Explosive transients:

Meeting report **Astronomers are finding common ground between gamma-ray bursters, supernovae and novae, thanks to more diverse and better data, report David Bersier and Michael Bode.**

Explosive transients have long been thought of as the one-hit wonders of the universe, spectacular and unpredictable, yet apart from the run-of-the-mill activity of the stars. But modern instrumental techniques and the sheer wealth of data mean that such time-dependent behaviour can be better examined and understood; novae, supernovae and gamma-ray bursters now represent a significant research field. This one-day conference in Liverpool, organized by David Bersier, Mike Bode, Shiho Kobayashi, Carole Mundell and Iain Steele of Liverpool John Moores University (LJMU), and sponsored by the RAS and LJMU, brought together those interested in all aspects of the field to discuss how transient behaviour illuminates astrophysical processes.

Paul Murdin (Institute of Astronomy, Cambridge, and Visiting Professor at LJMU), introduced the meeting, recalling the announcement of the discovery of gamma-ray bursters – some time after the actual discovery, which was made serendipitously with defence technology. Once the details were out in the open, further discoveries followed, thanks to dedicated and not-at-all secret instruments. Time-dependent behaviour of all types has now become a significant element of astrophysical enquiry.

Peter Garnavich (Notre Dame University) spoke about finding and characterizing supernovae and other transients with the Sloan Digital Sky Survey – and the potential to continue to do so, on a larger scale, with the Large Synoptic Sky Survey Telescope. Supernovae have become central to the understanding of the universe over the past 10 years, thanks largely to the use of Type Ia supernovae as distance indicators. Better sky coverage gave more data on nearby supernovae, and the cosmological focus has greatly increased the numbers at high redshifts. The result is a gap in the middle, the "redshift desert", where very few supernovae are found ($0.1<z<0.3$). The SDSS-II Supernova Survey was designed to fill that gap.

The survey used an efficient technique covering 300 square degrees of sky every two nights. Simultaneous detection of the u, g, r, i and z wavebands made measurement of supernova light curves very efficient; the short exposures allowed dense sampling. In the first year, software detected around 100 000 possible transients, which were scanned by eye to reduce to 11 000 possibilities and resulted in the discovery of 130 Type Ia supernovae. The next year of operations produced 193 Type Ia supernovae and the third year, 175. The survey also found three cataclysmic variables, a gravitational lens, and a handful of unusual transients including a rare helium dwarf nova.

This great dataset allowed Garnavich and colleagues to fill out the Hubble diagram and fit a lot more light curves for cosmology. They also correlated the width of the light curve with peak luminosity and examined the colour variation, comparing low- to high-redshift supernovae. Assuming that all colour variation was based on dust extinction, they found a statistically significant difference between low- and high-redshift supernovae. The big uncertainty was the colour pattern of supernovae – data from the LSST should reduce this. The survey also revealed a large range of rise times. The physics of the rise and fall may help with fitting light curves (Hayden *et al.* 2010).

The LSST offers far more scope for supernova observations. It will observe 20 000 square degrees down to a magnitude of 24.5, with all data in the public domain. It will have a $3.5°\times3.5°$ field of view, with a 2 second readout at 0.2 arcseconds per pixel. It is expected to find 10 000 supernovae per year with good light curves, and 300 000 per year in the general survey. Just as in SDSS-II, we can expect to get our share of oddballs, too – supernovae impostors, rare novae and stars that just disappear.

Re-reading the records

There are records of novae stretching back over 2000 years, and a vast database of nova observations from the 19th century onwards. **Brian Warner** (University of Capetown) described the recent burst of interest in optical observations of novae over the past three years as producing "a tsunami of papers". The origin of this enthusiasm is in part due to the opportunity to track pre-nova light curves, but the key to success has been returning to the original photographic plates to measure the pre-eruption magnitudes. Some published papers included errors and misidentifications; removing spurious results has produced a much more valuable dataset – and much that remains to be explained.

Detail in the data

Collazzi *et al.* (2010) found that only two novae out of 22 studied showed significant pre-eruption rises in brightness (V533 Her and V1500 Cyg). By contrast, the recurrent nova T CrB showed a pre-eruption dip. These events challenge theorists. For 30 classical novae plus 19 eruptions from 6 recurrent novae, they found that the average change in magnitude from before the eruption to long after the eruption is zero. However, they also found five novae (V723 Cas, V1500 Cyg, V1974 Cyg, V4633 Sgr, and RW UMi) with significantly large changes, where the post-eruption quiescent brightness is more than 10 times the pre-eruption level. These large post-eruption brightenings pose another challenge to theorists.

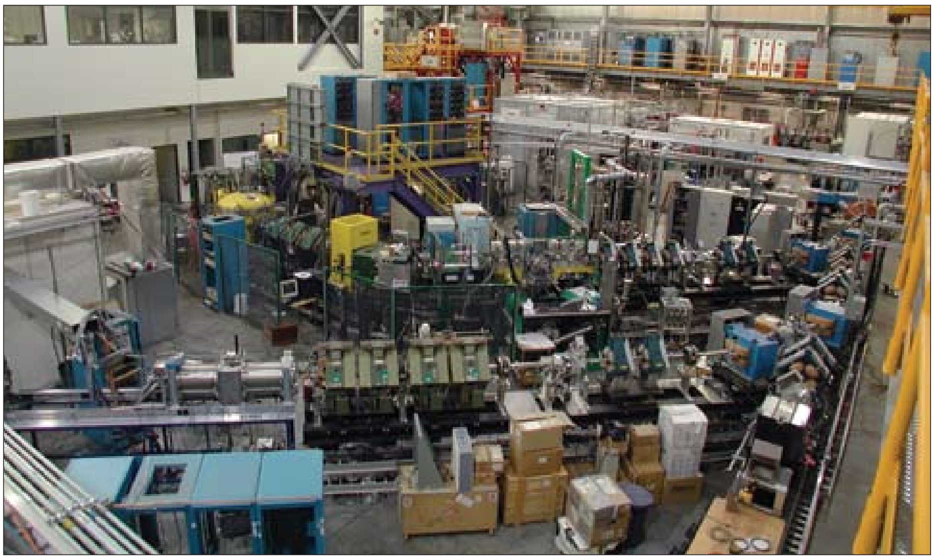
Schaefer and Collazzi (2009) showed that eight novae (V723 Cas, V1500 Cyg, V1974 Cyg, GQ Mus, CP Pup, T Pyx, V4633 Sgr and RW UMi) are significantly distinct from other novae. This group shares a suite of uncommon properties, characterized by post-eruption magnitudes much brighter than before eruption, short orbital periods, long-lasting super-soft emission following the eruption, a highly magnetized white dwarf (WD), and secular declines during the post-eruption quiescence. This may be explained if most novae do not accrete enough of their companion stars for continuous hydrogen burning, but some achieve this if the companion star is nearby (with short orbital period) and a magnetic field channels the matter onto a small area on the WD so as to produce a locally high accretion rate.

The past few years have also seen the emergence of a class of "luminous red novae" lying somewhere between novae and supernovae in absolute magnitude. Such objects have included nova M85 OT2006-1, which has a luminosity of five million times that of the Sun. More recently, Shri Kulkarni and collaborators (Kasliwal *et al.* 2010a) discovered the third example of these enigmatic objects: PTF10fqs, a luminous red nova in the spiral galaxy M99. These luminous red novae are of unknown origin, but have been speculated to arise from mergers or nova outbursts on very low mass white dwarfs.

At the other end of the luminosity scale, M M Kasliwal *et al.* (2010b) have recently announced the discovery with the Palomar 60 inch telescope of several sub-luminous, fast novae. These novae may arise on hot, massive white dwarfs, but again their origins and explosions are enigmatic.

Brad Schaefer and collaborators have now produced detailed light curves of 93 novae (Strope *et*

a time-variable sky



1: Inside the laboratory at TRIUMF in Vancouver, Canada, where nuclear reactions are studied to improve our understanding of the processes powering stellar explosions.

al. 2010), resulting in a classification system with seven main types. Schaefer *et al.* (2010) have also conducted a great deal of work on recurrent novae of recent times, including the prediction for the first time of a nova outburst – that of the recurrent nova U Sco in January 2010.

One other startling finding of recent times is that by Bob Williams and collaborators of transient heavy element absorption systems around maximum light in a majority of novae studied (Williams *et al.* 2008). Most of these systems are accelerated outward, and they all progressively weaken and disappear over timescales of weeks. The gas causing the absorption systems must be circumbinary and its origin is most likely to be mass ejection from the secondary star. Calculations of the amount of gas involved suggest around 10^{-5} solar masses at least. The absorbing gas exists before the outburst and Bob Williams and Elena Mason (Williams and Mason 2010) suggest it originates in the L3 point of the binary system and that the outburst ejecta then run into this material. In a separate paper, they suggest that the broadening of spectral lines suggests the quadratic Zeeman effect is in operation, which implies the presence of extremely strong magnetic fields, at the mega-Gauss level. These must originate in the white dwarf.

Which stars explode?

Sumner Starrfield (Arizona State University) spoke about the types of stars that give rise to these remarkable explosions. He noted that what types of stars erupt to form Type Ia supernovae remains uncertain, speculating that they may arise from close binary systems. A very interesting object in this context is the nova V445 Pup, which has no detectable hydrogen in its ejecta (described in detail in the poster by Patrick Woudt at this meeting).

Classical and recurrent novae arise from the white dwarf in a close binary pair. In the classical nova explosion the ejecta comprise about 10^{-4} of a solar mass enriched in elements such as helium, lithium, carbon, oxygen, nitrogen, neon and aluminium. Starrfield highlighted problems with the theory, notably the origin of the tremendous amount of material ejected in these novae that is not hydrogen or helium. It must have come from the white dwarf, but how does that mixing happen? Chemical diffusion would be too slow, so is it shear mixing in the accretion process, or convective "undershooting" during the thermonuclear runaway itself?

The compositions of the binary components are important in calculations of where and how the explosion takes place. The time taken to get to a runaway reaction does not depend just on the white dwarf – there is a range of parameters involved, including the accretion rate. There are also still uncertainties in the fundamental nuclear reaction rates. Developments so far show ever shorter times to explosion as knowledge of the nuclear physics improves.

What drives the explosion?

Work on some of those nuclear reactions was described by **Alison Laird** (University of York), who focused on the nuclear reactions powering stellar explosions. She showed that the rates for key reactions make a difference to the outcome of models, for example, in fitting light curves to X-ray bursts, where the rate of two key reactions involving argon and sulphur influence both the timing of the outburst and its peak luminosity. Nuclear physics has an impact on what is seen, as well as on the energy and decay products.

Part of the problem is to find the most important reactions among the many possibilities. Some 300 stable isotopes are known, and around 3000 unstable ones, but there may be around 7000 in total. It is impossible to study all of them, so the first stage is to determine which species and reactions are important, in terms of the conditions under which they take place, the reaction rates and their impacts on stellar evolution. Explosive nucleosynthesis involves high-pressure and high-temperature reactions, taking place over short timescales, with radioactive species playing a role. Most experiments on quiescent burning are undertaken at very low energies and can involve measurements stretching over a year. Explosive nucleosynthesis is more accessible: a study can be complete in days or weeks.

Observations typically give the final state of the system, for example the final abundances of key isotopes such as ^{18}F. The processes that produce and destroy this isotope are well understood, but the destruction processes have large uncertainties. Measurement in the lab is necessary in order to get the reaction rates and thence the final fluorine abundance. Laird and colleagues used the Canadian TRIUMF Isotope Separator and Accelerator (ISAC) (figure 1) beams to send an ^{18}F beam to an H target, measuring the probability of the reaction at different energies.

Their results have shown that X-ray bursts are associated with breakouts from the hot CNO cycle, which is slowed by bottlenecks at β-decay points. The rp-process (rapid proton capture process) produces much more energy and there are a series of breakouts as temperature increases, which change the reaction pathway and increase the energy output. However, none of these breakouts have been measured at close to realistic temperatures and they involve hard-to-make chemicals. As a result, the rates of the reactions, and whether or not they provide enough energy to power the X-ray bursts we see, remain unknown.

For supernovae, the key information is whether the r-process (rapid neutron capture process) takes place and what the nuclear input is, in terms of masses, isotopes and Q-values. The r-process is responsible for the production

Observing transients – now and in the future

Ian Steele (LJMU) highlighted the means for observing transients and following up new time-variable objects – in effect, providing the glue that joins together disparate observations.

In terms of providing targets, currently, there are the Palomar Transient Factory (PTF), PanSTARRS and, shortly, the LSST on the ground, together with Swift and Fermi in space. PTF and PanSTARRS are looking for transients, while LSST will open up a whole new era with its vast data collection rate. Swift has a trigger system to catch gamma-ray bursters, with gamma-ray, X-ray and UV coverage. Fermi is also a burst monitor, and generates a lot of data with an error box of around 1°.

For the future, Gaia will generate a lot of transient observations and will send out science alerts. It will return to fields about 80 times over the five-year mission and will generate alerts over 3–24 hours based on photometric variation. Gaia has a large focal plane and so will pick up supernovae, gamma-ray bursters and microlensing events as well as all types of variable stars.

At high energies, VERITAS, HESS and the future CTA will all find flares. Gravitational wave events will be picked up by enhanced ground-based GW detectors LIGO, GEO and VIRGO, which when working simultaneously will offer a very wide baseline and could locate events to 6°. If these instruments are able to locate sources of gravitational waves, there's an opportunity to locate the optical counterparts and maybe determine, for example, the burst signature of merging neutron stars. Alerts should give between half and one hour to find the optical counterpart.

The ICECUBE neutrino detectors in Antarctica pick up transient astronomical events from neutrino secondary radiation, with an error box of 1–2°. They look back through the Earth so the Antarctica instrument detects northern hemisphere events. There will also be the potential to discover transient events at other wavelengths, through LOFAR for example.

Follow-up requiring telescopes can be done robotically, but despite there being many such instruments, few of them are large. The Liverpool Telescope (figure 2) is particularly suitable. Transients such as gamma-ray bursts, gravitational microlensing events and events linked to exoplanets demand a wide range of instruments.

The speed of follow-up also requires thought. Traditionally, International Astronomical Union circulars have been used to announce discoveries, but it is a slow and bureaucratic process. The Astronomer's Telegram website (http://www.astronomerstelegram.org) offers circulars and reports by email, and requests a description and coordinates, etc. The limiting factor for speedy follow-up is that the reports are read by a human being. We need to get computer reading established if we are to scale up to the levels of discovery indicated for new instruments. There are also different systems in place for different objects, such as Supernova News, an early warning system involving automated email, the GCN for gamma-ray burst notices, which are computer-readable and include follow-up observers reports, some computer-readable and some not. The standard adopted by many observers is the VO Event, a reporting system that is readable by both computers and people, and details who, what, when, where and why, giving a reference and citations, with embedded pictures and other

of 50–70% of iron and heavier elements, but there has to be seed material for the r-process to build on. The triple-α process could do it, although it is slow, but a reaction route via ^{8}Li may have feasible reaction rates.

Laird stressed that there is a significant amount of work in this field now being undertaken in the UK. Nuclear physicists are investigating approachable aspects of explosive transients (Murphy *et al.* 2009, Beer *et al.* 2008). For novae, they are unravelling the hot CNO cycle, linking the production of ^{18}F and ^{26}Al with observations. For X-ray bursts, they study breakouts from the CNO cycle with waiting points where the rp-process is important. For supernovae, a target is the origin of seed material for the production of the high-mass elements.

Massimo della Valle (INAF Napoli) returned to direct astronomical data with a review of the three ages of supernovae observations: heroic times from 1930–1970, the golden age from 1970–1997, and modern times after 1998.

Heroic observers such as Baade, Zwicky and Minkowski made their observations on photographic plates and used an empirical classification into Types I and II, working from limited photometry and light curves. Type I had no hydrogen and very deep Si II features; they all had essentially the same light curve shape. Type II, on the other hand, were more individually varied and their spectra were dominated by hydrogen lines. In 1964 the story moved on when Bertola observed a supernova with a light curve in the typical shape of a Type I but a spectrum similar to Type II.

The golden age

In the golden age, an incredible number of bright supernovae were detected, with 4 m class telescopes and CCDs bringing higher quality spectra and follow-up observations to fainter magnitudes. The better spectra led to new classes of supernovae: Ib, Ic, IIb and IIc. This implies a certain amount of non-homogeneity, but the details also allowed observers to understand more about the process. For example, Bertola's peculiar object was a Type Ib supernova and in the mid-1980s it was identified as a star that, by the time it came to collapse, had lost its hydrogen envelope. Some of these unusual types of supernovae, such as 1987k with its disappearing hydrogen lines, are transition types that start as Type II but morph into Ib.

Modern times brought systematic searches with 4–10 m optical telescopes and the Hubble Space Telescope. Together with the use of small and robotic telescopes working in synergy, this has brought out the supernova–GRB connection. Large-area supernova surveys have produced lots more examples each year, revealing new types of explosive transients such as luminous blue variables, rare types of SNe and core-collapse explosions in unusual environments.

The GRB–supernova connection is highlighted by supernova 1998bw which seems to be associated with a GRB, with incredible energy output and a lack of H, He and Si II. It has a broad-lined Type Ic supernova spectrum with a very large luminosity and emits about ten times the energy of a typical supernova. Around nine of these supernovae/GRBs have been found, six of which are well studied because they are close by, and three at high redshift. GRBs are rare compared to supernova explosions, so very few of them – only something less than between 0.4 and 3% of Type Ibc supernovae – can become GRBs. Why do these very few Type Ic supernovae become GRBs, and most don't? The answer seems to lie in the special conditions required: a really massive star (>30–40 solar masses) that has lost most of its hydrogen and helium before collapse, and must be in a low-metallicity environment.

Della Valle went on to discuss the questions posed by unusual transients such as subluminous core-collapse supernovae, the so-called dark supernovae, and objects that fit between novae and supernovae, such as red faint supernovae, and SN2008ha. There are also ultra-bright supernovae, such as the hydrogen-rich 2006gy, which reached an absolute magnitude of –22 and showed an unusually broad light curve. Are such objects supernovae? And what about a supernova whose predecessor star looked like a luminous blue variable? Was it a pulsing LBV that exploded, or an outburst of a Wolf–Rayet star? It was certainly something that had never been observed before.

Della Valle set out a continuum from Type II

2: The 2m robotic Liverpool Telescope in its fully opening enclosure, with other telescopes of the Observatorio del Roque de los Muchachos in the background. (R J Smith 2005)

detail that make it a good way to pick out interesting events. In the UK we have eSTAR, based at Exeter (http://www.estar.co.uk).

Even higher energies?

Jim Hinton (University of Leicester) spoke about the potential of the Cerenkov Telescope Array to pick out transient events. The CTA will pick out flares in blazars – transients that go through several orders of magnitude variability in minutes – although they are slow compared to GRBs. But it is their high energy and transient nature that make them good targets for the CTA.

At greater than X-ray energies, existing ground-based instruments such as HESS, Veritas and Magic have the sensitivity to detect astronomical phenomena – and there are things to see. One can pick out cosmic rays from supernovae, pulsars, starbursts and even carry out galactic surveys. Information is also obtained on the IR background, gamma-rays, dark matter and annihilation signatures, for example. GRBs were a big part of the case made for building CTA. High-energy astrophysics also has applications in fundamental physics and has been a very successful field over the past five years. CTA as the next-generation instrument will be a global facility. It will be an array of Cerenkov telescopes and, while current facilities have two, three or four telescopes, CTA will have 100. It will be an order of magnitude more sensitive than current ground-based instruments, with a wider energy range (overlapping that of Fermi, but far more sensitive at equivalent energies), better angular resolution, and will be a major astronomical observatory for Europe in the next few decades.

The data coming in from Fermi suggest that there are photons at energies greater than 30 GeV, with some very large redshifts. There could certainly be 100 GeV photons. And, if the synchrotron radiation is interpreted correctly, the second component has the potential to be a powerful diagnostic of the conditions inside bursts. Fermi is already seeing a systematically delayed high-energy component, therefore late afterglows will be detectable. The design of the telescope is also flexible enough to be able to pick out optical afterglows. The fast cameras used to detect Cerenkov radiation flashes could also be used to find optical transients on a very short timescale – and it can be done effectively for free alongside the gamma-ray work.

In short, the CTA will be a powerful tool for detecting transient non-thermal phenomena. It won't be cheap, but the scale of the consortium makes it manageable. EU funding has been awarded for the engineering preparatory stage – and some of that €5.2m has come to the UK. The first telescope should be available in 2013, and CTA will take five years to build. But the science starts immediately; data will be taken from the start and building up to the full working capacity.

supernovae, through Types IIb, Ib and Ic, to GRB supernovae, with increasing mass on the main sequence. The mass of hydrogen involved decreases, as does their frequency. Type II supernovae, at more than 8 solar masses, are most frequent, while the GRB types originate in stars with around 40 solar masses but are much rarer. The new subtypes coming out of this research raise questions about our understanding of the processes involved, for example the alternative sources of energy to power ultra-bright supernovae, which demonstrate 10 times the energy in standard core-collapse supernovae.

Stacey Habergham (LJMU) then presented results of an optical study looking at core-collapse supernovae in a range of nearby galaxies and different environments in order to constrain their progenitors. 140 local spiral galaxies produced 178 core-collapse supernovae, 110 Type II supernovae and 68 Type Ibc supernovae. The distribution of these supernovae within galaxies showed a deficit of Type II supernovae, and an excess of Type Ibc in the central regions, interpreted as an increase in metallicity from Type II to Type Ib to Ic. The survey also showed that many of the supernovae came from disturbed galaxies with signs of interactions such as tidal tails, double nuclei or strong asymmetries. In the central regions of these disturbed galaxies, supernovae are preferentially Type Ibc rather than Type II, to the extent that within the central 10% of these galaxies, only Type Ibc occur and no Type II has been found. Overall these supernova distributions suggest a "top-heavy" initial mass function with a slope of close to 1 (Habergham *et al.* 2010). The strong central concentration may be a result of a nuclear starburst, although it could be that this central excess of Type Ibc supernovae is an artefact of survey incompleteness in the central regions, from the greater extinction among central region stars as a whole.

Zach Cano (LJMU) continued to explore the GRB–supernovae connection, looking at multi-wavelength observations. Long-duration GRBs appear to have a link to the core collapse of massive stars; their light curves and spectra include broadened lines suggesting speeds of around 10% the speed of light, together with colour changes and a bump in the optical/infrared region. Three case studies were described to illustrate these unusual objects. GRB060729, studied using Swift data, showed a clear bump 26 days after the burst, but the U band showed no or very little light from an associated supernova. The (longer wavelength) R band did appear to show supernova light. Working with the Swift assumption that the rate of decay is constant across all wavelengths, they were able to remove the GRB flux from the data. What is left looks like a supernova. The same process applied to the data from GRB090618, the second case study, also produces the characteristic supernova curve, complete with bump, but in this case there is also a distinct colour change, from an early blue GRB to a later red supernova. In short, Cano presented clear photometric evidence of supernovae associated with GRBs.

GRBs

Jonathan Granot (University of Hertfordshire) opened the GRB session with a whirlwind tour of what we know, do not know and would like to know about GRBs. These brief, intense and totally unpredictable flashes of high-energy gamma rays are the instantaneously most luminous objects in the universe. They are thought to be produced during the core collapse of a massive star or the merger of two compact objects (neutron stars or black holes) and provide direct access to regions of extreme physics (Lorentz factors $\Gamma > 100$), strong gravity and potentially large magnetic fields, as well as acting as important probes of the high-redshift universe. The technical challenge of observing completely unpredictable, time-variable and rapidly fading electromagnetic signals from space has driven development of advanced technological capabilities in satellite- and ground-based observatories over the last decade.

Recent progress in the study of GRBs comes mainly from the discovery of long-wavelength counterparts (afterglows), and their rapid, multi-wavelength follow-up. Afterglow observations have established that ultra-relativistic flows are associated with GRBs (Granot 2008). A blast wave caused by the interaction of the ejecta with the ambient medium provides a natural explanation for afterglow observations. Several wellmonitored afterglow light curves clearly indicate supernovae association with long GRBs (long defined as gamma-ray duration > 2 s). Their host galaxy type, star formation rates and location within the hosts also suggest massive stars as long-GRB progenitors. Some short GRBs arise in host galaxies with very low star-formation rates. This is consistent with the leading theoretical candidates for short-burst progenitors – compact stellar mergers – but direct observational confirmation is still required. Future detection of gravitational waves and neutrinos provide definitive tests of progenitor models.

Open questions

The origin of the high-energy gamma rays of GRBs is also an open question (Granot *et al.* 2009). Although a widely accepted mechanism for producing the prompt gamma rays is an internal dissipation in a relativistic flow, the dissipation and emission mechanisms are still highly uncertain. More fundamentally, a long-standing problem is how to accelerate a GRB outflow to ultra-relativistic velocities. Recent Fermi satellite observations show that some events require a Lorenz factor $\Gamma \sim 1000$ to avoid a high-energy cut-off from intrinsic pair production. The jet acceleration mechanism could be magnetic or thermal.

The Swift satellite has provided a range of puzzling observations in recent years: the plateau phase and chromatic breaks in early afterglow light curves cannot be explained in the standard model, and calls for further observational and theoretical investigations. Particle acceleration in collisionless shocks is believed to be responsible for the production of the non-thermal GRB emission. However, a theory of collisionless shocks based on first principles does not exist yet. More theoretical investigation is needed, and GRB observations could provide an ideal opportunity for diagnosing the physics of relativistic collisionless shocks in general.

Peter Curran (CEA, Saclay) discussed the physics of Fermi acceleration of electrons in astrophysical plasmas. This mechanism is thought to be important for accelerating electrons to relativistic speeds in shock fronts in AGN and GRB jets, X-ray binaries, supernovae and solar flares, and the resulting synchrotron radiation provides an important diagnostic tool to probe the energy distribution, p, of the population of radiating electrons (Starling *et al.* 2008). Curran examined whether there is a single, universal value of p, a distribution and/or variation across sources and source types. In the standard fireball model, a GRB afterglow is produced when the expanding relativistic blast-wave collides with and is decelerated by the circumburst medium; forward and reverse shocks are produced, with the forward shock emitting broad-band synchrotron radiation that fades with time. The spectral energy distribution at a given time has a characteristic shape that is determined by the location of the synchrotron injection and cooling frequencies and p. By self-consistently modelling the afterglow behaviour, the value of p can be derived and is found to lie in the range 2–2.4 for most bursts, consistent with theoretical predictions, although larger values (~3–4) are inferred in some cases. Curran showed that modelling of X-ray data from Swift for approximately 300 bursts suggests a Gaussian distribution of p values with a mean $p \sim 2.4$ and a standard deviation $\sigma = 0.6$, with the cooling frequency already lying below the X-ray band at the time of observation in 94% of GRBs (Curran *et al.* 2010).

Baryonic or magnetic jets?

Shiho Koyabashi (LJMU) discussed magnetization of GRB outflows. GRBs are produced by shocks in ultra-fast outflows of material moving at speeds close to that of light when a new black hole is formed. The mechanism for accelerating the ejected material to these extreme speeds in GRBs and other cosmological jets, however, is a long-standing and important unsolved problem in modern astrophysics. There are two competing models for relativistic GRB jets: baryonic jets and Poynting-flux – magnetically dominated – jets. The magnetic jet models are now attracting more attention from researchers (Zhang and Yan 2010). An attractive aspect of the magnetic models is that intrinsic magnetic fields may provide a powerful mechanism for collimating and accelerating the relativistic jet. When the outflow impacts on the ambient medium to produce shocks, a transient shock called the reverse shock is generated inside the outflow itself. The short-lived optical flash radiated from reverse shocks is a key element when magnetic properties are discussed (Mundell *et al.* 2007, Gomboc *et al.* 2008). Koyabashi discussed two methods based on relativistic hydrodynamics and optical flash observations.

Because the jet is believed to radiate photons via the synchrotron process – where electrons radiate energy as they spiral around magnetic field lines in the expanding flow – the emitted radiation is predicted to be highly polarized. The first detection of 10% polarization of an optical afterglow just 160 s after the explosion of GRB 090102 by the Liverpool GRB team (Steele *et al.* 2009) opens the exciting possibility of directly measuring the magnetic properties of GRB flows. A new polarimeter, RINGO2 on the Liverpool Telescope, was recently commissioned to allow detection of a larger number of fainter bursts and, for the first time, measure the temporal evolution of the polarization degree and position angle of early optical afterglows. RINGO2 measurements will open a completely new observational parameter space.

Maurice van Putten (Université d'Orléans) drew the day to a close by unifying the physics of some of the most energetic processes in the universe within a coherent theoretical framework centred on extraction of energy from spinning Kerr black holes via frame dragging and viscous spin down (van Putten 2009). The origin of high-energy (gamma-ray) photons from GRBs (in contrast to current accretion-driven models) and the generation of ultra-high-energy cosmic rays by low-luminosity AGN, such as Seyferts and LINERs (in contrast to powerful BL Lacs) would be explained within this single framework for stellar and supermassive black holes respectively (van Putten and Gupta 2009). In particular, highly collimated relativistic jets, if common to GRBs and AGN, could produce high-energy emission by gravitational spin-orbit coupling along the axis of rotation and low-energy emission from surrounding matter via a torus magnetosphere. Analysis of 600 GRB gamma-ray light curves suggests that viscous spin-down against matter at the innermost stable orbit is occurring and predicts future detections of radio and gravitational wave bursts with a bi-modal distribution of durations similar to that observed for GRB durations. Current and future astronomical facilities optimized for time-domain astronomy will provide exciting tests of these theoretical predictions and, together, will advance our understanding of gravito-magnetic processes in black hole-driven central engines and their role in the transient sky. ●

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Further information

The talks can be found at http://www.astro.ljmu.ac.uk/ras2010/schedule.shtml

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