STARS AS FUSION REACTORS*

Jayant V. Narlikar
Inter-University Centre for Astronomy and Astrophysics

Introduction

I am honoured to accept the invitation to deliver a lecture specifically aimed at college students and named after C.V. Raman whose name has been a source of inspiration for several generations of physicists. It may be asked : What has an astrophysicist like me in common with the Department of Atomic Energy which has instituted this award in collaboration with the Indian Physics Association? The answer is contained in the title of my talk.

Atomic Energy by nuclear fission is considered today a practical proposition as a source of energy, here on the Earth, while atomic energy by fusion is the holy grail which scientists all over the world are trying to acquire. Out there in stars it is the prime source of energy: stars have demonstrated that controlled nuclear fusion works. Indeed, as I will describe later in this talk, it was an astronomer who first pointed this out. Why is it that man is finding it difficult to emulate stars in this process? To find the answer, let us start at the beginning the story of a star's life.

There are two ways in which we can piece together the life history of a star. To understand them consider a parallel situation in which an intelligent extraterrestrial is trying to piece together the biography of man. The ET may be able to find all details by observing a human being from his/her birth in a maternity home to death after some seven or eight decades. This method has an advantage : it provides a minute account of everthing that happened in that individual's life. But this is outweighed by two serious disadvantages. First it takes the ET a long time to complete its survey. Second, at the end of it the information available is of one person only. As we know, the human population is full of variety and no single example can be considered typical.

The second method available to the ET is better suited to its objective : it provides a comprehensive picture of the human beings in a comparatively short time. This method consists of collecting data on the physical characteristics of a large group of the humans, such as found in a city. There the ET will find human beings at different stages of their life. Figure 1 illustrates this with a graph of heights and weights of people in a town. The plot is a conceptual one but illustrates the point I wish to make. Notice that from point A to B the plot shows a rising trend of weight with height. From B to C there is a plateau with no significant variation in height but a wide range of weights! There are fewer points on the rising sector than on the plateau.

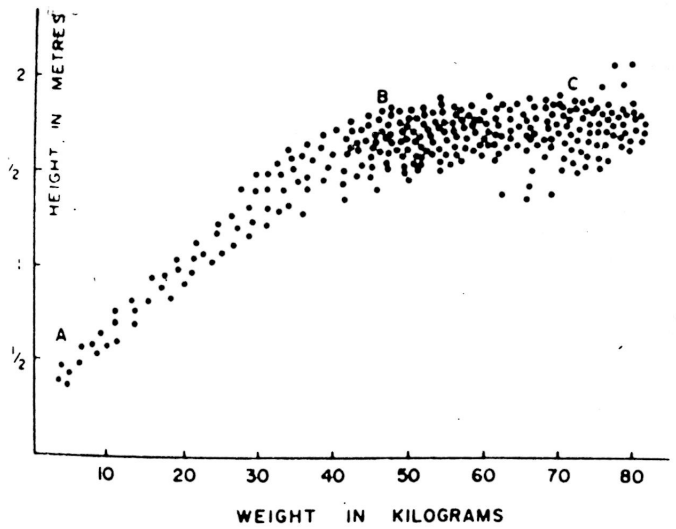


Fig. 1 - An imaginary plot of height vs weight for the typical human population.

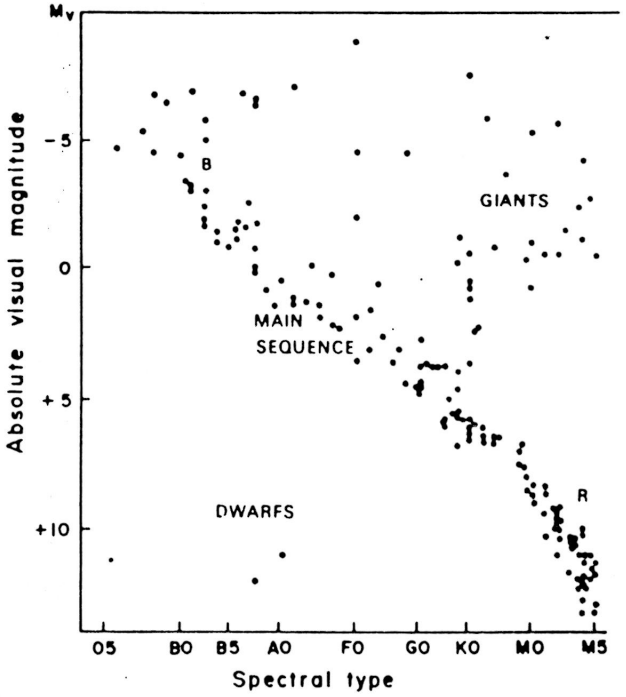
What does all this mean when interpreted statistically? Fewer points mean a typical human being spends a shorter span of life in a phase when his weight and height both increase. This is the 'growing' stage. The plateau represents adulthood which takes up the longer fraction of human life.

Such data supplemented with additional features like the thickness of hair on head, colour of hair, wrinkles in skin etc. can help the ET put together the sequence of human evolution. The data acquisition time by this method could be no more than a few months and the picture put up this way would be more comprehensive than the long term observation of a single individual.

Likewise, observing a single star throughout its life (of several billion years!) is not a practical proposition for us even if that star happens to be the Sun. Throughout the recorded human history there has been no discernable change in the Sun. Nor is there going to be one in the millennia to come. Rather we should cocentrate on groups of stars hoping to find in them a ariety in different stages of evolution. Do we have something analogous to Fig. 1 for stars?

The H-R Diagram

The astronomers E. Hertuzsprung and H. N. Russell found a way of plotting two stellar characteristics that can be considered analogous to Fig. 1. Known as the H-R diagram after its originators, this plot has the surface temperature of the star on the horizontal axis and its luminosity on the vertical one. Because of a wide variation in these quantities, the plots are made on the logarithmic scales with the surface temperatures increasing leftwards and luminosities increasing upwards. Fig. 2 describes the H-R diagram of a cluster of stars including our sun.



A Hertzsprung–Russell diagram for the nearest stars.

Fig. 2 - The H-R diagram of a nearby group of stars including the Sun

I will not go into the question of how temperatures and luminosities are determined. This procedure involves considerable inputs from physics and astronomy. The point to emphasize is that a star of low surface temperature looks reddish and one of high surface temperature looks bluish. Stars of intermediate temperature have the intermediate rainbow colours.

Notice that a majority of stars are distributed over a band stretching from bottom right (low temperature faint stars) to top left (high temperature luminous stars). This band is called the Main Sequence. Going by the human analogy we conclude that a large fraction of the star's life is spent on the Main Sequence. Next comes another lot of stars in the top right hand corner : these are luminous but reddish stars. Their physical size is very large which is why they are called red giants. Likewise stars at the bottom left are called white dwarfs for their faint whitish appearance and tiny size. Our sun lies in the middle of the Main Sequence : it is an average star in terms of size, luminosity, temperature and colour.

With these plots for various star groups can we piece together the biography of a star? I will next turn to this question which brings me to my central theme.

The Secret of Stellar Energy

What keeps the Sun shining? We can make a crude estimate of the Sun's energy reservor as follows. The sun and the planetary system have been in existence for about 5 billion years, if we go by the geophysical and nuclear age estimates. It is unlikely that the Sun has substantially changed from its present position on the Main Sequence.

Thus if we multiply its current luminosity of about 4×10^{33} erg s^{-1} by a time span of 5×10^{9} years @ 1.5×10^{17} s, we get the answer as 6×10^{50} ergs! How did the Sun acquire this vast store of energy?

In the last century two distinguished physicists, Lord Kelvin in the U.K. and Baron von Helmholtz in Germany had proposed a theory in which the Sun derives its energy from its gravitational contraction. Qualitatively this looked a reasonable hypothesis, but the age estimates of the Solar System in this century made it untenable. For, the gravitational energy that the Sun could have drawn upon till now does not come up even to one percent of the above figure. So the answer to the question lies elsewhere.

In the 1920s, the Cambridge astronomer A.S. Eddington made a systematic study of stars as gravitationally bound spheres of hot plasma (ionized

gas). In Eddington's picture the stars are held in equilibrium by strict balance of their inward gravitational pull by the internal pressures of plasma and radiation within them. To sustain enormous pressures the temperature in a typical star has to rise from a few thousand degrees at the surface to several million degrees at the centre. What kept the central core of a star so hot?

This question prompted Eddington to think of atomic energy. Earlier J.J. Perrin had conjectured that the fusion of four hydrogen nucler into a helium nucleus would release energy. This happens because the combined mass of four hydrogen nuclei exceeds the mass of the helium nucleus. The mass so lost would appear as energy according to Einstein's famous equation $E = Mc^2$. This was the energy that keeps the central core of the star hot and supplies the observed luminosity. So argued Eddington on the basis of his theory.

This statement was, however, challenged by the atomic physicists. The main bone of contention was : how could four positively charged nuclei surmount their mutual electrostatic repulsion and come close enough to be fused? Eddington believed that at temperatures of ten to forty million degrees in the centre, all the nuclei would be moving fast enough to facilitate collisions and subsequent fusion. The atomic physicists disagreed. In his book, **The Internal Constitution of the Star's** Eddington enclosed the following rejoinder.

"We do not argue with the critic who tells us that the stars are not hot enough for this purpose, we tell him to go and find a hotter place."

In a decade or so the controversy was settled - in Eddington's favour. Hans Bethe and von Weizsacker constructed models of the Sun in which the central source of energy was precisely as Eddington had conjectured. The models allowed one to calculate the luminosity and surface temperature of the star of any mass. And for the Sun, the answers agreed with data. That is, the Sun (whose mass is known) falls at the correct position in the H-R diagram.

As we consider different stellar models, we find that with increasing mass the stars move 'up' the Main Sequence. Thus the stars with low mass (compared to the Sun) are at the lower right end while the stars with large mass are at the upper left end. These are called respectively, the red dwarfs and blue giants.

The Giant Branch

The hydrogen to helium conversion takes a pretty long time to exhaust a star's hydrogen fuel. For the Sun the time taken will be altogether about 12 billion years of which the Sun has been in existence for 5 billion years. More massive stars exhaust their fuel sooner since the reaction in them goes much faster, while the low mass stars take longer time to burn out their fuel. Since the star's presence on the Main Sequence is related to the continuation of the nuclear fusion of hydrogen, we expect to see more red dwarfs than blue giants on the main sequence. Figure 2 bears this out.

But what happens when all the fuseable hydrogen is exhausted? The star's nuclear reactor is temporatily switched off and as a result its core finds itself unable to generate the balanceing pressure to hold off gravitational contraction. So the core shrinks.

Now it is a property of the hot plasma that compression makes it hotter. Thus the internal temperature may rise to hundred million degrees. And sooner or later it crosses the threshold that triggers off another nuclear fusion process. This next step has an interesting history which led another astronomer to provide a lead in nuclear physics.

If we wish to continue the fusion process further, we need to think of adding together hydrogen and helium or bringing two helium nuclei together. However we encounter a stumbling block either way since no stable nucleus results from such a fusion! Does the fusion process stop here? If so, how do we explain other stars like red giants?

Fred Hoyle, another Cambridge astronomer thought about the matter a good deal. If not two, can we bring **three** helium nuclei together to form carbon? Hoyle strongly believed that most chemical elements we see in the universe were made in stars. And the element carbon is an essential one to make since it also forms part of 'living' creatures. Thus Hoyle felt that Nature somehow had a way of making carbon.

Indeed physicists like E. Salpeter had considered the possibility of a triple fusion of helium to carbon. The net amount produced in a fusion process depends on the chance of the constituents coming together and

the rate at which the fusion reaction proceeds. Now normally the chance of three helium nuclei coming close to one another by chance encounters is small. So, whenever they get together, their fusion process must be very rapid. This is possible in a 'resonant' reaction when the energy of the final state almost matches the combined energy of the components. Hoyle calculated the resonant energy level for carbon which was higher than the energy of the 'normal' carbon level. Thus he predicted the existence of an 'excited' state of carbon nucleus to which the triple helium would lead. Nuclear physicists were skeptical of the whole argument until they verified by actual experiments that such an excited energy level does exist.

So it is possible to manufacture carbon in a fusion reactor with helium as the basic fuel provided high enough tempratures exist. The star, after it has stopped making helium has its core heated to such temperatures as I have mentioned earlier. The helium to carbon conversion releases more energy which increases the star's internal pressure so much that the outer envelope expands. This is how giant stars are formed. And, the process of expansion cools the envelope which now begins to look red.

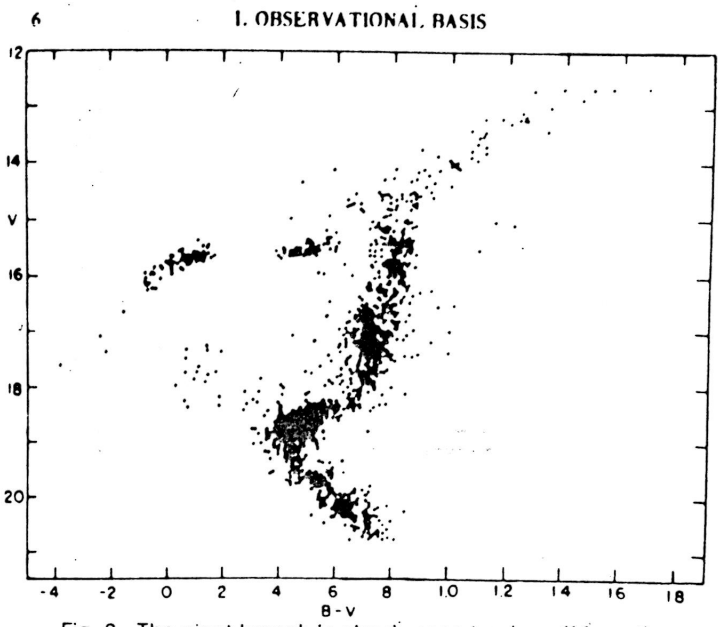


Fig. 3 - The giant branch in clearly seen turning off from the Main Sequence in this H-R diagram of the globular cluster M3.

In Figure 3 we see the H-R diagram for the globular star cluster M3 in which most massive stars have become giant stars while the less massive ones are still on the Main Sequence. The 'giant branch' seen in Fig. 3 deviating towards the left from the main sequence helps us to estimate the age of the globular cluster. For the turn off point represents stars about to become giants, i.e., stars who have just completed their hydrogen burning. Knowing the rate at which hydrogen is being burnt, we can calculate the duration of the process. Most globular clusters are thus estimated as being about 12-18 billion years old.

What happens when all the ignitable helium has been used up? The star goes through the same earlier sequence of events in which its carbon core shrinks, heats up and takes part in a further fusion process that takes it to oxygen. From here onwards, the fusion proceeds through the addition of helium each time to make up a larger nucleus. Thus we get C, O, Ne, S, ..., Si, ... Fe, Co and Ni. The last three (the iron group of elements) are the end points of the fusion process. From here on we cannot expect to form bigger nuclei by fusion. Why?

The answer lies in the circumstance that these three nuclei are the stablest and to build anything bigger we have to add rather than receive energy from the system. So far as the star is concerned its days of shining on the nuclear energy source are over.

By this time the star will have grown to enormous size. When the Sun becomes a giant it will engulf all the inner planets and also the Earth! But we need not worry about our future : the above catastrophe won't happen for at least another 6 billion years.

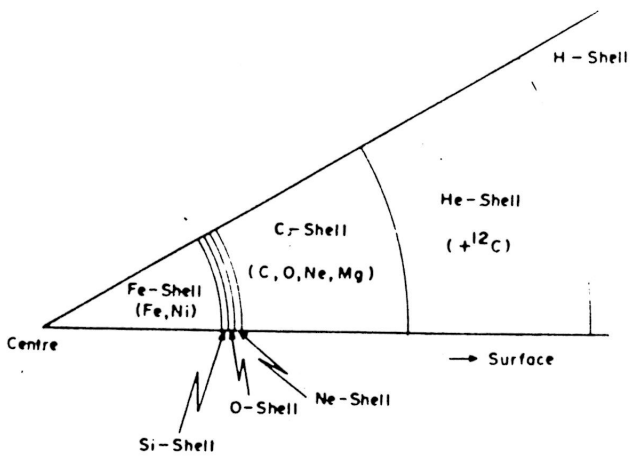


Fig. 4 - The onion skin structure of a giant star is shown in this wedge section

Figure 4 illustrates the internal structure of the star, often called the onion-skin-structure. As we go inwards we cross shells of progressively heavier nuclei

formed during the fusion process, the outermost shell being hydrogen and the innermost, the iron group.

What happens to the star next?

Star Explosions : A man entering middle age is advised to keep his weight in check - to shed some of it if he wishes to enjoy health and longevity. The star is also in need of such an advice! For, if the star is too massive in its giant stage, it explodes. Such a star is called a supernova. The supernova can be a dramatic sight. Fig. 5 shows the Crab Nebula which is the debris of a supernova that was seen to explode in the year 1054 on July 4. The reason we know the date so well is because the Chinese astrologers had kept meticulous records of it. They called it a guest star : because it brightened up during explosion and then faded away. To them the star appeared to have come, stayed for a few days and gone away like a guest.

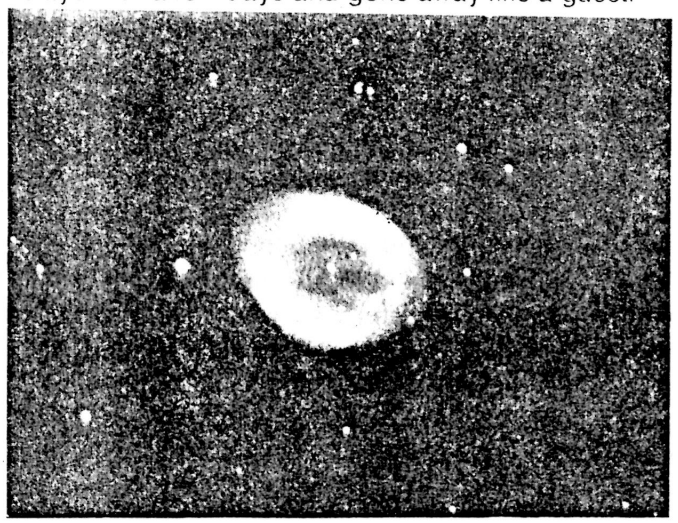


Fig. 5 - The crab Nebula. (Photograph by the Palomar Observatory)

In February 1987, astronomers were lucky to witness the explosion of the star Sanduleak into a spectacular supernova. Its aftermath is still being observed and documented. There was an unexpected bonus in this case : the particle physicists were able to observe neutrinos coming from the supernova in three of their detectors in different parts of the world. Supernova theory predicts that **just before** the star explodes, thermonuclear reactions in the core release a lot of neutrinos. For the Supernova 1987-A (as it is now called) the neutrinos were detected a few hous **before** the actual explosion of the star was observed.

The Supernova phenomenon disrupts all but the very central core of the star. What happens to the core? It usually survives as a very dense star tightly packed with neutrons, provided its mass does not exceed two solar masses. The tight packing produces a new kind of pressure called the degeneracy pressure arising from the quantum mechanical law known as Pauli's exclusion principle that limits the way neutrons can be packed in a given volume. For more massive cores, there is no effective degeneracy pressure to counteract the inward gravitational pull of the core. So it collapses till it becomes a **black hole.**

A black hole is the ultimate in gravitating objects. Its gravity is so strong that not even light escapes from it. The black hole is not seen , but its existence can be inferred from its gravitational effect on the surrounding matter. The strongest 'black hole candidate' is the unseen star in the double star system Cygnus X-1. Here the visible companion is going round and round and the unseen object is pulling in plasma from its surface. This plasma radiates X-rays as it heats up prior to falling into the black hole. The scenario is illustrated in Fig. 6.

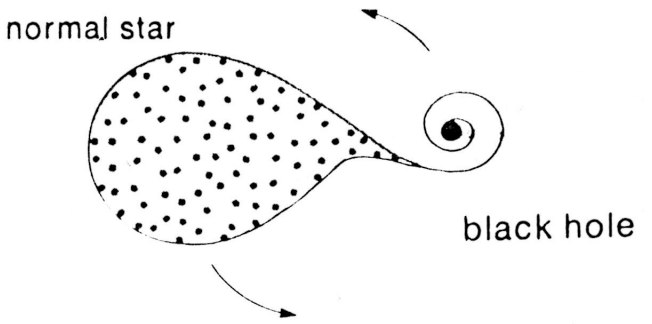


Fig.6 - The scenario involving a black hole in the binary X-ray source Cygnus X-1.

What about the low mass star that has become a red giant? The dividing line is somewhere around five solar masses. Below this mass limit the star sheds its mass by ejecting shells of gas from its envelope. These shells light up by the star's own light and are therefore called the 'planetary nebulae'. The ring nebula in Fig. 7 is an example of a planetary nebula.

Through such ejections the star may lower its mass below the magic number of 1.44 solar masses ... known as the Chandrasekhar limit (after its discovery by S. Chandrasekhar in the early 1930s). The star can then be supported against its own gravity by another kind of digeneracy pressure, this time arising from a close packing of electrons. If the mass is below the Chandrasekhar limit the star ends up as a **white dwarf.**

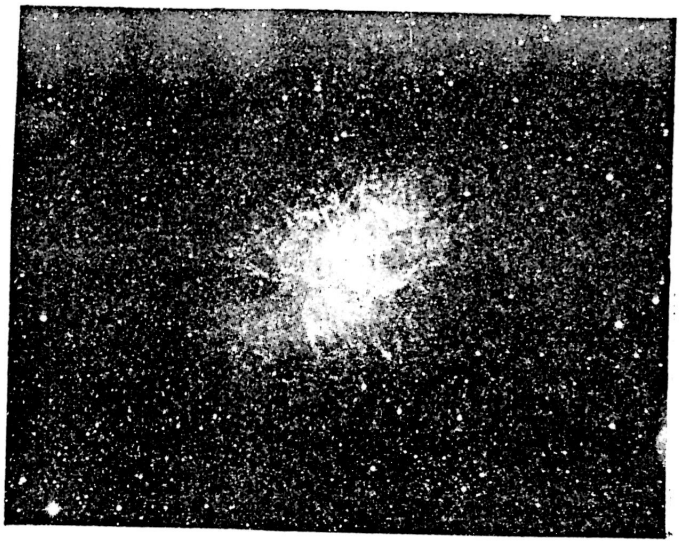


Fig.7 - The Ring Nebula - a planetary nubula formed by the lighting up by the star's light the gas shell ejected from its envelope. (Photograph by the Palomar Observatory).

Concluding Remarks

This is a brief account of the story of a star's life. I left out the beginning which I may now complete at the end. The star may have originated by the gravitational contraction of a lump of interstellar cloud of cold gas. Such clouds, called as molecular clouds because they contain several types of molecules, are seen all over the Galaxy. The Orion Nebula of Fig. 8 is one such huge cloud where star formation is taking place. A contracting cloud heats up as its density increases and initially radiates infra-red rays as found in the Orion Nebula. Once its central temperature crosses the threshold for nuclear reactions, the star 'comes of age', and radiates like the Sun.

What triggers the initial contraction of the cloud? In its initial diffuse stage the molecular cloud may not start its inward contraction, because its self gravity is too

Fig.8 - The Orion Nubula - a giant molecular clound in which star formation is going on.

weak. The belief is that the contraction is triggered off by the blast wave generated by the explosion of a nearby supernova. A push by such a wave would do the trick! The argument seems plausible and if correct would echo T. S. Eliot's famous line :

"In my end is my beginning."

Reference Text : 'From Black Clouds to Black Holes' by J.V. Narlikar, World Scientific (1984)