Stellar Evolution

The origin of stars

How they evolve

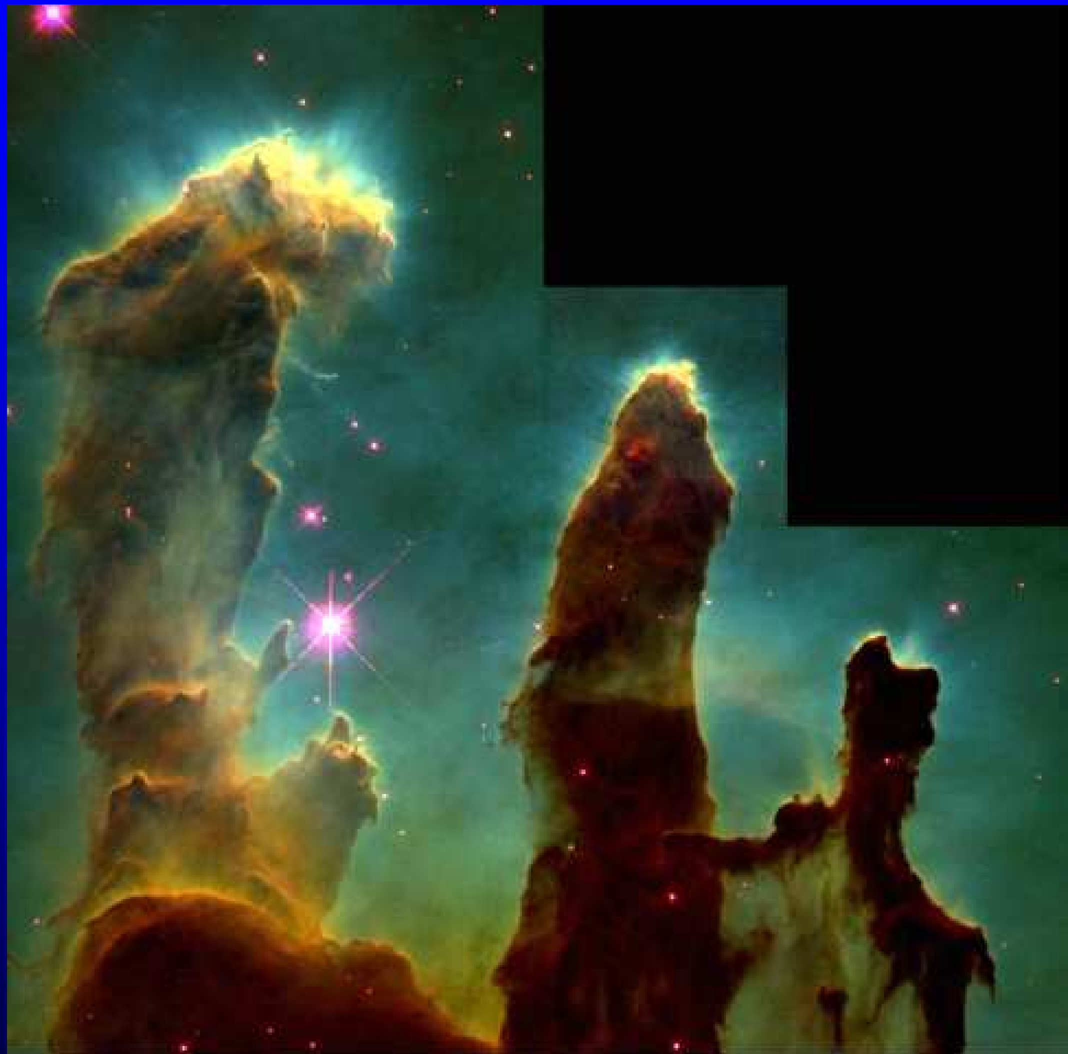
Their remnants

The Birth of Stars

- Stars condense out of Interstellar Clouds.
- James Jeans showed in 1926 that a cloud of gas of given density and temperature can only collapse if the mass is above a certain value.
- Large, dense and cool clouds contract.
- Small, low density and warm clouds expand.
- To allow the formation of stars we need a mass - called the Jean's Mass given by:
  - $M_j >= 3 \times 10^4 (T^3 / n)^{1/2}$ Solar Masses
  - Where n is the number of atoms per m^3

What will work?

	N	T	Mj	
• Interstellar Medium	2×10^5	8000	5×10^7	No!
• Atomic Clouds	10^8	100	3000	Yes
• Dark Clouds	10^9	10	30	Yes



The Eagle Nebula

What happens then?

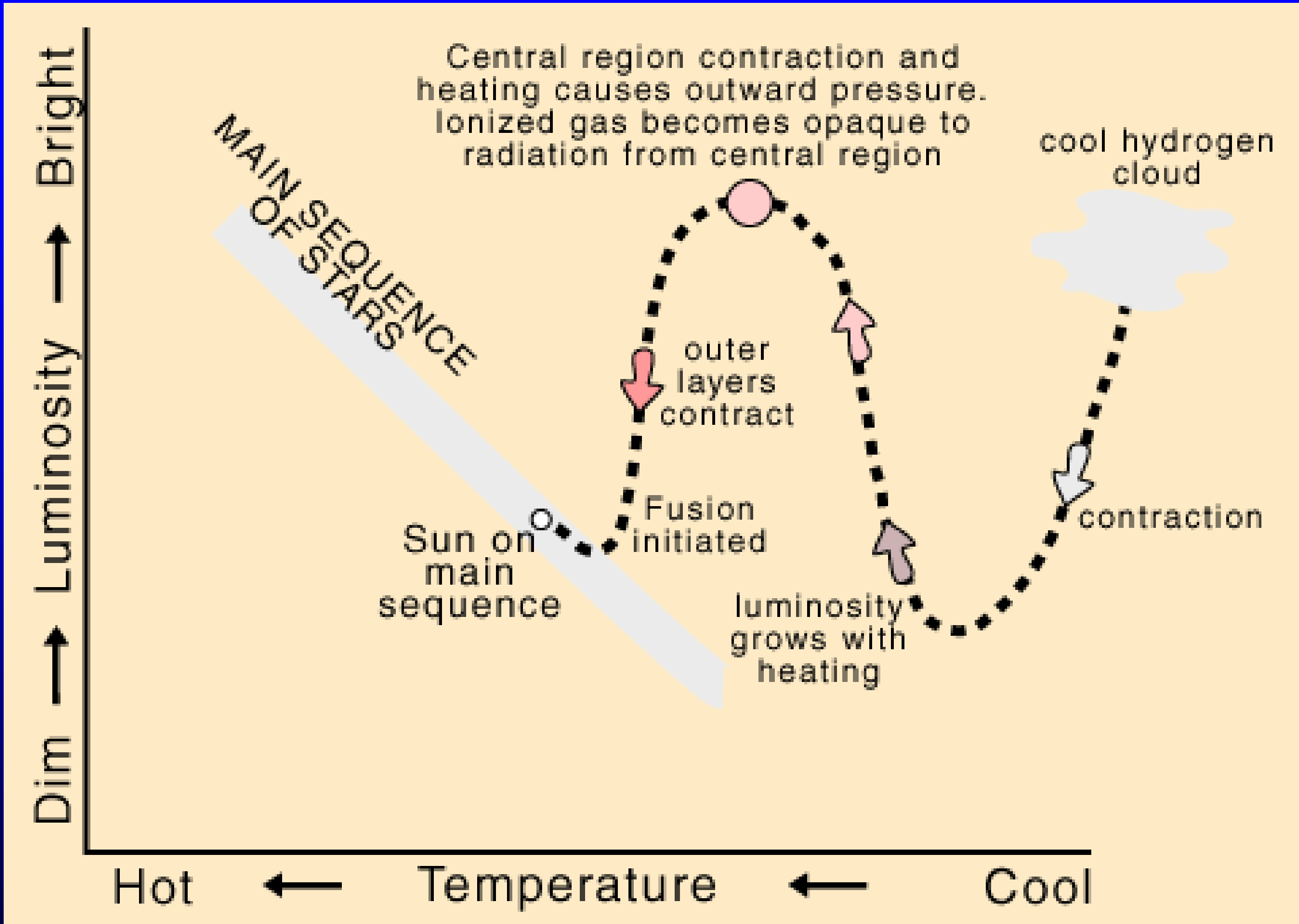
- Original, large clouds must fragment helped by turbulence, shock fronts and density waves.
- For Sun sized stars it has recently been shown that this will only work when gravity only just wins – a slow process!
- Can take 1000's or even millions of years.

A star forms

- 2 M_{sun} Density 6 x 10^{10} atoms m^{-3} T = 10K
  Radius 0.05 parsec.
- After 400,000 years, a hot core region is formed which soon collapses to give the nucleus of the future star.
- During the next 100,000 years the nucleus increases in size as the remainder of the cloud falls onto it.
- Then for 5 x 10^7 years the star as a whole collapses. The centre becomes steadily hotter
- As 10^7 K is reached, Nuclear Fusion begins and the star joins the main sequence.

The Protostar phase

- As the gas cloud collapses, there is a period of near constant luminosity.
- As it gets smaller it also gets hotter and the two effects cancel out.
- Our Sun's protostar would have been about 10 times more luminous.


Central region contraction and heating causes outward pressure. Ionized gas becomes opaque to radiation from central region
cool hydrogen cloud
MAIN SEQUENCE OF STARS
outer layers contract
contraction
Fusion initiated
Sun on main sequence
luminosity grows with heating
Dim → Luminosity → Bright
Hot ← Temperature ← Cool

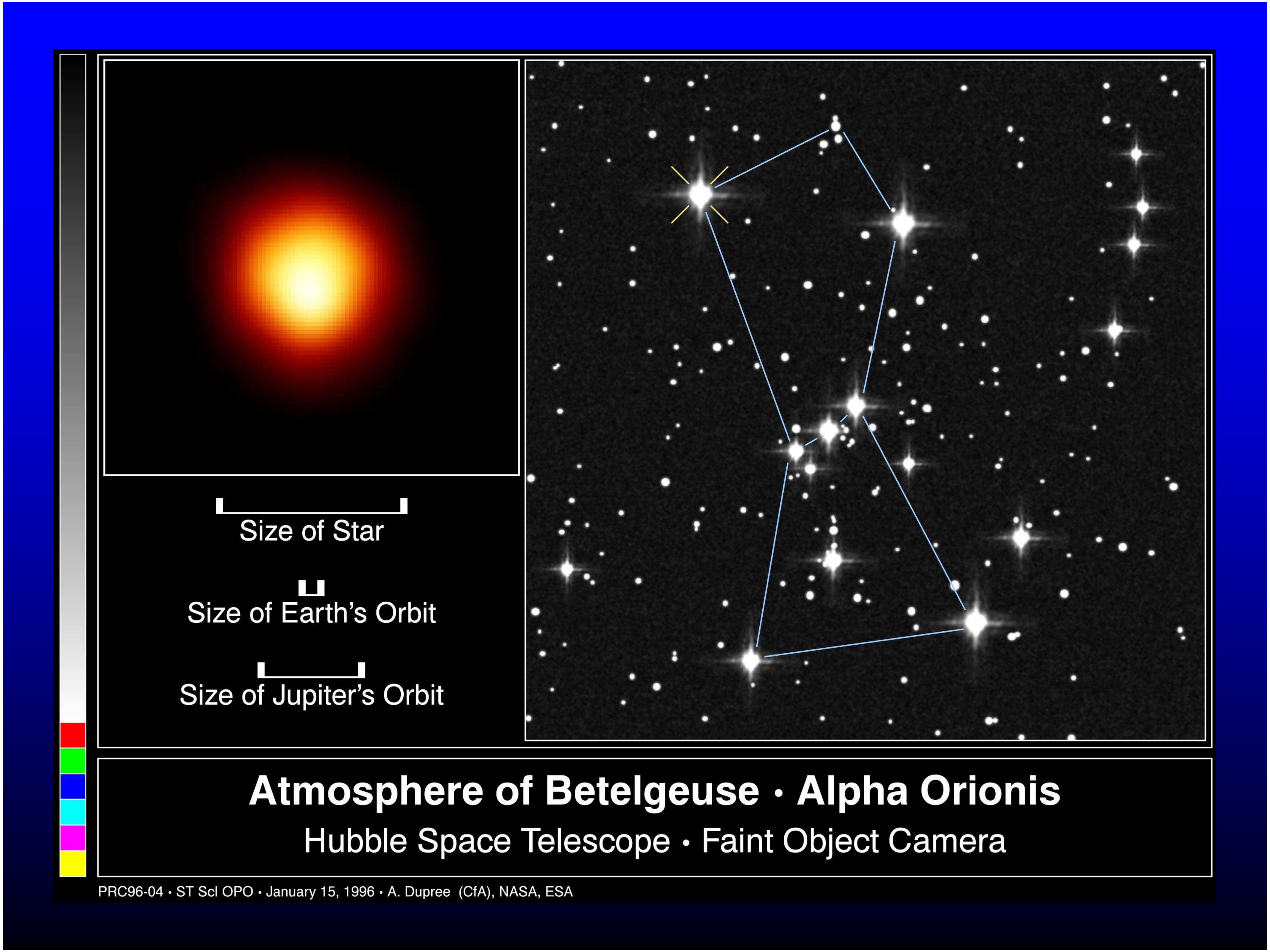
Two features.

- Angular Momentum problem:
  - If the cloud is rotating prior to the collapse, then rotation rates can increase by a factor of 1,000,000 and so resist contraction. This can be overcome if the protostar breaks up into two or more pieces rotating around each other to give a Binary or Multiple Star system.
  - Planetary systems can also take up the angular momentum

τ-Tauri phase

- The τ-Tauri phase
  - During the final stages of moving onto the main sequence the star will produce a very large stellar wind which will blow off much of its outer nebula into space.
  - A star like the Sun will shed about half its mass in the τ-Tauri phase in a great outflow of matter or solar wind.

Orion


Size of Star
Size of Earth's Orbit
Size of Jupiter's Orbit
Atmosphere of Betelgeuse • Alpha Orionis
Hubble Space Telescope • Faint Object Camera
PRC96-04 • ST ScI OPO • January 15, 1996 • A. Dupree (CfA), NASA, ESA

The Orion Nebula

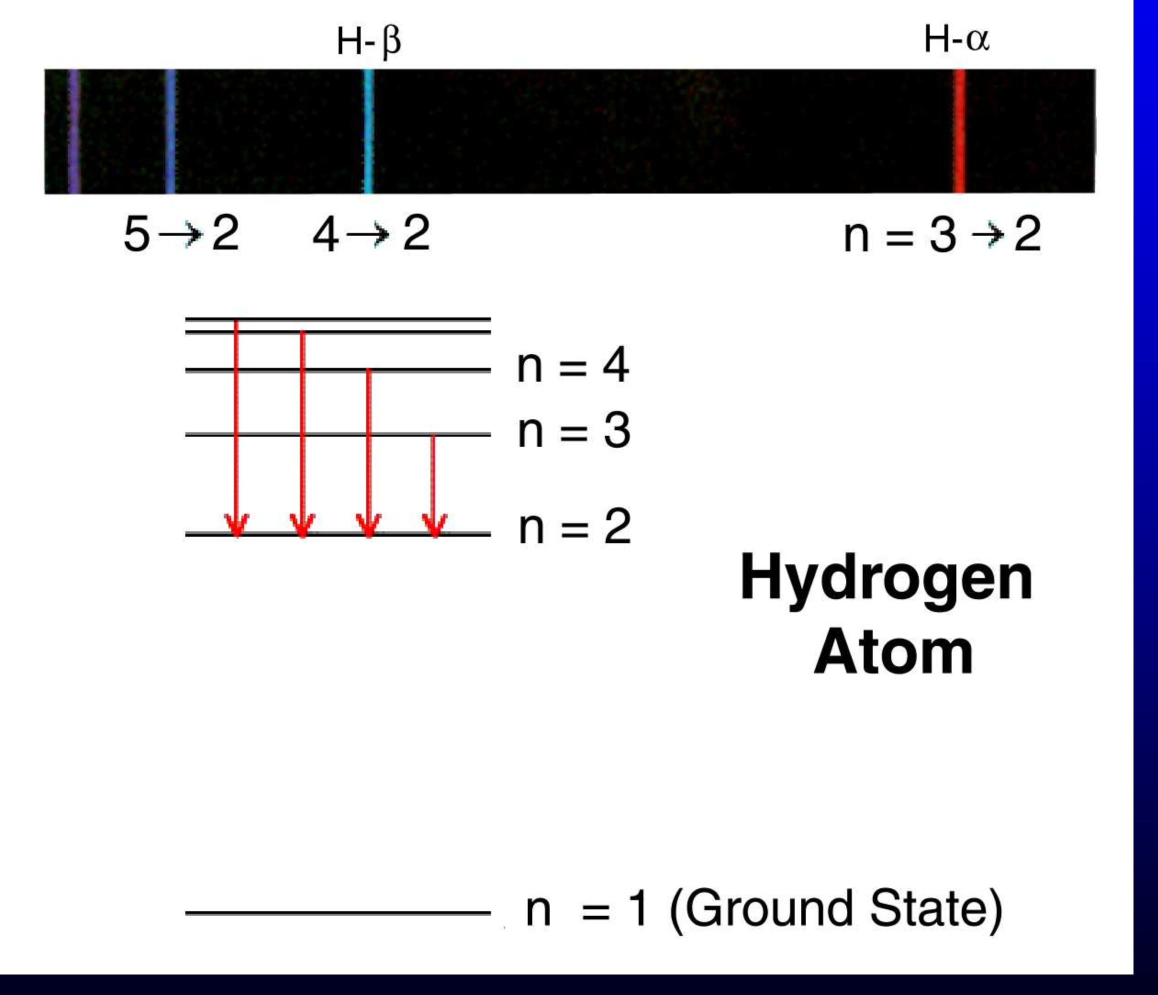
- A Stellar Nursery

Orion Nebula

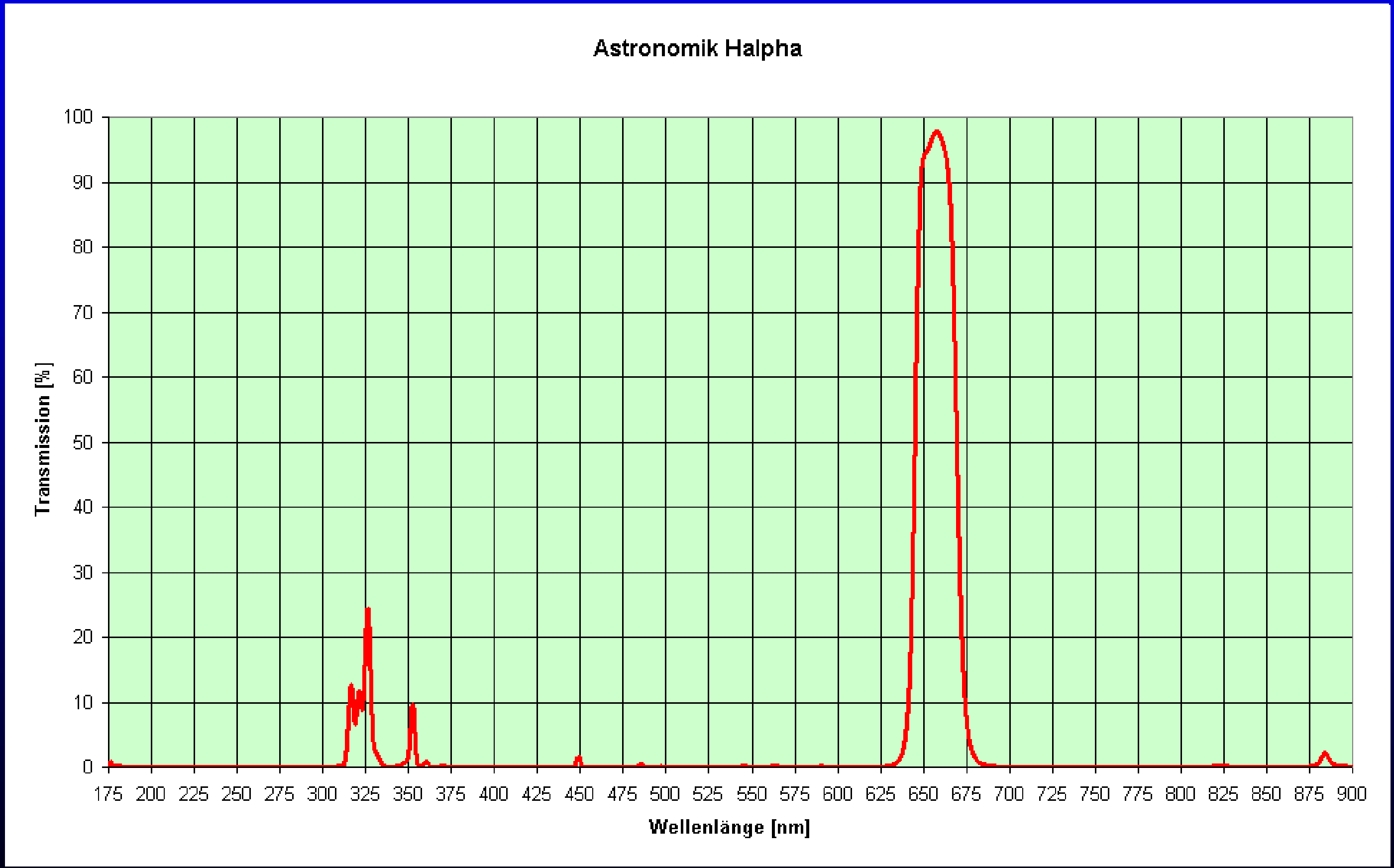
Orion Nebula

- The pink/red light comes from excited hydrogen.
- UV light from very hot young stars lifts the electron from its ground state. As they fall back to the second energy level of the hydrogen atom a series of spectral lines are emitted.
- The red colour comes from the H-α line.

Balmer Series

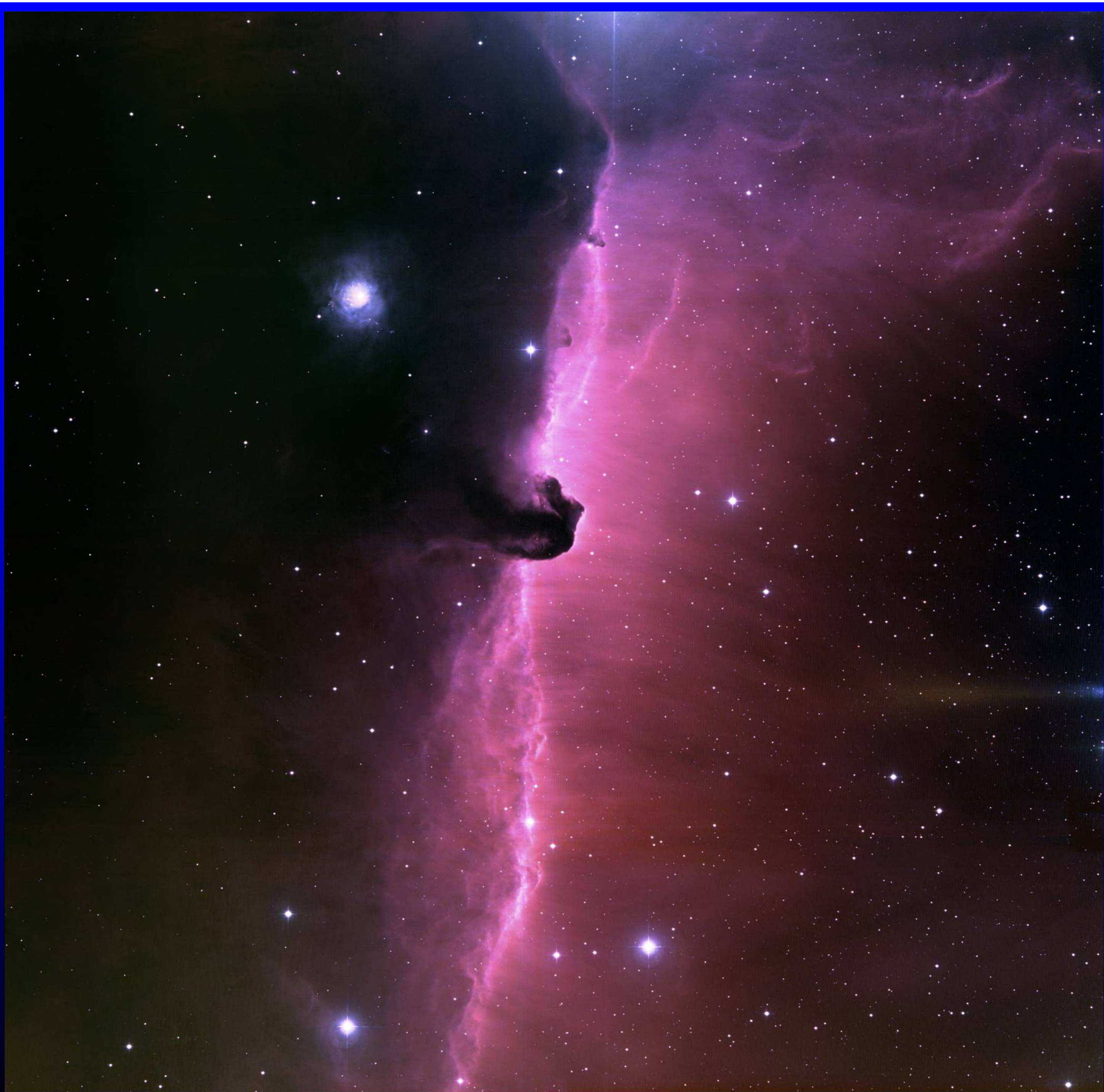


H Alpha Filter



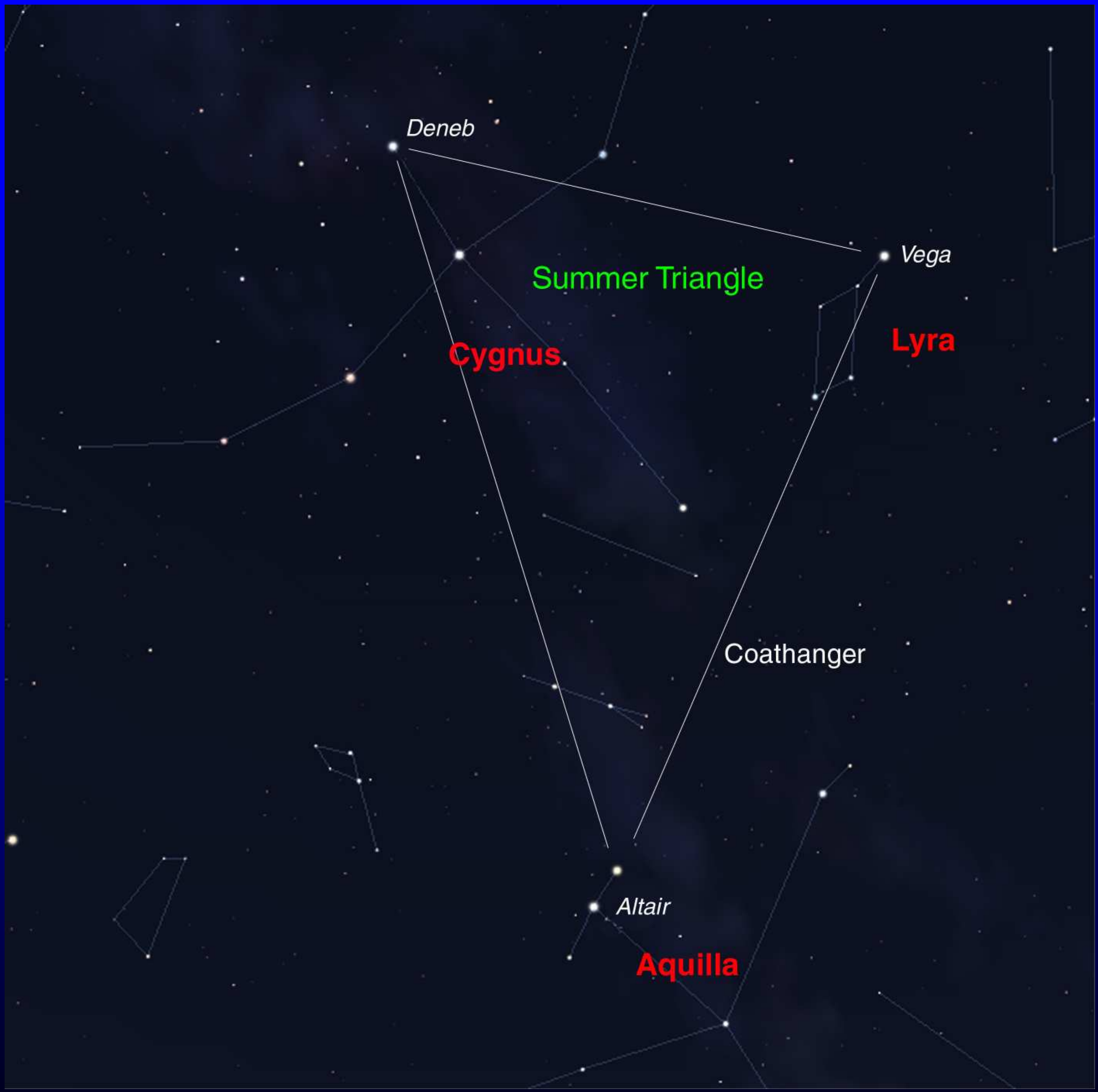
The Trapezium

Horsehead Nebula

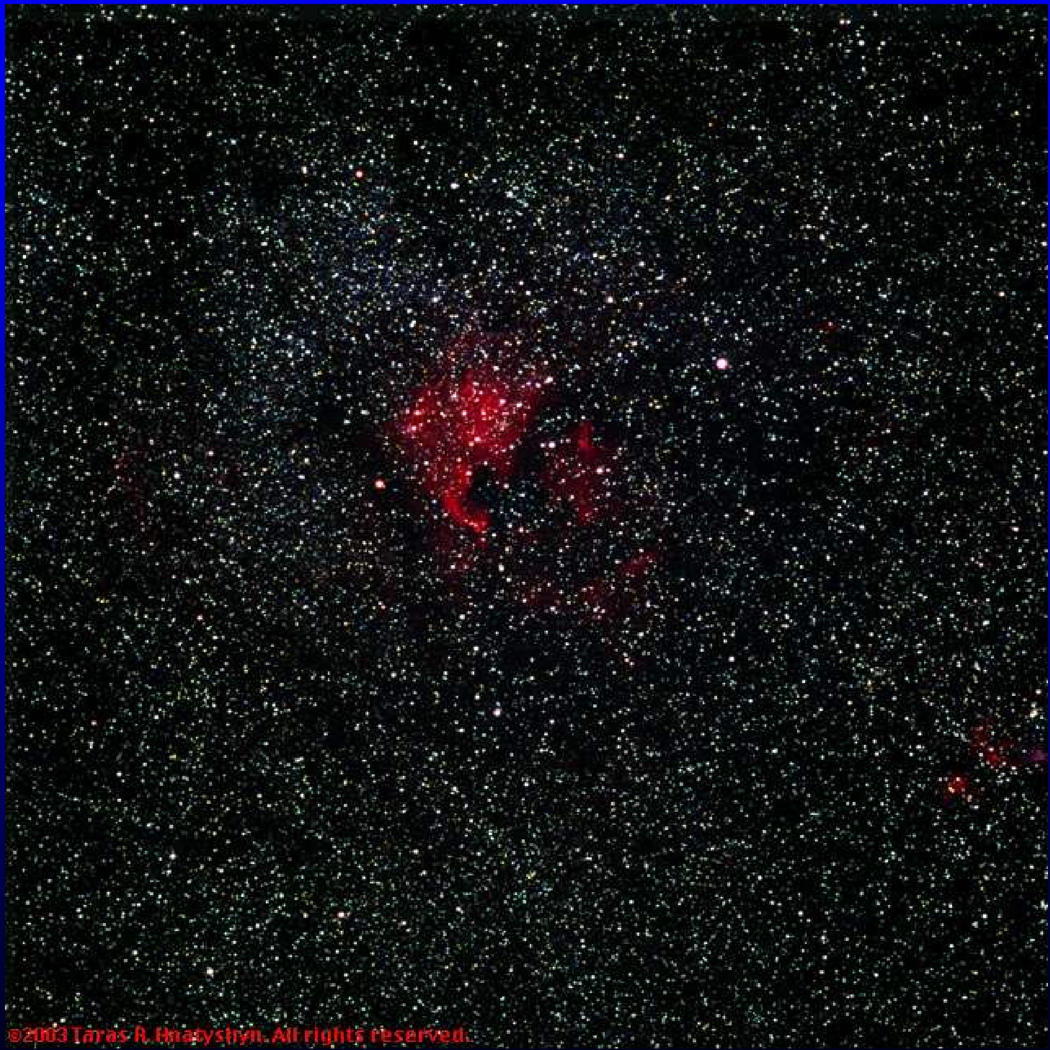


Summer Triangle

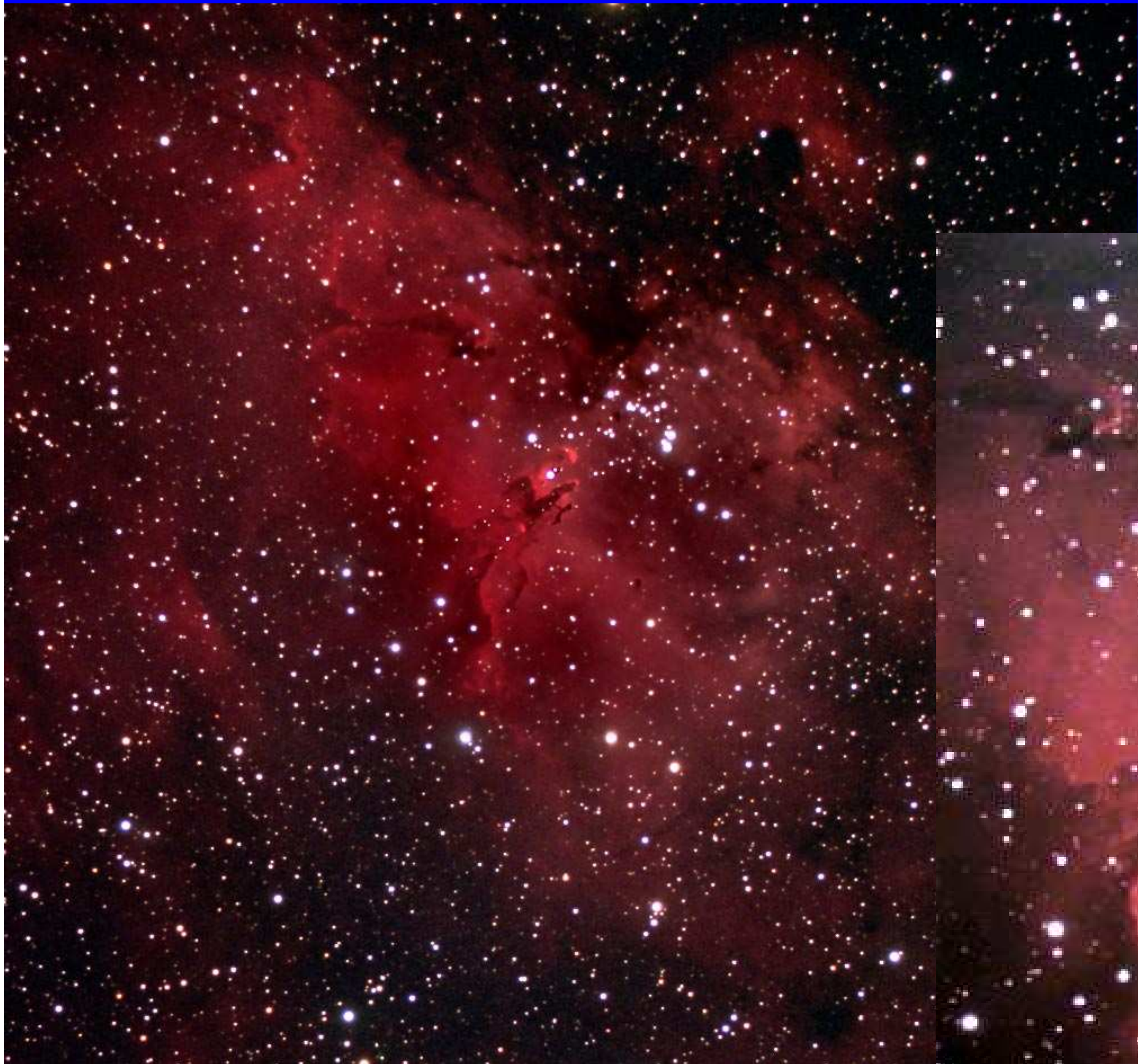
The region near Deneb has a lovely region of Nebulosity.



North American Nebula



The Eagle Nebula

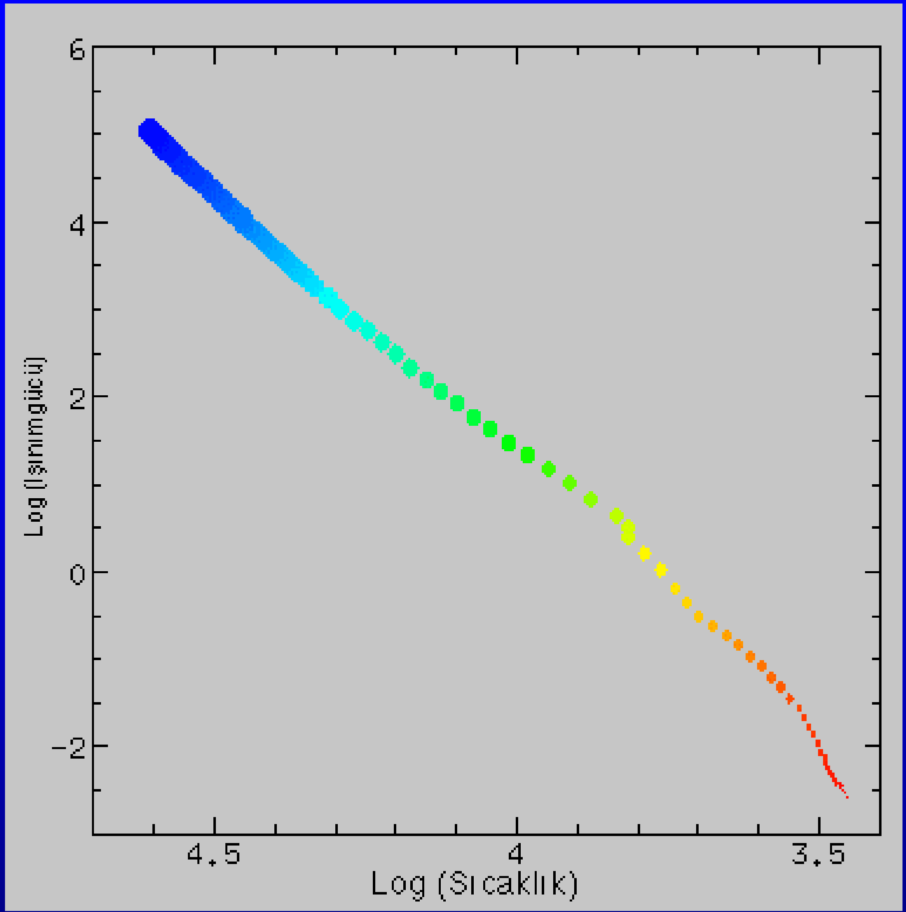


Open Star Clusters

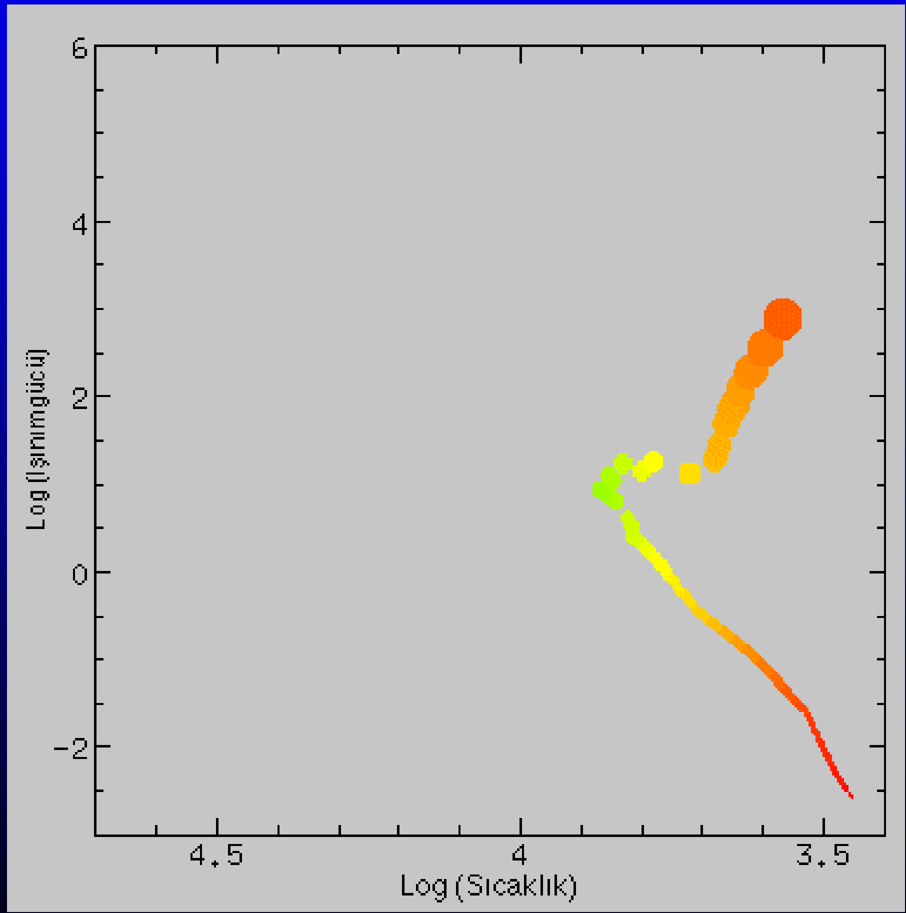
- As many stars must form together in one cloud of dust and gas we get clusters of stars. They have varied shapes and are called open clusters.
- The Pleiades Cluster is a nearby, young example.
- We find them along the plane of the Milky Way.

Hyades and Pleiades

Evolution



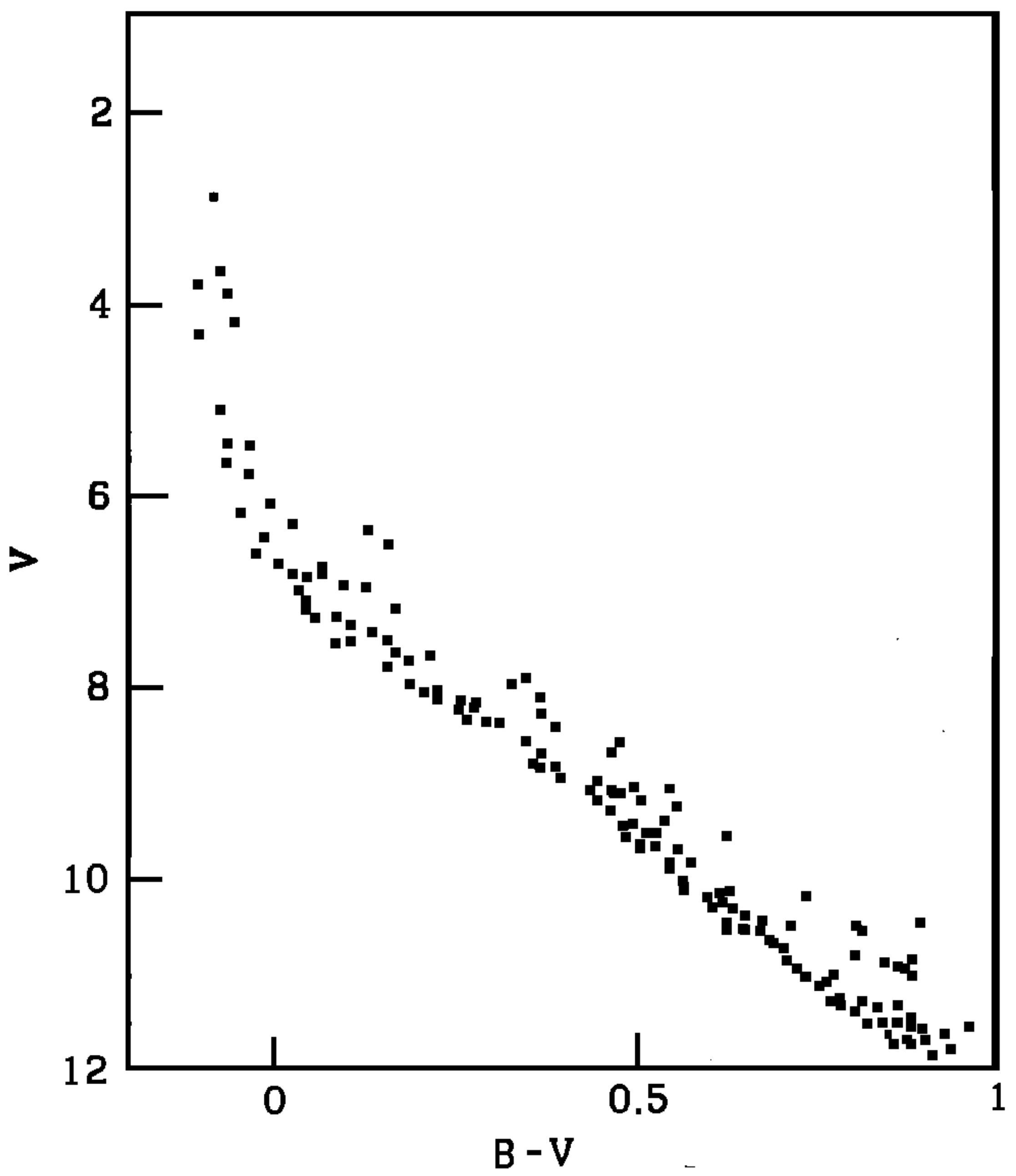
6
4
2
0
-2
4.5
4
3.5
Log (Işınımgücü)
Log (Sıcaklık)



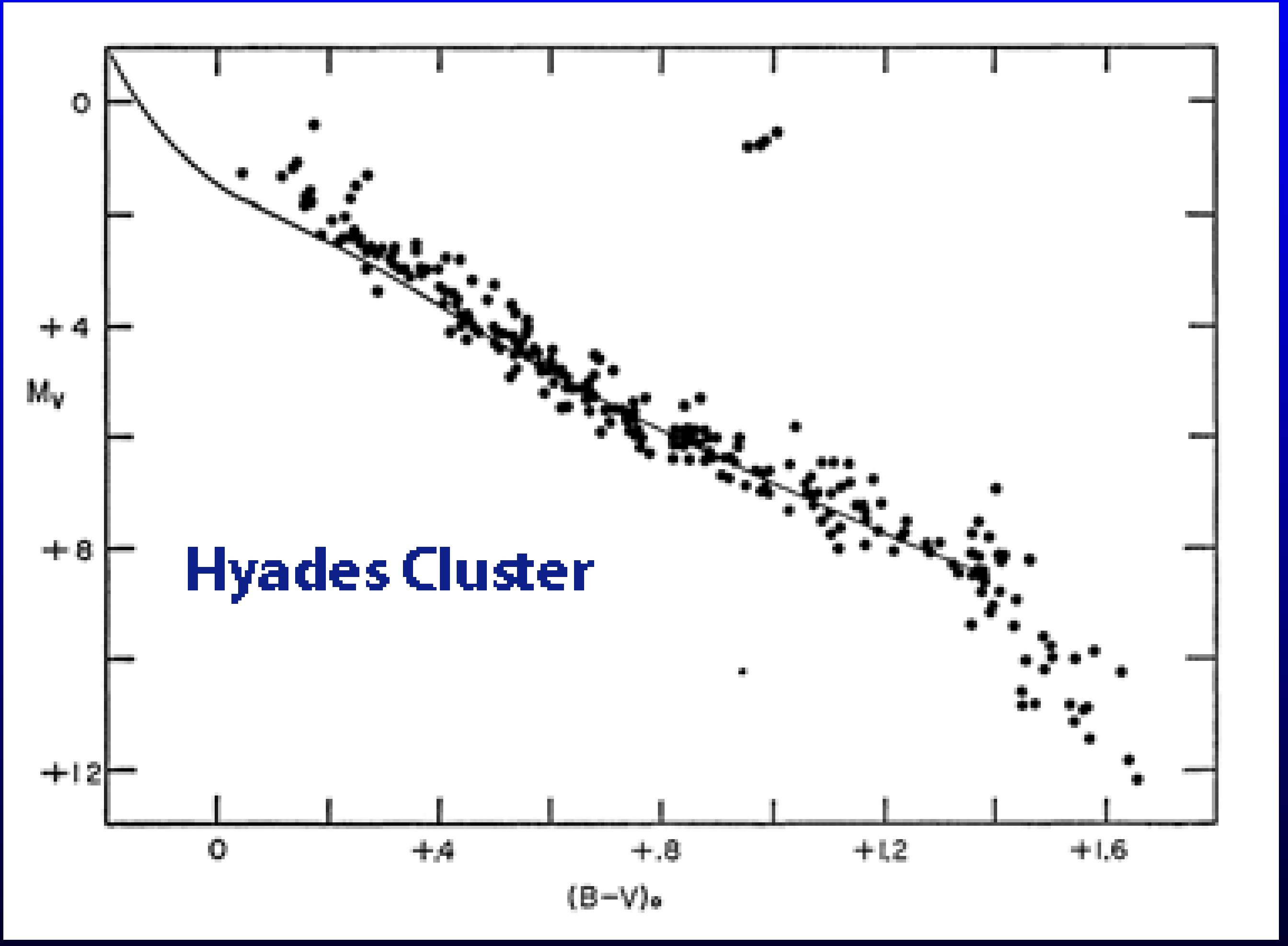
6
4
2
0
-2
4.5
4
3.5
Log (Işınımgücü)
Log (Sıcaklık)

Pleiades H-R Diagram

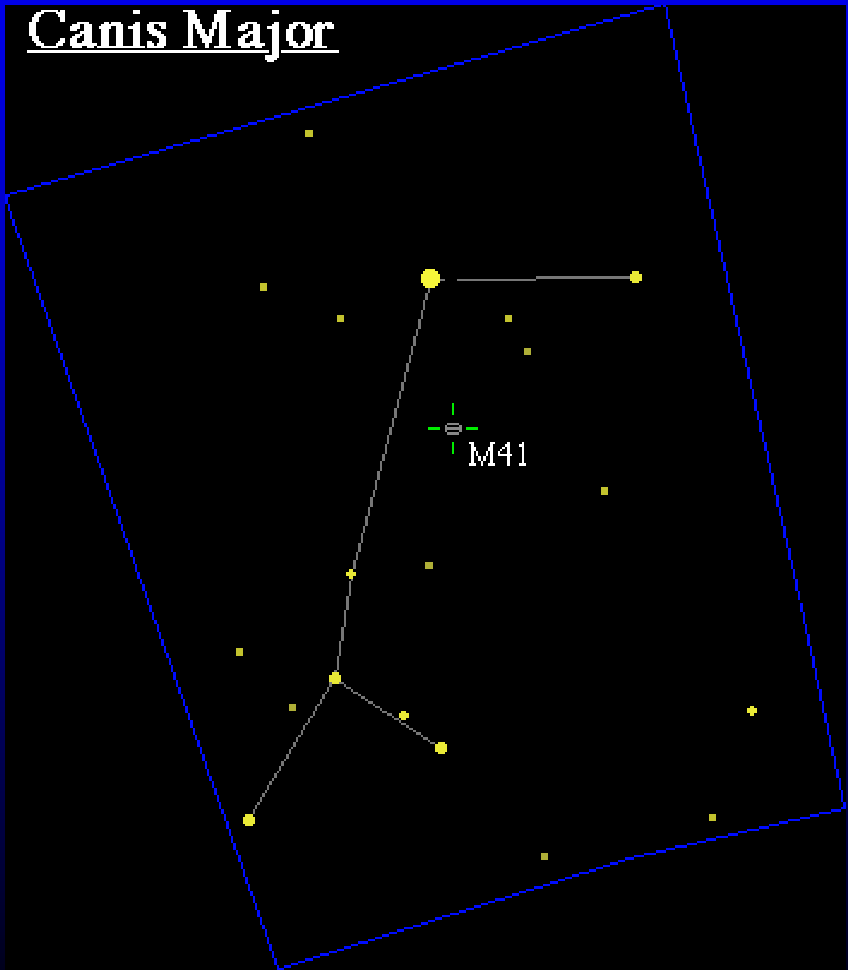
115 M yrs old



650 Million Years Old



M41



Double Cluster

M 35

M44 – The Beehive Cluster

Evolution of the Sun away from the Main Sequence

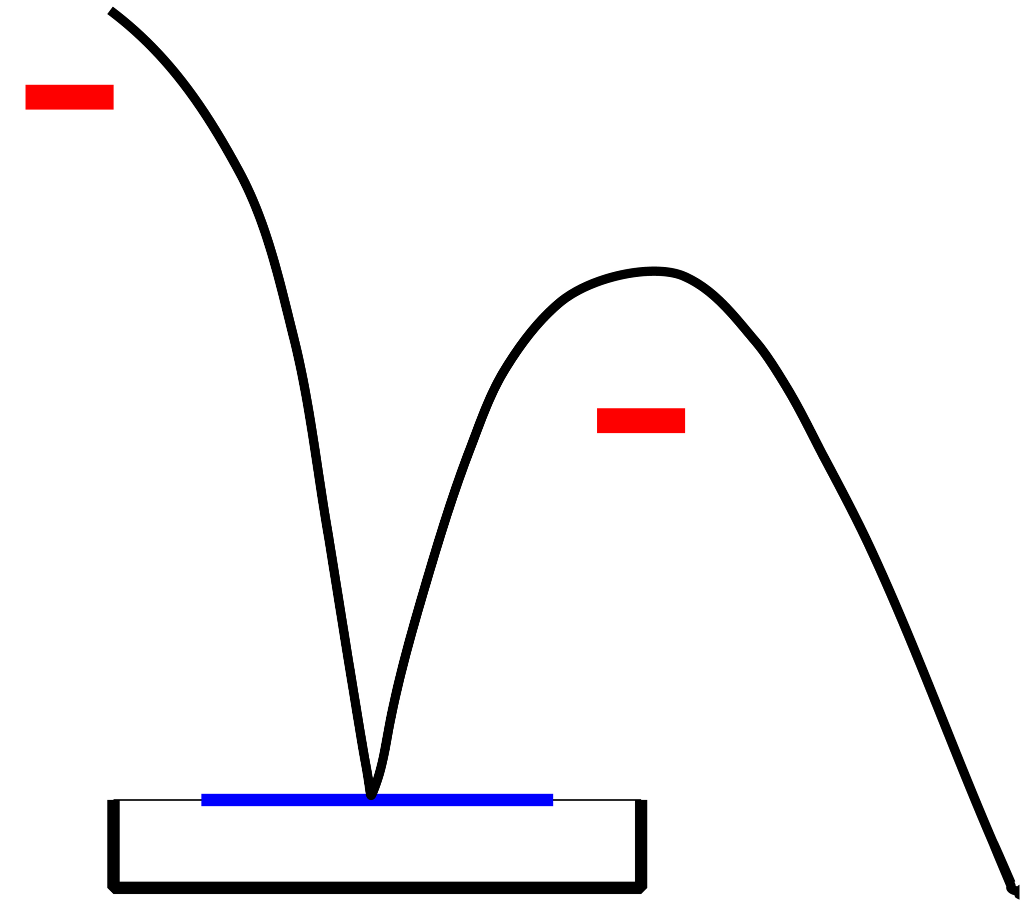
- When all the Hydrogen in the Core has been converted to Helium, nuclear fusion stops.
- Hydrogen continues to burn in a shell around the core.

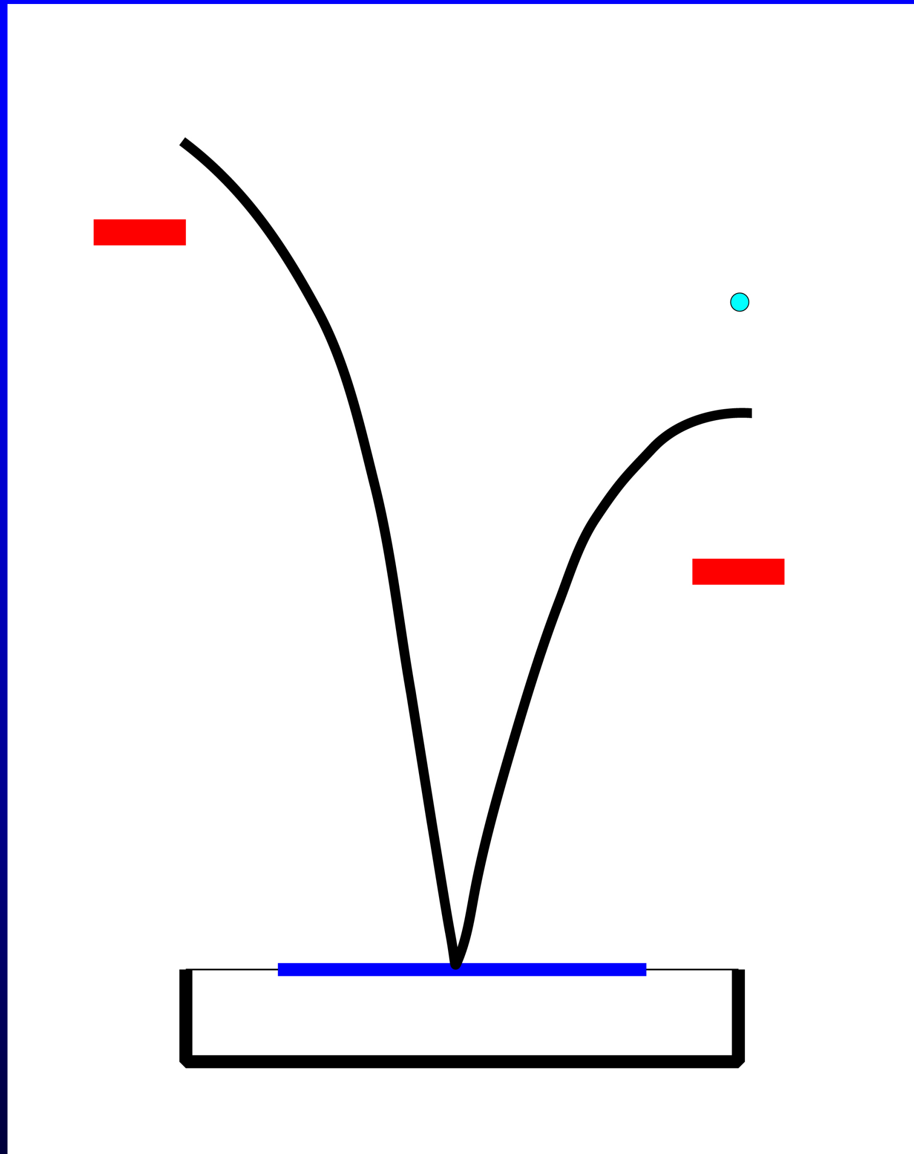
Fred Hoyle

- “Since carbon is so common and we ourselves are carbon based life, the stars must have discovered a highly effective way of making it – and I am going to look for it!”

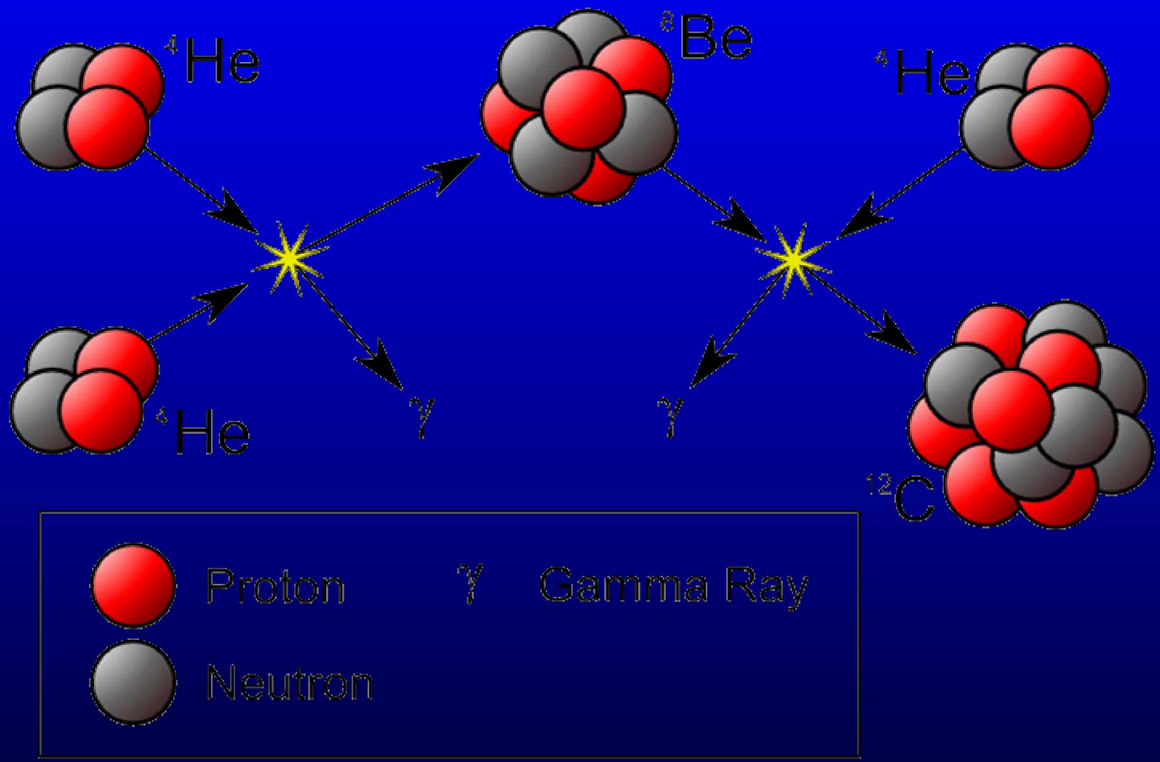
Triple-Alpha Process

- The three alpha particles that must come together will have too much energy and stable C-12 nucleus only results because there is an excited state of the nucleus at the appropriate energy above the ground state.
- The nucleus is initially in this state and then drops down to the ground state.





Triple Alpha Process



A Red Giant is Formed

- The star undergoes a major change in its structure:
  - The outer parts of the star expand – so it becomes cooler and thus appears redder.
  - But the expansion is so great that, though each sq metre radiates less energy (Stephan’s Law), the total energy radiated by the star increases.
  - Thus the star becomes more Luminous and is called a Giant Star – hence Red Giant.

The Helium Flash

- The core, now largely inert,with an expanding shell of Hydrogen burning around it, gradually collapses under gravity until the temperature reaches ~ 100 Million K.
- Then two Helium Nuclei make a Beryllium nucleus (highly unstable) which immediately fuses with another Helium nucleus to give a Carbon nucleus which IS stable.
- This is called the Triple Alpha Process.

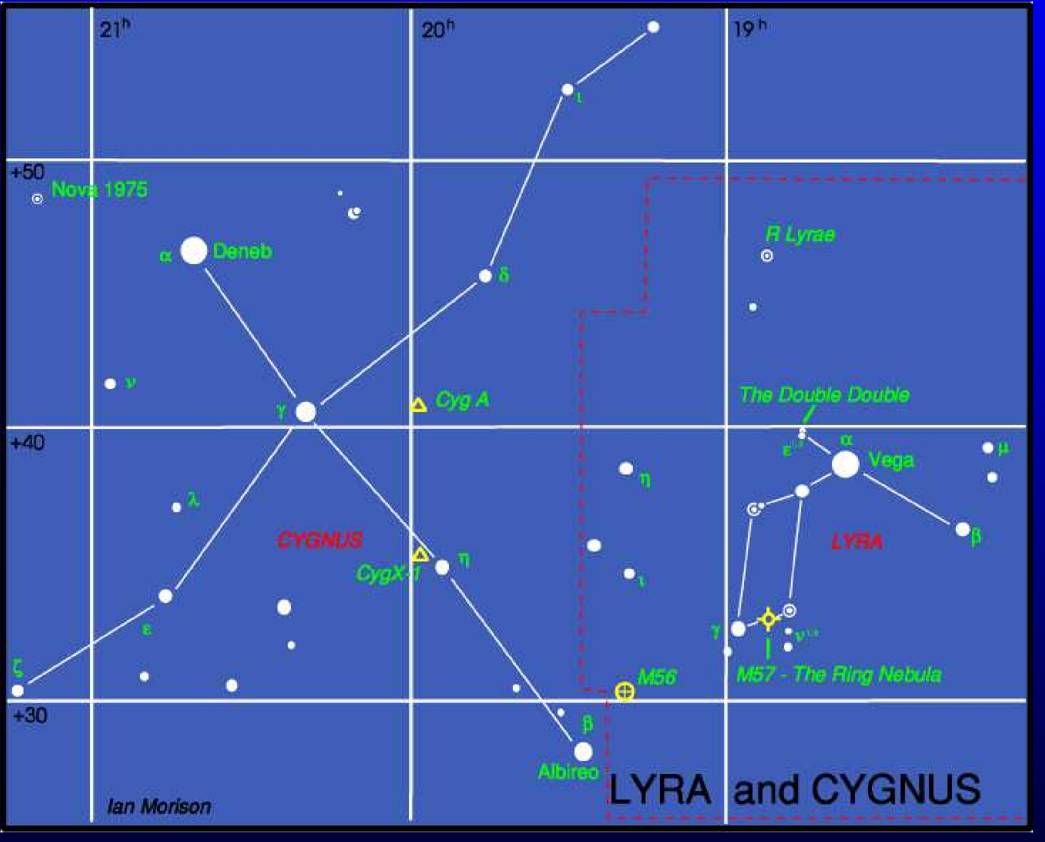
- The onset of the triple-alpha process occurs very rapidly and is called the Helium Flash.
- It lasts for a very few years when it produces a large amount of energy.
- The star again re-adjusts. The core gets bigger, the outer parts smaller .
- The star become smaller, hotter and less luminous.
- It becomes a Yellow Giant.
- During the next 100 million yrs the helium is burned in the core and the star remains stable.

- Round the Helium Burning Core is a shell of Hydrogen Burning
- In the heart of the Core the Carbon fuses with Helium to give Oxygen.
- The star expands again and may become a Red Super Giant. It is highly unstable.
- Finally much of the outer parts of the star are shed in a very strong solar wind.
- In perhaps just 1000 yrs, core becomes surrounded by a shell of of gas at ~ 10,000 K.
- We see the very hot, exposed, central core at its centre which shines in the UV and blue end of the spectrum.

Planetary Nebulae

- We know of about 1500 such objects (perhaps 10,000 in the Galaxy).
- William Herschel gave them the name Planetary Nebulae.
- The central star is very hot, sometimes up to 200,000 K – the hottest stars known.
- They are about the size of the Earth, and rapidly cool to become White Dwarfs, down to the lower left of the H-R diagram.
- The shells of excited gas can look very beautiful.

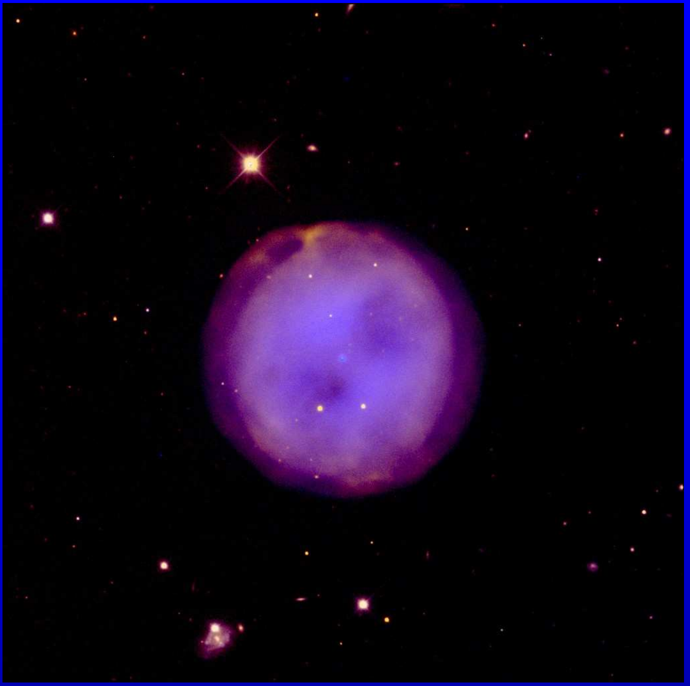
Ring Nebula in Lyra

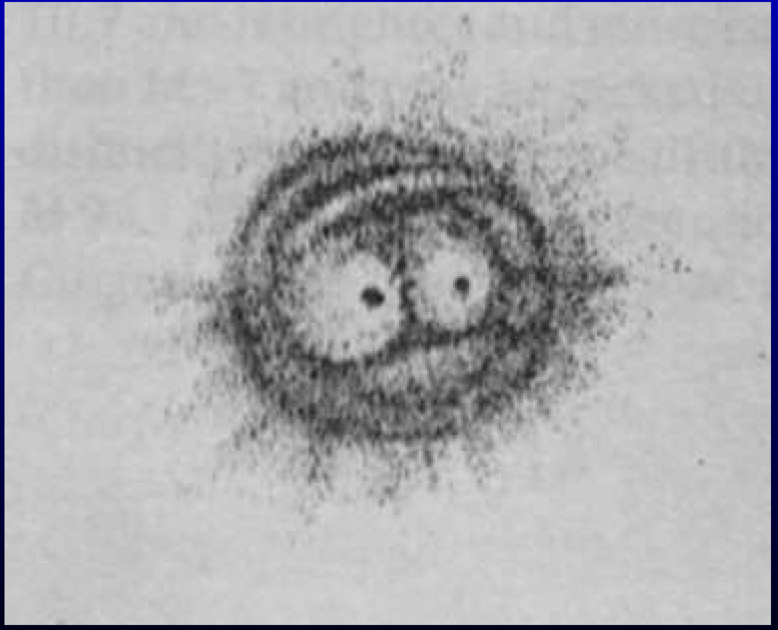


Ring Nebula

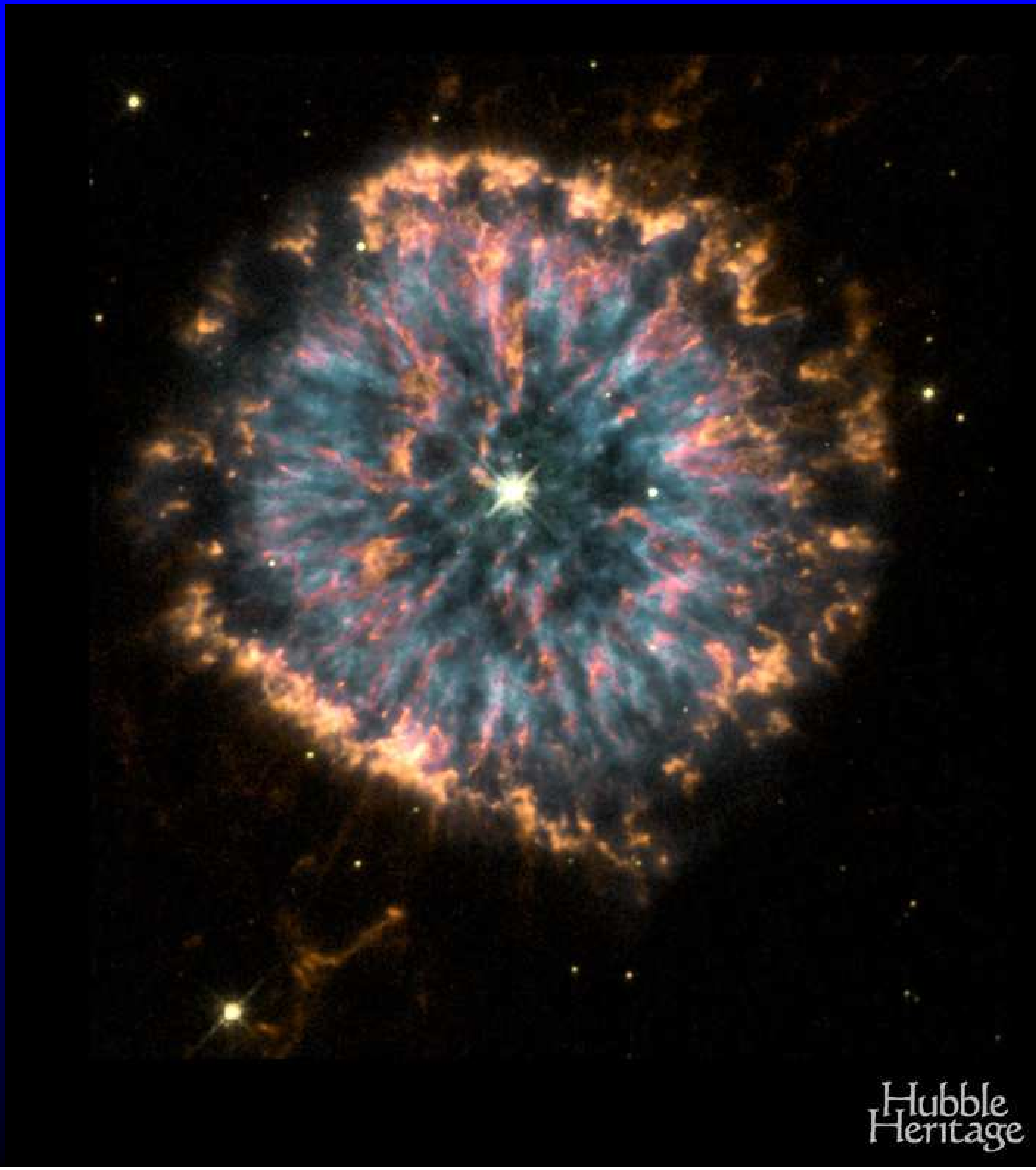
Dumbbell Nebula

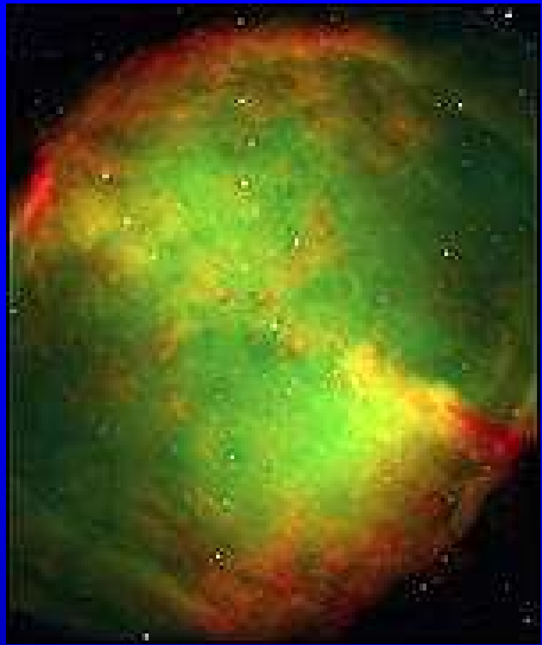
Owl Nebula

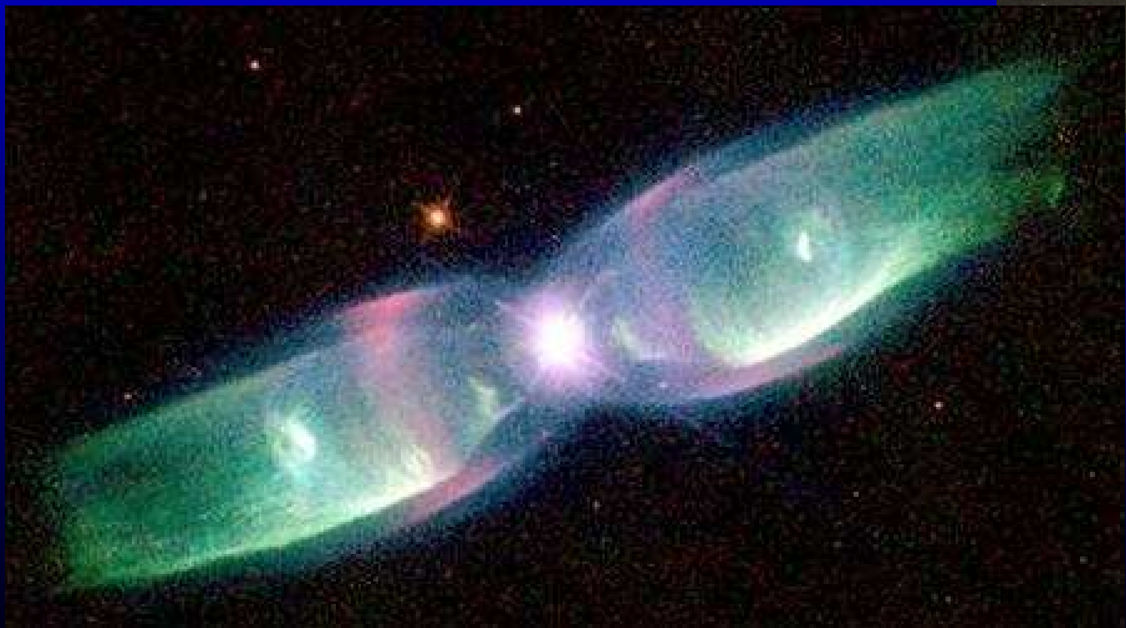




Helix Nebula


Hubble
Heritage

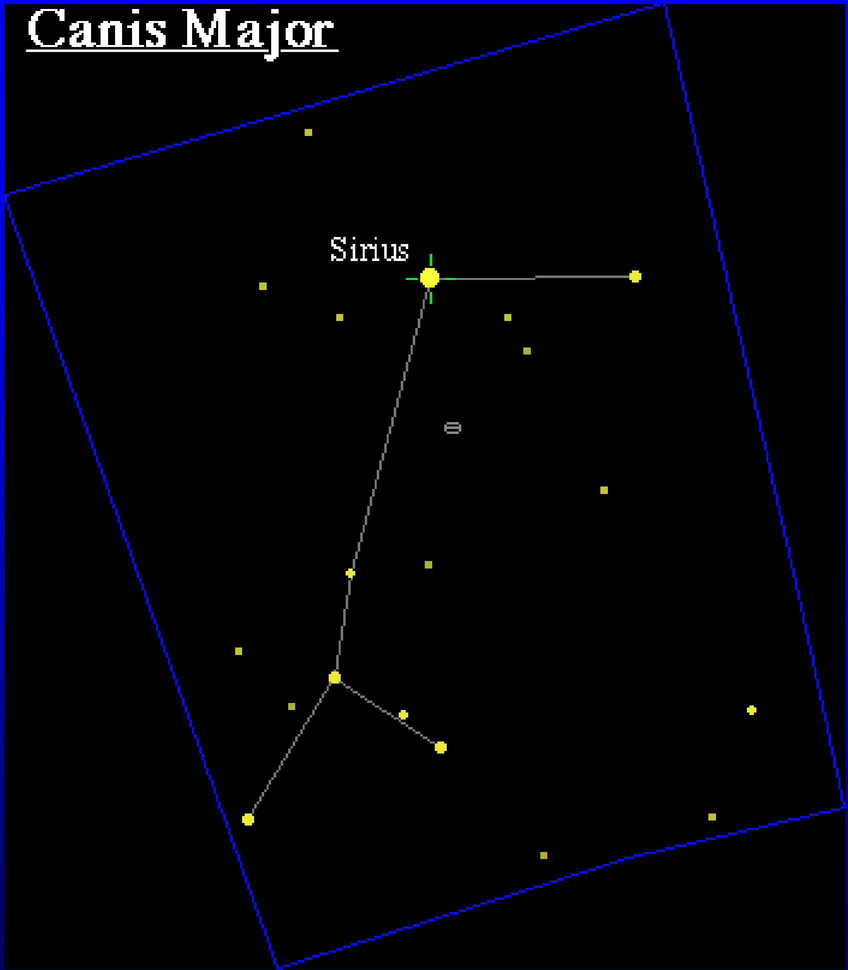


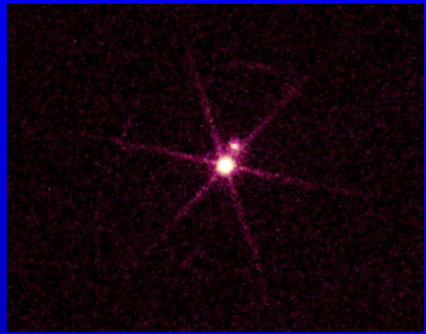


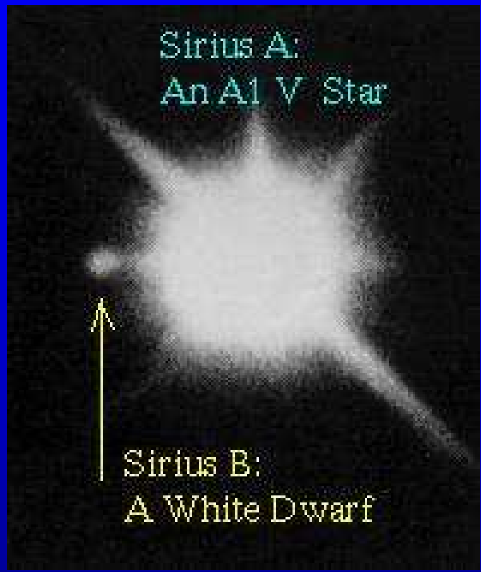
White Dwarfs

- They represent a stable phase in which stars, whose cores are less than 1.4 Solar Masses, called the Chandrasekhar Limit, live out the end of their lives.
- Chandra calculated this value when he was 19!
- He showed that because only two electrons (with opposing spins) can exist in one energy level, then, if matter is compressed, the electrons will finally resist further contraction provided the total mass (and hence gravitational force) is less that 1.4 solar masses.
- This is called Electron Degeneracy Pressure.

Sirius A and B

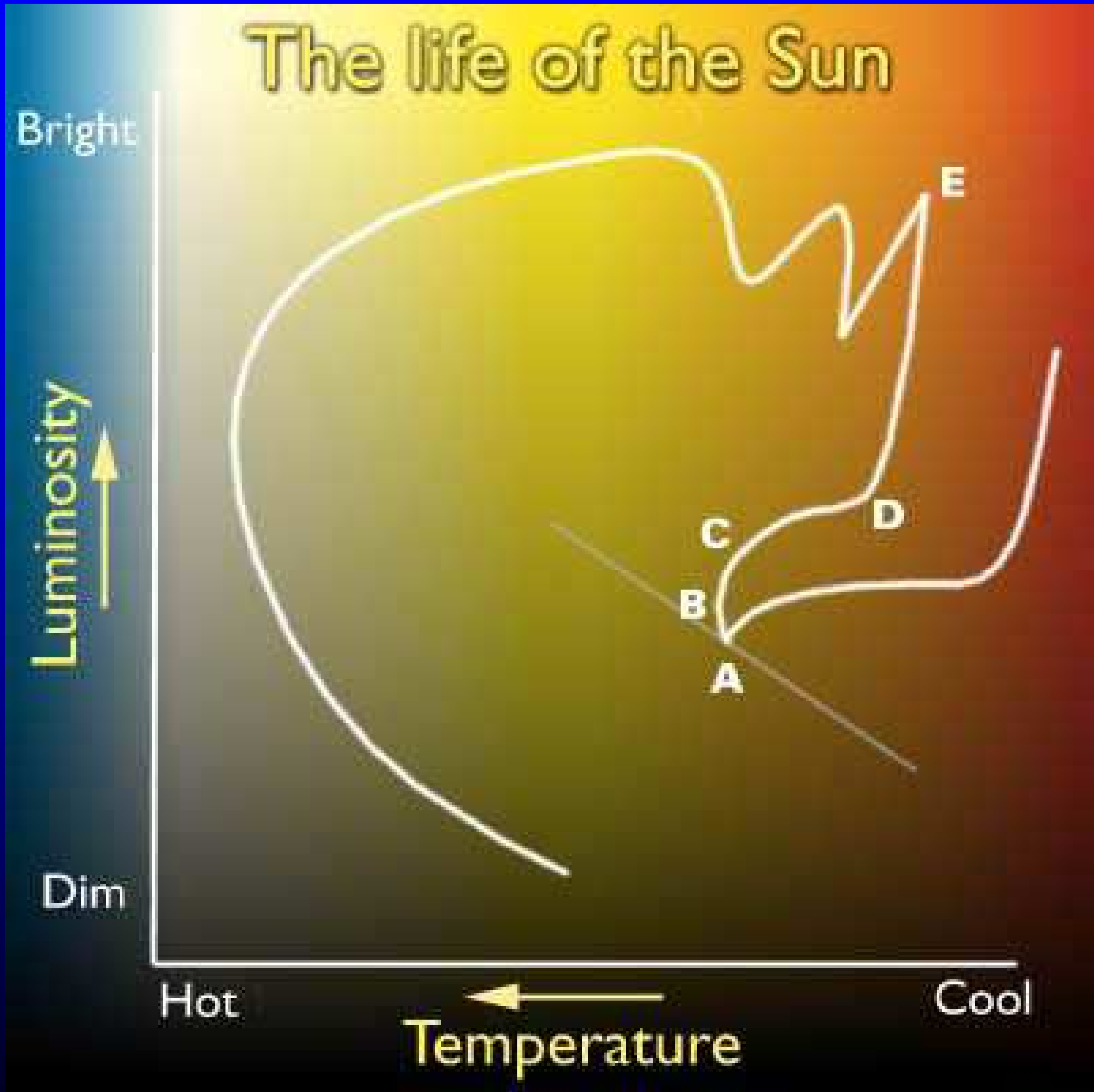


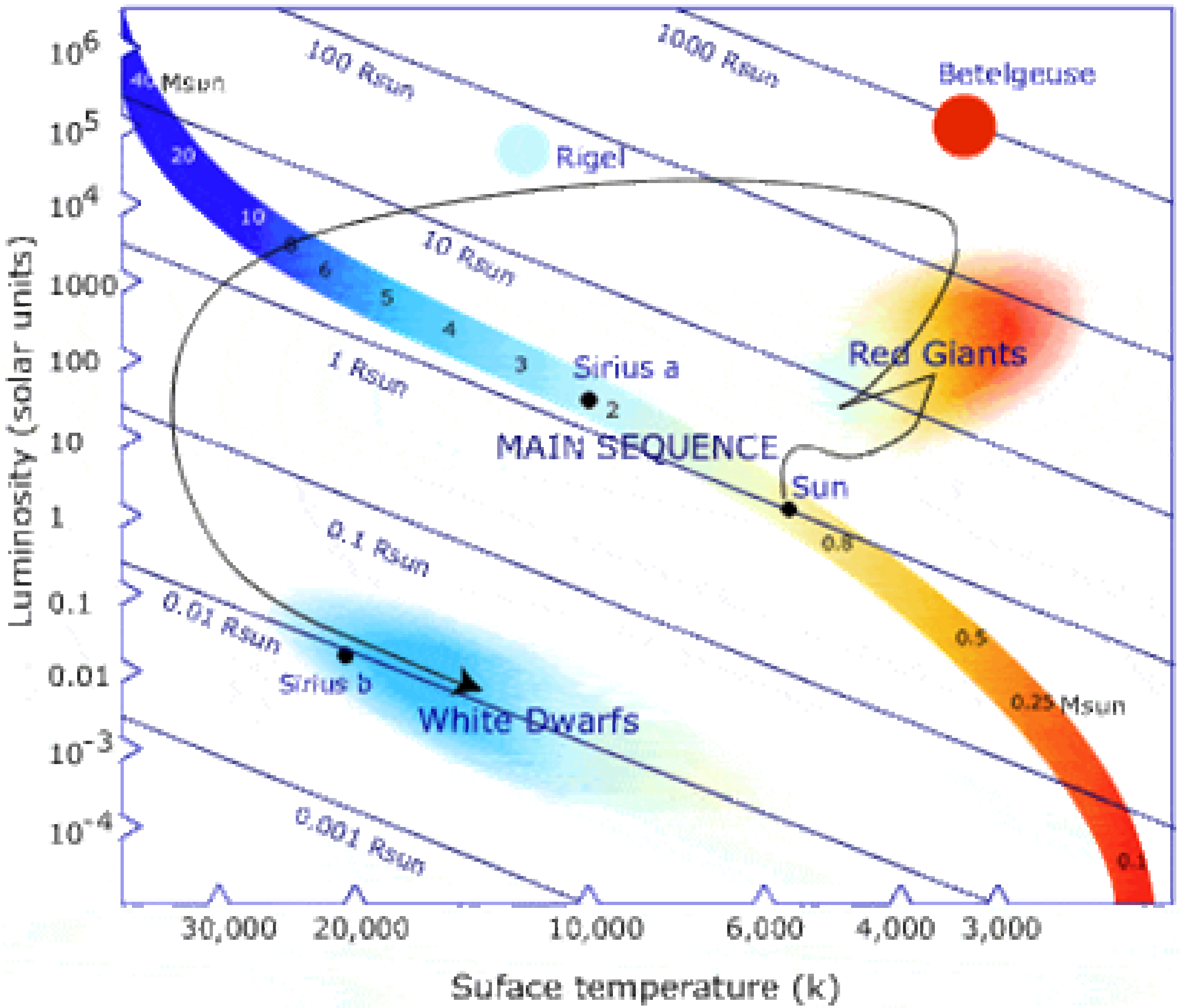




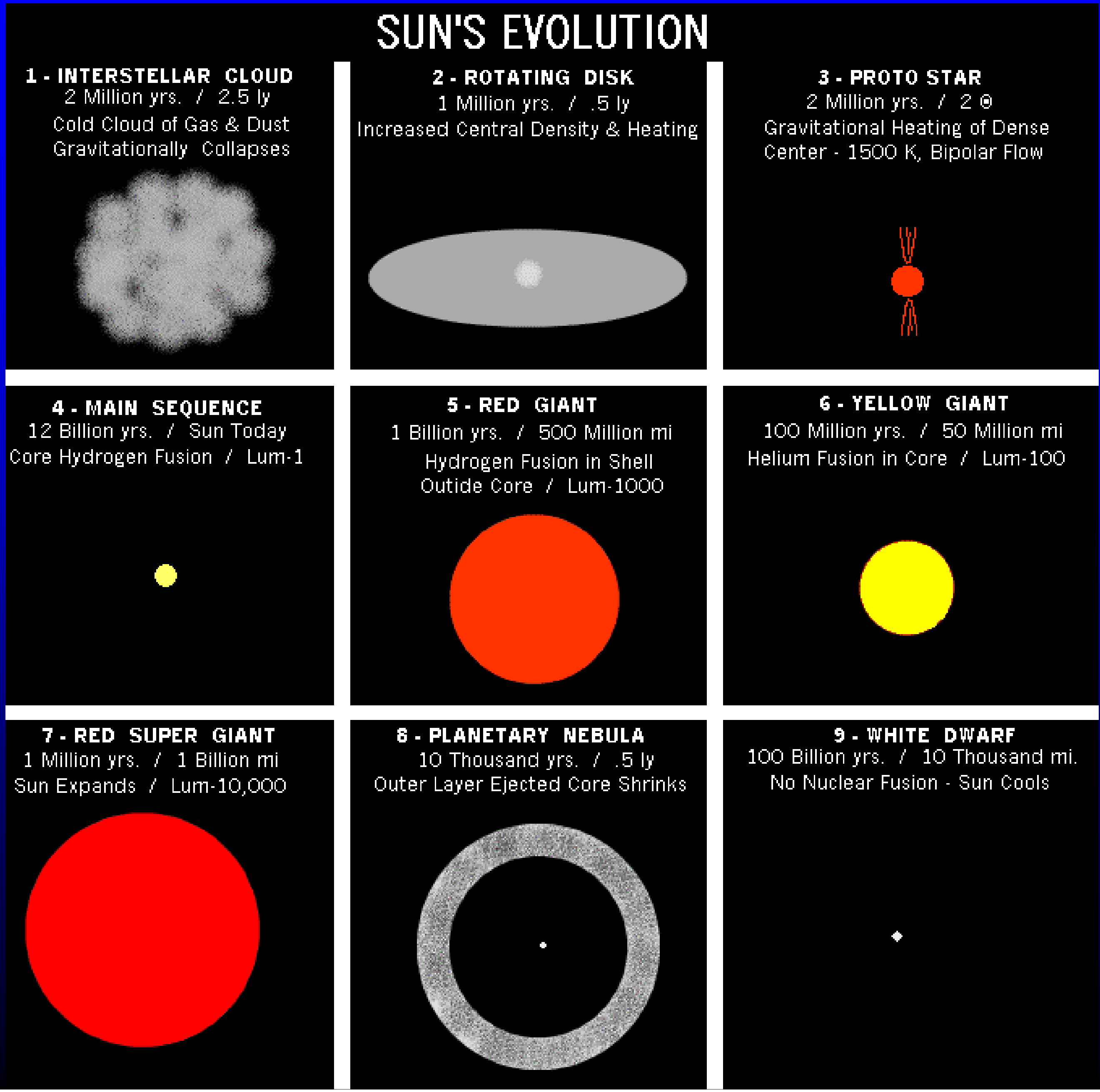
Black Dwarfs

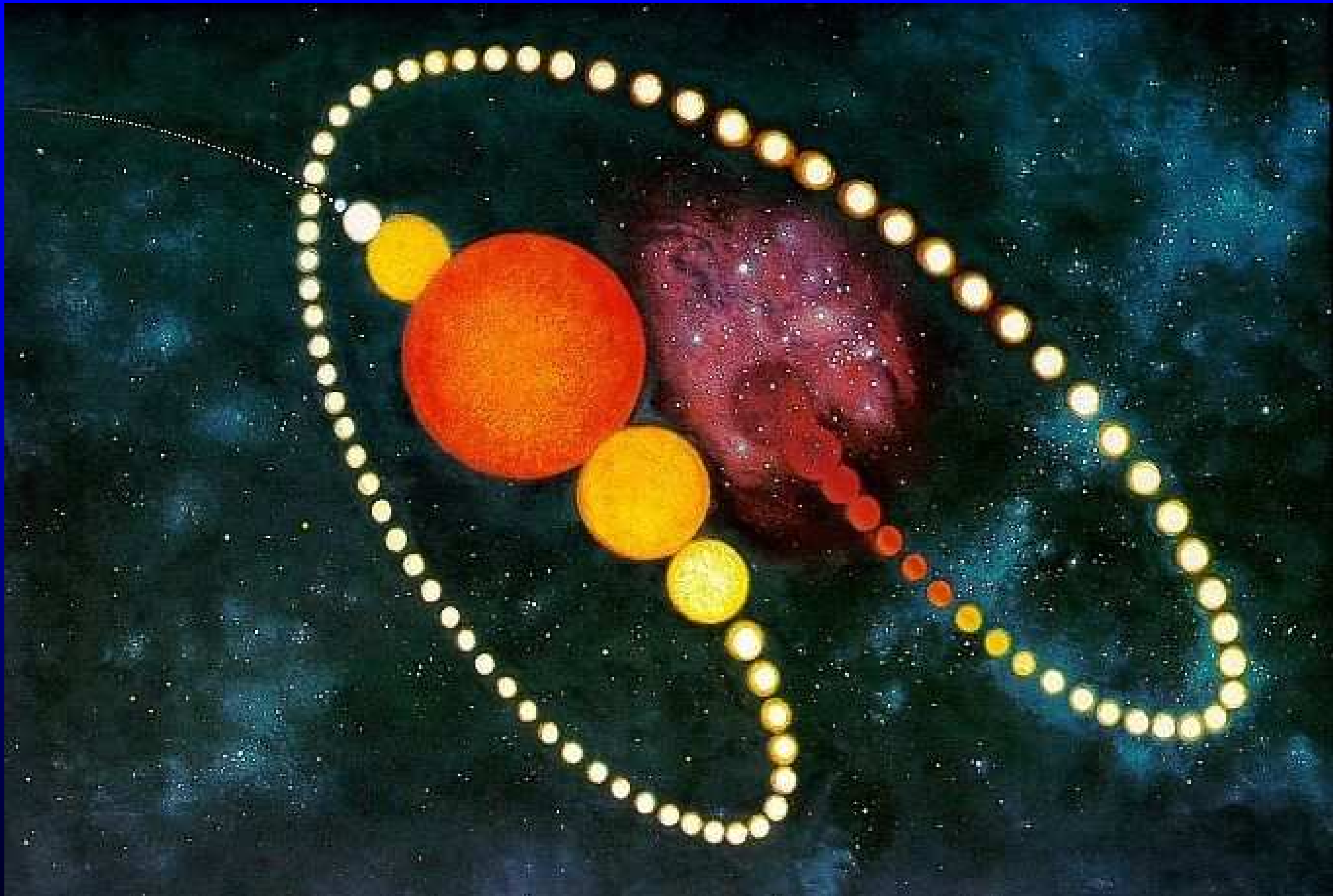
- Gradually, and ever more slowly, the white dwarf will cool moving down and to the right of the H-R diagram.
- Eventually they will no longer be visible and will become known as Black Dwarfs.
- This will take many billions of years so probably no Black Dwarfs exist as yet in our Galaxy.


The life of the Sun
Bright
Luminosity
Dim
E
D
C
B
A
Hot
Temperature
Cool



Luminosity (solar units)
10^6
10^5
10^4
1000
100
10
1
0.1
0.01
10^{-3}
10^{-4}
30,000
20,000
10,000
6,000
4,000
3,000
Suface temperature (k)
100 Rsun
1000 Rsun
10 Rsun
1 Rsun
0.1 Rsun
0.01 Rsun
0.001 Rsun
Betelgeuse
Rigel
40 Msun
20
10
8
6
5
4
3
2
Sirius a
MAIN SEQUENCE
Red Giants
Sun
0.8
0.5
0.25 Msun
0.1
Sirius b
White Dwarfs


SUN'S EVOLUTION
1 - INTERSTELLAR CLOUD
2 Million yrs. / 2.5 ly
Cold Cloud of Gas & Dust Gravitationally Collapses
2 - ROTATING DISK
1 Million yrs. / .5 ly
Increased Central Density & Heating
3 - PROTO STAR
2 Million yrs. / 2 ☉
Gravitational Heating of Dense Center - 1500 K, Bipolar Flow
4 - MAIN SEQUENCE
12 Billion yrs. / Sun Today
Core Hydrogen Fusion / Lum-1
5 - RED GIANT
1 Billion yrs. / 500 Million mi
Hydrogen Fusion in Shell Outside Core / Lum-1000
6 - YELLOW GIANT
100 Million yrs. / 50 Million mi
Helium Fusion in Core / Lum-100
7 - RED SUPER GIANT
1 Million yrs. / 1 Billion mi
Sun Expands / Lum-10,000
8 - PLANETARY NEBULA
10 Thousand yrs. / .5 ly
Outer Layer Ejected Core Shrinks
9 - WHITE DWARF
100 Billion yrs. / 10 Thousand mi.
No Nuclear Fusion - Sun Cools

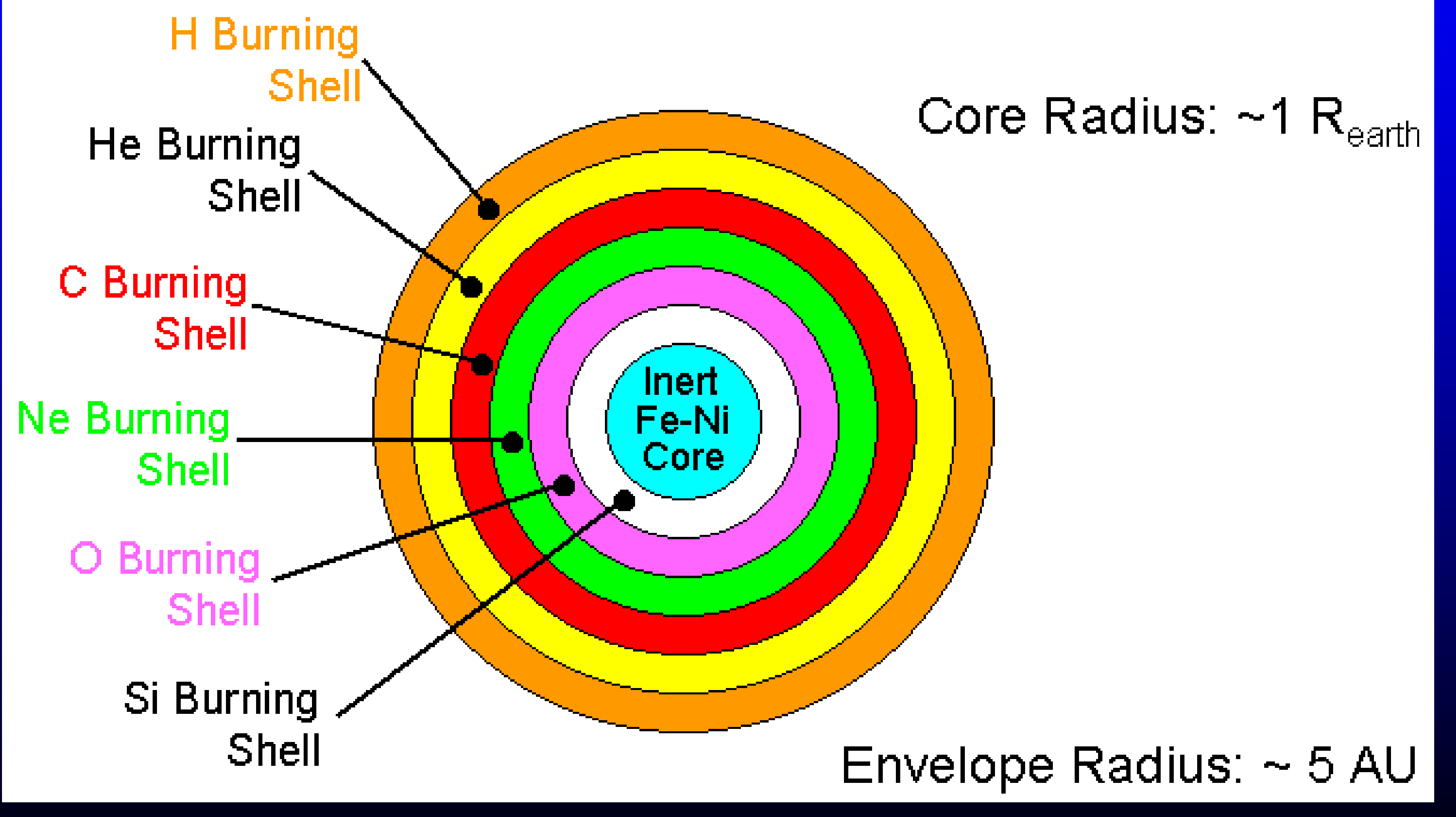


Evolution of more massive stars

- Stars of mass greater than ~ 8 M_{sun} convert the hydrogen into helium very rapidly using the CNO process.
- A star of 15 M_{sun} will leave the main sequence after ~ 15 million years!
- As they burn helium into carbon, they expand to radii similar to that of the orbit of Jupiter. They are cool but, due to their great size very bright.
- They can be up to 1,000,000 times brighter than our Sun.
- They are called Red Supergiants.

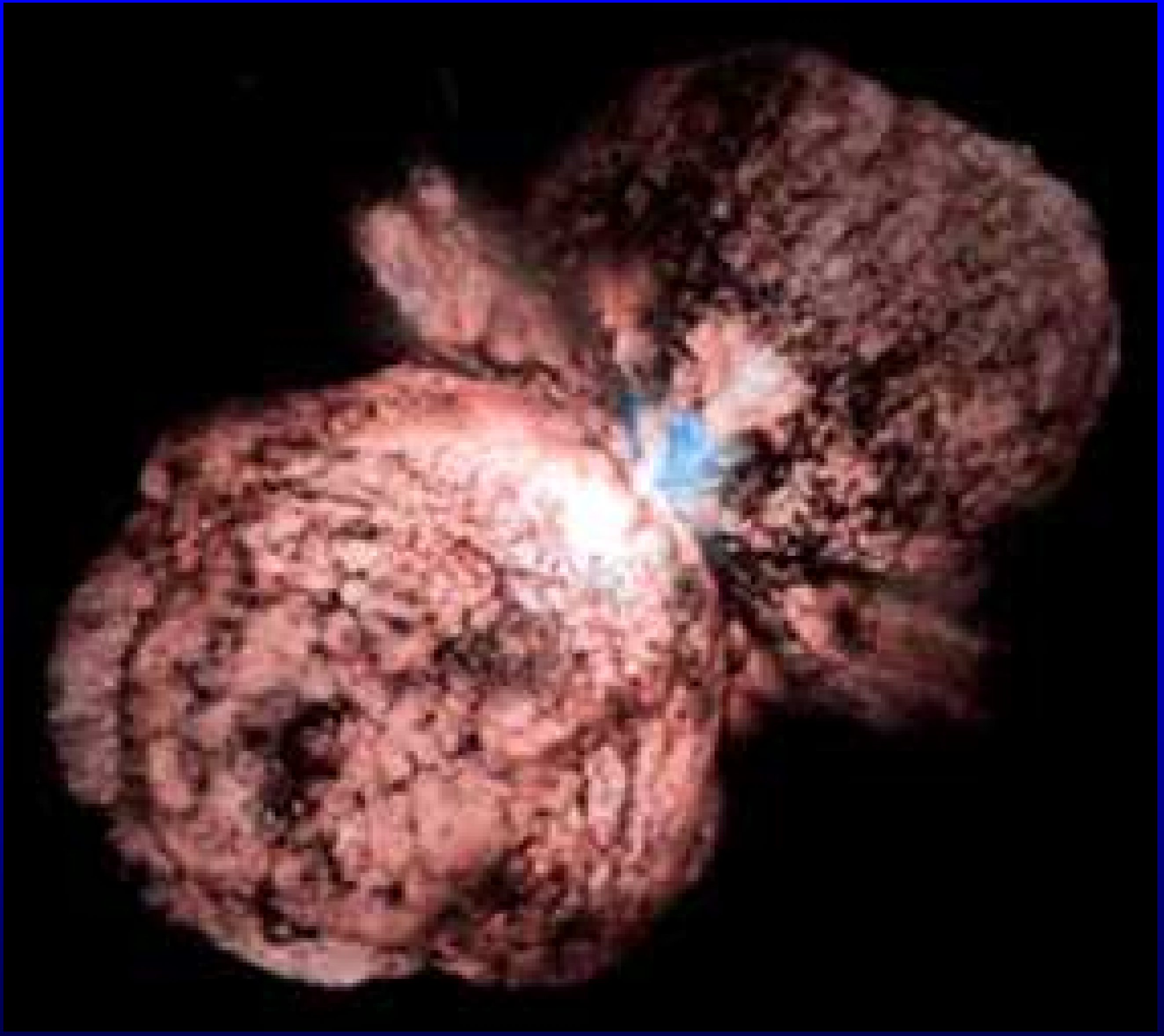
- They carry on the nuclear fusion process beyond that of lower mass stars as the pressures and temperatures in the core are greater.
- The centre of the core turns to iron with shells of lighter elements surrounding it. (Fusion can only produce elements up to Iron.)

Massive Stars



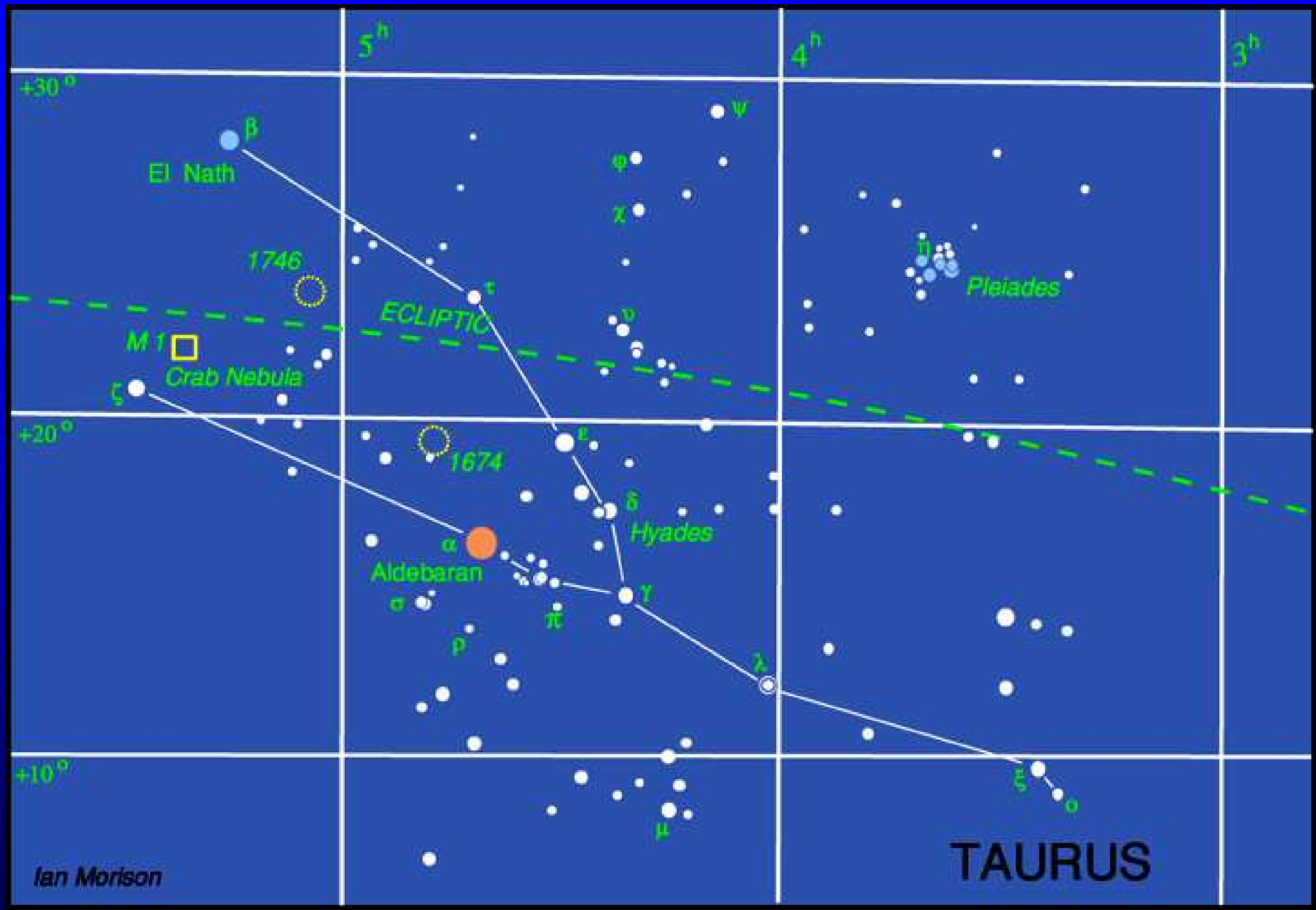
- These massive stars often blow off much of their outer layers towards the end of their life.
- A star Eta Carina blew off its outer layers in the 19th century.
- These massive stars are often variable stars as they oscillate in size and surface temperature.

Eta Carina



A supernova

- When the core is totally made up of iron, nuclear fusion stops and there is nothing to prevent the core collapsing - details later.
- The outer parts then fall in towards it and get highly compressed as the inner core rebounds.
- A thermo-nuclear explosion of epic proportions follows.
- In this supernova explosion, in just a few seconds, high speed neutrons can build up the elements beyond Iron producing gold and uranium for example .
- The outer parts – containing many heavy elements – are thrown off into space.


5h
4h
3h
+30°
+20°
+10°
β
El Nath
1746
M 1
Crab Nebula
ζ
τ
ECLIPTIC
ψ
φ
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ν
ε
1674
δ
Hyades
α
Aldebaran
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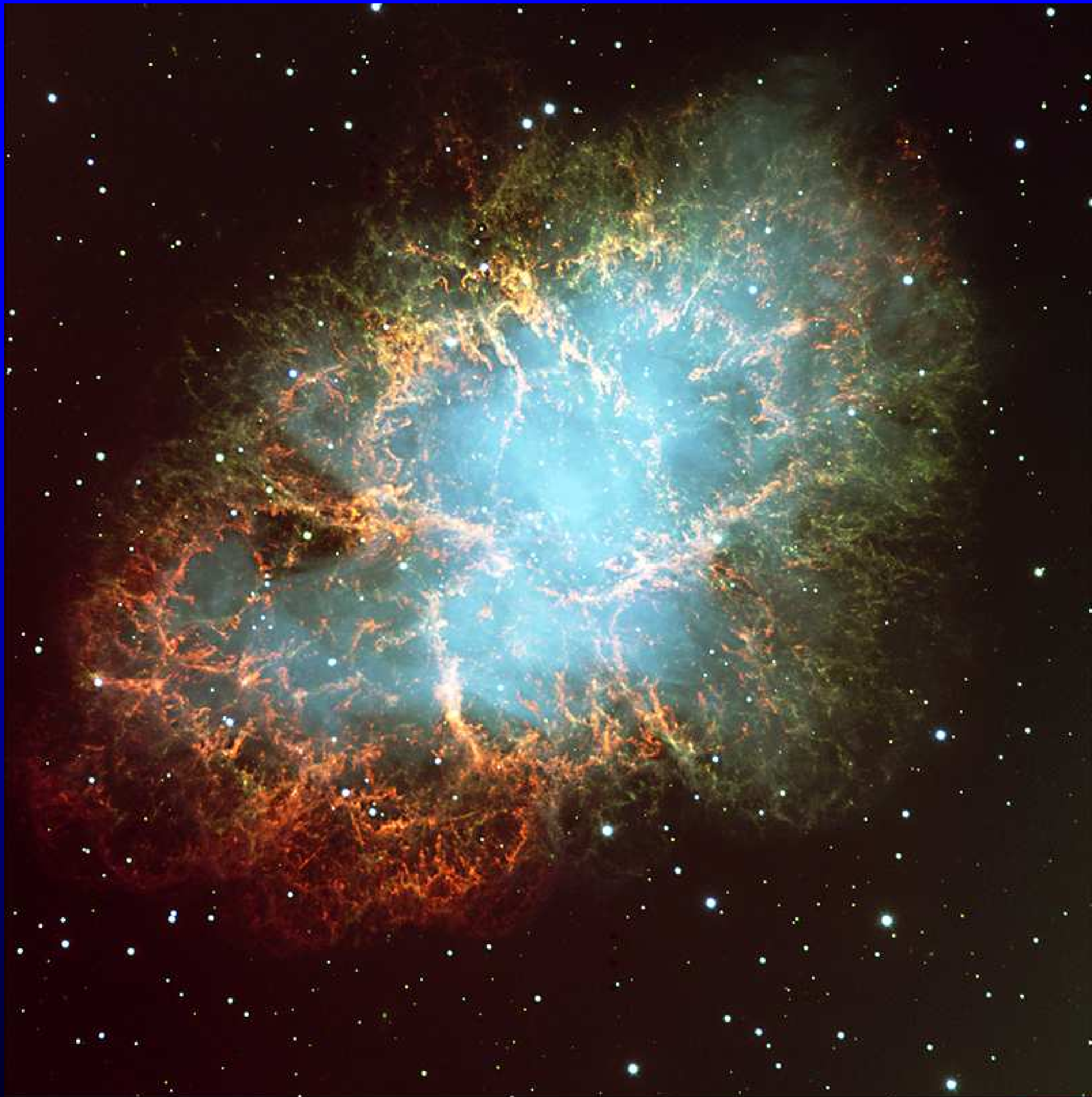
Pleiades
ξ
ο
μ
TAURUS
Ian Morison

Crab Nebula



The Crab Nebula in Taurus (VLT KUEYEN + FORS2)

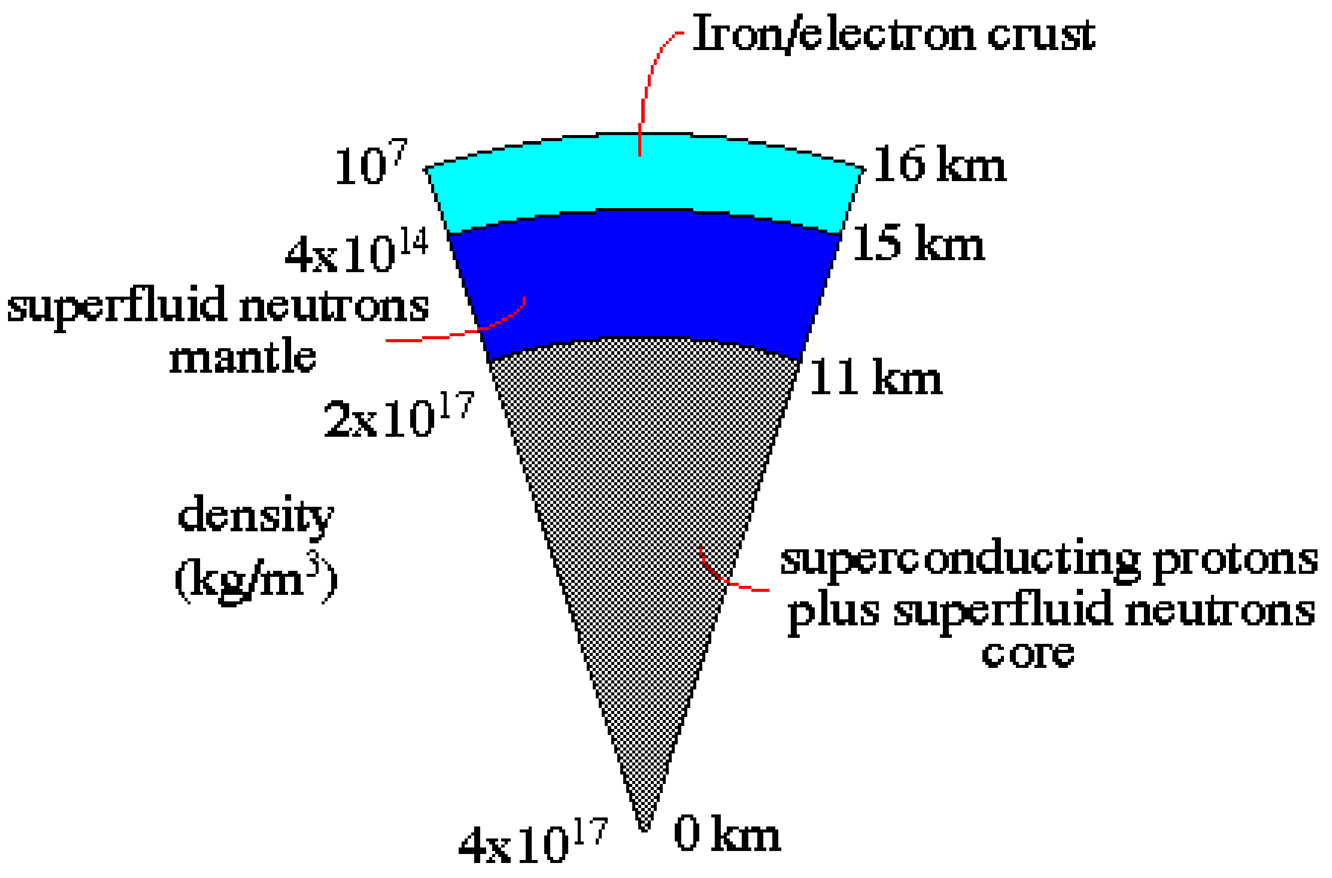
Neutron Stars

- If the mass of the core remnant is above the Chandrasekhar limit of 1.4 Solar Masses, electron degeneracy pressure can no longer support it against gravitational collapse.
- The majority of the protons and electrons fuse to form neutrons – so the remnant is called a Neutron Star
- Essentially a giant nucleus!

Neutron Degeneracy Pressure

- The gravitational collapse is finally halted when the neutrons reach a sufficiently high density and Neutron Degeneracy Pressure prevents further collapse.
- The core has contracted down to a radius of ~ 10km.
- Angular momentum conservation makes its spin very quickly.

Neutron Star Interior



Jocelyn Bell

Pulsars

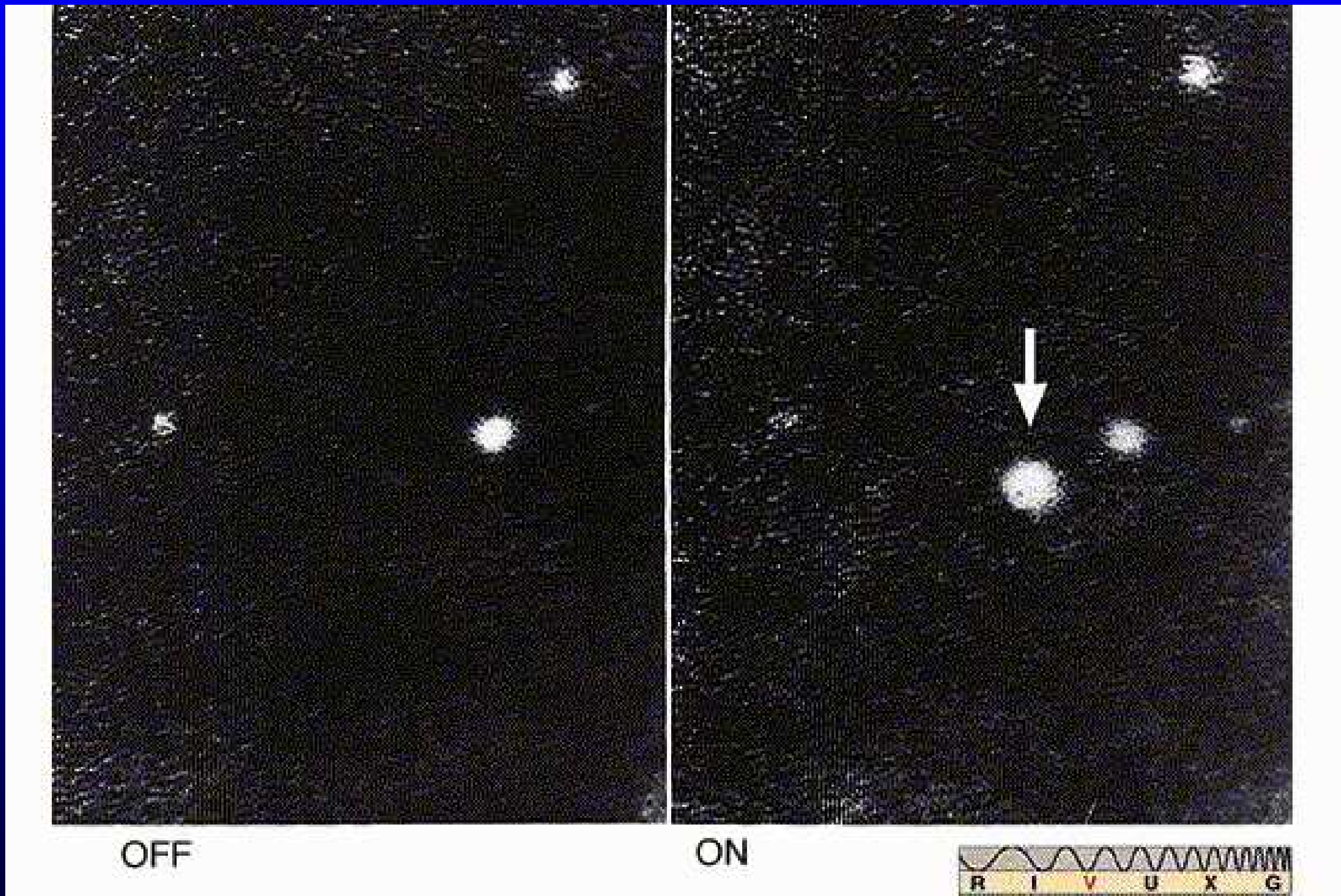
Jocelyn Bell and Tony Hewish detected very precisely times pulses of energy from a number of radio sources.

They first thought that they might be ET phoning home, and called the first LGM1.

In fact the very powerful rotating magnetic field of a neutron star can produce rotating beams of radio waves – and sometimes light.

As the beam points towards the Earth, we pick up regular pulses – hence the name PULSAR.

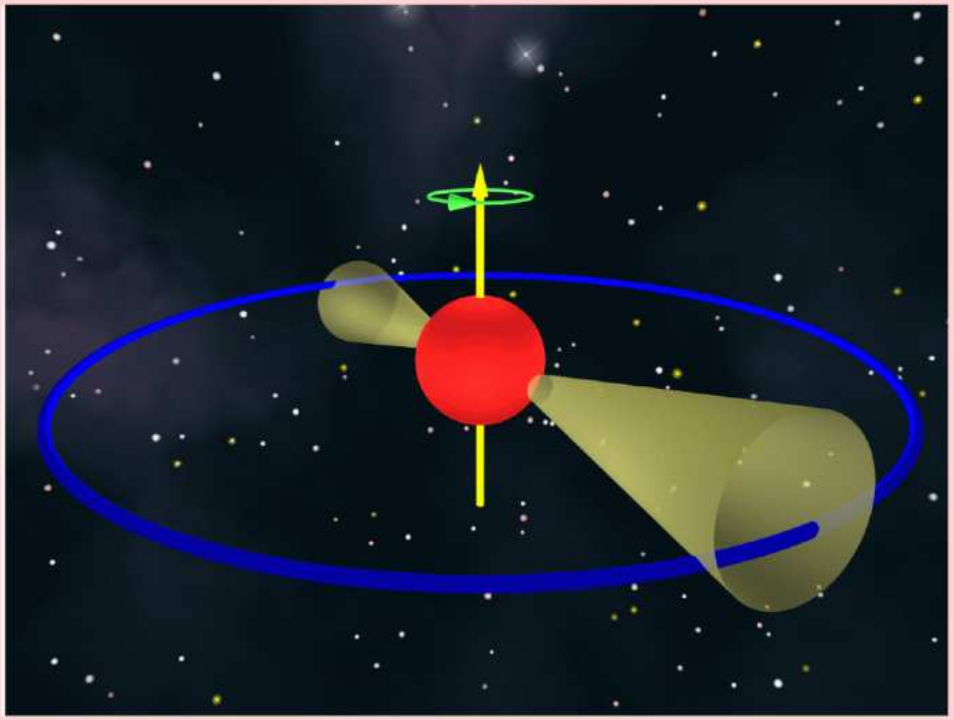
Crab Pulsar

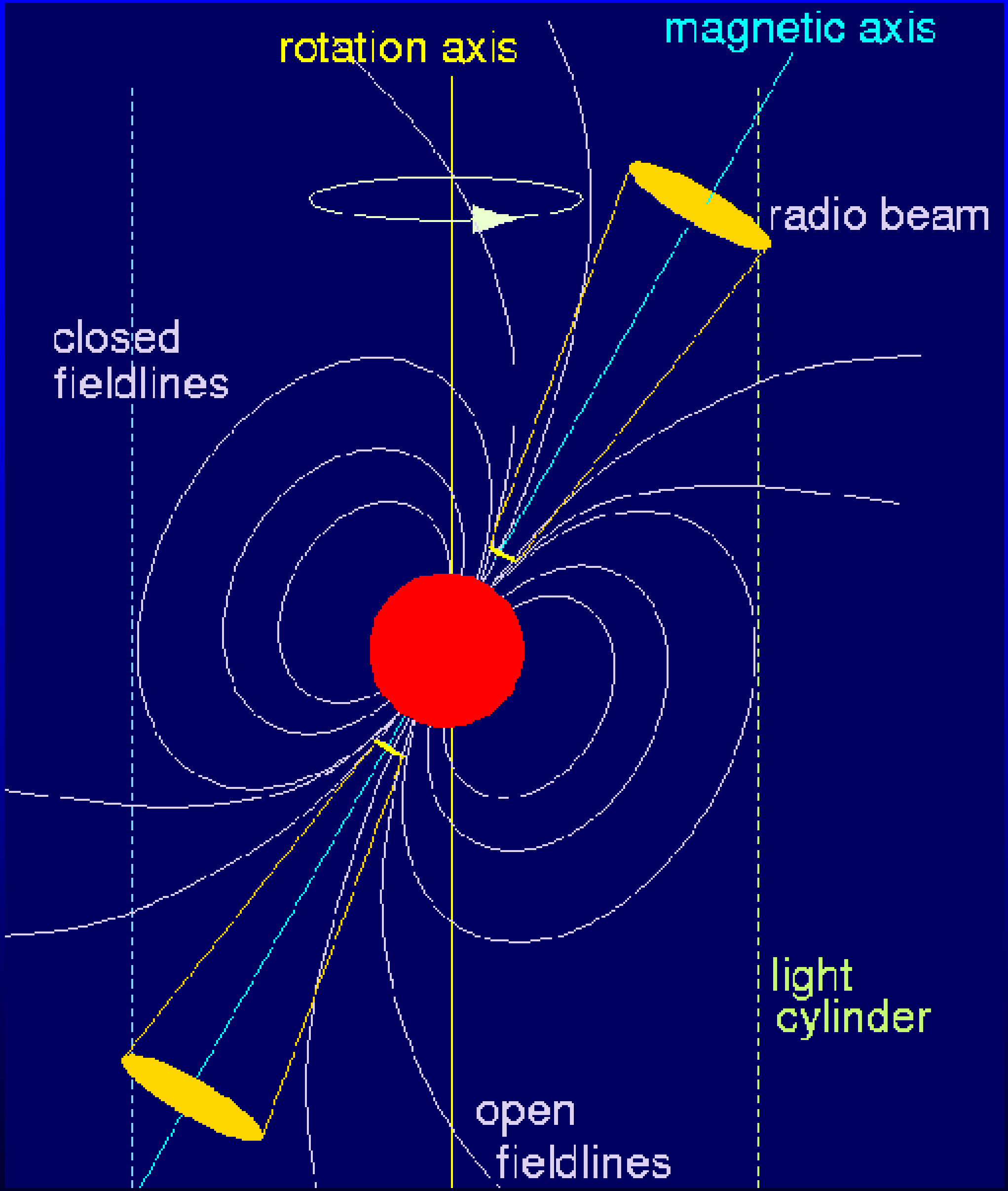

OFF
ON
R I V U X G

What is a Pulsar?

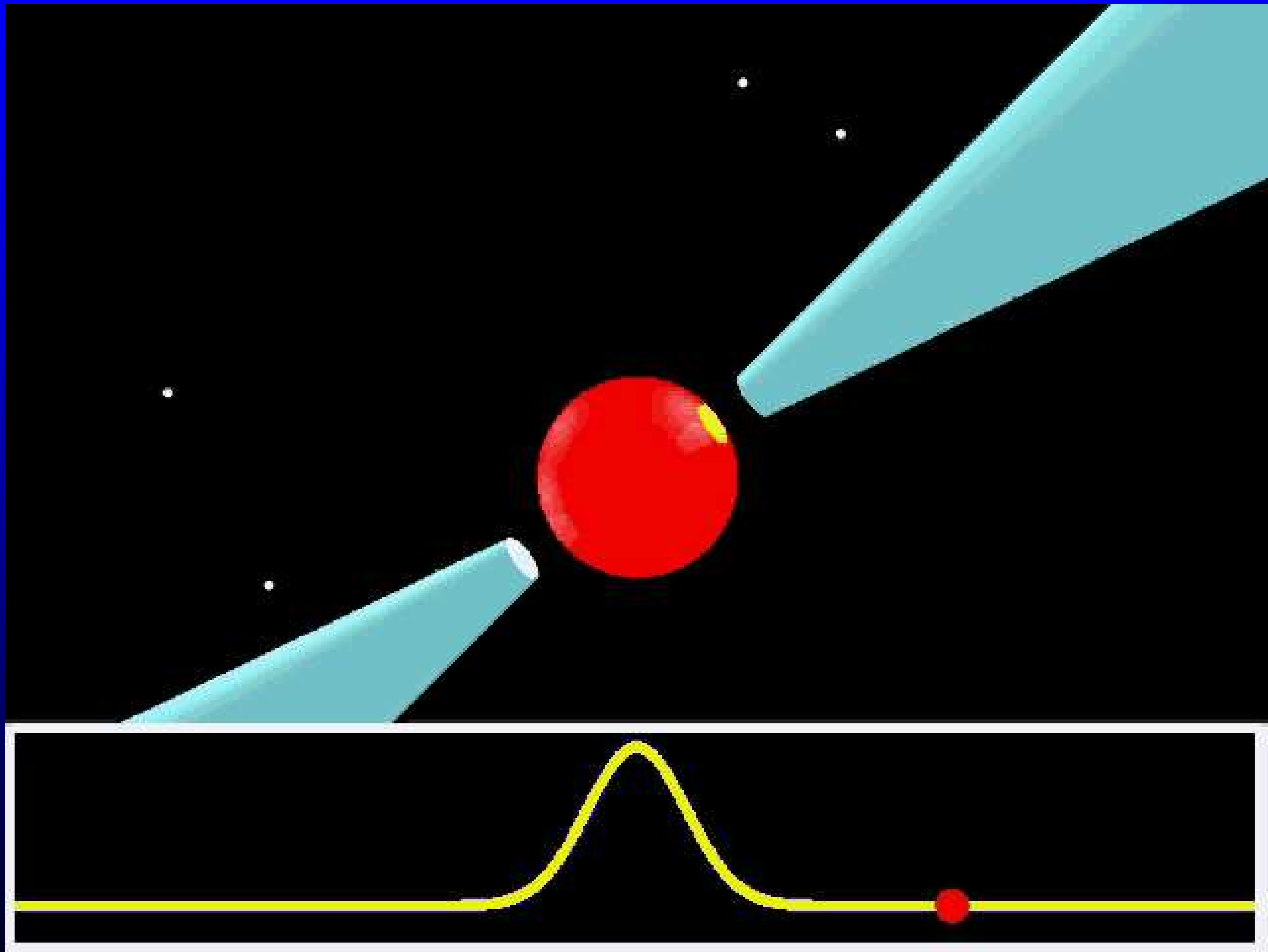
The Anatomy of a Pulsar

Mass	:	*~ 1.4 Solar Masses*
Diameter	:	*~ 20 Kilometres*
Density	:	*~ 600 Million Tonnes per cubic centimetre*
Magnetic Field	:	*Up to 10 Trillion times that of the Earth.*
Periods	:	*From 1.6 milliseconds up to 8 seconds*




rotation axis
magnetic axis
radio beam
closed
fieldlines
light
cylinder
open
fieldlines

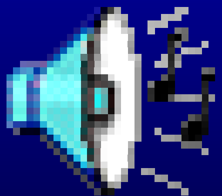
Rotating Beam

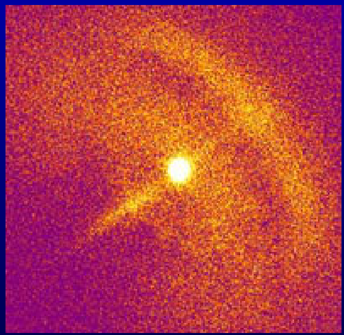


Pulsar Sounds

- The First Pulsar Detected by Jocelyn Bell at Cambridge.

- The Vela Pulsar





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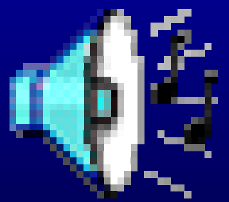
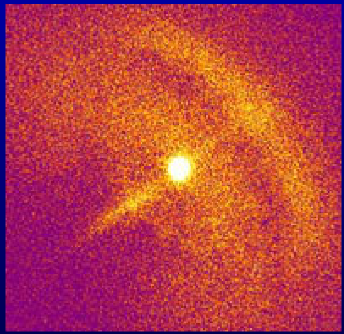
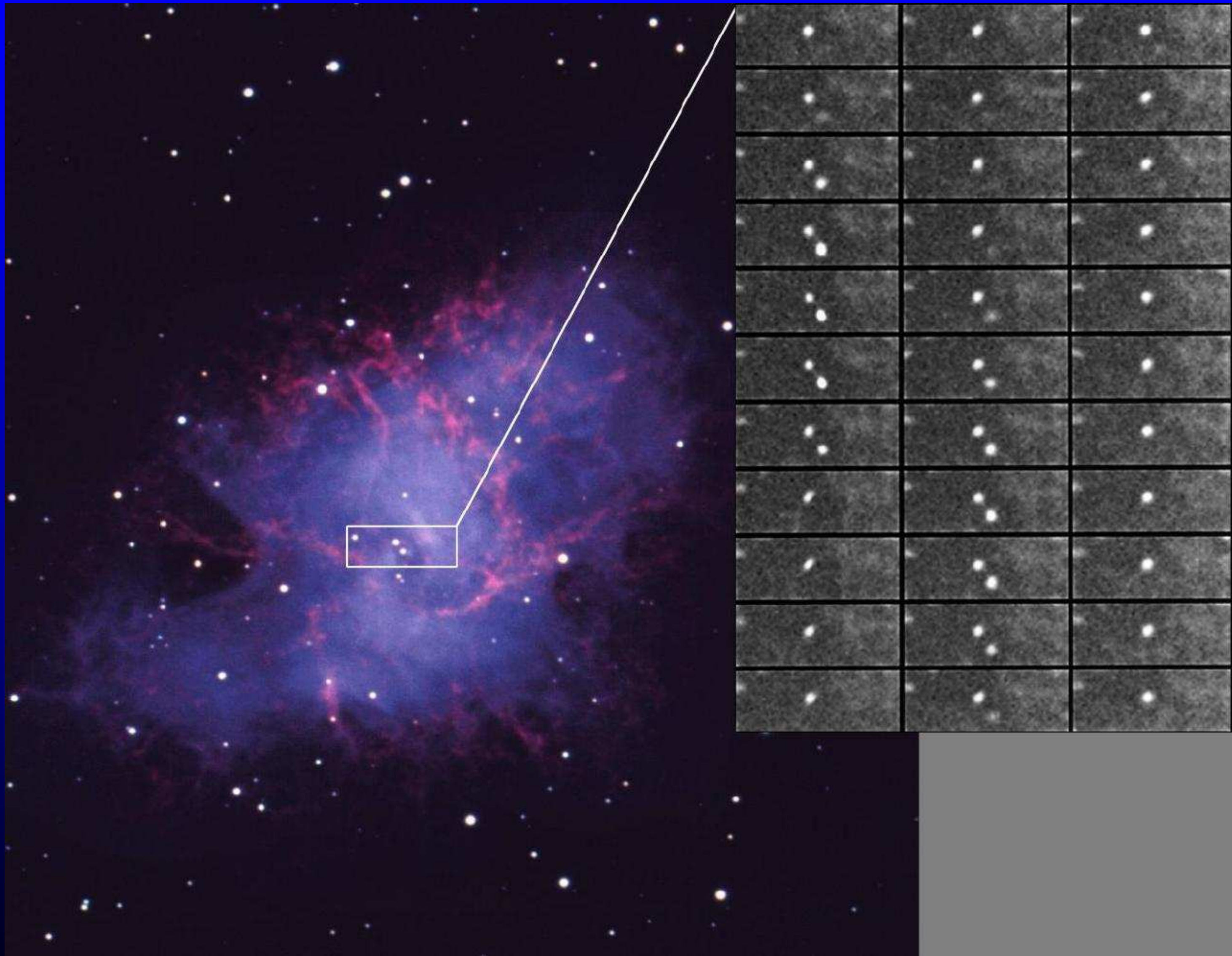
- The Vela Pulsar





The Crab Pulsar

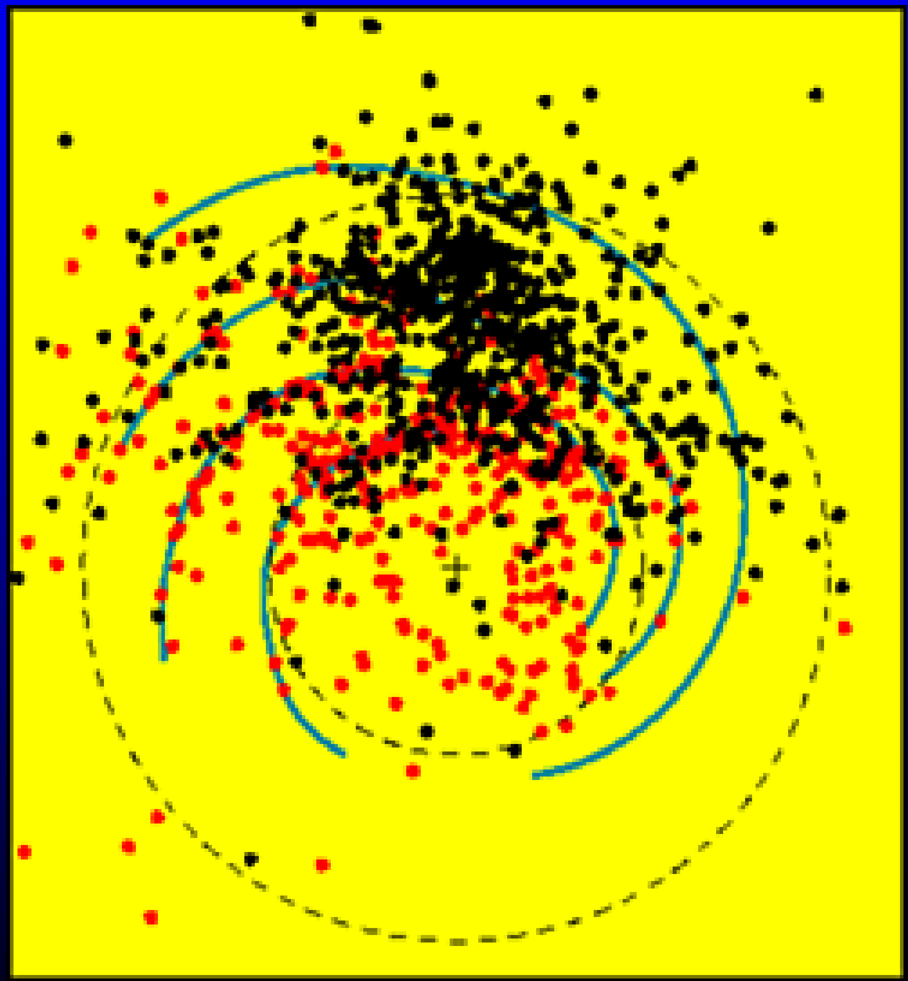


Globular Cluster 47 Tucanae

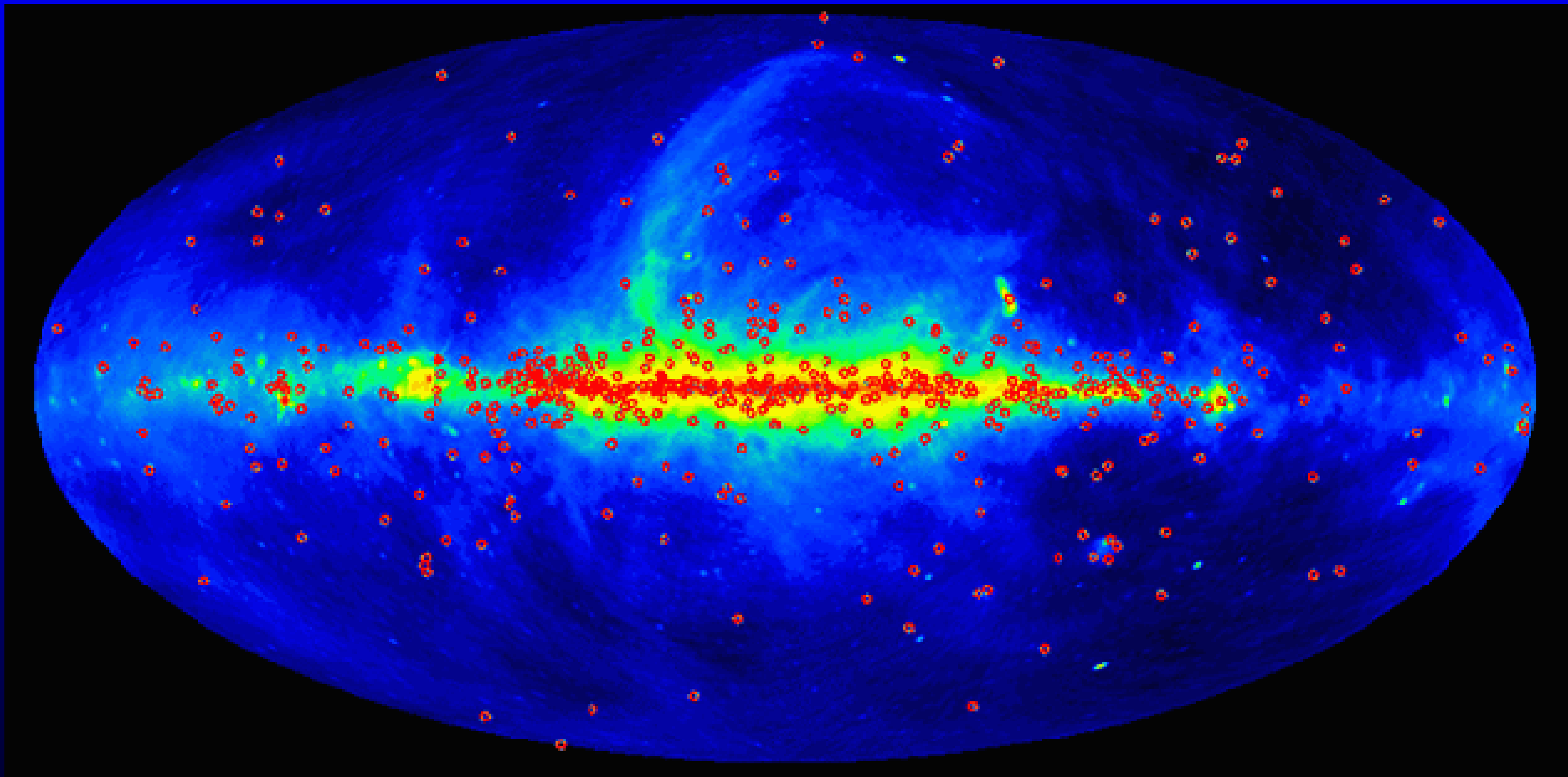
Pulsars in 47 Tucanae

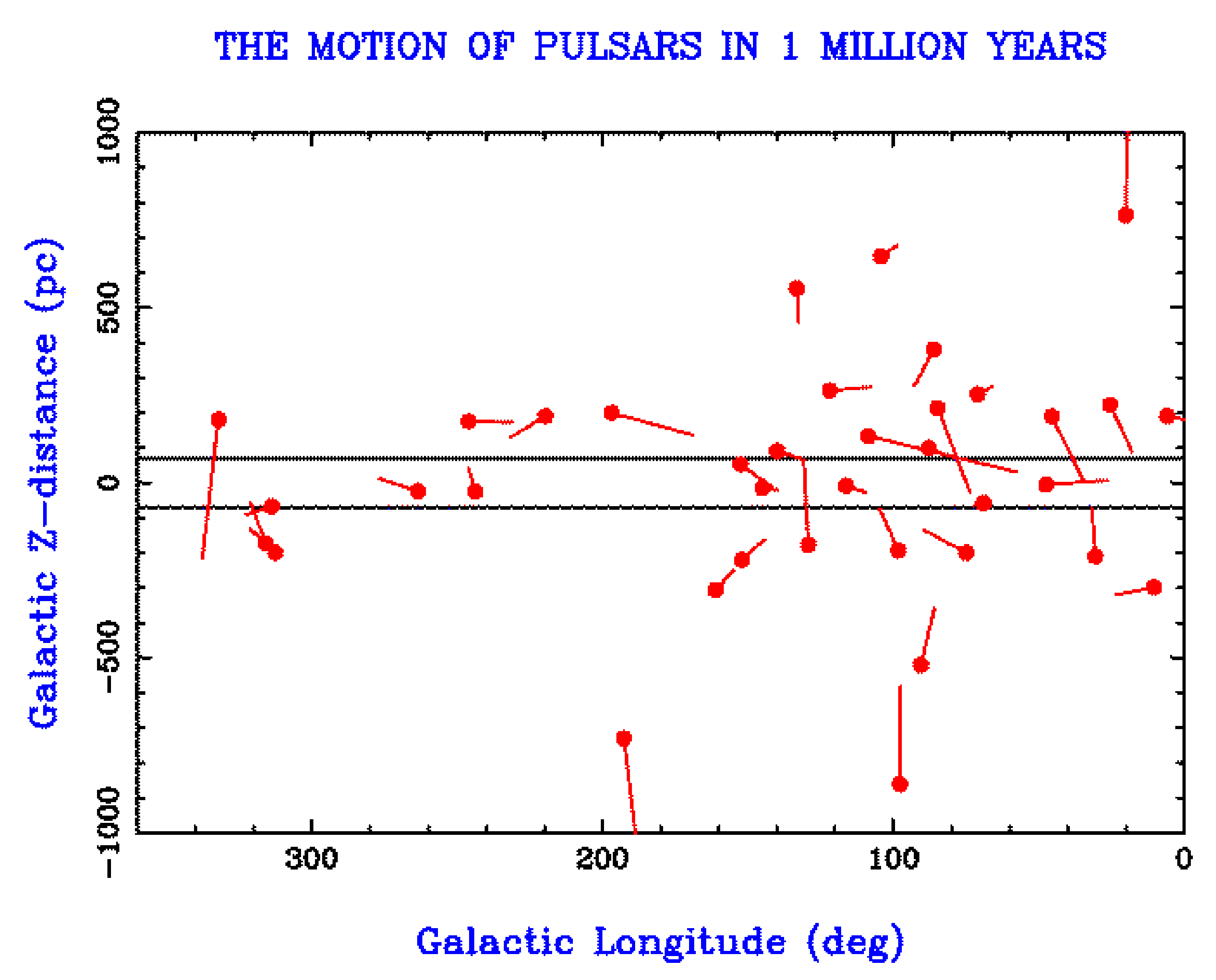
Parkes Multi-Beam Survey

New Pulsars in RED



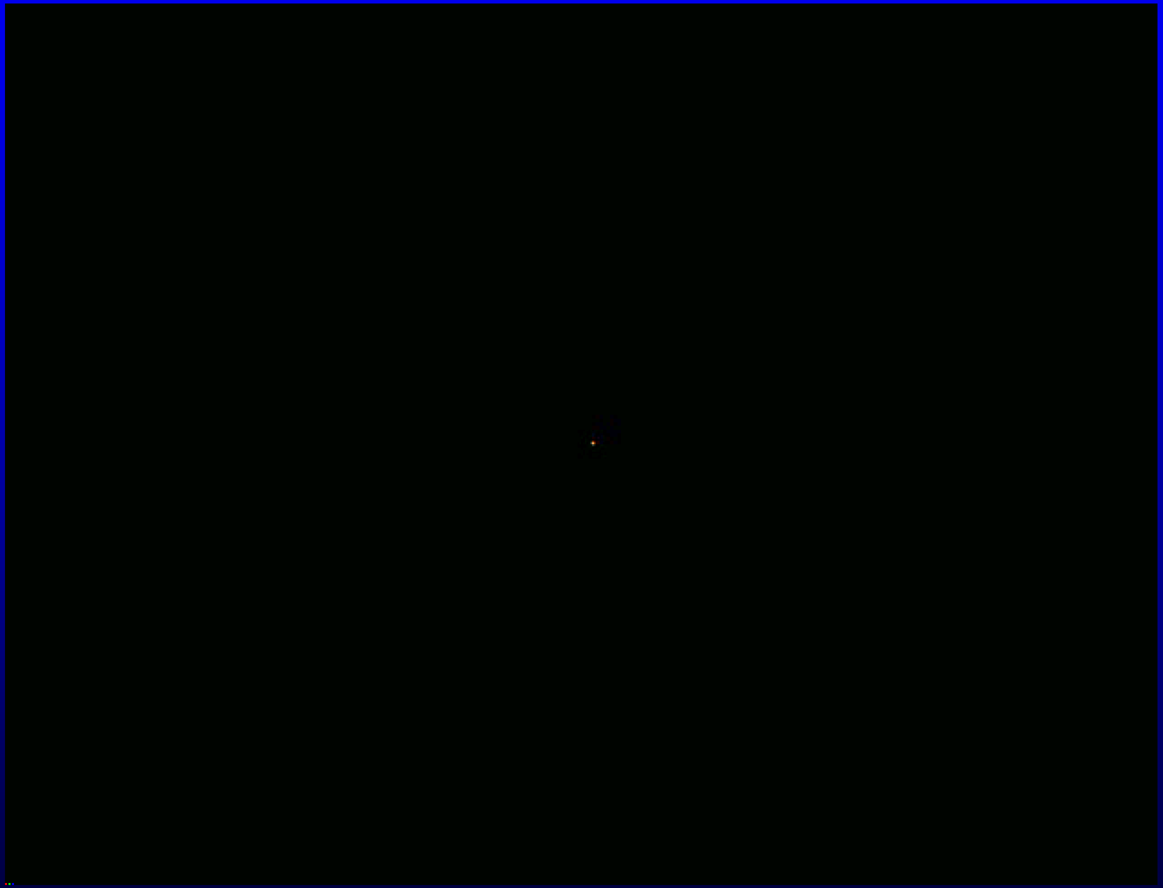
Pulsar Distribution





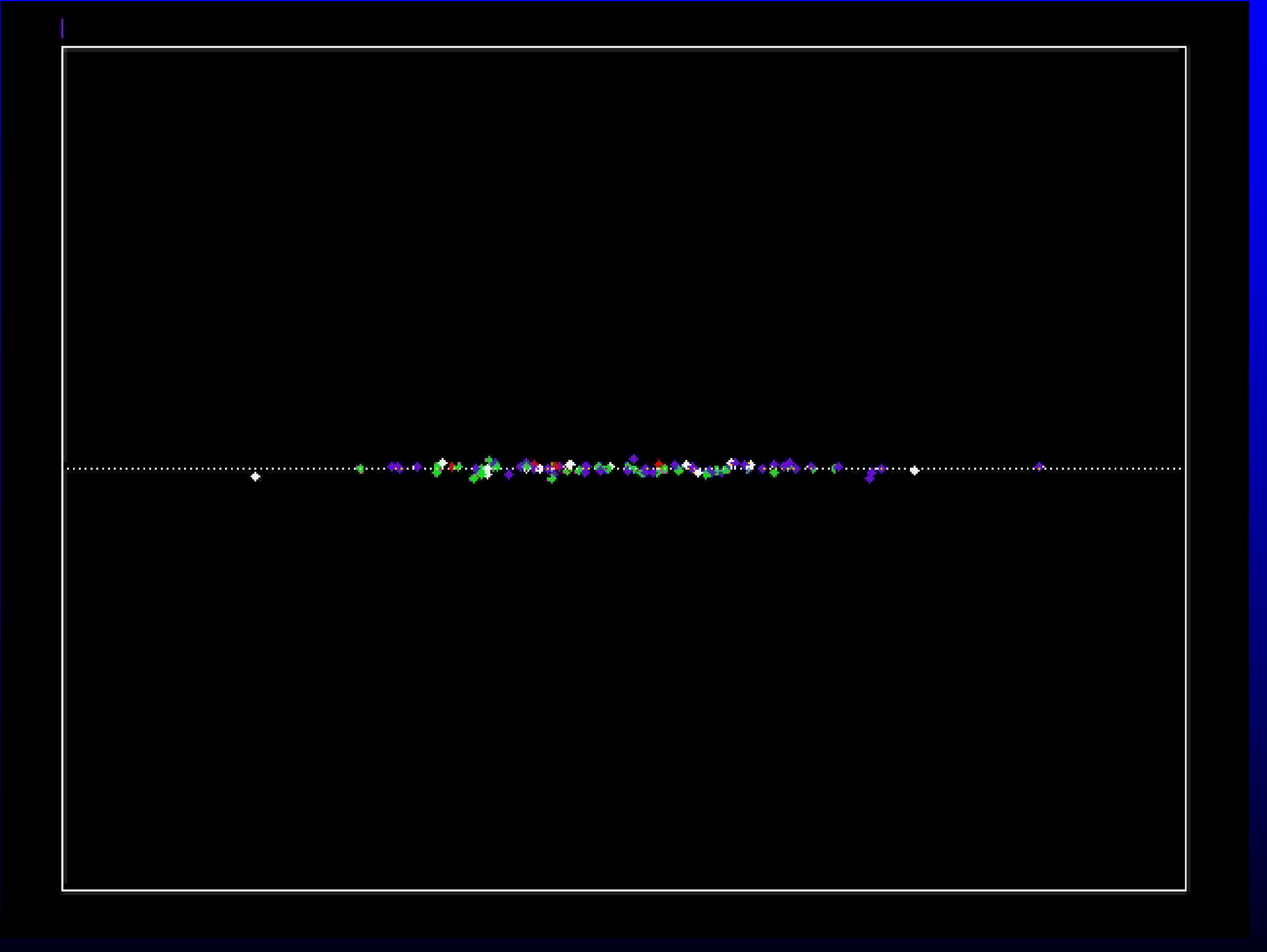
Pulsar Proper Motions measured with MERLIN. Average velocity ~300 km/s, greater than Galaxy's escape velocity

Pulsars are born with high velocities

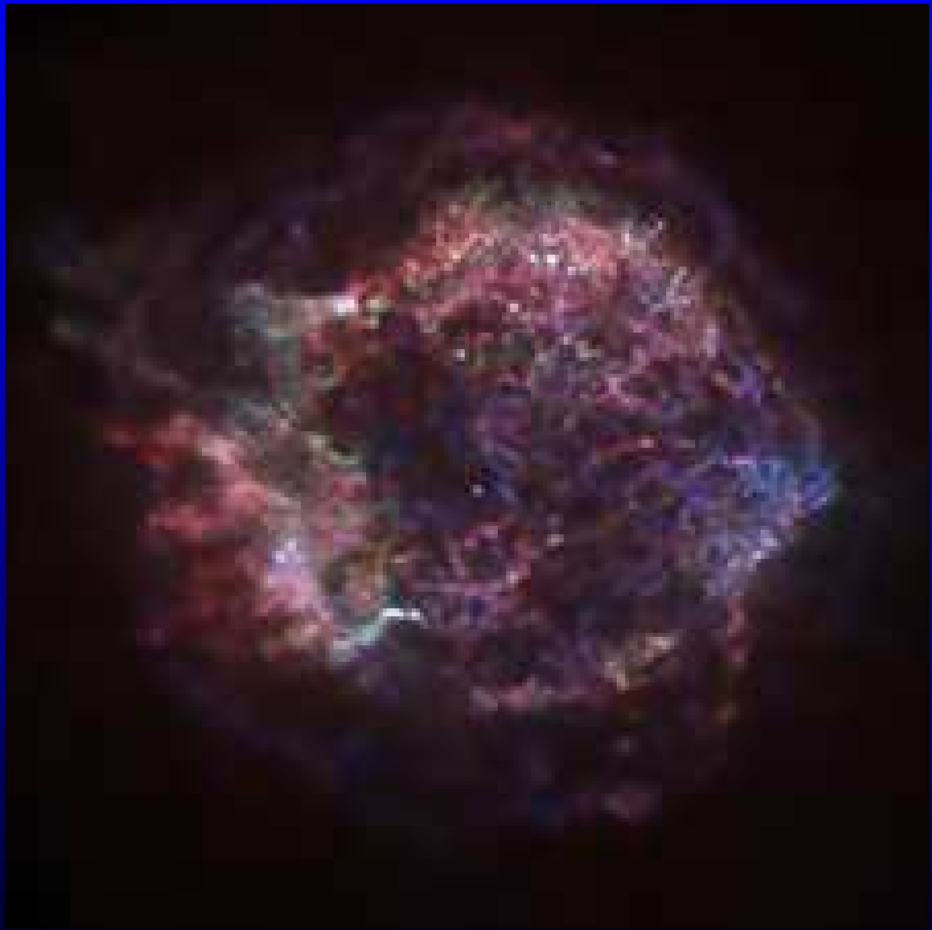


During a supernova explosion, the steller envelope may not be ejected symmetrically. The residual core, a spinning neutron star (pulsar), absorbs the recoil and is fired clear of the surrounding remnant

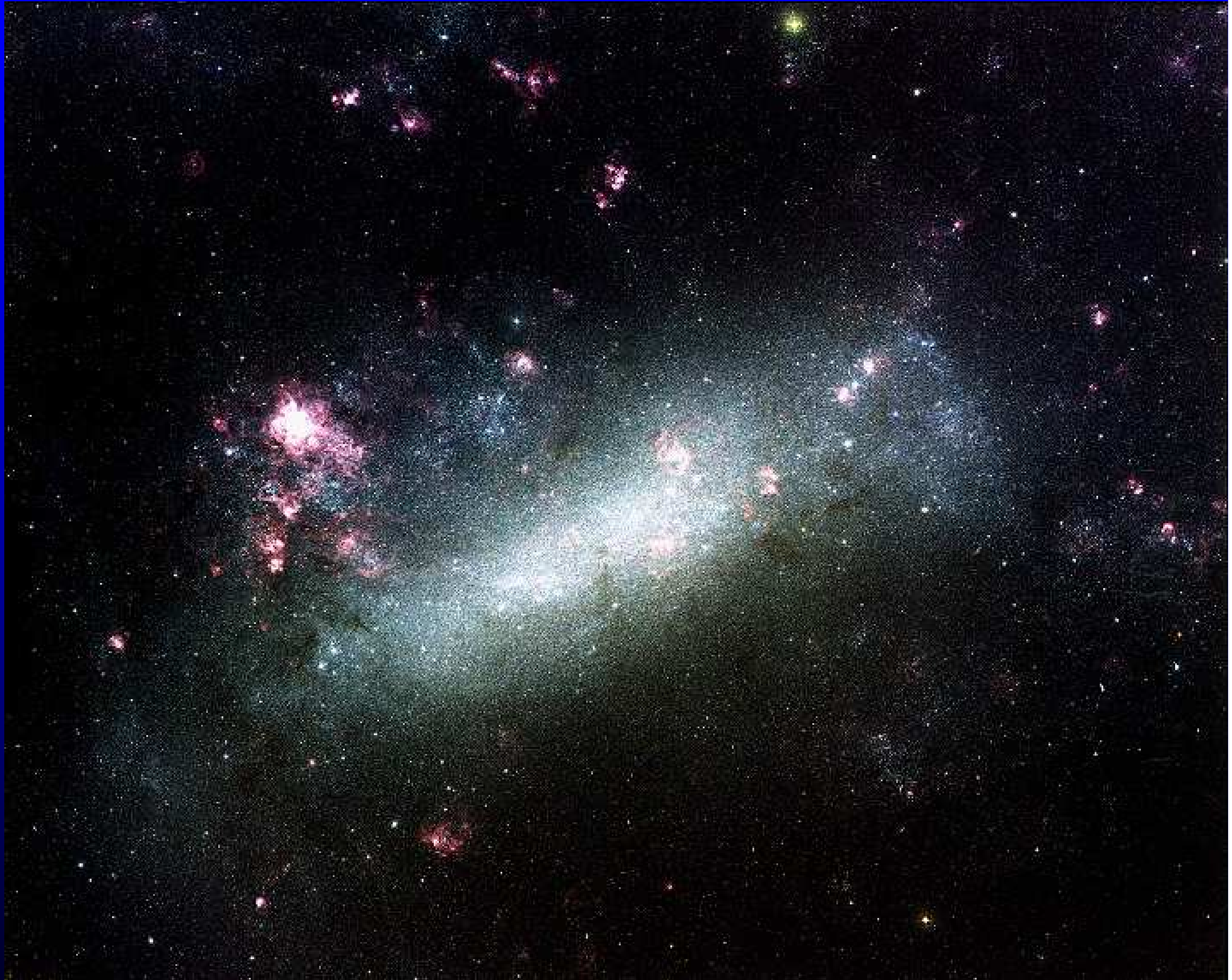
Pulsar Motion through the Galaxy



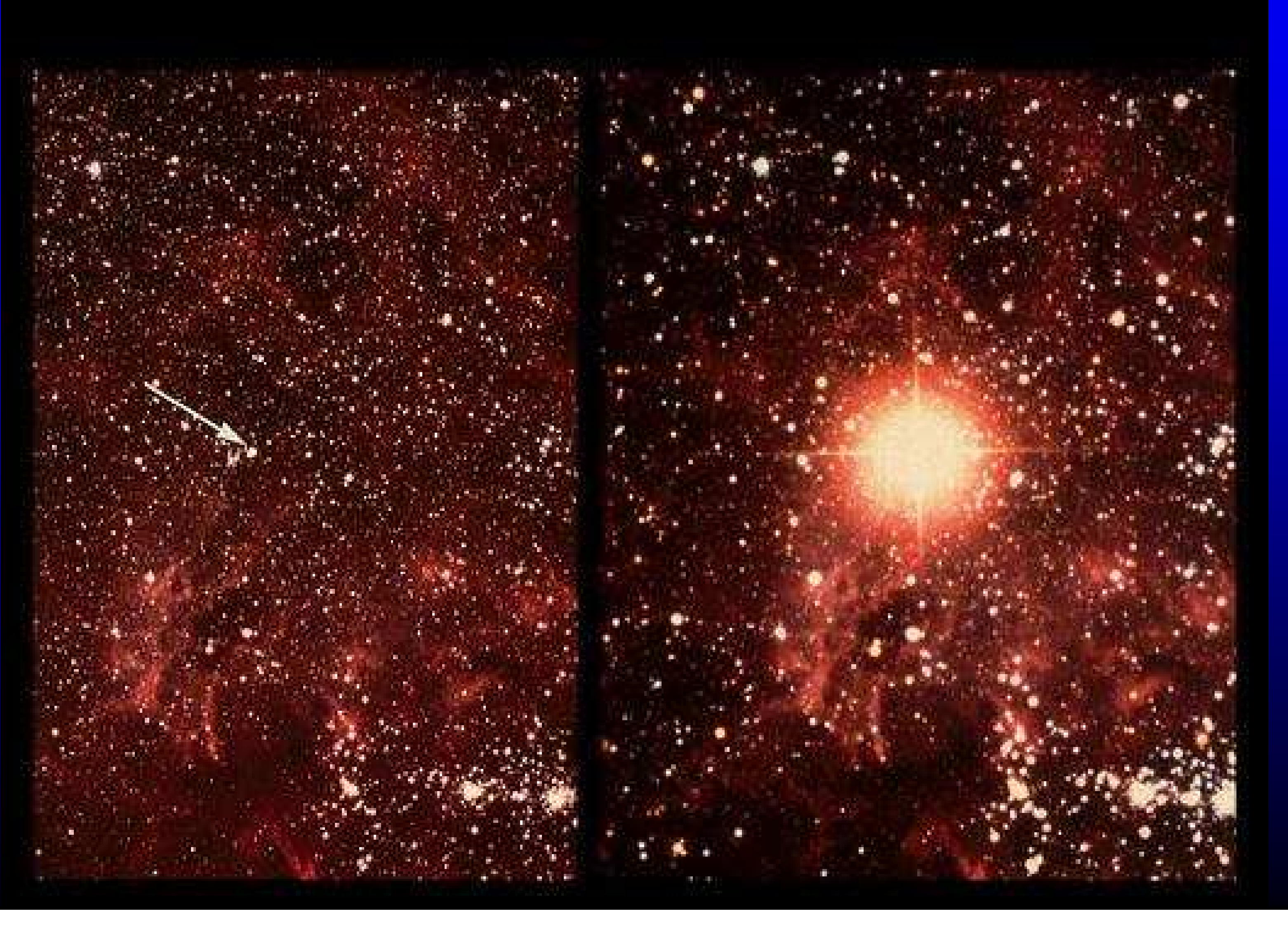
Tycho's Supernova Remnant

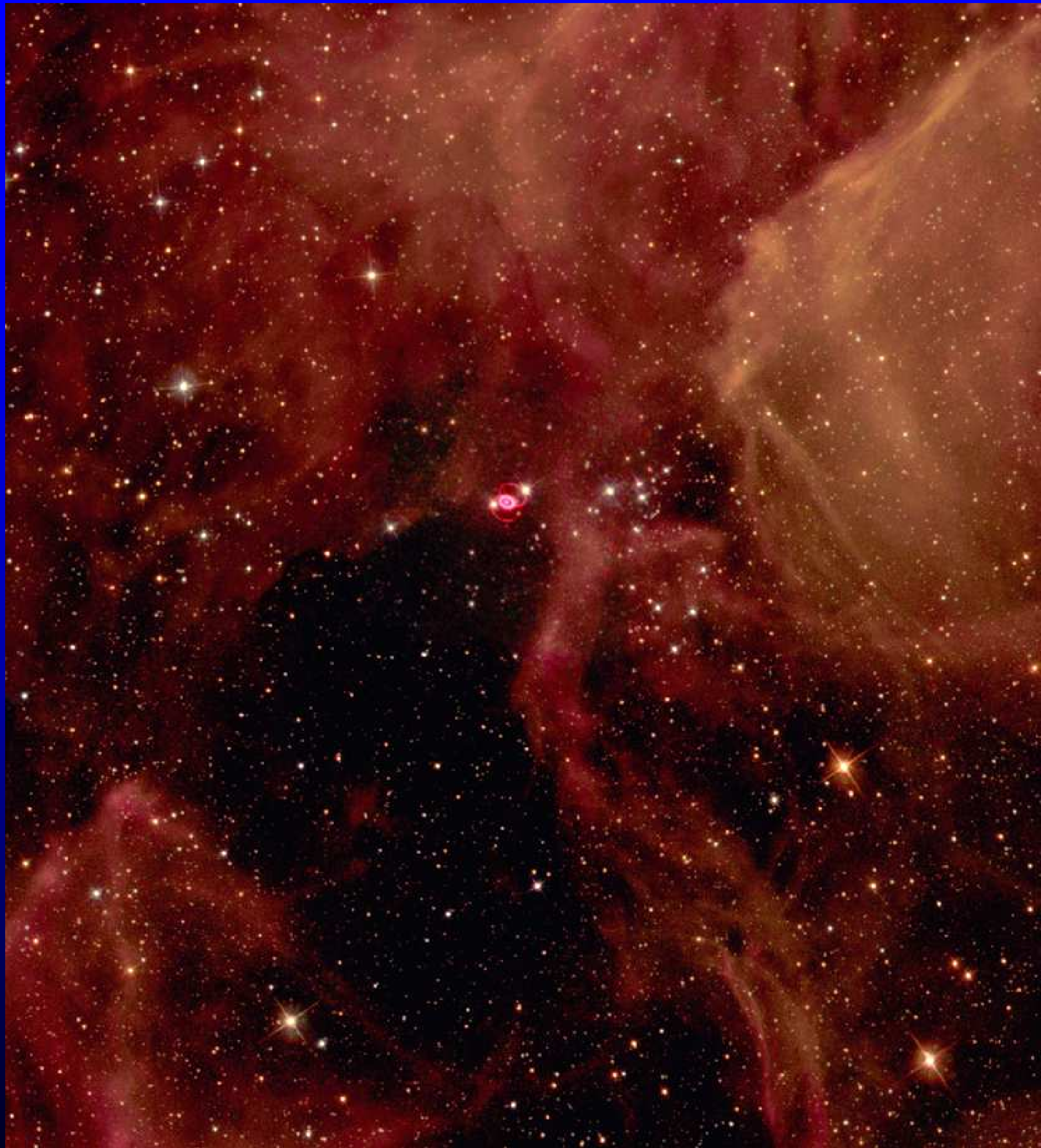


LMC

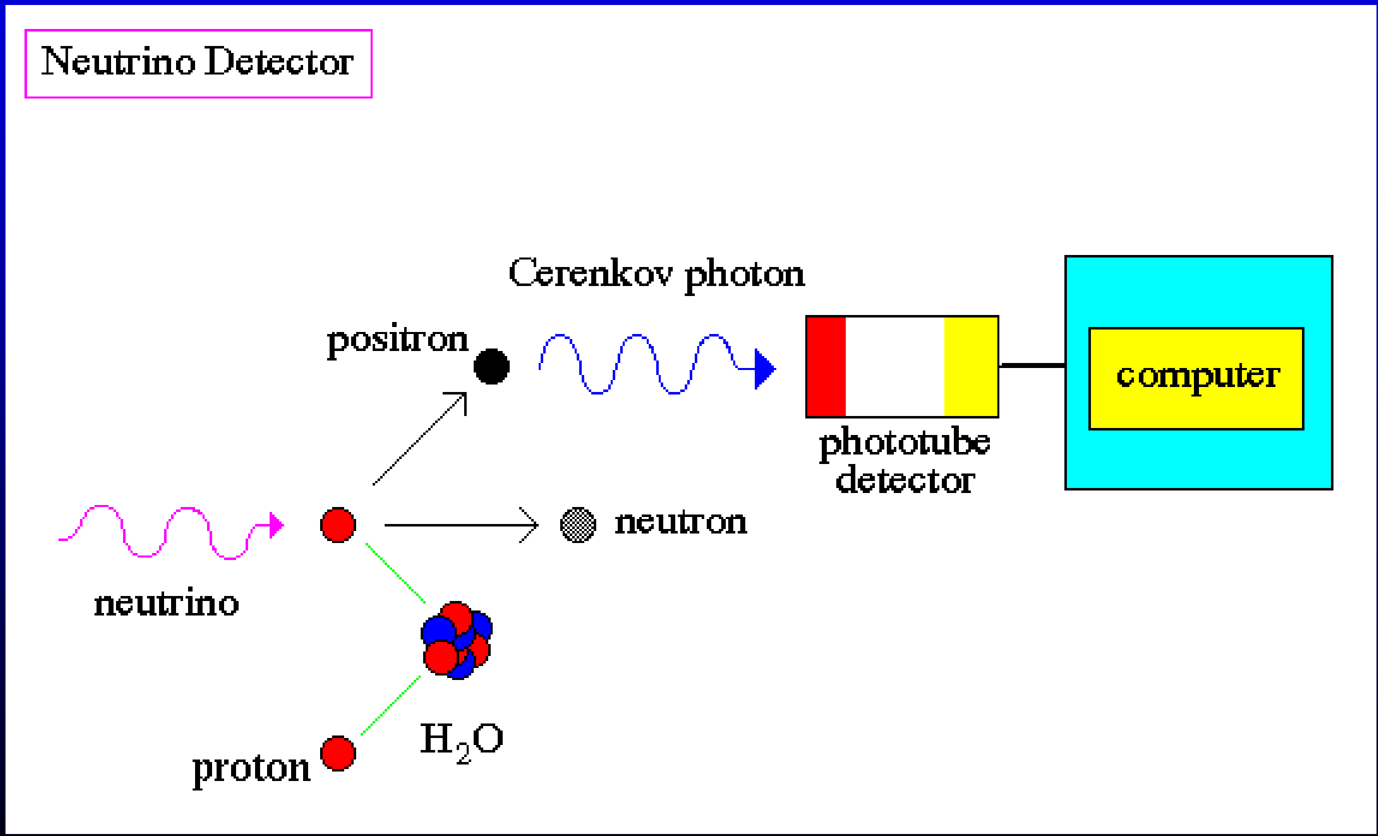


Supernova 1987A





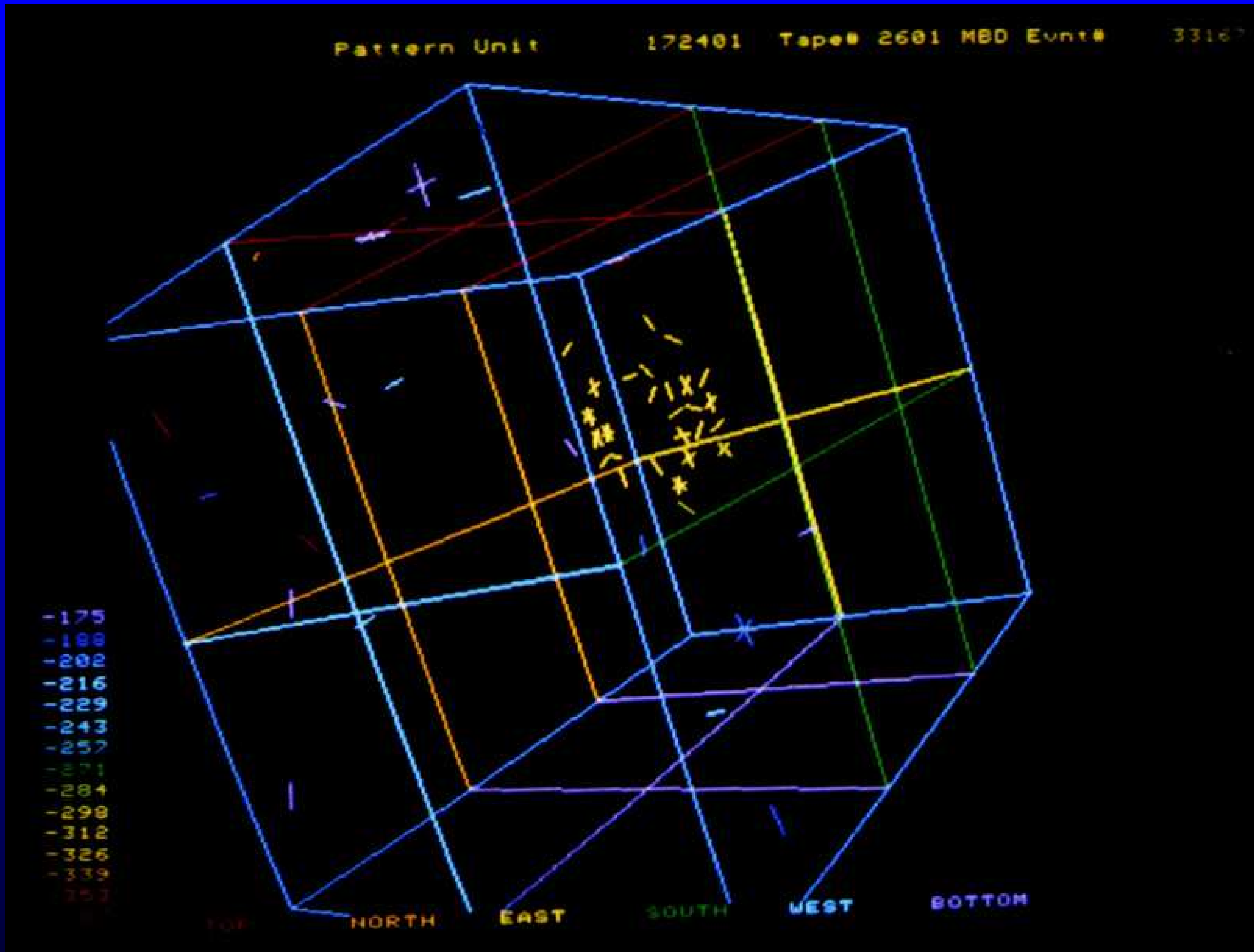
IMB - Ohio



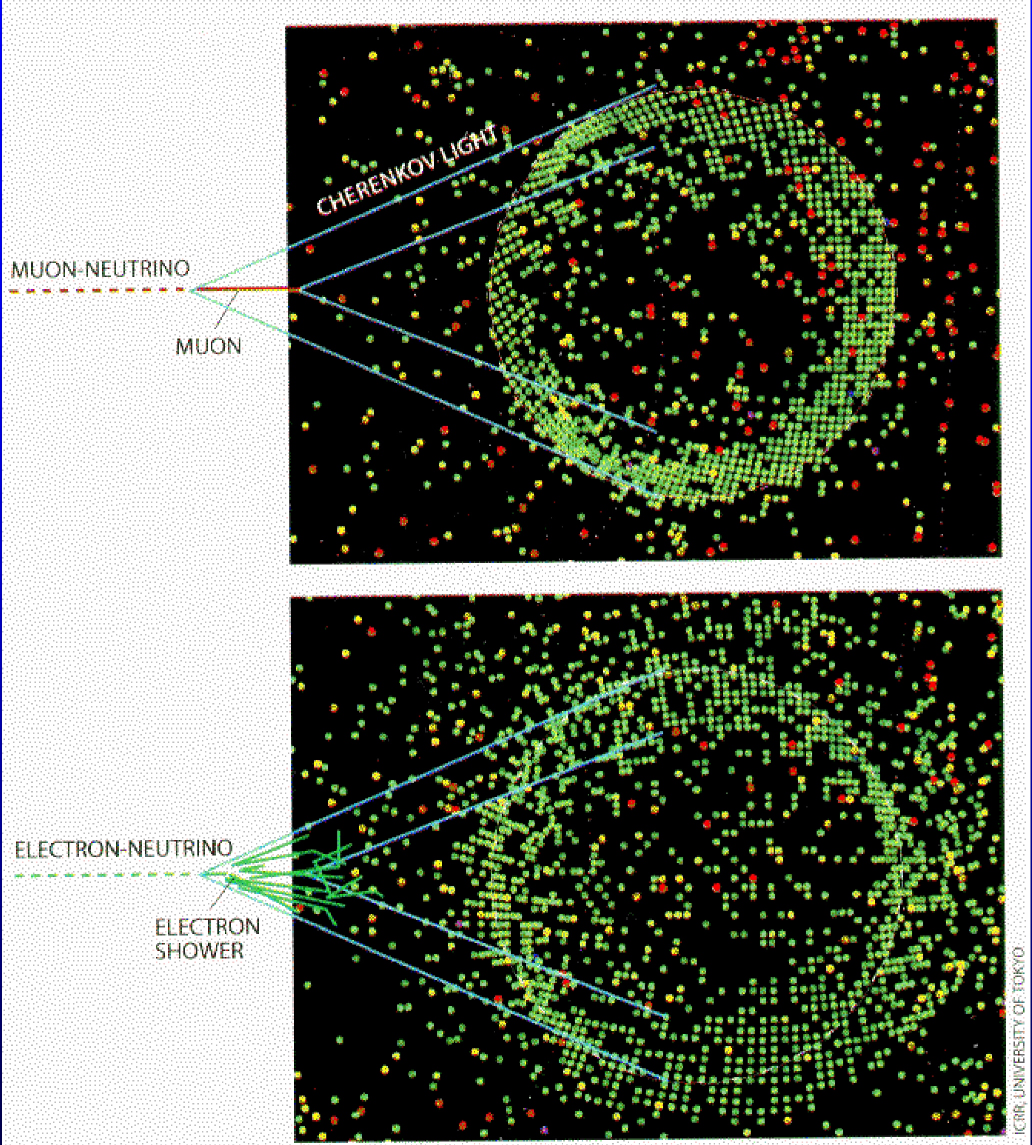
Neutrino Detector
Cerenkov photon
positron
phototube detector
computer
neutrino
neutron
proton
H_2O

Detections at IMB

- SN1987A produced 10^{57} neutrinos!
- At a distance of 170,000 light years that equals 10^{13} every sq metre.
- 10^{16} neutrinos passed through the IMB tank.
- There were 8 detections in 6 seconds
- Normally 3 per week.

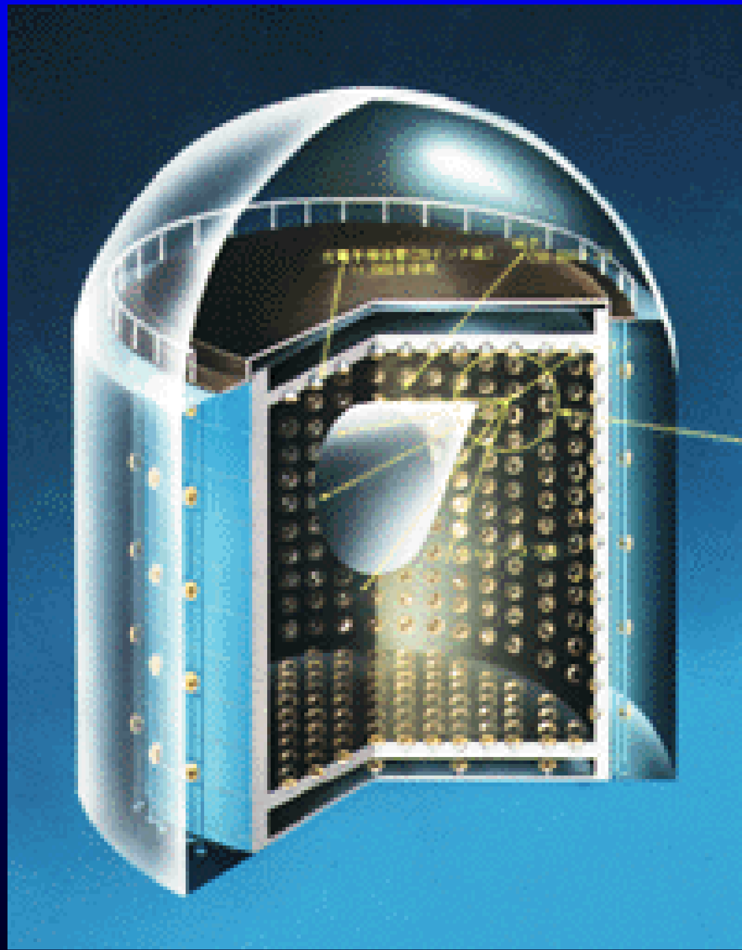


Pattern Unit 172401 Tape# 2601 MBD Evnt#
-175
-202
-216
-229
-243
-257
-284
-298
-312
-326
NORTH
EAST
WEST
BOTTOM

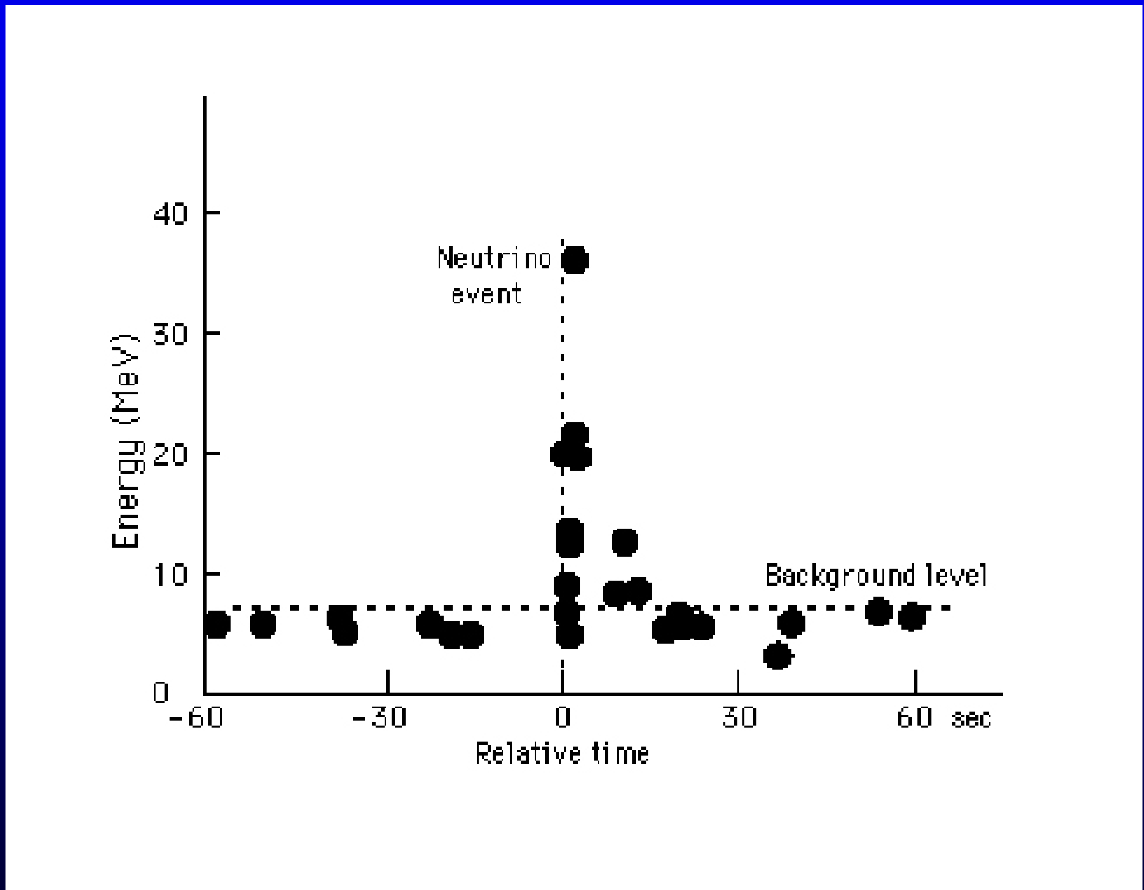


CONES OF CHERENKOV LIGHT are emitted when high-energy neutrinos hit a nucleus and produce a charged particle. A muon-neutrino (*top*) creates a muon, which travels perhaps one meter and projects a sharp ring of light onto the detectors. An electron, produced by an electron-neutrino (*bottom*), generates a small shower of electrons and positrons, each with its own Cherenkov cone, resulting in a fuzzy ring of light. Green dots indicate light detected in the same narrow time interval.

Kamiokande



Neutrinos from 1987A



Neutrino's arrival time

- The neutrinos arrived before the light!
- They came directly from the collapsing core.
- The light came from the surface of the star when the shock wave from the centre reached the surface – some time later.
- The observations put an upper limit on the Neutrino's mass.

Super Massive Stars and Black Holes

- If the mass of the core is greater than ~ 4 Solar Masses, then neutron degeneracy pressure can no longer prevent gravitational collapse.
- Possibly the matter dissolves into its constituent quarks and perhaps “quark degeneracy pressure” finally stops the collapse. (What I think)
- Might end in a singularity of no size. (I don’t think this will happen)
- But we can never “see” the result as the object will have become a Black Hole.

Black Holes

- As either the mass and/or density of an object of a given size becomes greater, the escape velocity from its surface becomes greater.
- There will come a point when the escape velocity exceeds the speed of light.
- Then not even light can escape.
- We call this a black hole.

Black Hole Masses

- Black holes can be of any size and mass.
- We only know of two types of example:
  - The remnants of giant stars perhaps 4 – 12 solar masses.
  - Those at the centre of galaxies 100,000 to 10 billion solar masses.

Black Hole Sizes

- We can calculate the size of the sphere from which no light can escape.
- The "surface" is called the event horizon and regarded as the size of the black hole – it is not the size of the compact object object at its centre. (if there is one!)
- The radius of the event horizon is called the Schwarzschild Radius.
- The Earth would become a black hole if compressed down to 3cm diameter!

Schwarzschild Radius Calculation

- The gravitational Potential Energy (PE) of a mass m at a distance R from a body of mass M is given by $-GMm/R$
- It can escape this gravitational potential if it is given kinetic energy where $\frac{1}{2} m v^2 = PE$

$$\frac{1}{2} m v^2 = GMm/R$$

- If the escape velocity is c:

$$c = (2GM/R_s)^{1/2}$$

$$c^2 = 2GM/R_s$$

$$R_s = 2GM/c^2$$

- This is the radius of the "surface" called the Event Horizon

Example

- What is the Schwarzschild Radius of a black hole whose mass is 8 solar masses?

$R_s = 2GM/c^2$

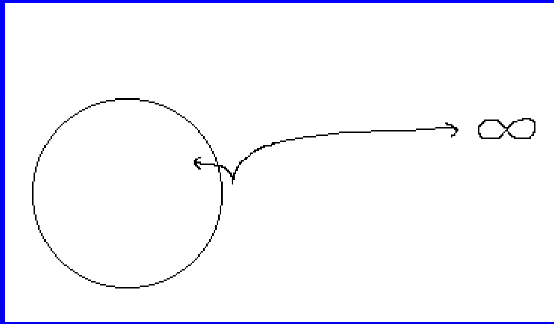
$$R_s = \frac{2 \times (6.7\times10^{-11}\ \mathrm{Nm^2kg^{-2}}) \times (8 \times 2 \times 10^{30}\ \mathrm{kg})}{(3 \times 10^{8}\ \mathrm{ms^{-1}})^2}$$

$= 24000\ \mathrm{m} = 24\ \mathrm{km}$

Black Holes are not totally Black!

- The incredibly strong gravitational field at the surface of the event horizon can create Particle-Antiparticle pairs.
- Three things can happen to a pair of particles just outside the event horizon:
  - Both particles are pulled into the black hole.
  - Both particles escape from the black hole.
  - One particle escapes while the other is pulled into the black hole.

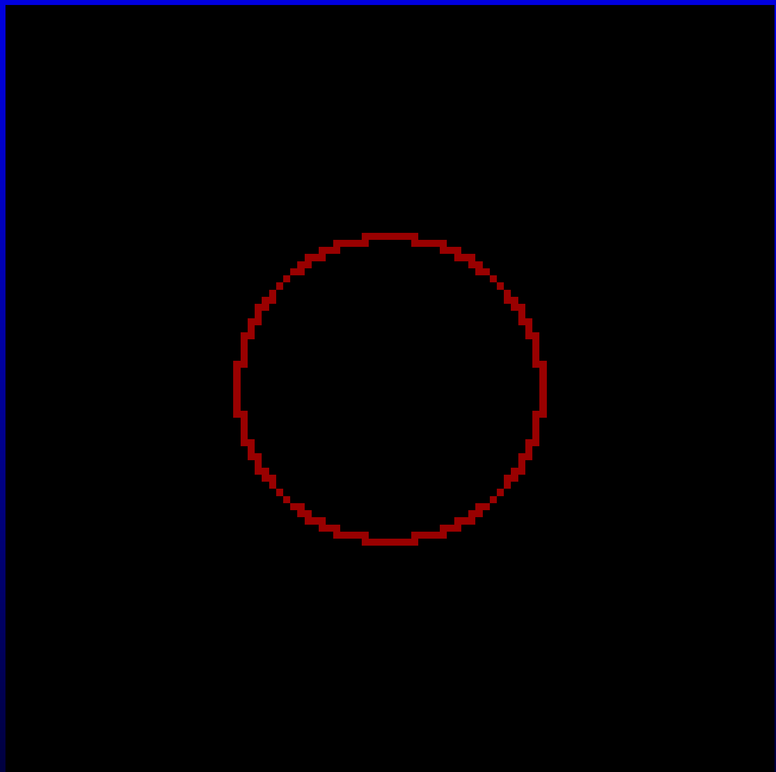
What might happen?



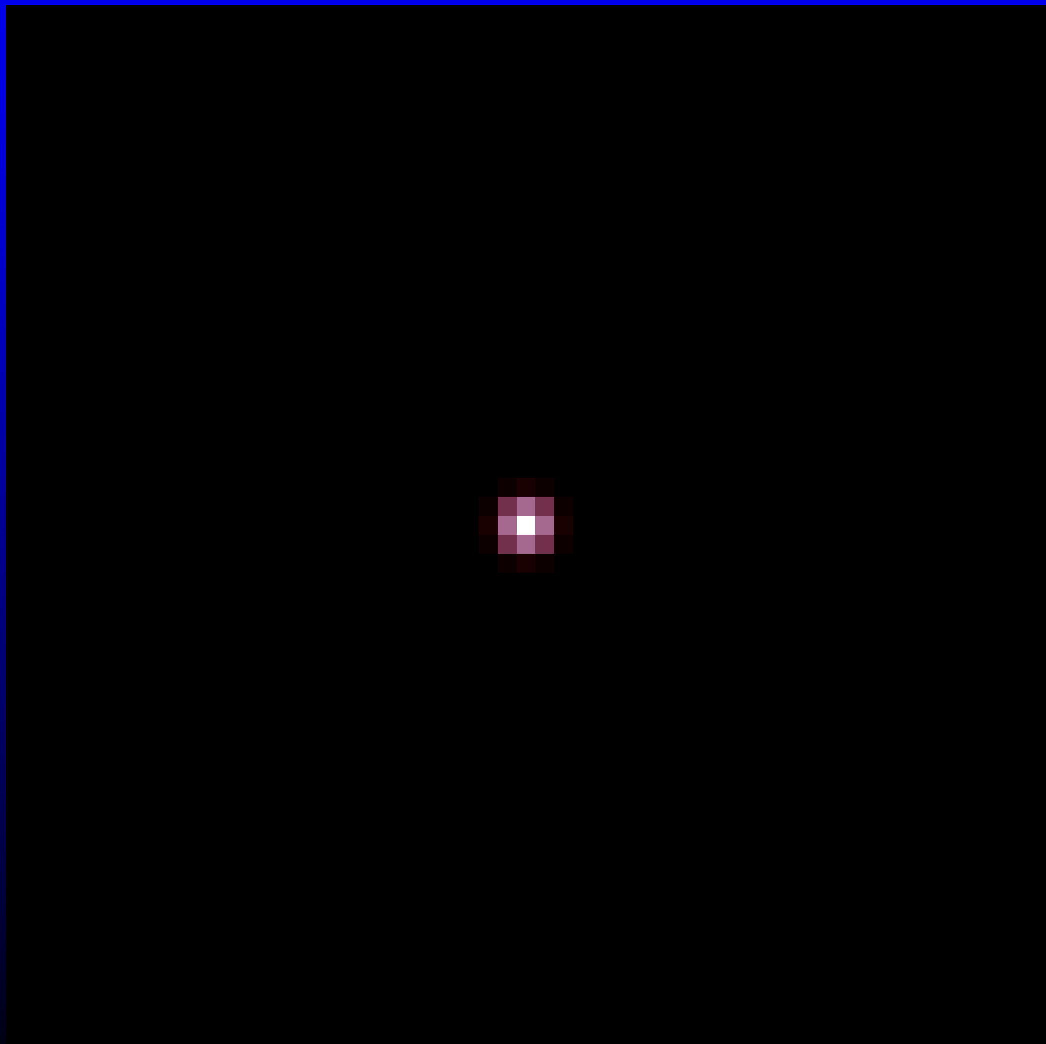
- For the third possibility, the particle that has escaped becomes real and can therefore be observed from Earth.
- The particle that was pulled into the black hole remains virtual and must restore its conservation of energy by giving itself a negative mass-energy.
- The black hole absorbs this negative mass-energy and as a result, loses mass and appears to shrink.
- The rate of power emission is proportional to the inverse square of the black hole's mass.

- The particles which leave the black hole are called “Hawking Radiation” after Stephen Hawkin who first showed that black holes will evaporate in time – eons for large ones!

Hawking Radiation from a small black hole



Final Evaporation!



- The lifetime of a black hole is linearly proportional to its mass:
  - 1 million tons - 30 yrs
- So if “low mass” black holes were created in the Big Bang they would have evaporated by now.
- More massive black holes created then might be “evaporating” now in an intense burst of gamma rays.
- We DO observe bursts of gamma rays, but believe that they are associated with the merging of neutron stars or black holes.

- So far we do not believe that we have seen a small black hole evaporate.
- Stephen Hawkin says that this is a pity as otherwise he would get a Nobel Prize!