MIXING BETWEEN BURNED CORE MATERIAL AND SURFACE LAYERS

Martin Schwarzschild
Princeton University Observatory

Dr. Pagel has given us a fine summary of the observations relevant to the topic I am to cover. Drs. Michaud and Vauclair have described in detail the potential effects of diffusive processes which might well explain, at least in part, the apparent abundance anomalies observed in the peculiar A stars and the magnetic A stars. In the paper following mine, Dr. Boesgaard will present the observational evidence regarding the abundance of the light elements lithium, beryllium and boron, and relate these observations to the theory of stellar envelopes. With these important topics expertly covered I shall restrict myself to the single question: How do some reasonably common types of stars, such as the carbon stars and the S stars, manage to show off at their surfaces, for us to observe, a fair sampling of the products of the nuclear burning going on deep in their cores?

In search for the answer to this question theoreticians have naturally first investigated the classical process of direct convective mixing. Could this simple process under special circumstances act all the way from the observable surface down to the burning layers? To the best of my knowledge no model constructed under our present standard assumptions has been found with such deep direct convective mixing -in spite of extensive searches, particularly regarding the shell flash evolution phases. This generally negative result does not apply to the particular case of the carbon isotope ratio. Models have been found with convective envelopes reaching down to temperatures not high enough for the carbon cycle to provide an energy source, but high enough to transmute C^{12} to C^{13}. Such enrichment of C^{13} at the bottom of the convective envelope can show up in diluted but observationally significant degree at the surface. This special item, however, does not change the fact that as yet no model seems to have been found in which an active burning shell is connected to the observable surface by direct convective mixing.

Classical convective mixing might nevertheless bring the products of nuclear burning to the surface through a process other than that of direct convective mixing, a process we might refer to as delayed

Edith A. Müller (ed.), Highlights of Astronomy, Vol. 4, Part II, 205-208. *All Rights Reserved.*

convective mixing. Dr. Iben (1975) has recently found a very clean case of such delayed convective mixing. He has followed a medium mass star through its second red giant phase during which helium shell flash burning occurs. After every flash for a little while a convective zone stretches outwards from the helium shell and deposits some of the flash products quite a way out in the star. Subsequently, when the heat wave caused by the flash works its way outwards the inner convective zone dies, but, for just a little while, the convective envelope extends far deeper into the star than normally, indeed deep enough to just reach into the region in which some burning products had been deposited previously. This temporarily extended convective envelope will then transport some burning products to the surface. Thus in a two-phase, delayed process nuclear burning products are, in fact, brought to the photosphere. In this specific case the effectiveness of delayed convective mixing is enhanced by the fact that the shell flash occurs cyclically so that the entire process repeats over and over again. This form of delayed convective mixing does not, however, appear to work for low mass stars (such as all the stars of the disk population or of Population II) according to several independent numerical investigations. One possible exception to this last statement might be represented by F G Sagittae, which appears to be a low mass star. It ejected a planetary nebula some time ago and may more recently have suffered one more shell flash sending it on a wild, fast loop through the Hertzsprung-Russell Diagram. In such an unusual state, characterized by a minute mass in the envelope, convection may be able to transport burning products to the surface in a magnificently observable way. I am not aware, however, of any way of interpreting this peculiar sequence of events which occurs extremely late in the life of a low mass star, as in any way connected with the processes which produce the common carbon and S stars.

A second case of delayed convective mixing has been presented at an earlier meeting during this Assembly by Dr. Lamb. He found that during an advanced evolution phase of a massive star the convective envelope reaches the layers in which, at a much earlier phase, strong hydrogen burning had occurred. Thus, here again, the products of nuclear burning at an early epoch are later brought to the surface by classical convection -however diluted.

The two cases I have cited for effective delayed convective mixing refer to medium mass or high mass stars. I am not aware of any similar theoretical success in this direction for low mass stars. In contrast, the observations clearly include low mass carbon and S stars. Altogether, therefore, I feel led to the conclusion that thus far we have not found the observationally required mixing mechanism in terms of classical convection. There remains, of course, the question whether present estimates of overshooting, i.e., the extension of turbulent motions from a convective zone into an adjacent stable zone, are reasonably correct. If the estimates derived by Shaviv and Salpeter (1973) are approximately right the effects of overshooting seem to be negligible in our present context. If, however, the extent of overshooting should be larger than these estimates by an order of magnitude -a possibility emphasized by Dr. Roxburgh in our discussions- the conclusions I have just described might well be altered. As for myself, however, I must admit that I have not yet understood a physical process that might lead to the required extent of overshooting.

Obviously, convection is not the only mechanism that can transport material from the stellar interior to the surface. Permit me to add some speculative comments on three phenomena which potentially could cause other transport mechanisms: rotation, magnetic fields, and steady mass loss. Rotation causes meridional circulation. The speed of this circulation might be sufficient for our present purposes, particularly if we permit ourselves the assumption of fast rotating stellar cores. Dr. Mestel, however, has shown that the rotation-driven meridional circulation generally prefers to divide into separate circulation cells rather than transgress a region in which the mean molecular weight changes. Since nuclear burning by its nature generally occurs in regions with substantial molecular weight gradients, rotation does not seem to be too likely a candidate to solve our problem through the meridional circulation it causes. On the other hand, differential rotation will generally cause turbulent motions within stars through sheer-flow instabilities. This turbulence provides a form of macroscopic diffusion which in turn might mix material from the inside with that of the surface layers. Dr. Schatzman has described to us his recent estimates of this process under the assumption that the sheer-flow instability of the differential rotation exceeds the neutrality limit everywhere only slightly. Under this assumption he finds macroscopic diffuse mixing potentially important for the transport of lithium, beryllium and boron inwards to destructively high temperatures. He estimates, however, that this process would not likely be sufficiently effective to transport nuclear burning products from the deep interior outwards.

My only comment regarding magnetic fields is that we obviously cannot at this time exclude internal magnetic fields as the agents or catalyst by which the products of nuclear burning get transported to the surface. On the other hand, I am not aware of a concrete process by which magnetic fields could accomplish our desired aim -clearly a statement referring to lack of knowledge rather than lack of physical possibilities.

Finally, regarding steady mass loss, we have listened to a vivid description by Dr. Mihalas of the characteristics and problems of stellar atmospheres and chromospheres which are dominated by a steady outflow of mass through them. Such atmospheres are obviously a fascinating topic in themselves and highly relevant for red giants, i.e., the type of stars which most concerns us here. If I understand Dr. Mihalas' developments correctly, however, atmospheres with stationary mass flow differ from static atmospheres very basically at low optical depths but not substantially at the higher optical depth of the photosphere -at least not when the mass loss rates are no larger than those indicated by the observations. Since conditions in the photosphere provide the boundary conditions for the stellar interior we may conclude that even substantial steady mass loss, though of great potential influence on the eventual evolution of the star, is not likely to alter our interior models noticeably and thus will probably not help us in the particular problem we are considering here.

In summary then, I would feel that for stars of high and medium mass we have at least some concrete models in which the products of nuclear burning are transported out to the surface with an efficiency quite likely high enough to fulfill the observational requirements. In contrast, for low mass stars which may well include the majority of those stars showing nuclear burning products at their surfaces, we do not yet seem to have found a concrete process to explain these observations. What new observations then may plausibly help most to drive theoretical investigations in the right direction? My estimate at this time would be that an observational concentration on low mass stars with abundance anomalies likely caused by nuclear burning might be both the most practical and the most effective approach. Finally, I suspect that the most vital guidance for the theoretical resolution of this fascinating problem may come from observations devised to tell us whether the relevant abundance anomalies occur exclusively after helium ignition, i.e., during the helium core burning phase (horizontal branch) or the helium shell burning phase (the second red-giant phase or asymptopic branch), or can already occur in the hydrogen shell burning phase, i.e., during the subgiant and the first giant phases.

REFERENCES

Iben. Jr. I.: 1975, Astrophys. J. 196, 525
Shaviv, G. and Salpeter, E.E.: 1973, Astrophys. J. 184, 191