New Windows on the Exploding Universe

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At Warwick, our astronomers work on questions that range from how the Universe evolves, to how planetary systems form and support life, to what gravitational waves and high-energy particles can tell us about the cosmos. This article focuses on one of the most exciting of these: the exploding Universe.

Stars live fast and die spectacularly

A star's fate depends on its mass. Sun-like stars swell into red giants, shed their outer layers and leave behind a white dwarf, a cooling ember about the size of the Earth. Much heavier stars end their lives in more violent supernova explosions that return a lot of material back into the interstellar medium and leave behind a compact remnant in the centre. This can either be a neutron star, a city-sized ball of matter of incredibly dense matter - denser than an atomic nucleus - or a black hole if the remnant is more than a few times the mass of the Sun.

Modern surveys are transforming our picture of the stars. For example, the European Space Agency's **Gaia** mission, which completed its sky-scanning in January 2025, made around three trillion observations of roughly two billion stars, mapping our Galaxy in unprecedented detail, much of its data is still to be released and many Warwick researchers work closely with Gaia data.

Stars don't like to be single

One of the conclusions from recent surveys is that stars don't like to be single. About half of Sun-like stars have a companion, and for the more massive stars a partner is almost the rule. In many pairs the stars evolve relatively unperturbed, but in close binaries they can swap material, merge, or explode. Binaries involving one or two of the compact objects mentioned above are particularly fascinating and are behind the most explosive and energetic objects.

For many decades, the only way to find stellar black holes was through their influence on a nearby companion star. When a black hole is feeding on gas pulled from a nearby star that gas heats up and blazes in in the X-ray spectrum, detectable with space-based X-ray telescopes. By weighing the components of these X-ray binaries in our own Galaxy, astronomers found black holes, typically between about 5 and 15 times the mass of the Sun. That became our expectation for what stellar black holes look like.

Ripples in space-time

In 1915 Einstein's general theory of relativity predicted that moving masses should send ripples through space-time itself, travelling at the speed of light. Close pairs of compact objects are ideal sources. As they orbit, they lose energy to gravitational waves, spiral together, and finally merge in a violent collision. The trouble is that by the time the ripples reach us one Earth they are almost unimaginably weak.

Detecting them took a century and some of the most remarkable engineering ever attempted. The **LIGO** detectors in the United States, with key UK involvement, are laser interferometers with 4 km arms, able to sense a change in length of about one part in 10^{23} (that 1 with 23 zeroes after it). In September 2015 they detected their first signal, GW150914. It came from two black holes of about 36 and 29 times the mass of the Sun, spiralling together and merging into a single black hole of about 62 solar masses. Now the keen reader might be doing their sums and notice that about 3 solar masses are missing. They were indeed radiated away as gravitational waves. For scale, the atomic bomb test at Bikini Atoll converted about one gram of matter into energy. GW150914 released some 6×10^{33} times more, in a fraction of a second!

What began with one detection is now a flood, with hundreds of events recorded. Many of the black holes are much heavier than those found in X-ray binaries in our Galaxy, and gravitational wave astronomy is rewriting the textbooks on how such objects form.

Catching the light

Two merging black holes are expected to be dark, unless there is gas near them that might be stirred. However, mergers involving neutron stars are different. The neutron stars can be torn apart, flinging out hot, radioactive debris that shines in what is called a **kilonova**. Detecting both the gravitational waves and the light is known as multi-messenger astronomy, and it tells us far more than either signal alone. It is also how we have learned that merging neutron stars are a major factory for producing heavy elements such as gold.

The challenge is considerable. The signals are short-lived and fade within days. The gravitational wave detectors give only a rough idea of where to look, often covering hundreds of square degrees of sky. And the sky is full of other things that change and flicker.

GOTO: a robotic sky-watcher

This is why Warwick leads **GOTO**, the **G**ravitational-wave **O**ptical **T**ransient **O**bserver, built with an international consortium of partners. It was designed before the first gravitational wave detection, for wide, rapid-response searches of the sky.

GOTO has two identical sites, one on La Palma in the Canary Islands and one at Siding Spring in Australia. Each has sixteen 40 cm telescopes, mounted in groups of eight, on robotic mounts

inside their own domes. Together, each site images 80 square degrees of sky, with 800 million pixels, roughly every 45 seconds, whenever the weather allows.

They generate a vast amount of data. To find anything new, images are subtracted from a reference image of the same patch of sky, so that only what has changed remains. This is not easy, because poor subtractions leave behind many false alarms. Machine learning now sifts through tens of thousands of candidates each night, leaving a handful for human inspection. The advances in machine learning methods means that we can now develop an autonomous system which makes decisions in minutes or less, and vastly reduces what the humans in the loop need to process. In one recent example, a very young supernova was caught within about twelve hours of exploding, and other telescopes quickly followed this discovery up.

In the last few years, **GOTO** has followed over a hundred gravitational wave events and discovered thousands of new supernovae. It also hunts for the counterparts of gamma-ray bursts, looks at sources of high-energy neutrinos, and tracks asteroids, comets and active galaxies. Because it covers the whole sky regularly, it is building a vast record of the changing Universe.

Science for everyone

Our data are also open to the public. Through the **Kilonova-seekers** project on the **Zooniverse** platform, thousands of volunteers from around the world have helped us inspect **GOTO** images, contributing millions of classifications, setting up a constructive humans versus the machines competition. Anyone can join at *kilonova-seekers.org* if you would like to know more or give it a go.

Still early days

The era of multi-messenger astronomy has arrived, and gravitational wave astrophysics is already changing what we know about stars and their remnants. But it is still early days, which is what makes it so exciting. While automation and machine-learning is becoming ever more capable, at the beating heart is still an excellent team of scientists and students and many dedicated volunteers.



Figure 1: The two stations of the GOTO array, covering both hemispheres from La Palma and Australia. Each station deploys two groups of eight wide-field telescopes, seen here inside the open domes.



Figure 2: A visualisation of a pair of merging neutron stars, leading to emission of gravitational waves but also the violent ejection of fast moving and neutron-rich material that we believe are the furnaces for a significant number of elements in the periodic table.