Topics in Observational Astrophysics

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Lecture 11
Gamma Ray Bursts (GRBS)

- Comparing SN and GRB rates
- Quick recap of core-collapse SN
- The Collapsar hypernovae model for GRBS
- Observational constraints
- The Fireball shock model
- Afterglow decay
- Short GRBs
- Animations

WR22 in the Carina nebula
- This Wolf Rayet star has M=78 solar masses.
- It has an O-star companion.
- It is 2.5kpc away.

Note: WR stars can have masses well below 40 solar masses. The WR classification is based on the presence of emission lines from ionised He, N and C in their spectra.
Comparing Supernovae and GRB rates

- In our Milky Way Galaxy the supernova rate is estimated to be:
  
  \[ 2.5 \pm 0.8 \text{ per 100 years or one every } 40 \pm 13 \text{ years} \]

- Core-collapse SN make up ~85% of the rate (progenitors with \( M > 8M_{\odot} \))
- Type Ia SN make up the rest, ~15%
- There are only a few GRBs per galaxy per Myr (not including beaming). There are about \( 10^4 \) SN for every GRB.
- Most of these (70%) are due to hyper-novae which are core-collapse events with progenitors with \( M > 40M_{\odot} \)
- Basically these hyper-nova GRBs come from the high mass tail of the stellar mass function.
- The other GRBs are thought to be due to NS-NS or NS-BH mergers.

Stellar Death: Core Collapse in High Mass Stars

- The structure just before core-collapse is described by an "onion-skin" model with an inert iron core the end product of the nuclear burning.
- The core is only 1% of the diameter of the star.
- The star rapidly approaches catastrophe, as the outer core continues to increase in mass. The nuclear burning processes have extracted all the available energy from the core.
- This situation is worsened by the very high-energy photons generated from the burning of the high mass elements causing the iron to photo disintegrate:
  \[ ^{56}\text{Fe} + \gamma \rightarrow 13^4\text{He} + 4\text{n} \quad \text{and} \quad \gamma + ^4\text{He} = 2p + 2n. \]
- This reduces the energy generation rate, and cools the core. In order to achieve the disintegration you need to have \( \sim 10^{45} \) J of energy for a 1.4 \( M_{\odot} \) core.
Stellar Death: Core Collapse in High Mass Stars

• We can work out that this is the energy required by using the binding energy difference per nucleon when comparing $^{56}$Fe and H, approximately 8 MeV, and calculating the number of iron atoms in the core from its total mass.
$$E = (1.4 \frac{M_{\odot}}{m_p}) \times 8\text{MeV} = 2 \times 10^{45}\text{J}$$

• The usual cycle where a core contraction produces an increase in temperature and pressure followed by ignition of a new nuclear fuel cannot work with the iron core and the star finds itself with no energy generation to counteract the force of gravity.

• Neutronisation, $e^- + p \rightarrow n + \nu_e$, then removes the degenerate electrons that were providing much of the pressure support.

• The core goes into free-fall collapse, with a timescale of the order of one millisecond. This timescale is very short because the density in the core is $\sim 10^{14}\text{kg m}^{-3}$.
$$t_{ff} = \frac{1}{\sqrt{G\rho}}$$

Stellar Death: Core Collapse in High Mass Stars

• The core is believed to reach nuclear densities and then to bounce, with the central portion becoming a neutron star or a black hole depending on the mass ($M_{\text{core}} \sim 2 M_{\odot}$ is probably the maximum mass for a neutron star) while the shock wave blows off the entire outer atmosphere of the star.

• For $8 M_{\odot} < M < 40 M_{\odot}$ this core collapse, triggered by the exhaustion of nuclear fuel, causes a supernova explosion. (Types II, Ib and Ic).

• The effect is to return the majority of the mass of the star into the interstellar medium. The central compact object now has a mass of the order of a few solar masses and the explosion liberates an enormous amount of energy, $\sim 10^{47}\text{J}$. This arises because the gravitational energy is liberated as the core collapses from $R = R_{\text{wd}} \rightarrow R = R_{\text{ns}}$ so that $E_{\text{bind}} \sim E_{\text{ns}} = GM^2/R_{\text{ns}} \sim 10^{47}\text{J}$.

• A type II supernova is so bright that for a short period it will be brighter than the entire host galaxy, reaching an absolute magnitude of $M_V \sim -20$. 
Long GRBs: Collapsar-hypernova Model

- A massive main sequence star runs out of nuclear fuel (or perhaps the core collapse is due to a merger with a companion star).
- Star must have M > ~40 solar masses to form a black hole.
- Has to be rapidly rotating to develop an accretion torus capable of launching a jet.
- Has to have low metalicity in order to strip off the hydrogen envelope such that the jet can reach the surface.
- Core-collapse creates a black-hole at the centre of the massive star.
- Blast-wave with a Lorentz factor of ~100 in the form of the jet shoots out of the star.
- Gamma rays are due to synchrotron emission and inverse-Compton emission.
- The afterglow is due to the jet blast wave hitting gas and dust near to the star.
- We see the GRBs when we’re looking down the gun barrel of the blast jet! ⇒ Many more occur unseen.
- Theory suggests that only 1 in 100,000 supernovae will be a GRB and this fits in with the observed SN and GRB rates.
- Afterglow seen in most cases. Host typically has a low mass.
- Always found in regions of high star formation rate as you’d expect for massive MS stars.

Observations of GRB 030329
The long GRB - Hypernova connection

- A relatively nearby event (~600Mpc).
- Afterglow spectrum was identical to that of the supernova SN1998BW (type Ic) confirming the hypernova hypothesis.
- SN1998BW had been tentatively associated with GRB980425 (they happened at the same time and the SN was in the GRB position error box).
- X-ray observations showed the same characteristic signatures of shocked and heated Oxygen as seen in SNe.
- There are other examples too, relating GRBs to type Ib and Ic Supernovae.
Gamma Ray Burst Models: Constraints from Observations

• The form of the afterglow spectrum and its evolution with time implies that the highest energy emission decays first.
• This is consistent with adiabatic dynamic evolution of a blast wave hitting an external medium.
• Observations imply that the cooling time for most electrons is longer than the dynamic time.
• The ejection sweeps up gas and the shock accelerates electrons creating electrons with a power-law energy distribution.
• These radiate energy as photons giving a power-law frequency distribution of the form \( F(\nu) = \mu \nu^{-\alpha} \)

Gamma Ray Burst Models: Constraints from Observations

• When thinking of luminosities and energies, etc, we have large values if the radiation is emitted isotropically and smaller values if it is beamed.
• If we ignore beaming the luminosity in gamma rays is \( \sim 10^{46} \text{ Js}^{-1} \) which is \( \sim 10^{14} L_{\text{edd}} \) (the Eddington luminosity) for a solar mass object.
• Similarly the energy in gamma rays is \( \sim 10^{47} \text{ J} \) which is \( \sim \) a supernova energy.
• The rate of gamma ray bursts is \( \sim 10^{-6} \) to \( 10^{-7} \text{ yr}^{-1} \text{ galaxy}^{-1} \), a factor of \( 10^{4} \) rarer than all supernovae.
• The characteristic temperature of these bursts is \( kT = 0.5 \text{ MeV} \) (the energy of a gamma ray photon which is approximately the energy of an electron-positron annihilation).
• The radius needed to achieve this temperature from the potential energy of material falling onto a stellar mass object is \( \sim 3 \times 10^{7} \text{ m} \).
Gamma Ray Burst Models: Constraints from Observations

• The spectrum of the gamma radiation is non-thermal and is therefore optically thin. This implies there is a low electron opacity and there are few baryons.
• There is also very rapid variability which implies a high Lorentz factor, \( \gamma \).
• The variability timescale that we observe, \( dt \sim \frac{r}{c} \gamma^{-2} \) is because the relativistic velocities reduce the timescales for variability by \( \gamma^{2} \) in the observer’s rest frame.
• Using our elementary estimate of the region sizes and energies, plus the observed variability timescale, implies that \( \gamma \sim 100 - 1000 \), reinforcing our conclusion that very few baryons are involved because accelerating material to \( \gamma > 100 \) requires enormous energy.
• As a result, our estimates are that the mass in the form of baryons < \( 10^{-5} M_{\odot} \).

The Fireball Shock Model

• To explain the production of the large energy emitted in gamma rays we need:
  1. A very high energy relativistic jet of particles (the fireball)
  2. A zone where the kinetic energy of the particles is turned in to gamma rays (the shock)
• The jet comes from rapidly rotating infalling material – a black hole engine
• This can be a collapsing core or 2 massive objects spiralling into each other.
• The shock is from shells of material moving at different speeds colliding.
• The shock waves travel at slightly different velocities and collide with each other to give rise to the internal shocks which produce the gamma ray burst itself. This explains the observed timescales.
• The shock wave continues and as it decelerates through interaction with the external medium it produces an external shock afterglow.
• This leads successively to gamma rays, x-rays, optical and radio emission in the afterglow.
• Within the x-ray region of the spectrum, iron lines may arise from x-ray illumination of a shell of material that was ejected earlier or from continuum x-ray radiation from the outer stellar envelope.
The Fireball Shock Model

- The various components we have include:
  - Compact inner engine.
  - Energy transport phase.
  - Conversion of kinetic energy to prompt gamma radiation: this is the gamma ray burst.
  - Conversion of remaining energy to radiation: this is the afterglow.
  - The afterglow model predicts a series of stages as the wave slows.

- A key prediction is a break in the spectrum that moves with time from the gamma to the optical band, and is responsible for the power law decay of the source flux.

- This $\nu_m$ break moves through the X-ray band in a few seconds but takes up to 1000s to reach the optical. Thus, observations within the first 1000s in the optical and UV are crucial if we are to see this early phase.

- While it is likely that all the GRBs have X-ray afterglows, not all have bright optical afterglows (at least after several hours). This may be due to optical extinction, but in some cases the optical afterglow may be present but decays much more rapidly and is a function of the density of the local environment.

- Prompt high quality X-ray, UV, and optical observations over the first minutes to hours of the afterglow are crucial to confirm this model which is why SWIFT was launched in late 2004.

- Continuous monitoring for days is then important since model-constraining flares can occur in the decaying emission.
Gamma Ray Bursts: Afterglow Decay

Very early on $\nu_m > \nu_c$
Later on $\nu_m < \nu_c$ (shown in fig)

$v_c \propto t^{1/2}$

$v_m \propto t^{-3/2}$

$F_\nu \propto \begin{cases} 
\nu^2, & \nu < \nu_a \\
\nu^{1/3}, & \nu_a < \nu < \nu_m \\
\nu^{-(p-1)/2}, & \nu_m < \nu < \nu_c \\
\nu^{-p/2}, & \nu_c < \nu 
\end{cases}$

- The $\nu_a$ break point corresponds to the frequency below which the GRB is opaque to radiation and so the spectrum attains the form of the Raleigh-Jeans tail of blackbody radiation.
- $h\nu_m$ is the minimum energy acquired by an electron after it crosses the shock wave.
- $\nu_c$ is related to the time it takes an electron to radiate away most of its energy.

Short GRBs

- Gamma ray burst duration is less than 2 seconds.
- Significantly fainter than long duration GRBs.
- Have more high energy gamma rays than the long duration bursts.
- Gamma ray energy falls off with time whereas the long duration GRBs are more constant with time during the burst.
- Sometimes found in regions of the host galaxy with very low star formation (so unlikely to be due to extremely massive stars).
- Afterglows are less common than for long GRBs which might be due to lack of surrounding material for beam to hit.
- Progenitor is probably a NS-NS or NS-BH merger.
- Beam not as collimated as for long GRBs.
- Binary loses orbital angular momentum by gravitational wave radiation and undergoes a merger (see binary pulsar earlier).
- Black hole formed in the NS-NS case.
- Problem: x-ray flaring seen many days after GRB event
- Problem: Failure to find host for some nearby short GRBs