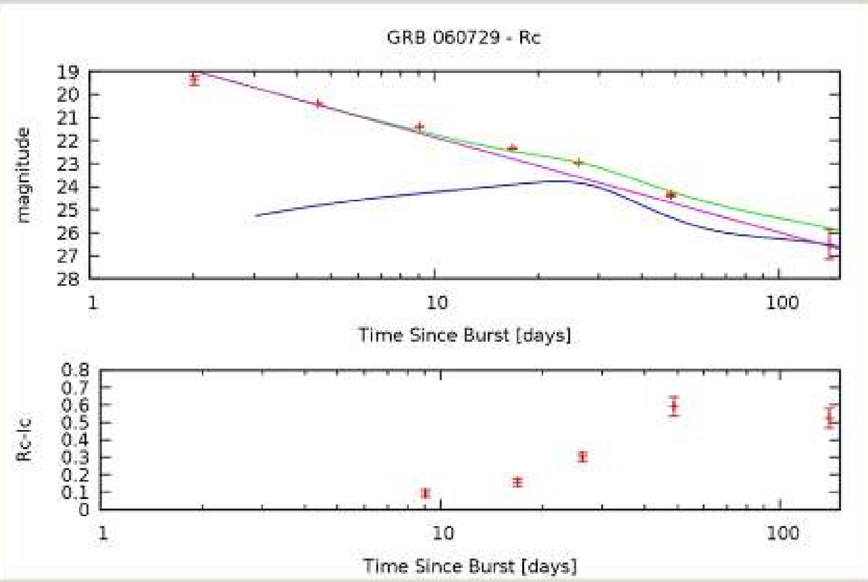


Colliding galaxies — such as the Antennae, above — generate numerous regions of intense star formation (seen as the brilliant blue regions surrounded by glowing hydrogen gas that appears pink in the image).

was spectroscopically and photometrically connected to SN 2003dh. This was the smoking gun that astronomers needed, and showed that at least some, if not all, GRBs are created when a massive star collapses and becomes a Type Ic supernova.

To date, all of the supernovae connected to GRBs are Type Ic, though not all Type Ic's generate gamma-ray bursts. The favored progenitor that can lead to the formation of a Type Ic SN is a Wolf-Rayet (WR) star. Wolf-Rayet stars are massive and short-lived, and occur in areas of galaxies undergoing intense star formation. A WR star has strong stellar winds that, in the latter stages of its life, expel its outer envelops of hydrogen and helium.

To absolutely connect a SN with a GRB, spectroscopic and photometric data needs to be acquired concurrently. However, due to detection limits of current spectrometers, this is only possible for nearby GRBs. For GRBs that are farther away, it's still possible to photometrically infer the presence of a SN with a GRB by taking a multitude of CCD images of a GRB with many photometric filters at UV, optical, and infrared wavelengths. When displaying the data as light curves, SN "bumps" are seen, which are accompanied by an increase in red color — such as those seen for GRB 060729 (see the illustration at lower left) — both of which are indicative of a supernova. This has been done for many GRBs, further vindicating the GRB-SN connection.



Cano et al. (2010)

Top: The R-band light curve of GRB 060729. By considering light from the GRB (purple line) and an underlying SN (blue line), the model (green line) fits the data (red points) very well, and a supernova "bump" is clearly visible. *Bottom:* A color plot for GRB 060729. An increase in red color (Rc - Ic) is seen after the SN peaks.

The Connection Strengthens

Additional evidence for the GRB-SN connection was the discovery that gamma-ray bursts occur in the brightest parts of their host galaxies. GRB host galaxies are typically small, irregular, blue galaxies that are generally lower in metallicity than the "average" galaxy at a given redshift. The brightest parts of the hosts are indicative of starbirth, which directly links GRBs to star formation.

Even more intriguing, up to 60% of the host galaxies of GRBs have recently undergone a galaxy merger or interaction. It has long been known that interactions between galaxies can trigger intense periods of star formation. Such episodes of starbirth are vigorous, leading to the formation of massive stars that are short-lived and explode at the end of their lives in spectacular fashion.

Furthermore, when studies of the positions of Type Ic SNe in their host galaxy were undertaken, they too were found to occur in the brightest parts of the host galaxies. Thus it seems that the conditions that give rise to Type Ic SNe also give rise to GRBs. But as mentioned earlier, while every GRB is seen to occur with a Type Ic SN, not every Type Ic SN produces a GRB. Indeed studies have shown that only 5% of Type Ic's give rise to a GRB. This leads to the conclusion that there must be some unusual conditions required for a GRB to occur.

Ideas of what that those special conditions might be are currently being investigated. Theoretically, low metallicity (seen in GRB hosts) and fast rotation of the GRB-producing progenitor are thought to be necessary. But as the progenitors of GRBs are stellar-sized objects, it is not possible to resolve them to directly detect these conditions. The best chance at resolving this issue is to create a robust theory that gives predictions that can be tested observationally.

The Final Puzzle Pieces

The title of this segment is a bit misleading, as the puzzle is far from complete. As mentioned, a current research focus is to determine the special conditions needed to generate a GRB. Right now, the current theory is severely lacking in robust explanations, though not for lack of effort by extremely gifted scientists.

Since the launch of Swift in 2005, observations of GRBs have generated more questions than answers. The standard model does not explain many observed features, and attempts by astronomers to fit the theory to the data end up needing ad-hoc alterations to the theory. It seems that the standard model actually explains the exceptions rather than the rule!

Other issues also need addressing. For one thing, the mechanism of how the progenitor forms the black hole and creates a jet of ejecta needs to be determined. The solution will be of great interest to those who model stellar evolution.

Another key topic is how the jets are created. The accepted explanation of the source of the multi-wavelength emission is synchrotron radiation. However, it is becoming increasingly evident that there may be more than one source of emission coming from the GRB or the region around the GRB.

One way to test the validity of the various models is to check for the presence of a magnetic field in the vicinity of the progenitor. Some theories predict a prevalent magnetic field, while others maintain that any generated magnetic field is local to the shocks. To observationally distinguish between these models, measurements of the polarization of optical emission are needed, and a start was recently made.

Using a unique polarimeter on the Liverpool Telescope, a polarization of 10% was recorded in GRB 090102, which is greater than can be explained by magnetic fields generated solely by shocks. (See "Gamma-Ray Burst Engine Finally Revealed" in *Mercury*, Winter 2010, page 11.) More observations are now needed to create, if possible, a larger sample to compare universal characteristics of GRB properties.

While numerous pieces of the GRB puzzle have yet to be uncovered, the general picture is finally emerging. Many talented minds are working hard to construct a robust theory of GRBs, while an army of GRB astronomers is working day and night (literally; see my Reflections column) to solve the enigmatic puzzle that is GRB astrophysics.

ZACH CANO *is a doctoral student at the Astrophysics Research Institute in Liverpool, England. When he is not knee-deep in images of GRBs, he is enjoying nature with his beautiful partner and learning to see the universe as it really exists.*

The gamma-ray burst GRB 080319B was so intense that, despite happening halfway across the universe, it could have been seen briefly with the unaided eye. The burst's extraordinary brightness arose from a jet that shot material almost directly towards Earth at nearly the speed of light.

GRB Satellites

Gamma-ray burst astrophysics is completely reliant upon satellites, since Earth's atmosphere blocks incoming gamma rays. GRBs are detected in space at gamma-ray and x-ray wavelengths, and the position of the x-ray afterglow is relayed to ground-based telescopes that perform follow-up observations at UV, optical, infrared, and radio wavelengths. Many of the telescopes on the ground are robotic, such as the Liverpool Telescope located on the Canary Islands, and respond to alerts automatically, taking images only seconds after the receipt of an alert.

Vela (1960s & 1970s)
This was the first satellite to detect a GRB. Created by the US military to keep watch over the USSR's nuclear activities, the discovery of a GRB by Vela 3 and 4 on July 2, 1967, was serendipitous.

NASA

NASA

Compton Gamma-Ray Observatory (1991–2000)
One of NASA's Great Observatories, the craft was launched in the early 1990s and acquired data for nearly a decade. During this time it was shown that GRBs appear uniformly in all directions in the sky, and it became clear that there are (probably) two different types of GRBs.

BeppoSax (1996–2002)
The launch of BeppoSax heralded the start of the "Afterglow Era." The first GRB to be located in X-rays was in 1997, and later in the same year the first redshift for a GRB was determined.

Agenzia Spaziale Italiana / BeppoSAX SDC

Spectrum and NASA E/PO, Sonoma State University, Aurore Simonnet

Swift (2005–present)
Accuracy at last! Swift is able to provide arcsecond positions of GRBs in seconds, and opened a window into the GRB phenomenon that was not anticipated.

Fermi (2008–present)
The Fermi Gamma-ray Space Telescope is the latest addition to the GRB-searching fleet of spacecraft. It has already discovered numerous oddities in the gamma-ray universe.

NASA / General Dynamics

by Zach Cano

Two Hours in the Life of a Doctoral Student

Reality interrupts a fabulous dream, but it's worth it.

It was the last lap of the Italian Grand Prix, and I accelerated out of the Senna Esses only two car-lengths behind the Ferrari of Michael Schumacher. Going into Parabolica, I braked late and pulled even closer. With the finish line beckoning, we both hit the throttle at the same time, but I was in his slip-stream and had the advantage. As my front wing approached his diffuser, I quickly ducked out of his slip stream and pull along side. Fifty meters to go and the finish line was approaching fast…30 meters and we were side by side…10 meters and my front wing was just inches ahead of his…5 meters….

Beep Beep Beep! BEEP BEEP BEEP!!

My mobile has just received a text, and I blink a couple of times as my brain adjusts to reality.

Beep Beep Beep! BEEP BEEP BEEP!!!

Then I remember. I'm on duty tonight. I pick up my phone and check the message. It's what I had hoped for. The Swift satellite has detected a gamma-ray burst (GRB) and sent out an alert that one of our robotic telescopes has automatically responded to. It's 4:00 am and I have no time to lose.

My name is Zach and I'm a second-year Ph.D. student at the Astrophysics Research Institute (ARI), which is part of John Moores University in Liverpool, UK. My doctoral project is to study the connection between core-collapse supernovae and GRBs, and to do this I need lots of optical, ultraviolet, and near-infrared images of gamma-ray bursts. At the ARI, we have a small GRB group that has access to three robotic telescopes: the Liverpool Telescope (located on the side of a mountain in the Canary Islands) and two Faulkes Telescopes (in Australia and Hawaii).

Whenever a GRB occurs and is detected by any of several satellites, alerts are immediately sent to ground-based telescopes. If we're fortunate and the seeing conditions at any of these telescopes is just right when GRB occurs, we're able to obtain images of the GRB.

Tonight was one such night. I'm on duty this week, which means that if an alert hits, I have to be awake and ready to roll. There's no time to waste, and as soon as the images appear, I download them onto my computer for analysis. For the analysis, I have a catalogue image of the region of sky where the burst occurred, which I visually compare with the images taken.

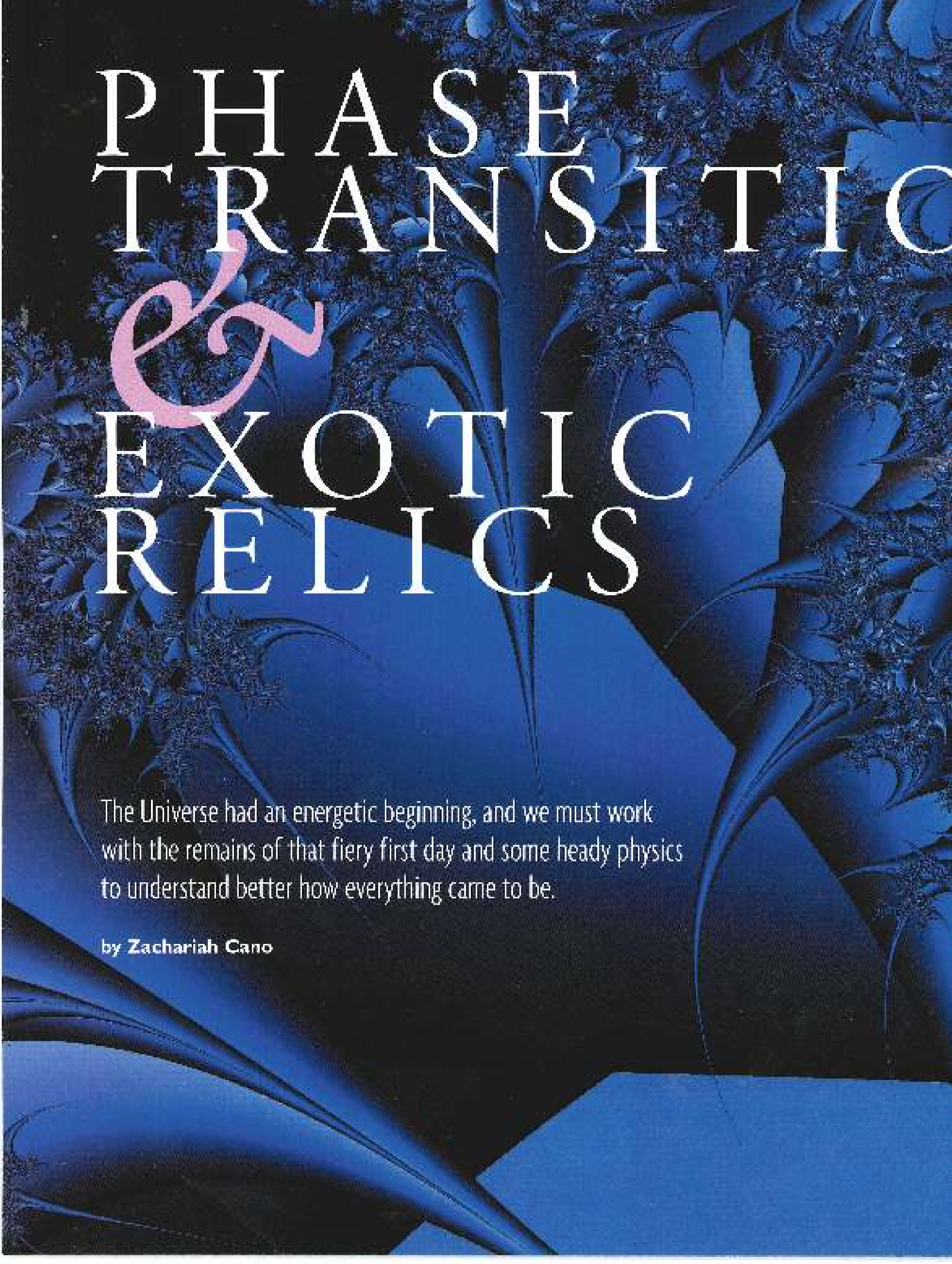
However, I'm not the only entity looking for a GRB transient. One of our team members has written a program that automatically detects transients in a series of images. If one is found, that makes our job all the easier. But tonight is not one of those nights.

The software has detected an object, but it turns out to be a red herring. So the search has to be done manually. Thankfully it was Swift that detected the burst, so the error-box (the region of the sky where the burst occurred) is quite small, and not many objects lie within. All I need do is check all of the objects in the error-box in a series of images to see if any of them have faded.

A short while later, my search is finished. I'm confident that I've found the GRB and measured how much it has faded. Group e-mails coming in from the other members of my team, who are also awake, confirm my detection. A surge of adrenaline further enhances my sense of elation, and I can't stop smiling. Not only have we found it, we have also confirmed that it's fading, and we are the first team in the world to do so! Time to draft a circular (GCN) declaring our result and send it to the rest of the world.

An hour later and the in-boxes of almost 1,000 GRB astronomers world-wide contain a message, with my name plus the names of my colleagues, declaring our detection of the GRB. It was an intense couple of hours, from the alert waking me from my wonderful dream, to the furious analysis of dozens of images, to the sending of our GCN — but hours that are emotionally rewarding. To be part of the GRB team at the ARI is very exciting and allows me to pursue my life-long passion of space and astronomy.

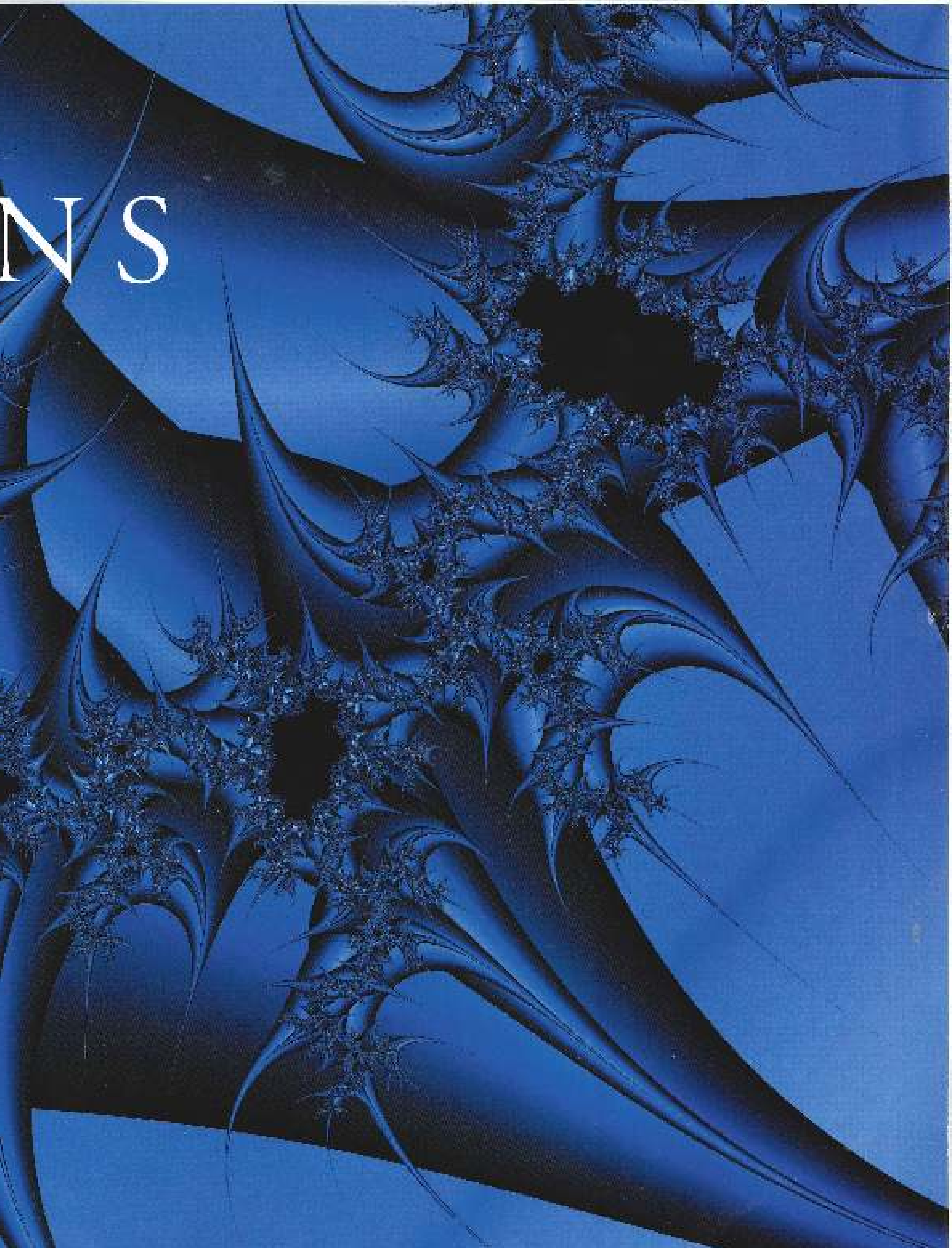
I have just started the second year of my doctorate, but the thought that I am already performing professional observations that a thousand other professionals will read is truly special. It is now 6:00 am and I feel on top of the world. (Elsewhere in this issue you can read my article about gamma-ray bursts.)



PHASE TRANSITIO & EXOTIC RELICS

The Universe had an energetic beginning, and we must work with the remains of that fiery first day and some heady physics to understand better how everything came to be.

by Zachariah Cano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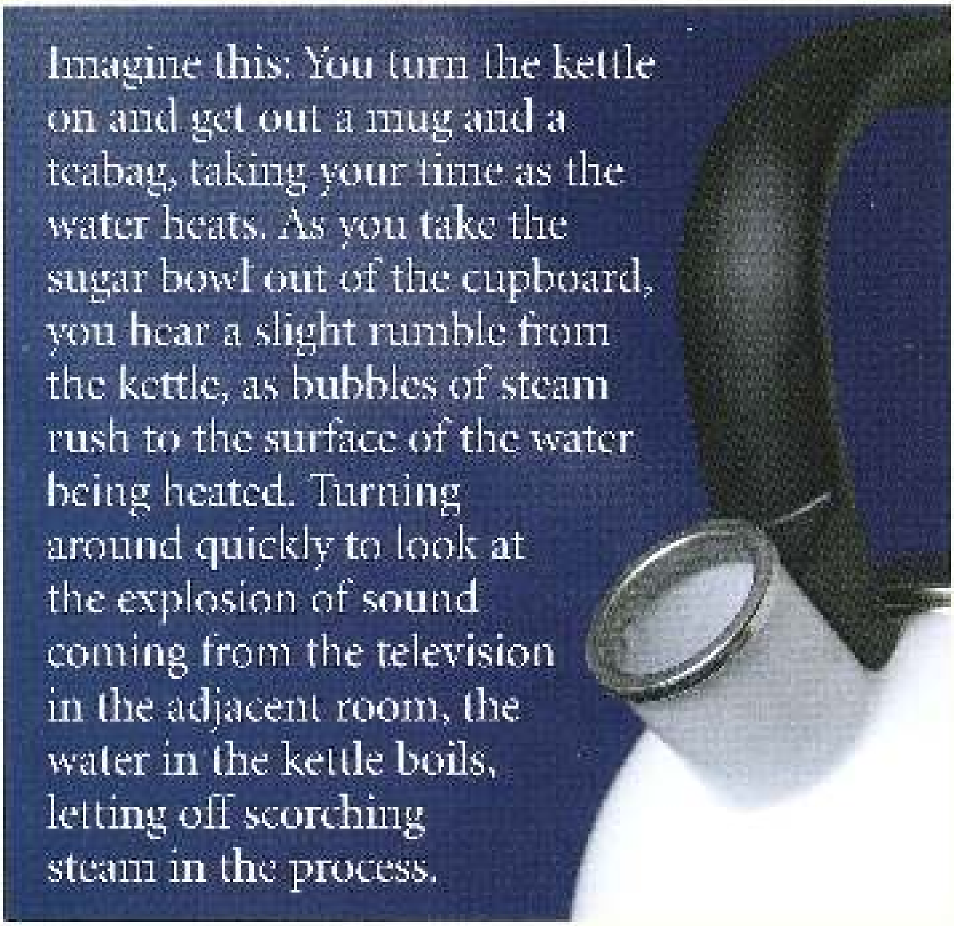


During the two-minute process of making a cup of tea, the water in the kettle underwent a phase transition from liquid to gas. This everyday analogy is reassuringly familiar and conceals very subtle yet profound implications for cosmology.

Time Leap Backward

Close your eyes and think backwards through time. Think first of what you did last night, then back to Neil Armstrong taking the first step on the Moon, then further back to the dawn of modern humans, and even further back to the demise of the dinosaurs. Move further and further backwards in time towards the moment of creation of the Universe. Now open your eyes.

As we move backwards in time towards that moment, prior to 1/100 of a second after the Big Bang, our current cosmological theories tell us that the Universe becomes hotter and denser until matter actually changes its phase—that is, it changes its properties and form.

Consider the previous analogy of water, which has three phases: (1) solid, (2) liquid, and (3) gas. While going from phase (1) to (2) to (3) it is important to notice an increase in symmetry, a quality of physical systems that comes in many forms such as translational and rotational. The liquid phase of water is rotationally symmetric because it looks the same regardless of which direction we look at it. The solid phase, however, is not rotationally symmetric as the ice crystals have a preferred lattice direction along which the H_2O molecules arrange themselves. The liquid form of water, then, is more symmetric than the solid form. And the gas phase is more symmetric still.

This analogy is useful for explaining the properties and behavior of matter in our universe. All matter started off in a symmetric phase and then passed through a series of phase transitions. And just like water, the phase transitions occurred at different temperatures. The result from the final phase transition is all of the matter particles with which physicists (and everyone else, for that matter) are familiar, such as electrons and protons.

Grand Unified Theories

Phase transitions have profound implications for the evolution of the Universe and its contents, and some direct "remnants" of these transitions exist today. To understand the place of phase transitions in modern cosmology, we must investigate Grand Unified Theories, or GUTs.

At the heart of all GUTs lies the Standard Model of Particle Physics. According to the Standard Model, all of physics can be explained in terms of the properties and interactions of a small number of fundamental particles. These particles are of three distinct types: leptons (e.g., electron), quarks (e.g., strange), and "gauge bosons" (e.g., photon). There are many other types of particles, yet only the three aforementioned are truly fundamental. For example, baryons such as protons are not fundamental, as they are a result of a particular arrangement of quarks.

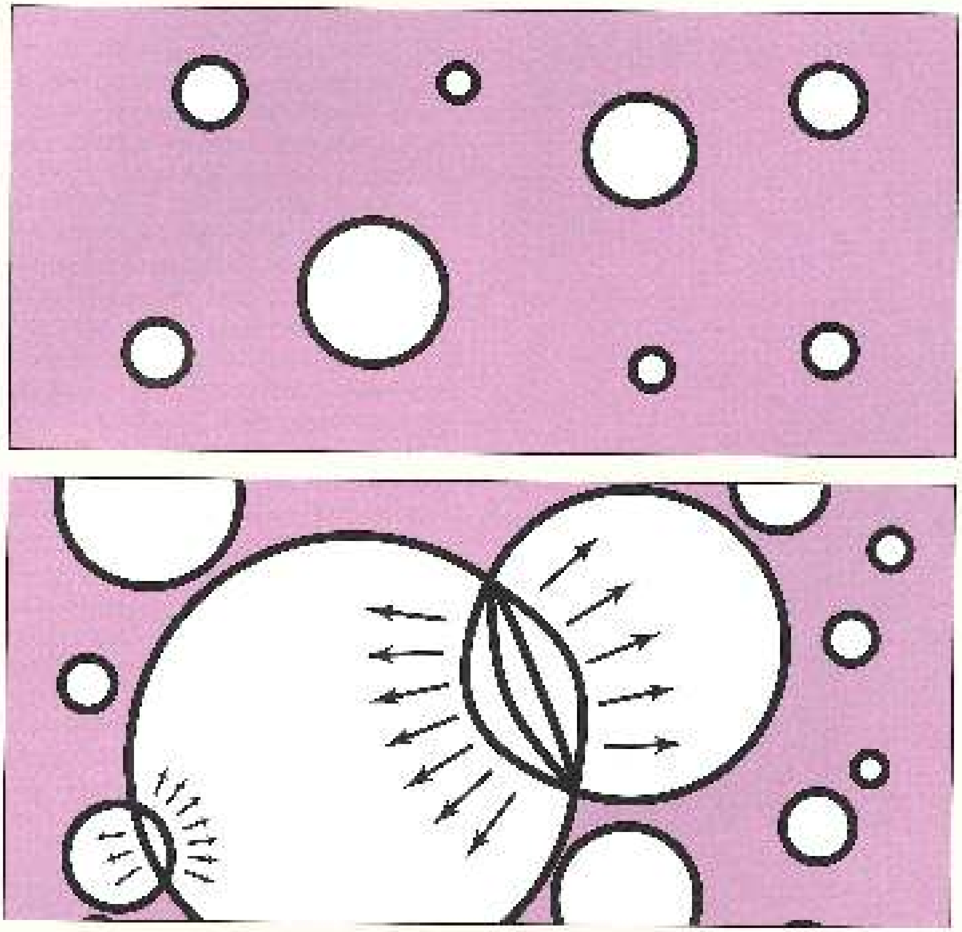
Current attempts at GUTs show that as we run the cosmic clock backwards and confront ever increasing temperatures (and, therefore, energies), the fundamental forces start to merge. These mergers happen at phase transitions.

The idea of phase transitions can be introduced to the Standard Model if one considers the very brief period after the Big Bang, during which the Universe underwent an initial phase transition in which the strong nuclear force and the electroweak force separated from a more fundamental force. This transition, while creating two new forces, also dumped an enormous amount of energy in the vacuum of empty space.

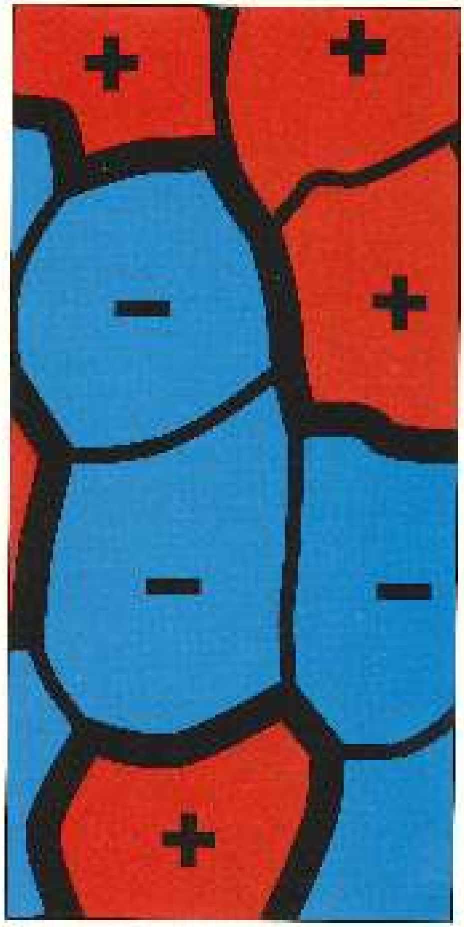
According to Alan Guth, a physicist at the Massachusetts Institute of Technology, this release of energy during the phase change would have exponentially expanded the Universe, increasing its radius by a factor of 10[illegible] (one thousand billion billion billion times!) almost instantaneously. This inflationary period ended some 10[illegible] seconds after the Big Bang. After the original phase transition, the Universe underwent further phase transitions, the final being the hadron-quark phase transition where free quarks coalesced into protons and neutrons.

Guth's inflation model complies with scientists' observations of the Universe. Indeed, the model is critical to our explanation of the Universe's evolution, and if physicists can demonstrate that some of the vacuum energy from the last phase transition is still around today, phase transitions, in general, could also explain the current expansion rate—and perhaps even acceleration—of the Universe.

All of this would be a nice picture if included inside a Grand Unified Theory. The aim of a GUT is to provide a testable and predictive theory that can explain the fundamental forces: electromagnetism, the weak and strong nuclear forces, and gravity. The basic premise of a GUT is that the known symmetries of all elementary particles resulted from a larger symmetry group. Symmetry was broken when the overall symmetry of an offspring group was less than that of the



1st-order phase transitions occur when bubbles of a new phase form in the middle of the old phase. These bubbles expand and collide until the old phase completely disappears. Illustration courtesy of T. Ford.



A network of two-dimensional domain walls can, in theory, partition the Universe into various cells. Illustration courtesy of T. Ford.

prior symmetry group. Whenever a phase transition occurred in the nascent Universe, part of that symmetry was lost (like liquid water freezing into solid ice) and, therefore, the symmetry group changed.

Symmetry Breaking

The cosmological significance of "symmetry breaking" is that symmetries can be restored at high enough temperatures (like ice melting into water). Theoretically, at sufficiently high temperatures, the unified "symmetric" phase could be obtained and observed, although, technologically, this will not happen for a while. Current attempts at GUTs predict that all of the fundamental forces will merge into a single primordial force at an energy around 10[illegible] GeV (giga-electron volts), which is 10[illegible] times larger than the highest energies achieved in particle accelerators now being used by scientists.

> **"Stephen Hawking suggests that symmetry breaking happened simultaneously everywhere."**

Phase transitions can be of two types: 1st order (dramatic) or 2nd order (smooth). 1st-order transitions occur through the formation of bubbles of the new phase in the middle of the old phase. These bubbles expand and collide until the old phase completely disappears—thus making the phase transition complete. Boiling water again is the useful analogy, as bubbles of steam form and rise to the surface of the water. Given enough time, all of the water will be replaced by steam bubbles, leaving the kettle dry.

Stephen Hawking holds a contrary view when applying this notion of phase transition to the Universe. He says that our universe could never have arrived at its present, observable state through 1st-order phase transitions. Indeed, according to Hawking, this process is too fast, and the initial bubble would have to have been bigger than the present universe. He suggests instead that the breaking of symmetry was a slower process and happening simultaneously everywhere. Hawking's proposal still has the whiff of phase transitions, somewhat similar to those of a 2nd-order transition.

Recall that 2nd order phase transitions occur smoothly. The old phase transforms itself into a new phase, either at a slow rate or and accelerated rate, but always in a continuous manner. Whatever the behaviour of the phase transition, if topological defects can form, then they will form. It was Tom Kibble of Imperial College London who first pointed this out using knowledge of quantum tunneling, and this process is now known as the Cosmological Kibble Mechanism.

Nagging Topological Defects

Topological defects form at phase transitions and come in a wide variety of stable arrangements. These configurations of matter are always in the older (and thus higher symmetric) phase and endure after the phase transition is complete. There are many types of defects such as domain walls, cosmic strings, and magnetic monopoles, to name just a few. The type of defect formed depends on the properties of matter in the earlier/more symmetric phase and on the nature of the phase transition.

Domain walls, two-dimensional objects that form when a discrete symmetry is broken at a phase transition, have peculiar, almost bizarre properties. For example, the gravitational field of a domain wall is repulsive rather than attractive. And as we shall see soon, a network of domain walls can (theoretically, at least) partition our universe into various cells.

Cosmic strings, one-dimensional objects that form when an axial or cylindrical symmetry is broken, are very thin, possessing a thickness of less than 10^{-12} (one trillionth) times the radius of a hydrogen atom. Yet despite being incredibly thin, cosmic strings are amazingly dense and may stretch across the entire Universe—a ten-kilometer length of a single string would weigh more than Earth itself!

> **"A 10-km length of a single cosmic string would weigh more than Earth itself!"**

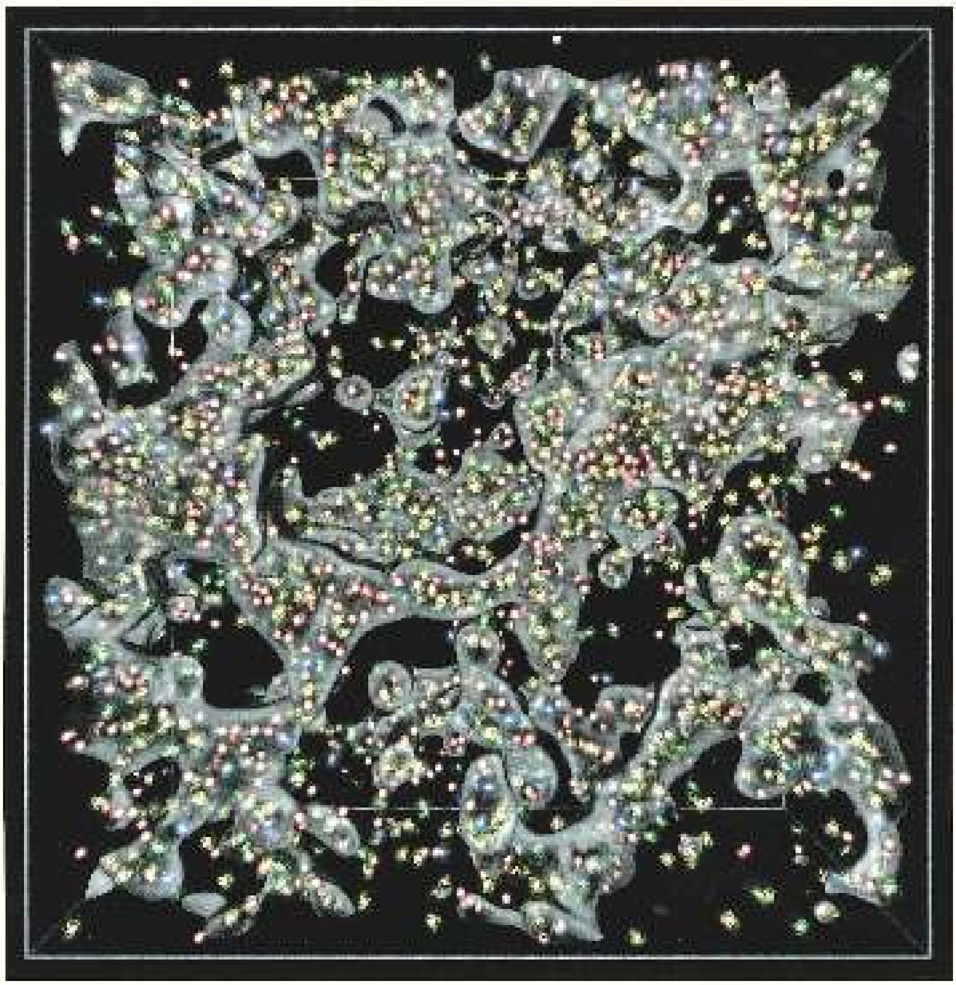
An example of a nearly zero-dimensional object, magnetic monopoles are point particles (i.e., they have no internal structure or excited states) and are a result of broken spherical symmetry. Monopoles are an inevitable prediction of GUTs, and, indeed, it was British mathematician Paul Dirac who first predicted the possible existence of monopoles. If magnetic monopoles did exist, they would be so abundant that they would contribute a billion times more density to the Universe than all the stars and galaxies combined. This extra density would very possibly have made the known Universe stop expanding and collapse in upon itself billions of years ago.

Due to the high energies necessary for their creation, such "exotic relics" could only come about in the extreme conditions just after the Big Bang, when the Universe's temperature and density were ultra-high. Even the most powerful particle accelerators on Earth cannot create these conditions. However, topological defects can be studied in the laboratory and are most commonly observed in condensed-matter systems. Simple examples are the domains in a ferromagnet—domain walls separate regions where magnetic dipoles are aligned.

Liquid crystals also exhibit an array of topological defects. Michael Grady from the State University of New York at Fredonia is convinced that our universe is a giant crystal growing in a five-dimensional liquid. You and I are "stuck" on the expanding solid surface, just as ordinary crystals grow on the surface of a three-dimensional liquid.

Universal Matters

It was Albert Einstein with his special theory of relativity who showed us that all causal effects in our universe can only propagate at the speed of light, c. However, his general theory of relativity implies that regions of our universe can actually be moving away from each other faster than the speed of light. This is allowed when you consider that it isn't the matter in these regions that is exceeding the speed of light—it is the speed of the stretch-



A small view of the large-scale structure of the Universe, manifest as clusters of clusters of galaxies. Illustration courtesy of the 2dFGRS team.

ing fabric of spacetime itself. And no speed restrictions are placed on the spacetime fabric. Accordingly, at an arbitrary time t, regions of the Universe separated by a distance d greater than $d=ct$ can know nothing about each other. Yet recent breakthroughs in quantum physics regarding quantum entanglement contradict the idea that all causal effects can only propagate at c, thus making communication with these "far-away" regions possible, although not very plausible.

In a symmetry-breaking phase transition, different regions of the Universe will choose to fall into different energy minima in the set of possible states. Mathematicians know this set of possible states as the vacuum manifold. If this happened in our universe, regions separated by more than $d=ct$ will be separated by domain walls. In more complicated theories, cosmic strings appear where the minimum energy states possess "holes." The strings correspond to a non-trivial winding around these holes.

Topological defects provide a unique link to the physics of the early universe. Furthermore, they can crucially affect the Universe's evolution. Given that they must form, topological defects are an unavoidable part of cosmology. But there are shortcomings with any model that predicts the existence of magnetic monopoles—from observations of the heavens and knowledge of particle interactions we conclude that they cannot exist (see "Patching Some Defects").

Conversely, cosmic strings are much more plausible, and, indeed, possible. They could be the seeds of galaxy and other large-scale-structure formation. They could also be responsible for the cosmic background radiation and perhaps the origin of some of the mysterious dark matter that dominates the material content of the Universe.

But there is more. A number of physicists are studying the Standard Model, phase transitions, symmetry breaking, and the utility of inflationary cosmologies to improve our understanding of the birth and evolution of our universe and perhaps others. Some models are exotic and easily excluded based on observations; others, however, are no less mind bending and are not so easily discarded. Still, then, we must work to understand. The only limits for any cosmological model depend solely upon our ingenuity, intuition, and imagination.

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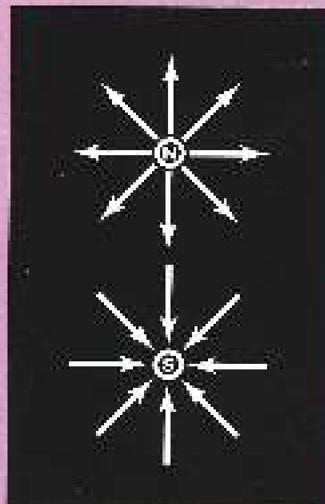
Patching Some Defects

Magnetic monopoles are cosmological catastrophes. From basic observations of our heavens and our knowledge of particle interactions we conclude that they do not exist. Therefore, cosmological models that predict these must be excluded.



Alan Guth's proposed inflationary theory comes to the rescue when trying to explain why there are so few, if any, magnetic monopoles. If inflation did occur just after the Big Bang, the whole of the Universe could have expanded from a region small enough to be traversed by light signals in the time since the expansion began. Thus, the observed smoothness of space could be explained, but more importantly, there would not be the large numbers of magnetic monopoles because our visible universe will have expanded from a region so small that at most only one magnetic monopole would have been created. This idea also removes the plausibility of domain walls existing in our universe, partitioning it into separate cells, as the Universe would have expanded from a region that light did traverse—a region of about a millimeter in size. – Z. C.

Bloody Moon

by Zachariah Cang

On a clear autumn night the moon hangs low in the sky, a large and awesome sight as rays of light from the sun reflect off the surface of the moon. Spread before for all of Brighton to see is a wave-riddled glare of the moon, bouncing up and down in a teasing dance, as light reflects off the surface of the English Channel. Tonight a full moon dominates the sky.

Rushing through space at over 5000 miles an hour the moon orbits in an ellipical path. Tonight the moon is passing through perigee, its closest approach to the earth in its orbit. This makes the moon appear very large in the sky, bringing the crater-strewn lunar surface a little bit closer to earth. The enlarged view of the moon creates an unusual influence on the life of earth. It is a beautiful sight for lovers walking by the seaside, however tonight, the animal world is in chaos.

There is a rustle in a set of bushes lingering by the pavement in Preston Park. Kept awake longer than usual by the intensity of the moon's presence, a male adder attacks a park squirrel, caught unaware while chattering with its friends. Across town in a posh Victorian flat in downtown Hove, for seemingly no reason at all, a fluffy white and pink-dyed poodle bites the hand of his 70-year-old master. Rushing to the emergency room faster than it takes time for the blood to dry on her wrinkled old hand, the old lady of the house ponders why her precious poochy bit her. In her long years she has heard stories, thought only to be old wives tales, about madness brought upon by the full moon. She remembers learning in school about 'moon madness', an illness named by nineteenth century doctors as lunacy[1]. Upon first reflection her own experiences had taught her that lunacy was preposterous, a naive way of thinking before the study of modern medicine. But if life had taught her one thing, it was that the world around her was always more than it seemed.

In reality, her precious poodle is badly affected by the full moon. The poor dog's psyche cannot comprehend why the big round circle in the sky keeps getting bigger and brighter. The bright full moon is very intimidating to the lowly poodle, which feels threatened and nervous and tends to act irrationally as a result. Several studies in modern science have shown that on a full moon, animal activity, especially attacks on other creatures, increases dramatically. In an accident and emergency hospital department in Bradford, England, during 1997 to the end of 1999, a group of five scientists set out to prove a hypothesis that the intensity of animal bites is affected by the moon's ever-changing lunar cycles. Including 1621 patients in their study, they came to the conclusion that the highest numbers of bites were on or around full moon days. They also went on to show that the intensity of bites seemed to follow the lunar cycles devotedly.

Domesticated pets and wild animals aren't the only creatures on earth that are affected by the moon. In fact, the moon has etched itself into almost every facet of everyday life, from the tides producing the waves that crash on upon Brighton beach, to the 28 1/2 day menstrual cycle. Over long years of man's existence, stories and myths have been created about the moon, such as the child's nursery rhyme "Jack and Jill", a modern day adaptation of "The Tale of Hyuki and Bil", which is an old German fable. You can look at any era of man's history and see that ancient human civilization has incorporated the moon into its many cultures. More often than not, the moon is regarded as a fertility symbol: as the face of the moon changes its phase from cycle to cycle, so too does life on earth go through its many cycles. There is so much evidence showing that the moon has profound effects on life on earth that one must wonder if the moon is also responsible for maintaining life on this planet, guiding us endlessly one cycle at a time. To consider this question, one must first understand the gravitational force that exists between the earth and the moon.

Gravity Kicks In... Just as the planets in the solar system are kept in orbit around the sun due to the sun's gravitational pull, so too the moon is kept in orbit around the earth. As the moon orbits the earth in its 29.53-day cycle[2], the moon exerts a gravitational pull on the surface of the earth, the effect being that water tends to accumulate at regions directly toward and opposite the moon. The tides on earth are a direct result of this tidal force. High tides occur because the centre of the earth feels a greater force towards the moon on the side of the moon so that the main body of the earth is pulled away from the water. Tidal forces also explain why we only ever see one side of the moon.

Approximately 4.7 billion years ago, in the early stages of the formation of the solar system, proto(planet)-earth collided with another protoplanet. Debris from that collision formed a short-lived ring around earth, not completely dis-similar to that of Saturn's. Slowly the ring started collapsed under its own weight, as rocks, boulders and minuscule grains of ice and metal started to clump together. To balance this inward gravitational attraction, internal pressures created an outward, balancing force. This force created heat, due to an ever-increasing rate of collision between clumps of matter. After a period of 70-100 million years of collapse and clumping, the moon was formed.

The moon began to cool and the first crust began to form 4.6 billion years ago. As the molten surface of the moon, and indeed all the inner planets (Mercury to Mars), started to cool, huge meteorites and asteroids bombarded their surfaces. Some of the bigger collisions would have created as much energy as 100's and 1000's of nuclear bombs. The constant bombardment lasted for around 700 million years, where after, the overall density of the solar system decreased as all the matter gravitationally collapsed to form the planets, comets, asteroids and Oort Cloud, which forms a spherical halo around the solar system.

As the moon formed and orbited the earth, the tidal force between the two astronomical bodies was higher than it is today. Long ago in the early history of the solar system the moon orbited closer to the earth than it does today. Due to the larger gravitational force between the earth and the moon, large lakes of lava formed in the bottom of some of the larger impact craters, creating the lunar maria (lunar seas) that we can see from earth. You can still see these effects today as the Mare Imbrium, the Sea of Rains, or the Mare Tranquillitatis, the Sea of Tranquility. These lunar "seas" are found primarily on the near side of the moon, where the tidal forces are greater. Tidal forces are also responsible for the fact that the moon's far side has a thicker crust of 100km, opposed to an average of 60km on the near side. Over the long millennia the moon's interior cooled as the moon slowly receded away from the earth.

The moon orbits the earth in a slow outward spiral, creeping year by year ever-slightly further away. The moon is receding from earth at a rate of 1.6km every 28,000 years, which is due to the complex gravitational interactions with the earth and sun. If the current rate of recession continues, in one billion years the moon will appear from earth to be 15% smaller.

Myth And Legend. Nothing surpasses the Moon's power to mesmerize and mystify. Many ancient civilizations regarded the moon as a higher deity that goes through cycles of renewal, waxing to full brightness and waning into obscurity. This renewal pattern is seen as a pattern of fertility, which is why many ancient civilizations worshipped the moon. Even Christianity reflects the moon's presence in the bible. As the moon waxes and wanes through its cycles, a three-day period of darkness occurs during the time of "new moon". After three days of complete darkness, the moon will reappear as a skinny sliver in the sky, thus reborn. In the bible, Jesus Christ died serving humanity, and remained perished for three days. On the morning of the third day, he arose from the dead, to start a new cycle in the kingdom of heaven. Easter occurs at the beginning of spring, which like so many other religions, recognizes when life is beginning another cycle. Easter is a potent symbol of fertility and the renewal of life. It is also thought that the origin of the cross was to symbolize the four quarters of the moon.

As well as being regarded as a symbol of fertility, the moon is also a sign of rain and water. In astrology, it is the moon's association with water that dominates its influence. Folklore claims that the waxing and waning of the moon reflects a monthly cycle of water content in the Earth and its produce, with the full moon time of greatest moisture. A halo around the moon is an ancient sign of rain, (which has scientific basis as the halo is caused by moisture in the earth's atmosphere). The smaller the halo, the higher the possibility of rain. If there are stars in the halo, some omens say that it will rain for that many days.

In Mayan mythology, Ix Chel was the old Moon goddess. Just recently scientists have been able to decipher the Mayan texts, and the ancient books revealed that the Mayans associated human events with moon phases. Mayans observed war-avoidance periods during lunar eclipses, and sacrificed virgin girls to their gods and goddesses under the light of a full moon.

As the Mayan legend unfolds, Ix Chel is portrayed as a malevolent and cranky old woman holding a serpent in her hand and wearing cross-bones on her skirt. The serpent was her assistant, and said to hold all the waters of the heavens in its long body. Ix Chel is also said to possess a jug that she overturns to send enormous amounts of water to earth, causing floods and rainstorms. However, this old woman also possesses a benevolent aspect to her personality. She was worshipped because she protected weavers and women in childbirth.

Over 5400 years ago, inhabitants of bleak and seemingly inhospitable Lewes Island created the Callanish stones. The Callanish stones are multiple circles of stone, similar to Stonehenge in England. According to local legend, the Scottish stones were positioned by the Mesolithic or "Middle Stone Age" nomadic tribes that inhabited the island, so to link Earth Mother and the moon. A dramatic event happens at Callanish that only occurs once a month for a few months every 18.61 years.

First the moon rises over the horizon, then slowly progresses across the sky, completely moving through the stones after five or so hours. The most amazing event occurs as the moon passes through the Callanish stones. If a person stands on the rocky hill at the south end of the Mesolithic sight, the moon is dramatically "reborn" with a person silhouetted within it. Imagine this occurring to a band of humans four and half thousand years ago. These humans, having not been desensitized by years of television, would have been mystified and awed by such a powerful sight. Most primitive civilizations were generally superstitious, due to strong religious beliefs, and the first humans to see that event must have been truly moved. The original purpose and meaning of the Callanish stones has been lost to history, but the most prevalent theory is that the stones were configured to make complex sightings of the moon, planets, sun and stars so as to accurately celebrate solstices.

Science Fact, Not Fiction! Debating the moon's influence is nothing more than speculative and philosophical unless hard facts are incorporated. There may be a real connection between the moon and life on earth. On average the menstrual cycle for women is exactly the same duration as the lunar synodic month. At the University of Miami, psychologist Arnold Lieber and his colleagues decided to test the old belief of lunacy. They collected data on homicides in Dade County, Florida over a period of 15 years, a total of 1887 murders. When they matched the data with the phases of the moon, they found to their astonishment that the two rose and fell together almost infallibly for the entire duration. As a full or new moon approached, the murder rate increased sharply, and a distinct decline occurred during the first and last quarters of the moon.

Just to prove that this was no statistical fluke, they repeated the experiment with data from Cuyahoga County in Ohio. Again the results showed the same effect. Another report by the American Institute of Medical Climatology to the Philadelphia Police Department called "The Effect of the Full Moon on Human Behaviour" showed similar results. This report showed that the full moon marked a monthly peak in various kinds of psychotically oriented crimes such as murder, arson, dangerous driving and kleptomania. Other studies have shown that suicide rates also increase around a full moon. The conclusion seems to be that people just seem to go a bit crazy during a full moon.

Crimes and violence aren't the only things affected by the 29.53 full moon cycle. In the Journal of the Florida Medical Association, Dr. Edson Andrews writes that in a study of 1,000 tonsillectomies, almost 82% of post-operative bleeding crises occurred nearer the full moon.

Scientists have also tried to prove the moon's influence over human fertility. A study of over half a million births in New York, between 1948 and 1957, showed maximum births just after the full moon, and a clear minimum at the new moon. Furthermore, a Swiss investigation which recorded 11,807 menstrual periods discovered the onset of bleeding occurred most often during the waxing moon than the waning moon, with a peak on the evening before new moon. On average the menstrual cycle for women is exactly the same as the lunar synodic month, and the human gestation period is exactly nine times the lunar synodic month (265.8 days).

Dr. Arnold Lieber of the University of Miami speculates that perhaps the human body, which, like the surface of the earth is composed of 80% water, experiences some kind of "biological tides" that affect our emotions. However, other scientists have pointed out that any biological tide would be swamped by the effect of the beating of our hearts and heaving of our lungs.

Everywhere the effect of the presence of the moon is apparent. From the dawn of man, humans have had a certain fascination with the moon, one of mystic and power and complete respect. Ancient civilizations worshipped the moon, believing it to possess godly powers. These are apparent even today when you look at Christianity and astrology. But even deeper, the moon could be responsible for maintaining life on this planet. The action of the tides could have kick-started chemical reactions in the seas. Gravitationally it also protects us, as it could act as a celestial shield against asteroid and comet impacts. But deeper still, the moon is so wondrous, and so close to earth, that it is not out of the realm of possibility that earth's faithful companion helped cradle our human race.

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[] In the 1842 Lunacy Act, a lunatic is defined as a demented person enjoying lucid intervals during the first two phases of the moon and afflicted with a period of fatuity in the period following after the full moon.

[] The time between successive full moons is called the synodic month. The time that it takes the moon to return to the same position in the sky relative to the background stars is called the sidereal month.