Topics in Observational Astrophysics

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Lecture 10
Gamma Ray Bursts (GRBS)

• Discovery
• Characteristics
• Long and short duration GRBs
• Energy distributions, sky distribution and time dilation
• Afterglows and counterparts
• What if one went off nearby?
• Redshift distribution and very high redshift examples

Gamma-Ray Bursts (GRBs): Discovery

• Gamma ray bursts are brief bursts of high-energy radiation that appear randomly in the sky, emitting the bulk of the energy above ~ 0.1 MeV.
• They were originally discovered in 1967 by the Vela spacecraft launched to check on undeclared nuclear weapons testing after the first test ban treaty.
• The detection of these bursts was published in 1973.
• Optical/x-ray counterparts were first seen in 1997 and redshifts were measured showing that are very distant.
• Excellent early data came from the Compton Gamma Ray Observatory (CGRO) launched in 1991 (and de-orbited in June 2000) and in particular from the Burst and Transient Source Experiment (BATSE) which was on board CGRO. BATSE recorded 2704 GRBs.
Gamma-Ray Bursts: Discovery

- Compton carried a collection of four instruments which together could detect an unprecedented broad range of high-energy radiation called gamma rays.
- These instruments are the Burst And Transient Source Experiment (BATSE), the Oriented Scintillation Spectrometer Experiment (OSSE), the Imaging Compton Telescope (COMPTEL), and the Energetic Gamma Ray Experiment Telescope (EGRET).

Burst And Transient Source Experiment (BATSE)

- The Burst And Transient Source Experiment (BATSE) was an all-sky monitor, detecting and locating strong transient sources called gamma-ray bursts as well as outbursts from other sources over the entire sky.
- There were eight BATSE detectors, one facing outward from each corner of the satellite, which were sensitive to gamma-ray energies from 20 keV to over one MeV.
- At the heart of the BATSE detectors were NaI crystals which produce a flash of visible light when struck by gamma rays. The flashes were recorded by light-sensitive detectors whose output signal was digitized and analyzed to determine the arrival time and energy of the gamma ray which caused the flash. Each BATSE detector unit consisted of a large area detector sensitive to faint transient events along with a smaller detector optimized for spectroscopic studies of bright events.
Gamma Ray Bursts: General Characteristics

- Gamma-ray bursts are detected at the rate of about one a day.
- During a burst they outshine every other gamma-ray source in the sky, including the Sun.
- There is quite a variety in the appearance of the gamma-ray bursts.
- Some show a single pulse over a very short time interval, others show smooth bursts without any fine structure, some show distinct, well separated episodes of emission and some are very erratic and chaotic.
Gamma Ray Bursts: General Characteristics

- BATSE had four energy channels that provide good information on the gamma ray spectrum for each burst.
- It detected about 2700 bursts in total over its nine years of operation (~1 per day).
- For the brightest bursts, other instruments on the GRO have provided high resolution spectral data.
- This is the brightest event ever detected by BATSE.

Gamma Ray Bursts: Temporal Characteristics

- The duration of gamma ray bursts ranges from about 30 ms to over 1000 seconds.
- However, the duration, like the burst morphology, is sometimes difficult to quantify because it depends on the intensity and background and time resolution of the experiment.
- The above figure (left) shows the distribution of duration of 222 gamma ray bursts from the BATSE catalogue.
- At the short duration end we may be missing bursts because the instrument takes 64 ms to trigger.
- Apart from that we can see two broad peaks at around 0.5 seconds and about 35 seconds, with a minimum at around two seconds. The short ones are probably NS-NS mergers and the long ones are core-collapse (M > 40M₀) hyper-novae.
- We also find that the shorter bursts tend to have a harder spectra (higher percentage of energy in the most energetic photons) (right hand figure).
Two types of GRBs

- Two types: Long duration, greater than 2 seconds and short duration, less than 2 sec.
- The long duration ones are confidently thought to be the death-throes of a very massive (>40 solar masses) hot star called a Wolf-Rayet star (the collapsar-hypernova model).
- Pre-2007 data from a GRB discovered with SWIFT suggested that the short duration ones come from neutron stars falling into a black hole or neutron star mergers. Old merging binaries.
- Recent Gravitational Wave data supports this hypothesis (GW170817)
- Long GRBS associated with regions of star formation
- Short GRBS can be in galactic halos

Gamma Ray Bursts: Spectral Characteristics

- Most of the power in a gamma-ray burst is emitted above 50 keV.
- Most bursts have a simple continuum spectrum that stays much the same throughout the burst.
- The figure opposite shows a typical spectrum of the gamma-ray burst measured on all four experiments on CGRO. This plots the spectral energy density against frequency so it shows where most of the energy actually is.
- Fitting a simple slope through the spectrum produces a spectral index distribution that is plotted in the lower figure.
- Fits to the spectra of many bursters show a functional form of:
  \[ N(E) = AE^\alpha e^{-E/E_0} \]
  for lower energies and for high energies of the form:
  \[ N(E) = BE^\beta; \quad \alpha > \beta \]
Gamma Ray Bursts: Spatial Distribution

- The sources of gamma-ray bursts could be local, for example objects such as neutron stars, or cosmological, in which case this would imply that enormous energies are involved.
- The distribution on the sky shows no evidence of anisotropy which implies that these objects are not concentrated in the disk of the galaxy nor are they close to the centre of the galaxy.
- They could be part of a very extended milky-way halo distribution, but the halo would have to be large enough that the position of the Sun away from the galactic centre could not be seen. This implies that such a halo has a radius $R > 200$ kpc, significantly larger than any other galaxy-connected structures.
- The above figure shows the all sky distribution of all the bursts detected by BATSE in galactic coordinates.
- It is clear that these events are not confined to local group galaxies or the Virgo cluster or indeed the local supercluster because we would see the structures on this distribution.

Gamma-ray Bursts: Time Dilation

- For a simple model then we know that on average, fainter sources will be at a greater distance. If gamma ray bursts are cosmological we should see a time dilation of the pulse length so that
  
  $$ t_{\text{observed}} = t_{\text{rest frame}}(1+z), $$
  
  where $z$ is the redshift.
- Given the wide variety of properties of different bursts it is a difficult experiment to perform.
- How can we measure $\Delta t$?
- We can look at the average pulse profile of stronger (nearer) and weaker (further) bursts and compare them statistically.
- This is shown in the figure opposite where we see that the weaker bursts (the outer profiles) appears stretched (dilated) by about a factor of two when compared with the stronger (inner) profile data.
- This implies their distances are cosmological.
Gamma-ray Bursts: Pulse Delays

- There is also evidence that the pulses appear first at the highest energies and gradually become more obvious at lower energies.
- It appears as a delay which is energy dependent and is shown in the plots here.

GRB satellites

- Compton/BATSE - launched 1991
- HETE-2 - launched 1996
- Beppo-SAX – x-rays and $\gamma$-rays, launched April 1996
- INTEGRAL – launched Oct 2002
- SWIFT- launched Nov 2004
- Fermi Gamma Ray Space Telescope
- Detections can be “triangulated” to pin down position on sky for rapid follow-up observations both from the ground and from space.
Gamma Ray Bursts: the Search for Counterparts

**Beppo-Sax:**

optical counterparts not detected until 1996

- The CGRO was very successful at detecting bursts but had a positional accuracy that was very poor, typically 1-5 degrees on the sky.
- For objects at cosmological distances it is impossible to associate the GRB with an optical counterpart when the optical images have approximately 4,000,000 objects per square degree.
- An Italian-Dutch x-ray satellite called Beppo-SAX was launched in 1996 to provide a wide range of x-ray detection capabilities, from 0.1 to 200 keV with good spatial resolution. It had systems to detect gamma ray bursts that could then trigger automatic x-ray imaging and provide good positional accuracy measurements to better than one arc minute.
- It was able to respond to the detection of a burst on timescales of ~ 5 hours.
- It was therefore able to begin measuring the X-ray afterglow 5 hours after the burst.
- Other telescopes could then also rapidly begin to look for the afterglow using the Beppo-Sax position.

• Very soon after launch, Beppo-SAX started to measure the x-ray fluxes of a number of gamma ray bursts as a function of time.
• The above picture shows Narrow Field Imager pictures of the afterglow of GRB970508 taken at six hours (on left) and three days after the burst’s trigger showing how the intensity fades.
• The white circle is the initial Wide Field Camera error box.
The Neil Gehrels SWIFT Observatory

Or just SWIFT for short.


Has X-ray and UV/optical telescopes for rapid afterglow follow-up observations.

Observed its 1000th GRBs on Oct 27th, 2015 (~91 per year or ~1 every 4 days).

• BAT – Burst Alert Telescope. Gamma ray detector.
• UVOT – Ultra-violet optical telescope.
• XRT – X-ray telescope.

• BAT detects a GRB. Position determined to 4 arcmin within its 1.4 steradian FOV (~11% of the whole sky).
• Within 10 sec SWIFT slews to point the UVOT and XRT at the GRB. Accurate position known in ~3 minutes.
• Ground-based follow-up starts ASAP.
Gamma Ray Bursts: The SWIFT Mission

- The NASA SWIFT gamma-ray mission is now making prompt multi-wavelength observations of gamma-ray bursts and their associated afterglows. There are three instruments on-board, covering the gamma-ray, X-ray and UV/optical bands. Using these instruments SWIFT measures GRB positions with arc-second accuracy, within a few minutes of their discovery. SWIFT is the first satellite to observe GRBs at other wavelengths during the crucial first few hours.

- SWIFT is also performing the first sensitive hard X-ray survey of the sky.
GRB010222
The optical and x-ray light curves
Gamma-ray burst itself lasted 5 minutes (unusually long)

This GRB (GRB030329) had an R magnitude of R=12.6, 1.5 hours after the burst itself

Figure 1. The afterglow flux in X-rays (1.0 keV plotted in blue), optical (V, B, R and I plotted respectively as blue, green, red and yellow dots) and radio (7.7 GHz diamond, 8.5 GHz square and 19.2 GHz star plotted in red). The curves show the best fit model in X-ray (1 keV), optical (R-band) and radio (8.5 GHz).
5.6 days after burst

9.8 days after burst
18.6 days after burst

34.7 days after burst
Gamma Ray Bursts: Afterglow Decay

- The typical time decay of the afterglow, seen in the x-ray region of the spectrum, has a power-law-like decay.
- Many GRB afterglows have now been detected, with detections sometimes extending to radio wavelengths and over timescales of many months.
- Most of these have now been identified with their host galaxies.

Gamma Ray Bursts: Optical Transients

- A close-up of the optical transient shows both a point-like source (the bright emission) plus the extended emission (below and to the right) from what is thought to be the distant host-galaxy.
- This image was taken with the Hubble Space Telescope in the V-band.
- In general there is a separation between the afterglow and the galaxy implying that these events are not at the galaxy centres. Most likely they are not in the galaxy halos.
Gamma Ray Bursts: Optical Transients

- Another example of an optical counterpart to a gamma-ray burst is shown here.
- The optical transient appears to be superposed on an extended irregular galaxy.
- The optical transient has a magnitude of $V=25.4 \pm 0.1$ and the galaxy has an integrated magnitude of $V=24.3 \pm 0.15$.

Gamma Ray Bursts: Optical Transients

- The optical transients detected are very faint, with magnitudes around 24-26. Even so, redshifts can be measured.
- They allow the host galaxies to be identified and their redshift measured as well.
- We have now got a significant number of redshifts many of which are very high (see figure).
- Observations like this establish the cosmological origin of gamma ray bursts without any doubt.
- The host galaxies typically show an excess of star formation.
- We observe approximately 300 bursts per year out to some look-back time $t$.
- The density of galaxies is approximately $n_0 = 0.02\ Mpc^{-3}$ so that number of galaxies $\sim n_0 (4\pi/3)(ct)^3 \sim 3\times 10^9$.
- This suggests that there will be $\sim$ one burst observed per galaxy every $10^7$ years – this number includes the effects of beaming.
Gamma Ray Bursts: Effects on Earth of a nearby event?

- If a GRB occurs within a few kiloparsecs and it is beamed in our direction it could have devastating effects.
- Initially, only the UV part of the radiation would reach the ground and this short burst would probably not do too much damage.
- However, the bulk of the energy is dumped in the upper atmosphere and there would be chemical reactions involving oxygen and nitrogen.
- Nitrogen oxides would deplete ozone removing our UV shield for many years.
- Nitrogen oxides produce smog, blocking light and possibly causing global cooling.
- Nitrogen dioxide would produce acid rain.
- It has been suggested that the Ordovician-Silurian extinction, 450 million years ago, was caused by a GRB which destroyed the Earth’s ozone layer.

Gamma Ray Bursts: Optical Transients

- This shows the observed energy-redshift relation for 17 GRBs with optical spectroscopic redshifts as of 27 October 2000.
- Blue (yellow) denotes that the redshift was found with emission (absorption) lines from the presumed host galaxy.
- The energy is derived from the $\gamma$-ray flux and assumes that the GRB emits the energy isotropically (which it doesn’t!).
Cumulative redshift distribution for long GRBs

- Solid line is the data
- Other lines are models
- $S$ is the jet opening angle power law index
- The mean jet opening angle is estimated to be 11 degrees
- Mean $z$ is 1.3

From Le and Mehta, 2017

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Gamma Ray Bursts: Optical Transients

- We now have a lot of information about the host galaxies within which gamma ray bursts are detected.
- From the distances of these galaxies we conclude that the luminosity of a gamma ray burst is astonishingly high, perhaps comparable to the entire luminosity of the universe (at least for a few seconds)!
- We get this by multiplying the luminosity of the sun ($3.8 \times 10^{26}$W) by the number of stars in a galaxy ($2 \times 10^{10}$) times the number of galaxies ($10^{10}$). This is $\sim 8 \times 10^{46}$ W, and the brightest gamma ray bursts are $\sim 10^{46}$ W (assuming the energy goes equally in all directions, which it doesn’t).
- Some long GRBs have no detected optical afterglow – they maybe at enormous redshifts?
# Very high redshift GRBs

<table>
<thead>
<tr>
<th>Name</th>
<th>redshift</th>
<th>Burst duration</th>
<th>notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRB 090429B</td>
<td>z=9.4</td>
<td>5.5 sec</td>
<td>• Photometric redshift, z&gt;7.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• No optical/UV afterglow seen</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>• IR afterglow detected</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• No host galaxy seen</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Estimated burst energy 3.5x10^{52} ergs</td>
</tr>
<tr>
<td>GRB 090423</td>
<td>z=8.2</td>
<td>10 sec</td>
<td>• Spectroscopic redshift</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• No optical/UV afterglow seen</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• IR afterglow detected</td>
</tr>
<tr>
<td>GRB 080913</td>
<td>z=6.7</td>
<td>8 sec</td>
<td>• Spectroscopic redshift</td>
</tr>
<tr>
<td>GRB 050904</td>
<td>z=6.3</td>
<td>200 sec</td>
<td>• Spectroscopic redshift</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• The X-ray luminosity is 100,000 times the brightest AGNs.</td>
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<td></td>
<td></td>
<td></td>
<td>• There is variability on timescales of minutes to hours.</td>
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These provide evidence that massive stars formed at very early times in the Universe.