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A REVISED SPECTRAL CLASSIFICATION SYSTEM IN THE RED FOR S STARS

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ABSTRACT

Low-dispersion observations of S stars in the region 5450–7000 Å have been used to establish a revised temperature classification scheme for these objects. Bands of TiO and ZrO and the Na D lines are found to be useful in placing all S type stars on a common temperature scale. Temperature subtypes for those objects exhibiting both ZrO and TiO bands are assigned by a modified version of the Keenan 1954 system. For the pure S stars, a new system is introduced utilizing the ZrO bands and the D lines. Comparisons between the revised types and photometric colors demonstrate an improvement over Keenan's system, especially for the pure S stars. Further, a new abundance index is proposed based on the relative strength of the bands of YO as compared to ZrO and TiO. It appears that this index is fundamentally related to the C/O ratio, though it may also be affected somewhat by the general enhancement of *s*-process elements.

Subject headings: stars: abundances — stars: late type — stars: spectral classification — stars: S-type

I. INTRODUCTION

Of the red-giant stars, the S stars are distinguished by the presence at low dispersion of ZrO bands in the blue, visual, and red spectral regions. Because some members of the class exhibit TiO bands while others do not, as a group they are thought to be chemically intermediate between the M giants and the C stars. The sequence M–MS–S–SC–C is thought to be one of increasing carbon-to-oxygen ratio as well as *s*-process element abundance due to internal processing during post–main-sequence evolution.

The classification system devised by Keenan (1954) is still in general use for these rare objects. The temperature class is based upon a weighted sum of eye estimates of TiO and ZrO band strengths, while the "abundance" parameter essentially measures the ratio of ZrO to TiO band intensities. The system was intended to be similar to the two-dimensional Keenan and Morgan (1941) C system for carbon stars in that both temperature and abundance types were to be assigned from the spectra. For carbon stars, the temperature class is based upon the atomic-line spectrum and color gradient, while the abundance parameter is merely the apparent strength of the C_2 bands. But unlike the C system, the S system uses no atomic-line criteria. Temperature and abundance types are both assigned from molecular band strengths alone.

The Keenan system has suffered from two drawbacks. First, although effective in describing the overall appearance of an S spectrum, the abundance parameter has not been successful as an indicator of any one chemical peculiarity. The ZrO/TiO ratio has long been recognized to be affected by both the C/O ratio (Bidelman 1950 and references therein) and the Zr/Ti ratio itself (Merrill 1956). Recently Keenan and McNeil (1976) have revised the S type notation by eliminating the abundance parameter as originally defined by Keenan. Instead, the strengths of the ZrO and TiO bands are listed separately along with the temperature classification. This change not only makes the S system more like the C system, but also allows for temperature assignments to be based independently on other criteria while retaining the observed intensities of ZrO and TiO to indicate abundance variations.

The second problem is that the temperature types assigned to the pure S stars are too early for temperatures measured by other means. When TiO is absent, the classification is based solely on ZrO; and since these bands do not increase as rapidly with decreasing temperature as those of TiO, the pure S stars are classified too early. The Keenan system should not be used for the SC stars, where the ZrO bands are never strong.

Since the molecular bands are so sensitive to abundance differences, a system based on atomic-line criteria should give more satisfactory classifications than one based on band strengths alone. On the plates taken for this study, the atomic-line spectrum in the red for a TiO-strong S star is quite difficult to observe because of the extensive overlapping of the TiO bands. These stars, however, have not undergone as radical a chemical change as the pure S type stars; thus the Keenan system should provide accurate types. For the pure S stars, atomic-line criteria are available, but here only the D lines of sodium are resolved. Although much controversy surrounds the use of the D lines as a temperature criterion (§ III), they were found to be a useful classification parameter for most high-abundance S types. Finally, the behavior of the YO bands (Keenan 1966*a*) in the S stars suggests that their intensities should also be considered, along with those

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of the ZrO and TiO bands, in a classification scheme for these objects.

II. OBSERVATIONAL MATERIAL

Image-tube slit spectrograms spanning the region 5450–7000 Å were taken with the Meinel spectrograph attached to the Warner and Swasey Observatory 91 cm telescope. The dispersion used was 105 Å mm^{-1}, with a resolution estimated to be 5 Å, and the spectra were widened by 0.6 mm. Keenan's (1954) list of stars was the primary source for candidate objects, but the program was supplemented by Stephenson's (1976) General Catalogue of S Stars. The plates were visually examined, and eye estimates of line and band strengths were assigned on systems established separately for ZrO, TiO, YO, and the D lines. The technique suggested by Merrill, Deutsch, and Keenan (1962) of estimating temperatures by comparing bands arising from different vibrational levels for a particular molecule was not feasible at this dispersion. The TiO strengths are based on comparisons with M-giant spectra; the ZrO intensities, on Keenan's (1954) system for the S stars.

Representative spectra are illustrated in Figure 1 (Plate 6). Like the M giants, the TiO-strong S stars generally show few atomic lines in this region. Even the D lines are weak, and for the cooler objects TiO λ5847 completely masks them. Not only are the lines overlain by the bands, but even in the regions apparently free from strong bands no atomic lines appear. AA Cyg is atypical since TiO usually obliterates the D lines.

The pure S stars, however, display atomic-line spectra that approach the richness found in the carbon stars, although at this dispersion they are not distinct. A blended feature due to Zr I λ6134, Ba II λ6141, and Zr I λ6143 mimics the YO λ6132 band, but the λ5972 band can be used to estimate the YO strength since no atomic lines are visible at this position in the cool SC and C stars. The D lines are prominent because of the absence of TiO λ5847, although ZrO λ5849 can weaken them when ZrO is exceptionally strong. The structure of ZrO λ5849 differs from TiO in that the absorption is composed of a series of more rectangular components like other ZrO bands, as opposed to the broader, overlapping bands of TiO. In the M and S stars, no lines except the D lines were found to be useful at this dispersion as classification criteria.

III. OBSERVED FEATURES

a) ZrO *Bands*

Bands of ZrO arising from four different systems are photographed on these plates: the β and γ triplet systems, and the newly assigned $^1\Sigma^+–X\,^1\Sigma^+$ and $^1\Pi–X\,^1\Sigma^+$ systems (Phillips and Davis 1976*a*, *b*). Table 1 lists the characteristic bandheads and the relative intensities as given by Pearse and Gaydon (1963). Keenan used the β system in the visual to assign ZrO intensities, but the red γ system is stronger and a more reliable indicator of ZrO on the image-tube plates. The usefulness of the $^1\Sigma^+–^1\Sigma^+$ and $^1\Pi–^1\Sigma^+$ systems is limited by TiO λλ5847, 6159, which also precludes the use of the D lines for classifying the TiO-strong stars.

The primary criteria for the ZrO strengths are the γ system R_1 and R_2 branches of the $\Delta v = 0$ sequence while the β system supplements the classification. Keenan's system of absolute band strengths is used except for an adjustment of the lower end of the scale. In his system the MS stars have a ZrO strength less than or equal to 1. The S stars are defined as having a strength of at least 1.5. Because of the poor resolution of the image tube, the finer shades of ZrO intensity that Keenan was able to see cannot be distinguished. The weakest bands for the image-tube plates were assigned a value of 1 and included Keenan strengths of 1 and 1.5. The material does not justify a correction to the Keenan scale, and the error translated to the spectral type amounts to less than half of a subclass, which is smaller than the error of estimation. The scatter between ZrO observations here and by Keenan was found to be about one-half a type.

b) TiO *Bands*

Assignment of TiO intensities is based on the criteria used for the M giants in the red (Table 2). For the M0 to M4 giants, the appearance and strength of various bands are used for classifying the stars; but because of the presence of ZrO and night-sky Hg I

TABLE 1

OBSERVED ZrO BAND HEADS

λ	Intensity[a]	Assignment[b]
6542.8	5	γ (2, 2) R_1
6508.0	9	γ (1, 1) R_1
6473.7	10	γ (0, 0) R_1
6412.3	6	γ (2, 2) R_2
6378.4	8	γ (1, 1) R_2
6344.9	9	γ (0, 0) R_2
6292.8	7	γ (2, 2) R_3
6261.0	8	γ (1, 1) R_3
6229.4	9	γ (0, 0) R_3
6154.3	...	$\Pi–\Sigma$ (1, 0)
6021.3[c]	3	γ (1, 0) R_2
5977.7[d]	3	γ (3, 2) R_3
5926.4	...	$\Sigma–\Sigma$ (2, 2)
5892.8[e]	...	$\Sigma–\Sigma$ (1, 1)
5849.4[f]	...	$\Pi–\Sigma$ (2, 0)
5748.1	8	β (1, 1) R_3
5718.1	10	β (0, 0) R_3
5658.1	5	β (1, 1) R_2
5629.0	6	β (0, 0) R_2
~5577[g]	...	β (1, 1) R_1?
5551.7	5	β (0, 0) R_1

[a] Intensities from Pearse and Gaydon 1963.

[b] γ system assignments by Phillips and Davis 1979.

[c] Seen only when ZrO is strong.

[d] Near to, but separated from, YO λ5972.

[e] Blended with Na D and $\Pi–\Sigma$ (3, 1) λ5893.3.

[f] Blended with $\Sigma–\Sigma$ (0, 0) λ5859.3.

[g] Wavelength from low-dispersion plates; assignment is expected value.

TABLE 2

CLASSIFICATION CRITERIA FOR M GIANTS

TYPE	BAND DESCRIPTION[a] Keenan	Ake	CONTAMINANTS
M0..........	λ6159 clearly seen; λ5448 present	Appearance of λ6159, λ5448	ZrO λ6154, N.S. λ5461
M1..........	λ5448 clearly seen	λ6159 forms break; λ5847 faintly seen	ZrO λ5850, N.S. λ6130
M2..........	λλ5448, 6159 stronger	λλ5448, 6159 strengthen; λ5847 distinct; λ6651 faintly visible	
M3..........	λλ5597, 5847 present	λ5847 stronger; λ6651 strengthening; λ5810 present	
M4..........	λλ5759, 5810 distinct	λ5847 forms break; λ5810 strengthens	
M5..........	VO λ5736 present	All bands strengthen	VO is not seen in S stars
M6..........	VO λ5736 slightly weaker than λ5759	All bands strengthen	
M7..........	λ5736 = λ5759; λλ5591, 5615 farily strong	All bands strengthen	
M8..........	λ5736 > λ5759; λ5591 comparable with λ5597	All bands strengthen	

[a] All bands are due to TiO unless otherwise indicated.

emission, TiO intensities for the S stars were difficult to judge. The strongest TiO bands in this region, λλ5448, 5847, 6159, are contaminated by Hg I λ5461 and ZrO λλ5849, 6154. The weaker TiO band λ5810 and the sequence λλ6651, 6681, 6714 were relied upon more heavily than they would be for the M giants. Furthermore, VO λ5736 is used as a criterion beginning at M5, but for the S stars VO is undependable since it is even more sensitive to the free-oxygen supply than is TiO. Therefore the latest types are classified merely by the increasing absolute strength of TiO, a process which no doubt leads to larger errors than for earlier classes. Comparing TiO measures by Keenan with those here indicates that errors of as much as 1.5 classes are possible.

When summing ZrO and TiO for determining spectral types, Keenan used the M-type + 1 for TiO because an M0 star already exhibits appreciable TiO, and hence should be assigned a TiO strength of 1. For the revised classification scheme used here, however, TiO intensities for the S stars are equal to the M subdivision instead of being one more than the type. The rationale behind this change originates from an attempt to eliminate the effect of ZrO's higher dissociation energy on the temperature assignment. When proceeding from the K to the M stars, ZrO should appear before TiO, and since the intensities are proportionally added together, adding 1 to the M type exaggerates the coolness of the star. An S1 type would be assigned to a star when TiO is absent, D = 1, but ZrO appears with strength less than 1. In this system, M0 and S1 stars would have the same temperature.

c) YO *Bands*

The strongest observable bands in the red are λ5972 and λ6132. The band at λ6132 is the feature Keenan (1966*b*) prefers to estimate, but nearby atomic lines easily imitate the bands on the image-tube spectrograms when YO is weak. The band at λ5972 is well separated from ZrO λ5977 and otherwise falls in a relatively uncontaminated region. It is the band we have chosen to measure, although λ6132 is used as a supplement if the contribution of other lines is judged to be small.

d) *Sodium* D *Lines*

For the pure S stars the D lines appear in strength comparable to those of the carbon stars. The λ5849 ZrO band, when exceptionally strong, does weaken the feature, but not to the extent of the stronger λ5847 TiO band. When present, the D lines in nearly all S stars are equivalent to carbon types C5–C7, which is not surprising since the temperature of a C5 star corresponds to that of an early M giant. Only one star, SU Mon, has outstandingly strong D lines. Several others have D lines approaching the strength of those of SU Mon, but unlike this star their entire spectra indicate low temperatures.

For the carbon stars, the suitability of the D lines as a temperature parameter has been questioned on two accounts: photometric temperatures do not correspond exactly to C subtypes, and the weak-banded C8 and C9 stars are hotter than the D lines indicate. Photometric temperatures for the carbon stars are nearly independent of the C type (Richer 1971), but Yamashita (1975) and Peery (1975) suggest the discrepancy may lie with interstellar reddening. Moreover, because of stratification effects, photometric temperatures may not be appropriate for the line-forming regions where the absorption spectrum originates. Honeycutt, Faÿ, and Warren (1974) find that their [0.57 μm] − [0.68 μm] colors correlate well with Yamashita types except for the stars with large color excesses. They suggest that these stars have developed dust shells indicating that the surface boundary temperatures may be lower than for normal C stars.

Gordon (1967) and Yamashita (1972) have found that D strengths for C5 to C7 stars are consistent with spectral types assigned from atomic-line ratios in the blue, but Gordon notes that classes C8 and C9 appear more like C5 stars. Since these "D-line" stars are also weak-banded, lowered opacity has been suggested as the reason for the enhanced Na D. Scalo's (1973) calculations demonstrate that if the weak-banded stars are interpreted as having C/O just slightly greater than 1, then at a certain optical depth one can see deeper in the atmosphere than for normal carbon stars. Since sodium is mostly ionized and we are seeing into a region with higher electron pressure, Na appears to be under-ionized compared to other carbon stars.

Since most S-star D lines are comparable to the middle C types rather than Gordon's D-line stars, we expect them to give types consistent with other atomic-line criteria. Undoubtedly when C/O is nearly unity, atmospheric transparency enhances the strong lines of the neutral species of easily ionized metals because of pressure broadening and changes in the ionization equilibrium in the line-forming regions. But the observations indicate that while the stars with $D \geq 5$ do not have bands as strong as they should, they are not especially weak-banded like the D-line stars. Although the use of the D lines as a temperature criterion seems to be a step backward due to their sensitivity to C/O, we note that both TiO and ZrO are also C/O dependent, and this is why weighted sums are used for the classification. The D lines cannot be used by themselves as in the carbon stars; but by considering ZrO, the temperature assignment remains stable as C/O approaches 1. In fact, as shown by Piccirillo's photometry (§ V), the D lines of the pure S stars increase in strength with decreasing temperature even when affected by ZrO λ5849; from observations of long-period variables over their light cycles, the D lines are well behaved and increase in strength with decreasing light.

We conclude that while C/O differences influence the intensity of the D lines, they are still useful as a temperature criterion except for the extremely strong D-line S and SC stars and the stars of latest C types. These stars will require further study along with objects such as AA Cyg and BI And which show strong ZrO, YO, and TiO, and hence are not free-oxygen deficient, and yet also have moderately strong Na D. Even SU Mon exhibits TiO weakly.

IV. THE CLASSIFICATION

For the stars with TiO, Keenan's method of computing the temperature type is retained. It provides a smooth transition from the M giants to the S stars. Because Keenan added 1 to his TiO intensities, the location of the zero point of the revised system lies one or one-half class earlier than his. For these stars then: S type = the stronger of TiO and ZrO + one-half the weaker of these. In the same vein the temperature classes of the pure S stars are given as: S type = the stronger of ZrO and Na D + one-half the weaker of these.

To indicate abundance differences, Keenan and McNeil (1976) have proposed that the ZrO and TiO intensities also be listed separately in the classification. Although we used TiO equivalent to M type for temperature assignment, the abundance parameter for TiO should remain as TiO + 1. While this notation may lead to some confusion, it is preferable to show that TiO is first observed by "Ti 1" than "Ti 0" and that ZrO and TiO are of comparable strength when the abundance indices are equal. Since the ideal system would use different temperature and abundance criteria anyway, the use of TiO intensities in two ways is not unreasonable.

The results of the S star observations are given in Table 3. This table gives the actual estimated intensities for TiO, YO, ZrO, and Na D as well as the final full spectral types. The transition from TiO-strong to pure S types was so smooth that some objects could be classified by both sets of temperature criteria. When assigning types for stars that show both TiO and the D lines, usually the stronger of the two was summed with ZrO.

The assigned "abundance indices" are defined in the following section.

V. DISCUSSION

a) Comparisons with Photometric Colors

Recently Piccirillo (1977) has measured color temperatures for Keenan's stars by means of a modified version of the Wing (1971) eight-color, narrow-band system, which samples a region extending from 6500 to 11,000 Å. The color temperatures were determined by fitting a blackbody curve through the continuum points so that the observations are not affected as much by molecular bands as is broad-band photometry. For the coolest stars, however, the bands overlap to such an extent that the shortward continuum point is depressed and the star appears much cooler than it really is (Wing 1972). Because of this Piccirillo has noted that his temperatures below 2500 K are probably too low. In fact, all temperatures may be somewhat too low since the observations have not been corrected for interstellar reddening.

From a comparison with Piccirillo's photometry, the present revised classification scheme appears to be a substantial improvement, as hoped, over the older system. The relevant data, omitting Mira variables, are plotted in Figure 2. Keenan's types for the more extreme S stars are too early for their color temperatures, but the new system has brought them into line with the other stars. Moreover, the scatter has been reduced for the TiO-strong stars by classifying them 0.5 to 1 class earlier than Keenan. The two most discrepant stars are SU Mon and +24°620. SU Mon has apparently been classified too late because of its strong D lines, while +24°620 may perhaps be subject to significant interstellar reddening.

TABLE 3

OBSERVATIONS OF S STARS

Star	R.A. (1900)	Date (day-mo-yr)	Var	Mag	Phase	TiO[a]	YO	ZrO	Na D	Spectral Type	Abund. Index	Notes
X And.	00h10m9	10-24-75	M	8.8	−25	X	1	4	3	S5.5e Zr 4	5	
		11-14-76		8.8	+17	X	1	4	3	S5.5e Zr 4	5	
R And.	00 18.8	9-29-75	M	6.6	−24	X	3	6	4	S8e Zr 6	4	1
		11-14-76		8.7	−32	[b]	2.5	5	4.5	S7.5e Zr 5	4	
U Cas.	00 40.8	1-08-75	M	8.5	+17	1	1.5	2	0.5	S2.5e Zr 2 Ti 2	3	
		9-29-75		9.1	−5	4:	4	5	[b]	S7 Zr 5 Ti 5:	3	2
		8-21-76		10.6	+49	3	2.5	3	[b]	S4.5e Zr 3 Ti 4	3	
RR And.	00 46.0	10-24-75	M	9.4	−34	5	2	3	[b]	S6.5e Zr 3 Ti 6	2	
S Cas.	01 12.3	8-25-75	M	10.5	+42	2::	1	4	7::	S5e:: Zr 4 Ti 3::	4	
RZ Per.	01 23.6	8-28-75	M	9.7	+3	X	0.5	2	3	S4.5e Zr 2	5	3
		9-28-75		9.9	+33	X	1	3	4	S5.5e Zr 3	5	
V401 Per.	01 55.7	10-23-75	. . .	. . .	. . .	4	0	2	[b]	S5 Zr 2 Ti 5	1	
SU Tri.	02 12.3	10-23-75	L*b*?	. . .	. . .	4	0	2	[b]	S5 Zr 2 Ti 5	1	
BI And.	02 19.8	9-29-75	SR	. . .	. . .	3	4	6	4	S7.5 Zr 6 Ti 4	3	
BD Cam.	03 33.5	9-29-75	. . .	. . .	. . .	2	0.5	2.5	1	S3.5 Zr 2.5 Ti 3	2	
WX Cam.	03 41.5	11-12-75	L*b*	. . .	. . .	1::	3:	4	4	S6 Zr 4 Ti 2::	3:	
+24°620.	03 59.6	11-11-75	. . .	. . .	. . .	2	0	2	1	S3 Zr 2 Ti 3	2	
T Cam.	04 30.4	9-29-75	M	8.3	−16	1:	3	6	2.5	S7.5e Zr 6 Ti 2:	4	
		11-15-76		8.3	+5	1:	3	6	2.5	S7.5e Zr 6 Ti2:	4	
+79°156.	04 38.4	11-11-75	. . .	. . .	. . .	3	0.5	1	1	S3.5 Zr 1 Ti 4	1	
TV Aur.	04 50.6	9-29-75	SR*b*	. . .	. . .	1:	3	5	5	S7.5 Zr 5 Ti 2:	4	4
GP Ori.	04 57.1	11-14-75	SR?	. . .	. . .	X	0	0.5	8	SC8 Zr 0.5	6	
RZ Lep.	05 14.5	10-24-75	SR*b*	. . .	. . .	2	0.5	3	1	S4 Zr 3 Ti 3	2	
HD 35155.	05 17.6	10-23-75	. . .	. . .	. . .	2	0	1	0.5	S2.5 Zr 1 Ti 3	2	
DY Tau.	05 36.1	3-20-77	L*b*	. . .	. . .	6:	0	0	[b]	M6:	[b]	
+5°1000.	05 37.8	3-20-77	. . .	. . .	. . .	1:	0	1	2	S1.5: Zr 1 Ti 2:	2	
BB Tau.	05 46.1	3-20-77	L*b*	. . .	. . .	X	2	2	3	S4 Zr 2	4:	
FU Mon.	06 17.2	4-11-75	SR	. . .	. . .	X	0	0.5	5.5	SC5.5 Zr 0.5	6	
V613 Mon.	06 43.0	2-03-75	SR*b*?	. . .	. . .	2	0	1.5	1	S3 Zr 1.5 Ti 3	2	
R Lyn.	06 53.0	4-11-75	M	8.3	+1	X	2	4	2.5	S5.5e Zr 4	4	
R Gem.	07 01.3	10-23-75	M	9.9	+112	X	2	5	5.5	S8e Zr 5	5	
−8°1900.	07 20.2	3-20-77	. . .	. . .	. . .	X	1	3	2.5	S4.5 Zr 3	5	
FX CMa.	07 22.4	1-06-75	SR*b*	. . .	. . .	X	1	3	3	S4.5 Zr 3	5	
SU Mon.	07 37.5	1-06-75	SR*b*	. . .	. . .	X	1.5	3	6.5	S8 Zr 3	4	5
T Gem.	07 43.4	1-06-75	M	8.9	−4	1:	2.5	5	1.5:	S5.5e: Zr 5 Ti 2:	4	
		10-24-75		9.0	+11	1.5	1	3	1	S4e Zr 3Ti 1.5	4	
NQ Pup.	07 48.3	11-16-76	L*b*	. . .	. . .	3	0.5	2	0.5	S4 Zr 2 Ti 4	2	
V Cnc.	08 16.0	1-06-75	M	8.2	+20	X	1.5	4	2.5	S5.5e Zr 4	5	6
		2-03-75		9.1	+48	X	1.5	4	2.5	S5.5e Zr 4	5	
+6°2063.	08 50.3	2-16-76	. . .	. . .	. . .	3	0	0.5	1	M3S	1	
RS Cnc.	09 04.4	4-08-75	SR*c*?	. . .	. . .	6	0.5	0.5	[b]	M6S	1	
S UMa.	12 39.6	5-07-75	M	10.5	−77	X	2	5.5	4.5	S8 Zr 5.5	5	
		5-17-75		10.0	−67	X	2	5.5	4	S7.5 Zr 5.5	5	
		6-10-75		8.9	−44	X	2:	5	4	S7e Zr 5	5	
		6-17-75		8.8	−37	X	3	5	4	S7e Zr 5	4:	
		6-27-75		8.5	−27	X	3	4:	4:	S6e Zr 4:	4:	
		7-30-75		8.1	+6	X	1	3	2	S4e Zr 3	5	
		8-17-75		8.4	+24	X	2	5.5	3	S7e Zr 5.5	5	
		8-29-75		8.8	+36	X	1.5	5	3	S6.5e Zr 5	5	
		4-09-76		8.7	+33	X	1.5	4	2	S5e Zr 4	5	
AV CVn.	13 16.9	4-11-75	L	. . .	. . .	X	0.5	2	1	S2.5 Zr 2	5	

TABLE 3—*Continued*

Star	R.A. (1900)	Date (day-mo-yr)	Var	Mag	Phase	TiO[a]	YO	ZrO	Na D	Spectral Type	Abund. Index	Notes
HD 121447........	13 50.3	4-11-75	...	...	...	X	0	0.3	2	SC2 Zr 0.3	[b]	7
R Cam............	14 25.1	5-17-75	M	8.8	−61	6	3.5	4	[b]	S8 Zr 4 Ti 7	2.5	
		6-27-75		9.0	−21	3	3.5	5	[b]	S6.5e Zr 5 Ti 4	3	
		6-29-75		9.0	−19	3::	3.5	5	[b]	S6.5e Zr 5 Ti 4::	3	
		4-24-76		8.2	+10	3	2	4	[b]	S5.5e Zr 4 Ti 4	3	
ST Her...........	15 47.8	3-24-75	SR*b*	...	...	7	1.5	0.5	[b]	M7S	1	
HD 155819........	17 08.8	6-29-75	...	...	...	2	0.5	0.5	1.5	M2S	1	8
FT Ser...........	17 16.0	7-30-75	...	...	...	1:	2:	4	4	S6: Zr 4 Ti 2:	4	
V812 Oph.........	17 36.7	8-24-76	SR*b*	...	...	5:	1:	3.5:	[b]	S7:: Zr 3.5: Ti 6:	1	
Ste 540..........	17 55.4	8-28-75	...	...	...	2	0	0.5	1	M2S	1	
V679 Oph.........	18 37.1	6-29-75	L*b*	...	...	0.5	2.5	4	2.5	S5.5 Zr 4 Ti 1.5	4	
SV Sct...........	18 48.0	8-07-75	M	...	...	X	0	0.5	3	SC3 Zr 0.5	6	9
Ste 584..........	18 53.5	7-31-75	...	...	...	[b]	0	0	2	[b]	[b]	10
V915 Aql.........	18 58.5	6-10-75	L*b*	...	...	4	0	2	[b]	S5 Zr 2 Ti 5	1	
T Sgr............	19 10.5	7-30-75	M	10.5	+83	[b]	2	5	3	S6.5e Zr 5	4	11
EP Vul...........	19 29.1	8-20-76	L*b*	...	...	1:	3	5	3	S6.5 Zr 5 Ti 2:	4	12
R Cyg............	19 34.1	7-14-76	M	10.5	+71	2:	4	7	7::	S8e Zr 7 Ti 3:	4	
Vys 12...........	19 37.2	10-14-76	...	...	...	X	1.5	4	3	S5.5 Zr 4	4.5	
χ Cyg............	19 46.7	6-21-75	M	5.4	+29	8	3.5	3	[b]	S9.5e Zr 3 Ti 9	1	
CM Cyg...........	19 55.9	6-30-75	M	10.5	+3:	X	0.5	1	3.5	S4e Zr 1	5	13
		11-14-76		10:	+0:	X	0	0.5	2	SC2 Zr 0.5	6	
AA Cyg...........	20 00.8	7-31-75	SR*b*	...	...	4	3.5	5	4	S7 Zr 5 Ti 5	3	14
HD 191589........	20 05.6	8-25-75	...	...	...	0	0	0.2	2	M0S	2	15
KZP 8465.........	20 09.8	6-30-75	...	...	...	7	0.5	1	[b]	S7.5 Zr 1 Ti 8	1	
SZ Cep...........	20 12.9	7-30-75	M	8.6	+17:	X	2.5	5	3	S6.5e Zr 5	4	
+23°3992.........	20 18.2	10-24-75	...	...	...	2	0.5	2	1	S3 Zr 2 Ti 3	2	
V865 Aql.........	20 18.8	7-30-75	M	...	...	7	3::	1:	[b]	S7.5e: Zr 1: Ti 8	1	
		8-10-76		...	...	7	2	0.5	[b]	M7Se	1	
V441 Cyg.........	20 23.3	11-08-75	SR*a*	...	...	3.5	3	4	1	S6 Zr 4 Ti 4.5	3	
AD Cyg...........	20 27.6	8-25-75	L*b*	...	...	1:	3	5	4	S7 Zr 5 Ti 2:	4	
Z Del............	20 28.1	6-29-75	M	9.5	−18	3	2:	1.5	[b]	S4e Zr 1.5 Ti 4	2.5	
FF Cyg...........	20 35.1	11-14-76	M	10.8	...	[b]	1.5	5	3	S6.5e Zr 5	5	
ER Del...........	20 37.9	8-20-76	L*b*	...	...	4	2:	2.5	[b]	S5.5 Zr 2.5 Ti 5	2.5	
CY Cyg...........	20 43.3	8-27-75	L*b*	...	...	X	0	0	5	SC5 Zr 0	6	
BV Vul...........	20 53.0	10-24-75	SR*a*	...	...	1:	3	5.5	4	S75. Zr 5.5 Ti 2:	4	
V471 Cyg.........	21 03.2	8-20-76	L*b*	...	...	1:	2	5	4.5	S7.5 Zr 5 Ti 2:	4	
T Cep............	21 08.2	7-14-76	M	6.7	−5	8	1::	0	[b]	M8	[b]	16
+31°4391.........	21 11.5	8-20-76	...	...	...	1	0	2	1.5	S2.5 Zr 2 Ti 2	3	
LX Cyg...........	21 52.1	8-27-75	M	10.0	−13	X	0	1	5:	S5.5e: Zr 1	5	
		11-14-76		11.4	−58	X	0	0.5	3	SC3e Zr 0.5	6	
X Aqr............	22 13.2	8-10-76	M	8.0	−5	6.5	0	0	[b]	M6.5e	[b]	17
SX Peg...........	22 45.5	10-24-75	M	9.3	...	X	2.5	5	6	S8.5e Zr 5	4	
		11-08-75		9.1	...	X	2.5	4.5	5	S7.5e Zr 4.5	4	
HR Peg...........	22 49.7	7-29-75	...	...	...	4	0.5	1	1	S4.5 Zr 1 Ti 5	2	
+28°4592.........	23 24.8	8-08-75	...	...	...	1	0	1	2	S1.5 Zr 1 Ti 2	1	
BG And...........	23 26.2	8-28-75	M	10.0	−17:	7:	4	5	[b]	S9.5e: Zr 5 Ti 8:	2.5	
		8-10-76		8.7	+13:	3	2.5	3	1	S4.5e Zr 3 Ti 4	3	
WY Cas...........	23 52.9	9-12-77	M	...	...	X	1.5	4.5	4	S6.5e Zr 4.5	5	18
IW Cas...........	23 57.5	8-25-75	M	...	...	X	1.5	4	4.5	S6.5e Zr 4	5	
		11-12-75				X	1.5	5	5	S7.5e Zr 5	5	
		10-15-76				X	1.5	5	4.5	S7.5e Zr 5	5	

[a] X = No TiO is present. [b] No estimate could be made

NOTES TO TABLE 3

1. The bright maximum of 1975 was followed by a faint maximum in 1976. The disappearance of TiO at bright maxima for R And has been noted by Terrill 1969.
2. Faint maximum.
3. Bidelman 1954 reports ZrO weak, Ba II strong. The atomic-line spectrum in the red is quite prominent and is suggestive of SC characteristics.
4. Bidelman (unpublished) comments that the blue spectrum is composite with a secondary spectrum of gF.
5. Stephenson and Ross 1970 note SU Mon's resemblance to the SC stars because of its extraordinary D lines and violet depression. The assigned type is probably too late because of the D lines.
6. ADS 6763. Bidelman 1954 suggests secondary may be optical.
7. Merrill 1927 and Davis 1934 noted weak ZrO in the blue, but Bidelman and Keenan 1951 reclassify it as a cool Ba II star. Keenan 1950 classifies it as S0. Because of its strong violet depression and marginal presence of ZrO, the SC notation is used here.
8. Classified as S by Bidelman (unpublished). Rejected as S by Keenan 1954 and Stephenson (Wing and Yorka 1977).
9. Bidelman 1954 notes weak bands, strong Sr I λ4607. If ZrO strengths when far from maximum, the SC classification may be changed.
10. Dearborn 5230. Stephenson 1975 reclassifies it as a reddened M2 star.
11. F3 IV companion (Culver and Ianna 1975).
12. Stephenson 1976 corrects the identification; once thought to be CE Vul.
13. Bidelman 1954 notes no TiO, but ZrO and Sr I λ4607 present.
14. Stephenson 1976 suggests that ZrO may vary greatly.
15. Bidelman 1957 reports that it resembles M0 Ib or II, but ZrO is present and Sr II and Ba II are strong.
16. ZrO in the infrared only (Spinrad and Newburn 1965). ZrO in the red and visual cannot be seen since TiO dominates the entire spectrum.
17. ZrO reported only once for this star by Vyssotsky.
18. Herbig 1965 found that at $m_v = 15$ a G-type spectrum appears. Mavridis 1960 suggests WY Cas to be a possible member of NGC 7789. If the secondary were found to be a dwarf, it would fall on the main sequence of the cluster as given by Burbidge and Sandage 1958.

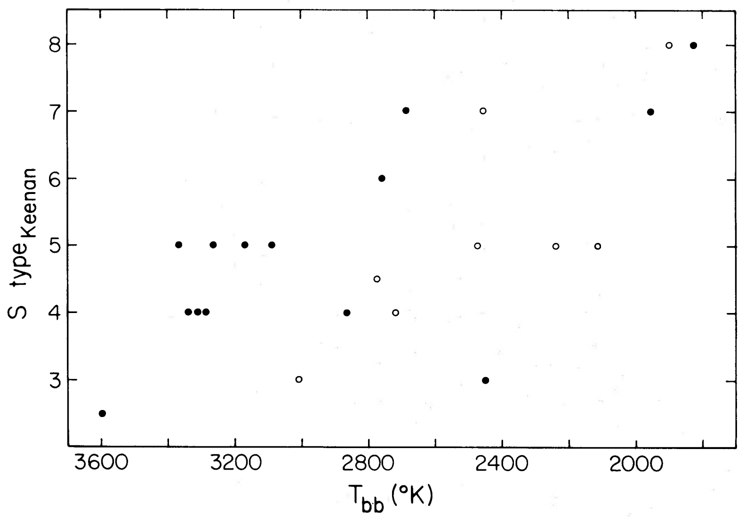

FIG. 2*a*

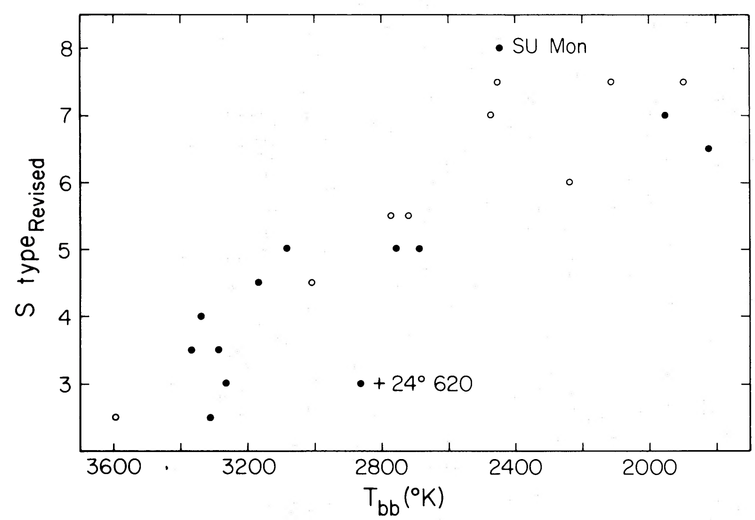

FIG. 2*b*

FIG. 2.—(*a*) Kennan's spectral types and (*b*) revised types versus Piccirillo's color temperatures. Open circles are Keenan's abundance classes 8 and 9.

A comparison of the revised types against Eggen's (1972) $(R - I)_0$ colors shows very substantial scatter. The spectral type, $(R - I)_0$ relation is apparently poorly defined because of the dependence of broad-band colors on molecular band strengths. The great variety of the S type stars hinders the development of a consistent relation between spectral types and broad-band colors for them.

b) The Use of YO, ZrO, *and* TiO *as Abundance Indicators*

The anomalous behavior of the bands of YO in cool giants has been known for some time. Merrill, Deutsch, and Keenan (1962) found that YO appeared only in a few of the cooler objects and seemed to be stronger in the MS than in the M stars. Although they noted that the YO-strong M giants seemed to have more transparent atmospheres, they suggested that an increase in the heavy-element content of the stars explained the appearance of YO. Later, Keenan (1966*a*) commented that a plot of the strengths of the YO and ZrO bands "raises the suspicion that the abundances of yttrium and zirconium do not correlate completely."

A plot similar to Keenan's, using the present data, is shown in Figure 3. Although the bands are stronger in the later types, YO is strongest when ZrO and TiO are strong, and is weaker if either ZrO is weak (as for an MS star) or TiO is weak (as in the pure S stars). The spread of points about the main relation suggests real abundance differences between the two molecules. It is also significant that the YO-strong stars located above the mean relation also show TiO.

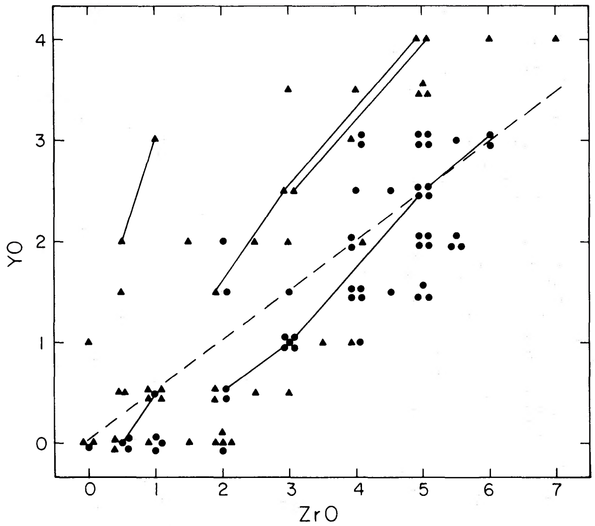

FIG. 3.—YO versus ZrO. Triangles are stars with TiO ≥ 2. The dotted line is a linear fit for all stars. Observations of some variables observed more than once are connected.

However, another factor is involved: Scalo (1974) and Scalo and Ross (1976) have recently considered in some detail how the YO intensities in both M and S stars are affected if the C/O ratio is increased from the solar value to near unity. The C/O ratio directly affects oxide concentrations by controlling the free-oxygen supply through CO, and indirectly affects the oxide band strengths by changing the continuous opacity due to H_2O. As C/O increases, the less stable oxides (such as VO and TiO) cannot compete as well for the decreasing concentration of free oxygen, and the bands of the more stable oxides (such as YO, ZrO, and LaO) increase in strength due to increasing observable column densities as the H_2O opacity decreases.

Of the three molecules here considered, the ZrO/TiO ratio is the most sensitive to C/O since the difference in dissociation energy is the largest; but since Zr is an *s*-process element, the ratio is also greatly affected by the degree of *s*-processing that may have occurred. In fact, Boesgaard (1970) finds that this ratio correlates well with the atomic Zr/Ti abundance ratio for the M, MS, and S stars. The YO/ZrO ratio, on the other hand, has the advantage that both metals are *s*-process elements. If the *s*-process mechanism always produces Zr and Y in the same ratio, then the relative molecular band intensities will only be dependent upon temperature and C/O. Moreover, the smaller difference in dissociation energy between YO and ZrO is compensated by the fact that YO is very sensitive to C/O variations because dioxide formation is more important than for ZrO (e.g., Scalo and Ross; Wyckoff and Clegg 1978). As the concentration of free oxygen diminishes, YO strengthens dramatically as YO_2 is depleted. Not until C/O is very close to unity does the YO concentration decrease.

The calculations by Scalo and Ross suggest that the stars can be crudely divided into six C/O categories based on the relative strengths of TiO, ZrO, and YO; these are listed in Table 4. The quoted values of C/O may not be definitive, but are listed to illustrate how small changes in the interval $0.9 \leq C/O \leq 1$ may be observable. The following picture emerges. As the C/O ratio begins to increase, TiO does not weaken but YO and ZrO appear. On our plates the YO system is not as strong as that of ZrO; thus, the abundance index 1 stars will show strong TiO, weak ZrO, and weak or absent YO. As the C/O ratio approaches 0.90, YO strengthens with respect to ZrO due to YO_2 dissociation, and TiO remains strong; these are the index 2 stars. When C/O reaches 0.93, the stars of index 3 will have YO (scaled by a factor of 2) as strong as ZrO, but TiO weakened. In index 4, where C/O = 0.95, YO begins to weaken with respect to ZrO, and TiO is weak or absent. The index 5 stars have C/O ≥ 0.95 and are characterized by ZrO being more than twice as strong as YO, and TiO absent. The SC stars, where only ZrO is marginally present, are classified as abundance index 6.

The spectra in Figure 1 are arranged in order of this index. Although the stars have nearly the same temperature type, the TiO λ6651 sequence decreases with increasing abundance index, YO peaks at index 3, and ZrO is strongest in index 4 or 5.

By its very nature, the abundance index defined here is very different from that of Keenan, since it is almost certainly related to the C/O ratio rather than to the heavy-element abundance. Unfortunately the oxide bands are not as sensitive to C/O for the earlier types. For these objects, distinctions are hampered by the weakness of all features, especially the YO bands, and the assignment of abundance class can be inexact. The discrimination is qualitative, and the assignment of a star to a given index depends on the judgment of the observer.

We hesitate to term this index a C/O index because it is not directly observable in the stellar spectra and also may well be influenced by factors not yet considered, such as differences in absolute magnitude. Rather it is an inference from the spectrum. Its value lies in its attempt to explain that part of the behavior of YO that cannot be attributed to temperature differences. The precise interpretation of the index, which has been determined for all of the S stars observed, will require much further work.

TABLE 4

DEFINITION OF THE ABUNDANCE INDEX

Index	Spectral Characteristics	C/O[a]
1.........	TiO ≫ ZrO and YO	< 0.90
2.........	TiO ≥ ZrO ≥ 2 × YO	0.90
3.........	2 × YO ≥ ZrO ≥ TiO	0.93
4.........	ZrO ≥ 2 × YO > TiO	0.95
5.........	ZrO ≥ 2 × YO; TiO = 0	> 0.95
6.........	ZrO weak; YO, TiO = 0	~ 1
7.........	CS and carbon stars	> 1

[a] Value estimated from Fig. 14 of Scalo and Ross 1976.

VI. SUMMARY

Observations of ZrO, TiO, and Na D have been used to define a new spectral classification system for the S stars. The original Keenan classification scheme is found to be adequate for the stars showing bands of TiO, with only a slight zero-point revision. For the stars showing weak or absent TiO bands, the D lines replace TiO for summing with ZrO to determine the temperature type. Finally, a new abundance index is proposed based on the relative strengths of YO, ZrO, and TiO which appears to be closely related to the atmospheric C/O ratio in the S stars.

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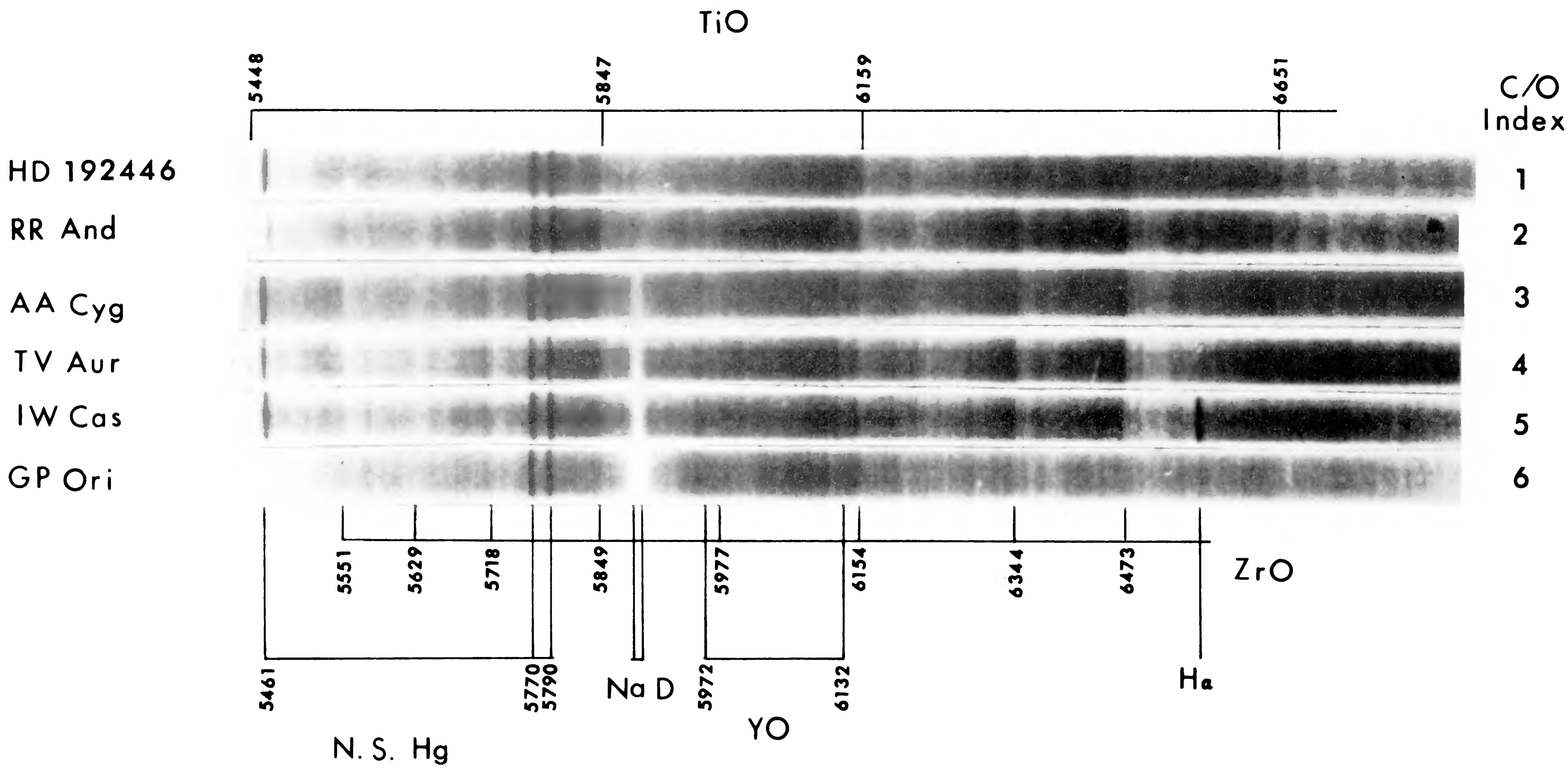

FIG. 1.—Low-dispersion spectra of S stars of temperature classes 7 and 8 arranged by the new abundance index

AKE (*see* page 539)