Stellar Evolution

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1 Protostar

Stellar evolution starts with the gravitational collapse of a giant molecular cloud. Typical giant molecular clouds are roughly 100 light-years (9.510^{14} km) across and contain up to 6,000,000 $M_{\odot}$ (1.210^{37} kg). As it collapses, a giant molecular cloud breaks into smaller and smaller pieces. In each of these fragments, the collapsing gas releases gravitational potential energy as heat. As its temperature and pressure increase, a fragment condenses into a rotating sphere of superhot gas known as a protostar.

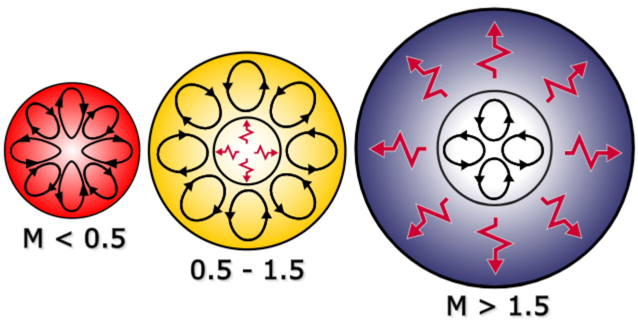
A protostar continues to grow by accretion of gas and dust from the molecular cloud, becoming a pre-main-sequence star as it reaches its final mass. Further development is determined by its mass. Mass is typically compared to the mass of the Sun: 1.0 $M_{\odot}$ (2.010^{30} kg) means 1 $M_{\odot}$.

2 Brown dwarfs and sub-stellar objects

Protostars with masses less than roughly 0.08 $M_{\odot}$ never reach temperatures high enough for nuclear fusion of hydrogen to begin. These are known as brown dwarfs.

3 Main sequence

For a more-massive protostar, the core temperature will eventually reach 10 million kelvin, initiating the protonproton chain reaction and allowing hydrogen to fuse, first to deuterium and then to helium. In stars of slightly over 1 $M_{\odot}$, the carbonnitrogenoxygen fusion reaction (CNO cycle) contributes a large portion of the energy generation. The onset of nuclear fusion leads relatively quickly to a hydrostatic equilibrium in which energy released by the core maintains a high gas pressure, balancing the weight of the star's matter and preventing further gravitational collapse.



4 Mid-sized stars: $M = (0.5 - 10)M_\odot$

4.1 Subgiant

When a star exhausts the hydrogen in its core, it leaves the main sequence and begins to fuse hydrogen in a shell outside the core. The core increases in mass as the shell produces more helium. Depending on the mass of the helium core, this continues for several million to one or two billion years, with the star expanding and cooling at a similar or slightly lower luminosity to its main sequence state. Eventually either the core becomes degenerate, in stars around the mass of the sun, or the outer layers cool sufficiently to become opaque, in more massive stars. Either of these changes cause the hydrogen shell to increase in temperature and the luminosity of the star to increase, at which point the star expands onto the red giant branch.

4.2 Red-giant-branch

The expanding outer layers of the star are convective, with the material being mixed by turbulence from near the fusing regions up to the surface of the star. For all but the lowest-mass stars, the fused material has remained deep in the stellar interior prior to this point, so the convecting envelope makes fusion products visible at the star's surface for the first time. At this stage of evolution, the results are subtle, with the largest effects, alterations to the isotopes of hydrogen and helium, being unobservable. The effects of the CNO cycle appear at the surface during the first dredge-up, with lower 12C/13C ratios and altered proportions of carbon and nitrogen. These are detectable with spectroscopy and have been measured for many evolved stars.

The helium core continues to grow on the red giant branch. It is no longer in thermal equilibrium, either degenerate or above the Schoenberg-Chandrasekhar limit, so it increases in temperature which causes the rate of fusion in the hydrogen shell to increase. The star increases in luminosity towards the tip of the red-giant branch. Red giant branch stars with a degenerate helium core all reach the tip with very similar core masses and very similar luminosities, although the more massive of the red giants become hot enough to ignite helium fusion before that point.

4.3 Horizontal branch

Low mass stars do not produce enough gravitational pressure to initiate normal helium fusion. In the helium cores of stars in the 0.8 to $M_\odot$ range, which are largely supported by electron degeneracy pressure, helium fusion will ignite on a timescale of days in a helium flash . In the non-degenerate cores of more massive stars, the ignition of helium fusion occurs relatively slowly with no flash. Due to the expansion of the core, the hydrogen fusion in the overlying layers slows and total energy generation decreases. The star contracts, although not all the way to the main sequence, and it migrates to the horizontal branch on the HertzsprungRussell diagram, gradually shrinking in radius and increasing its surface temperature.

4.3.1 Helium flash

Very brief thermal nuclear fusion, process which is accelerated by increased temperature, of large quantities of helium into carbon through the triple-alpha process in the core of low mass stars. However, a fundamental quality of degenerate matter is that changes in temperature do not produce a change of volume of the matter until the thermal pressure becomes so very high that it exceeds degeneracy pressure. In main sequence stars, thermal expansion regulates the core temperature, but in degenerate cores this does not occur. Helium fusion increases the temperature, which increases the fusion rate, which further increases the temperature in a runaway reaction. This produces a flash of very intense helium fusion that lasts only a few minutes, but briefly emits energy at a rate comparable to the entire Milky Way galaxy. In the case of normal low mass stars, the vast energy release causes much of the core to come out of degeneracy, allowing it to thermally expand (a processes requiring so much energy, it is roughly equal to the total energy released by the helium flash to begin with), and any left-over energy is absorbed into the star's upper layers. Thus the helium flash is mostly undetectable to observation, and is described solely by astrophysical models.

4.3.2 Instability stripes: pulsations

Stars in the instability strip pulsate due to He III (doubly ionized helium). In normal A-F-G stars He is neutral in the stellar photosphere. Deeper below the photosphere, at about 25,00030,000K, begins the He II layer (first He ionization). Second ionization (He III) starts at about 35,00050,000K. When the star contracts, the density and temperature of the He II layer increases. He II starts to transform into He III (second ionization). This causes the opacity of the star to increase and the energy flux from the interior of the star is effectively absorbed. The temperature of the star rises and it begins to expand. After expansion, He III begins to recombine into He II and the opacity of the star drops. This lowers the surface temperature of the star. The outer layers contract and the cycle starts from the beginning.

4.4 Asymptotic-Giant-Branch

The AGB phase is divided into two parts, the early AGB (E-AGB) and the thermally pulsing AGB (TP-AGB).

4.4.1 E-AGB

the main source of energy is helium fusion in a shell around a core consisting mostly of carbon and oxygen. During this phase, the star swells up to giant proportions to become a red giant again. The star's radius may become as large as one astronomical unit. (second dredge-ups)

4.4.2 TP-AGB

Now the star derives its energy from fusion of hydrogen in a thin shell, which restricts the inner helium shell to a very thin layer and prevents it fusing stably. However, over periods of 10,000 to 100,000 years, helium from the hydrogen shell burning builds up and eventually the helium shell ignites explosively, a process known as a helium shell flash. The luminosity of the shell flash peaks at thousands of times the total luminosity of the star, but decreases exponentially over just a few years. The shell flash causes the star to expand and cool which shuts off the hydrogen shell burning and causes strong convection in the zone between the two shells. When the helium shell burning nears the base of the hydrogen shell, the increased temperature reignites hydrogen fusion and the cycle begins again. The large but brief increase in luminosity from the helium shell flash produces an increase in the visible brightness of the star of a few tenths of a magnitude for several hundred years, a change unrelated to the brightness variations on periods of tens to hundreds of days that are common in this type of star. (third dredge-ups)

4.4.3 Stellar wind

A stellar wind is a flow of gas ejected from the upper atmosphere of a star. AGB stars suffer mass loss in the form of a stellar wind: star may lose 50% to 70% of its mass, the loss rate is $\dot{M} > 10^{-4} M_{\odot} yr^{-1}$, and $v = 20kms^{-1}$) for slow winds.

4.5 Post-AGB

These mid-range stars ultimately reach the tip of the asymptotic-giant-branch and run out of fuel for shell burning. They are not sufficiently massive to start full-scale carbon fusion, so they contract again, going through a period of post-asymptotic-giant-branch superwind to produce a planetary nebula with an extremely hot central star. The central star then cools to a white dwarf. The expelled gas is relatively rich in heavy elements created within the star and may be particularly oxygen or carbon enriched, depending on the type of the star. The gas builds up in an expanding shell called a circumstellar envelope and cools as it moves away from the star, allowing dust particles and molecules to form. With the high infrared energy input from the central star, ideal conditions are formed in these circumstellar envelopes for maser excitation.

4.6 Planetary nebula

A mechanism for formation of most planetary nebulae is thought to be the following: at the end of the star's life, during the red-giant phase, the outer layers of the star are expelled by strong stellar winds. After most of the red giant's atmosphere is dissipated, the ultraviolet radiation of the hot luminous core, called a planetary nebula nucleus (PNN), ionizes the outer layers earlier ejected from the star. Absorbed ultraviolet light energises the shell of nebulous gas around the central star, causing it to appear as a brightly coloured planetary nebula.

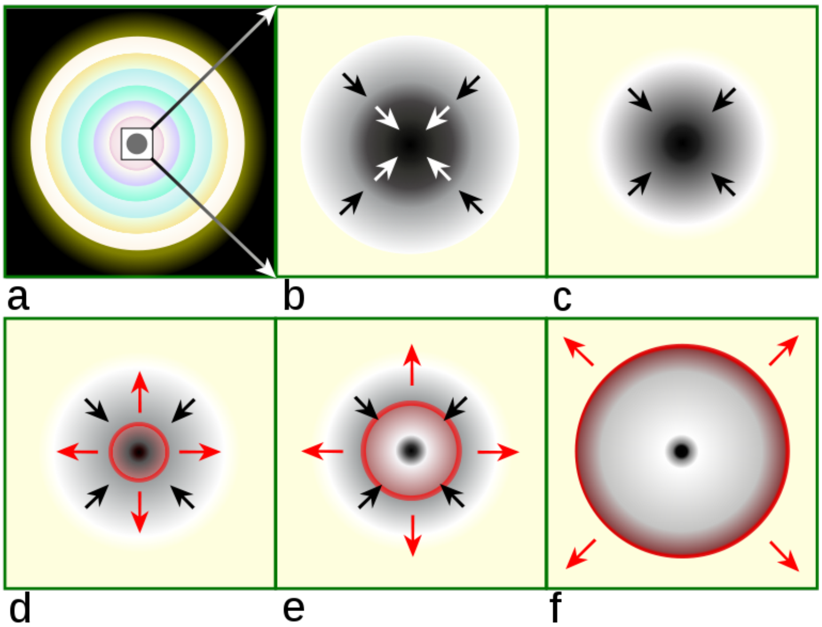
5 Massive stars: $M > 40M_\odot$

Extremely massive stars are very luminous and thus have very rapid stellar winds ($v > 2000kms^{-1}$, $\dot{M} < 10^{-6}M_\odot yr^{-1}$), lose mass so rapidly due to radiation pressure that they tend to strip off their own envelopes before they can expand to become red supergiants, and thus retain extremely high surface temperatures (and blue-white color) from their main-sequence time onwards.

5.0.1 Supernovae type II

Once the nucleosynthesis process arrives at iron-56, the continuation of this process consumes energy. The nuclear fusion becomes unable to sustain the core against its own gravity so the stars can undergo core collapse. The collapse may cause violent expulsion of the outer layers of the star resulting in a supernova, or the release of gravitational potential energy may be insufficient and the star may collapse into a black hole or neutron star with little radiated energy. Core collapse can be caused by several different mechanisms:

- Electron capture: electron capture by magnesium in a degenerate O/Ne/Mg core causes gravitational collapse followed by explosive oxygen fusion, with very similar results.
- Exceeding the Chandrasekhar limit: when a massive star develops an iron core larger than the Chandrasekhar mass it will no longer be able to support itself by electron degeneracy pressure and will collapse further to a neutron star or black hole.
- Pair-instability: the production of free electrons and positrons in the collision between atomic nuclei and energetic gamma rays, temporarily reduces the internal pressure.
- Photodisintegration: A sufficiently large and hot stellar core may generate gamma-rays energetic enough to initiate photodisintegration directly, which will cause a complete collapse of the core.



a. The onion-layered shells of elements undergo fusion, forming an iron core.

b. That reaches Chandrasekhar-mass and starts to collapse. The inner part of the core is compressed into neutrons.

c. Causing infalling material to bounce.

d. And form an outward-propagating shock front (red). The shock starts to stall.

e. But it is re-invigorated by a process that may include neutrino interaction. The surrounding material is blasted away.

f. Leaving only a degenerate remnant.

Il ferro-56, non impiegabile per la fusione nucleare, si accumula inerte al centro dell'astro. Pur essendo sottoposto ad altissime sollecitazioni gravitazionali, il nucleo non collassa per via della pressione degli elettroni degeneri, uno stato in cui la materia talmente densa che una sua ulteriore compattazione richiederebbe che gli elettroni occupino tutti il medesimo livello energetico. Tuttavia, per il principio di esclusione di Pauli, un medesimo livello energetico pu essere occupato solamente da una coppia di identici fermioni con spin opposto; di conseguenza, gli elettroni tendono a respingersi, contrastando in questo modo il collasso gravitazionale.

Quando la massa del nucleo ferroso raggiunge e supera il limite di Chandrasekhar, la pressione degli elettroni degeneri non pi in grado di contrastare efficacemente la gravit e il nucleo va incontro ad un catastrofico collasso; la parte pi esterna del nucleo, durante la fase di collasso, raggiunge velocit dell'ordine dei $70000 kms^{-1}$, pari al 23% della velocit della luce. Il nucleo in rapida contrazione si riscalda, producendo fotoni gamma ad alta energia che decompongono i nuclei di ferro in nuclei di elio e neutroni liberi tramite un processo noto come fotodisintegrazione. Man mano che la densit del nucleo aumenta incrementa anche la probabilit che gli elettroni e i protoni si fondano (tramite un fenomeno noto come cattura elettronica), producendo altri neutroni e neutrini elettronici. Poich questi ultimi raramente interagiscono con la normale materia, essi fuggono via dal nucleo, portando con s energia ed accelerando il collasso, che va avanti in una scala temporale di alcuni millisecondi. Non appena il nucleo ha raggiunto un livello di contrazione tale da subire un distacco dagli strati ad esso immediatamente esterni, questi ultimi assorbono una parte dei neutrini prodotti, dando inizio all'esplosione della supernova.

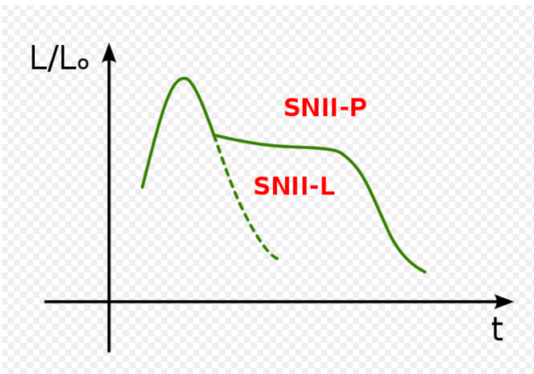
Il collasso del nucleo viene arrestato da una serie di interazioni repulsive su piccola scala, come l'interazione forte, che intervengono tra i neutroni; a questo punto la materia, in caduta verso il centro della stella, "rimbalza", producendo un'onda d'urto che si propaga verso l'esterno. L'energia trasportata dall'onda degrada gli elementi pesanti presenti nel nucleo, ma cos facendo perde energia, arrivando ad arrestarsi in prossimit della parte esterna del nucleo.

Il nucleo di neutroni neoformato ha una temperatura iniziale di circa 100 miliardi di kelvin, 105 volte la temperatura del nucleo del Sole. La maggior parte di questa grande energia termica deve essere dispersa perch possa formarsi una stella di neutroni stabile; il processo di dispersione dell'energia termica accompagnato da un'ulteriore emissione di neutrini. Questi neutrini, caratterizzati da differenti sapori e accoppiati dalle rispettive antiparticelle, gli antineutrini, si formano in numero molto maggiore rispetto ai neutrini formatisi per cattura elettronica. I due meccanismi di produzione dei neutrini permettono di disperdere l'energia potenziale gravitazionale del collasso rilasciando un flusso di neutrini con un'energia di circa 1046 joule (100 foe) in un lasso di tempo di una decina di secondi. Tramite un processo non ancora pienamente compreso, circa 10^{44} joule (1 foe) vengono riassorbiti dal fronte d'onda in stallo, provocando un'esplosione.

L'esplosione di una supernova lascia come residui, oltre ad un resto nebuloso, un residuo di materia degenere: la stella compatta. A seconda della massa originaria della stella (non tenendo eventualmente in conto l'intensit dell'esplosione e la quantit di materia da essa espulsa nello spazio) si possono formare due differenti residui: se la stella progenitrice ha una massa inferiore a 20 $M_{\odot}$ si viene a formare una stella di neutroni; se invece la massa superiore a questo tetto massimo, il collasso gravitazionale porta il nucleo a raggiungere le dimensioni del raggio di Schwarzschild, andando a formare un buco nero. Il limite di massa teorico per questo tipo di collasso nucleare fissato in circa $4050M_{\odot}$; al di sopra di questo tetto si ritiene che una stella collassi direttamente in buco nero senza dar luogo all'esplosione di una supernova, sebbene delle incertezze nei modelli del collasso nucleare di una supernova rendono il calcolo di questi limiti ancora piuttosto incerto.

5.0.2 Curve di luce e spettri insoliti

L'analisi dello spettro di una supernova di tipo II mostra normalmente la serie di Balmer dell'idrogeno ionizzato; ed proprio la presenza di queste linee la discriminante tra una supernova di questa categoria ed una supernova di tipo Ia. La differenza nel tracciato grafico tra i due tipi di supernova sarebbe dovuta al fatto che, nel caso delle supernovae II-L, si ha l'espulsione della maggior parte dello strato di idrogeno della stella progenitrice,[28] mentre il plateau del tipo II-P sarebbe dovuto ad un cambiamento nell'opacit alla radiazione dello strato esterno: le onde d'urto ionizzano l'idrogeno dello strato esterno, provocando un considerevole aumento dell'opacit che evita l'immediata fuga dei fotoni dalla parte pi interna dell'esplosione. Solamente quando la fascia di idrogeno si raffredda abbastanza da consentire la ricombinazione degli atomi neutri lo strato diventa trasparente lasciando passare i fotoni.



6 Stellar remnants

After a star has burned out its fuel supply, its remnants can take one of three forms, depending on the mass during its lifetime.

6.1 White dwarf

For a star of $1M_{\odot}$, the resulting white dwarf is of about $0.6M_{\odot}$, compressed into approximately the volume of the Earth. White dwarfs are stable because the inward pull of gravity is balanced by the degeneracy pressure of the star's electrons, a consequence of the Pauli exclusion principle. If the white dwarf's mass increases above the Chandrasekhar limit, which is $1.4M_{\odot}$ for a white dwarf composed chiefly of carbon, oxygen, neon, and/or magnesium, then electron degeneracy pressure fails due to electron capture and the star collapses. Depending upon the chemical composition and pre-collapse temperature in the center, this will lead either to collapse into a neutron star or runaway ignition of carbon and oxygen. Heavier elements favor continued core collapse, because they require a higher temperature to ignite, because electron capture onto these elements and their fusion products is easier; higher core temperatures favor runaway nuclear reaction, which halts core collapse and leads to a Type Ia supernova. These supernovae may be many times brighter than the Type II supernova marking the death of a massive star, even though the latter has the greater total energy release. This instability to collapse means that no white dwarf more massive than approximately $1.4M_{\odot}$ can exist (with a possible minor exception for very rapidly spinning white dwarfs, whose centrifugal force due to rotation partially counteracts the weight of their matter). Mass transfer in a binary system may cause an initially stable white dwarf to surpass the Chandrasekhar limit. If a white dwarf forms a close binary system with another star, hydrogen from the larger companion may accrete around and onto a white dwarf until it gets hot enough to fuse in a runaway reaction at its surface, although the white dwarf remains below the Chandrasekhar limit. Such an explosion is termed a nova.

6.2 Neutron stars

When a stellar core collapses, the pressure causes electrons and protons to fuse by electron capture. Without electrons, which keep nuclei apart, the neutrons collapse into a dense ball (in some ways like a giant atomic nucleus), with a thin overlying layer of degenerate matter (chiefly iron unless matter of different composition is added later). The neutrons resist further compression by the Pauli Exclusion Principle, in a way analogous to electron degeneracy pressure, but stronger. These stars, known as neutron stars, are extremely small (on the order of radius 10 km) and are phenomenally dense. Their period of rotation shortens dramatically as the stars shrink (due to conservation of angular momentum); observed rotational periods of neutron stars range from about 1.5 milliseconds (over 600 revolutions per second) to several seconds. When these rapidly rotating stars' magnetic poles are aligned with the Earth, we detect a pulse of radiation each revolution. Such neutron stars are called pulsars, and were the first neutron stars to be discovered. Though electromagnetic radiation detected from pulsars is most often in the form of radio waves, pulsars have also been detected at visible, X-ray, and gamma ray wavelengths

6.3 Black holes

If the mass of the stellar remnant is high enough, the neutron degeneracy pressure will be insufficient to prevent collapse below the Schwarzschild radius. The stellar remnant thus becomes a black hole. The mass at which this occurs is not known with certainty, but is currently estimated at between $2 - 3M_{\odot}$.

7 Binary star

A binary star is a star system consisting of two stars orbiting around their common barycenter.

7.1 Cataclysmic variables

When a binary system contains a WD with a RGB or MS star. The white dwarf accretes matter from the companion. Therefore, the secondary is often referred to as the donor star. The infalling matter, which is usually rich in hydrogen, forms in most cases an accretion disc around the white dwarf. Material at the inner edge of disc falls onto the surface of the white dwarf primary. A classical nova outburst occurs when the density and temperature at the bottom of the accumulated hydrogen layer rise high enough to ignite runaway hydrogen fusion reactions, which rapidly convert the hydrogen layer to helium. If the accretion process continues long enough to bring the white dwarf close to the Chandrasekhar limit, the increasing interior density may ignite runaway carbon fusion and trigger a Type Ia supernova explosion, which would completely destroy the white dwarf.

7.2 Type Ia supernova

Is a type of supernova that occurs in binary systems. Physically, carbonoxygen white dwarfs with a low rate of rotation are limited to below 1.44 $M_{\odot}$. Beyond this, they re-ignite and in some cases trigger a supernova explosion. Somewhat confusingly, this limit is often referred to as the Chandrasekhar mass, despite being marginally different from the absolute Chandrasekhar limit where electron degeneracy pressure is unable to prevent catastrophic collapse. If a white dwarf gradually accretes mass from a binary companion, the general hypothesis is that its core will reach the ignition temperature for carbon fusion as it approaches the limit.

7.2.1 Single degenerate

One model for the formation of this category of supernova is a close binary star system. The progenitor binary system consists of main sequence stars, with the primary possessing more mass than the secondary. Being greater in mass, the primary is the first of the pair to evolve onto the asymptotic giant branch, where the star's envelope expands considerably. If the two stars share a common envelope then the system can lose significant amounts of mass, reducing the angular momentum, orbital radius and period. After the primary has degenerated into a white dwarf, the secondary star later evolves into a red giant and the stage is set for mass accretion onto the primary. During this final shared-envelope phase, the two stars spiral in closer together as angular momentum is lost. The resulting orbit can have a period as brief as a few hours. If the accretion continues long enough, the white dwarf may eventually approach the Chandrasekhar limit.

7.2.2 Double degenerate

A second possible mechanism for triggering a Type Ia supernova is the merger of two white dwarfs whose combined mass exceeds the Chandrasekhar limit. The resulting merger is called a super-Chandrasekhar mass white dwarf. In such a case, the total mass would not be constrained by the Chandrasekhar limit.

7.3 X-ray binaries

When a binary system contains a NS or BH with a RGB star.

7.4 Type Ib and Ic

These supernovae, like those of Type II, are massive stars that undergo core collapse. However the stars which become Types Ib and Ic supernovae have lost most of their outer (hydrogen) envelopes due to strong stellar winds or else from interaction with a companion. These stars are known as WolfRayet stars, and they occur at moderate to high metallicity where continuum driven winds cause sufficiently high mass loss rates. Observations of Type Ib/c supernova do not match the observed or expected occurrence of WolfRayet stars and alternate explanations for this type of core collapse supernova involve stars stripped of their hydrogen by binary interactions. Binary models provide a better match for the observed supernovae, with the proviso that no suitable binary helium stars have ever been observed. Since a supernova can occur whenever the mass of the star at the time of core collapse is low enough not to cause complete fallback to a black hole, any massive star may result in a supernova if it loses enough mass before core collapse occurs.

7.5 Gamma-Ray Burst

They are the brightest electromagnetic events known to occur in the universe. Bursts can last from ten milliseconds to several hours. After an initial flash of gamma rays, a longer-lived "afterglow" is usually emitted at longer wavelengths (X-ray, ultraviolet, optical, infrared, microwave and radio). The most widely accepted mechanism for the origin of long-duration GRBs is the collapsar model, in which the core of an extremely massive, low-metallicity, rapidly rotating star collapses into a black hole in the final stages of its evolution. Matter near the star's core rains down towards the center and swirls into a high-density accretion disk. The infall of this material into a black hole drives a pair of relativistic jets out along the rotational axis, which pummel through the stellar envelope and eventually break through the stellar surface and radiate as gamma rays.

7.5.1 Long gamma-ray bursts ($\Delta t > 2$ sec)

Almost every well-studied long gamma-ray burst has been linked to a galaxy with rapid star formation, and in many cases to a core-collapse supernova.

7.5.2 Short gamma-ray bursts ($\Delta t < 2$ sec)

A subclass of GRBs (the "short" bursts) appear to originate from a different process: the merger of binary neutron stars.