Stellar Astrophysics and Evolution

Summer of Science Project Report

B. Malavika
190260014

Mentor:
Siddhant Tripathy

Contents

1 Preliminaries

1.1 Hydrostatic Equilibrium

Let us consider the theoretician's dream: a spherically symmetric, non rotating star on which there are no net forces acting and hence no net acceleration. There may be internal unbalanced forces of course, such as convection, but we assume them to average out to nil on the whole. Further we assume that the stellar material is so constituted that the internal pressures are uniform. The following quantities defined will be used throughout the text.

r : Radial distance from stellar centre (cm)
R : Total stellar radius measured from the centre (cm)
$\rho(r)$: Mass density at a distance r ($\mathrm{g\,cm^{-3}}$)
$T(r)$: Temperature as a function of r (K)
$P(r)$: Pressure as a function of r ($\mathrm{dyne\,cm^{-2}}$)
M_r : Mass contained within a radius r (g)
M_R : Total stellar mass (g)
L_r : Luminosity, i.e. energy flow rate at r ($\mathrm{erg\,s^{-1}}$)
L_R : Total stellar luminosity ($\mathrm{erg\,s^{-1}}$)
$g(r)$: Local acceleration due to gravity at r ($\mathrm{cm\,s^{-}2}$)
G : The universal gravitational constant $= 6.6726 \times 10^8$ ($\mathrm{g^{-1}\,cm^3\,s^{-}2}$)

Let us consider a thin shell at a distance r from the stellar centre, having density $\rho(r)$. Since the volume element for a shell of thickness dr is $4\pi r^2 dr$, we have:

$$dM_r = 4\pi r^2 \rho(r) dr$$

$$M_r = \int_0^r 4\pi r^2 \rho(r) dr \tag{1}$$

This is the Equation of mass conservation.

Now consider a 1 cm^2 area at a radius r. Let us consider the volume element with this area, and thickness dr. Now, the gravitational force acting inwards is given by:

$$\rho(r) g(r) dr = \rho(r) \frac{GM_r}{r^2} dr$$

This gravitational force must be balanced by some outwards force. This force is provided by the pressure imbalance in the stellar material which acts radially outwards. Pressure disbalance

$$= P(r) - P(r+dr) = -\frac{dP(r)}{dr}dr$$

Adding the gravitational and differential pressure forces yields

$$\rho\ddot{r} = -\frac{dP}{dr} - \frac{GM_r}{r^2}\rho$$

by hypothesis, net forces are zero hence $\ddot{r} = 0$, and we obtain

$$\frac{dP(r)}{dr} = -\rho(r)\frac{GM_r}{r^2} \tag{2}$$

This equation is known as Equation of Hydrostatic Equilibrium.

1.2 Virial Theorem

We will now derive the virial therorem. Consider the scalar product $\sum_i \mathbf{p}_\mathrm{i}.\mathbf{r}_\mathrm{i}$ where $\mathbf{p}_\mathrm{i}$ is the vector momentum of a free particle with mass m_i located at position $\mathbf{r}_\mathrm{i}$.

$$\begin{aligned}\frac{d}{dt}\sum_i \mathbf{p}_\mathrm{i}.\mathbf{r}_\mathrm{i} &= \frac{d}{dt}\sum_i m_i\dot{r}_i.\mathbf{r}_\mathrm{i} \\ &= \frac{1}{2}\frac{d}{dt}\sum_i \frac{d}{dt}m_i r_i^2 \\ &= \frac{1}{2}\frac{d^2 I}{dt^2} \end{aligned} \tag{3}$$

where I is the moment of inertia $I = \sum_i m_i r_i^2$. On the other hand,

$$\begin{aligned}\frac{d}{dt}\sum_i \mathbf{p}_\mathrm{i}.\mathbf{r}_\mathrm{i} &= \sum_i \frac{d\mathbf{p}_\mathrm{i}}{dt}.\mathbf{r}_\mathrm{i} + \sum_i \mathbf{p}_\mathrm{i}.\frac{d\mathbf{r}_\mathrm{i}}{dt} \\ &= \sum_i \mathbf{F}_\mathrm{i}.\mathbf{r}_\mathrm{i} + \sum_i m_i\dot{r_i}^2 \\ &= \sum_i \mathbf{F}_\mathrm{i}.\mathbf{r}_\mathrm{i} + 2K \end{aligned} \tag{4}$$

where $K = \frac{1}{2}\sum_i m_i\dot{r_i}^2$ is the Kinetic energy. From equation (3),

$$\frac{1}{2}\frac{d^2 I}{dt^2} = 2K + \sum_i \mathbf{F}_\mathrm{i}.\mathbf{r}_\mathrm{i} \tag{5}$$

where $\sum_i \mathbf{F}_\mathrm{i}.\mathbf{r}_\mathrm{i}$ is the mutual interaction between all particles. Let $\mathbf{F}_\mathrm{ij}$ be the gravitational force on particle i due to particle j. Then, $\mathbf{F}_\mathrm{ij} = -\ \mathbf{F}_\mathrm{ji}$

$$\sum_i \mathbf{F}_\mathrm{i}.\mathbf{r}_\mathrm{i} = \sum_{i<j} (\mathbf{F}_\mathrm{ij}.\mathbf{r}_\mathrm{i} + \mathbf{F}_\mathrm{ji}.\mathbf{r}_\mathrm{j})$$
$$= \sum_{i<j} \mathbf{F}_\mathrm{ij}.(\mathbf{r}_\mathrm{i} - \mathbf{r}_\mathrm{j})$$

But $\mathbf{F}_\mathrm{ij} = -\frac{Gm_i m_j}{r_{ij}^3}(\mathbf{r}_\mathrm{i} - \mathbf{r}_\mathrm{j})$ where $r_{ij}\ = |\mathrm{r_i} - \mathrm{r_j}|$. Therefore

$$\sum_{i<j} \mathrm{F_{ij}}.(\mathbf{r}_\mathrm{i} - \mathbf{r}_\mathrm{j}) = -\frac{\sum Gm_i m_j}{r_{ij}} = Virial$$

The middle number here is nothing but the Gravitational self energy in discreet form. This means:

$$Virial = \Omega \tag{6}$$

And:

$$\frac{1}{2}\frac{d^2 I}{dt^2} = 2K + \Omega \tag{7}$$

Eq. (7) is known as the Virial Equation. At any general $r < R$ this becomes

$$\frac{1}{2}\frac{d^2 I}{dt^2} = 2K + \Omega - 3P_s V_s$$

Where P_s and V_s are the pressure and volume at the surface of a shell of radius r. We now interpret what the energy K represents. We had

$$2K = \sum_i m_i v_i^2 \tag{8}$$
$$= \sum_i \mathbf{p}_\mathrm{i}.\mathbf{v}_\mathrm{i} \tag{9}$$

The scalar protuct of $\mathbf{p}$ and $\mathbf{v}$ measures the rate of momentum transfer and is related to pressure of an isotropic gas by

$$P = \frac{1}{3}\int_p n(\mathbf{p})\mathbf{p}.\mathbf{v} d^3\mathbf{p} \tag{10}$$

where n($\mathbf{p}$) is the number density of particles with momentum $\mathbf{p}$ and the integration is over all momenta. Since the sum in (8) and (9) includes all particles, (10) only needs to be integrated over total volume V to obtain,

$$2K = 3\int_V P dV$$

And since $dM_r = \rho dV$, we have

$$2K = 3\int_M \frac{3P}{\rho} dM_r \tag{11}$$

From (7) this becomes,

$$\frac{1}{2}\frac{d^2I}{dt^2} = 3\int_M \frac{3P}{\rho} dM_r + \Omega \tag{12}$$

This equation now enables us to solve for different stars, given the choice for equilibrium of state

2 Overview of Stellar Evolution

2.1 Young Stellar Objects

Young Stellar Objects (YSO) are stars that mainly include protostars and pre-main sequence stars. A protostar is a contracting mass of gas which represents an early stage in the formation of a star, before nucleosynthesis has begun. The energy source is gravitational potential energy so the total lifetime is very short; and they are convective throughout. YSOs are characterized by their variability, higher infrared luminosity due to presence of dust around them and higher activity on stellar surface.

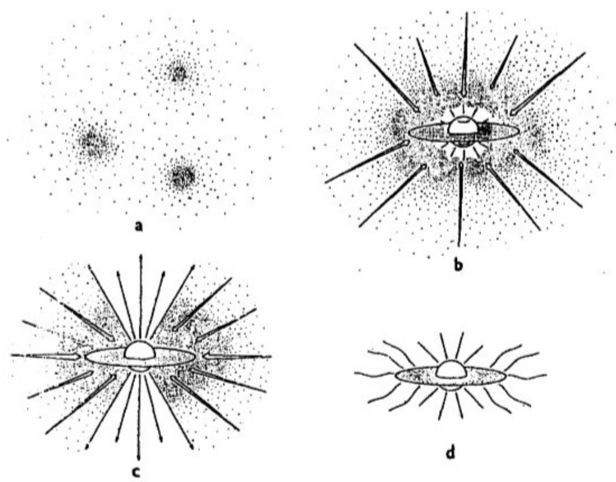

Figure 1: This cartoon illustrates the four stages of star formation. From Shu et al. (1987)

2.2 Zero-Age Main sequence

ZAMS stars are recently formed, unevolved stars that have started nuclear reactions in their core by converting hydrogen to helium. Stars in the ZAMS phase change very little in luminosity, effective temperature and radius.

2.3 Main Sequence

Stars spend most of their lifetimes on the main sequence. Stars having larger masses, have more fuel, but also higher temperature. Therefore they burn faster and brighter than stars with low mass. Nuclear reactions take place, converting hydrogen to helium in the core, by two methods—proton-proton chain or CNO cycle.

For stars with mass less than 1.5 $M_\odot$ (where $M_\odot$ is solar mass), production of helium via p-p chain takes place and convection is responsible for transporting power in the stellar envelope.

For stars with mass greater than 1.5 $M_\odot$, temperatures are high enough for the CNO cycle to take place and power is transported by radiation.

Stars with initial mass of less than 0.3 $M_\odot$ remain fully convective throughout their lifetimes. They remain on the main sequence for about 100 billion years after which they run out of all their fuel. Due to their small size and convective envelopes, their temperatures do not become high enough to ignite helium and so the core contracts and becomes a white dwarf.

Over time, a star keeps fusing hydrogen and the helium is deposited in the core. Most main sequence stars change only very slowly in internal structure and external appearance. When four (ionized) hydrogen particles fuse to one (ionized) helium particle, eight separate particles (including electrons of course) become only three. Thus, since $P = nkT$, and a fixed central pressure is needed to counter gravity, the stellar core must slowly contract and heat up. This makes the nuclear reactions go faster and the star gradually brightens. The surface temperature, on the other hand, goes down. Our own sun, at formation 4.6 Gyr ago was 25% fainter and somewhat bluer than the present-day sun. Eventually, the hydrogen fuel supply runs low and the star enters the "Red Giant Phase".

2.4 Red Giant Phase

Only stars with initial mass greater than 0.3 $M_\odot$ reach the red giant phase. Fusion of hydrogen continues to take place in a shell outside the inert helium core.

In this phase the helium core undergoes contraction, releasing gravitational potential energy which drives the hydrogen fusion reaction to go faster. This releases more heat and the total luminosity of the star increases. The core contraction is mirrored by an envelope expansion, decreasing the surface temperature and making the star look redder.

Since, in the red giant phase 10% of the mass of the star is hydrogen fuel, and luminosity is ten times the luminosity in the main sequence, the stars have a RGB lifetime of only 10% of their main sequence lifetime.

As hydrogen continues to burn in a shell around the helium core, mass of the helium core increases, thus increasing the central density and central temperature.

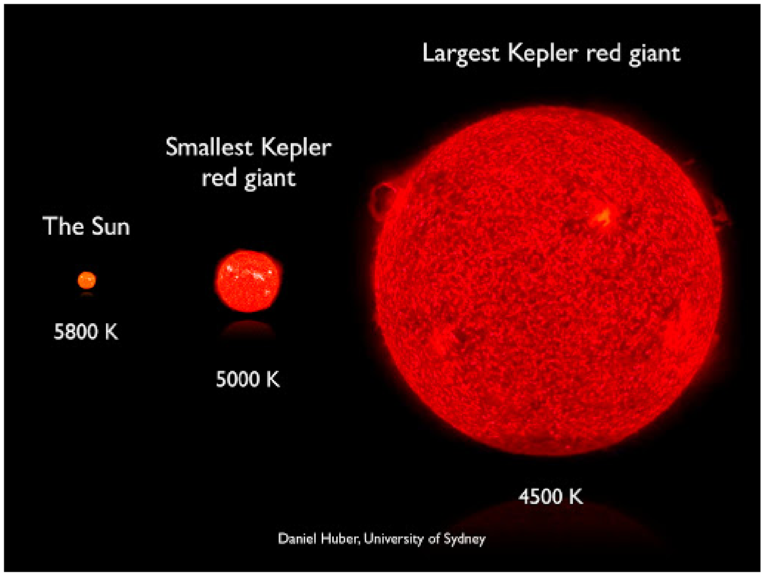

Figure 2: This figure shows the sizes of red giant stars compared to the Sun. Data obtained from Kepler mission

2.5 Helium Flash

Stars with an initial mass less than 1.5 times the mass of the sun (but more than 0.4 $M_{\odot}$) require some heating before they can start the helium fusion process in their core.

In such stars, helium in the stellar core is partially degenerate because central temperature is about 10^8 and central density is around 10^6. The helium thus ignites in an explosion, better described as "Helium Flash".

A fundamental quality of degenerate matter is that increases in temperature does not result in expansion of the matter. 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. The vast energy release causes much of the core to come out of degeneracy, allowing it to thermally expand, however, consuming as much energy as the total energy released by the helium flash, and any left-over energy is absorbed into the star's upper layers.

This renders the flash mostly undetectable. After the expansion, there is a rapid decrease in luminosity accompanied by an increase in effective temperature and the star heads to left in a *Hertzsprung-Russell diagram*, or more simply, the HR diagram.

More massive stars ignite helium successfully and there is no rapid structural change.

2.6 Helium Core Burning

Helium burning occurs via the triple-α process which takes place when temperatures are high enough for two He nuclei to overcome the coulombic barrier and fuse; and density is high enough for a third nuclei to fuse with the unbound "di-alpha" in the 10^{-16} seconds it holds together. Carbon and oxygen are the major products with the former being produced dominantly in smaller stars while massive stars have more oxygen.

Stars the are not badly shaken up by the helium flash go immediately into the Red 'Super' Giant Phase. For less massive stars, their colour and temperature correspond to that of the Horizontal Branch in an HR diagram.

2.7 Asymptotic Giant Branch

Adjustment for the helium core exhaustion is less drastic because energy is produced by the CNO cycle that takes place in a thin shell. In this phase double shell burning takes place, as the core once again contracts and heats up, enough to start helium fusion in a thin shell around the carbon-oxygen core. In case of small to medium sized stars, core contraction is accompanied by envelope expansion and its subsequent cooling. Stars in AGB are therefore very bright so their lifetime is less than 1% of their main sequence lifetime.

Most double shell stars are unstable to pulsations and this results in wind blowing off from the stellar surface with speed comparable to the escape velocities (10-30 km s^{-1}). The wind density is also large enough for the star to lose about 10-50% of its initial mass before the wind in stopped. If the density keeps increasing to about $10^{-}4\ M_{\odot}\ yr^{-1}$, it becomes a superwind. This explains why stars of mass 1 $M_{\odot}$ end up as white dwarfs of 0.6 $M_{\odot}$ mass.

2.8 Later Phases

This section concerns stars with initial mass less that 6-10 $M_\odot$.

Here, the post-AGB stars have lost enough mass due to winds that we can now see into their deeper, hotter layers. The ejecta from the star harbours dust (so that much of the light from the star is reprocessed into infra-red) and OH molecule masers, so that there stars are called OH/IR stars.

Around 10,000 years later, enough layers have been uncovered so that photons are now leaving directly from a layer of 50,000 K. These photons ionize the ejecta and we are able to observe emission lines mostly consisting of hydrogen, along with some of carbon, oxygen, nitrogen and other light, abundant species. The expanding, ionized ejecta is called a *planetary nebulae* (PN) which is a misleading name, they have nothing to do with planets.

After 10,000 years, the PN disperses into the general interstellar material, leaving behind a residual core called a planetary nebula nucleus (PNN) which has now cooled to the point of emitting few ionized photons. Central temperatures have dropped from 10^8 to 10^7 K and so the nuclear reactions turn off. The core therefore becomes a C-O white dwarf of mass 0.55-1.3 $M_\odot$. Its only energy source is residual heat of the atomic nuclei. The white dwarf eventually fades to a luminosity of 10^{-5} $L_\odot$ in 10 billion years.

There exists a very narrow, mass range for which nuclear reactions start again and a core of O, Ne and Mg.

2.9 Advanced Evolutionary Phases

This section deals with stars of initial mass greater than 6-10 $M_\odot$. They can burn more fuel than just H, He and that does not affect the profligacy with which they burn it. By the time C, O burning takes place, the core is so hot that copious neutrino fluxes are produced and they depart without maintaining stellar luminosity.

Carbon, oxygen and silicon (if temperature is high enough) burning produce many heavier elements, the most abundant of which are elements from Mn to Zn— also known as the “Iron Peak”. Of these Fe is the most abundant.

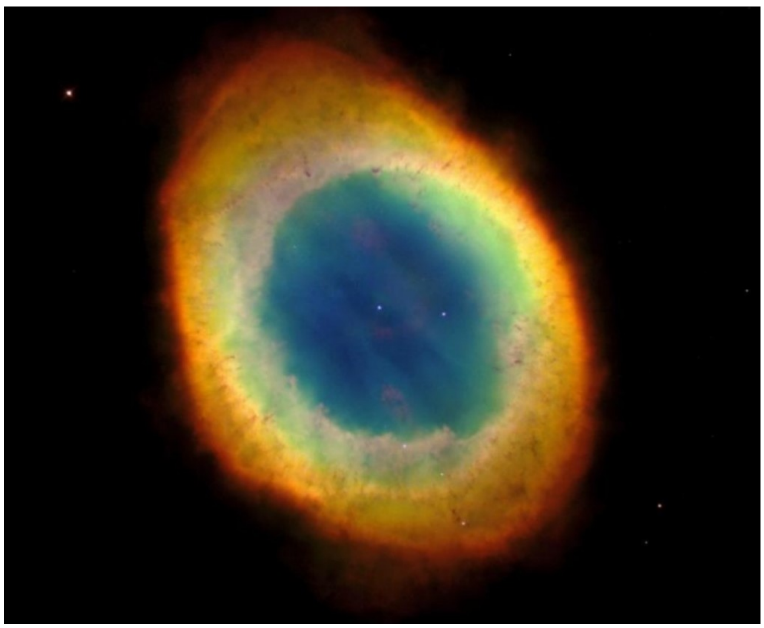

Figure 3: Hubble Space Telescope image of the Ring Nebula, showing its nearly circular structure, green glow in the central part of the nebula, and faint white dwarf star located in the very center. Image obtained from NASA Space Telescope Science Institute

All fusion beyond helium fusion takes place in very short duration (on a galactic timescale). In fact silicon fusion has a duration of just a few days. Due to this reason, the outer layers do not respond to changes in the inner layers.

The core of iron peak elements is relentlessly approaching the maximum mass that can be supported by degenerate pressure (1.2 $M_\odot$ for heavy elements). Moreover, further contraction cannot ignite the already tightly-bound nuclei of A= 56. The core must therefore collapse.

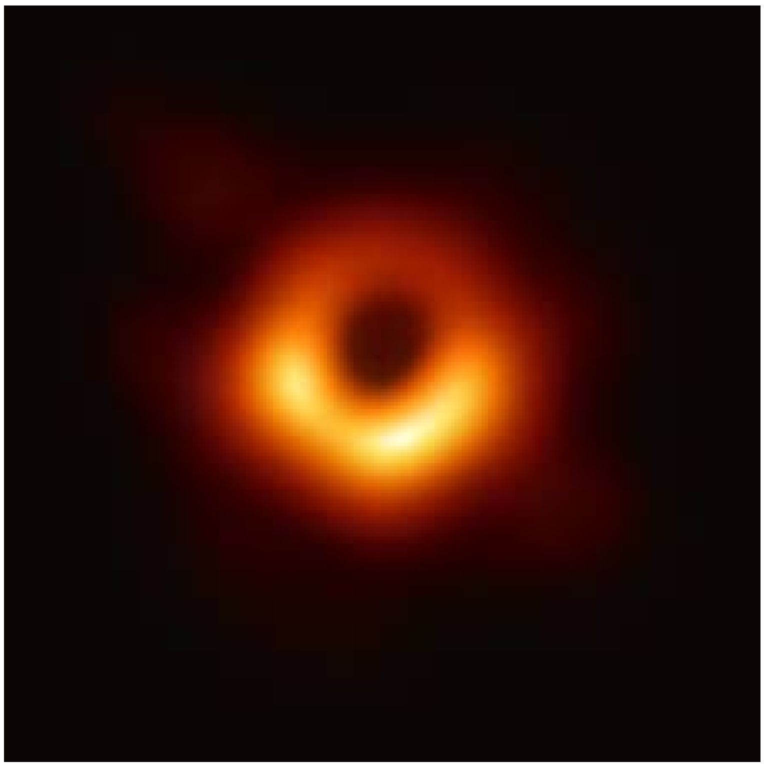

Figure 4: The supermassive black hole at the core of supergiant elliptical galaxy Messier 87, with a mass of around 7 billion times the Sun's, as depicted in the first image released by the Event Horizon Telescope (10 April 2019)

2.10 Core Collapse and Nucleosynthesis

There are two widely accepted triggers for core collapse –photodisintegrations or electron capture through inverse beta decay.

Photodisintegration is a process through which atomic nuclei in the core absorbs high energy gamma rays and goes into excited states. For atomic nuclei with $A < 56$, this process is endothermic. Therefore, the gas is cooled, which removes the support of thermal pressure.

The second process involves inverse beta decay which is brought about due to the following –increasing density forces electrons into higher momentum states, and thereby, into higher kinetic energy states. As the kinetic energy of the electrons exceeds the threshold energy (due to the difference between $M_{product}$ and $M_{reactant}$ and relativistic mass effect) for inverse beta decay to happen, electron capture taken place, and converts electrons and protons into neutrons. As more electrons are 'captured' the number of electrons decrease, removing the support of electron degeneracy pressure.

The core collapses suddenly, in a timescale similar to that of t_{dyn}. Tremendous amounts of energy are released in a short time, and the products include a core collapse supernova and a neutron star. Since the core collapse brings together many heavy nuclei, neutrons and energy, processes like the r-process (the source of Th and Ur in the universe), p-process (produces ^{235}U and ^{238}U) s-process, take place.

3 Variable Stars

Some stars vary in brightness in a recurrent, more or less periodic fashion. Their periods may vary from a timescale of t_{dyn} to t_{nuc}. The following are some types and causes of variable stars.

3.1 Some Broad Categories

3.1.1 Eclipsing and Ellipsoidal Variables

If a pair of stars orbit each other, you, the observer, may be located close enough to the orbital plane to have one pass in front of the other and block its light for a portion of each orbital period. Because the eclipse tells us that the system is nearly edge on, eclipsing binaries are among the sorts particularly useful in measuring stellar masses. Even if there is no eclipse, the gravitational field of one star may distort the shape of its companion into an ellipsoid, so that you see a larger star area when the stars are side-on to you than when they are end on. This will also result in periodic variability, though of a lesser useful sort.

3.1.2 Spotted, Rotating Stars

The sun is an example of this class. Its brightness varies both at its rotation period and through the 11-year sunspot cycle. The variation is, however, only about 0.1% (and curiously though, the sun is brighter when it has more spots because the extra brightness of the bright vein like facular regions of the photosphere more than makes up for the darker spots).

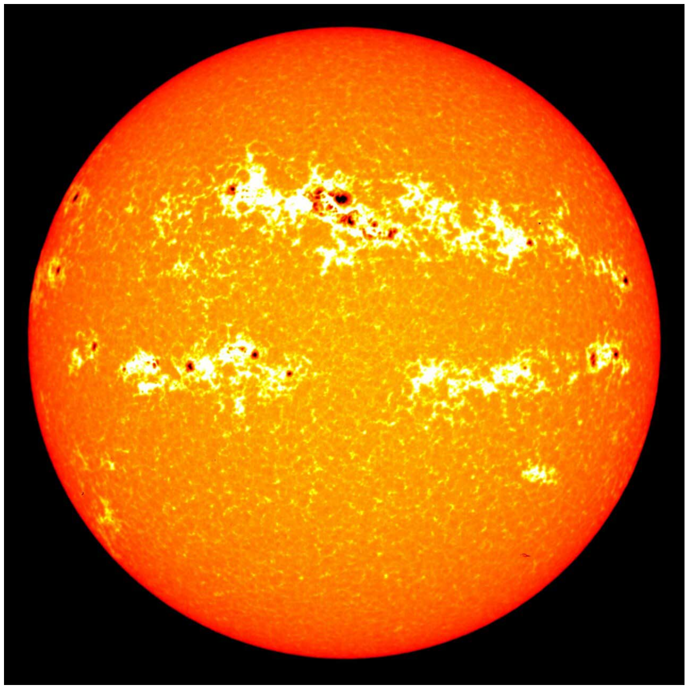

Figure 5: Sunspots can be seen on this image of solar radiation. Each sunspot lasts a few days to a few months, and the total number peaks every 11 years. The darker spots accompany bright white blotches, called faculae, which increase overall solar radiation. Credit: NASA/Goddard/SORCE

Larger fluctuations in brightness happen among younger, rapidly rotating stars of types G, K and M, and among close binary pairs, where the rotation period is locked to the orbit period. The majority view is that rapid rotation plus the convective atmosphere of these cool-surfaced stars permits the operation of a dynamo, producing a magnetic field, which, in turn. Drives spot formations and other kinds of stellar activity. Relatively strong variability of this sort is associated with emission of x-rays and radio waves from the solar or stellar corona and other indications of youth and activity.

3.1.3 T Tauri Stars, FU Orionis Stars and Luminous Blue Variables

These are stars that are very young or very massive and bright or both. They are probably both accreting material from a disk and blowing off material at their poles, and may be heavily spotted as well. The result is non-periodic flaring and variability. Surrounding gas and dust frequently show up in images and spectra of these stars, and very occasionally it is possible to tell which bits are flowing in and which are being ejected, sometimes in jets. Rapid rotation and magnetic fields are also part of the picture.

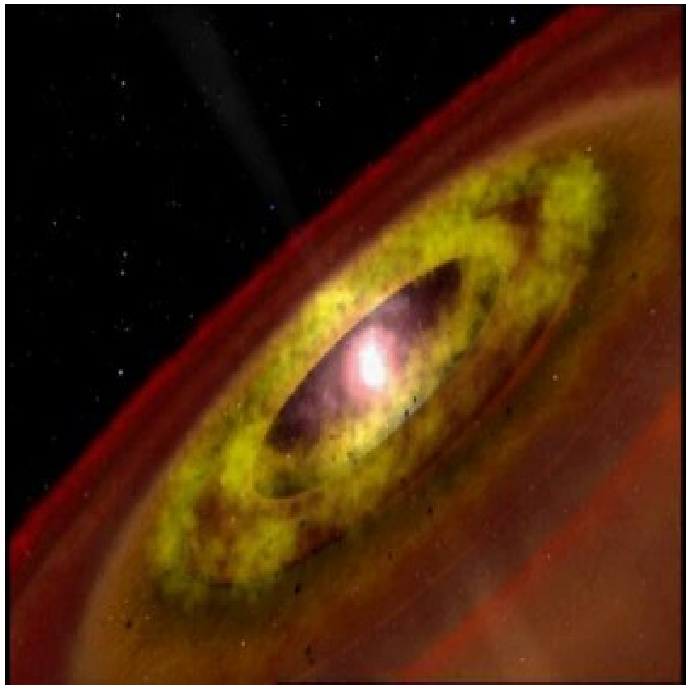

Figure 6: Artist's impression of a T Tauri star with a circumstellar accretion disc

3.1.4 Last Helium Flash and Formation of Atmospheric Dust

These two physically different causes of variability appear together because one is often the precursor to the other. Post AGB stars can experience one last helium-flash (see §2.5) which puffs up their envelope and brightens the star until it starts to resemble a red giant. The prototype of this kind of variability is FG Syge. It and other members of its class also display unusual elemental abundances in their spectra due to helium flash driving its outer convection zone.

R CrB variables are highly evolved stars with carbon rich atmospheres. They unpredictably fade by many magnitudes over few weeks and brighten again over months. The missing light comes out as infrared, and it is caused by sudden carbon dust condensation in the cool stellar atmosphere, which gets blown out again because of radiation pressure.

3.2 Pulsational Variables

These are the most useful variable stars because the length of time in which they brighten and fade again, i.e. their periods, are frequently correlated with their absolute brightness, so that they can be used to measure distances to star clusters anywhere in the Milky Way and to nearby galaxies.

Stellar pulsation can be purely in and out (radial nodes) or include material slopping around in latitude and longitude (non-radial nodes). Their pulsation might be driven by some instability, and the restoring force that brings the gas back where it started from can be gravity or pressure or magnetic fields. In this sense, the instability is intrinsic to the star and not due to external influences; hence, such stars are often referred to as intrinsic variables. The type of instability and the restoring force employed by the star can be used to differentiate between different types of variables, some of the more common ones being:

- *Classical Cepheids*, usually just called Cepheids are young metal rich stars, with spectral types F6-K2 and periods of days to months. The more luminous ones have longer periods. They appear to be purely radial pulsators.
- *W Vir variables* behave similar to Classical Cepheids but are metal-poor, older and lower-mass stars.
- *RR Lyrae variables* are stars with spectral type A2-F2 and were formerly known as cluster type variables or cluster Cepheids because they are common in globular clusters. They have periods of a day down to a couple of hours and are useful in determine distances to globular clusters in out galaxy in nearby galaxies.
- *δ Scruti variables* have periods ranging from about 30 minutes to 8 hours and pulsate in radial and non-radial pressure nodes although gravity may be present. Amplitudes tend to be low.
- *Mira variables*, are luminours red supergiants belonging in the class of Long Period Variables with periods ranging from roughly 100 to 700 days. Radial nodes seem to be the norm. RV Tauri stars are an extreme version with low mass and large luminosity, so that a second pulse starts before the atmosphere has had time to fall down from the previous one.
- *The Rapidly Oscillating Ap* stars are characterized by low amplitude, short period photometric variations, typically 10 minutes, strong magnetic fields, and enhanced surface abundances of exotic elements such as strontium and europium. The observed light variations are modulated in amplitude by the rotation of the star and it is thought that the pulsations are carried around by an off-axis

magnetic field as the star rotates.

3.3 Explosive Variables

These are the stars that release a great deal of nuclear or gravitational energy in a hurry. The cataclysmic variables are close star pairs with a white dwarf in orbit with a main sequence or red giant companion. The white dwarf accepts material from its companion, one sort of variability arises when the rate of acceptance or accretion and therefore the rate of release of gravitational potential energy changes. When enough hydrogen-rich material has accumulated on the surface of the white dwarf it fuses explosively.

3.3.1 Novae

Nova and recurrent nova explosions is the name given to these outbursts fueled by degenerate hydrogen ignition.

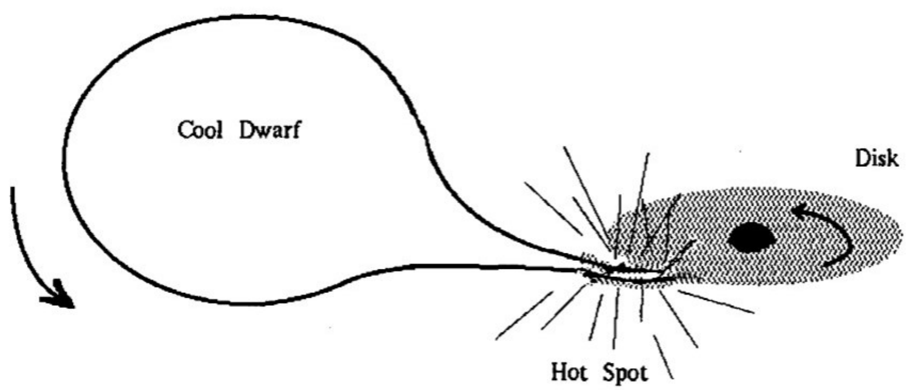

Figure 7: Drawing depicting mass accretion from a donor star to a cataclysmic variable with accretion disk as intermediate.

As seen in the above drawing, mass is gravitationally drawn from the donor star and forms an accretion disk around the cataclysmic variable. The material gradually makes its way through the disk and deposits onto the variable. The subsequent explosion results in a release of $10^{44} - 10^{45}$ ergs of energy and $10^{-5} - 10^{-4} M_{\odot}$ of mass.

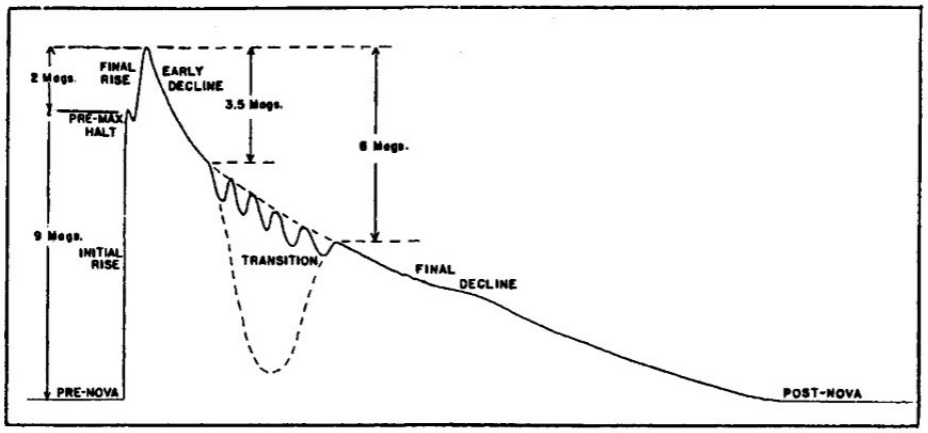

Figure 8: Light output curve for a typical nova as is explained below

As seen above, there is a fast rise lasting perhaps a day, followed by a decline in brightness that may be quite variable from nova to nova. In the "fast" novae the decline may take a couple of weeks to reduce the visual brightness by two magnitudes. "Slow" novae may take a few months to accomplish the same thing. Between the initial rise and eventual decline, there may be a plateau near the peak lasting an hour or so in fast novae but extending over days in slow ones. As indicated in the figure, the decline phase may be interrupted by oscillations or a pronounced trough.

3.3.2 Supernovae

Supernovae are the most spectacular variables of all. At maximum light, they are as bright as a whole, smallish galaxy, and recognizing them for what they are was part of the total process between 1900-1925 CE that sorted out the approximate size of the Milky Way and demonstrated the existence of other galaxies. There is a sort of family resemblance among all supernovae - they get really bright in a matter of days and fade in months to years. Their spectra display very broad features, indicating velocities of thousands of $\mathrm{km\,s^{-1}}$. And they blow out a solar mass or more of material at these large velocities that can then be seen as supernova remnant for thousands of years thereafter.

There are two basic categories of Supernovae– Type I and Type II. Type I spectra show no evidence of any hydrogen, though it is the most abundant element just about any place you look in the universe, while Type II spectra have strong emission and absorption features due to hydrogen.

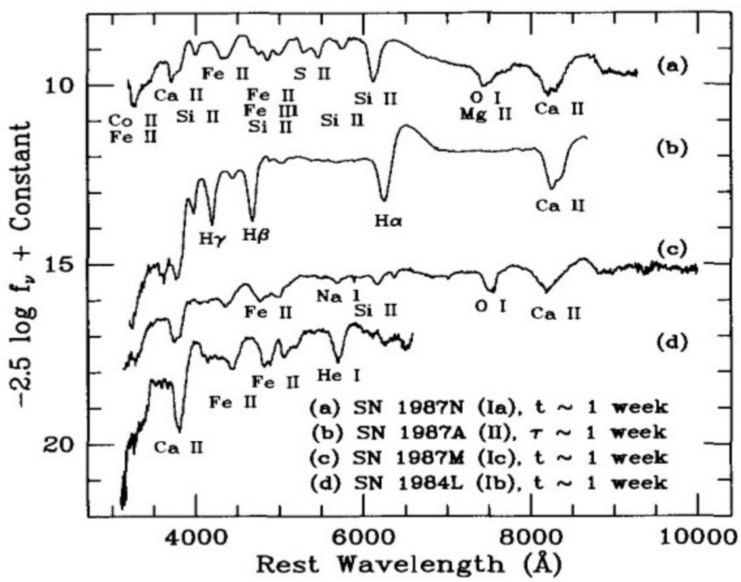

Figure 9: Spectra of four major types of supernovae captured about one week after maximum light in B Band ("t $\sim$ 1 week") or core collapse ("$\tau \sim$ 1 week")

This is illustrated in Fig.9, where the spectra of four types are plotted against wavelength. Three of the spectra, corresponding to Type I subtypes Ia, Ib, and Ic, show strong features due to ionized irons, calcium, etc., but not a sign of hydrogen. (If there is hydrogen between us and the SN we may see some, but this would be accidental).

The Type II spectrum, on the other hand, has strong hydrogen absorption lines. In addition, Type II events always, or nearly always occur in galaxies with recent, vigorous, star formation and in regions of that star formation (i.e, among Pop I stars), while Type I events can also occur in elliptical galaxies and galactic bulges and halos (i.e, among Pop II Stars). Type II's expel more mass but at lower velocity, and there are also systematic but rather subtle differences between the two sorts of light curves. Type II's are considerably more likely to be picked up as radio and x-ray sources, usually at later times than the visible light peak.

The distinction between Type I and II supernova almost, but not exactly, corresponds to a very fundamental difference in what is going on in the two cases. Type II events (Which are a commoner sort, though somewhat fainter and so harder to discover) are the products of collapsing cores of massive stars. The basic energy source is the gravitational energy released in the collapse, often more than 10^{53} erg. Of this, most comes out in neutrinos, 1% or so in kinetic energy of the ejecta, and less than 0.1% in visible light and other electromagnetic radiation. Evidence for this mechanism includes the presence of the collapsed core (pulsar or rapidly rotating magnetized neutron star) at the center of SN1054 remnant, the Crab Nebula, and the burst of neutrinos seen from SN1987A.

In an ordinary Type II event, there is a good deal of the original hydrogen rich envelope left when the core collapses, which is heated and ionized by the outgoing blast wave, producing the hydrogen line in the spectra. If a massive star has lost its hydrogen envelope (in a strong wind or by transfer to a companion star) before its core collapses, there will be no hydrogen lines.

3.4 SN Remnants

The supernova remnants (SNRs) we see range in age from less than 20 years (SN1987A is just getting big enough to resolve) to 10^4 or more. Many are sources of radio waves and x-rays as well as visible light. Where there is a central pulsar, it continues to pour energy into the remnant until the gas is too dispersed to be seen. Pulsar-less remnants nevertheless remain bright for as long as the expanding ejecta are plowing into surrounding interstellar gas. They look brightest around the edges.

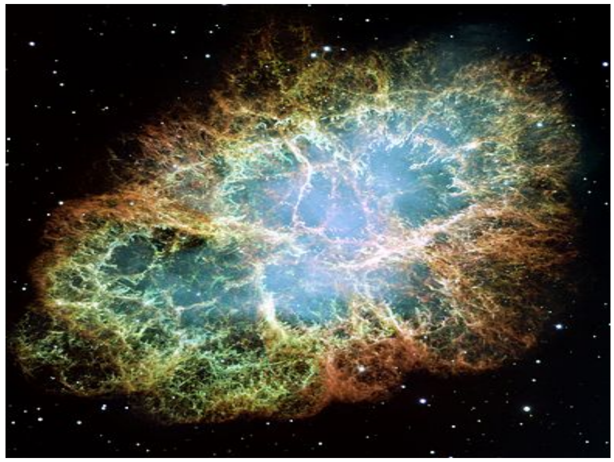

Figure 10: Hubble Space Telescope mosaic image of Crab Nebula assembled from 24 individual Wide Field and Planetary Camera 2 exposures taken in October 1999, January 2000, and December 2000

The Crab Nebula, pulsar fed and left from the supernova seen by the Chinese, Arabs, and possibly Europeans in 1054 C.E, is the best known and most thoroughly studies supernova remnant. Recent x-ray images show energy from the pulsar being beamed out along the long axis of the prolate nebula, which is brightest at the center.

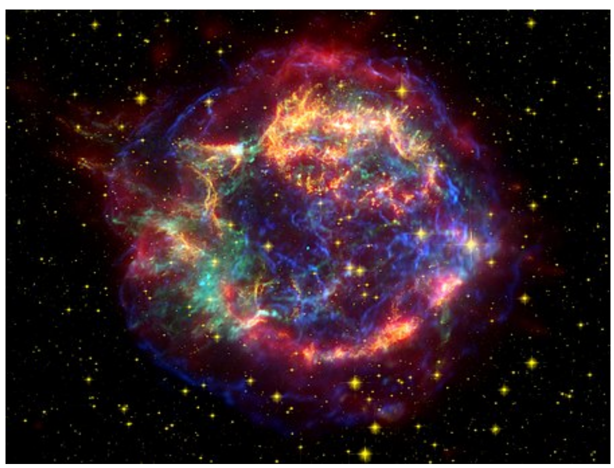

Figure 11: A false color image of Cassiopeia A, composited of data from three sources: Red is infrared data from the Spitzer Space Telescope, gold is visible data from the Hubble Space Telescope, and blue and green are data from the Chandra X-ray Observatory. The small, bright, baby-blue dot just off-center is the remnant of the star's core.

Cas A (the brightest radio source in Casseiopia) is the remnant of SN1685. Our view of its optical emission is partly blocked by dust, but the radio and x-ray images show that it is brightest around the edges, consistent with the absence of a detectable pulsar (though there is a central faint, point source, which could be a residual neutron star or a block hole accreting some material from its surroundings). The gas in both of these SNRS includes lots of hydrogen, so presumably they would have been classified as Type II supernovae.

Supernova remnants are important in the great scheme of things as heaters and stirrers of interstellar gas, probably as triggers to collapse gas clouds to initiate star formation, and probably as the accelerators of cosmic rays – particles, mostly protons, with kinetic energies greatly exceeding $m_p c^2$ which pervade the Milky Way and other galaxies. Cosmic rays produce most of our lithium, beryllium, and boron, make ^{14}C in the upper atmosphere, and are a major source of mutations in terrestrial creatures.

4 Binary Stars

Half or more of all dots of light you see in the sky are actually binary stars, or gravitationally bound pairs. Binary stars are one of the classical subject areas of astronomy, as they represent the only way of determining the masses and radii of normal stars to high precision and accuracy. This makes them astrophysically vital: the properties of stars in binary systems are used to calibrate theoretical stellar models, determine the distances to nearby galaxies, and support asteroseismological studies.

4.1 Types of Binary Stars

4.1.1 Visual Binaries

The first type of binary star to be observed was the spatially-resolved class. These are also called visual binaries (because they can be identified by eye) and astrometric binaries (because it is possible to determine their orbits from measurements of the relative positions of the two stars).

4.1.2 Spectroscopic Binaries

Are systems in which the periodic change of stellar speed along our line of sight is large enough for the Doppler shift to be detectable.

For a "single-lined" spectroscopic binary system (SB1) – one can measure rotational velocites (RVs) for only one component whereas for a "double-lined" spectroscopic binary system (SB2) –RVs are measurable for both components.

Spectroscopic binaries are easier to study if they have short orbital periods, large masses and a high inclinations, in order to maximise the amplitude of the RV variation. On the other hand, it is more difficult to measure RVs for massive stars because they have few spectral lines and high rotational velocities. Spectroscopic binaries are useful for measuring the multiplicity fraction of stars which varies as a function of mass, age and chemical composition and can be used to probe the star-formation process.

4.1.3 Eclipsing Binaries

These systems are those in which one star passes in front of the other from our point of view, wholly or partially blocking its light, so that we see periodic variability. These are the most useful kind of binary star because of the huge number of physical properties that can be measured to high precision and accuracy.

4.2 Formation and Early Evolution

Several decades of research into the formation of binary and multiple stars has concluded that a single formation process or dynamic interaction cannot explain large number of double stars and the very large variety in their mass ratios and orbital elements. Instead, double stars seem to emerge at several points in the star formation process. Six mechanisms have been proposed to influence double star formation, and in three of these the development and influence of the protostar cluster is a critical factor.

- Molecular Cloud Fragmentation ($r > 100$ AU): Binaries form "in place" during the turbulent collapse of a massive, dense cloud core, which creates a clustered central distribution of stars that become gravitationally bound in the last stages of contraction and mass accretion.
- Protostar Disk fragmentation ($r < 100$ AU): Computer simulations strongly suggest that the disk of accreting material around a contracting protostar is highly susceptible to density variations that cause fragmentation into a companion star or, in systems with a high content of heavier elements (high metallicity), planetary systems. These companion protostars modulate the angular momentum, accretion rates and mass ratio of the evolving protobinary, and are strongly associated with the appearance of Herbig-Haro jets. Infrared surveys suggest that >80% of mass outflows and polar jets occur in binary protostellar systems.

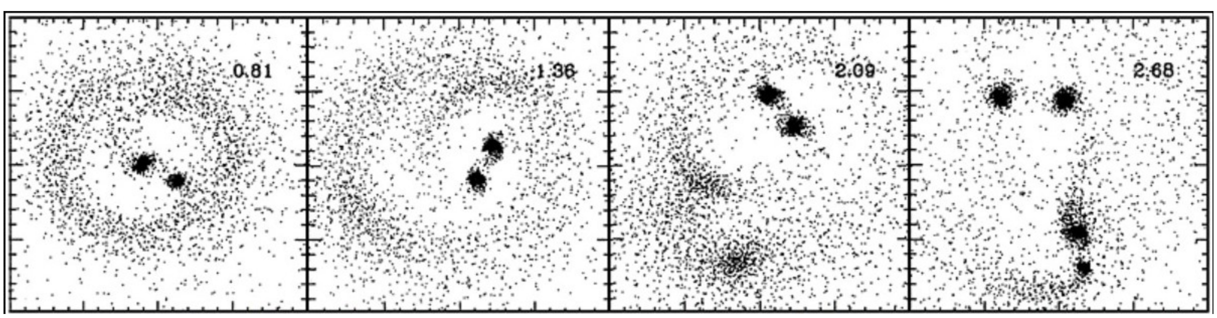

Figure 12: An early smoothed particle hydrodynamic (SPH) computer simulation of protostar disk fragmentation (Bonnell & Bate, 1994b)

- Competitive Accretion & Mass Segregation: A protostar grows more massive by accreting gas and dust from its surroundings, but at masses characteristic of a Type A star ($\sim 10 M_{\odot}$ radiation from the emerging star becomes powerful enough to push back surrounding dust and prevent further accretion. How then do the most massive (O and B) stars attain masses as high as $150 M_{\odot}$ Forced accretion of gas and dust and the occasional collision or merging of protostars, within the gravitational well of a dense cluster core, appear to be the only plausible mechanisms, and mimic on a small scale the formation of massive black holes at the center of many galaxies. This is consistent with the observation of the most massive stars and binary systems near the center of many protostar and star clusters. The same environment that produces forced accretion and protostar collisions would produce sufficiently frequent encounters to explain the high multiplicity fractions in high mass stars.

- Dynamical interactions ($r < 10$ AU, and "brown dwarf desert"): The orbits of double systems within a recently formed protostar cluster will bring binary and multiple systems into gravitational interaction, with complex results. The main effect will be to strip low mass and brown dwarf components from multiple systems, sending them out of the protostar cluster as high velocity or "runaway" stars. Disruptive gravitational encounters can also "harden" (increase the orbital energy and reduce the orbital radius) already formed binary orbits. These interactions have been proposed to explain the many binary systems with orbits < 1 AU, which are too close to emerge from protostellar disk fragmentation. Simulations by Reipurth & Mikkola (2013) suggest that an originally triple system can evolve by dynamical interactions into a wide "pair" consisting of a close binary with a distant component that is later stripped from the binary by disruptive encounters with passing stars or clouds of interstellar matter.
- Gas induced orbital decay ($r < 1$ AU): Orbital periods of already close protobinary systems may be shortened further by friction between the protostars and the surrounding protocluster gas cloud, during the interval after the stars have accreted most of their mass but before the stars begin nuclear fusion and the cloud is dispersed by stellar radiation. This would produce the contact and interacting binary systems observed in the Galactic population.
- Parallel Dispersion ($r > 1000$ AU): "Soft" or "fragile" binaries are too widely separated to survive even one or two orbits through a protostar cluster. Instead, they may bind when released in parallel trajectories (Galactic orbits) as their natal star cluster becomes gradually unbound, or when unstable triple or higher order systems break apart.

The consensus opinion of double star astronomers is that the very different orbital period, distance and eccentricity profiles of binary systems requires the contribution of very different star formation mechanisms, acting in a very different sequence or with different relative effects, due to differences in the mass, structure and turbulence of the natal giant molecular cloud, the presence and size of a protostar cluster, and the spacing and dynamics of protostar systems and accretion disks.

4.3 Mass Transfer

Lets consider a binary system with two stars, M_1, the primary (more massive) and M_2, the secondary with $M_1 > M_2$. Therefore M_1 will evolve out of main sequence before M_2. Sooner or later the primary star evolves off the main sequence and expands to become a red giant. If its companion is sufficiently far away, no mass transfer takes place and they evolve as separate entities. However, in the case of a "close" binary, when one star overfills its Roche lobe, material from the star is transferred to the accretor. This is illustrated in the following figure (Fig. 11)

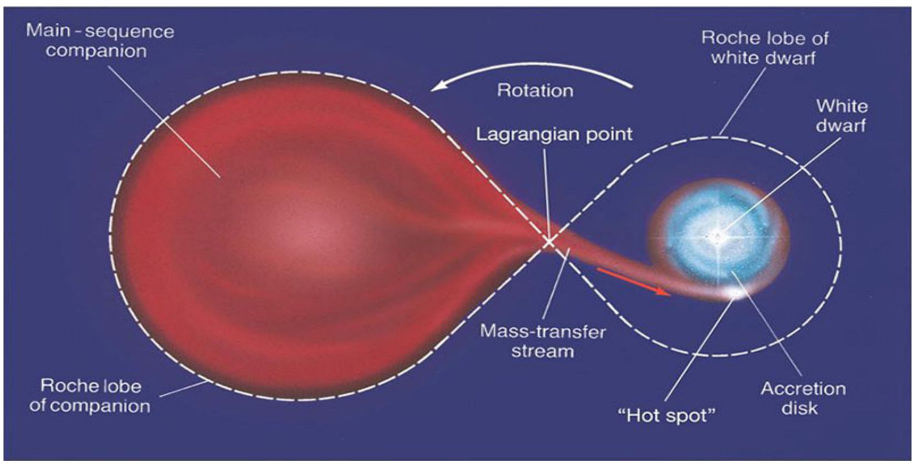

Figure 13: Diagram of a binary star system, showing the Roche lobes of a red giant star (left) and a white dwarf

There are three cases to be considered when mass transfer is to take place: Case A where the lobe is filled during post-main sequence evolution, Case B where filling occurs while the donor star is a red giant, and Case C where the overfill ocuurs when the primary star is in or is evolving to an AGB star.

When material from M_1 starts spilling onto M_2, the lobe starts to shrink at the same time the star tries to expand. Now M_1 dumps its material on a thermal or Kevin-Helmholtz timescale, but M_2 can only adjust and accept on a longer timescale. Thus its envelope puffs up until it too fills its Roche lobe, producing a common envelope binary.

A situation of Case A mass transfer between two stars with initial masses $M_1 = 9M_\odot$ and $M_2 = 5M_\odot$ is shown in Fig. 14.

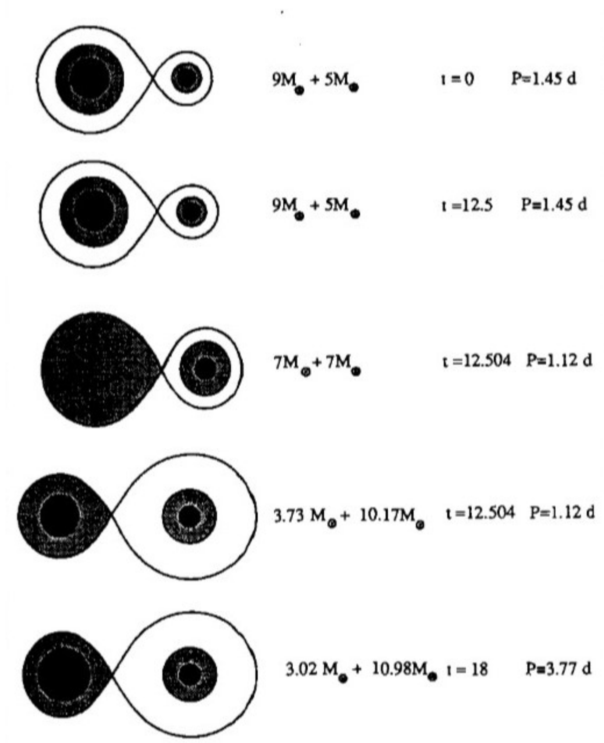

Figure 14: An example of mass transfer via Case A. Initial masses are 9 and $5M_\odot$ with a period of 1.45 days. Times(t) is given in millions of years. From de Loore and Doom (1992)

5 Star Formation

In outline, star formation occurs across three distinct stages, which are completed after roughly 10 to 30 million years.

1. ***Spiral arm shock waves and supersonic turbulence fragment and compress cold, giant molecular clouds (GMCs) into sheets and filaments, which contract gravitationally into dense cloud cores***

   About 4% to 8% of the Galaxy mass (equivalent to 8 to 16 billion solar masses) is in the form of an interstellar medium (ISM) consisting of atomic hydrogen and helium, molecular hydrogen and "dust" (grains of ice, graphite and silicates). The ISM is confined to the Galaxy disk by lines of magnetic flux and internal friction, and revolves at different speeds than the Galaxy spiral arm density waves. As a result, the gas clouds encounter spiral waves sweep across the ISM and compress it into dark, cold (10 K) giant molecular clouds (GMCs). A single cloud can be comparable in mass ($\sim 10^4 - 10^6 M_\odot$) and diameter (50-150 pc) to a globular cluster.

   Clouds are normally supported against their own gravity and held within the Galaxy disk by lines of magnetic flux. But turbulence from the passage of spiral arm shock waves and from nearby supernova explosions can compress the filaments further into cloud cores with a mass of around $10^2 - 10^3 M_\odot$ and a radius of 0.5 to 1 parsec (more than 10^5 AUs). These cores are the seeds of star formation.

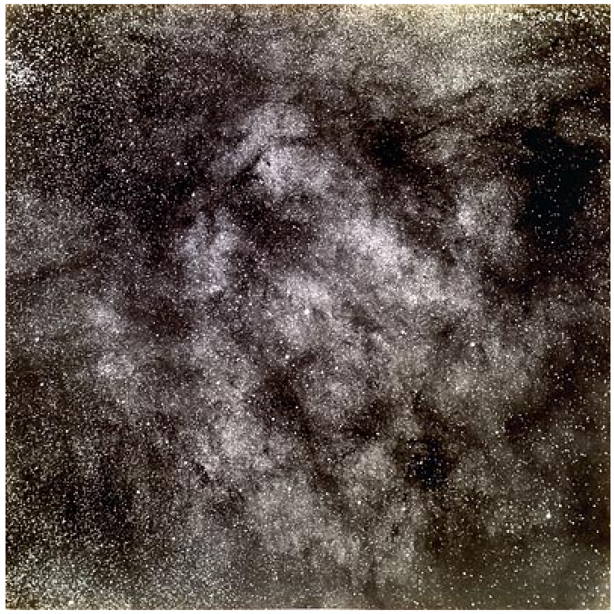

Figure 15: Giant molecular clouds, whose turbulent and fragmented texture is beautifully captured in early Milky Way photographs made by E.E. Barnard

2. ***At a critical density, cloud cores collapse under their own gravity to form protostellar objects (PSOs); these burn deuterium, gather mass and dissipate angular momentum inside a circumstellar accretion disk and a cloud "cocoon" of hot dust***

   Each cloud core is a concentration of mass within a certain spatial radius. When this mass concentration exceeds a limit known as the Bonnor-Ebert density, gravity overwhelms the thermal pressure and magnetic support within the cloud core and an isothermal free fall collapse occurs, forming one or more disklike, rotating protostellar objects (PSOs), each with a radius of $\sim$ 1-5 AU and a mass of around 10–3 $M_\odot$

   The collapse removes thermal support underneath the surrounding gas, which falls toward the PSO. This "late" infalling gas forms a rotating accretion disk around the PSO with a radius up to $\sim$100 AU. Computer simulations suggest that accretion disks with masses near and above $\sim 1 M_\odot$ form spiral shock waves and asymmetric mass concentrations which create binary/multiple protostellar objects through disk fragmentation. In other words, binary and multiple star systems begin to form well before star formation is completed.

When gravity contracts the PSO far enough to raise the central temperature above 2000 K, molecular hydrogen (H2) is ionized and the protostar becomes opaque, creating a radiant surface or "photosphere". A second core collapse to around 0.3 AU occurs, deuterium fusion begins and raises core temperature to 10^6 K, and the protostar luminosity rises from 5 $L_\odot$ to over $1000 L_\odot$ almost entirely in the infrared. The clouds of dust and gas become almost transparent in the infrared, and at their high luminosities these protostars become visible deep inside the surrounding dust clouds and while still within the "brown dwarf" mass range.

Mass continues to accrete from the surrounding cloud into the circumstellar disk, and from the disk into the YSO. This process is still poorly understood, but it seems likely that the accelerating angular momentum in the collapsing matter is braked by torque and stellar winds from the accretion disk, while matter that cannot adhere to a rapidly spinning protostar is blown away in bipolar jets along the rotational axis, at velocities up to $\sim$100 km s^{-1}, which create the energetic mass outflows observed as Herbig-Haro jets. These jets create shock waves in the surrounding cloud core that can initiate new protostar formation.

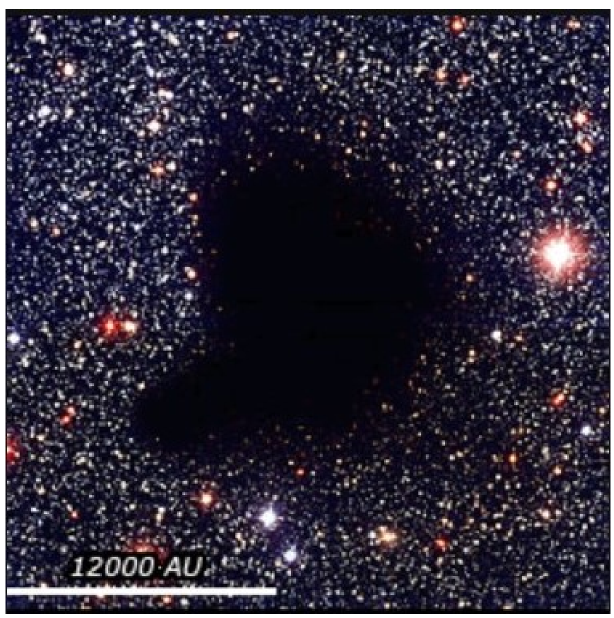

Figure 16: cloud cores are visible as discrete Bok gobules found in star forming regions

3. ***After roughly one million years of accretion, the PSO attains sufficient mass and density to initiate hydrogen fusion. Planets may form from the remnant disk, otherwise radiation from the new star evaporates the gas/dust "cocoon" and the star takes its place on the main sequence***

   The protostar gains more than 90% of its mass through irregular accretion events. At the same time, it dissipates roughly 99% of the angular momentum it inherited from the GMC via disk gravitational/magnetic torque, binary orbital energy, and dynamic interactions with other protostars.

   The protostar gradually gains mass and contracts under its own gravity until the core reaches fusion temperatures (the hydrogen burning limit at about 10^7 K). The resulting enormous increase in surface temperature and UV radiation pushes back and photoevaporates the accretion disk and surrounding cloud "cocoon", ending mass accretion. At this point the object appears as a young stellar object (YSO) or T Tauri star.

   The new star descends to its "mature" position on the main sequence, where it remains for most of its existence.

References

Carl J. Hansen, Steven D. Kawaler, and Virginia Tumble. *Stellar Interiors : Physical Principles, Structure, and Evolution.* Springer- Verlag New York, Inc., 2004, 1994.

Astronomical files from black oak observatory - handprint. https://www.handprint.com/ASTRO/, March 2014. Accessed on 25-05-2020.

John Southworth. Binary stars: a cheat sheet. 2019. URL http://arxiv.org/abs/1912.13400.