Introduction to Astrophysics

Michaelmas Term, 2020: Prof Craig Mackay

Module 6:

- Supernovae: Basic types.
- Core collapse SN: energetics, neutrino production, rates, spectra, light curves, radio-active decay.
- Type Ia SN: trigger, use as standard candles.
- Supernovae. Evolution of remnants, shock fronts, SN1987A.
- Hypernovae: Gamma-Ray Bursts (GRBs), discovery, general characteristics.
- Gamma Ray Bursts: search for counterparts, Beppo-Sax, SWIFT, afterglows, redshifts, long and short duration GRBs, collapsar-hypernovae, neutron star mergers, observational constraints on theories, fireball-shock model.

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What is a supernova?

- Observationally a “nova” means a new star. It’s basically something that flares up in brightness by a significant amount so that something is seen where there wasn’t something before.
- A supernova is an extreme and unusual case of this. It is an extremely violent stellar explosion causing an increase in brightness by a factor of $> 10^8$ and at its peak brightness has a luminosity comparable to that of a whole galaxy.
- The high luminosity lasts for several months.
- Supernovae are rare: about one every 40 years in our Milky Way galaxy.

- We are well overdue for one, but hopefully not to close by!

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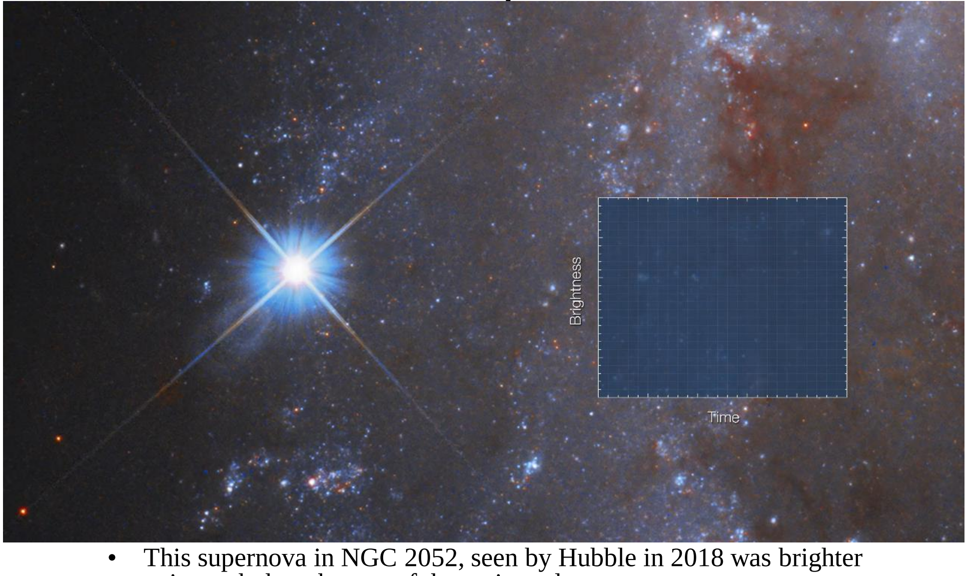
What is a supernova?



- This supernova in NGC 2052, seen by Hubble in 2018 was brighter at its peak than the rest of the entire galaxy.

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Classification of Supernovae

- The basic classification scheme is to do with the observed spectrum and was established before supernovae were fully understood.
- Type I spectra ***have no hydrogen lines*** (but lines such as He, Fe, Si, Ca, and Co are prominent).
- Type II supernovae ***do have strong hydrogen lines***.
- A letter can be added to the spectral-type numeral to indicate the type of light-curve seen or other spectral features.
- In terms of origin, there are two basic kinds of supernovae: ***Type Ia supernovae*** occur when a white dwarf close to the Chandrasekhar mass limit accretes material which causes a nuclear explosion and ***the rest*** (types II, Ib and Ic supernova) occur when a very massive star ($M>\sim 9M_{\odot}$) exhausts all its nuclear fuel.

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Supernovae Types

Type	Characteristics	Trigger
Ia	Si II line at 615.0 nm	Fusion in a white dwarf
Ib	He I at 587.6 nm. No Si II line at 615.0 nm	Fusion ends. Core collapse
Ic	Weak or no He I. No Si II	Fusion ends. Core collapse
II-P	Has a plateau in its light curve	Fusion ends. Core collapse
II-L	Has a linear light curve	Fusion ends. Core collapse

The precursors of type Ib and Ic supernovae are thought to have lost their outer layers of hydrogen via stellar winds (very massive stars) or interaction with a companion. See GRBs later.

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Stellar Death: Core Collapse in High Mass Stars

- We have already seen that the lifetimes of high mass stars with masses in the range of 10 to 100 solar masses are very short on cosmic scales.
- The fuel available is proportional to the mass, and there is a strong dependence of luminosity on mass: $L \sim M^3$. Therefore the lifetime $t \sim 1/M^2$ and the evolutionary timescales for the most massive stars can be a short as one million years, compared to 10^{10} years for stars of about one solar mass.
- On the main sequence nuclear fusion converts hydrogen into helium in the core of the star.
- While it is on the main sequence the helium in the core will build up.
- The hydrogen in the core eventually becomes exhausted. The central region of the star contracts enough to raise the temperature and pressure in a shell surrounding the helium core enough to initiate nuclear reactions. This is the stage where a shell of hydrogen is burning round the helium core.
- Eventually the temperature in the core becomes high enough to ignite (non-degenerate) helium burning via the triple-alpha reaction to form carbon.
- The helium in the core then becomes exhausted. The central part of the star contracts enough to raise the temperature and pressure in a shell surrounding the carbon core high enough to initiate nuclear burning of helium. We now have helium and hydrogen burning in shells.
- The star builds up successive layers of burning as next the carbon core ignites and exhausts, and the carbon burning in a shell begins. Temperatures are now in excess of 100 million K in the core of the star.

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Nuclear Burning

Reaction	min temp	timescale ($25M_{sun}$)
• $H \rightarrow He$	Log(T)=6.7	70 Myr
• $He \rightarrow C$	Log(T)=8.0	500 kyr
• $C \rightarrow O$	Log(T)=8.8	600 yr
• $O \rightarrow Si$	Log(T)=9.0	6 months
• $Si \rightarrow Fe$	Log(T)=9.6	1 day

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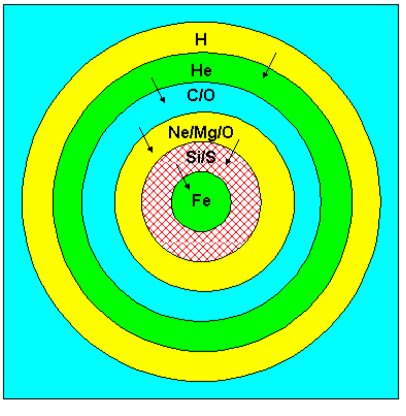
Stellar Death: Core Collapse in High Mass Stars



- The structure is now described by an "onion-skin " model with an inert iron core the end product of the nuclear burning.
- Note that the core is only 1% of the diameter of the star.
- Throughout the sequence luminosity has increased somewhat and the outer atmosphere has expanded by a considerable factor, causing the surface temperature of the star to drop. The atmosphere does not have time to react significantly to the rapid cycles of core exhaustion and shell ignition. The overall effect is for the star to move almost horizontally from left to right in the Hertzsprung-Russell diagram, from a blue supergiant to a red supergiant.

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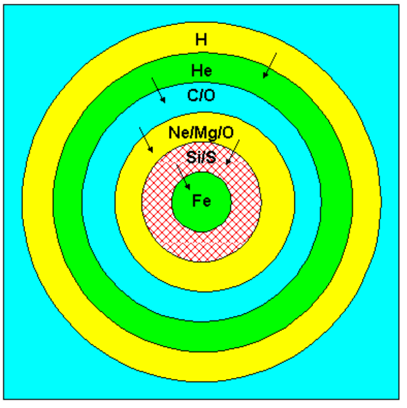
Stellar Death: Core Collapse in High Mass Stars



- The star is rapidly approaching 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: $^{56}Fe + \gamma \rightarrow 13\ ^{4}He + 4\,n$, and $\gamma + {}^{4}He = 2p + 2n$, equivalent to undoing 10^{10} years of nuclear energy generation in a star like the sun. This reduces the energy generation rate, and cools the core. In order to achieve the disintegration you need to have ~10^{45} J of energy for a 1.4 $M_{\odot}$ core.

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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. $E = (1.4\ M_{\odot} / m_p) \times 8\text{MeV} = 2 \times 10^{45}$ 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 milli-second. This timescale is very short because the density in the core is ~ 10^{14} kg m^{-3}.
- 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 ($M_{core} \sim 3\ M_{\odot}$ is probably the maximum mass for a neutron star) while the shock wave blows off the entire outer atmosphere of the star.
- This core collapse, triggered by the exhaustion of nuclear fuel, causes a Type II supernova explosion. (and 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, ~10^{47} J. This arises because the gravitational energy is liberated as the core collapses from $R = R_{wd} \rightarrow R = R_{ns}$ so that $E_{bind} \sim E_{ns} = GM^2/R_{ns} \sim 10^{47}$ 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~-20.

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Type II Core-collapse Supernovae: Energetics

- Let us now look at the energy budget for a core-collapse supernova explosion.
- Fe → H photodisintegration is ~ 10^{45} J. (first coolant)
- $e^- + p \rightarrow n + \nu_e$ also gives ~ 10^{45} J in the form of neutrinos. (second coolant)
- The gravitational energy from the ensuing core collapse to R_{ns} (or indeed to R_{bh}) is 10^{46} to 10^{47} J.
- However, the observed kinetic energy of the material ejected ($M \sim 10\ M_\odot$ and $v \sim 20000$ km s^{-2}) ~ 10^{44} J.
- Radiation emitted over ~ 1 year is about ~ 10^{42} J.
- So where does all the gravitational energy go?
- Mostly it goes into neutrino-anti-neutrino pair production as the core collapses to form a neutron star. Neutrinos are weakly interacting fermions with zero (or at least a very small) mass.
- Three types (electron, muon and tauon neutrinos) are made in a number of exotic high energy processes.
- Neutrino mean free path = d, takes R^2/d^2 steps to reach surface of the neutron star.
- Time between collisions = d/c $\Rightarrow$ $t_{escape} \sim R^2/dc$
- Neutrinos have a very low cross-section for interaction with matter, but at the extreme densities within a neutron star there is a significant probability of scattering within the core. We therefore predict that one of the consequences of a supernova explosion (that creates a neutron star not a black hole) is that we would expect a massive neutrino burst with a timescale ~ t_{escape}.
- This theory was confirmed in 1987.

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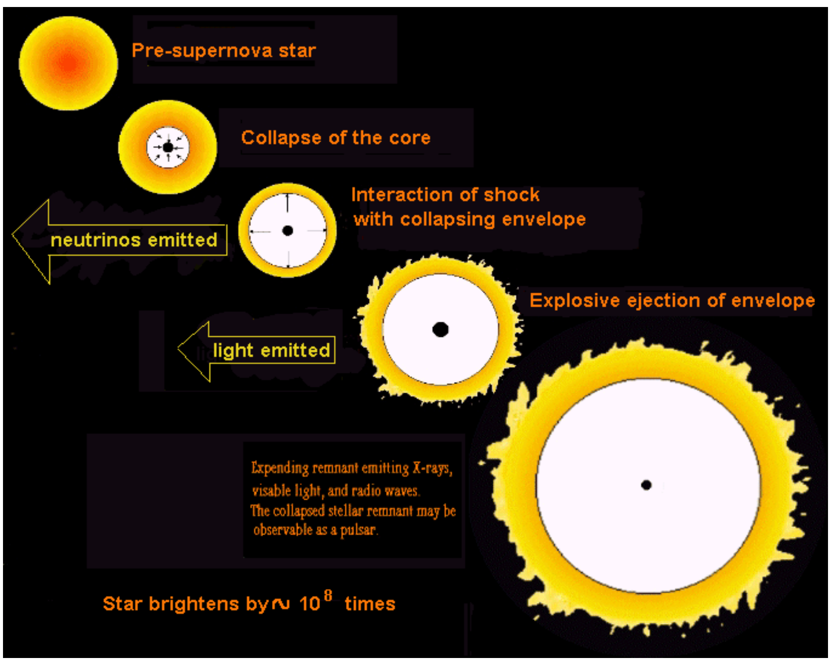
Supernova 1987A: Neutrino Detection



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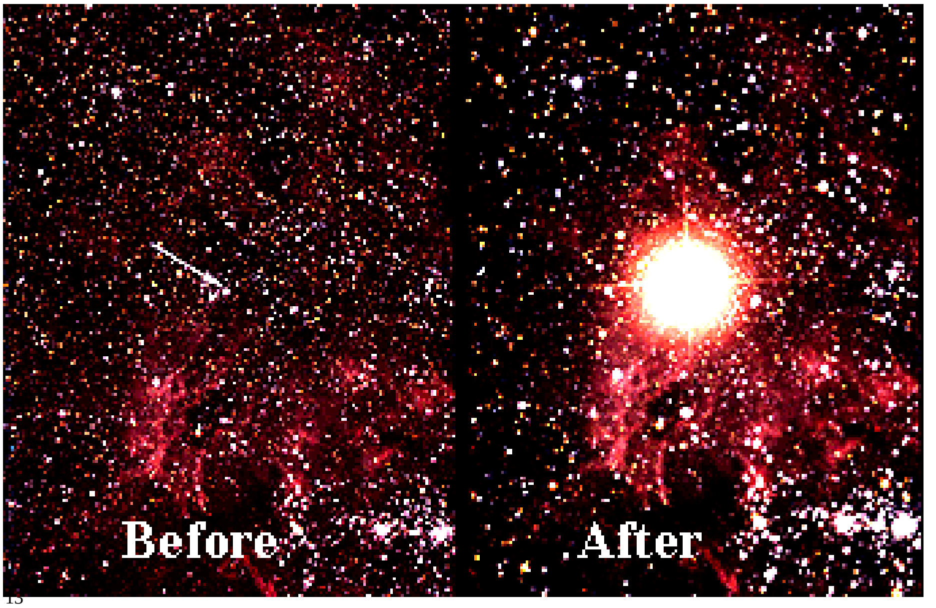
Supernova 1987A: Optical Detection



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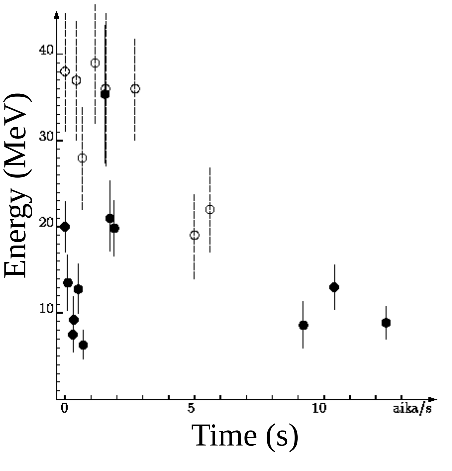
Supernova 1987A: Neutrino Detection

- Two neutrino detectors, one in Japan and one in the US detected about 20 electron neutrinos over about 12 seconds on 23 February, 1987.
- The background rate is typically one event per week.
- The observations tell us about the energetics of the supernova as follows:
- The energy emitted in antineutrinos was (3-6) 10^{45} J
- The energy emitted in all neutrinos was (2 ± 1) 10^{46} J.
- The kinetic energy was (1.4 ± 0.1) 10^{44} J
- The duration of the neutrino pulse was ~12 seconds.
- These results confirm the theory really quite well.



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Stellar Death: Core Collapse in High Mass Stars

- The observed supernova event occured because the outer stellar shells collapse onto the neutron star surface as it rebounds creating a shock wave that propagates out through the extended envelope.
- The radiation is seen at different wavelengths according to when it reaches the surface.
- The optical flash is seen 2-3 hours after the neutrinos are detected.
- We learned a great deal from Supernova 1987A which occurred in the Large Magellanic Cloud, one of the nearest galaxies to us (at a distance of about 50 kpc it is a companion to our own Galaxy).

- We were also able to get some basic physics out of this. The small spread in the arrival time of the neutrinos as a function of energy allows us to set a very tight limit on the rest mass of the neutrino.
- The low luminosity seen in the light curve of SN1987A and the fact that the progenitor star was hot and blue were something of a surprise.
- It is now believed that the star was a red giant ~40,000 years before the explosion but then evolved to become a blue giant (mass exchange in a binary).
- The deeper potential well of a blue giant (denser) meant the energy went more in to ejecting material than it would have for a red giant – hence less radiation than a normal type II supernovae.

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The Expected rate of Core-collapse Supernovae

- The number of supernovae must depend on the number of stars formed as a function of their mass. This is called the Initial Mass Function, the IMF.
- The observed IMF can be fitted by a power law $n(M) \propto M^{\alpha}$.
- For stars brighter than about 0.5 $M_{\odot}$ we find that $\alpha \sim -2.3$ while the slope becomes shallower for masses less than about $0.5M_{\odot}$.
- By integrating over a mass range of 0.1 $M_{\odot}$ to 100 $M_{\odot}$, and using the limit that $M_{sn} > 8M_{\odot}$ we can find the fraction that will lead to a supernova event.
- For $\alpha \sim -2.3$ we find that the fraction that will turn into supernovae is about 1%.
- If the star formation rate is approximately constant on timescales much greater than the lifetime of the supernovae precursors then we can say that the supernova rate is approximately 1% of the star formation rate.

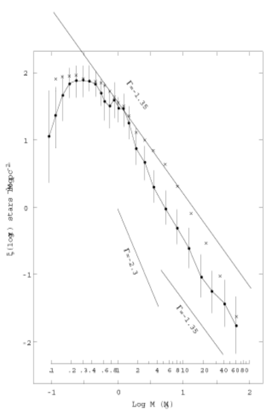

Figure 1: Field star IMF in the solar neighborhood. Plotted are star numbers per logarithmic mass interval. Crosses: solar-neighborhood IMF of [45]; points with error bars: revised field star IMF of [54]. The straight lines indicate slopes of −1.35 (Salpeter slope), and −2.3 (power-law approximation to the high-mass end of the Miller-Scalo IMF) at arbitrary normalization. The extrapolation of the Salpeter IMF to 0.1 $M_{\odot}$ highlights the difference between this IMF and a more realistic IMF with a flattening at low masses.

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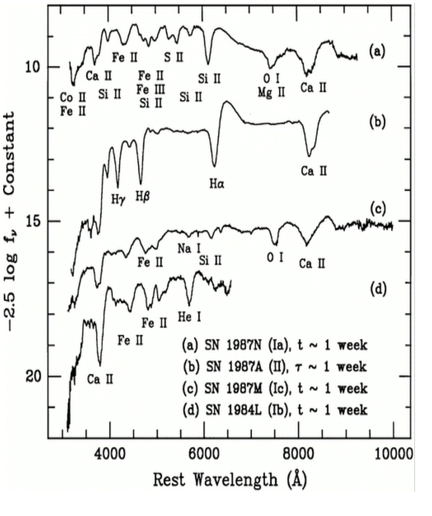
Expected rate of core-collapse Supernovae

- Averaged over many star forming regions this is probably a reasonable assumption.
- We can make various crude estimates of the star formation rate within a large galaxy like the Milky Way.
- The star formation rate, $R^* \sim N_{stars}$/ Age (lifetime).
- $N_{stars} \sim$ (galaxy luminosity)/$L_\odot$
- Or $N_{stars} \sim$ (galaxy mass in stars)/$M_\odot$
- We can get an idea of the galaxy mass because of the circular velocity of the sun about the galactic centre obeys $v^2 \sim GM/R$.
- From this we will deduce that we expect to have a small number ~ 1 per year.
- In fact we see a much lower rate than that in practice. The fraction of the mass in the galaxy in unobscured stars that are bright enough to evolve to produce supernovae is small and so we would predict perhaps only one supernova seen from Earth every 100 years.
- Last two in our galaxy: SN1572 (V = -4) and SN1604 (V = -2.5). We're overdue one!

Supernovae: Observed Properties

- Recall that Type II supernovae have strong hydrogen lines whereas the Type I have no hydrogen but lines of He, Fe, Si, Ca, Co are prominent.
- The absorption lines are very broad and are displaced blue-ward of the systemic velocity of the precursor star. This implies a high velocity (10,000-20,000 km s^{-1}) outflow of material, with P Cygni line profiles.
- Supernovae reach an extreme luminosity, comparable with the entire host galaxy ($M_v \sim$ -18 to –20), in just a few days followed by a much slower decline over many years.
- The form of the light curve tells us a great deal about the energy sources that drive the expanding supernova shell.



Supernovae: Observed Properties

P Cygni Profiles

- This type of line profile was named after the first star that was studied which showed this phenomenon (not a supernova).
- It is seen in a number of different kinds of objects including hot massive stars (where it is caused by a stellar wind), pre-main sequence stars such as T Tauri stars and in supernovae.
- The profile is produced by an expanding shell which absorbs light from the central source and emits light of its own .
- The emission peak comes from material moving at right angles to the line of sight while the blue-shifted absorption feature is caused by the approaching matter which intercepts photons coming from the central star.

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P Cygni profiles

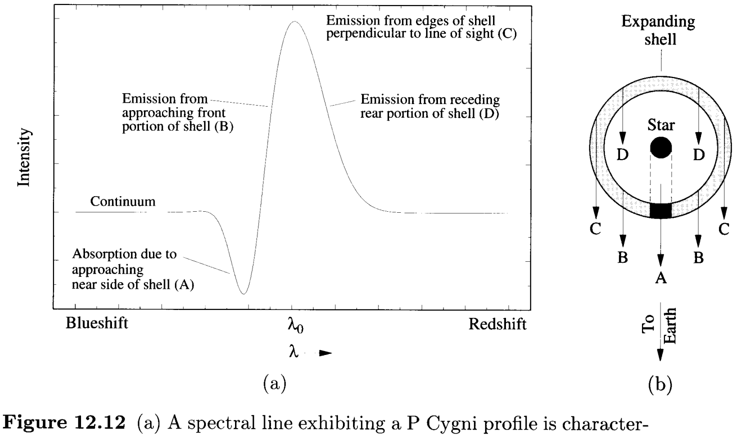

Figure 12.12 (a) A spectral line exhibiting a P Cygni profile is characterized by a broad emission peak with a superimposed blueshifted absorption trough. (b) A P Cygni profile is produced by an expanding mass shell. The emission peak is due to the outward movement of material perpendicular to the line of sight, while the blueshifted absorption feature is caused by the approaching matter in the shaded region, intercepting photons coming from the central star.

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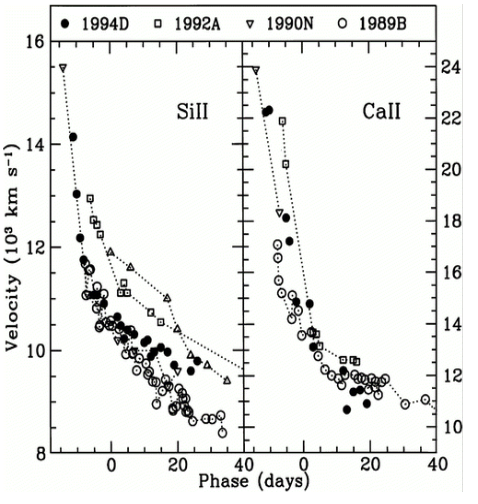
Supernovae: Observed Properties

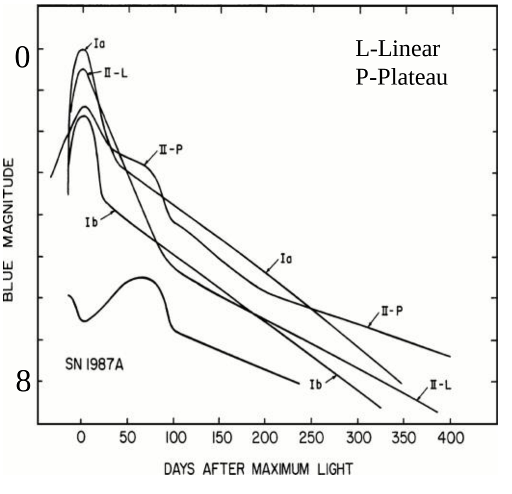
- In supernovae the shock wave moves through the star and raises the temperature so dramatically that explosive nucleosynthesis occurs.
- When R ~ 2000 km, T ~ 10^{10} K and E ~ 10^{44} J.
- It is in this expanding shell that the very heaviest elements are formed, from Fe up to uranium (endothermic reactions).
- It is a major source of enrichment of the interstellar medium.
- Most of the elements CNO and above arise from such supernovae events.
- In addition a number of unstable isotopes are formed which decay with time.
- By measuring the spectrum accurately we can plot the way that the expansion is decelerating due to interaction with the interstellar medium.



See P-Cygni profiles discussed earlier

Supernovae: Observed Properties: Light Curves

- The light curves of SN are complicated.
- They decay gradually but a variety of different physical processes must be taking place in the rapidly expanding shells where the physical conditions are themselves changing very rapidly.
- One of the things that turns out to be very important is the radioactive decay of unstable isotopes which are generated as the shock passes through the outer layers of the star's atmosphere.
- For example the decay of ^{56}Ni with a half life of 6.1 days, and the decay of ^{56}Co with a half life of 77.7 days can be seen in these light curves.
- $^{56}Ni \rightarrow {}^{56}Co + e^+ + \nu_e + \gamma$ and $^{56}Co \rightarrow {}^{56}Fe + e^+ + \nu_e + \gamma$
- Also ^{57}Co has a half life of 271 days.



Supernovae: Observed Properties: Radioactive Decay

- It is the energy that is released by the decay of these isotopes that powers the expanding supernovae remnants.
- Decay rates of species: $\frac{dN}{dt} = -\lambda N$
- Energy deposition rate: $\propto \frac{d}{dt}\left[\frac{1}{L}\frac{dL}{dt} = -\lambda\right]$

$$\frac{d\log_e L}{dt} = -\lambda$$

- Light curve slope: $\frac{d\log_{10} L}{dt} = -0.434\lambda$

$$\frac{\dot{N}}{N} = \frac{\dot{L}}{L} = -\lambda$$

- > slope of mag vs t: $\gg \frac{dM}{dt} = -1.086\lambda$
- Can show that: $\text{and } \tau_{\frac{1}{2}} = \frac{\log_e 2}{\lambda}$
- We can deduce the half life from the rate at which the magnitude declines and therefore can identify the decaying species.

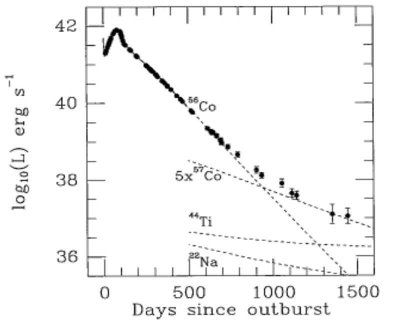


FIG. 2.—Bolometric evolution of SN 1987A through day 1444. The solid line from day 1 to 500 represents the estimates of the bolometric flux based on the *U* to *M* integration (see Suntzeff & Bouchet 1990), and the filled circles represents the *U* to 20 μm integration. The dotted lines represent the estimates for the energy deposition (WPH89) for the four radioactive nuclides, except that the ^{57}Co has been raised to 5 times solar. The initial masses of these radioactive nuclides are: ^{56}Ni (and subsequently ^{56}Co), 0.075 $M_{\odot}$; ^{44}Ti, 1×10^{-4} $M_{\odot}$; ^{22}Na, 2×10^{-6} $M_{\odot}$; and ^{57}Co, 0.009 $M_{\odot}$ (5 times solar). By day 700, the observed bolometric flux is greater than the amount of energy deposited by ^{56}Co and another energy source is present.

This is a powerful test of the theory of the way the shock waves pass through the shell and of explosive nucleosynthesis. The large amounts of ^{56}Ni explain why the light curve of Type II-P supernovae have such a clear plateau.

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Type Ia Supernovae

- We have seen that Type II Supernovae are triggered by the core collapse of massive young stars in star forming regions. There is a large range of mass of the precursor star with a variety of different envelope properties and evolutionary states.
- Type II SN are very luminous but the peak luminosity varies by more than four magnitudes.
- Hydrogen is present in the spectrum as the outer layers of the star were never subject to nuclear burning.
- However, the Type Ia Supernova are different.
- These are generally not associated with star forming regions but rather are seen in places where the stellar population is almost exclusively made up of older stars.
- The spectrum show no evidence of hydrogen but lots of Fe and other elements around Fe in the periodic table.
- There is much more consistency between the light curves of different Type Ia supernovae than is found for other supernovae types.
- It is believed that what happens here is that matter from the outer envelope of a star is dumped onto the surface of a white dwarf (which is mostly made of carbon). As its mass increases it gets very close to the Chandrasekhar limit.
- This causes an explosion of the white dwarf – a Type Ia supernova.
- The explosion is thermonuclear, C $\rightarrow$ Fe and Fe peak elements.

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Type Ia Supernovae

- The current view is that the Chandrasekhar limit is never actually attained, so that collapse is never initiated. No neutron star is formed and there is no neutrino burst.
- Instead, the increase in pressure raises the temperature near the centre, and a period of convection lasting approximately 1,000 years begins.
- At some point in this simmering phase, carbon fusion occurs—the location and number of points where it happens is still unknown.
- Oxygen fusion is initiated shortly thereafter, but this fuel is not consumed as completely as carbon.
- Once fusion has begun, the temperature of the white dwarf starts to rise.
- Degeneracy pressure is independent of temperature, so the white dwarf is unable to regulate the burning process in the manner of normal stars. The nuclear reactions run away. It is a bit like the Helium flash for low mass stars but much more violent.
- A substantial fraction of the carbon and oxygen in the white dwarf is burned into heavier elements within a period of only a few seconds, raising the internal temperature to billions of degrees.
- This energy release from thermonuclear burning ($\approx 10^{46}$ J) is more than enough to totally disrupt the star. Matter is typically ejected at speeds on the order of 5-20,000 km/s, or roughly 3% of the speed of light.
- The typical visual absolute magnitude of a Type Ia supernovae is M_v = -19.3.

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Supernovae rates in the Milky Way

- In our Milky Way Galaxy the supernova rate is estimated to be:

  2.5 ± 0.8 per 100 years or one every 40 ± 13 years

- Type II SN make up 78% of the rate
- Type Ib SN make up ~7% of the rate
- Type Ia SN make up ~15%
- The Type II and Type Ib SN occur in the young thin disk
- The Type Ia SN occur in the older thick disk
- There have been 5 visible SN in the last ~1000 years
- The predicted rate of visible SN is ~ one every 300 years

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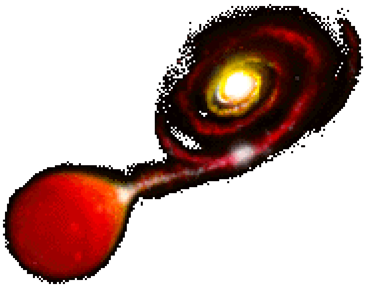
Type Ia Supernovae: Formation

- In a binary star the more massive star will evolve into a white dwarf first. Later the atmosphere of the smaller star will start to expand as it approaches the red giant phase in its evolution. If it is a close binary system then the outer atmosphere of this expanding red giant can extend beyond the gravitational saddle point between the two stars and end up on the surface of the white dwarf.
- The white dwarf finds its mass increasing and eventually when it gets near the Chandrasekhar mass limit it will create a supernova explosion.
- Unlike the Type II Supernovae, the critical mass at which this happens is well-defined, the composition of the material being dumped onto the surface of the star is also known and therefore the behaviour of these explosions is always very similar.
- In principle this means that Type Ia Supernovae will make ideal standard candles.



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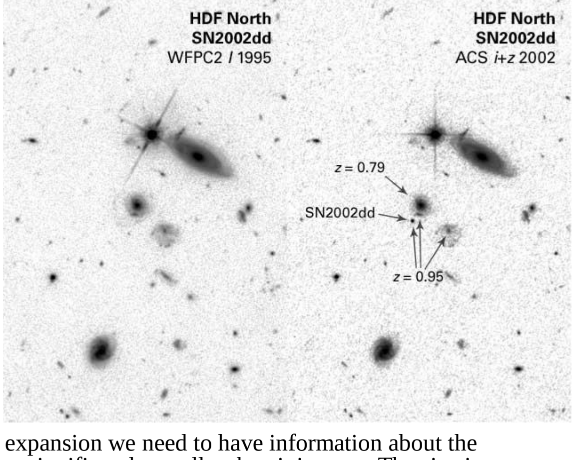
Type Ia Supernovae as Standard Candles

- In order to understand the expansion of the universe, and in particular to discover whether there is any change in the rate of expansion of the universe, type Ia supernovae provide a key diagnostic of the geometry and matter content of the universe.
- The cosmological model provides a relationship between the red shift and the distance so that, for example, the more matter the universe contains, the greater the rate of deceleration.



- To measure the rate of change in expansion we need to have information about the universe at some stage when it was significantly smaller than it is now. The size is inversely proportional to $1/(1+z)$ where z = redshift = $\Delta\lambda/\lambda$.
- This means that the universe was half its present size at a redshift of $z = 1$.
- Type Ia supernovae are bright enough to be used as standard candles at high redshifts. The pictures show a very high red shift (z=0.95) supernova that occurred.

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Type Ia Supernovae as Standard Candles

- The absolute magnitudes and the light curves of these supernovae are not all identical. The range of absolute magnitudes is more than one magnitude and the decay times vary by nearly x2.
- However an empirical relationship has been established between the absolute magnitude at the peak of an event and the rate of decline of its light curve.
- There is a further problem that observations are not in practice made at the same rest wavelength. The very substantial red-shift of the most distant object means that they are often observed at a rest wavelength in the ultraviolet whereas nearby ones with which they are being compared are observed in the visible.
- Nevertheless astronomers have developed methods of stretching and scaling the light curves so that they can be put on a single scale.
- There have now been major observational surveys (in 1987, 20 were found: in 1999 177 were found and in 2002, 296 were found). Within the redshift range z= 0.5 to 1, tens of SN were detected.
- There are two groups principally interested in this, one in Berkeley and one Harvard. Both groups find the same answer: distant SN appear dimmer than we'd expect implying that the expansion rate of the universe is not slowing down as fast as we expect from gravity alone.
- The interpretation of this may be quite complicated. It could be due to:

1. Something wrong with General relativity or cosmology
2. A repulsive force, some kind of dark energy density
3. A problem with Type Ia SN as standard candles (for example are they really all of the same composition?) We know that the earliest stars would have formed out of the gas that had not been enriched whereas more recent ones would have already had some kind of chemical history.
4. Possibly the universe is not as transparent as we think if there is a moderate amount of dust.

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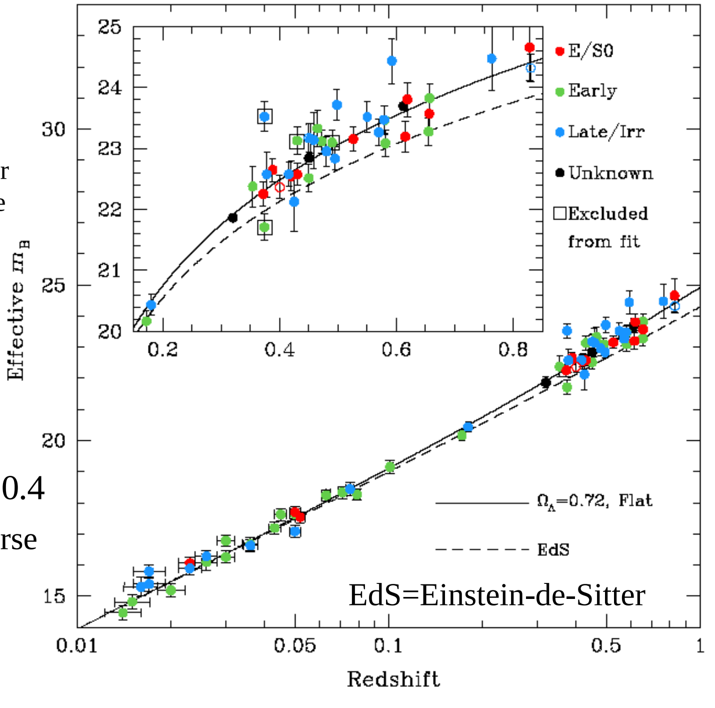
$\Lambda \neq 0$!?

Hubble diagram for distant super-novae



Best fits give

$$\Omega_\Lambda \sim 1.3\Omega_M + 0.4$$

For a flat universe Ω_Λ=0.72 and Ω_M=0.28

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The Evolution of Supernova Remnants

- We have seen that when a supernova explodes the material is ejected into the interstellar medium at a high velocity, typically 20,000 km s^{-1}.
- The interstellar medium (ISM) is of very low density, it has a temperature of ~ 10,000 K and it consists mostly of ionised hydrogen.
- Let us assume that the interstellar medium is a perfect gas, so that P = nkT.
- The sound speed in the ISM , $c_s^2 = P/\rho = kT/m_p \sim 10$ km s^{-1}.
- Therefore as the SNR expands it creates a shock wave.
- The supernova remnant evolves through three distinct phases:

1. *Free expansion phase*

- Here the expansion velocity v ~ constant, ~ 0.1 c. The radius of the supernovae remnant increases linearly with time since the explosion. The temperature of the remnant is high, generating x-rays and gamma rays. This phase will continue until the mass of the ISM swept up is ~ M_{ejecta}. This phase will last approximately 1000 years.

2. *Snowplough phase*

- Once the amount of matter in the ISM swept up is > M_{ejecta}, then the remnant will slow down and cool down. This leads to more emission at optical wavelengths.

3. *Fade away into the ISM phase.*

- In this phase the swept up mass is much greater than the amount of matter ejected from the supernovae and the expansion velocity reduces to something comparable with the random velocities in the interstellar medium which will be of the order of the sound speed, ~ 10 km s^{-1}.

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The Evolution of Supernova Remnants

- What happens in the shock front itself? We can look at it in either the frame of the interstellar medium or in the rest frame of the shock (which is actually a lot more useful).

- In the frame of the static interstellar medium we have:

Going this way

Shocked material	||	Quiescent ISM
High velocity	||	Low velocity
High temperature	||	Low temperature
Higher density	||	Low density

- In the rest frame of the shock (more useful) we have:

Velocity v_2	||	Velocity v_1
Density ρ_2	||	Density ρ_1
Temperature T_2	||	Temperature T_1
Pressure P_2	||	Pressure P_1 (~0)

- We conserve mass so $\rho_1 v_1 = \rho_2 v_{2.}$
- We conserve momentum so that $P_1 + \rho_1 v_1 * v_1 = P_2 + \rho_2 v_2 * v_2$
- We also conserve energy. There are three components of the energy:
- The kinetic energy of the bulk of gas, $\frac{1}{2}mv^2$, the internal energy of the gas motion of gas particles, and the work done on the gas at the shock front.

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The Evolution of Supernova Remnants

- We then estimate the work done as being the difference between the bulk kinetic energy coming into the shock front less the bulk kinetic energy leaving the shock front plus its internal energy.

$$v_1\left(\frac{1}{2}\rho_1 v_1^2\right) - v_2\left(\frac{1}{2}\rho_2 v_2^2 + \frac{3}{2}P_2\right) = v_2 P_2$$

bulk KE in – bulk KE out – int. E = work done

- Eliminate P_2 and v_1 using previous equations: $\left(\frac{\rho_2}{\rho_1}\right)^2 . \mathrm{v}_2^{\,3} - 5\frac{\rho_2}{\rho_1}.\mathrm{v}_2^{\,3} + 4.\mathrm{v}_2^{\,3} = 0$
- Cancelling out the v_2^3 term gives us a quadratic equation: $\left(\frac{\rho_2}{\rho_1} - 4\right)\left(\frac{\rho_2}{\rho_1} - 1\right) = 0$

  with solutions: so $\rho_1 = \rho_2$ or $\rho_2 = 4\rho_1, \mathrm{v}_1 = 4\mathrm{v}_2$
- Only in this case (2) does something happen: $P_2 = \frac{\rho_2}{\mu M_H}.kT_2$
- From this we get the temperature of the ideal gas using: $or : T_2 = \frac{P_2 \mu M_H}{\rho_2 k}$
  (μ is the mean molecular weight, M_H the mass of hydrogen)

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The Evolution of Supernova Remnants

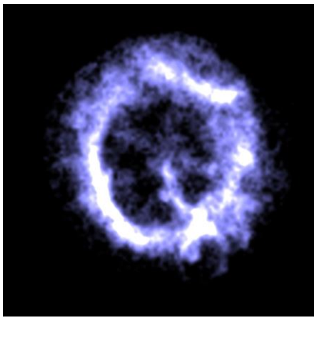
- We use momentum conservation from above to eliminate P_2. $P_2 = \left(\rho_1 \mathrm{v}_1^{\,2} - \rho_2 \mathrm{v}_2^{\,2}\right)$

$$>> T_2 = \frac{\left(\rho_1 \mathrm{v}_1^{\,2} - \rho_2 \mathrm{v}_2^{\,2}\right)\mu M_H}{k}$$

- From earlier calculations we have: $\rho_2 = 4\rho_1, \mathrm{v}_1 = 4\mathrm{v}_2$
- And so we get T in terms of the ejecta velocity. $>> T_2 = \frac{3.\mu M_H}{16k}\mathrm{v}_1^{\,2}$

- From observations we know that the ejection velocity is > 10,000 km s^{-1}, so this implies that the gas is raised to a temperature T ~ 10^7 K.
- Equating hν = kT, we see that the radiation emitted by the shock front is going to be at x-ray energies.

- E0102-72 is a supernova remnant in the Small Magellanic Cloud, a satellite galaxy of the Milky Way. This galaxy is 190,000 light years (55Kpc) from Earth.
- E0102 -72, which is approximately a thousand years old, is believed to have resulted from the explosion of a massive star. Stretching across forty light years (12pc) of space, the multi-million degree source resembles a flaming cosmic wheel.
- This is an x-ray image taken by the Chandra X-ray satellite.



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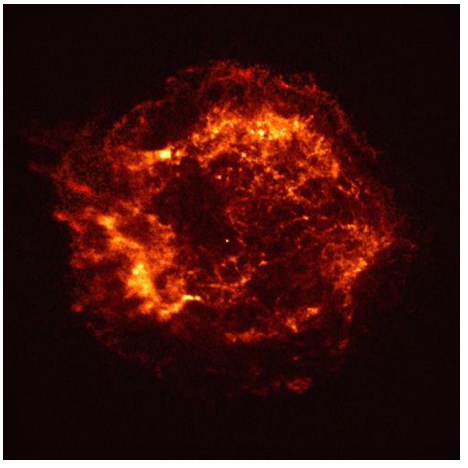
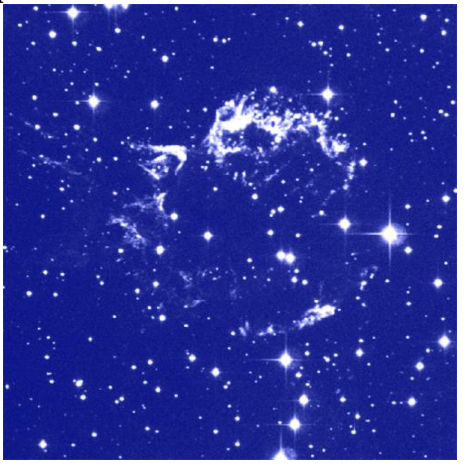
The Evolution of Supernova Remnants





- This is the supernovae remnant known as Cassiopeia A. It is approximately 330 years old and at a distance of 3 kparsecs. Its diameter is about 3 parsecs. The gas has a temperature T ~ 5 x 10 ^{6} K.
- These two images are (on the left) an x-ray image taken with Chandra satellite (note the remarkable angular resolution of better than one arc second), and on the right a picture of the same supernovae remnant taken in the optical where the gas that is imaged has a temperature T ~ 10 ^{4} K.

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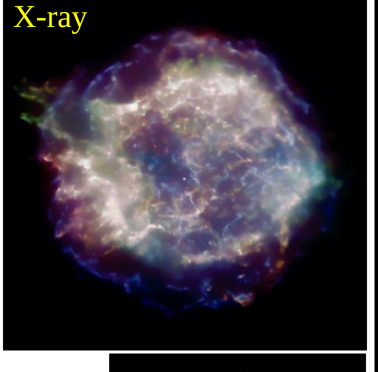
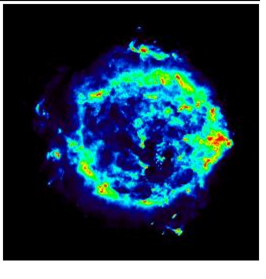
Cassiopeia A (SNR)





Radio

IR, 4.5 microns

Exploded about 330 years ago

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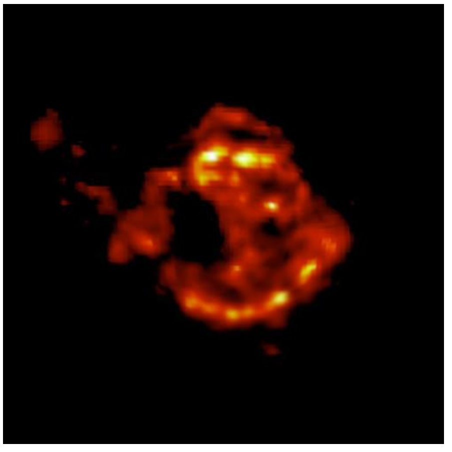
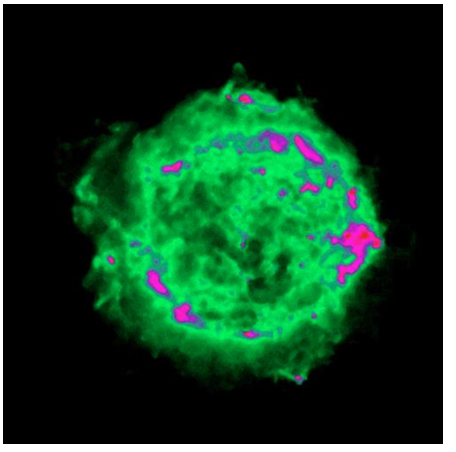
The Evolution of Supernova Remnants





- Two further images of Cassiopeia A are shown here.
- The one on the left is an infrared (15 micron) image taken with the ISO satellite and where most of the emission is from hot dust with a temperature T ~ 200 K. The dust may have been ejected in a mass loss phase before the supernovae or possibly as part of the supernovae explosion .
- On the right is shown an image taken at radio wavelengths by the VLA (very large array) at a wavelength of 21 cms, where most of the emission is non-thermal synchrotron emission.

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The Evolution of Supernova Remnants

- What do we know about the expansion rates?
- At early times the velocity of ejection is approximately constant, and the radius goes up linearly with time.
- At later times the mass swept up from the ISM is significant. We may assume that initially the losses are not significant (principally because there are no efficient cooling mechanisms) and therefore we find that the shock is being driven by pressure.
- This gives us:

$$P \propto \rho v^2 \propto \frac{E}{r^3}$$

$$v = \frac{dr}{dt} >> \frac{dr}{dt} \propto r^{\frac{-3}{2}}$$

- We integrate:

$$\int r^{\frac{3}{2}} dr = \int dt >> r^{\frac{5}{2}} = at + c$$

- The boundary condition is:

$$r = 0 \text{ at } t = 0 >> c = 0$$

- Showing that the expansion is slowed down a lot.

$$>> r \propto t^{\frac{2}{5}}$$

- Eventually the temperature drops to a point where there are many more cooling mechanisms and there are large losses of energy through radiation.
- Eventually the remnant slows down and merges into the ISM.
- Supernovae are important because they are the main source of elements with masses > Fe, a major source of energy injection into the ISM, and a trigger for further generations of star formation, and the high temperatures in the shocks are a source of high-energy photons and particles as well as cosmic rays.

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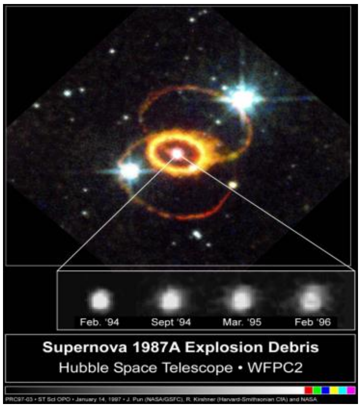
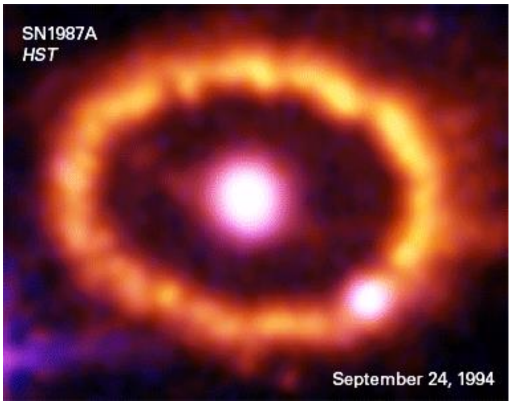
SN1987a Recent Results





- The supernovae which in these pictures is just becoming resolved, is only the central object, and it illuminates rings of material which were present long before the supernovae exploded.
- In the right hand image you can see the expanding shock wave from the central supernovae progressively excites more of the gas blobs in the ring which then produce hydrogen emission lines.
- The supernovae is not ejecting material symmetrically, with the main expansion being perpendicular to the pre-existing ring of gas.

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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 by the Vela spacecraft launched to check on undeclared nuclear weapons testing after the first test ban treaty.
- The detection of these bursts was not de-classified until 1973 once it had been demonstrated that the Sun was not the source.
- Since then, many more sophisticated burst detectors have flown.
- There are now about many thousands of observational and theoretical papers that have been written about them and yet they remain one of the least well understood of all objects observed in the universe.
- They must not be confused with soft gamma ray repeaters (SGRs) of which only three are known and are now identified with supernovae remnants. We will not consider these further.
- We will deal with classical gamma ray bursts. Sometimes their sources are called gamma ray bursters.
- Our main data come 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) and SWIFT, launched in 2004.
- Two good references may be found at: "From gamma-ray bursts to fast radio bursts" by Sri Kulkarni, Nature Astronomy, **2**, pages 832–835(2018), and "Short-Duration Gamma-Ray Bursts", Edo Berger, Annual Review of Astronomy and Astrophysics 2014 52:1, 43-105

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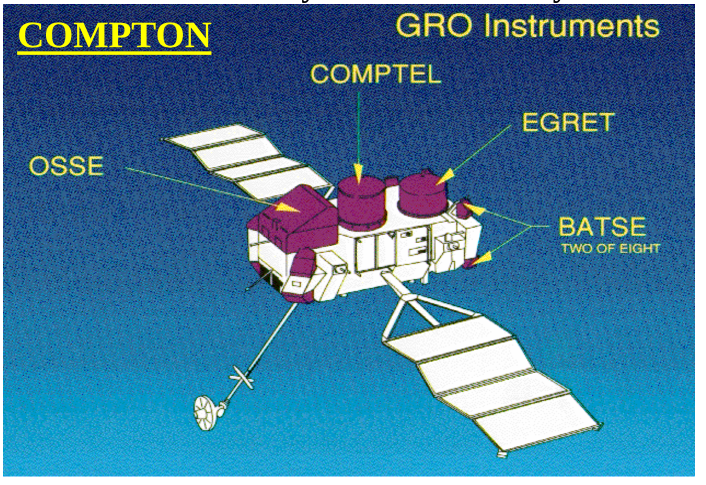
Gamma-Ray Bursts: Discovery



- 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).

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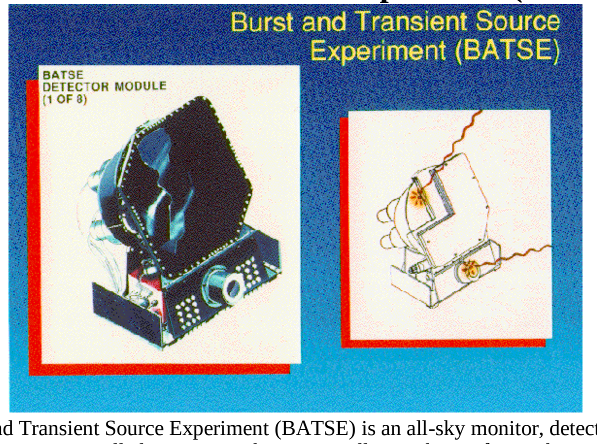
Burst And Transient Source Experiment (BATSE)



- The Burst And Transient Source Experiment (BATSE) is 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 are eight BATSE detectors, one facing outward from each corner of the satellite, which are sensitive to gamma-ray energies from 20 keV to over one MeV.
- At the heart of the BATSE detectors are NaI crystals which produce a flash of visible light when struck by gamma rays. The flashes are recorded by light-sensitive detectors whose output signal is digitized and analyzed to determine the arrival time and energy of the gamma ray which caused the flash. Each BATSE detector unit consists of a large area detector sensitive to faint transient events along with a smaller detector optimized for spectroscopic studies of bright events.

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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.

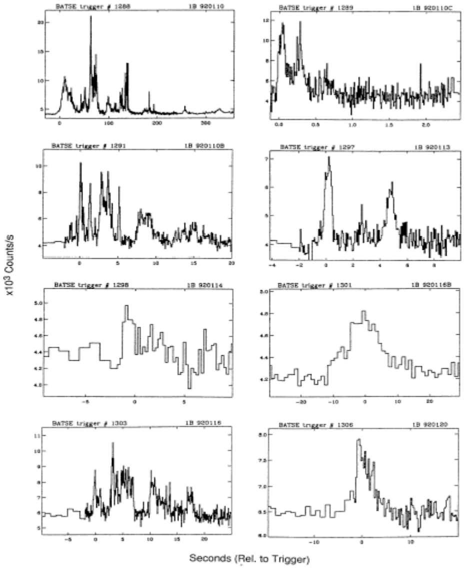

Figure 1 Sample page from the *First BATSE Catalog of Gamma-Ray Bursts* (Fishman et al 1994b), indicating the diversity in the time profiles, intensities, and durations of gamma-ray bursts.

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Gamma Ray Bursts: General Characteristics

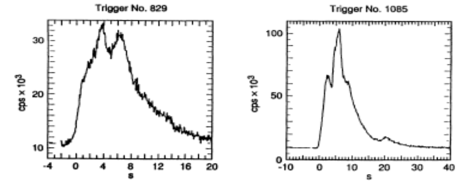


Figure 2 Examples of strong bursts that show no structures on fine time scales.

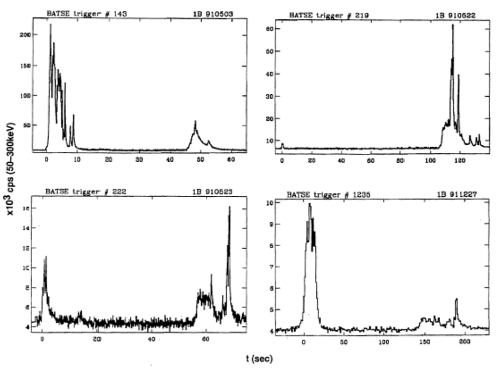


Figure 3 Some gamma-ray bursts that have distinct, well-separated episodes of emission.

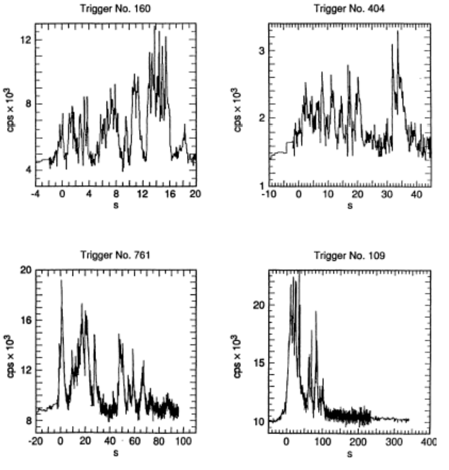
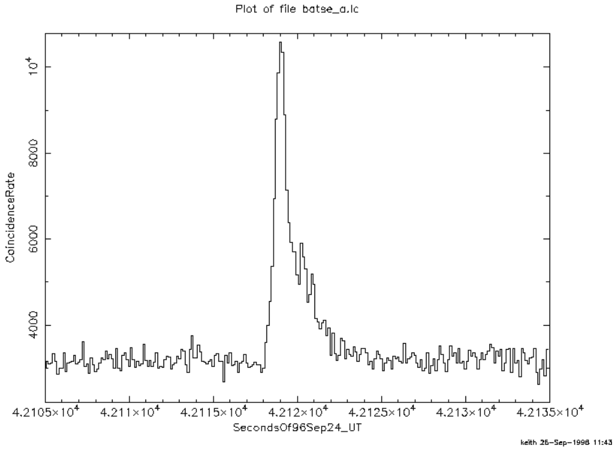


Figure 4 Examples of gamma-ray bursts with extremely complex temporal structures.

Gamma Ray Bursts: General Characteristics



- BATSE has four energy channels that provide good information on the gamma ray spectrum for each burst.
- It detected about 2700 burst 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.

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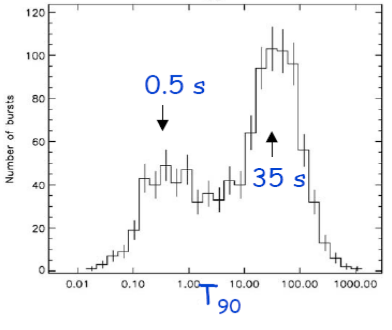
Gamma Ray Bursts: Temporal Characteristics



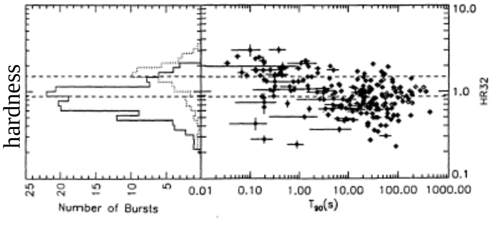


Figure 7 The hardness vs duration of gamma-ray bursts. The shorter bursts tend to have harder spectra, as measured by a hardness ratio. (From Kouveliotou et al 1993b.)

- 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.
- 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).

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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: $N(E) = BE^{\beta}, \alpha > \beta$

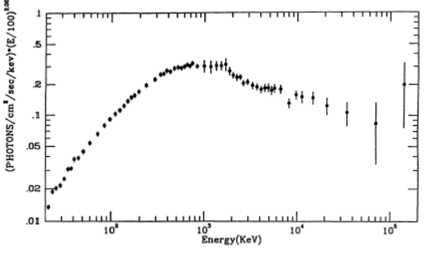

Figure 10 The spectrum of GB 910503, measured by all four experiments on the *Compton Gamma Ray Observatory* (Schaefer et al 1994d).

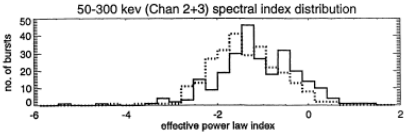

Figure 11 The distribution of power-law indices for a large number of bursts, as measured by the BATSE large-area detectors. (From Pendleton et al 1994c.)

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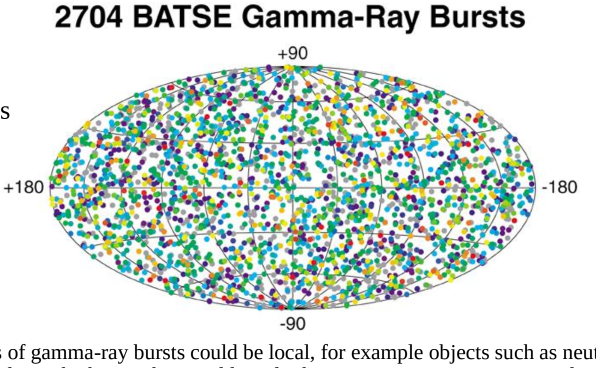
Gamma Ray Bursts: Spatial Distribution

Galactic coordinates



- 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.

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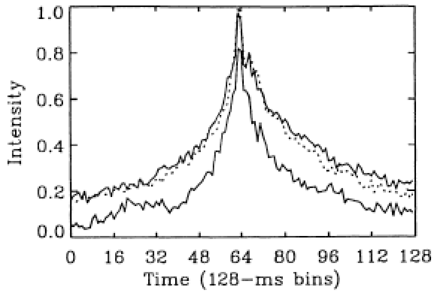
Gamma-ray Bursts: Time Dilation

- 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

$$t_{observed} = t_{restframe}(1+z), \qquad \text{where } z \text{ is the redshift.}$$

- Given the wide variety of properties of different bursts it is a difficult experiment to perform.

- How can we measure Δt?
- 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.



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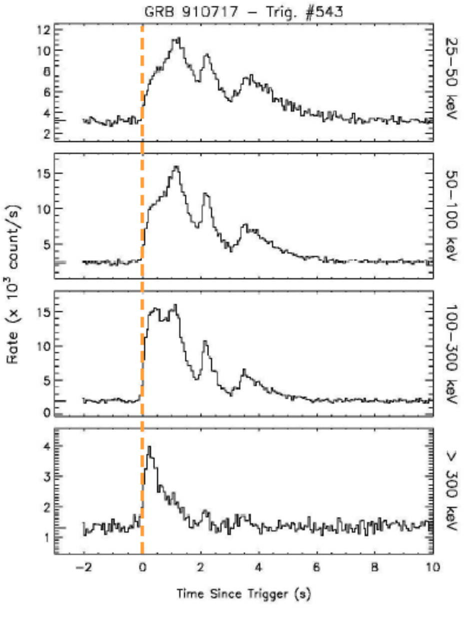
Gamma-ray Bursts: Pulse Delays

- 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.



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GRB satellites

- Compton/BATSE - launched 1991
- HETE-2 - launched 1996
- Beppo-SAX – x and γ, launched April 1996
- Integral – launched Oct 2002
- SWIFT- launched Nov 2004
- GLAST - Gamma-ray Large Area Space Telescope, later renamed the Fermi Gamma-ray Space Telescope, launched 2008
- ASCA – 1993-2000, x-rays
- RXTE – x-rays, launched 1995
- Detections can be “triangulated” to pin down position on sky for rapid follow-up observations both from the ground and from space.

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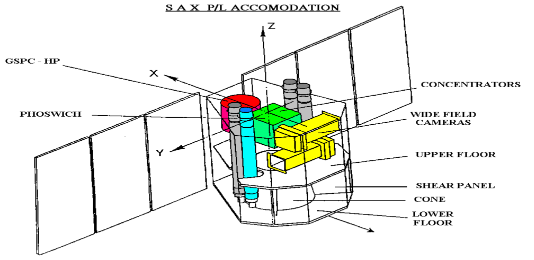
Gamma Ray Bursts: the Search for Counterparts



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 also rapidly begin to look for the afterglow using the Beppo-Sax position.

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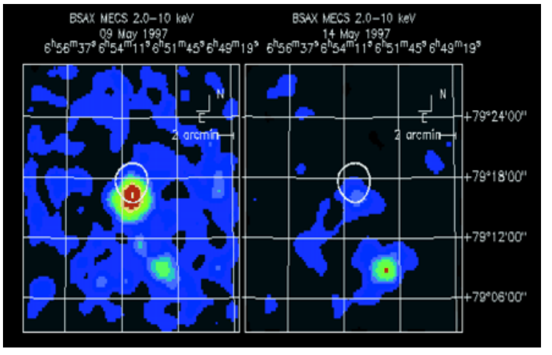
Gamma Ray Bursts: the Search for Counterparts



- 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.

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SWIFT
(now The Neil Gehrels Swift Observatory)

launched 20th Nov 2004.

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

Had observed ~1500 GRBs up to present (~2 per week).

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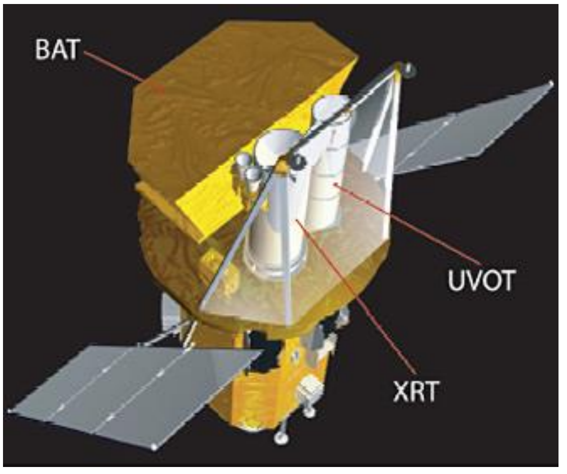

SWIFT

- 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 as soon as possible.

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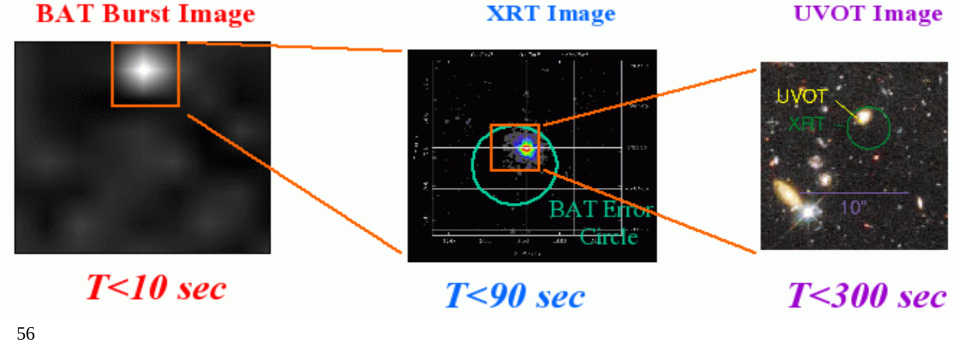
Gamma Ray Bursts: The SWIFT Mission

- 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 during the crucial first few hours.
- SWIFT is also performing the first sensitive hard X-ray survey of the sky.



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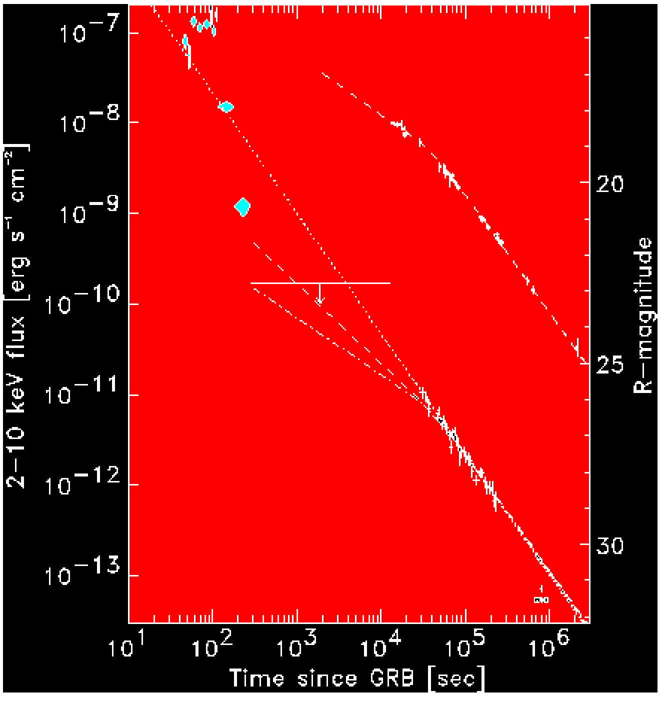
Optical image of a GRB afterglow



GRB010222

The optical and x-ray light curves

Gamma-ray burst itself lasted 5 minutes (unusually long)

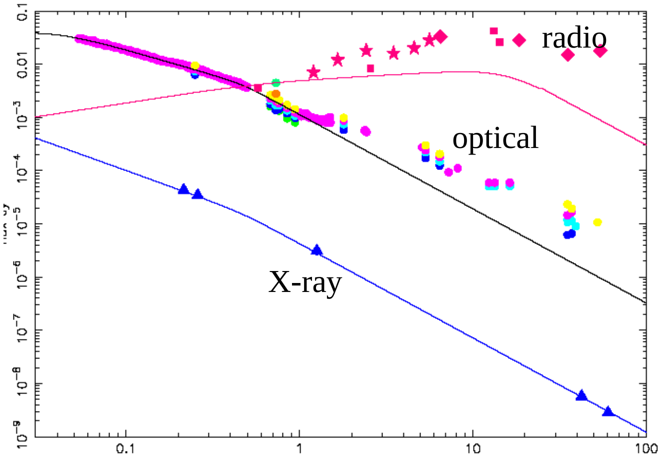


Figure 1. The afterglow flux in X-rays (1.0 keV plotted in blue), optical (V, B, R and I plotted respectively as blue, green, red and yellow dots) and radio (7.7 GHz diamond, 8.5 GHz square and 15.2 GHz star plotted in red). The curves show the best fit model in X-ray (1 keV), optical (R-band) and radio (8.5 GHz).

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

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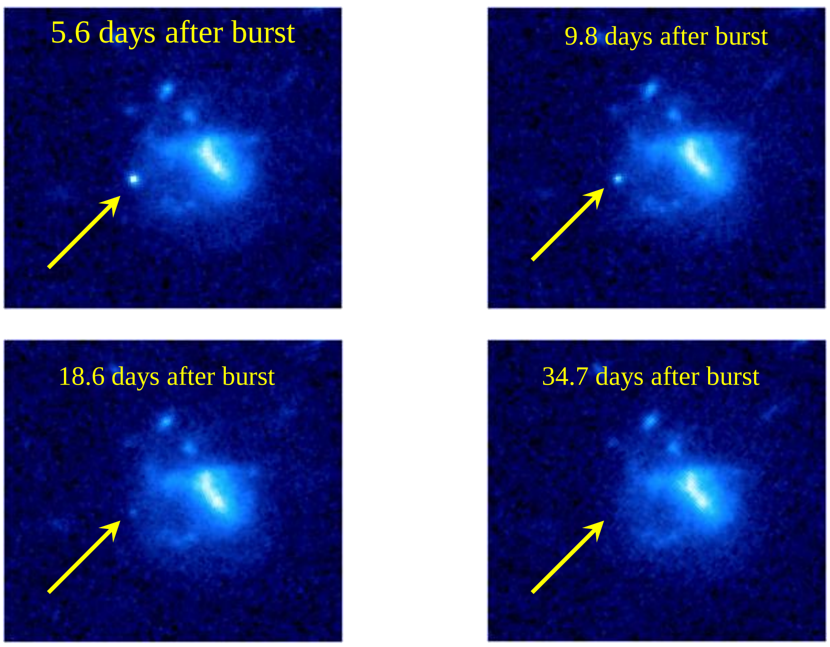

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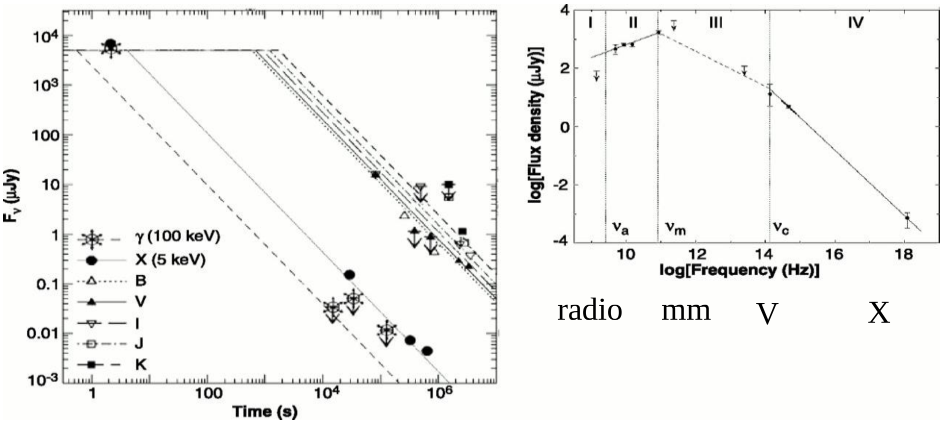
Gamma Ray Bursts: Afterglow Decay



- The typical time decay of the afterglow, seen in the x-ray region of the spectrum, has a power-law-like decay.
- Several tens of 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.

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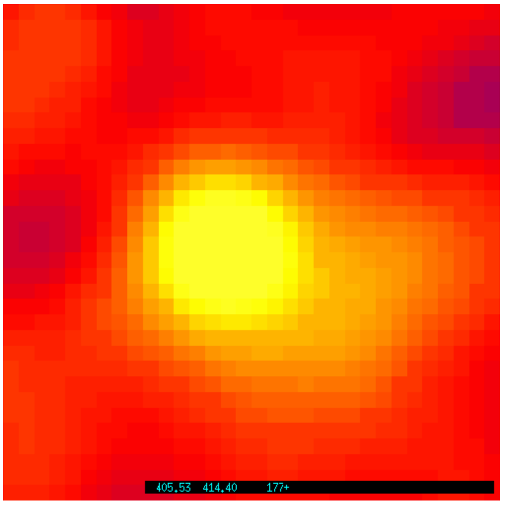
Gamma Ray Bursts: Optical Transients

- 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 but are associated with the stellar populations of galaxies.



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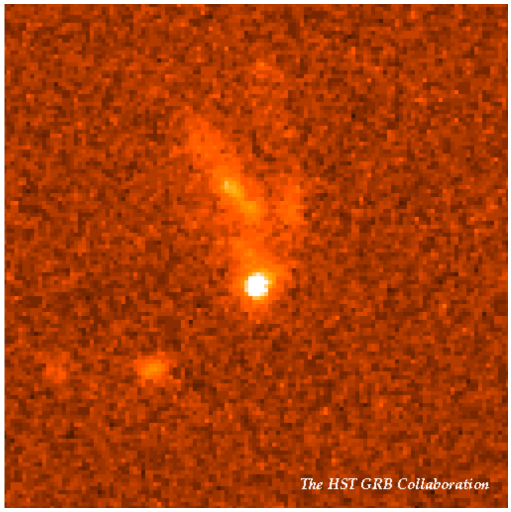
Gamma Ray Bursts: Optical Transients

GRB 990123

- 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 +/- 0.1 and the galaxy has an integrated magnitude of V=24.3 +/- 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, next slide).
- 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 $n_o = 0.02$ Mpc^{-3} so that number of galaxies ~ $n_o(4\pi/3)(ct)^3 \sim 3\times10^9$.
- This suggests that there will be ~ one burst per galaxy every 10^7 years.
- 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.

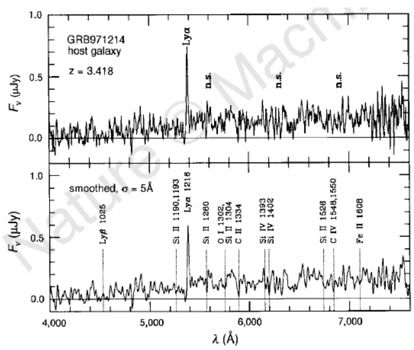
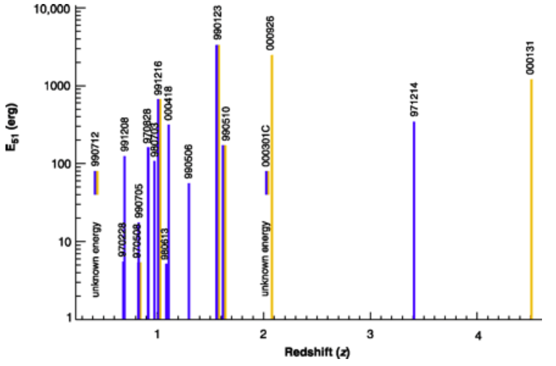


Figure 3 The composite Keck spectrum of the host galaxy of GRB971214. The top panel shows the original data, with the locations of the prominent night sky (n.s.) emission lines indicated. The bottom panel shows the same spectrum smoothed with a gaussian with $\sigma = 5$ Å, which is approximately equal to the effective instrumental resolution. Locations of several absorption features commonly seen in the spectra of $z \approx 3$ galaxies are indicated. The redshift, $z = 3.418$, has been derived from the mean point of the Lyα emission and absorption features, as described in the text. The log of the observations and the details of the spectrograph settings can be found in Table 2. The 'lower' resolution data were reduced completely independently by two of the authors (S.G.D. and K.L.A.), using independent reduction packages. The results are in an excellent mutual agreement. The 'higher' resolution data are also fully consistent with them, showing essentially the same spectroscopic features. The useful wavelength range spanned by the lower-resolution data is ~4,000–7,600 Å, and the higher-resolution data spans ~4,900–7,300 Å. All of the spectra have been averaged with appropriate signal-to-noise weighting, after suitable resampling.

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 γ-ray flux and assumes that the GRB emits the energy isotropically (which it doesn't!).

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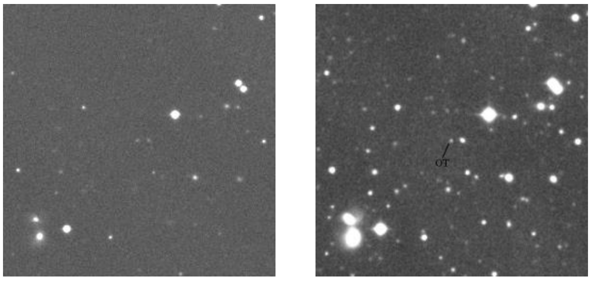
Gamma Ray Bursts: Optical Transients



- 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 x 10^{26}W) by the number of stars in a galaxy (2x10^{10}) times the number of galaxies (10^{10}). This is ~ 8 x 10^{46} W, and the brightest gamma ray bursts are ~ 10^{46} W (assuming the energy goes equally in all directions, which it doesn't).
- Some long GRBs have no detected afterglow – they maybe at enormous redshifts?

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A very high redshift Gamma Ray Burst discovered by SWIFT

- As an example of a result from SWIFT, a GRB has been found which is the most distant X-ray source ever detected.
- It is called GRB050904, and has a redshift of 6.295.
- The X-ray luminosity is 100,000 times the brightest AGNs.
- There is variability on timescales of minutes to hours.

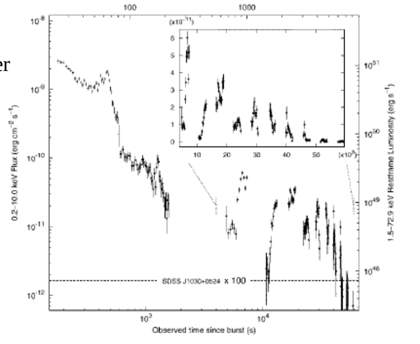

FIG. 1.—*Swift* XRT 0.2–10.0 keV light curve of GRB 050904 (~1.5–72.9 keV in the rest frame). The equivalent isotropic luminosity at $z = 6.29$ is plotted on the right axis. WT and PC mode data are indicated by crosses and dots, respectively. The flux of one of the most luminous X-ray sources known, the AGN SDSS J1030+0524, is plotted for comparison. We have had to multiply its flux by 100 to get it on the plot. SDSS J1030+0524 was the most distant known X-ray source before GRB 050904 and is, conveniently, at nearly the same redshift ($z = 6.28$). *Inset*: Linear blow-up of the data from ~10–70 ks to illustrate the variability of the source at late times. The very hard spectral index at early times ($\Gamma \sim 1.2$) and the long BAT T_{90} for this burst indicate that most of the WT mode data is dominated by prompt emission. However, the continued large-amplitude variability more than 1.5 hr after the GRB trigger (in the rest frame), and the still relatively hard spectrum ($\Gamma \sim 1.9$), suggests that the XRT light curve is dominated by emission from the central engine during the first 12 hr of observations.

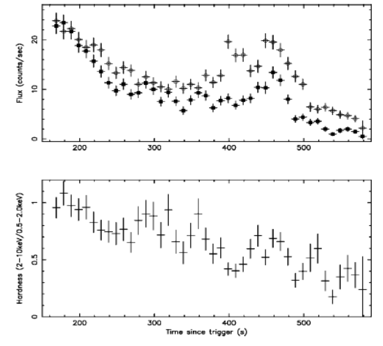

FIG. 2.—*Top*: Soft (0.5–2.0 keV; *open circles*) and hard (2–10 keV; *filled squares*) early light curve of GRB 050904. *Bottom*: Hardness ratio of the early light curve. The hard-to-soft evolution, observed in most GRB prompt emission, is fairly monotonic outside the flares, where small deviations are discernible.

- Plots from Watson et al (2006), Astrophys J., vol 637, L69 (Feb 1, 2006)

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).
- Recent data from a GRB discovered with SWIFT suggests the short duration ones come from neutron stars falling into a black hole or neutron star mergers. Old merging binaries.

- Note that Beppo-Sax is mainly sensitive to bursts longer than about 5-10 seconds.

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 formed when the blast-wave reaches the stellar surface.
- 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! $\Rightarrow$ 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.

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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 SNs.
- There are some other examples too, relating GRBs to type Ib and Ic Supernovae.

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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.

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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 $F(\upsilon) \propto \upsilon^{-\alpha}$
- 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 ~ 10^{46} Js^{-1} which is ~ 10^{14} L_{edd} for a solar mass object.
- Similarly the energy in gamma rays is ~ 10^{47} J which is ~ a supernova energy.
- The rate of gamma ray bursts is ~ 10^{-6} to 10^{-7} yr^{-1} $galaxy^{-1}$, a factor of 10^4 rarer than all supernovae.
- The characteristic temperature of these bursts is kT = 0.5 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 ~ $3x10^7$ m.

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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, γ.
- The variability timescale that we observe, dt ~ (r/c) γ^{-2} is because the relativistic velocities reduce the timescales for variability by γ^{-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} $M_{\odot}$.

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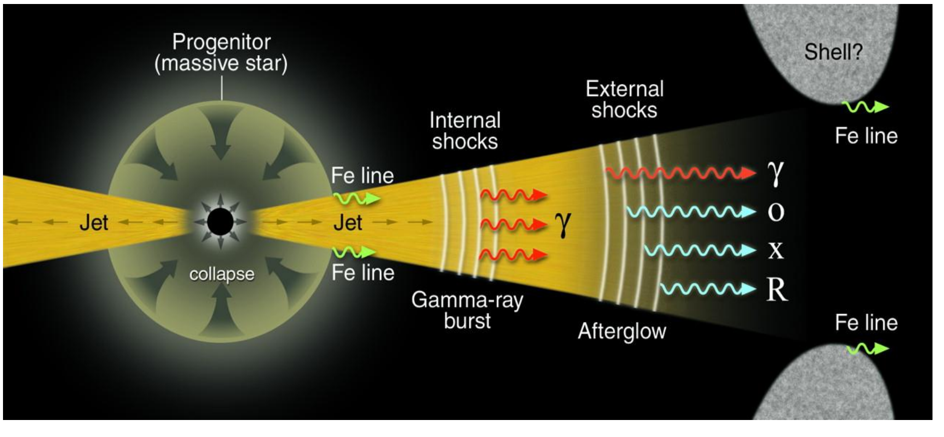
The Fireball Shock Model



- 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.

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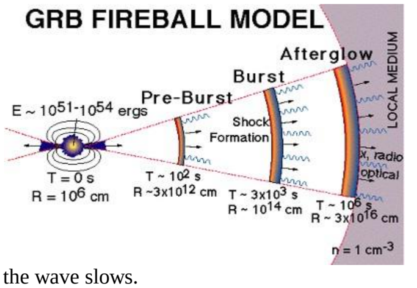
The Fireball Shock Model



- The various components we have include:
- Compact inner engine.
- Energy transport phase.
- Conversion of kinetic energy to prompt gamma radiation: this is the 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 ν_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 hours and days is then important since model-constraining flares can occur in the decaying emission.

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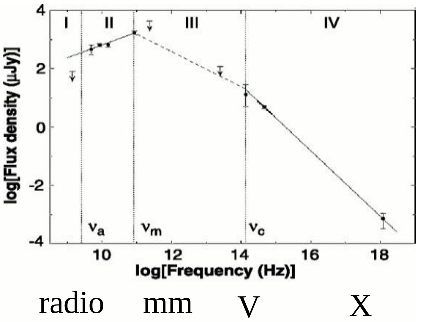
Gamma Ray Bursts: Afterglow Decay

Very early on $\nu_m > \nu_c$

Later on $\nu_m < \nu_c$

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

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



radio mm V X

- The ν_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.
- The two other break points, ν_m and ν_c, are related to the minimum energy acquired by an electron after it crosses the shock wave and the time it takes an electron to radiate most of its energy, respectively.

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