AstroTalk: Behind the news headlines of Oct. 2019–Jan. 2020

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Explosions galore!

When it comes to the biggest and brightest explosions in the Universe—known as ‘gamma-ray bursts’ (GRBs)—recently published research suggest that it takes two stars to make them happen.

The new research, led by astronomers at the University of Warwick in the UK, solves the mystery of how stars spin fast enough to create conditions to launch a jet of highly energetic material into space. The astronomers found that tidal effects similar to those acting between the Moon and the Earth are the answer.

The discovery was made using simulated models of thousands of so-called ‘binary’ star systems, that is, solar systems that have two stars orbiting one another.

More than half of all stars are located in binary systems, and this new research has shown that they need to be in binary stars in order for those massive explosions to be generated.

A long GRB, the type examined in the recent study, occurs when a massive star of about 8 to 10× the total content of our Sun goes supernova, collapses into a neutron star or black hole, and fires a relativistic jet of material into space.

Such ‘core-collapse’ supernovae occur when the iron core of a massive star collapses under the force of gravity and then rebounds, generating pressure waves and shocks that propagate outwards. Superluminous supernovae represent a rare class of core collapse supernovae whose luminosity, equal to 10–1,000 billion Suns, is too high to be powered by the usual process that drives supernovae, the radioactive decay of nickel; there is simply not enough nickel present to do it. Superluminous supernovae seem to be associated with so0called long-duration GRBs, which last for a few seconds up to several minutes, lending support to the idea that they too are powered by a spinning remnant.

The source of the energetics implied has been hotly contested, with suggestions including shocks from the ejected material or pulsating instabilities interacting with surrounding material. The most favoured model, however, is the sustained injection of energy from a source like a spinning compact remnant: a neutron star or an accreting black hole.

Long-duration GRBs are different from the more common GRBs that last for under a few seconds. The long-duration bursts are suspected of being sustained by the rotational energy of a spinning compact object left behind from a supernova.

Astronomer Matt Nicholl (Smithsonian Center for Astrophysics, USA) and four colleagues have proposed a unifying model for superluminous supernovae and long-duration GRBs in which a spinning neutron star has a slight misalignment between its spin axis and its magnetic axis. The consequence is that substantial fractions of the spinning power are supplied both to the supernova and to a jet of particles moving at speeds close to the speed of light that enabled the long burst. Moreover, the scientists can predict the radio emission and thermal wind effects, and to address some of the transient effects that appear in these dramatic events.

In fact, instead of the progenitor star collapsing radially inwards, it is thought to flatten down into a disk to conserve angular momentum—the conservation of angular momentum (the rotational equivalent of linear momentum) within an isolated system is a basic, unbreakable law in physics. As the material falls inwards, that angular momentum launches it in the form of a jet along the polar axis.

However, to form that jet of material, the star has to be spinning fast enough to launch material along the axis. This presents a problem, because stars usually lose any spin they acquire very quickly. By modelling the behaviour of these massive stars as they collapse, the University of Warwick researchers have been able to constrain the factors that cause a jet to be formed.

They found that the effects of tides from a close neighbour—the same effect that has the Moon and the Earth locked together in their spin—could be responsible for spinning these stars at the rate needed to create a GRB.

GRBs are the most luminous events in the Universe and are observable from Earth when their jet of material is pointed directly at us. This means that we only see around 10–20% of the GRBs in our skies.

Lead researcher Ashley Chrimes (Warwick University) said,

> "*We're predicting what kind of stars or systems produce gamma-ray bursts, which are the biggest explosions in the Universe. Until now it's been unclear what kind of stars or binary systems you need to produce that result.*
>
> *The question has been how a star starts spinning, or maintains its spin over time. We found that the effect of a star's tides on its partner is stopping them from slowing down and, in some cases, it is spinning them up. They are stealing rotational energy from their companion, a consequence of which is that they then drift further away.*
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> *What we have determined is that the majority of stars are spinning fast precisely because they're in a binary system.*"

The novel study used a collection of binary stellar evolution models created by researchers from the University of Warwick and the University of Auckland

(New Zealand). Using a technique called 'binary population synthesis,' the scientists managed to simulate this mechanism in a population of thousands of star systems and so identify the rare examples where an explosion of this type can occur.

Dr. Elizabeth Stanway, also from the University of Warwick, said,

> "*Scientists haven't modelled in detail for binary evolution in the past because it's a very complex calculation to do. This work has considered a physical mechanism within those models that we haven't examined before, that suggests that binaries can produce enough GRBs using this method to explain the number that we are observing.*
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> *There has also been a big dilemma over the 'metallicity' of stars that produce gamma-ray bursts. As astronomers, we measure the composition of stars and the dominant pathway for gamma-ray bursts requires very few iron atoms or other heavy elements in the stellar atmosphere. There's been a puzzle over why we see a variety of compositions in the stars producing gamma-ray bursts, and this model offers an explanation*."

Ashley added,

> "*This model allows us to predict what these systems should look like observationally in terms of their temperature and luminosity, and what the properties of the companion are likely to be. We are now interested in applying this analysis to explore different astrophysical transients, such as fast radio bursts, and can potentially model rarer events such as black holes spiralling into stars*."

It is becoming increasingly clear that the composition of the star influences what happens during the explosion.

In a separate recent study led by researchers at Kyoto University, Japan, a team of international researchers observed that some stars exploding as supernovae may release part of their hydrogen layers to their companion stars before the explosion.

> "*In a binary star system, the star can interact with the companion during its evolution. When a massive star evolves, it swells to become a red supergiant star, and the presence of a companion star may disrupt the outer layers of this supergiant star, which is rich in hydrogen. Therefore, binary interaction may remove the hydrogen layer of the evolved star either partially or completely*," says team member and postdoctoral researcher Hanindyo Kuncarayakti from the University of Turku in Finland.

As the star has released a significant part of its hydrogen layer due to the close companion star, its explosion can be observed as a 'Type Ib' or 'Type IIb' supernova. A more massive star explodes as a 'Type Ic' supernova after losing its helium layer because of stellar 'winds.' Stellar winds are massive streams of energetic particles from the surface of the star that may remove the helium layer below the hydrogen layer.

> "*However, the companion star does not have a significant role in what happens to the exploding star's helium layer. Instead, stellar winds play a key role in the process as their intensity is dependent on the star's own initial mass. According to theoretical models and our observations, the effects of stellar winds on the mass loss of the exploding star are significant only for stars above a certain mass range*," says Kuncarayakti.

The research group's observations show that the so-called hybrid mechanism is a potential model in describing the evolution of massive stars. The hybrid mechanism indicates that during its lifespan, the star may gradually lose part of its mass both to its companion star as a result of interaction as well as due to stellar winds.

> "*By observing stars dying as supernovae and the phenomena within, we can improve our understanding on massive star evolution. However, our understanding of massive star evolution is still far from complete*," states Professor Seppo Mattila from the University of Turku.

In addition to these exciting developments related to GRBs, in the past few months we have seen major progress in our understanding of other bright explosions and supernova events as well.

As a case in point, Swedish and Japanese researchers have, after ten years, found an explanation to the peculiar emission lines seen in one of the brightest supernovae ever observed, known as 'SN 2006gy.' At the same time, they found an explanation for how the supernova developed.

SN 2006gy is one of the most studied superluminous supernovae, but researchers have been uncertain about its origin. Astrophysicists at Stockholm University (Sweden) have, together with Japanese colleagues, now discovered large amounts of iron in the supernova through spectral lines that have never previously been seen either in supernovae or in other astrophysical objects. That has led to a new explanation for how the supernova arose.

> "*No-one had tested to compare spectra from neutral iron, that is, iron in which all electrons are retained, with the unidentified emission lines in SN 2006gy, because iron is normally ionised (which means that the iron atoms have one or more electrons removed). We tried it and saw with excitement how line after line lined up just as in the observed spectrum*," says Anders Jerkstrand from Stockholm University.

> "*It became even more exciting when it quickly turned out that very large amounts of iron were needed to make the lines—at least one-third of the Sun's mass—which directly ruled out some old scenarios and instead revealed a new one*."

The progenitor to SN 2006gy was, according to the new model, a binary star consisting of a white dwarf of the same size as the Earth and a hydrogen-rich massive star as large as our entire solar system in close orbit.

As the hydrogen rich star expanded its envelope, which happens when new fuel is ignited in the late stages of a star's evolution, the white dwarf was caught in the envelope and spiralled in towards the centre of the companion. When it reached the centre the unstable white dwarf exploded and a Type Ia supernova was born. This supernova then collided with the ejected envelope, which is flung out during the inspiral, and this gigantic collision gave rise to the light of SN 2006gy.

> "*That a Type Ia supernova appears to be behind SN 2006gy turns upside down what most researchers have believed*," says Anders Jerkstrand.
>
> "*That a white dwarf can be in close orbit with a massive hydrogen-rich star, and quickly explode upon falling to the centre, gives important new information for the theory of double star evolution and the conditions necessary for a white dwarf to explode*."

Our understanding of the evolution of binary stars has been boosted significantly in recent years, so it is no surprise that new results challenge our perception of the most visible and most explosive events in the Universe. These are exciting times, and we look forward to more explosive revelations in the near future!

Figure 1: Artist's impression of a gamma-ray burst with an orbiting binary star. (*Credit: University of Warwick/Mark Garlick*)

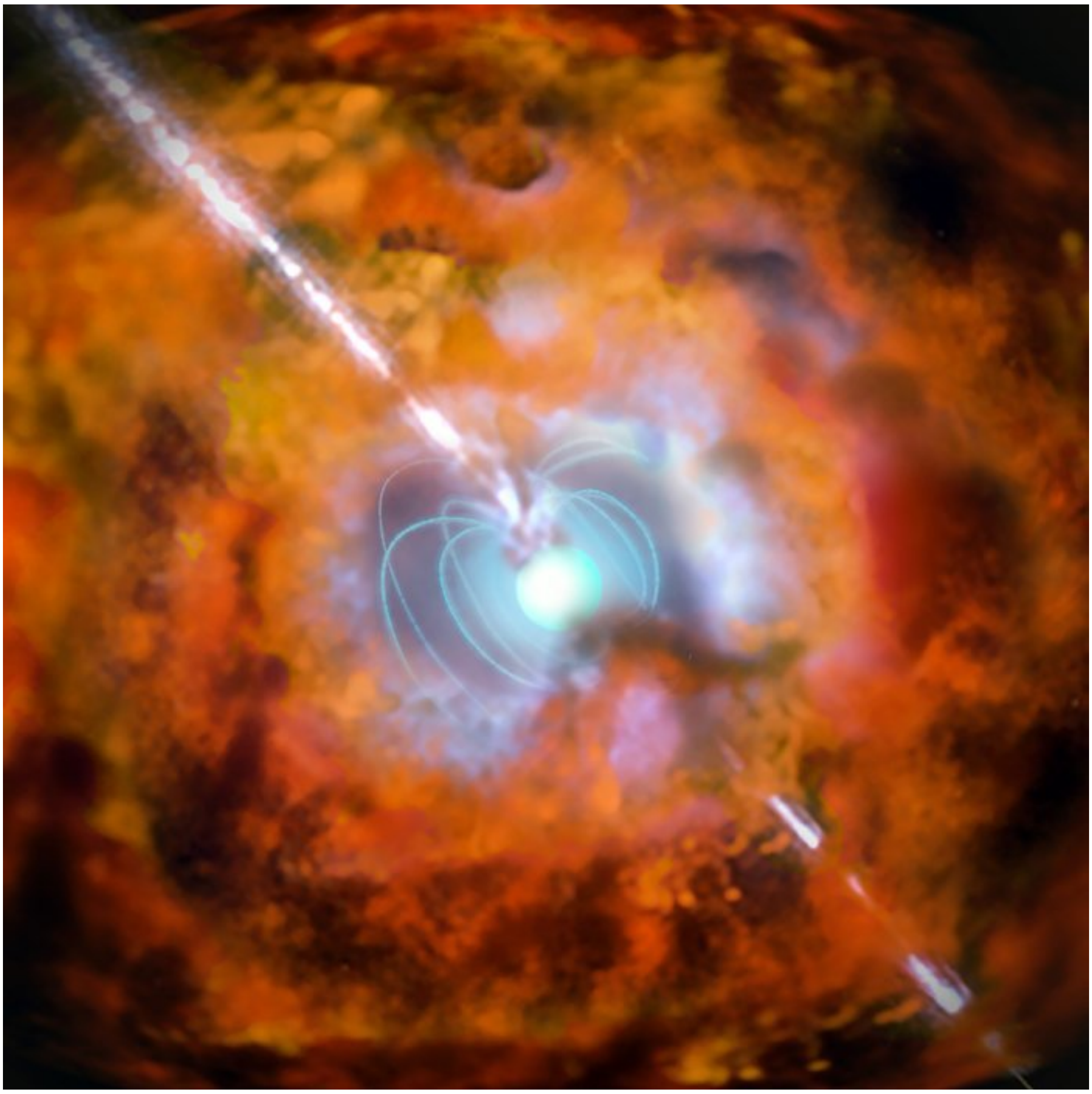

Figure 2: Artist's impression of a superluminous supernova and an associated gamma-ray burst being driven by a rapidly spinning neutron star. (*Credit: ESO*)

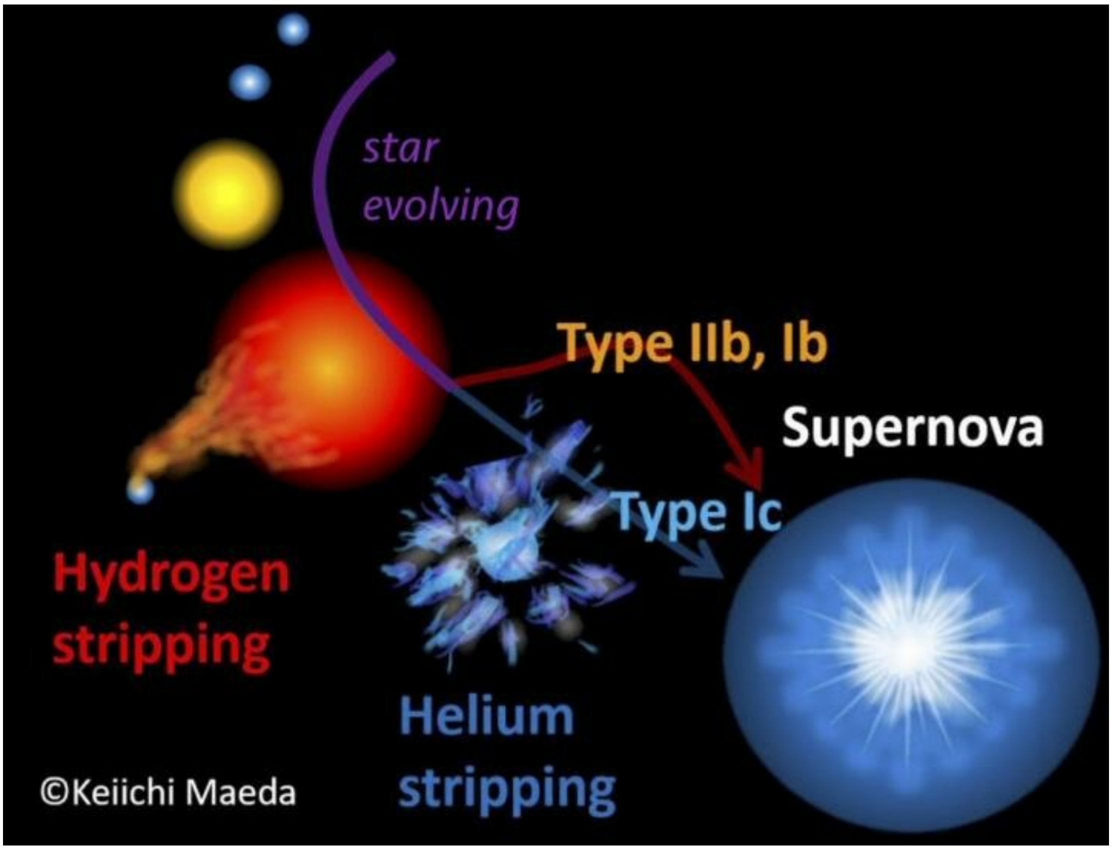

Figure 3: A massive star evolving and becoming a red supergiant, and finally exploding as a supernova. A binary companion may strip the star's hydrogen away (producing supernovae of Type IIb/Ib), and for a more massive star the stellar wind expels the remaining helium layer (producing supernovae of Type Ic). (*Credit: Keiichi Maeda*)

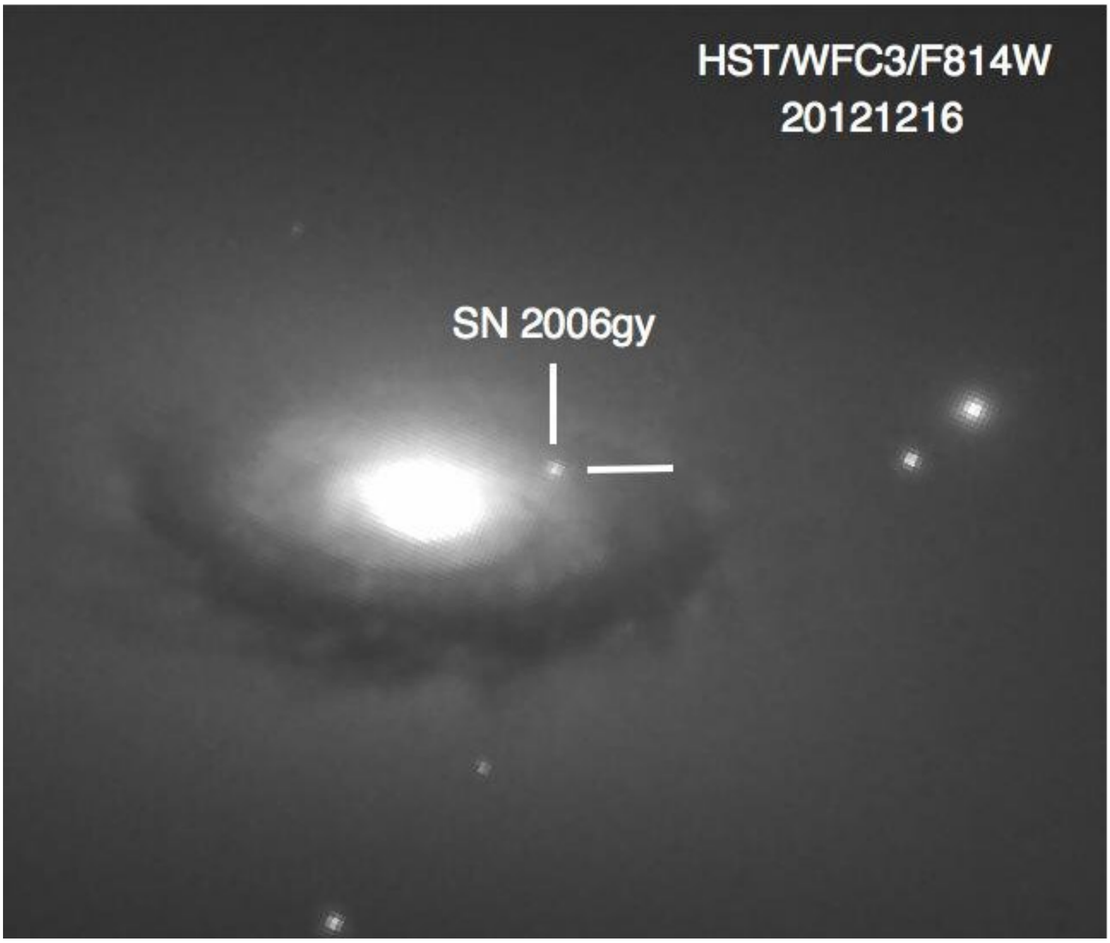

Figure 4: The supernova SN 2006gy. (*Credit: Fox et al. 2015*)

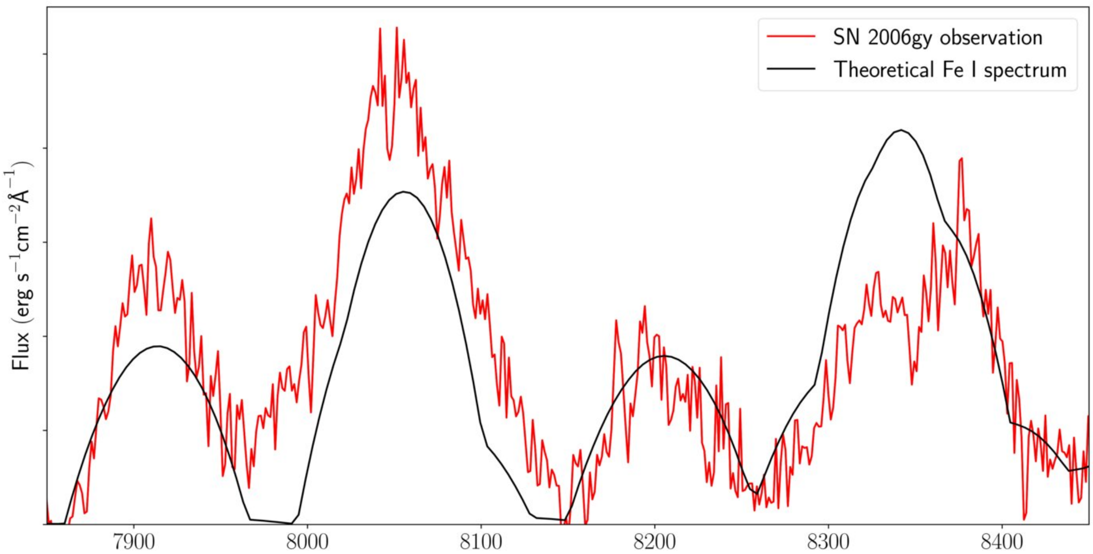

Figure 5: Previously unidentified lines in the spectrum of the supernova SN 2006gy could now be traced to the presence of neutral iron. The red line shows the observed spectrum, the black curve the theoretical iron spectrum. (*Credit: © MPA*)