

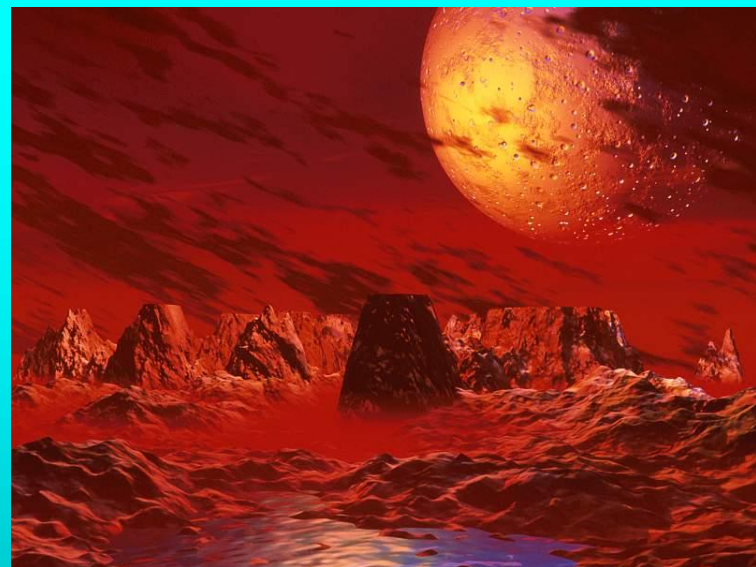
MODERN ASTROPHYSICS

The 20th century brought an appreciation of the colossal scale of the universe, and an explanation of how it all worked. The understanding of the stars came from nuclear physics, quantum electrodynamics, and special & general relativity. Modern elementary particle theory probes fantastically high energies (section 5.3), but astrophysical phenomena near black holes or in the early universe are

incredibly violent, & involve even

higher energies (section 5.4).

On a much smaller scale, humans have for the first time left the earth, going to the moon and sending probes beyond Pluto – in 2005 a probe touched down on Saturn’s moon Titan. 3 places in the Solar System apart from the earth might harbour life (Mars, Europa, & Titan), although this is unlikely. However there are many trillion planets in our galaxy alone (one of 100 billion galaxies in the visible universe). We still lack a basic understanding of crucial steps in the origin of life on earth, & have little clue what kinds of complex organised structures may have evolved elsewhere. It is a safe bet that if we met some of these we might not recognise them as such. Most discussions of alien life assume it will have some structural resemblance to what we already know – this seems unlikely given the very long sequence of earth-specific accidents which gave life on earth.

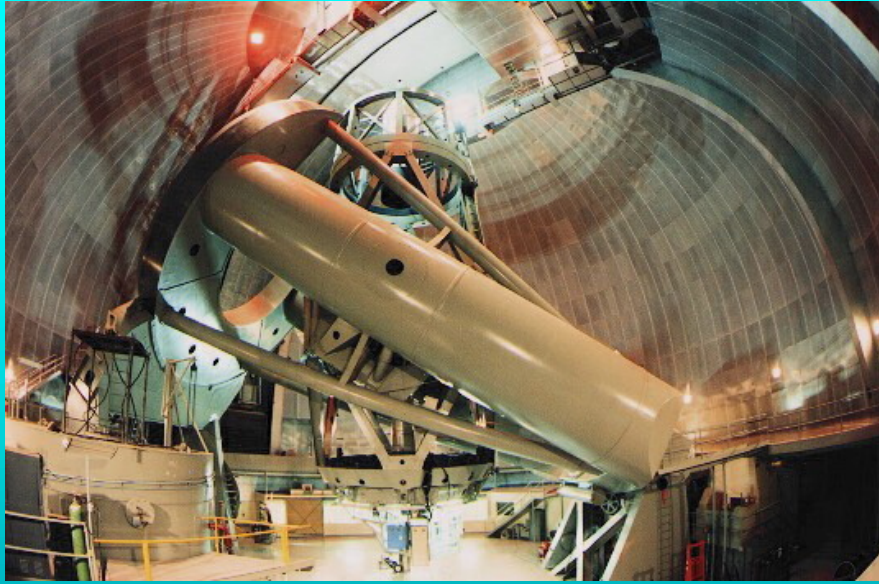


Artists impression of a planet and alien life in some distant star system.



Landing of Huygens probe on Titan, Jan 2005

PROBING DEEP SPACE: TERRESTRIAL TELESCOPES



The 200-inch Hale telescope (Palomar mtn), built in 1948



The 10-metre Keck telescopes in Hawaii

Just as important was the development of powerful radio telescopes (pioneered in the UK). These revealed high-energy processes in very distant galaxies, & also allowed mapping of our own galaxy. Radio waves were emitted in profusion by interstellar gas & dust, by the sun, & by planets like Jupiter



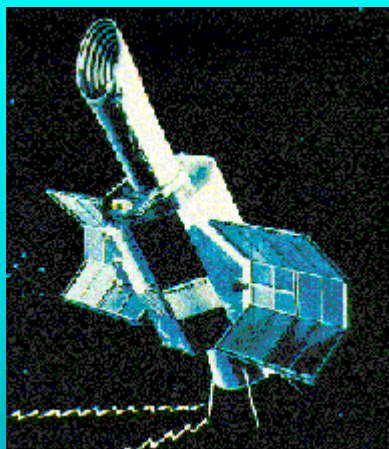
The 250-ft Jodrell Bank radio telescope



The VLA (Very Large Array), a set of 26 dishes, each of 25 m, which can be moved along rails stretching 15 miles from the centre

SPACE TELESCOPES & PROBES

Space probes have taken us beyond the filtering & distortion of the earth's atmosphere. In the optical realm the Hubble Space Telescope (HST) can take week-long exposures. Orbiting telescopes are also designed to see in the IR, UV,



The International UV explorer satellite

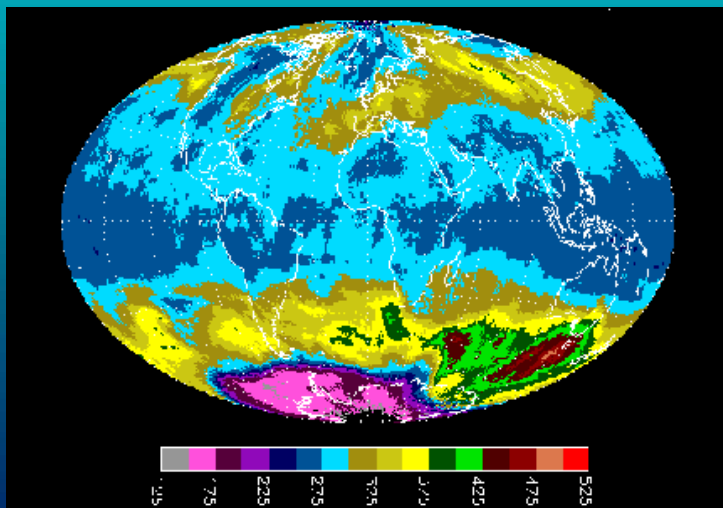
X-rays, and Gamma rays (none of which penetrate the atmosphere), as well as probe the earth. Space probes have been sent all over the solar system



RIGHT: Cos-B gamma-ray telescope satellite under construction.



The HST (above); & launch (below)



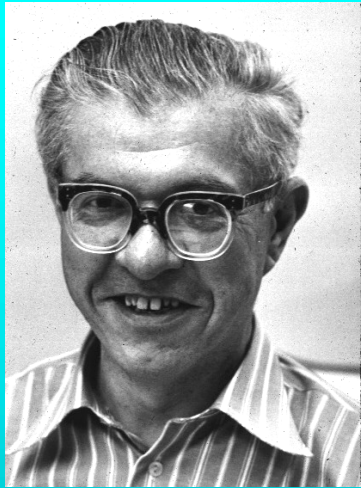
Ozone map of the earth, made by TOMS-ozone orbiting spectrometer



The Pathfinder probe on Mars



The Giotto probe, which visited Halley's comet

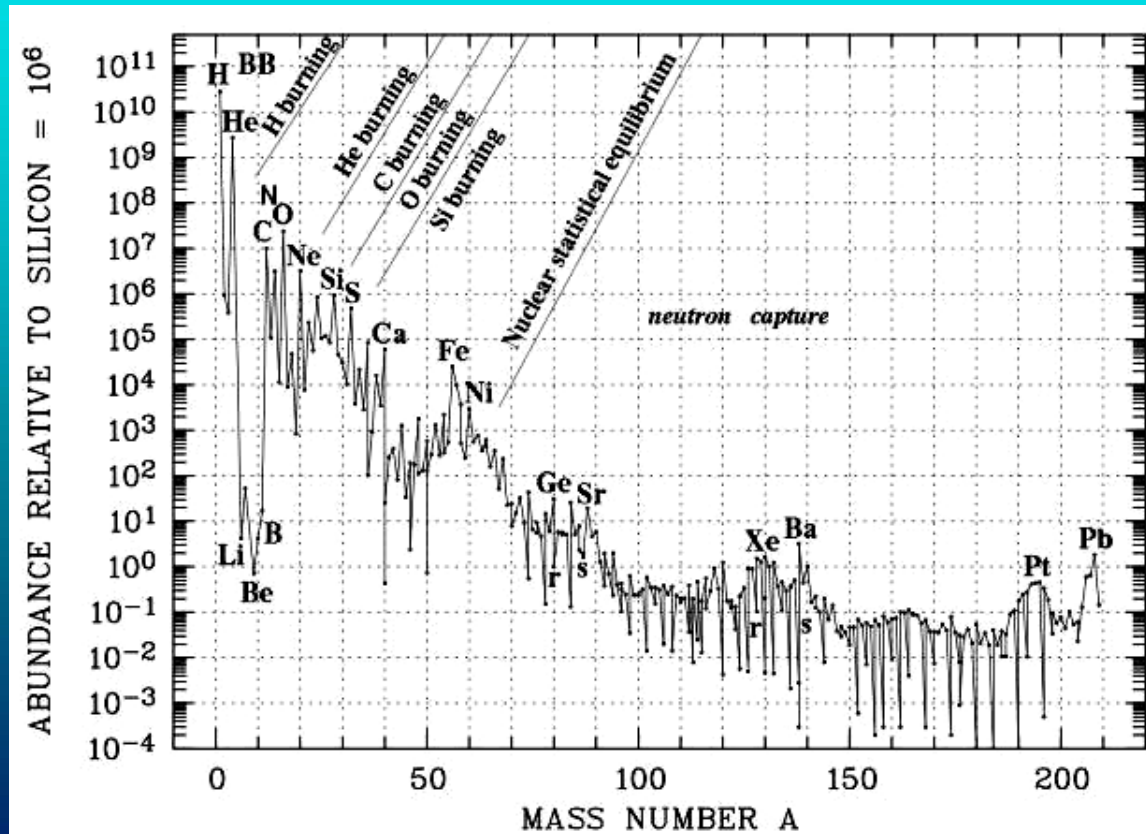


Fred Hoyle (1915-2001)

It was rapidly realised that nuclear fusion powered the stars, and the key contributions were made in 1939 by H Bethe and over several decades by Chandrasekhar (see next few slides); within a few decades this became one of the best understood parts of physics.

But where did the elements come from in the first place? One of the great early successes of nuclear astrophysics was the explanation/prediction of the cosmic abundance of nuclear species in the early universe, before stars began to produce higher elements through fusion in their cores. A key early figure was F Hoyle.

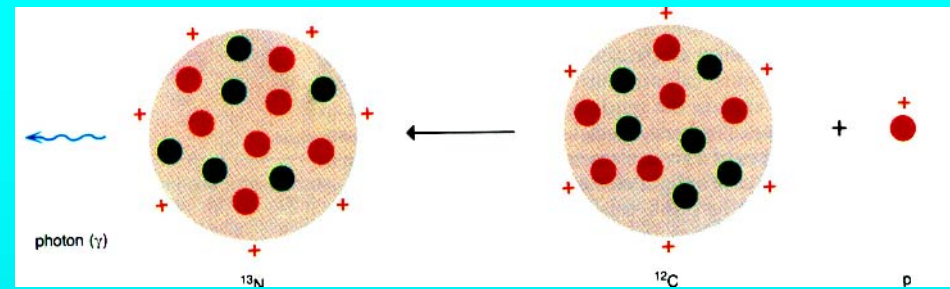
Working at various stages with Fowler, Burbidge & Burbidge, and Talyer, Hoyle worked out the extensive chain of reactions (even predicting an unknown resonance in the Be nuclear spectrum, without which nucleosynthesis could not have occurred). We now know the detailed timing of all this in the stages after the Big Bang, and theory agrees well with observation. Ironically Hoyle did not initially believe in the Big Bang, and pushed instead a 'Steady State' theory.



Abundance of nuclear species in the universe (Note logarithmic scale)

FUSION in STARS

This is extremely complex- there is a huge variety of interconnected chain reactions. For it to proceed the different nuclei must be at high T. The radiation emitted during the fusion keeps T high. In principle nuclear fusion can keep producing ever heavier nuclei up to Fe (whose nucleus has 26 protons and 30 neutrons). To make heavier elements requires higher energy to smash the nuclei together, and thus higher T. The centre of the sun, where H is fused to He is at 14.7×10^6 K, but the centre of a blue supergiant, where Fe is being produced, is at several billion degrees.



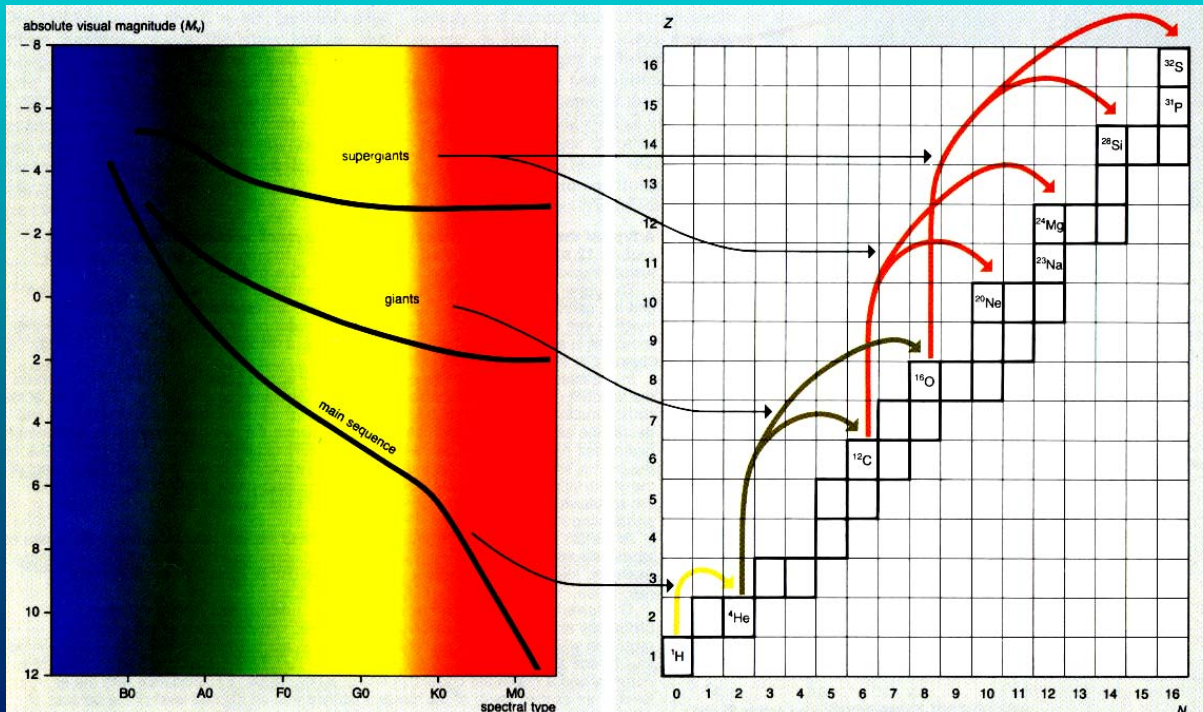
A simple fusion process- a proton fuses with C-12 to make N-13, with emission of a photon.



H Bethe (1907-2005)



S Chandrasekhar (1910-1995)

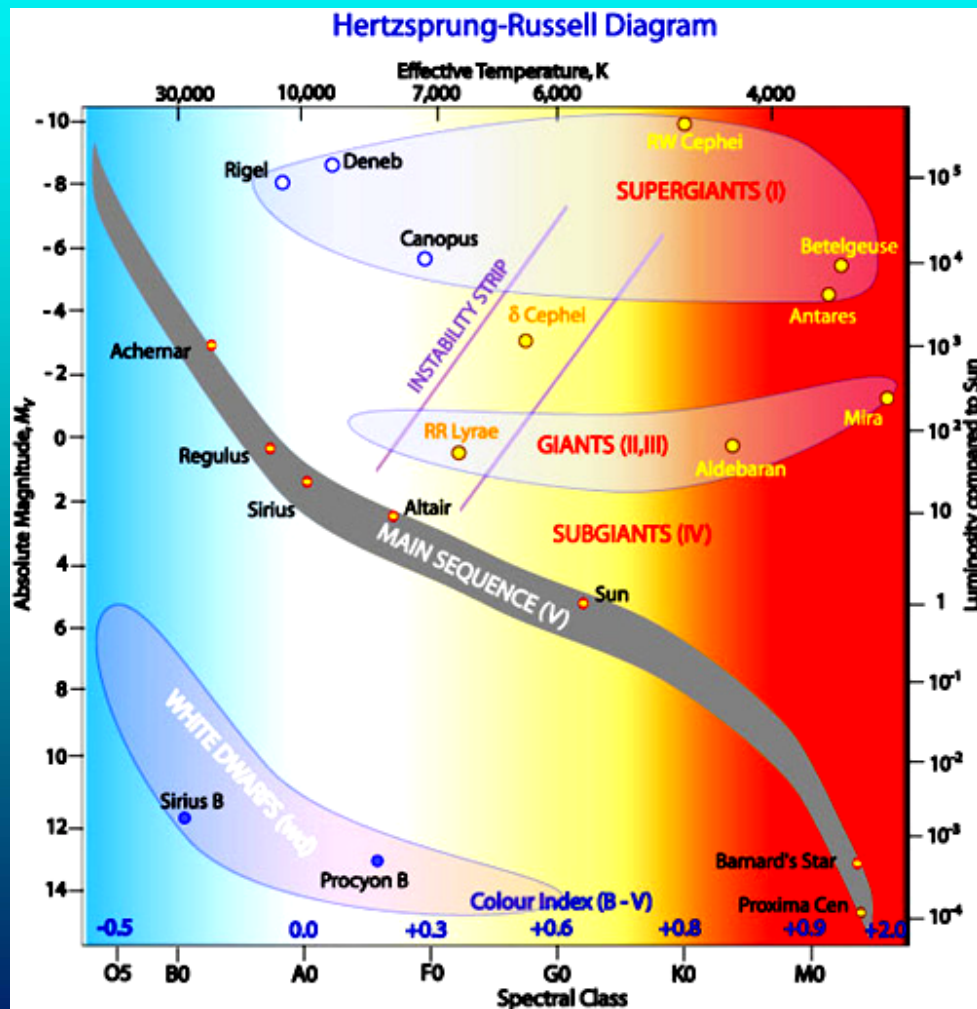


Some of the many nucleosynthesis processes involved in stars

However Fe is the most stable nucleus- one cannot go farther with fusion. If it is a light star it cannot even get to Fe – low mass stars would be blown apart by the radiation pressure from a ν high T core. Thus the heavier elements are created in supergiants only.

STRUCTURE of the STARS

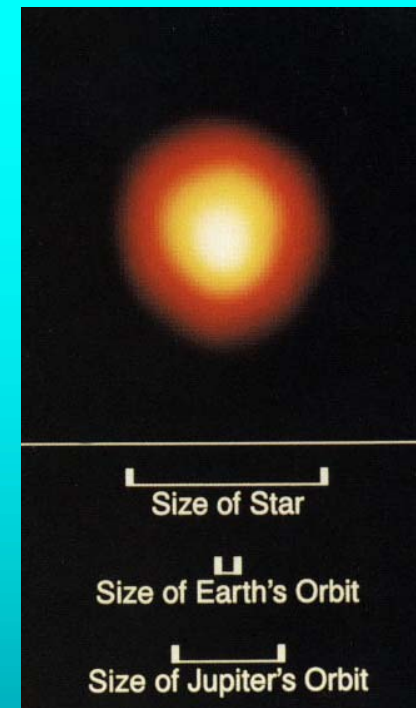
Once the basic nuclear reaction chains in stars were understood, it became possible to give a very detailed theory of their structure and evolution. The stars are so far away that it has only recently been possible to image a few of Them – and yet we understand their internal structure in great detail, far better than we do that of the earth!



It was first noted a century ago by Hertzsprung & Russell that in a diagram plotting luminosity vs surface temperature, almost all stars lay on the 'Main Sequence', running from extremely feeble 'red dwarfs' to v luminous blue giants.

Most stars are small red dwarfs, with masses from 0.05-0.5 solar masses, and luminosities down to 1/100,000th of the sun. A much smaller fraction are very big – stars with masses > 20 solar masses are 'supergiants', with luminosities from 10,000 – 5 million suns. Red supergiants can be huge, with diameters similar to our solar system. On the other hand white dwarfs can be no larger than the earth.

Stars have very similar compositions – their differences arise from mass differences and differences in lifetime. Their initial composition is that produced in the early Universe (roughly 80% hydrogen).



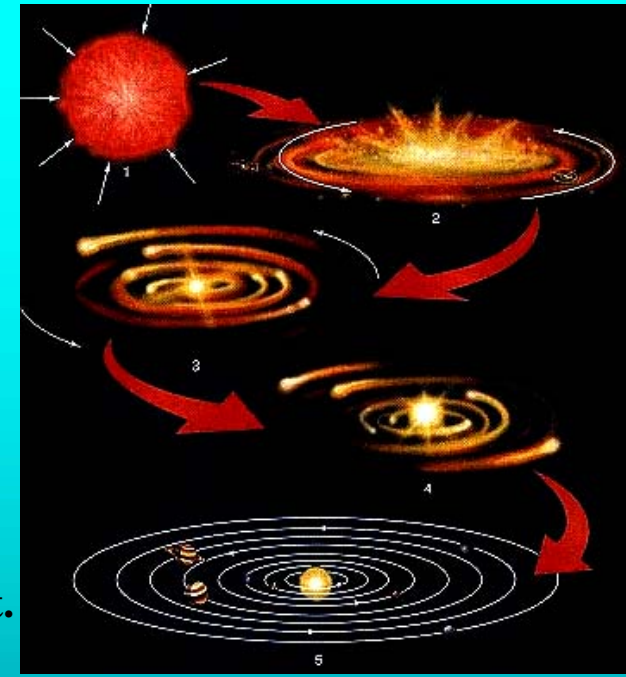
FORMATION of STARS & PLANETS



The open cluster M35 (top) and the globular cluster NGC 2158 (bottom)

The original 'nebular hypothesis' for the creation of the Solar System came from I Kant in 1755 (also suggesting the correct structure for the Milky Way). Extended by Laplace, Jeans, & others, supplemented by quantum mechanics and computer studies, this basic picture is still believed correct.

A large condensation of gas and dust slowly collapses under self-gravitation, often initiated by shock waves from nearby supernovae. Angular momentum is partially transferred away, but the residue still induces rapid rotation as the cloud collapses – it spins up into a disc. Light escapes along the axis of this disc as it slowly condenses into planet-size objects (which then sweep up the remainder).



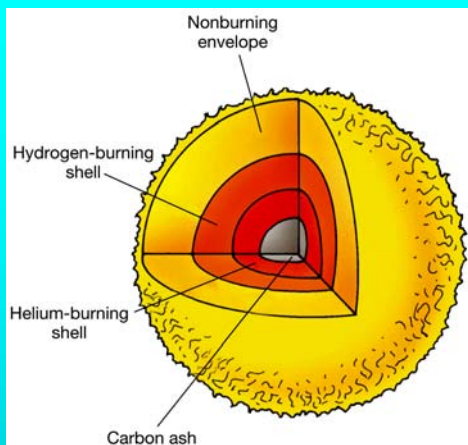
The nebular collapse of Kant (1755)

In recent years many star systems have been found in the process of formation –often lots of stars condense out of a single cloud, forming clusters. Moreover, many planets have now been detected indirectly around other stars – their motion perturbs that of the parent star, and they can even be detected passing in front of it. These 'extrasolar planets' come in all shapes and sizes. Almost every star appears to have a planetary system, often much larger than our own Solar System.



Gomez's 'Hamburger'

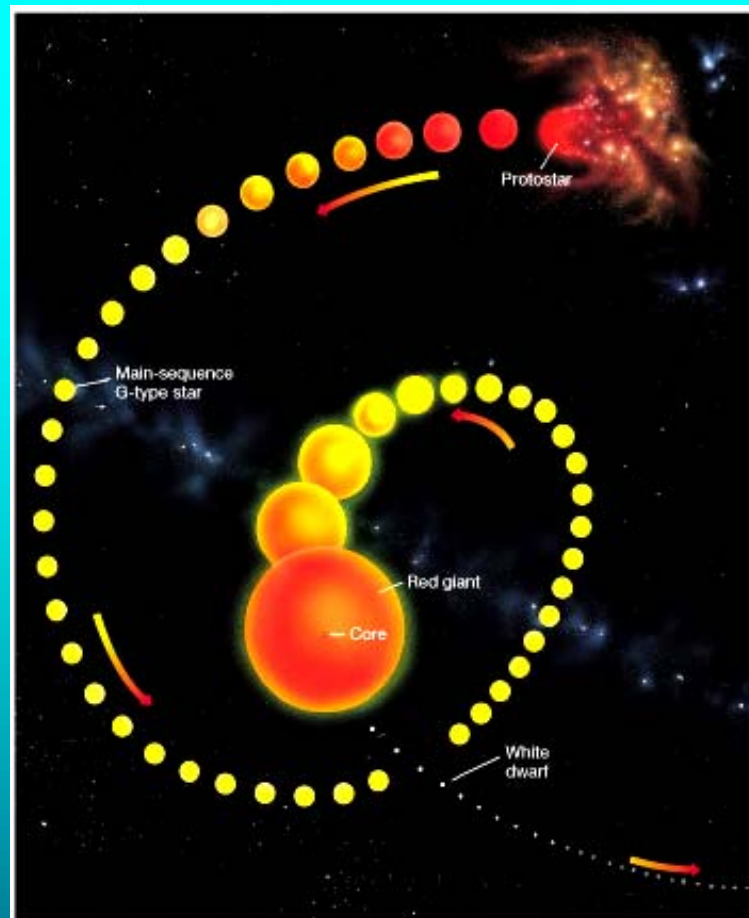
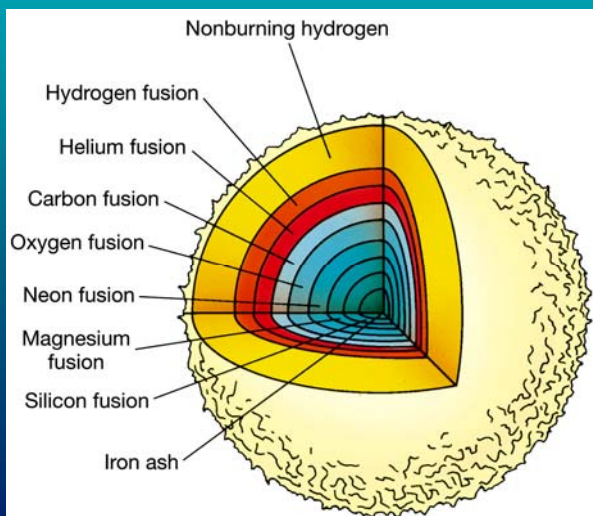
The LIFE CYCLE of STARS



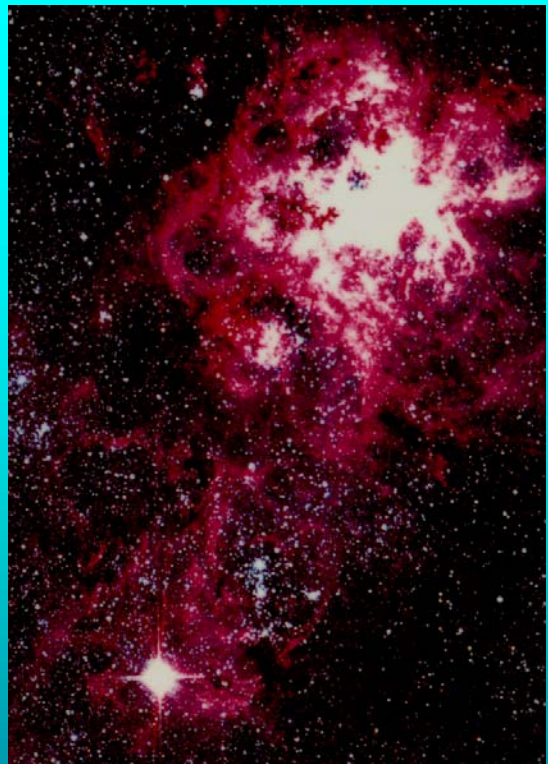
In main sequence stars, life begins with Hydrogen fusion burning in the core, at a temperature ~ 15 million K, producing Helium. As the hydrogen runs out, the core temperature rises & the Helium burn to form Carbon. The star then swells to a red giant, increasing to 1000 solar luminosity. When the fuel is exhausted, it collapses to a white dwarf, with densities 1 million times that of water. The lifetime depends on the mass.

The sun will last 10 billion yrs before its red giant phase. However small red dwarfs will last over 100 trillion yrs. Eventually the white dwarfs cool to become dense 'black dwarfs' – stellar relics.

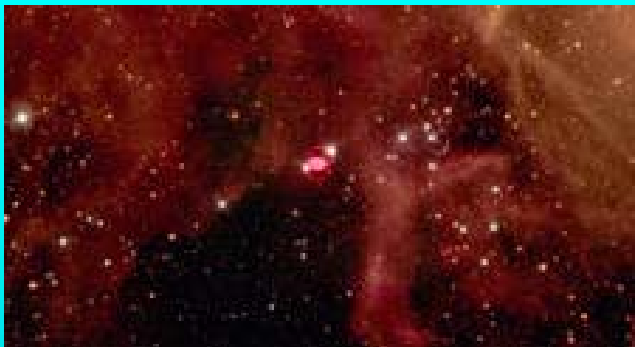
On the other hand massive stars become supergiants, which use up their Hydrogen after only a few million yrs, and then proceed to synthesize all the elements up to Iron – this heats their cores to temperatures of many billions of degrees, with intermediate fusion reactions going on in shells throughout the star. At this time the star is unstable, blowing off gobs of gas & dust. Once the core is transformed to Fe, the fuel has run out – the star then collapses.



NUCLEOSYNTHESIS in SUPERNOVAE



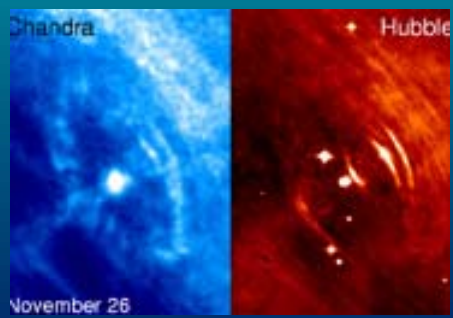
SN 1987A in the Larger Magellanic Cloud (lower left)



SN 1987A, v. high magnification, 10 yrs later

A massive star ends its life in a catastrophic collapse (taking only 10-50 secs), followed by an explosive rebound, which in only minutes converts a mass of several suns into energy ($E = mc^2$). These energies allow fission processes which synthesize elements beyond Fe, creating almost all heavy elements in the universe.

The remaining stellar core has nothing to support it, & collapses to a neutron star or black hole. This can still emit radiation – occasional flares are caused by matter falling into the star – this matter exists in the ‘accretion discs’ around the star..



Centre of M1, in X-rays & in red light

凡十一日没三年三月乙巳出東南方大中祥符四年正月丁丑見南斗魁前天禧五年四月丙辰出軒轅前星西北大如桃速行經軒轅太星入太微垣掩右執法犯次將歷屏星西北凡七十五日入濁没明道元年六月乙巳出東北近濁有芒彗至丁巳凡十三日没至和元年五月己丑出天關東南可數寸歲餘稍没熙寧二年六月丙辰出箕度中至七月丁卯犯箕乃散三年十一月丁未出天囷元祐六年十一月辛亥出參度中犯掩側星壬子犯九游星十二月癸酉入奎至七年三月辛亥乃散紹興八年五月守婁

Observation of Crab Supernova in 1058 AD



Crab Nebula M1 now, 945 yrs later- it is several light yrs across

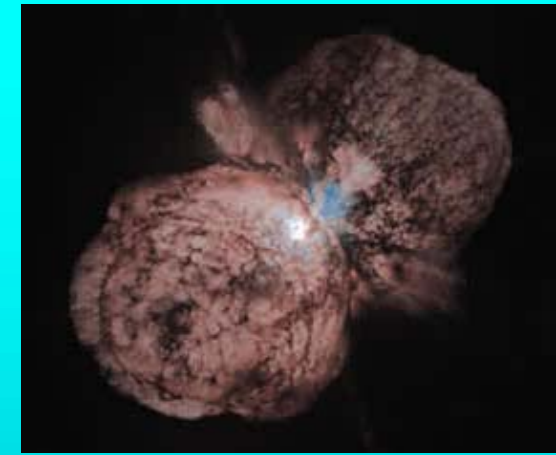
The STUFF of LIFE

The material blown off from a supernovae is moving fast-sometimes $>10,000$ km/sec; it is rapidly dispersed around the galaxy. Material blown off from unstable giant or supergiant stars contributes even more to the interstellar medium.

Supernova material crashing into the medium creates shock waves which compress the medium & initiate gravitational collapse of gas & dust clouds – thereby starting a new round of stellar creation. The supernova material seeds these clouds with heavy elements- from which the planets, and we ourselves, are made. Supernovae thus created the earth & everything on it.



IC 418- the 'spirograph' planetary nebula



Blow-off from Eta Carinae in 1880-90 obscures the central star



The Vela supernova remnant extends over many light years, still glowing.



A close-up shows a shock front (& a meteor track on the photo)