S DORADUS TYPE; HUBBLE-SANDAGE VARIABLES

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ABSTRACT. The luminous S Dor variables or Hubble-Sandage variables have gained considerable interest during the past few years for their exceptional (if compared to normal luminous hot stars) stellar wind properties. They seem to represent a short intermezzo in the evolution of the very massive stars prior to becoming WR stars. More recent results on S Dor variables (mainly of the LMC) are briefly summarized. Since most of the data have been or are going to be published elsewhere only an outline will be presented here.

1. INTRODUCTION

S Dor variables or Hubble-Sandage variables belong to the most luminous stars ($M_{pg} \approx -7$ to -11.5) in the universe. They are characterized by irregular photometric variations of more than one magnitude on timescales of years to decades. They show a strong UV-excess ($(U-B) \lesssim -0.8$) and are redder at visually bright phases. First low dispersion spectrograms of five objects of this class in M31 and M33 were discussed by Hubble and Sandage (1953). More detailed spectroscopic studies of the LMC-S Dor variables (cf. e. g. Thackeray (1974) and literature quoted therein) have shown that their highly variable spectra are characterized by strong Balmer emission lines and pronounced forbidden lines ([Fe II], [N II] etc.) which dominate the maximum and minimum spectra, respectively.

The last review on S Dor variables or Hubble-Sandage variables has been represented during the IAU Symposium No. 67 by Sharov (1975). Since that time considerable technical advances have been made allowing to obtain spectrograms of high resolution of the brightest S Dor variables in the optical range (e. g. with CASPEC attached to the 3.6 m ESO telescope) and in the satellite UV with IUE. In

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addition infrared data in the JHKL(M)(N) passbands have been obtained for a number of these variables. Some of the more recent results on LMC-S Dor variables are nummarized in the following.

2. S DOR VARIABLES OF THE LMC

Three S Dor variables are known to be members of the LMC: the prototype S Dor, R71 (Thackeray, 1974) and R127 (Stahl et al. 1983). Since these LMC objects are only slightly reddened and comparatively close, they can be studied in more detail than S Dor variables in other galaxies. In a series of papers (Wolf et al., 1980, Wolf et al. 1981, Stahl and Wolf, 1982, Appenzeller and Wolf, 1982, Stahl et al., 1983, Stahl et al., 1985) our group has discussed detailed photometric (UBVRIJHKL) and spectroscopic (ground-based and IUE) observations of these three LMC-S Dor variables. The most important results of these investigations can be summarized in the following way: S Dor variables are hot OB supergiants which during maximum are surrounded by cool ($T_e \approx 8000 - 10\,000$ K), dense ($N_e \approx 10^{11}$ cm^{-3}), slowly expanding ($v_{exp} \approx 100 - 200$ km s^{-1}) envelopes. The mass-loss rate during maximum is of the order of 10^{-4} $M_\odot yr^{-1}$; it is by about a factor 100 lower during minimum phases. On the other hand the bolometric luminosity of the S Dor variables seems to remain almost constant. The observed brightness variations in the visual and photographic range are regarded as a consequence of the variable mass-loss rate and a correspondingly variable redistribution of the spectral flux.

A particularly detailed discussion of the envelope characteristics of the prototype S Dor has been carried out on the basis of extensive coordinated observations by our group quite recently (cf. Leitherer et al.; this volume and Leitherer et al. 1985).

From the data a model was derived according to which a hot stellar core (which can only be observed in the minimum phase) is surrounded by a cool envelope of highly variable extent and with physical conditions similar to the atmospheres of late B or early A supergiants. This "pseudo-photosphere" appears essentially static although it shows radial velocity variations of small amplitude (≈ 10 km s^{-1}) indicative of large scale pulsation-like motions. From the pseudo-photosphere the strong wind ($\dot{M} \approx 5 - 10 \cdot 10^{-5}$ $M_\odot yr^{-1}$) starts at low velocity ($v_o \approx v_{sound}$) and gets slowly accelerated approaching its terminal velocity ($v \approx 130$ km s^{-1}) only at large distances ($r > 10\ R_*$). The flat velocity law is similar to that of P Cygni (Waters, 1984). Possible mechanisms which may drive the unusual wind (compared to the wind of normal hot stars) of S Dor variables are discussed elsewhere in this volume (Appenzeller, 1986).

3. EVOLUTIONARY STATUS

During the past few years the S Dor variables have gained considerable interest in connection with current theories of the evolution of very massive ($M \gtrsim 50\ M_{\odot}$) stars with mass loss. It has been suggested (Sterken and Wolf 1978, Humphreys and Davidson 1979, Wolf et al. 1980) that the S Dor variables which are located around the upper envelope of known stellar luminosities (Fig. 1) represent a short-lived phase as immediate progenitors of the massive WR stars. Presumably during this S Dor phase of enhanced mass loss matter is rapidly removed from the surface of massive stars until the processed matter characterizing the spectra of late WN stars becomes visible.

This earlier suggestion got further support from Maeder's (1983) computation of evolutionary tracks of very massive stars including the S Dor phase. The best witness for this scenario, however, appears to be the recently discovered S Dor variable R127 of the LMC. This star had earlier been classified by Walborn (1982) as a transition Of/WN9-10 star before an S Dor-type outburst was observed by Stahl in 1982 (cf. Wolf and Stahl, 1983). For a detailed description of this key object for the understanding of the evolutionary status of S Dor variables see Stahl et al. (1983) and Stahl and Wolf (1985).

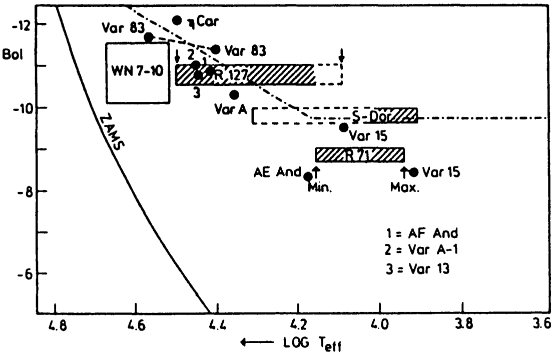

Fig. 1. Location of the LMC-S Dor variables R71, S Dor, and R127 in the HRD. Also included in the figure are the S Dor variables or Hubble-Sandage variables of M31 and M33 (Humphreys et al., 1984) and the upper envelope (dashed-dotted line) of known stellar luminosities (Humphreys and Davidson, 1979). The approximate position of the late WN-type stars is also given.

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Discussion : WOLF.

MASSEY :

If Jay Gallagher were here, he'd point out that the distribution of H-S variables in M33 doesn't match that of WR stars, i.e., they are not found where they should be if they are very massive stars. Couldn't these objects be lower mass (30 M_o) binaries? What is their distribution in the LMC?

WOLF :

There is little evidence that the S Dor phenomenon is due to binarity. Due to the position of the S Dor variables in the HRD close to the Humphreys-de Jager limit we regard the evolutionary status outlined above as more plausible. The prototype S Dor is situated in the HII region N119. R127 is close (but clearly outside) to the giant HII region 30 Dor. R71 is a problem; it is not a member of any association.

WALBORN :

The distribution of typical Hubble-Sandage variables indicates that they are somewhat older than the youngest HII complexes. On the other hand, Eta Carinae may be considered an extreme Hubble-Sandage variable, and it is located in the Carina Nebula in association with 03 and WN-A stars. It has a mass probably between 100 and 200 Mo.

KUDRITZKI :

I think, the question where the HS-variables come from and what they are at the moment can be settled by looking at the progenitors. I promise to pay a high prize in the forms of beer or champagne to anybody who can give me calibrated spectra of R127 in the pre-HS stage, when it was still an Of-star.

WOLF :

We do not have calibrated spectra of R127 at quiescence. But there are several related stars, classified by Walborn (1977), with spectra very similar to R127 at quiescence. From one of these stars (Sk-67°266) we have CASPEC spectra of high quality. However it seems to me that the spectra of these stars are too peculiar for fine analytic abundance determinations. In this respect the more moderate S Dor variable R71 seems more promising. This object was also observed by us with CASPEC during a quiet phase and shows a rather normal early B-supergiant spectrum.

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GRAHAM :

1) About how long is the period of accelerated mass loss activity in S Dor variables likely to last?

2) Is it possible that such stars are progenitors of massive WR stars which have ring nebulae around them?

WOLF :

1) The period of enhanced mass loss characterizing the S Dor-phase is supposed to be of the order of 10^3 to 10^4 years.

2) In fact it is suggested by us that the S Dor-variables are progenitors of massive WR stars. We found narrow (NII) 6548, 6583 lines (total width of zero intensity about 120 kms^{-1}) in the three LMC-S Dor variables indicative of ring nebula as observed around the galactic S Dor variable AG Car. In the case of R127 Stahl from a deep CCD image found clear evidence for extended structures presumably due to a nebulosity.

VIOTTI :

The observations seem to suggest at least two mechanisms which could be responsible for the large variability in these very luminous objects :

(1) changes in the structure of the atmosphere, like in the MC stars mentioned by B. Wolf and in AG Carinae (this galactic object is presently varying from 6 to 8^m at constant M_{Bol}), and

(2) dust formation, around stars, as in the case of Eta Car. This latter one could well be responsible for the large variability of the Hubble-Sandage variables in other galaxies, but one needs extreme IR monitoring of these faint stars to know more about these problems.

It is anyhow clear that in the theoretical HR diagram, most of these stars (maybe all) are moving right and left at constant bolometric luminosity. Since the temperature variations are short time changes, related to changes in the stellar structure, not to evolutionary effects, one should not use this parameter to describe the evolutionary stage of the Hubble-Sandage variables.

BOHANNAN :

In looking at the bright emission-line stars in the LMC, I find 9 stars that are spectroscopically similar to S Dor, 10 if you count R127. They are found in emission regions or associations at about the same frequency as other early-type supergiants. One can get a handle on the lifetime of the S Dor phase by allowing 2 to 3 times as many Wolf-Rayet stars. The S Dor-like stars I've identified in the LMC span nearly 5 magnitudes in luminosity.

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