1975ApJ...197L..25S

THE ASTROPHYSICAL JOURNAL, 197:L25–L27, 1975 April 1
© 1975. The American Astronomical Society. All rights reserved. Printed in U.S.A.

# FOSSIL DUST SHELLS AROUND LUMINOUS SUPERGIANTS

RICHARD STOTHERS
Institute for Space Studies, Goddard Space Flight Center, NASA, New York
*Received 1974 December 20*

## ABSTRACT

The observed frequency with which infrared excesses appear in F, G, and K supergiants of luminosity class Ia supports the idea that these excesses arise in a "fossil" circumstellar dust shell that was formed during a prior M-supergiant phase of evolution. The required leftward evolution of the star on the H-R diagram would then imply that the Ledoux, rather than the Schwarzschild, criterion for convective mixing is the correct criterion to use in stellar evolution calculations.

*Subject headings:* circumstellar shells—convection—infrared—luminous stars—stellar evolution

## I. INTRODUCTION

The origin of the infrared excesses observed in a few luminous F, G, and K supergiants is still obscure. The simplest explanation is a cool circumstellar dust shell reradiating in the infrared the absorbed light from the supergiant (Gillett, Hyland, and Stein 1970). In two particular cases, Cameron (1971) and Stothers (1971) have proposed that the supergiant has an invisible black-hole companion which is surrounded by a thick ring of radiating dust. More recently, for three of the supergiants, Humphreys and Ney (1974*a*, *b*) have invoked a companion that is itself a very cool M-type supergiant. However, the proposed binary models are unsatisfactory in those cases where an early-type companion is already known to be present. The real answer probably involves, in most cases, the formation of a circumstellar dust shell.

It is suggested here that the dust shell originates during a prior M-supergiant phase of evolution. M supergiants are known to have strong infrared excesses and to be building up prominent circumstellar dust shells (e.g., Gehrz and Woolf 1971). As the supergiant subsequently evolves toward earlier spectral types, the rate of mass loss drops, the effective temperature of the outflowing radiation increases, and the shell is gradually dispersed. Those yellow supergiants that are evolving *toward* M supergiants would not be expected to have such "fossil" dust shells. However, any yellow supergiant might, of course, be building up a much weaker shell if it is losing some mass (cf. Sargent and Osmer 1969) and if grains can condense in such a hot environment.

## II. PREDICTIONS OF THE THEORY OF STELLAR EVOLUTION

Theoretical calculations of stellar evolution indicate that the pre–main-sequence evolution of an M supergiant into earlier spectral types may be severely distorted and disguised by the deep immersion of the star in protostellar material (Larson 1972). In any case, it is fairly certain that the observed supergiants to be discussed below are highly evolved stars (unlike, possibly, the heavily obscured $\eta$ Car objects). Therefore, after a normal main-sequence phase, a massive star will evolve into an M supergiant either once or twice. The situation for stars of 15 and 30 $M_\odot$ is illustrated in figure 1, where the different evolutionary tracks (Stothers and Chin 1975) have been constructed on the basis of two different theories of convective mixing in the unstable intermediate zone that always develops inside evolving massive stars. Notice that, in contrast to our earlier models where mixing was ignored (Stothers and Chin 1973), the present models for both masses based on the Ledoux cri-

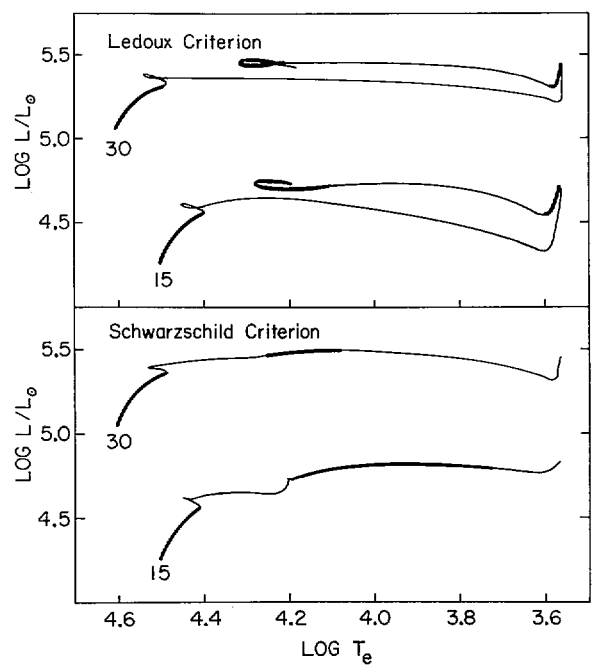


FIG. 1.—New evolutionary tracks for stars of 15 and 30 $M_\odot$ are shown in the theoretical H-R diagram. The adopted initial (hydrogen, metals) content is $(X, Z) = (0.739, 0.021)$. Two different criteria for convective mixing have been employed, as indicated on the figure. The tracks run from the beginning of core hydrogen burning to the end of core helium burning. In the case of the tracks based on the Ledoux criterion, the third crossing of the yellow-supergiant region (during the phase of core helium exhaustion) is omitted from the figure. The slow phases of nuclear burning are indicated by heavy lines.



© American Astronomical Society • Provided by the NASA Astrophysics Data System

1975ApJ...197L..25S



terion for convection leave the region of M supergiants during the phase of core helium burning, execute a "loop" toward much earlier spectral types, and then return to the region of M supergiants. On the other hand the models based on the Schwarzschild criterion for convection never reach the region of M supergiants until the *end* of core helium burning. In both cases, the later stages of stellar evolution take place only in the red-supergiant configuration (Stothers and Chin 1969).

Clearly, our suggested explanation for the infrared excesses in yellow supergiants makes sense only if the Ledoux criterion for convection is the correct criterion to use. In fact, it is possible to apply statistical data on the observed frequency of the infrared excesses in order to check this hypothesis. However, we first mention that the lowest mass at which the two criteria for convection yield different evolutionary tracks lies somewhere between 10 and 15 $M_\odot$, and therefore our attention focuses chiefly on the more massive stars.

### III. COMPARISON WITH OBSERVATIONS

According to recent surveys, 36 supergiants with spectral types F to K have been observed extensively in the infrared (Stein *et al.* 1969; Gillett *et al.* 1970; Humphreys, Strecker, and Ney 1971; Gehrz and Woolf 1971; Woolf 1973; Ney and Humphreys 1974; Humphreys and Ney 1974*a*, *b*, *c;* Hackwell and Gehrz 1974). Omitting the peculiar star R CrB, we find that only one supergiant (BM Sco) out of 12 with luminosity class Ib or Iab has an infrared excess, and this excess is probably due to matter ejected as a result of the variability of the star. However, among the supergiants with luminosity class Ia, infrared excesses occur fairly frequently, although the frequency diminishes toward earlier spectral types (cf. Hackwell and Gehrz 1974), as shown in table 1.

TABLE 1

FREQUENCY OF SUPERGIANTS OF LUMINOSITY CLASS Ia THAT SHOW STRONG INFRARED EXCESSES

| Supergiants | A | F | G | K |
|---|---|---|---|---|
| Strong excesses..... | 0 | 2 | 5 | 3 |
| Total..... | 7 | 10 | 11 | 3 |

Observationally, it is known that most yellow supergiants with luminosity classes Ib and Iab belong to a moderately young population group whose latest spectral types are normally middle K, except for a sprinkling of later spectral types that are explained theoretically by the final stages of stellar evolution. When a star of this population group "loops" out of the K-supergiant region of the H-R diagram during core helium burning, it probably possesses only a negligible circumstellar shell, since grain formation is expected to be important chiefly at spectral type M. The mass range of supergiants in this population group is roughly 4–9 $M_\odot$. A full discussion of the observational data and of the theoretical models will be presented by T. R. Carson and the author at a later date. Here we note the relevant fact that the lack of observed infrared excesses in yellow supergiants with luminosity classes Ib and Iab is in accord with our hypothesis.

The youngest population group, on the other hand, contains supergiants of luminosity class Ia, and has M supergiants in relative abundance; F, G, and K supergiants are extremely rare. The theoretical explanation for this is simply that the Hayashi line is shifted to later spectral types at higher masses. Of the yellow supergiants that show an infrared excess, only AX Sgr, W Cep, HR 5171a, and RW Cep have reasonably well-determined luminosities (Stothers 1972*a;* Humphreys *et al.* 1971). Their inferred masses are about 15, 30, 45, and 50 $M_\odot$, respectively. A high mass must also characterize the extremely long-period Cepheids that show evidence of abundant circumstellar material (Havlen 1972; Feast 1974). Since the average mass of all yellow Ia supergiants with luminosities known from association membership (Stothers 1972*a*) is $\sim$25 $M_\odot$, the dust shells are obviously not confined to the stars of extreme mass alone.

By adopting the Ledoux criterion for convection, the lifetimes theoretically predicted for massive stars in the first, second, and third yellow-supergiant phases are approximately in the ratio 1:3:2. Thus about one-half of the yellow Ia supergiants might be expected to show strong infrared excesses. This predicted frequency is in comfortable agreement with the observed ratio of 10:24 for all the yellow Ia supergiants together, or 8:14 for just the G and K types alone (the two F supergiants with infrared excesses may be peculiar in other ways [Humphreys and Ney 1974*b*]).

There is some evidence (see the observational papers listed above) that the infrared excesses occur more frequently, and are more intense, at a given spectral type when the luminosity is brighter than normal. This might be due to the more sudden shift out of the M-supergiant region for stars of higher masses, coupled with a probably cooler surface temperature and stronger mass outflow at a given spectral type. Thus a highly luminous star would be able to maintain a visible dust shell to an earlier spectral type than would a star of lower luminosity.

In a rough way, the time scale associated with the buildup of a shell must be some significant multiple of the time required for a photospheric particle to reach the inner radius of the shell. By using a shell radius of 10 stellar radii and a particle velocity of 10 km s$^{-1}$ (Gehrz and Woolf 1971), the travel time from the surface of an M supergiant to the shell is 10–100 yr. Likewise, the dissipation time would also be some sizable multiple of this value. Now the secular time scale of evolution through the region of yellow supergiants is quite rapid, being $10^4$ yr (15 $M_\odot$) or $10^3$ yr (30 $M_\odot$). It seems possible that a dust shell could survive a good fraction of this period of time.

### IV. FURTHER IMPLICATIONS

The discovered circumstantial evidence in favor of the Ledoux criterion for convection in stars is bolstered by some additional evidence, of which the following is

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1975ApJ...197L..25S



probably the most reliable: (1) the relatively brighter bolometric magnitudes of blue supergiants as compared with red supergiants in the same cluster (Stothers and Lloyd Evans 1970; Stothers 1972*b*); (2) the observed location of the "zone of occupation" for blue supergiants in the H-R diagram (Stothers and Chin 1975); and (3) the reasonable masses derived by the pulsational *Q*-value method for variable M-type supergiants in associations, on the assumption that they are in the early stages of core helium burning (Stothers and Leung 1971). On the other hand, the Ledoux criterion cannot at the present time account for the large observed blue-to-red ratio of supergiants at the highest masses, while the Schwarzschild criterion can (except at the highest masses of all). Further observational tests of the two criteria are needed, or else an improvement in the theoretical models, or, best of all, both.

## REFERENCES


Cameron, A. G. W. 1971, *Nature*, **229**, 178.
Feast, M. W. 1974, *M.N.R.A.S.*, **169**, 273.
Gehrz, R. D., and Woolf, N. J. 1971, *Ap. J.*, **165**, 285.
Gillett, F. C., Hyland, A. R., and Stein, W. A. 1970, *Ap. J.* (*Letters*), **162**, L21.
Hackwell, J. A., and Gehrz, R. D. 1974, *Ap. J.*, **194**, 49.
Havlen, R. J. 1972, *Astr. and Ap.*, **16**, 252.
Humphreys, R. M., and Ney, E. P. 1974*a*, *Ap. J.* (*Letters*), **187**, L75.
———. 1974*b*, *Ap. J.*, **190**, 339.
———. 1974*c*, *Pub. A.S.P.*, **86**, 444.
Humphreys, R. M., Strecker, D. W., and Ney, E. P. 1971, *Ap. J.* (*Letters*), **167**, L35.
Larson, R. B. 1972, *M.N.R.A.S.*, **157**, 121.
Ney, E. P., and Humphreys, R. M. 1974, *Pub. A.S.P.*, **86**, 304.
Sargent, W. L. W., and Osmer, P. S. 1969, in *Mass Loss from Stars*, ed. M. Hack (Dordrecht: Reidel), p. 57.
Stein, W. A., Gaustad, J. E., Gillett, F. C., and Knacke, R. F. 1969, *Ap. J.* (*Letters*), **155**, L3.
Stothers, R. 1971, *Nature*, **229**, 180.
———. 1972*a*, *Pub. A.S.P.*, **84**, 373.
———. 1972*b*, *Ap. J.*, **175**, 431.
Stothers, R., and Chin, C.-w. 1969, *Ap. J.*, **158**, 1039.
———. 1973, *ibid.*, **179**, 555.
———. 1975, in preparation.
Stothers, R., and Lloyd Evans, T. 1970, *Observatory*, **90**, 186.
Stothers, R., and Leung, K. C. 1971, *Astr. and Ap.*, **10**, 290.
Woolf, N. J. 1973, *Ap. J.*, **185**, 229.


RICHARD STOTHERS: Institute for Space Studies, Goddard Space Flight Center, NASA, 2880 Broadway, New York, NY 10025

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1975ApJ...197L..25S

© American Astronomical Society • Provided by the NASA Astrophysics Data System