# Gresham College Main logo

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**Transient Universe**

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A signature of most astronomical processes is the enormous timescales involved - cosmic objects live and evolve over millions or billions of years. The chance of witnessing an exciting change in the appearance or behaviour of any one source during a human lifetime has always been pretty low. This is now changing, due to new advances in technology that are enabling the fast-growing field of *time domain* astronomy to add a new dimension to our science. Comparison of observations can be made using archival data stored from several decades of observations, and we are now in an era of automated observations where robotic telescopes (both on the ground and out in space) continually scan the skies for any rapid changes. We no longer have to rely so much on chance to discover new transient phenomena as they occur. Instead astronomers and their telescopes now regularly monitor for changes in certain populations of astronomical sources – variations in their colour, brightness, shape, spectrum and in position, and which occur on timescales shorter than a millisecond.

There are many different kinds of transient behaviour observed, and we see plenty in our own Solar System: spectacular flares are unleashed from the surface on the Sun as a response to rapid changes in its magnetic activity, and comets disintegrate to grow long tails as they warm up in their orbit around the Sun. Further afield, displacements in the precise position of nearby stars relative to more distant ones show us how local stars in the Milky Way are moving; or periodic changes in the brightness or motion of stars can reveal the presence of surrounding exoplanets. Today I shall be concentrating on some of the changeable behaviour displayed by objects well beyond our Solar System, including those both inside our own Galaxy and at cosmological distances. I shall look at some of the objects that are both *variable* in their behaviour – on timescales of seconds, weeks, months and years – and *transient –* where sometimes far more dramatic changes are observed in one-off events.

# variable stars

Many stars vary in brightness, either following a regular periodic cycle or undergoing sporadic flaring. Sometimes the fluctuations in the luminosity are entirely due to external events – such as gravitational microlensing, which can temporarily cause the light of distant objects to increase due to the gravitational field of a foreground star passing between us and it; or due to transits of exoplanets periodically dimming the light of the disc; or when a star (such as the famous variable star Algol) is part of a binary system, where stars of very different brightnesses regularly eclipse one another. Other stars change in luminosity due to internal changes within the star.

## flare stars

The Sun shows a tiny (0.1%) but regular fluctuation in its luminosity linked to its cycle of magnetic activity. It can also undergo far more dramatic activity, when flares of energetic light (such as that observed in the ‘Carrington event’ of 1859) are released from strongly magnetic regions on its surface. But many other stars show far more spectacular variations in behaviour, undergoing sudden outbursts in brightness (at all wavelengths) for only a few minutes. Known as *flare stars,* these objects tend to have fairly predictable recurrences of activity, and appear to mostly be relatively isolated, dim red dwarfs. The source of the flaring behaviour is thought to be the same as for the Sun, powered by sudden releases of energy when the magnetic fields within the stellar atmosphere snap into a simpler configuration. Only this year (in April 2014) the *Swift* satellite discovered the strongest, hottest, and longest-duration sequence of stellar explosions from a nearby red dwarf star, which erupted into a succession of seven powerful flares during a fortnight. The young star, known as DG CVn, is only a third the mass and size of the Sun, and is only about 35 million years old. On most days it shines with less than about thousandth the luminosity of the Sun, yet the first flare it produced in this sequence of eruptions was over ten thousand times more powerful than any Solar flare ever recorded.

## pulsating variables

Many variable stars display very predictable and regular changes in both their luminosity and spectrum which are due to physical changes within the star itself, which lead to radial pulsations in its size. The Doppler shifts in the spectra track motions of the stellar surface to and away from us that exactly follow the variations in brightness. These stars display a cycle of expansion and contraction that is created by instabilities in their cooler outer layers. Changes in the temperature (and thus ionisation state) of this gas create changes in opacity – ie whether the outer atmosphere either blocks the outward flow of internal energy, storing it until it heats up so much it expands; or whether the gas is more transparent and permits the energy to escape freely, to then cool down and contract. A feedback process develops between these two states with a natural rhythm, or resonance, which produces a well-defined period of pulsation. There are many subtly different types of variable stars but perhaps the most famous are the *Cepheid variables*, which are very young, massive and bright supergiant stars that vary with regular periods ranging from days to months. Henrietta Swann Leavitt discovered that the period of this pulsation (and hence variability) is determined by their intrinsic brightness, a property that could be exploited to determine distances to external galaxies hosting such variable stars.

# variable nebulae

Many young stars are embedded in nebulae consisting of the remains of the cloud of gas and dust that they formed from.

The walls of the nebulae are constantly eroded by the action of the stellar winds and highly energetic ultraviolet light from the young stars; but it would still take thousands of years before we would notice any changes in the structures. There are a few nebulae whose appearance has been seen to alter, however, and in all cases it’s not because the structure of the clouds is changing, but due to changes in the way the nebula is illuminated.

### Light echoes

One of the most luminous Cepheid variables is RS Puppis, a star ten times more massive than our Sun and 200 times larger, which rhythmically brightens and dims (by a factor of 5) over a six-week cycle. During this period it is possible to observe not just the fluctuation of the starlight itself, but changes in the way the light is reflected by the surrounding dust clouds, appearing as pulses of light propagating outwards. This is known as a *light echo.*

V838 Mon is a relatively normal star which underwent an unexpected outburst in brightness in 2002, temporarily becoming one of the brightest stars in our galaxy (at 600,000 times more luminous than our Sun!) before fading away again a few months later. The increase in brightness wasn’t due to a nova or a supernova explosion marking the end of the star’s life, as it didn’t break apart or eject much matter into space, and indeed we don’t know what triggered this sudden and brief release of luminosity. However, this outburst had consequences for the appearance of the cloud of dusty material that surrounds the star, which was seen to change over the following few years. Even though it might look like it, the changes in the cloud are not due to the matter it contains expanding outwards, but instead they mark the passage of a light echo from the star. The light from the outburst is reflected by successively more distant shells of material within the cloud; and the last light echo recorded in the images comes from matter located about three light years away from the star.

### shadowing and illumination

Despite its name, Hubble’s variable nebula was actually discovered by William Herschel in 1783. It is named for Edwin Hubble instead, as he was the first to notice that it changes in brightness and structure over periods of months. The nebula is a fan-shaped cloud of gas and dust about one light-year wide which is lit up by the bright star R Mon. R Mon is a young star, only about 300,000 years old, which has a mass around ten times that of the Sun. It varies in luminosity - mainly because it is still in the relatively early part of its life - and is completely obscured from view. We can only see it through the light that is scattered by the dust particles in the surrounding nebula. Dense clouds of dust that surround the star cast dark shadows onto the nebula; and as these clouds move, the shadows on the cloud also move, changing the way the dust is illuminated, and giving rises to apparent changes in its structure,

A similar process is responsible for changes seen Hind's nebula, a cloud of gas and dust about 4 light-years in diameter. Soon after its discovery 1852, the nebula began to fade in brightness until it was lost from telescopic view by 1868. It has been gradually brightening again since the 1930’s. The cloud is illuminated because it reflects the light from a star known as T Tauri, which happens to be the prototype of a certain type of very young stars. T Tauri will develop to resemble the Sun, but at the moment it’s less than a few million years old. This is sufficiently early in the processes of its formation that it varies in brightness. Thus here the variable nebula changes in brightness in response to the changes in the flux from the star, but not necessarily at the same time. Infrared observations suggest that the situation may be more complicated, as they reveal the presence of a much younger stellar object completely hidden within the nebula.

# Herbig-Haro objects

Some very young proto-stars have distinct properties that identify them as *Herbig-Haro objects* (named for the astronomers George Herbig and Guillermo Haro who first studied them in the 1950s); in particular they are characterised by narrow high-speed jets of matter that extend over many light-years. Sometimes the young stellar object is completely obscured from view, and only the jets reveal its presence. A star forms at the centre of a condensation within a cloud of gas and dust, accreting more matter on to it; it takes a while for a newly-fledged star to sort out the delicate balance between the onset of nuclear fusion and the accretion of further matter, and during this process a large spinning cocoon of gas and dust gathers around it. Some of this material may well eventually go on to form a planetary system in the future, but at this early stage, some of the disc material accreted towards the star is instead funnelled out along the poles of the spin axis of the star, squirting out to form the narrow jets. The jets may be fired for a few hundreds of thousands of years after the star’s birth, and stop once the star finally ceases accreting matter from its surrounding disc. But while these jets are powered, the matter they contain is expelled from the system at very high speeds. Material at the leading outer edge of the jet crashes into the cold gas and dust of the nearby interstellar medium. It is slowed down by these interactions, and a bow shock is formed at working edge of the jet. Meanwhile gas piles up in the jet behind it, and collisions between the faster-moving and slowed material create shocks within the jet itself, which heat the gas and cause it to glow in knots and streams. Both the structure within the jets and the bow shocks at the interface with the interstellar medium are seen to evolve on fairly short timescales, as knots of gas brighten and fade as matter is rapidly heated and then cools. Observations of these changes show basic principles of how the jets interact with their surroundings; these are relatively easy to observe in Herbig-Haro objects, and the results can inform understanding of other, more remote jetted sources. They also reveal how these young stars influence their neighbourhood in their very early period of life. The time evolution of the Herbig-Haro objects shows that the material does not flow through the jets as a steady stream, but that it is launched sporadically in clumps, this more intermittent behaviour perhaps tracing the sporadic way material falls from the disc onto the star.

# supernovae

But the most dramatic of all variations in stars are from those that undergo an enormous outburst at the extreme of their life.

## Historical observations

Abrupt changes in the brightness of stars have been observed since antiquity, and represented a disturbing departure from the predictability of the rest of the Heavens; when a new star suddenly appeared in the sky, it was often interpreted as an omen and be the source of consternation. A *Nova* – literally ‘new star’ – is the outburst that marks the final collapse of stars like our Sun at the end of their life, and on average one might be visible to the unaided eye about once every decade or so. Their brighter cousins the *supernovae* – the explosions accompanying the demise of a far more massive star at the end of its life – are far rarer, usually occurring only centuries apart; there have been fewer than ten supernovae noted in historical records. To be visible to the unaided eye, the supernovae would most likely erupt from stars within our own Galaxy.

### SN1572

When a new star erupted in the constellation of Cassiopeia in November 1572, it rivalled Venus in brightness at its peak luminosity, and it then faded gradually from view over two years. It has become known as *Tycho’s supernova*, as Tycho Brahe observed it intensively, and published his findings in *De nova et nullius aevi memoria prius visa stella* ("Concerning the Star, new and never before seen in the life or memory of anyone”) in 1573, wherein he demonstrated that ‘new’ stars such as this weren’t tailless comets as previously thought.

### SN1054

Perhaps more famous historical supernova is the one which made its appearance in July 1054, to be recorded as a bright ‘guest star’ by Chinese, Japanese and Arab astronomers. These records allowed the later identification of the supernova remnant formed from the debris ejected from the star during the explosion. Known as the Crab nebula, this supernova remnant contains a collapsed neutron star (in fact it is a pulsar) at its core, and at 6,500 light-years away, the nebula is close enough that we have been able to track its expansion directly over the last few decades. Today it is about 10 light-years across, and the outer layers of the star expelled in the explosion are expanding outwards at over 1,000 kilometers per second.

## Modern supernova observations

Supernovae are rare events, with one on average exploding per century per galaxy. But we no longer have to rely on the chance luck of unaided-eye observation to find one, or wait for one to erupt from a star in our own Milky Way: we can now systematically search for them in other galaxies.

### automated discovery of supernovae

Methodical searches for supernovae in distant galaxies began in the 1930’s, and involved the arduous task of comparing images of distant galaxies recorded on photographic plates by eye. Now we can use robotic telescopes to carry out an automated and systematic survey of many galaxies from one night to the next. These telescopes use detectors with a large field-of-view (*ie* they can observe a large part of the sky at a time), and powerful computers undertake routine analysis and comparison of the data, rapidly flagging sudden changes as possible targets of interest. A quick response to a detection is important to ensure detailed follow-up observation can occur while the supernova is still bright. Not only do we get the best signal (and thus the clearest information) from the supernova at the peak of outburst, but we can learn much from how luminous it is at the peak, and the rate at which it fades: such as the amount of energy output and mass ejected during the explosion; its location in the host galaxy; possibly the distance to the host galaxy; and development of features in the spectrum change and evolve from one week to the next, revealing the type of supernova, and information about its possible progenitor.

## science from supernovae

Supernovae allow us to test our understanding of the physics involved in the very sudden core-collapse of stars at the end of their life, by providing vital data for theoretical models of the lifecycles of stars with masses larger than about ten times that of the Sun. On a slightly broader context, knowing the location of a supernova within a galaxy and identifying the progenitor helps astronomers track the star formation history of that galaxy. This allows us to map the progressive chemical enrichment of the interstellar medium (as remember, all heavy elements are forged at the core of massive stars and then redistributed to the immediate environment during the supernova explosion), as well as estimate how much energy is being deposited into the immediate environment by these stellar explosions. From such studies we can begin to see how successive supernovae have influenced the evolution of their host galaxy, an area of research known as galactic ‘ecology’.

## Cosmology from supernovae

‘Type Ia’ supernovae – those caused not by the gravitational collapse of a massive star, but instead by the accretion of matter from a companion star onto a white dwarf – are used to measure the geometry of the Universe and thus constrain cosmological parameters. The discovery that distant Type 1a supernovae were observed to be fainter – and thus more distant – than indicated by their redshift presented the first evidence for the accelerated expansion of the universe, which requires that that the matter-energy content of the Universe is predominantly dark energy. New wide-field surveys are thus concerned with detecting many more further, fainter supernovae in order to extend our mapping of the expansion of the Universe to far greater distances. The ultimate aim is to get enough data that we can measure the rate of change of the acceleration to provide a discriminant between different theories of dark energy. The importance of Type 1A supernovae to cosmology also means that we need to fully understand the physics of the explosion. Thus the wide-field searches for supernovae are not only about obtaining further data points to map this expansion, but to discover and observe nearby examples, in order to check our understanding of these explosions, particularly if they uncovered any assumptions inherent in our interpretation. Identification of the types of binary system that give rise to Type 1A supernova is required, as the properties of the donor star may well affect how the thermonuclear explosion is triggered. There is so much potential diversity of donor stars, and these differences might subtly influence the outcome of the explosion. But so far successful detections for any surviving companion stars are lacking.

### M82 supernova discovery

Supernovae can still be found by serendipity. Just earlier this year there was the remarkable discovery of SN2014J in the nearby bright galaxy M82 by students and their teacher at the UCL Observatory in Jan 2014. M82 is only 12 million light-years away, and this is one of the closest supernovae to be seen in a while.

## Supernova 1987a

However, the closest supernova to be observed in almost four centuries is SN1987a, which exploded in the outskirts of the Tarantula Nebula, an enormous star formation region in the Large Magellanic Cloud 170,000 light-years away from Earth. The supernova was first observed from Earth in Feb 1987, and a burst of neutrinos was detected at the same time, the first to be directly associated with the eruption of a supernova. The properties of the neutrinos observed agree with theoretical models of stellar core collapse, which predict that most of the energy released has to be carried away in this manner. Given that the Tarantula Nebula is such a well-mapped region, the progenitor star was rapidly identified as a blue supergiant; its mass suggests it should have collapsed into a neutron star but as yet one has not been detected. Presumably it is completely obscured from view, is not a pulsar, and is not yet actively accreting matter.

### development of the ejected debris

Since the original outburst, astronomers have been monitoring how the appearance of the supernova has changed, due to both the expansion of the outer layers of the stellar atmosphere that were thrown off, and the way that the shock wave has affected the surrounding interstellar medium. The remnant of debris from the star is seen to be expanding out at 7,000 km/s, and forms a slightly elongated cloud, glowing because it is heated by the decay of radioactive elements created in the explosion. The energetic ultraviolet light of the explosion has excited and thus highlighted a ring of material around the star that is now glowing. The ring is about a light-year across, and probably is created from material shed by the progenitor star in the later stages of its life, perhaps some 20,000 years or so before the supernova explosion itself. A shock wave from the explosion has propagated outwards at speeds of nearly 60 million km/hr and has then been colliding with, and shock-heating the matter in this ring to sufficiently high temperatures for it to give off X-rays. The first glowing spot in the ring was detected in 1997, and since then another 30 or so have developed. The number and size of these spots should increase over the next few years until they form a continuous ring – and at that stage it could be bright enough to further illuminate the surroundings of the supernova’s environment, and maybe reveal if there is any other matter expelled by the star before it exploded. Changes in the spectrum of the light from the supernova showed when the gas in the circumstellar ring became excited to glow after about 3 years, and reddening of the spectrum probably marks the formation of dust within the ejecta. Velocity structure within the emission lines trace clumps forming, asymmetrical ejection of material, and the mixing of different layers of ejecta, and shocks as it slams into the surroundings.

## eta carina

Another very volatile star whose behaviour has been followed for many years may be a proto-supernova, known as Eta Carina. This is the dominant star in a binary system lying about 7,500 to 8,000 light-years distant from Earth. It has a mass of around 120 solar masses and it is expected to explode as a supernova in the near future – where ‘near future’ in an astronomical context could mean any time between the next decade and the next millennium! The star was first catalogued in 1677 by Edmond Halley, and was observed to brighten and dim over the next hundred years or so. From 1820 it started to increase in luminosity rapidly, becoming 10 times brighter within seven years; and by April 1843 it had become the second brightest star in the night-time sky. This outburst persisted for a couple of decades until it faded away to become invisible to the unaided eye during the last century (modulo the occasional short-lived eruption). Eta Carina shed some ten-twenty solar masses worth of material during its outburst in the mid 19th century, some of it moving outwards at speeds around 700,000 km/hour, slowing to form twin giant lobes of dusty nebula around the star. The reason for the enormous outburst is not well understood, but is most likely linked to the opacity of the outer layers. Even now the star is still losing material through a strong wind that blows from its surface, carrying away about a solar mass about every thousand years.

Light echoes are now being observed from the major outburst of Eta Carina 170 years ago. These are again caused by the way that light from the explosion that was originally directed away from us has since been reflected off dust clouds in the immediate environment, and deflected back towards Earth. Similar to the case of V838 Mon, even though the shape of the structure appears to change, it’s just an illusion created by the way the light reaches successively more distant layers of dust cloud. Observations of this light echo gives us a second chance to observe the outburst, and map the development of the brightness variations with time – just now with much better telescopes and instruments than were available in 1843!

# transient radio sources

A *transient* source is one that releases a short-lived burst of energy, and many are observable primarily in the radio waveband. They tend to divide into *slow transients* with durations from a minute up to weeks or months; and *fast transients* where a burst of radiation lasts only milliseconds or nanoseconds.

## Fast transients

The fast transients show a signal that is dispersed on arrival – *ie* different frequencies arrive at slightly different times, due to the passage of the signal through charged gas (plasma) *en route* from source to Earth. The more plasma lying along the line of sight to the source, the greater the delay in some frequencies. Thus the measured dispersal of the signal indicates how far the light has travelled. The amount of dispersal in the radio signal from fast transient sources indicates that they are probably extra-galactic, as it requires that they have travelled through much more plasma than is contained within our galaxy. However, that hasn’t made it any more possible to identify the type of source producing these fast transients,

which currently remains ambiguous.

## Slow transients

Greater success has been made with the slower transients, which seem to be associated with more regular sources that are producing synchrotron and bremsstrahlung emission, such as accreting compact objects, stars that are flaring, and supernova. In particular, jets from compact objects (sometimes known as *microquasars*) could be variable on these timescales as they are directly linked to the sporadic nature of accretion processes.

# gravitational accretion

Observational astronomy started in the visible waveband, where the light is dominated by sources shining (directly or indirectly…) because of nuclear fusion - stars, nebulae, and where they are all gathered into galaxies. With the opening of other astronomical wavebands such as the radio, it became clear that transient sources are ubiquitous. They are best observed in the high-energy wavebands such as X-rays; such sources are powered by accretion of matter under the force of extreme gravity onto *compact objects* such as black holes, white dwarfs of neutron stars. Most of the radio and X-ray transients trace accretion in binary stellar systems, around active supermassive black holes at the cores of galaxies. Gravitational accretion of matter is naturally highly variable, as the energy output depends on irregularity within the fuel supply and the process of accretion. Sources change brightness with time; they burst, flicker and pulsate.

# X-ray Binary systems

## x-ray transients

Even though it is the waveband that most directly traces accretion processes, variable X-ray sources were only picked up after sufficient rocket flights could provide a comparison of source properties with time. The first X-ray transient was discovered during a rocket flight in 1967, as a time-varying source that had not been visible in that part of the sky two years previously. It then completely disappeared four months later… to then be recovered briefly in 1968. Shortly afterwards a second *X-ray transient* was found, and the floodgates were open. X-ray transients can be seen to brighten by a factor of up to 100,000 on timescales of minutes to hours, with variability observed on other timescales ranging between tens to hundreds of seconds.

### Optical counterparts

The identification of the type of object producing these transients had to await development of X-ray telescopes and detectors which afforded much better positional accuracy, and thus the opportunity for detailed follow-up of the source in other wavebands. The optical counterparts of the transients were found to be binary systems of stars, but binary systems where one star – the more massive – had already reached the end of its life to become a compact object*.* This object – whether a white dwarf, neutron star or black hole – is in a position to accrete material from its less evolved companion; this is a particularly easy process if the donor star is itself in a late stage of life and has inflated into a red giant, where the outer parts of its extended atmosphere are only loosely tied by gravity.

### X-ray variability

The energy released as the accreted matter falls under gravity heats it until the gas glows brightly, and there is also thermonuclear ignition of the accreted mater at the surface of the compact object. The accretion process naturally produces a recurrent but irregular flaring in luminosity with time that is very different from the kind of outburst of a supernova explosion: it’s not a one-off outburst, but more of an extreme variation in the luminosity output on unpredictable timescales. The same source can switch on and off at irregular intervals, and still produce an occasional but dramatic X-ray burst (which can peak within a few seconds) which might then sometimes recur within a few hours. All of this behaviour is expected from the fall of matter onto a compact object. First of all, the rate of accretion can vary. Perhaps the proximity of the stars to each other varies as they travel around their orbits, or the material is torn from the donor star in irregular chunks. There will be interactions within the accretion stream itself, which is expected to be a chaotic environment; the closer into the compact object, the faster the flow of material. Matter falling on different orbits will collide, and liberate even more energy as light. The similarity of the X-ray spectra when the source is bright and when it is less bright implies that the same basic process is operating at different levels – maybe just the rate of accretion is different when the sources are at their faintest, and when there is no active accretion only a residual background of X-ray emission from the source remains, such as thermal emission from the hot surface of the neutron star.

X-ray transients are generally classified into two types, according to the mass of the companion (donor) star. Because this star is part of a binary system, it is possible to determine the mass of the compact object from the orbit of the companion.

### LMXBs

If the donor star mass is relatively low, the system is termed a *low mass X-ray binary* (LMXB). The star has expanded to fill the full volume around it where material can stay gravitationally bound (known as the Roche lobe), and matter is accreted via an accretion disc. In such systems the compact objects tend to have masses measured to be between 3 and 12 Solar masses, and are most likely to be black holes (75%) and neutron stars (25%).

### HMXB

A *high-mass X-ray binary* (HMXB) contains a supergiant donor star, with a mass around tens of times greater than the Sun in orbit around a compact object which is more likely to be a neutron star. In such systems it seems that the matter being accreted originates in a dense stellar wind emanating from the supergiant, which is directed down to the surface of the neutron star along the lines of its strong magnetic field, where it is funnelled onto the poles. As it falls towards and onto the surface of the neutron star, the entrained material is rapidly decelerated and heated through a series of shocks.

Variations in the brightness of HMXBs again come from variations in the supply of accreted matter. The nature and magnetic activity of the donor star determines how structured, or clumpy its stellar wind is. A bright outburst from a HMXB could be triggered when the neutron star encounters a particularly dense clump of stellar wind, or if the stars follow a large eccentric orbit around each other, the likelihood of a bright outburst is increased when the two stars are closest to each other. There are other factors that could influence the rate or structure in the accretion flow, magnetic or centrifugal influences that might slow or hinder the fall of material into the neutron star’s magnetosphere.

### importance of X-ray transients

Study of X-ray transients allow astronomers to map out and characterise the range of binary systems throughout the galaxy, and how different viewing angles, stars involved, and orbital patterns can all subtly change the behaviour a system. Observations also allow direct study of how plasma is affected by extreme gravitational or magnetic fields. As the supergiant partners of the binary system are so massive that they are very young, locating and studying HMXB’s can track the kind of star formation that has occurred recently across the disc of a spiral galaxy.

# Gamma-ray bursts

## discovery of GRBs

Some of the strongest transient sources occur at even higher energies, and are known as gamma-ray bursts (GRBs). They were discovered serendipitously in the late 1960s by military satellites such as *Vela* series (USA) and *Kronus* (USSR), which were monitoring the Earth’s atmosphere to check for bursts of high-energy radiation that would reveal if nuclear weapons had been detonated. As the satellites spent some of their time slewing across the sky, they could also make astronomical detections, and even monitor the variability of certain cosmic sources over a period of years. When these data were declassified in the early 1970’s, they were made available to astronomers. Many flashes of gamma-ray light had been detected during the missions. These outbursts occurred all the time, appeared from any direction in the sky, lasted anywhere from less than a second to a few tens of seconds, and during this time some of them temporarily become the brightest source in the whole sky. But even though a new phenomenon had been discovered and recorded, the positional accuracy of these detections was frustratingly imprecise, so nothing much more could be learnt at the time about the kind of source giving rise to the outbursts. Like X-rays, gamma-rays photons are so energetic that they will pass through normal mirrors or lenses – they can’t be easily focussed.

All that could be deduced was that the isotropy of sources around the sky indicated that they had an extragalactic origin, as there was no preferential association with the location of the Milky Way in the sky. Even this simple inference already marked them out as outstanding sources, as to be this bright from extragalactic distances meant that they had to be incredibly luminous events. GRBs continued to be detected over the next couple of decades, but determination of their true luminosity and distance remained elusive. Major advances had to await the kind of satellites that became operational in the 1990’s. The *Burst and Transient Source Experiment* (*BATSE*) on the *Compton Gamma-Ray Observatory* launched in 1991 discovered 2,700 GRBs (and even more X-ray transients) lasting on timescales between a millisecond to 1000 seconds; and the all-sky monitor on the *Rossi X-ray Timing Experiment,* which scanned most of the sky every hour and a half, also discovered thousands of transients.

## observational properties of GRBs

### occurrence and duration

The distribution of their location on the sky leads us to assume that GRBs are an extragalactic population. They occur at the rate of several a day, and last for timescales between less than a second to tens of seconds. If we plot the flux observed against time in a *lightcurve,* its shape differs from one GRB to another. Some show a very sharp rise in flux followed by a slow decay, while others display successive peaks in brightness with variations on timescales of milliseconds. About a quarter of the GRBs observed last for less than a couple of seconds, and their light curves are very narrow, start with a sharp peak, and their spectra are ‘harder’ ie they show more of the higher energy light. The other GRBs have much more stretched light curves, and can last for minutes, which means it’s a lot easier to get data on these sources, such as mapping out the substructure in variations in detail. The systematic differences in both spectrum and the duration suggest that the short and the long bursts have different origins – but to test this, you have to be able to identify the progenitor.

### The afterglow

Despite only appearing as a flash of gamma-rays for a few seconds or less, GRBs are also characterised by an *afterglow* that persists once the original burst disappears. Apparent in lower-energy wavebands, such as the X-ray, radio and optical, the afterglow can last for several weeks before fading completely. This light can be observed (slightly more at leisure) with other telescopes that have a much better ability to pinpoint the exact position of the source than gamma-ray detectors, and thus give us a much better chance to identify the cosmological object responsible for the initial flash. The first detection of a GRB afterglow in the X-rays was made in May 1997 by the *Beppo-Sax* satellite, and this detection was confirmed by subsequent follow-up in the radio and optical. An optical spectrum allows determination of the redshift of the source, and hence its distance from Earth. This source, GRB 970508, was confirmed to be at least 6 billion light-years away. Observations of the afterglow in the radio indicated that the source of the radio waves had expanded almost at the speed of light, supporting ideas that that GRBs were some kind of relativistically expanding explosions.

## The origin of GRBs

Part of the problem about explaining GRBs is that gamma-rays are the most energetic form of electromagnetic radiation.

The need to accelerate particles to such large energies means that gamma-ray emission is associated with extreme environments, such as those containing shocks, jets, strong magnetic fields or electric fields, very high temperatures; conditions that are found in sources like accreting black holes and neutron stars, supernova explosions and remnants.

### the luminosity of a GRB

Today all longer-duration GRBs for which a redshift has been established are known to lie at cosmological distances. Knowledge of the distance enables us to translate the flux observed into a knowledge of the total luminosity released, and the amount of energy implied is staggeringly large, and indeed so large that we struggle to come up for a reasonable mechanism to liberate so much energy within such a short time. We can reduce the amount of energy inferred if we say the luminosity is not emitted in every direction equally, but instead is focussed into a tight beam, or jet, so that we see a GRB only when the beamed emission is directed towards us. Relativistic beaming effects within a very narrow jet of material moving close to the speed of light, and close to the line of our sight, can artificially boost the observed flux. The narrower the jet, the more the energy requirement is reduced, and by the time you reduce the opening of the jet to only

1 degree, the energy has dropped by a factor of 50,000 (and to semi-reasonable levels). [Broader beams of emission will reduce the luminosity required by lesser factors of 100s to 1000s, which is not really enough.] Even with this beaming, the luminosity inferred still implies that the GRBs are some of the most luminous objects anywhere in the Universe. Narrowing the area over which the radiation is released may reduce the energy problem, but it does mean we only see a fraction of all the GRBs, as there must be many more that aren’t directed our way. The opening angle of the jet thus also has major implications for the total number of GRBs that occur, and how commonly they occur. For each GRB that we do observe, there must be many more that we miss; the opening angle of 1 degree implies that for every GRB we observe, there are 49,000 pointed away from us.

## Theories of GRB formation

Most ideas for the formation of GRBs link them to the death of very massive stars. Even then, these can’t be commonplace massive stars, as despite making allowances for the focussed beams of radiation release, they are still rare enough occurrences given the vast numbers of possible massive stars across the Universe. The host galaxies of the longer-duration GRBs are more luminous in the ultraviolet, which is interpreted as a signature of recent star formation; the ultraviolet light is emitted by a population of very massive and consequently, short-lived, stars.

### Hypernova explosion

Imagine a particularly massive progenitor star that has reached the end point of its life: it has exhausted its possibilities for nuclear fusion within its core, and then undergoes rapid gravitational collapse to form a black hole. But a GRB can’t be a normal supernova explosion, as you need to liberate more energy than can occur during just the simple gravitational collapse of the massive core. First of all, in order to release the kind of power we observe, it has to be an extreme star, one with a mass in the region of 50-100 times greater than that of the Sun. Then the explosion itself will be a super-supernova, known as a *hypernova.* Then, at the very moment of the collapse, we also need to launch highly relativistic jets to shoot outwards. These slam into both the outer layers of the star’s atmosphere, and the surrounding interstellar medium, sweeping it in front until the matter in the jet is finally slowed down, at which point any remaining kinetic energy dissipates in the form of shocks within the jet. These shocks can accelerate charged particles to create non-thermal emission (such as synchrotron and inverse-Compton emission), and the whole interaction excites the material in surroundings to powers the observed afterglow which fades more slowly with time.

How you create the jets at the exact moment the entire star blows itself apart is less well understood. Some ideas suggest that the progenitor might have been a particularly fast rotator, with the creation of jets linked to rapid spin-up associated with the conservation of angular momentum as the star dramatically shrinks. The jets might then form from material squeezed out along the rotational axis of the newly-formed black hole; if it is spinning incredibly fast, it’s easier to expel material out along the poles of rotational than trying to push it out at in an equatorial direction. Regardless, we need to tap into the energy released from the gravitational collapse of the massive core, and also appeal to energy generation from very rapid accretion of matter onto the black hole in a very short time, released in a matter of only a few tens of seconds.

### neutron star mergers

The much shorter-duration GRB’s, those whose outbursts last shorter than 2 seconds, are thought to have a different originating mechanism. Less is known about them in all regards, as the quickness of the outburst and the faintness of the afterglow makes it much harder to obtain the positional accuracy required for determination of their redshift and thus distance. Thus we know far less about the probable progenitor objects. One suggestion is that they produced at the final moment of a merger of a neutron star, either with a companion neutron star or black hole. The end product would be a(n even more massive) rapidly rotating black hole surrounded by an accretion disc of debris. Again, how we launch luminous but highly collimated jets during the collapse is uncertain, but the less prominent afterglow would be explained by the lack of material in the immediate environment; both objects having been created in supernova explosions that will have already evacuated a neat bubble within the local vicinity.

## Why are GRBs important?

GRBs are studied not just because they are the most spectacular events. It’s expected that once we have a better handle on their formation mechanisms, we’ll know more about how matter behaves under extreme conditions; how black holes are formed, and how they launch jets, and the effect that such objects can have on the surrounding interstellar medium. Once we have a better understanding of nearer GRBs, the fact that they can be seen at all redshifts means that we have the possibility of investigating the properties of the first generations of star formation in the very earliest galaxies.

# magnetars

The most extreme explosions – even more extreme than the GRBs, although not unrelated – are from a sub-class of neutron stars known as *magnetars,* which are associated with gamma-ray sources known as *soft gamma-ray repeaters.* These sources which give off large bursts of gamma-rays and X-rays at irregular intervals. While all neutron stars have incredibly strong magnetic fields, due to the way the magnetic field of the progenitor becomes more concentrated as it shrinks, magnetars possess magnetic fields that are a hundred to a thousand times more powerful than a typical neutron star; they are the most magnetic objects known in the Universe. They presumably form in the same way as ordinary neutron stars, but perhaps some combination of physical properties in the original massive star (such as its temperature, magnetic field strength and rotational rate) conspire to concentrate the magnetic field more than usual. Such strong magnetic fields can easily accelerate particles to high enough energies to produce the X-ray and gamma-ray emission seen. Current ideas focus on the suggestion is that outbursts are triggered by starquakes on the surface of the neutron star. When these happen, a lot of magnetic energy is released to power the exceptionally strong GRBs. Only three of these extreme outbursts have been observed, in 1979, 1998 and 2004.

### SGR 1900+14

The known gamma-ray repeater SGR 1900+14 exploded in August 1998 to create a spectacular GRB. Despite the source lying 20,000 light-years away, the outburst was so intense that it affected Earth’s atmosphere, ionising the atoms in the night-time ionosphere to levels comparable to the normal daytime level. The *RXTE* X-ray satellite, received its strongest signal from this burst, even though it was looking at a different part of the sky, and should normally have been shielded from the radiation. The signal was so strong that it saturated detectors on some instruments, and triggered automatic safety mode switches on others.

### 1806-20,

Another gamma-ray repeater known as SGR 1806-20 blasted Earth in December 2004, the largest GRB yet on record, again repeatedly rattling the Earth’s ionosphere. The magnetar gave off more energy in one-tenth of a second than our sun has released in 100,000 years, and the flash was so bright that gamma-rays were even detected as reflected off the Moon!

# Future prospects for time domain astronomy

Transient and variable sources are detected in all wavebands, and our ability to detect and respond to them as they happen is improving with new and planned observational facilities to discover and analyse them.

## radio

Observations at radio wavelengths can be carried out from ground-based telescopes, relatively unaffected by intervening gas and dust (or weather…). New generations of radio telescopes are more sensitive to fainter signals, and yield much higher spatial resolution than previously available. *LOFAR*, the *Low-Frequency Array for radio astronomy* is an array of radio telescopes using 25,000 small antennae concentrated in 48 larger stations distributed across Europe. It started collecting data in 2012, and will be instrumental in monitoring for radio transients, as it is capable of mapping 60% of the entire sky in one night. Similarly, the *Square Kilometre Array* is expected to become fully operational in the 2020’s, at which point it will be world’s largest telescope, and sensitive to all kinds of radio transient events.

## X-rays

Modern X-ray detectors constantly scan the sky searching for new transients. For example, *MAXI* (*Monitor of All-sky X-ray Image*) is a Japanese X-ray survey instrument operating from on board the *International Space Station.* It carries out a survey of the full sky every 96 minutes precisely to search for X-ray transients and to monitor their behaviour as they go into outburst by enabling rapid follow-up with other X-ray satellites.

## gamma-rays

The *Swift* satellite was launched in 2004, designed specifically with the aim of characterising the properties of GRBs, and it is still operating successfully. The instruments on board detect the initial burst, and trigger an automatic X-ray telescope follow-up observation in order to refine the positional accuracy; thus enabling ground-based follow-up within a minute of the outburst being detected. As of October 2013, *Swift* had detected more than 800 GRBs. The most recent Gamma-ray telescope is the *Fermi* space telescope, launched in 2008. It has a Large Area Telescope (LAT) and a Gamma-ray Burst Monitor. By scanning around the entire sky every 3 hours, it builds up an increasingly detailed picture of the gamma-ray sky, mapping out the steadier sources of gamma-ray emission (such as accreting supermassive black holes in active galaxies), as well discovering thousands of transient events.

## optical

The recently-launched ESA *Gaia* satellite is in the process of repeatedly surveying the whole sky over a period of five years. Part of its mission is to automatically detect transients, and then provide immediate alerts to the astronomical community to facilitate ground-based follow-up. But looking even further into the future, there is a complete game-changer on the horizon, in the form of the *Large Synoptic Survey Telescope* (*LSST*). This will be a ground-based survey telescope expected to be operational at the beginning of the next decade. Not only will it be sufficiently sensitive to detect faint objects in short exposures, but its detector will be the largest digital camera in history, with an exceptionally wide field of view. It will image a patch of the sky 7 Moon widths on a side at a time – one image from the *LSST* will be equivalent to 3000 images from the Hubble Space Telescope! The *LSST* will take a 15-second image every 20 seconds, and map all the sky available to it twice every week; the camera is expected to take over 200,000 pictures each year. In its first week of operation it should find 400 supernovae, rising to 4000 supernovae within 4 months, let alone many other transient sources we cannot even begin to anticipate. Time domain astronomy really is the astronomy of the future!

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