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VISIBLE SPECTRUM OF π^1 GRUIS: IDENTIFICATION OF NEW $e\,^1\Pi$–$X\,^1\Sigma^+$ AND $^1\Sigma^+$–$X\,^1\Sigma^+$ BANDS OF ZrO

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ABSTRACT

New molecular features identified with the $e\,^1\Pi$–$X\,^1\Sigma^+$ and $^1\Sigma^+$–$X\,^1\Sigma^+$ transitions of ZrO, in the 5840–7210 Å spectral region of the S star π^1 Gru, are presented. The measured band positions are in accord with the laboratory and predicted spectra of the molecule. The proposed new identifications suggest that molecular features due to the oxides of *s*-process elements are stronger and more extensive in stellar spectra than in the laboratory.

Subject headings: line identifications — molecular processes — stars: individual — stars: S-type

I. INTRODUCTION

Knowledge of the spectral characteristics of stars of type S is of vital value in studies of stellar evolution and nucleosynthesis. Molecular features due to ZrO in the spectra of S type stars are known to be conspicuously strong even in the low dispersion of 300 Å mm^{-1}. Despite the well-established presence of the 3682 Å band (b–X system) and bands of the triplet systems (α, β, and γ) in S stars, no detailed identifications of the visible singlet systems of ZrO were available prior to the recent work of Wyckoff and Clegg (1978). These authors identified seven bands of the 6495 Å system ($e\,^1\Pi$–$X\,^1\Sigma^+$) and the 5860 Å band ($^1\Sigma^+$–$X\,^1\Sigma^+$), in the 5840–7100 Å wavelength region of the spectra of R Cyg near minimum light.

In this paper, we report the identification of new ZrO molecular features of the spectra of π^1 Gru, covering the region 5840–7210 Å. More than 20 molecular features are identified with the 6495 Å system, while 11 bands are tentatively ascribed to the 5860 Å system. All the identified bands are degraded to longer wavelengths. The measured bands are found to be compatible with the laboratory and predicted band positions.

II. LABORATORY DATA

Phillips and Davis (1976*a*) identified the 5860 Å band as the (0, 0) band of a new $^1\Sigma^+$–$X\,^1\Sigma^+$ transition of ZrO. Additionally, they observed new bands at 5893, 5926, and 5961 Å and assigned them as the (1, 1), (2, 2), and (3, 3) bands, respectively. Subsequently Phillips and Davis (1976*b*) reported a comprehensive study of the 6495 Å system ($e\,^1\Pi$–$X\,^1\Sigma^+$), by identifying 18 new bands in the 5849–8341 Å domain, besides the known 6495 Å (0, 0) band. Furthermore, they presented the predicted new bands of this system, which may be useful in studies of stellar spectra.

Based upon the above investigations, we have recently evaluated the Franck-Condon intensity factors for bands of the $e\,^1\Pi$–$X\,^1\Sigma^+$ and $^1\Sigma^+$–$X\,^1\Sigma^+$ transitions (Murty 1980). The results of this study indicate the possible presence of additional bands, hitherto unidentified in the above systems. Predicted new band head positions are also presented to aid both the laboratory and stellar spectral studies (Murty 1980).

III. OBSERVATIONS

The red giant π^1 Gru (S5,7:e) is a slightly varying irregular variable star. It is a very bright southern star (m_v = 5.8–6.4) and intense spectrograms may thus, easily be obtained. Moderate dispersion spectra (46 Å mm^{-1} at Hα) in the region 5800–7300 Å employed in the present study were obtained (by Mr. M. Makkadean for Dr. M. K. V. Bappu, during the course of an investigation of atomic lines in cool star spectra) on 1978 November 14, with the image-tube spectrograph attached to the Cassegrain focus of the 40 inch (1 m) Kavalur telescope.

Relevant portions of the spectrograms are displayed in Figure 1. The strong molecular features of ZrO (γ system), YO (orange system), and CeO are labeled at the bottom of each spectrum. Strong features identified with the $e\,^1\Pi$–$X\,^1\Sigma^+$ and $^1\Sigma^+$–$X\,^1\Sigma^+$ transitions of ZrO are indicated with wavelengths at the top of the spectra.

IV. BAND IDENTIFICATIONS OF ZrO

Band head measurements and assignments of the stellar features in the region between 5849 and 7201 Å, identified with the ZrO $e\,^1\Pi$–$X\,^1\Sigma^+$ and $^1\Sigma^+$–$X\,^1\Sigma^+$ transitions, are given in Tables 1 and 2, respectively. In both the tables, the identified band positions in the spectra of π^1 Gru are given in column (1). The measured band heads are corrected for a radial velocity of -20 km s^{-1} and have mean errors of the order of $\sim \pm 0.4$ Å. In column (2) is presented the rough visual intensity estimate (on a scale of 0–10) of the identified bands. Columns (3), (4), and (5) give,

TABLE 1

BAND HEAD MEASUREMENTS AND ASSIGNMENTS OF $e\ ^1\Pi$–$X\ ^1\Sigma^+$ TRANSITION OF ZrO IN π^1 GRUIS

Wavelength λ (Å) π^1 Gru (1)	Intensity (visual est.) (2)	Wavelength λ (Å) R Cyg (3)	Wavelength λ (Å) lab (4)	Wavelength λ (Å) predicted (5)	Assignment v', v'' (6)	Masking Source (7)
5849.2	5	5849.3	5849.4	5849.3	2, 0	
5893.4	2	...	5893.4	5893.4	3, 1	Na D; ZrO $^1\Sigma^+$–$X\ ^1\Sigma^+$
5938.1	3	...	5937.8	5937.9	4, 2	
5981.5	5	...	5982.7	5982.7	5, 3:	ZrO γ
6027.0	2	...	...	6028.0	6, 4	ZrO γ
6073.2	3	...	...	6073.6	7, 5	
6119.3	4	...	...	6119.7	8, 6	ZrO γ
6153.9	7	6154.3	6154.3	6154.3	1, 0	
6201.5	4	6201.0	6200.9	6200.9	2, 1	CeO
6248.1	3	...	...	6247.8	3, 2	ZrO $^1\Sigma^+$–$X\ ^1\Sigma^+$
6295.3	2	...	...	6295.0	4, 3	
6343.1	1	...	...	6342.7	5, 4	CeO
6390.7	1	...	...	6390.8	6, 5	
6494.5	9	6494.4	6495.3	6495.4	0, 0	
6545.1	3	(6545.1)	...	6544.7	1, 1	
6594.7	1	...	...	6594.4	2, 2	
6931.6	6	6932.9	6931.7	6931.7	0, 1	
6984.4	5	6987.8	6984.5	6984.5	1, 2	atm. H_2O
7037.1	2	7037.5	7037.7	7037.7	2, 3	atm. H_2O
7090.7	1	7092.6:	7091.3	7091.2	3, 1	atm. H_2O
7146.1	1	...	7145.4	7145.1	4, 5	atm. H_2O
7201.1	3	...	...	7199.4	5, 6:	atm. H_2O

respectively, wavelengths of the bands observed in R Cyg by Wyckoff and Clegg, bands observed in the laboratory spectra by Phillips and Davis, and the predicted band positions by Phillips and Davis, and by Murty. The band head assignments are given in column (6), followed by column (7) which indicates the masking sources.

a) Bands of the $e\ ^1\Pi$–$X\ ^1\Sigma^+$ Transition

It may be seen from Table 1 that the identified ZrO molecular features in π^1 Gru are in harmony with the laboratory and predicted bands. The (0, 0) band of the $\Delta v = 0$ sequence is seen to be the most intense band, followed by (1, 0) and (0, 1) bands of the $\Delta v = \pm 1$ sequences, respectively. In the $\Delta v = 0$ sequence, only one band at 6495 Å (0, 0) is known from the laboratory study of the transition. In the present investigation, two more bands at 6545 Å (1, 1) and 6595 Å (2, 2) are observed. The unidentified band at 6545 Å observed in R Cyg by Wyckoff and Clegg is thus now identified with the (1, 1) band of this system.

Four new bands at 6248 Å (3, 2), 6295 Å (4, 3),

TABLE 2

BAND HEAD MEASUREMENTS AND ASSIGNMENTS OF $^1\Sigma^+$–$X\ ^1\Sigma^+$ TRANSITION OF ZrO IN π^1 GRUIS

Wavelength λ (Å) π^1 Gru (1)	Intensity (visual est.) (2)	Wavelength λ (Å) R Cyg (3)	Wavelength λ (Å) lab (4)	Wavelength λ (Å) predicted (5)	Assignment v', v'' (6)	Masking Source (7)
5859.8	6	5859.3	5859.8	5860	0, 0	
5893.4	2	...	5892.9	5894	1, 1	Na D; ZrO e–X
5927.4	1	...	5926.4	5929	2, 2:	
6213.8	3	...	...	6213	0, 1	
6248.1	3	...	...	6249	1, 2	ZrO e–X
6284.5	1	...	...	6285	2, 3	
6319.8	1	...	...	6321	3, 4	
6356.0	3	...	...	6357	4, 5	ZrO γ
6393.1	1	...	...	6393	5, 6	ZrO γ
6429.0	1	...	...	6430	6, 7	CeO
6644.6	1	...	...	6646	1, 3:	ZrO γ
6683.0	2	...	...	6684	2, 4:	

6343 Å (5, 4), and 6391 Å (6, 5) are located together with the known (1, 0) and (2, 1) bands in the $\Delta v = +1$ sequence. Of the four intense bands of this sequence, the (1, 0) and (4, 3) bands are free from any interfering features. In the 5849–6119 Å region, seven bands of the $\Delta v = +2$ sequence are observed, of which three at 6027 Å (6, 4), 6073 Å (7, 5), and 6119 Å (8, 6) are new. The band at 5982 Å appears to be intense, but its assignment as the (5, 3) band is doubtful because of its blending with the intense ZrO γ (3, 2) band.

Bands of the $\Delta v = -1$ sequence are observed in the interval 6931–7201 Å. Band identifications in this region are complicated due to measuremental inaccuracies of the band head positions combined with the blending of terrestrial O_2 and H_2O. Terrestrial absorption features smudge out the stellar features in the region longward of 6866 Å (see Moore, Minnaert, and Houtgast 1966). Fortunately, the (0, 1) band at 6932 Å is so strong that it overwhelms the interfering terrestrial feature. In addition to the five known bands of this sequence, one more band at 7201 Å (5, 6) is tentatively identified.

Of the 22 bands identified in the spectra of π^1 Gru, 10 are new, which are yet to be observed in the laboratory spectra. Evidently, this study suggests that further laboratory investigation of the ZrO $e\,^1\Pi$–$X\,^1\Sigma^+$ transition, aimed at identifying new bands in the 6000–7200 Å region, is needed.

b) *Bands of the* $^1\Sigma^+$–$X\,^1\Sigma^+$ *Transition*

In addition to the intense (0, 0) band at 5860 Å, 11 more bands in the region between 5890 and 6690 Å are tentatively assigned to the $^1\Sigma^+$–$X\,^1\Sigma^+$ transition. As can be seen from Table 2, most of the bands of this system are relatively very weak and are masked by the bands of the ZrO e–X and γ-systems. Of the three intense bands of the $\Delta v = -1$ sequence, the 6214 Å (0, 1) is the only band lying in the unmasked region. The agreement between the observed and predicted band positions, as seen from Table 2, is not quite satisfactory. However, this observation is less disturbing when we consider the fact that the predicted positions given in column (5) are based upon the approximate molecular constants of this system and consequently the reliability of these wavelengths is admittedly very low. Nevertheless, the predicted positions provide a crude guide to the location of new bands of this system. We hope that the proposed stellar identifications will inspire renewed efforts to discern new bands of the system in the laboratory spectra. A successful identification of the $\Delta v = \pm 1$ sequences of the system might prove of considerable interest and relevance.

V. CONCLUDING REMARKS

Molecular features due to ZrO hitherto unknown in the laboratory are identified in the spectra of the S star π^1 Gru. The present investigation thus demonstrates that molecular features due to the oxides of the *s*-process elements are stronger and more extensive in stellar spectra than in the laboratory. This could be due entirely to the phenomenon of enhanced abundances of *s*-process elements that we may be witnessing in the cooler S stars. However, also to be considered are the chemical equilibrium conditions in a stellar atmosphere with a carbon/oxygen ratio approximately equal to unity, since we see from Figure 1 (Plate 5) that no TiO feature at 6158 Å or at 7054 Å is present, while features due to ZrO, YO, and CeO are strongly identified.

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PLATE 5

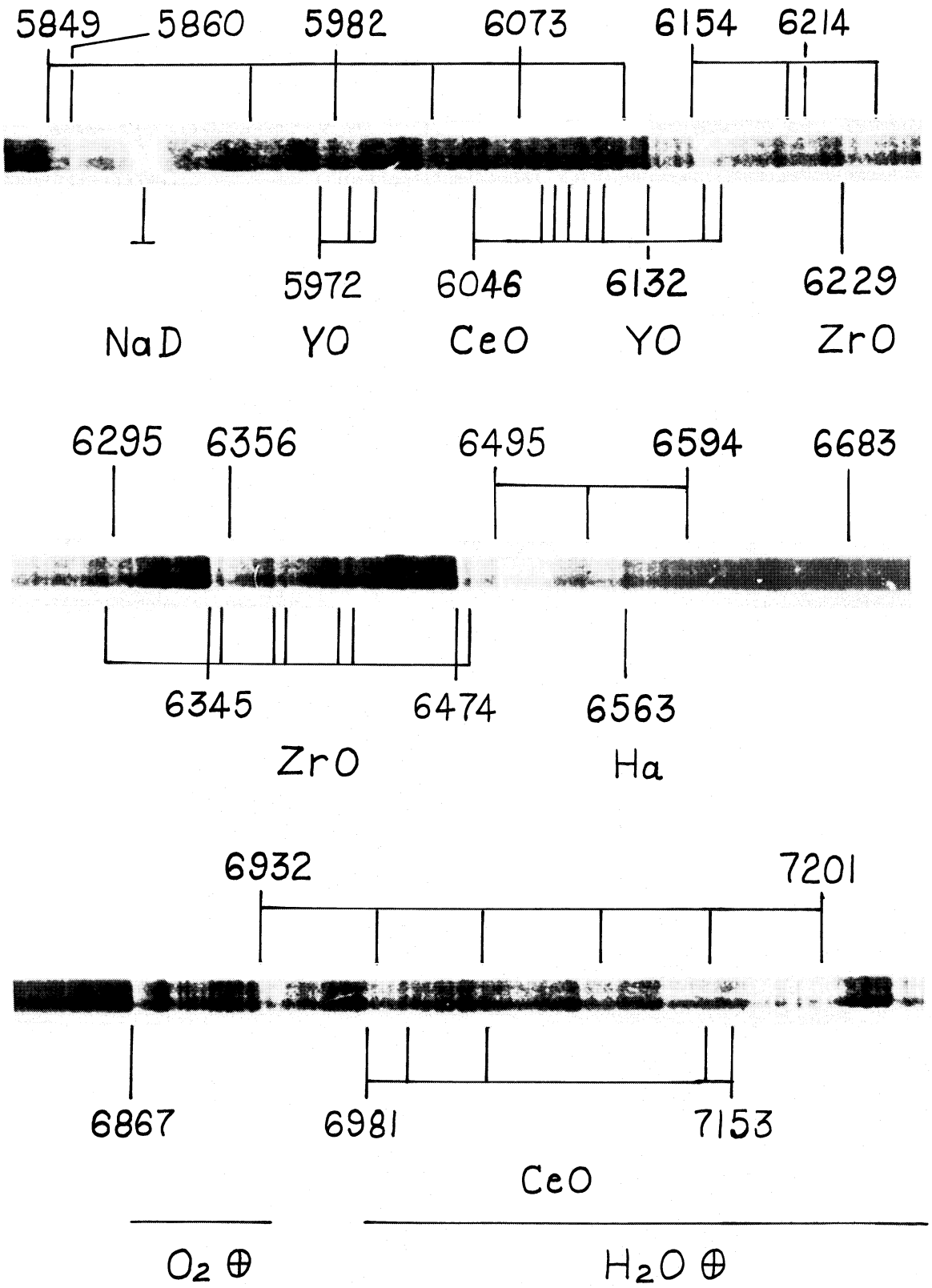

FIG. 1.—Image-tube spectra (original dispersion 46 Å mm^{-1} at Hα) of π^1 Gru. Intense band features identified with the $e\ ^1\Pi$–$X\ ^1\Sigma^+$ and $^1\Sigma^+$–$X\ ^1\Sigma^+$ transitions of ZrO are labeled with wavelengths at the top of each spectrum.

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