Gamma-ray bursts, galactic nuclei and cosmic evolution

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This lecture summarises some aspects of gamma-ray bursts, a topic to which Bohdan Paczyński made crucial contributions. It then, more briefly, comments on quasars and active galactic nuclei, where the accretion processes studied by Paczyński and his Polish colleagues play a key role. The lecture concludes with some remarks on cosmology and cosmic evolution.

1 Introduction

It's a pleasure to address the Polish Astronomical Society, which includes so many colleagues and friends whose work I admire, and which produces such an excellent and high-quality journal. It's a special privilege to have been invited to give this special lecture to honour the memory of a great scientist and great personality who we all so much miss.

I first met Bohdan Paczyński in 1971 when he visited the Institute of Astronomy in Cambridge. He was already well known for the 'Paczynski code', which was being used by colleagues of mine like Peter Eggleton who were studying stellar structure and evolution. He showed how much could be done by what now seem very modest resources. And he was unselfish in documenting his code carefully so that others could use it. At that time he already displayed the characteristics that stayed with him for the rest of his all-too-short life: exceptional insight, a reluctance to be overcomplicated, and a commitment to supporting and encouraging others. Of course his Polish colleagues can testify to this far more compellingly than I can.

I'm going to do two things in this talk. First, I'll discuss in some detail gamma ray bursts, a topic I'm specially familiar with, to which Bohdan made pioneering contributions. Then, as a sequel or 'footnote' to Dr Kluzniak's lecture, I'll briefly describe why the accretion processes he addressed are important in the centres of galaxies, and set them in the context of galaxy formation. I conclude with brief comment on the broad scenario of cosmological evolution. (Another of Bohdan's great contributions, of course, was to the topic of microlensing: this also I will ignore, because Dr Udalski has a separate paper on the wonderful results from OGLE.)

But let's start by reminding ourselves of two things. The endpoint of massive stars is violent – leading to Type II supernovae. And the endpoint of interacting binary star systems (one of Bohdan's life-time enthusiasms) can be compact stars, which inexorably spiral together via a combination of drag forces and gravitational radiation. Both these phenomena are believed to be crucial to the understanding of one of the most extreme and baffling objects in the Universe: gamma ray bursts.

2 Gamma ray bursts

Gamma-Ray Bursts (GRBs) were serendipitously discovered in the late 1960s by the Vela satellites which were monitoring the Nuclear Test Ban Treaty between the US and the Soviet Union. It took several years before the discoverers assured themselves that these very intense transients were not sinister, but were natural phenomena from beyond the Solar System (Klebesadel et al., 1973).

They were perplexing – indeed for a time the number of proposed models exceeded the number of detected bursts! (Ruderman, 1975) The models ranged from comet infalls, through stellar cataclysmic events, to events associated with supermassive black holes at the center of galaxies. The gamma-ray telescopes of the time had poor positional accuracy, and transmitted data to Earth only many hours after the trigger. This precluded prompt follow-up in other wavebands. But data gradually accumulated. (It's fitting to recognise, incidentally, that despite the disappointing overall scientific output from the USSR's massive space programme, Mazets and his group (Mazets et al., 1981) made important contributions to GRB studies in the 1970s and 1980s.)

Most theorists at that time suspected that the bursts originated within our Galaxy – for instance via some kind of 'burping' in neutron star magnetospheres. But Bohdan Paczyński was the most vocal and effective advocate of a 'cosmological' view. He proposed this view (Paczynski, 1986) at a time when the issue of 'galactic versus cosmological; was, in my view, genuinely an open one. But by the end of the 1990s, it was clear that Bohdan was right. The Compton Gamma Ray Observatory (CGRO) obtained, over a decade, the positions of $\sim$ 3000 GRBs. They were uniformly distributed over the sky (Meegan et al., 1992). This plainly supported Bohdan's view, though some argued that it was still consistent with a galactic origin if the bursts were far out in the galactic halo. I had the privilege of chairing a debate on the distance of gamma ray bursts, where Bohdan was opposed by Don Lamb of Chicago University. This event took place in the same location, in Washington, as the famous 1924 debate between Curtis and Shapley on the nature of the 'nebulae'.

The case for cosmological distances was not, however, completely settled until 1997, when the Beppo-SAX satellite localized the X-ray afterglow of a burst precisely enough to enable a host galaxy to be identified – and this galaxy had a high redshift (van Paradijs et al., 1997).

The gamma-ray light-curves display great variety and complexity. Nonetheless it turned out that that GRBs can be classified into two duration classes, short and long, with a dividing line at ~ 2 s. The power-law time-decay of the light curve was also observed, in a number of cases, to exhibit a steepening after $\sim 0.5 - 1$ day, suggesting (for reasons explained below) that the emission was collimated into a jet, of typical opening half-angle $\sim 5^\circ$. This eased the energy requirements. Even so, at cosmological distances the implied time-integrated energy output is $\sim 10^{50} - 10^{51}$ erg. This is more energy than our Sun emits over its ten billion year lifetime, and about as much as the entire Milky Way emits over a hundred years – and is mainly concentrated into gamma rays.

The short duration (tens of seconds) and fast variability $\gtrsim 10^{-3}$ s of the γ-ray emission, indicates that the energy comes from the gravitational potential of a compact stellar-mass source. The consensus view is that the short bursts are triggered by mergers of binary neutron stars or black hole-neutron star binaries. The long bursts, however, are likely to be associated with the core collapse of massive stars and the rapid accretion into the resulting black hole. Initially it was thought that this would result in a GRB and a failed supernova, but later observations showed an unusually luminous core collapse supernova of type Ic associated with some GRBs; these supernovae have since been referred to as hypernovae. The predicted rate of occurrence of binary mergers and of hypernovae is sufficient to account for the number of bursts observed, even if the γ-rays are beamed to the extent that only one event in 100-1000 is observed. (We expect less than one observable burst per million years from a typical galaxy, but the detection rate can nonetheless be of order one per day because they are so powerful that they can be detected out to the Hubble radius).

These objects are stupendously bright. In a normal supernova, energy suddenly released in the core percolates out to the surface in a few weeks – giving the characteristic light curve. But in a gamma burst this energy forces its way out along jets – and if the jet points towards us we're briefly zapped by a beam that outshines even the brightest quasar by a factor of a thousand.

There is still no agreed detailed model. However, some firm conclusions can be drawn. For instance, the fact that photons of over 100 MeV are detected provides compelling evidence for ultra-relativistic expansion. To avoid degradation of the spectrum via photon-photon interactions these photons must, in the comoving frame, be shifted below the pair-production threshold $\mathrm{mc}^2 = 0.511$ MeV. The outward flow must therefore have a bulk Lorentz factor Γ of at least 100.

Since each baryon in the outflow must be given an energy exceeding 100 times its rest mass, a key requirement of the central engine is that it must concentrate a lot of its energy into a very small fraction of its total mass. This favours models where magnetic fields and Poynting flux are important. A simple way to achieve a high efficiency and a nonthermal spectrum is by reconverting the kinetic energy of the flow into random energy via shocks, after the flow has become optically thin. This is a feature of most models. There may also be a thermal component, coming from a 'photosphere' in the jet, which would typically, taking the Doppler shift into account, be observed at around 100 keV energies below the electron-positron formation threshold, thus diminishing the pair production threshold.

Incidentally, the evidence for a narrow jet is based on the observed steepening of the light curve of the afterglow after around a day, which is attributed to the transition between the early expansion, when the relativistic beaming angle (due to aberration is narrower than the opening half-angle) and the late expansion, when the relativistic beaming angle as become wider than the jet, $\Gamma^{-1} \geq \theta$ leading to a drop in the effective flux.

The launch of the Swift satellite in 2004 resulted in a number of interesting new discoveries. One instrument on the spacecraft detects the bursts and locates them to about 2 arcminutes accuracy. This position is then used to automatically slew the spacecraft, typically within less than a minute, re-pointing the high angular resolution X-ray and UV instruments towards the event. The positions are also rapidly sent to Earth so that ground telescopes can follow the afterglows. This has led to the discovery of bursts with very high redshifts: GRB090423 at a spectroscopically confirmed redshift z = 8.2 (Tanvir et al., 2009), and GRB090429B, at a photometric redshift $z \sim 9.4$ (Cucchiara et al., 2011). They can in principle be unique probes of the intervening intergalactic medium at epochs when the Universe was as low as $1/20^{th}$ of its present age. Also, since the long bursts are the endpoints of the lives of massive stars, their rate gives information about the star formation rate at early eras. Finding even one at a redshift of as much as 15 would offer crucial clues to how the cosmic dark age ended.

Swift succeeded in localizing the host galaxies of a number of short bursts. Unlike the long ones, these are not restricted to locations with a high star-formation rate. Furthermore, low-redshift short bursts show no evidence for simultaneous supernovae, as do many long bursts. These results reinforce the interpretation that short bursts arise from an old population of stars, probably due to mergers of compact binaries such as double neutron star or neutron star-black holes. But the physics of such objects – involving dense matter, strong magnetic fields, neutrino cooling, and so forth – is so complicated that it will be a long time before we understand the full and varied phenomenology.

It will be a lot easier to understand the physics of the actual radiation emission when we have data spanning a wider energy spectrum. So the Fermi satellite, launched in 2008, was an important advance. It carries two instruments: the Gamma-ray Burst Monitor (GBM) and the Large Area Telescope (LAT). The GBM measures the spectra in the energy range from 8 keV to 40 MeV, determining their position to $\sim 5^\circ$ accuracy. The LAT measures the spectra in the energy range from 20 MeV to 300 GeV, locating the source positions to an accuracy of $< 1^\circ$. The GBM detects ~ 250 bursts per year, of which on average 20% are short bursts; the LAT detects bursts at a rate of ~ 8 per year. The data reveal two unexpected features of the GeV emission of bursts. The onset of the GeV emission is delayed relative to the onset of the MeV emission (by a few seconds in long bursts, and a fraction of a second in short bursts). And the GeV emission generally lasts for much longer then the MeV emission, decaying as a power law in time and lasting up to a 1000 s in some cases.

In the longer term, detection of non-electromagnetic radiation – neutrinos or gravitational waves – also offers an exciting prospect.

The demarcation into two classes of bursts is already proving too simplistic to be the whole story. For example, some bursts detected by Swift are extreme magnetar flares caused by the sudden readjustment (and release of stored energy) in the magnetosphere of a highly magnetized ($\gtrsim 10^{14}$ G) neutron star. These are of interest for phenomenologists but are a confusing complication for those seeking correlations between the observable parameters of bursts.

Moreover, the Swift spacecraft has revealed another type of object that is of great interest, and which was a surprise: bursts characterized by unusually persistent and prolonged emission, and located at the centre of their host galaxy. These are interesting both to astrophysicists and to relativists, as they may be triggered by a long-predicted effect that has not before been conclusively detected: the tidal capture and disruption of a star by a massive black hole. One particular burst, Swift J 164449.3 was exceptionally prolonged in its emission (Burrows et al., 2011). This phenomenon has been studied since the 1970s, first via analytic models (e.g. Rees 1988) and subsequently by progressively more powerful numerical simulations. There are several key parameters: the type of star, the pericentre of the star's orbit relative to the tidal radius, and the orientation of the orbit relative to the black hole's spin axis. In most astrophysical contexts, the captured stars would be on highly eccentric orbits (i.e the orbital binding energy would be small compared to that of a circular orbit at the tidal radius). So if a star were disrupted, the debris would continue on eccentric orbits, but with a spread of energies of order the binding energy of the original star. Indeed nearly half the debris will escape from the black holes gravitational field completely; the rest will be on more tightly bound (but still eccentric) orbits, and would be fated to dissipate further, forming a disc much of which would then be accreted into the black hole. A pericentre passage at (say) 2 or 3 times would not disrupt a star completely, but would remove its envelope, and induce internal oscillations, thereby extracting orbital energy and leaving the star vulnerable on further passages. On the other hand, a star that penetrates far inside the tidal radius (but not so close to the black hole that it spirals in) will be drastically distorted and compressed by the tidal forces, perhaps to the extent that a nuclear explosion occurs, leading to a greater spread in the energy of the debris than would result from straight gas dynamics.

There have in recent years been detailed computations of these processes, and also of the complicated and dissipative gas dynamics that leads to the accretion of the debris, and the decline of the associated luminosity as the dregs eventually drain away. There are two generic predictions: the debris enveloping the black hole should initially have a thermal emission with a power comparable to the Eddington luminosity of the black hole; and at late times, when the emission comes from the infall of debris from orbits with large apocentre, the luminosity falls as $\mathrm{L} \propto \mathrm{t}^{-5/3}$.

The high energy radiation, were this model correct, would come from a jet generated near the black hole (a transient version of what happens in a quasar). Modeling is still tentative, and is difficult because there is no reason to expect alignment between the angular momentum vectors of the black hole and of the infalling material (see e.g. McKinney et al. 2013) This is an unsteady version of the 'donut' described by Dr Kuszniak. These exceptional bursts offer model-builders an instructive 'missing link' between the typical long ('Type 1') burst, involving a massive star, and the jets in AGNs which are definitely generated by processes around supermassive black holes.

So let me now offer a few comments on the role of supermassive holes in active galactic nuclei.

3 Supermassive black holes

We celebrated in 2013 the 50th anniversary of Maarten Schmidt's discovery of quasars – hyperluminous beacons in the centres of some galaxies, which vastly outshine the total luminosity of all the stars and gas in their host galaxy. Quasars were historically important because they showed that galaxies contained something more than stars and gas – and that 'something', as was later realized, is a huge black hole lurking in their centres. They gave huge impetus to the then-new subject of relativistic astrophysics. The gravitational effects of previously known objects – ordinary stars and and galaxies – were weak enough to be adequately described by Newtonian theory – Einstein's general relativity was no more than a tiny correction. Not so, however, for quasars (nor for the neutron stars that were discovered a few years later).

In the West (and we are thinking back to an era when the Iron Curtain was almost impermeable) the inspirational gurus for relativistic astrophysics were John Wheeler, at Princeton and Dennis Sciama in Cambridge (who I was privileged to have as my own advisor). In the Soviet Union, Y. B. Zelvdovich led a powerful group of theorists who progressed in parallel with those in the West. (The 1960s saw the first real advance in understanding black holes since the work of Oppenheimer and Snyder in the late 1930s. And it's interesting to conjecture how much the 1960s work Oppenheimer might have pre-empted if World War II hadn't broken out the very day this paper appeared).

Quasars are specially bright because they're energised by emission from magnetized gas swirling into a central black hole. The first person to develop this scenario was one of my mentors, Donald Lynden Bell – just a few years after the work of Penrose, Hawking and others who showed that black holes were standardized objects. And the study of accretion has been crucial to our understanding of quasars – and it is to this subject that Paczyński, Abramowicz and their colleagues here made such crucial contributions.

Because quasars are so luminous they allowed astronomers to see several billion years back in time. This gave a boost to cosmology – another topic where relativity is crucial. The most distant reliably-known quasar, discovered two years ago has a redshift of 7.1. The redshift stretches the wavelength of its light so much that the Lyman alpha line of hydrogen, normally in the far ultraviolet, is shifted almost into the infrared. And another great discovery of the 1960s was compelling evidence that our universe had expanded from a hot dense state. Space is warmed to 3 degrees above absolute zero by microwaves with a thermal spectrum – the expanded and cooled afterglow of the 'hot big bang'.

4 Some general comments on cosmology

Our present cosmos manifests a huge range of temperature and density – from blazingly hot stars, to the dark night sky.

People sometimes worry about how this intricate complexity emerged from an amorphous fireball.

It might seem to violate the second law of thermodynamics – which describes an inexorable tendency for patterns and structure to decay or disperse.

The answer to this seeming paradox lies in the force of gravity. Gravity enhances density contrasts rather than wiping them out. Any patch that starts off slightly denser than average would decelerate more, because it feels extra gravity; its expansion lags further and further behind, until it eventually stops expanding and separates out. Computer simulations have shown how small-amplitude inhomogeneities in the early universe can thereby evolve into our complex cosmos.

And there's one important point. The initial fluctuations fed into the computer models I showed weren't arbitrary – they're derived from the observed fluctuations in the temperature of the microwave background which comes from very early eras.

The radiation has travelled from a time when the universe was a billion times denser than it is now – and the temperature was 3000 degrees. The temperature differences only one part in 100000, and these signify regions of above-average or below-average density. But these are the fluctuations fed in as initial conditions to the simulations, and these are then computing forward, they're amplified by gravity into the conspicuous structures in the present universe. This vindicates the claim that structure emerges by clustering of the gravitationally-dominant dark matter during cosmic expansion.

So we've started to understand how the slight ripples – overdensities and underdensities present at half a million years – condensed out, into the first stars and galaxies, ending the cosmic dark age. But what about further back? In one important respect things are simpler early on, because there were no structures – everything expanded smoothly. And we're definitely vindicated in extrapolating back to 1 second, because we can calculate the proportions of helium and deuterium produced and they match beautifully with what's observed – indeed we can probably be confident back to a nanosecond. That's when each particle had about 50 GeV of energy – an energy that can be achieved in the LHC – and the entire visible universe was squeezed to the size of our solar system.

But questions like 'where did the fluctuations come from?' and "why did the early universe contain the actual mix we observe of protons, photons and dark matter?" take us back to the even briefer instants when our universe was hugely more compressed still – when energies were 10^{16}GeV, where experiments offer no direct guide to the relevant physics.

According to a popular theory, the entire volume we can see with our telescopes 'inflated', at 10^{16} GeV, from a hyper-dense blob not merely as small as the solar system but no bigger than a tennis ball. The theory, called 'inflation' helps to explain why our universe is expanding at the 'right' rate – it didn't re-collapse before structures could form, nor did it expand so fast that gravity couldn't pull together the structures.

And, amazingly, it suggests that the fluctuations – probed in the greatest detail by the Planck Spacecraft – that now reach across the sky and are the seeds of structure formation, arose from quantum effects when the entire universe was of sub-microscopic size.

And this theory offers clues to another fundamental question: How large is physical reality?

We can only see a finite volume – a finite number of galaxies. That's essentially because there's a horizon – a shell around us, delineating the distance light can have travelled since the big bang. But that shell has no more physical significance than the circle that delineates your horizon if you're in the middle of the ocean. We'd expect far more galaxies beyond the horizon. There's no perceptible gradient across the visible universe – that suggests it stretches thousands of times further. But that's just a minimum. If it stretched far enough, then all combinatorial possibilities would be repeated. Far beyond the horizon, we could all have avatars.

And there's something else. The 10^{16} GeV physics of the inflation era is still conjectural. But some of the options would lead to so-called 'eternal inflation' scenario, in which the aftermath of 'our' big bang could be just one island of space-time in an unbounded cosmic archipelago[1].

For now, the idea of multiple 'big bangs' is speculative – but it's physics, not metaphysics. A challenge for 21st century physics is to answer two questions. First, are there many 'big bangs' rather than just one? Second – and this is even more interesting – if there are many, are they all governed by the same physics or not? Ed Witten, the guru of string theory, doesn't think so – he thought that there could be a huge number of different vacuum states – different microphysics.

Many patches could be still-born or sterile – the laws prevailing in them might not allow any kind of complexity. We therefore wouldn't expect to find ourselves in a typical universe – rather, we'd be in a typical member of the subset where an observer could evolve.

What about the far future of our universe? In 1998 cosmologists had a big surprise. It was by then well known that the gravity of dark matter dominated that of ordinary stuff – but also that dark matter plus baryons contributed only about 30 percent of the critical density. This was thought to imply that we were in a universe whose expansion was slowing down, but not enough to eventually be halted. But, rather than slowly

[1] When the multiverse is mentioned, it's sometimes asserted that domains that aren't observable aren't part of science. But I think that's the wrong way to look at it. We can't observe the interior of black holes, but we believe what Einstein says about what happens there because his theory has gained credibility by agreeing with date in many contexts where we can make observations. Likewise, if we had a theory that described physics at 10^{16} GeV that had been corroborated in other ways, then if it predicts multiple big bangs we should take that prediction seriously.

decelerating, the Hubble diagram of Type 1a supernovae famously revealed that the expansion was speeding up. Gravitational attraction was seemingly overwhelmed by a mysterious new force latent in empty space which pushes galaxies away from each other.

But there was independent evidence supporting this. According to Einstein's theory, a straightforward low-density universe would have negative curvature – the three angles of a big triangle would add up to less than 180 degrees. This can be tested from microwave background measurments. That's because there's a straightforward effect that makes the temperature ripples more conspicuous for a particular wavelength – about 300,000 light years. This so-called 'doppler peak' was first revealed by a balloon-borne experiment called Boomerang, and has been confirmed by the Planck data. It's on an angular scale that's consistent with a flat universe.

I mention this because it would be possible from the Boomerang data to predict that the expansion was accelerating. For the universe to be 'flat', 70 percent would need to be in some unclustered form. Moreover, this component cannot have been dominant in the past, because it would have inhibited the growth of cosmic structure. Therefore, its density falls off more slowly than that of the matter as the universe expands. It therefore has negative pressure (the 'PdV work' done during the expansion is negative.). And in Einstein's equations that implies acceleration.

If we'd just had the supernova Hubble diagram, some of us wouldn't have been convinced. But these two interlinked and almost simultaneous discoveries together clinched the case. The issue now is the nature of the dark energy – is it time-independent, like Einstein's cosmological constant, or was it different in the past? There are various constraints, and attempts to pin down the dependence are an important motive for new projects to study high-redshift galaxies. But I mention these projects today because one of Bohdan's few ventures into cosmology has renewed interest in this context. The so-called Alcock-Paczynski test (Alcock & Paczynski, 1979) compares the angular width and redshift spread in clusters, and could discriminate such models.

The long-term nature of this mysterious repulsive force determines the eventual fate of our universe. If it gets weaker and eventually changes sign, there could be a big crunch. If it gets ever-stronger, then stars, planets and our remote descendents will be ripped apart. But the best and most 'conservative' bet is that this force is unchanging – Einstein's cosmological constant in a modern guise. If that's so we'd predict an ever colder and ever emptier cosmos. Galaxies accelerate away and disappear over an 'event horizon', rather like an inside-out black hole. All that's left will be the remnants of our Galaxy, Andromeda, and smaller neighbours. Protons may decay, dark matter particles annihilate, there'd be occasional flashes when black holes evaporate – and then silence.

5 Concluding comments

And that's perhaps a good note on which to finish this over-long lecture, except to offer brief comments on the future of astrophysics. The 1960s were exhilarating for young astrophysicists – when so much was new, the old guys didn't have a big head-start over the youngsters. And some of them, expecially Bohdan, had a head start because of they quickly became adept in computing. But I'm not here to be nostalgic. Indeed, today's an equally good time for young researchers – the pace of advance has crescendoed rather than slackened. Instrumentation and computer power have improved hugely.

Up till now progress has been owed 95 percent to advancing instruments and technology – less than 5 percent to armchair theory. I'd expect that balance to continue. But there is one big change, brought about by fact that computer simulations have hugely advanced in power and expanded in range. In the old days, they were used for spherical stars, and N-body dynamics. Attempts at 3-D and at problems like star formation seemed over-ambitious, and seldom led to results that were both surprising and believable. There is of course still scope for simple analytic modelling based on the essential physics (at which Bohdan was so brilliant) but there are four areas in particular where computational advances have been spectacular.

There has been huge progress in simulating the emergence of cosmic structure – incorporating gas dynamics as well as gravity. Such models have convincingly shown how the 'cosmic web' develops. The feedback from stars and AGNs is still, however, modeled rather crudely.

3-D hydrodynamics and MHD have allowed modelling of accretion flows: thin discs, slim discs, and donuts. And jet formation and propagation, in gamma ray bursts and active galaxies, can also now be modeled.

Plasma processes in magnetospheres, and especially shock waves and particle acceleration in shock waves, can now be better simulated.

And fourthly, breakthroughs in computing time-dependent general relativity have allowed calculations of the wave-form of gravitational radiation released by compact objects, the recoil resulting from mergers of unequal holes, and related topics.

And of course the huge data-rate of modern telescopes couldn't have been efficiently analysed had there not been parallel advances in computer power.

All these techniques are open to younger counterparts of Bohdan Paczynski. Let's hope some are encouraged to follow in his pioneering tracks, and that they will combine new insights with powerful computing, and thereby push our subject excitingly forward in the coming decades.

I am grateful to the Polish Astronomical Society for inviting me, and especially to Bożena Czerny and Marek Abramowicz for their kind hospitality and support during my stay in Warsaw. I am grateful to Peter Meszaros for collaboration on gamma ray bursts. Fuller details and references on that topic are to be found in our article Ashtekar et al. (2014), to be published by Cambridge University Press in 2015.

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