THE PROBLEM OF SPECTRAL CLASSIFICATION OF STARS IN THE SEQUENCE S-SC-C

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ABSTRACT

The sequence of stars starting with type S and extending through the SC stars into the red carbon stars are brought into the following revised system of classification:

Type	Criteria	Type	Criteria
SX/1	TiO>>ZrO and YO.	SX/6	ZrO strong. No TiO.
SX/2	TiO> ZrO and YO.	SCX/7	ZrO weak. D-lines strong.
SX/3	TiO= ZrO,YO fairly strong.	SCX 8	No ZrO or C_2. D-lines strong.
SX/4	ZrO> TiO, YO strong.	SCX/9	C_2 weak. No ZrO. D-lines strong.
SX/5	ZrO>>TiO.		

In this table X stands for the temperature type and the number to the right of the slant line is an abundance index which, as suggested by Ake (1978), is essentially a measure of C/O. Intensities of ZrO and TiO are given also.

Between the S-type stars and the carbon stars lies the comparatively small group of SC stars which have spectra in which there are no strong bands of either the metallic oxides or C_2. Their variety has been attributed both to the delicate balance struck between their abundances of carbon and oxygen and to their rapid evolution through the shell-burning stages. Thus their importance in providing evidence of surface conditions during these crucial evolutionary phases is much greater than their numbers might suggest.

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That there is a continuous spectral sequence S-SC-C became clear from the work of Bidelman (1954), Stephenson (1965), Catchpole and Feast (1971), and Greene (1971); but satisfactory criteria and a notation defining the sequence remained to be developed. The system devised by Keenan (1954) for S stars assigned temperature classes according to a weighted sum of ZrO and TiO band strengths, and used an abundance parameter based upon the ZrO/TiO ratio. This scheme ceases to be useful, however, for any stars in which the oxides are weakened by a lack of available oxygen, and recent computations of dissociative equilibrium (Tsuji 1965; Greene, 1972; Scalo, 1974) confirm that for C≥0 practically all the oxygen is locked up in the very stable molecule CO. Accordingly, the old abundance types were abandoned in the Atlas of the Spectra of the Cooler Stars (Keenan and McNeil, 1976).

We present here a revised classification that will work throughout the sequence. The abundance parameter is essentially that introduced by Ake (1978), and from the arguments of Scalo and Ross (1976) it appears to measure primarily the ratio C/O. The scheme is shown in Table I, where the first index number is the temperature type, represented by X, and the number to the right of the slant line is the new abundance parameter. The criteria used to estimate this parameter, somewhat modified from those given by Ake, are listed in the second column. These criteria have been found rather easy to apply in practice. The rough estimates of the value of C/O, given in the third column, are probably accurate only near C/O = 1, and are meant only to be illustrative. Since we are not justified at the present time in assuming that the ratio Zr/Ti is necessarily proportional to C/O, it is suggested in the first column that the intensities of ZrO and TiO be added, especially if there are any grounds for suspicion that these absolute intensities are lower in the given star than expected for its temperature class.

The sequence in the blue at approximately the temperature of an M4 giant is illustrated in Fig. 1. The differences became more conspicuous in the visual region and at lower temperatures. For hotter stars, on the other hand, one cannot recognize all the abundance classes easily and will probably make use of only a few of them.

The assignment of temperature types is a more difficult problem. In the revised system we have tried to keep them on the same scale as those of the 1954 system for S stars, which was tied to the temperature scale of the M giants. For spectra of such different appearances, however, the criteria must be changed drastically. One obviously desirable change is to make more use

TABLE I

SEQUENCE FROM MS STARS TO CARBON STARS AT TEMPERATURE TYPE X

C/O INDEX			
TYPE	CRITERIA	ESTIMATED C/O	EXAMPLES
MXS + Zr	Strong TiO, ZrO barely visible		HD 170970
SX/1 + Ti, Zr	TiO > > ZrO and YO	<0.95	BS 8714
SX/2 + Ti, Zr	TiO > ZrO and YO	0.95:	BS 1105 HD 35155
SX/3 + Ti, Zr	TiO = ZrO, YO strong	0.96	V 635 Sco
SX/4 + Ti, Zr	ZrO > TiO, YO strong	0.96	R And
SX/5 + Ti, Zr	ZrO > > TiO	0.97	CoD -28 6970 AD Cyg
SX/6 + Zr	ZrO strong. No TiO	0.98	R Cyg R Gem
SCX/7 + Zr	ZrO weak. D-lines strong	0.99	GP Ori
SCX/8	ZrO and C_2 either absent, or both very weak. D-lines strong	1.00	VX Aql TT Cen
SCX/9 + C_2	C_2 very weak. D-lines strong	1.05	BD +38 955
SCX/10 = CX^1,2	C_2 = 2. D-lines rather strong	1.1:	WZ Cas

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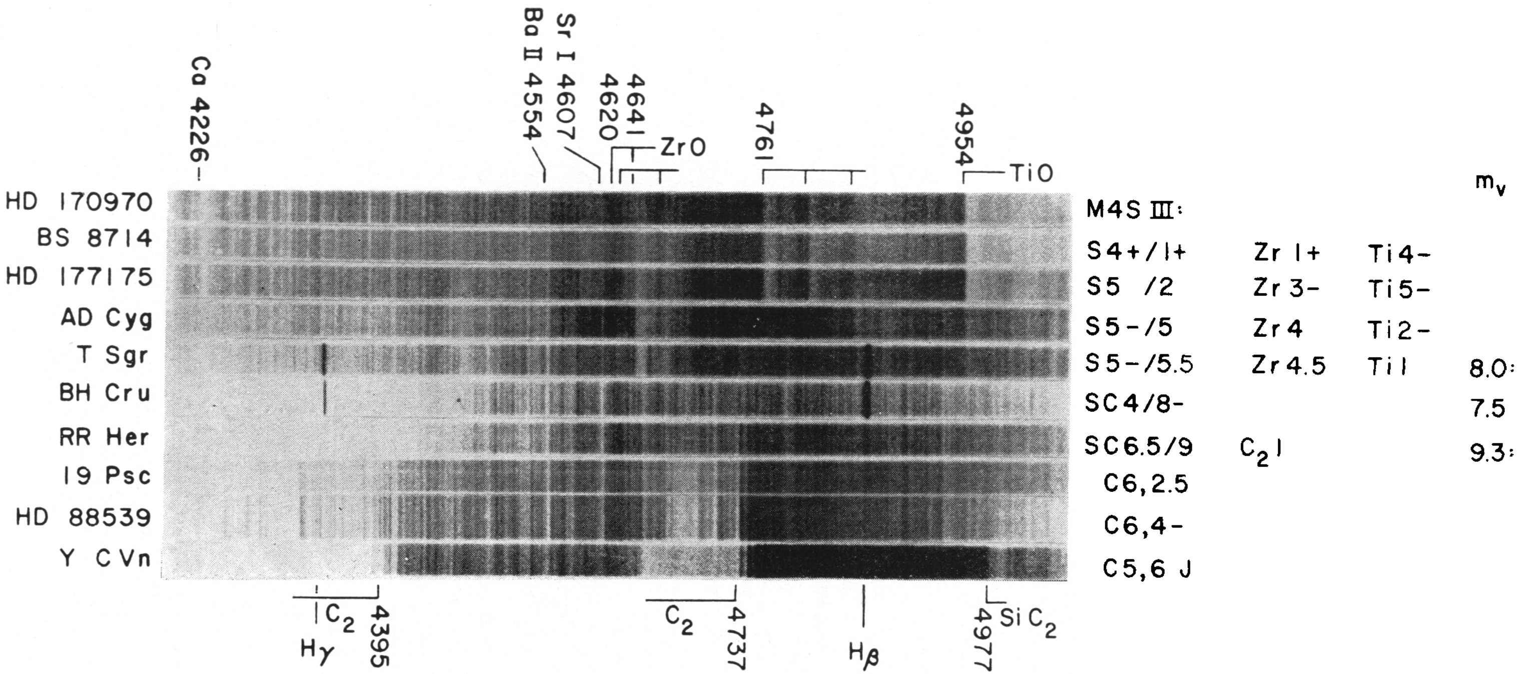

Fig. 1. C/O sequence in the blue for stars having the temperature of an M4 giant. The only prominent Zr0 bands are then 0,0 heads of the blue system, which is weaker than the red system. Note absence of bands in BH Cru.

of ratios of lines or bands to avoid the effect of composition on their absolute strengths, but we cannot afford to ignore completely the rapid increase in ZrO and TiO intensities in many S stars as the temperature is lowered.

The criteria of temperature which appear most promising at the present time are listed in Table II. Since they are scattered over a spectral range of about 2500 Å, and in certain types are obscured by other features, it is only rarely that more than two of them can be applied to any one spectrogram.

The ratio of BaII (1) 4554 to Sr I (2) 4607 is valuable because of its great sensitivity to temperature, as shown by its variation with phase in Mira variables. It should, of course, be affected by pressure differences also and it is possible that discrepancies between this ratio and the other temperature criteria will eventually prove a clue to luminosity differences, but we have not yet been able to find any convincing examples.

The ratio λ5305/λ5552 has long been known to show a sudden increase in S stars of low temperature, as can be seen in Fig. 1 of Keenan (1954), but has not been used much in classification because very few direct spectrograms have been exposed well throughout this region. Both of these bands have generally been considered to originate from the lowest level of the ZrO molecule. The R1 head of the 0,0 transition of the yellow system is at 5552 Å, but there is some doubt as to the identification of the 5305 Å band. On a spectrogram taken of R Gem at m_V = 7.2 on Feb. 24, 1953 at 20 Å/mm, a rather strong double head was measured at 5304.7 and 5306.0 Å. Dr. D.N. Davis has kindly informed us that a spectrogram of R And, taken thirteen days before maximum at magnitude 6.3, gives wavelengths of 5304.55 Å and 5305.8 Å and another apparent head of 5308.15 Å. The only stellar measurement of this band in a Mira variable near minimum light is the recent one of Wyckoff and Clegg (1978) on a plate of lower dispersion (42 Å/mm) of R Cyg. They list a single feature at 5304.3 Å. In the laboratory Lowater (1932) measured two weak heads of ZrO at 5304.63 and 5305.96 Å, the former being assigned to the 1,0 transition. In the Vatican Atlas (Gatterer, Junkes, Salpeter, 1957), however, the ZrO bands near this position are so weak that Rosen omits them from his table of wavelengths. In view of the completely different behavior with temperature of the 5305 and 5552 Å bands in S stars, it is likely that there is a contribution of some other molecule than ZrO to the 5305 Å head at the lower temperatures. The Vatican Atlas shows a weak, unclassified band of HfO at 5306.5 Å and a

TABLE II

TEMPERATURE CRITERIA IN THE S-SC-C SEQUENCE

Criterion	Useful Range
1. Total strength of ZrO and TiO bands	Type S as far as SX/7
2. Ba II 4554/Sr I 4607	On blue plates of stars in which these lines are not distorted by bands of TiO, ZrO or CN. Especially good for SC stars
3. Cr 4254, 4274, 4290/Fe lines	On blue plates of the hotter S, SC and C stars
4. ZrO +? 5303/ZrO 5552	On green plates of nearly pure S stars. Very sensitive to lower temperatures
5. Na D-lines	Type SC and some pure S stars
6. CaCl	The two red bands are strong only when the temperature is low, in SC stars, but are sometimes anomalously weak
7. λ6450/λ6456	On red plates these two blends are good indicators in SC stars, except where ^{13}CN is strong

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double 2,4 head of YO at 5306.0 Å and 5304.5 Å, but there seems no reason to expect any of these bands to become dominant features at low temperatures. This uncertainty in identification, however, need not prevent the band ratio from being useful for temperature classification.

The strength of the D-lines of sodium has generally been used as a primary criterion of temperature in the carbon stars, though observers recognize that overlying continuous absorption, mostly by molecules, can affect their appearance. Since the diminution of this absorption appears to account for the great strength of the D-lines in SC stars, we should expect them to strengthen more consistently in this group of stars as the temperature drops. Even here, however, individual spectra may show marked discrepancies. One complication is the appearance of the bands of CaCl on the carbon side of the SC group at low temperatures. Along with the 0,0 bands of the red system, which appear as a pair of absorption features centered near 6182 and 6208 Å, strong bands of the orange system are seen overlapping the D-lines (Fig. 2). On low-dispersion spectrograms these make the D-lines look much wider and stronger than the actual lines due to sodium. This would not interfer with classification if both features increased monotonically as the temperature goes down, but the CaCl bands behave somewhat erratically, at least in Mira variables, as Rybski (1973) pointed out. We make use of both the D-lines and CaCl bands, but with caution.

The final criterion listed in Table I and shown in Fig. 2 is the ratio of the two blended features whose centers lie at about 6450 Å and 6456 Å. The first of these appears to be a blend of lines of Ca 19, Co 31, V 48 and CN band lines. The contributors to 6456 Å include La 1 6454.5 and 6456.0, possibly Tc I 6455.9, Ca 19, and CN band lines. From examination of coudé spectrograms of RZ Peg we conclude that the strengthening of this blend at low temperatures is due primarily to the low-level lines of lanthanum. This feature is most useful in SC stars. In S stars it is obscured by ZrO bands. In carbon stars the CN bands tend to become dominant, and when ^{13}CN is present the peak between 6450 and 6456 Å disappears.

On Plate 31 of the Atlas of Keenan and McNeil the two blends can be seen, but are not labelled. It should be noted that at the top of that plate the feature marked as "CN 6332" is misidentified. It is actually a complex blend of Zr, Ti, Fe and La lines at about 6358 Å.

When we reach the carbon stars we find an inconsistency

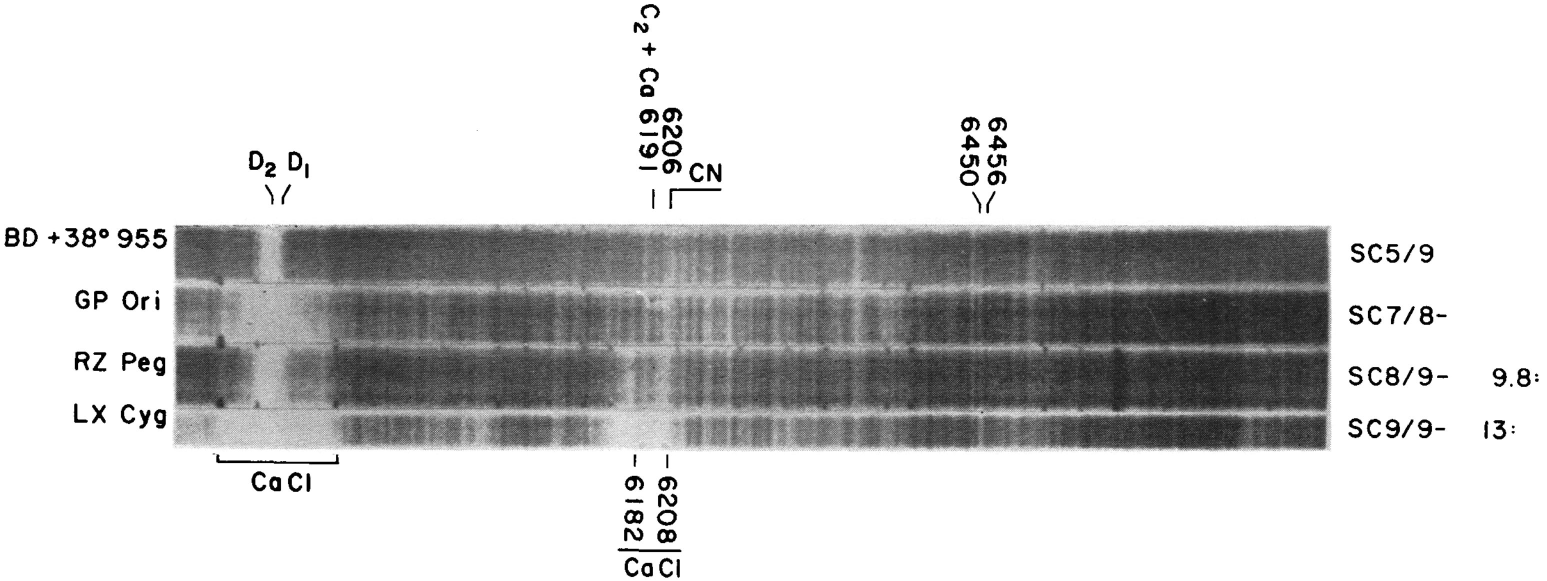

Fig. 2. Temperature sequence in the red region of SC stars. Note the ratio 6450/6456 and emergence of CaCl at lower temperatures.

in the notation for temperature types. This appears in the last line of Table I, where the equivalent carbon-star designation for the temperature type corresponding to SCX/10 is written as X^1. This is because C0 was assigned to the earliest of the red carbon stars, which have approximately the temperature of a G5 giant (Morgan, Keenan, 1941). In contrast, S0 and SC0 correspond to an M0 giant. Near C6 the two indices become nearly equivalent. The entire C classification is generally recognized now as unsatisfactory, but we continue to use it until a complete revision becomes possible - and this may well require sets of spectrograms of higher dispersion and extending over greater spectral ranges than those that have been widely available heretofore.

In summary, the revised MK classification presented here for the S-SC-C sequence provides convenient abundance classes which are primarily a measure of C/O. The notation is slightly longer than that of ordinary M stars, but this is not a serious objection to stars which are so few in number. If we wish to describe more physical variables we cannot avoid the use of more symbols. The scale of temperature types also is consistent in principle, but the types assigned to individual stars must be considered as provisional until enough spectrograms are obtained to allow better correlation of the criteria in different spectral regions. We hope to complete a catalog of the revised types for a representative selection of stars during the coming year.

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DISCUSSION

Mendoza: How do you measure the C/O ratio?

Boeshaar: Scalo (1974, Ap. J. 194, 361), and in particular, Scalo and Ross (1976, Astron. and Ap. 48, 219) have calculated synthetic band head profiles of TiO, ZrO and YO using model atmospheres with varying C/O ratio and temperature. They have shown that the behavior of these bands in going from type M and type S to types SC and C can be explained by changing the C/O ratio from about 0.95 to greater than unity.

Of course, there are also the effects of the enhancement of the S-process elements to be taken into account in explaining the appearance of the molecular bands in these stars.

Keenan: In other words, it seems plausible to call our abundance criterion a measure of the C/O ratio, but the estimates of this ratio in our table are to be considered only as convenient indicators, and should not be taken too literally.

Wing: I would like to underscore the difficulty of judging the temperatures of the S-type stars. Features that would be expected to be sensitive to temperature, such as the sodium D-lines or CaI 4226 A, turn out to be particularly sensitive to the C/O ratio. It is not always appreciated that features that do not involve oxygen or carbon directly can have a great sensitivity to the C/O ratio. This comes about because the entire structure of the atmosphere is sensitive to the C/O ratio — that is, the relations between temperature, pressure, and optical depth are different in S stars than in either M or C stars because the balance of C and O results in greatly reduced concentrations of the most important molecular opacity sources. The spectral features that seem to be most sensitive to this atmospheric structure effect are those involving neutral atoms of easily ionized elements, namely the atomic lines of NaI, CaI, and LiI, and the molecular bands of CaH and CaCl. None of these features, therefore, can safely be used as a temperature criterion.

Boeshaar: I would like to comment that we have been investigating the spectral features under consideration as temperature criteria in a preliminary manner. We still have too few spectrograms of these stars to assess the relative value of each criterion. I would also like to emphasize that we are aware of the indirect effect of the C/O ratio on these temperature criteria, e.g. the Na "D" lines, and suggest that the C/O index be determined from each spectrogram first, before attempting to assign a temperature type.

Cowley: With regard to your use of BaII to SrI as a temperature criterion, do you feel confident that the Ba/Sr abundance ratio is constant among the S stars? Do you also use this ratio for the carbon stars?

Boeshaar: At present I know of no studies which have checked the constancy of the Ba/Sr ratio in S stars. The assumption, not necessarily valid, is usually made that, since both Ba and Sr are S-process elements, they will be enhanced equally.

In the case of the carbon stars, C_2 and CN features are usually superimposed on the BaII 4554 Å and SrI 4607 Å lines.

Feast: At the South African Astronomical Observatory we have extensive 1-3.5μ photometry of S, C, and SC stars. These form a well defined sequence. What is still in doubt, both in the case of the IR photometry and perhaps the spectra, is the relative dependence of this sequence on temperature and on abundance.

Boeshaar: You are quite right, this is precisely what we are attempting to clarify spectroscopically.

Nandy: Have you detected any feature in your spectra in the wavelength range concerned which can be attributed to unidentified molecules?

Boeshaar: There are many unidentified features in the spectra of S and SC stars. In particular, see Wyckoff and Clegg (1978, Monthly Notices). The unidentified 4925 A line we see in IW Cas has been attributed by them to CaO.

In LX Cyg near minimum light there is a strong unidentified band seen near 5598 Å. The exact wavelength is uncertain since our image tube spectra are rapidly going out of focus in this spectral region. However, since no ZrO is clearly seen in this SC star, it is questionable whether this feature is due to LaO at 5600 Å.

Keenan: In further reply to Dr. Cowley's question concerning the BaII 4554/SrI 4607 ratio, we realize that the ratio should be sensitive to luminosity as well as to temperature, but its behavior in Mira variables seems to reflect temperature effects primarily. In carbon stars both features are obscured by either the green CN bands, or the C_2 bands.