JOINT COMMISSION V

Late Evolution of Low Mass Stars

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INTRODUCTORY REMARKS ON LATE STAGES OF EVOLUTION OF LOW-MASS STARS

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These largely historical remarks were meant for those in the audience that had not followed the developments in recent years.

One of the great achievements of astrophysics in this century was the discovery of the source of the solar (and stellar) energy: the fusion of hydrogen into helium. It became also clear that once the conditions for hydrogen burning become unfavourable the star switches to the burning of helium: a contraction of the central region increases the temperature and pressure until the helium starts to burn into carbon and oxygen. In this way one imagines that stars during their lifetime go through successive phases of atomic fusion, with the endproduct of the previous phase as the fusion element for the one following. This succession can continue until the iron core is reached; thereafter the fusion becomes exothermic, and is no longer a viable source of energy; perhaps a supernova should follow here. As we know now (and will be discussed here), this succession is interrupted by mass loss; most stars do not develop beyond the second core, one of carbon and oxygen.

A major step forward was made by Schwarzschild and Härm (1953) when they proved that red giants consist of a very small core surrounded by a teneous envelope; the two parts contain comparable amounts of mass, and yet the density in the core is 10^8 times that in the envelope; the high central density implies that the electron gas in the core is degenerate. This result led Shklovskii (1956) to argue that planetary nebulae are blown-up examples of red giants, with the central star as the core and the nebular gas as the envelope. He also suggested that the star at the center would become a white dwarf, once the planetary nebula had disappeared by expansion. Important arguments in favour of Shklovskii's suggestion were that (i) the birth rates of planetary nebulae and white dwarfs are about the same and (ii) the red giants and the planetary nebulae have about the same distribution in the Galaxy. Against the proposition was the argument that the mass of ionized gas in the planetary nebula (say, 0.1 $M_\odot$) is significantly less than that of the envelope of red giants (say, 1 $M_\odot$).

Models of stellar interiors were strongly improved during the sixties and seventies. Some results are the following. There are two red giant branches, depending on whether the stellar core is He-degenerate (the First Giant Branch, or FGB) or C/O-degenerate (the Asymptotic Giant Branch, or AGB). Stars will increase in luminosity and thus rise along each giant branch, while the core mass grows because of the burning hydrogen just outside the core. The degenerate He-core will be produced only in stars with mass <2 Msun and only such stars will populate the FGB. The maximum mass of the He-degenerate core is 0.45 $M_\odot$, corresponding to a maximum FGB luminosity of 2000 $L_\odot$. When a star reaches this maximum, helium in the centre of the core will begin to burn into C and O, and the configuration of the star changes drastically; it becomes a Horizontal Branch or clump star. Later it will develop a degenerate C/O core and become an AGB star. The mass of the core will grow and so will the stellar luminosity; this continues (if nothing stops the growth) until the core mass reaches the Chandrasekhar limit; taking this to be 1.4 $M_\odot$ the corresponding luminosity is 50,000 $L_\odot$. Stars with a mass between 2 and 8 $M_\odot$ will have a non- degenerate He-core, not enter the FGB, but enter the AGB with a degenerate C/O core. Stars with a mass > 8 $M_\odot$ will not enter the FGB and AGB, but presumably will develop all possible cores and end up as a supernova.

In the picture just described a star on FGB will automatically be stopped in its climb if its core mass exceeds a given maximum, but a star on the AGB will not be prevented to grow a degenerate core with a mass above the Chandrasekhar limit. Thus in this picture all stars with an initial mass > 1.4 $M_\odot$ end as a supernova. But this cannot be true: in our Galaxy there are at most two to three supernovae per century, and this is less than the number of stars > 1.4 $M_\odot$ that die in a century. Thus only a small fraction of AGB stars can become a supernova: the climb along the AGB, the growth of the degenerate C/O core has to be stopped. But how? Mass loss!

Before discussing this look first at other important facts following from the modelling: (i) It is a consequence of the so-called Paczynski relation that all AGB stars will rise in luminosity on the same time scale of about 1.2 Myr. (ii) Rising along the AGB the mass of the layer of helium on the outside of the core increases constantly; ultimately the helium starts to burn into carbon in a brief, run-away process

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(thermal pulse). During this pulse the freshly produced C may be deposited into the envelope and mixed by convection with the gas in the outer envelope, thus changing the atomic composition of the whole star (the so-called "3rd dredge-up"). Here appears to lie the origin of the "carbon stars" with their excess abundance of carbon.

Let me come to mass loss now. Underlying all computer simulations was an important assumption that theory could not check from first principles: namely, that the mass of a star is constant in time, and that there is no significant loss of mass. Here observations complemented the theory.

First, a puzzling discovery was the existence of white dwarfs in the Pleiades cluster. The cluster has an age of about 80 to 100 Myr, which means that only stars of mass more than 5 $M_\odot$ have evolved away from the main sequence. If a 5 $M_\odot$ star gives rise to a white dwarf of less than 1.4 $M_\odot$, where did the rest of the matter go? How was this matter lost and why? The same puzzle was posed by the discovery by the Kiel group that most white dwarfs have a mass of about 0.6 $M_\odot$; their progenitors should be stars of about 1.0 to 1.2 $M_\odot$ -thus there must have been significant mass loss.

A clear sign of on-going mass loss at a significant rate, was the discovery by infrared astronomers that many long period variable stars have (i) a strong excess at near IR wavelengths and (ii) OH/H_2O/SiO maser emission. Thick circumstellar shells and mass loss rates up to 1 $M_\odot$ in 10,000 yr are indicated. Another sign was in the solution of the mystery that the mass of ionized gas in a planetary nebula is less than that of the envelope of the red giant: in 1978 Kwok et al. proposed that planetary nebulae are often surrounded by an invisible, but massive halo, consisting of neutral material ejected by a red giant in an earlier phase. Such a halo also explains the often sharp edge of the nebula, which is unexplicable if free expansion is assumed.

Thus observations led to the conclusion that mass loss on the AGB is significant-and hence that it affects the evolution. The time scale for mass loss -i.e. $M/(dM/dt)$- can be as small as 0.1 to 1.0 Myr, smaller than the nuclear time scale, mentioned above, of 1.2 Myr.

During the eighties the observational results have been further strengthened, much helped by the systematic all sky survey of IRAS that yielded tens of thousands of new AGB stars with strong circumstellar shells -carbon rich stars as well as oxygen rich stars. Infrared observations, measurements of molecular line emission at mm wavelengths and detailed modelling of the circumstellar shell led to much improved estimates of the mass loss rate. And very importantly, a large number of objects have been recognized that are probably stars evolved beyond the AGB phase and on their way to become planetary nebulae; also quite a number of very young planetary nebulae have been discovered.

All these results lead to a working hypothesis about the last phase of evolution of stars, and I guess that most speakers today will adhere to this scheme, or at least use it as a reference. It has to be realised, however, that the hypothesis below holds for single stars -not for those double stars where the partners influence effectively each others development. The working hypothesis advocated for this meeting is summarized in the following figure (page 3).

Finally: Although this is a meeting of IAU commision 34 (Interstellar Matter) and not a meeting of commission 33 (Galactic Structure) I draw the attention to how useful AGB stars are for studies of the inner Galaxy: their high luminosity, emitted predominantly in the infrared beyond a few micron make them traceable throughout the Galaxy. All single stars below 8 $M_\odot$ are believed to pass through this infrared phase. Although the phase lasts only very briefly, statistically enough stars are present. AGB stars are therefore practically ideal objects to study the stellar population of the inner Galaxy, a topic that not too long ago appeared to be locked away in thick clouds of dust.

REFERENCES

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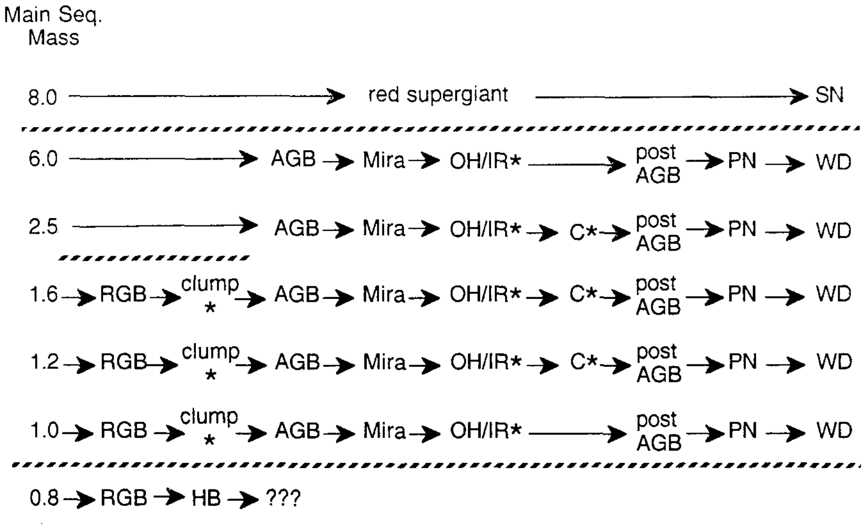
Figure

WORKING HYPOTHESIS :



Main Seq.
Mass

8.0 → red supergiant → SN

6.0 → AGB → Mira → OH/IR* → post AGB → PN → WD

2.5 → AGB → Mira → OH/IR* → C* → post AGB → PN → WD

1.6 → RGB → clump * → AGB → Mira → OH/IR* → C* → post AGB → PN → WD

1.2 → RGB → clump * → AGB → Mira → OH/IR* → C* → post AGB → PN → WD

1.0 → RGB → clump * → AGB → Mira → OH/IR* → post AGB → PN → WD

0.8 → RGB → HB → ???

RGB:	stars with a degenerate He core
Mira's:	pulsating AGB stars of high luminosity
OH/IR*:	pulsating AGB stars like Mira's, but with longer periods and obscured by dust envelope
post-AGB*:	mixed bag - in any case: no long pulsations any more