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SPECTROSCOPY OF MIRA VARIABLES AT DIFFERENT PHASES

MICHAEL W. CASTELAZ[1] AND DONALD G. LUTTERMOSER

Department of Physics and the Southeastern Association for Research in Astronomy, Box 70652, East Tennessee State University, Johnson City, Tennessee 37614

Electronic mail: castelam@etsu-th.edu

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ABSTRACT

Spectroscopic measurements of Mira variable stars, as a function of phase, probe the stellar atmospheres and underlying pulsation mechanisms. Modeling the atmospheres is difficult due to the hydrodynamic nature of the gas as deduced from the large light variations and velocity measurements of various spectral lines. Many questions still need to be resolved concerning the atmospheres of these stars. Are the depths of formation of the molecular species such as TiO, VO, and ZrO produced in an extended region above the layers where Balmer line emission occurs or below this *shocked* region? What is the explanation for the Balmer-line *increment*, where the strongest Balmer line at phase zero is Hδ and not Hα? Furthermore, why is the Hϵ line virtually absent in the spectra of Miras when the other Balmer lines are strong? A new program of low resolution (1.08 Å/pixel) spectroscopy from about 6000 Å to 8750 Å is presented in this paper. The spectra are taken in a region which includes Hα, TiO, VO, ZrO, and the Ca II infrared (IR) triplet. Spectra of nine Mira variables are presented. Seven Mira variable stars (o Cet [Mira], U Ori, R Leo, V CVn, R CVn, V Boo, and χ Cyg) were observed at more than one phase. Two other Mira variables (R Tri and R Gem) were observed at a single phase, but both show strong Hα emission. In this paper, we investigate the final question listed above by noting variations in the Ca II IR triplet in relationship with Hα variations as a function of phase. These preliminary observations suggest that Hϵ's observational characteristics result from an interaction of Hϵ photons with the Ca II H line. © *1997 American Astronomical Society.* [S0004-6256(97)03310-4]

1. INTRODUCTION

Mira-type stars are large, cool, long period variable stars whose visual light variations exceed 2.5 magnitudes over periods from 150 days to ~500 days. These stars are located on the asymptotic giant branch and offer the opportunity to study a transitional phase in stellar evolution. These stars are an important component in seeding the ISM with C, N, and O. The light curves of Mira variables depend on the surface temperature, radius, and opacity, all which vary as the star pulsates. These pulsations extend the atmosphere beyond that of the hydrostatic equilibrium configuration and enhances mass loss in these stars (Bowen 1988). Photometric and spectroscopic measurements of their light curves provide a means to probe the stellar atmospheres and underlying pulsation mechanisms occurring in these late-type stars.

Important work has been done studying the effects of molecular species such as TiO on spectral classes and temperatures, and the relation of TiO absorption to emission from the photosphere. Wing (1967) did 27-color narrowband photometry to measure CN, TiO, VO, and ZrO in Miras. He found that the TiO bands are very sensitive to temperature, and can be used to determine color temperatures and subdivisions of type M stars. One of the most startling discoveries was the behavior of diagrams of molecular band strength versus temperature. Gigantic loops are executed by Mira variables in the molecular band-temperature plane, and these loops follow different paths in different cycles. The behavior suggests that the dynamics in atmospheric layers producing the molecular absorptions and the continuum are semi-independent.

Lockwood & Wing (1971) present light curves of 25 Mira variables at 1.04 μm. The 1.04 μm photometry measures radiation emitted by photospheres of Mira variables throughout their cycles. Features in light curves can be interpreted in terms of temperature, radius, and spectral types. Comparison of the 1.04 μm emission with visual maxima shows that bright visual maxima are produced by high photospheric temperatures and bolometric luminosities, or produced by molecular dissociation in the outer layers of the stellar atmosphere.

Also, their light curves suggest a sudden increase in photospheric temperature at minimum. Lockwood (1973) measured TiO band strengths near 1 μm and found that TiO bands are seen for stars M3 and later. The bands are useful for spectral classification. Celis (1984) who took spectra centered in 4500 Å and 7000 Å (86 Å/mm) of 28 Mira variables, used the spectra and *UBVRI* photometry to calibrate the $V-R$, $R-I$ two-color diagram in terms of spectral type. These spectral, narrowband, and broadband studies suggest that TiO resides in an atmospheric layer not associated with the photosphere. Determining the atmospheric conditions in which the TiO forms and dissociates would help in forming a complete stellar atmosphere model for Mira variables.

Modeling Mira variable atmospheres is difficult. Several

[1]Visiting Astronomer, Dark Sky Observatory, Appalachian State University.

TABLE 1. Coordinates and ephemerides of the variable stars.

Star	RA (2000)	Dec (2000)	Sp. Type	V_{max}	V_{min}	Period (d)	Epoch 2430000+
o Cet	02 19 20.7	−02 58 23	M7IIIe	2.00	10.10	331.65	8457
R Tri	02 37 02.2	34 15 51	M4IIIe	5.50	12.60	266.40	8001
U Ori	05 55 49.2	20 10 31	M8III	5.30	12.60	372.45	5953
R Gem	07 07 21.3	22 42 13	S	6.00	14.00	369.63	8124
R Leo	09 47 33.4	11 25 46	M8IIIe	4.40	11.30	312.57	7339
V CVn	13 19 27.9	45 31 38	M6IIIa	6.80	8.80	191.88	4930
R CVn	13 48 57.1	39 32 34	M6IIIe	7.30	12.90	327.97	8971
V Boo	14 29 45.2	38 51 41	M6e	7.00	11.30	258.22	8095
χ Cyg	19 50 33.9	32 54 53	S	3.30	14.20	406.80	8037

hundred day periods, light variation of at least 2.5 magnitudes, Balmer line *emission* near visual maximum, and small velocity shifts in *absorption* lines, all constitute a challenge in producing a consistent model of these stellar atmospheres. For example, Balmer Hα emission is typically weaker than Hβ which in turn is weaker than Hγ near peak visual brightness. Hδ is seen as the strongest Balmer emission line at this phase. As one continues on to the lines higher in the series (i.e., towards shorter wavelengths), the lines once again weaken. This *Balmer increment* is just opposite of what would be expected, Hα having the largest oscillator strength, should be stronger than Hβ and the higher order Balmer lines should be weaker as you go down the line (i.e., one should see a Balmer line *decrement*). For years, this has been attributed to TiO absorption which hide Hα, Hβ, and Hγ fluxes (Merrill 1940; Gillet 1988). However, recent NLTE radiative transfer calculations of hydrodynamic models representative of Mira variables (Bowen 1988) suggest that the Balmer increment results from radiative transfer effects in the hydrogen lines themselves when formed in a shocked atmosphere (Luttermoser & Bowen 1992; Luttermoser *et al.* 1997). This controversy can be solved by answering the questions of where do the TiO lines form in these stars and do their formation depths change with phase?

Another feature that is striking however is the weakness (and often absence) of the Hϵ line (3970.074 Å) in the Balmer series at maximum visual brightness (see Gillet 1988). Even Merrill (1940) noted this and suggested an interaction between the Hϵ transition and the Ca II H line (3968.470 Å) wing may be the cause for the weakness of Hϵ. However, we have found no further work on this suggestion in the literature.

If the Ca II H line is intercepting outward bound Hϵ photons, what becomes of these photons? The Ca II H & K resonance lines in the violet part of the spectrum share the same upper levels as the Ca II infrared (IR) triplet. These IR lines lie at 8498.023 Å ($3^2D_{3/2}-4^2P_{3/2}$), 8542.091 Å ($3^2D_{5/2}-4^2P_{3/2}$), and 8662.141 Å ($3^2D_{3/2}-4^2P_{1/2}$). The 8498 Å and the 8542 Å lines share the same upper level as the K line at 3933.664 Å, while the 8662 Å line shares the same upper level as the Ca II H line. It is possible that the Hϵ photons are being scattered by the Ca II H line out to IR wavelengths via the 8662 Å line. If this is the case, then one should see a *filling-in* of the 8662 Å line in comparison to the other two lines as the hydrogen Balmer lines become stronger emission features as one approaches maximum visual brightness. Then after maximum visual brightness, when the hydrogen lines begin to weaken, one should see the λ8662 Ca II line become a deeper absorption feature. Our observing program described here is the first monitoring program of this type for the Mira variables.

The spectra of Mira stars are dominated not only by the TiO γ system, but also the VO γ system and ZrO in our sample. The TiO features are thought to be produced in a layer somewhat far from the photosphere. Haniff *et al.* (1992) present optical aperture synthetic images of Mira's photosphere at 6500 Å, 7007 Å, and within a TiO bandhead at 7099 Å, with the star phase ~0.94. They find asymmetry in the images, with the TiO image one and a half times larger than the photospheric images. Also, narrowband speckle interferometric measurements taken in the TiO 7120 Å bandhead and outside at 7400 Å by Labeyrie *et al.* (1977) shows that the diameters of R Leo and o Cet are twice as large in the TiO feature than outside of it. So, a model atmosphere, based on the spectra observed over a TiO bandpass, provides parameters such as T and log g in an atmospheric layer far from the photosphere. In addition, the Balmer emission lines must be formed in an atmospheric layer where temperatures are on the order of 10,000 K (Gillet 1988). TiO cannot exist in the same layer because it would dissociate.

The primary aim of this paper is to present a new program of spectroscopy of Mira variables at different phases. By taking spectra at different phases we probe the effects the pulsation mechanism has on atmospheric parameters. The first set of new low-resolution spectra (120 Å/mm) is taken over the spectral range from about 6200 Å to 8800 Å of 9 Mira variables to probe their atmospheres. The equatorial coordinates, spectral types, magnitudes, and ephemerides of these Mira stars are given in Table 1 and taken from the SIMBAD Database. The only selection criteria for the stars under study are maximum visual magnitude brighter than 7 magnitudes, and declinations between 10 and 50 degrees so measurements can be made at small air masses at the meridian.

2. OBSERVATIONS

Spectra of Mira variable stars were taken between 1996 February and 1997 January using a low-resolution spectrograph. The spectrograph was used at both the Southeastern Association for Research in Astronomy (SARA) 0.9-m telescope at Kitt Peak, and Appalachian State University's

TABLE 2. Observation log.

Star	Observation date	Observation JD 2455000+	Visible phase	V	Integration time (Sec)	Telescope
o Cet	11 Oct 1996	367.5	0.62	9.4	600	SARA 0.9-m
	14 Dec 1996	431.5	0.81	5.9	600	DSO 0.45-m
R Tri	11 Oct 1996	367.5	0.28	9.9	600	SARA 0.9-m
U Ori	2 Mar 1996	144.5	0.32	12.6	600	SARA 0.9-m
	11 Oct 1996	367.5	0.94	6.4	600	DSO 0.45-m
	14 Dec 1996	431.5	0.12	6.7	600	DSO 0.45-m
	26 Jan 1997	474.5	0.24	7.9	1200	DSO 0.45-m
R Gem	11 Oct 1996	367.5	0.96	6.2	600	SARA 0.9-m
R Leo	17 May 1996	220.5	0.35	7.0	1200	SARA 0.9-m
	14 Dec 1996	431.5	0.02	4.5	300	DSO 0.45-m
	26 Jan 1997	474.5	0.16	5.3	300	DSO 0.45-m
V CVn	1 Mar 1996	143.5	0.18	7.6	600	SARA 0.9-m
	17 May 1996	220.5	0.60	8.6	1200	DSO 0.45-m
R CVn	1 Mar 1996	143.5	0.00	7.3	600	SARA 0.9-m
	17 May 1996	220.5	0.23	9.6	1200	SARA 0.9-m
	26 Jan 1997	474.5	0.00	7.3	600	DSO 0.45-m
V Boo	1 Mar 1996	143.5	0.76	9.0	600	SARA 0.9-m
	17 May 1996	220.5	0.05	7.1	3600	SARA 0.9-m
χ Cyg	17 May 1996	220.5	0.78	8.9	1200	SARA 0.9-m
	11 Oct 1996	367.5	0.14	6.9	240	SARA 0.9-m

Dark Sky Observatory (DSO) 0.45-m telescope located near Boone, NC. A converter lens was used at both sites to convert the respective telescope f-ratio to about $f/11$ for the spectrograph.

The spectrograph was configured with a 600 g/mm grating. The slit width was 100 μm. At the SARA 0.9-m telescope, the slit width is 3 arcseconds, and at the DSO 0.45-m telescope, the slit width is 4 arcseconds. At both sites, the slit was parallel to the hour angle. A cooled 768 $\times$ 512 CCD camera with 9 μm square pixels was used to record the spectra. The camera was not cooled for observations made in 1996 December. The spectral resolution is 1.08 Å per pixel, covering 768 pixels, or 829 Å.

We began this program in 1996 February by taking spectra of the TiO and VO features from 6930 Å to 7760 Å. Beginning in 1996 October we expanded the program by taking spectra to include the Ca II IR triplet and Hα. The October data set does not include the 8542 and 8662 Ca II infrared triplet lines. All data after October does include all three Ca II infrared triplet lines.

Table 2 gives the log of observations for each star, which includes dates of observation, phase, approximate visual magnitude, wavelength range of the spectra, and observing site. The phases listed in Table 2 were determined from American Association of Variable Star Observers predictions (Mattei 1996) and refer to the visual phases, with phase 0 corresponding to maximum visual brightness. The approximate visual magnitudes are interpolated by a sine curve between average maximum and minimum. We include R Tri and R Gem, which have been taken at a single phase thus far, because they show strong Hα emission.

Dark frames and sky frames were taken for flat fielding purposes. Spectra of neon lamp emission were taken with the stellar spectra and used for wavelength calibration. We flat-fielded the images and extracted the spectra using MIRA software. The extracted spectra were wavelength calibrated using the spectrum of neon superimposed on the CCD frame with the stellar spectrum (Crowe *et al.* 1996).

3. RESULTS

The spectra for the Mira variable stars taken at more than one phase are shown in Figs. 1(a)–1(g). The wavelengths of TiO, VO, ZrO, the Ca II IR triplet, Hα, and terrestrial oxygen are marked above each set of spectra. For reference, Table 3 lists the wavelengths for these spectral features. In 1996 March and May, spectra were taken at only one grating setting covering the TiO bandpass. In 1996 October, the spectra include the Hα wavelength region, but do not extend beyond the Ca II IR Triplet wavelength region. The 1996 December and 1997 January data do include the Ca II IR Triplet.

Several spectral features overlap. We find ZrO and VO absorption at 6574 Å and 6578 Å, respectively. Also, VO and TiO absorb at 7865 Å and 7861 Å, respectively. Due to the low dispersion of our spectra, these features will be blended. So, without high-resolution spectroscopy, the contribution of each of these features to a spectrum cannot be determined.

We are interested in the Ca II IR triplet as compared to the presence of Hα as a function of phase, since we are assuming that variations in Hϵ will mimic variations in Hα. Unfortunately, only data taken in December and January cover the spectra from wavelengths shortward of the Hα feature to wavelengths beyond the Ca II 8662 Å feature. In these spectra, the Ca II IR triplet lines are not strong, as expected for stars later than M0 (Zhou 1991). Figures 2(a) and 2(b) show the Hα feature of the R CVn spectrum at phase 0.00 (JD 2455474.5) and the Ca II IR triplet features of o Cet at phase 0.81, which are representative of the other spectra. We detect the Ca II 8662 Å feature in o Cet, U Ori, R CVn at phases

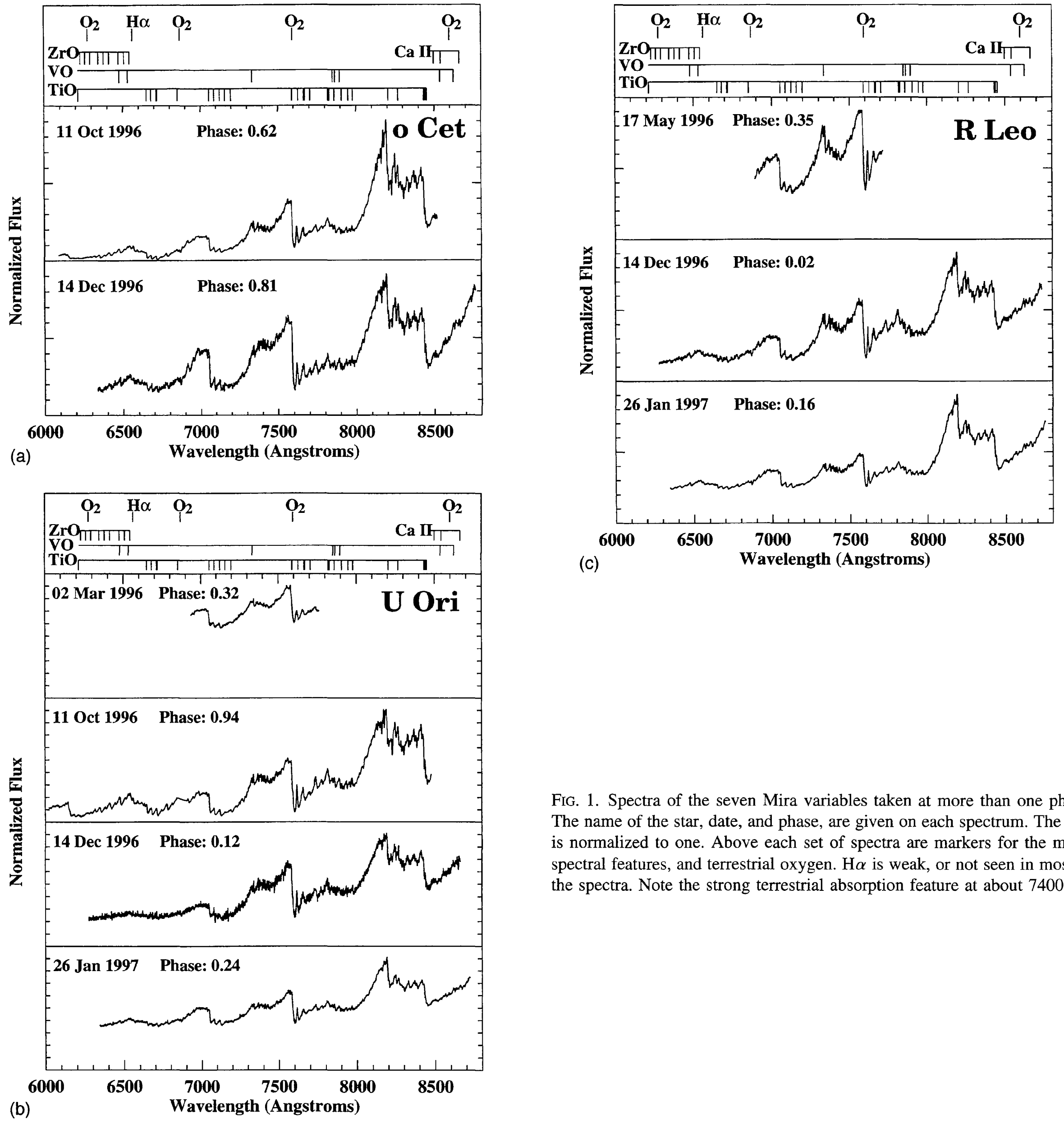

FIG. 1. Spectra of the seven Mira variables taken at more than one phase. The name of the star, date, and phase, are given on each spectrum. The flux is normalized to one. Above each set of spectra are markers for the major spectral features, and terrestrial oxygen. Hα is weak, or not seen in most of the spectra. Note the strong terrestrial absorption feature at about 7400 Å.

0.81, 0.12, and 0.00 (JD 2455474.5), respectively, as well as R Leo at phases 0.02 and 0.16.

A weak Hα feature is detected for R Leo at phase 0.02 and R CVn at phase 0.00 (JD 2455474.5). Two stars in our program which have been observed only once thus far do show strong Hα emission. The stars are R Tri and R Gem at phases 0.28 and 0.96, respectively. Figures 3(a) and 3(b) show their spectra. Figures 4(a) and 4(b) show an expanded view of Hα emission from the R Tri spectrum, with the *o* Cet, R Leo, and R CVn Hα spectra superimposed. Although we detect Hα in R Leo and R CVn, the amount of emission is very weak compared to that of R Tri.

Hα is not detected in the spectra of *o* Cet at phase 0.81 and U Ori at phase 0.12. There is a *small bump* near the position of Hα in the spectrum of *o* Cet at phase 0.62. However we feel that it is not large enough to be classified as an emission line. Neither the Hα nor the Ca II IR triplet is detected in the spectrum of U Ori at phase 0.24. The spectrum of R Leo at phase 0.16 does not have Hα emission, and only weak Ca II 8662 Å, and no obvious Ca II 8498 Å or 8542 Å lines.

In the spectra taken during 1996 October, χ Cyg does have weak Hα emission, and the spectrum of U Ori does not show Hα emission. Since these spectra do not extend beyond Ca II 8662 Å, a comparison between the strength of Hα and Ca II 8662 Å cannot be made.

We are also interested in comparing the TiO γ system and VO molecular features as a function of phase to Hα emission. The spectra are not flux calibrated, so we cannot give absolute integrated line fluxes, but we can make qualitative

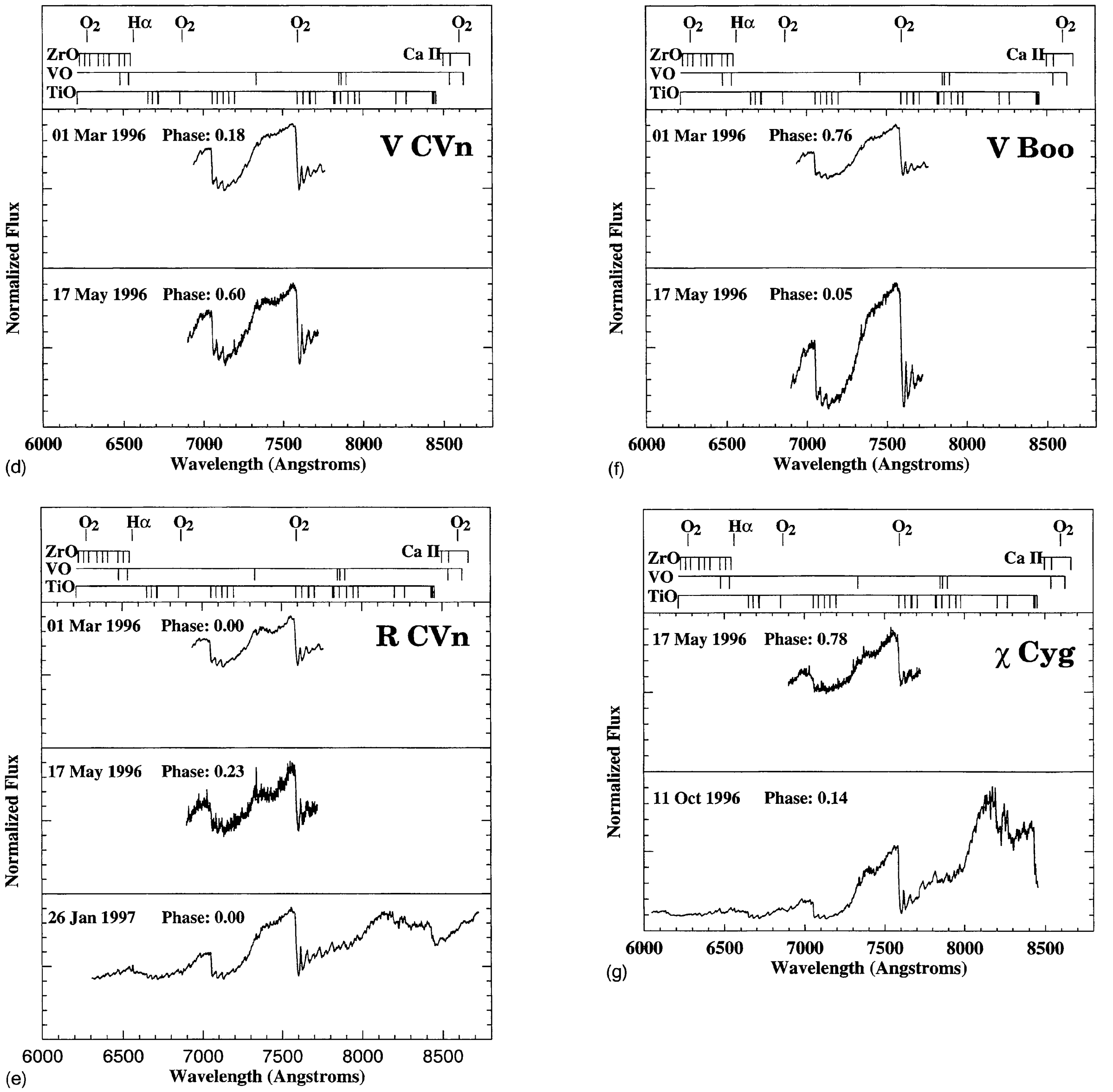

FIG. 1. (continued)

TABLE 3. Wavelengths of prominent spectral features.

Spectral feature	Wavelength (Angstroms)
Terrestrial oxygen	6276.6, 6867.2, 7593.7, 8597.8
Balmer Hα	6562.8
ZrO γ system	6229.4, 6260.9, 6292.8, 6344.9, 6378.3, 6412.3, 6473.7, 6508.1, 6543.0
Ca II infrared triplet	8498.0, 8542.1, 8662.1
VO bands	6477.8, 6532.8, 7333.8, 7850.9, 7865.0, 7896.0, 8537.7, 8624.0
TiO γ system	6215.2, 6651.5, 6681.1, 6714.4, 6719.3, 6852.3, 7054.5, 7087.9, 7125.6, 7159.0, 7197.7, 7589.6, 7628.1, 7666.4, 7672.1, 7705.2, 7820.1, 7828.0, 7861.0, 7907.3, 7948.6, 7978, 8205, 8268, 8433, 8442, 8452

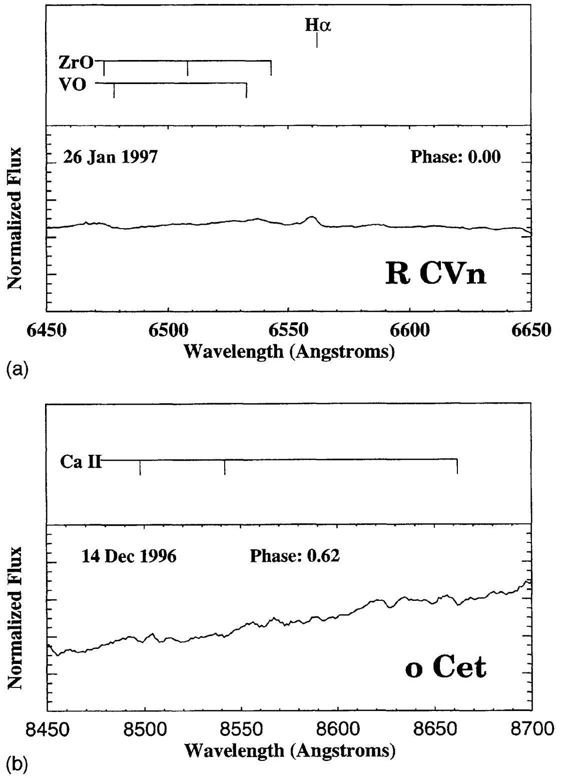

FIG. 2. (a) Expanded view of the Hα feature in the spectrum of R CVn taken at phase 0.00 on 1997 January 26, and (b) expanded view of the Ca II 8498, 8542, and 8662 Å infrared triplet features in the spectrum of *o* Cet at phase 0.81 on 1996 December 14.

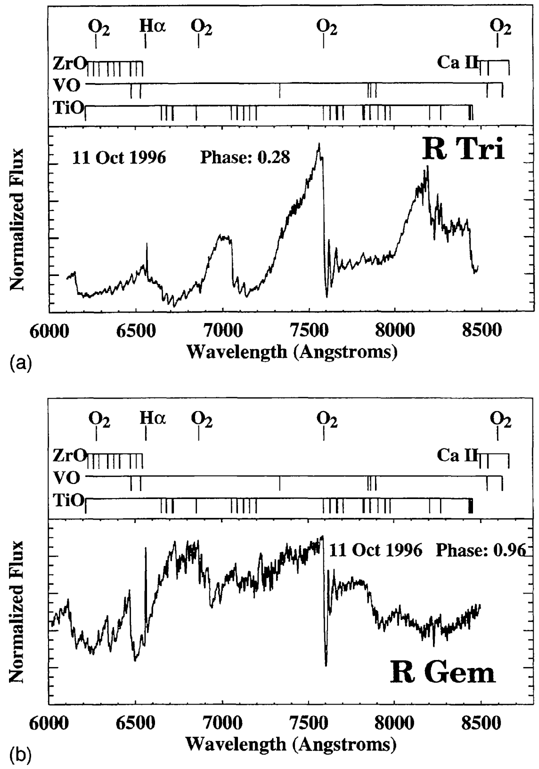

FIG. 3. Spectra of R Tri and R Gem taken at phase 0.28 and 0.96, respectively. These spectra show the strength of the Hα feature that may be expected from a Mira variable star. Although R Gem is near maximum light when Hα is expected, R Tri unexpectedly shows large Hα emission when it is at phase 0.28.

comparisons. We observe TiO and VO in all spectra, regardless of the presence of Hα emission. ZrO is not detected in *o* Cet at phase 0.81, U Ori at phase 0.12, and R Leo at phase 0.02 because all of these spectra were taken in 1996 December. The CCD was not cooled, so the spectra have more noise than spectra taken at other dates. The ZrO absorption features are covered by the noise in the spectra. Absorption due to ZrO is seen in all other spectra.

4. DISCUSSION

One point of this research program is to systematically determine $T_{\rm eff}$ and log g as a function of phase for the Miras in our sample. We will report on the results of this work in a future paper. Here, we wish to test the idea that the apparent lack of Hϵ emission at 3970 Å when the other Balmer lines are strong emission features is anticorrelated with the strength of the Ca II absorption line at 8662 Å. As reported in the Introduction, this anticorrelation results from Hϵ photons being scattered by the Ca II H line out to the Ca II line at 8662 Å, causing this Ca II absorption line to be *filled in* with respect to the other two Ca II IR triplet lines.

We use Hα as a proxy for the Hϵ line. In the search for the presence of Hα, we have found strong Hα emission from R Tri at phase 0.28. All other stars are consistent with some Hα emission near maximum light, even though they are relatively weak when compared to R Gem or R Tri.

We carried out the following analysis on these spectra. (1) Two points were selected on either side of the absorption or emission feature. The wavelengths of these points were kept constant for all measurements. The observed *profile* was integrated across the wavelength window resulting in an integrated flux f_l. (2) A straight line was connected between these two points to represent a *pseudocontinuum* and the integrated flux f_c calculated for it. (3) We then determined a relative *line strength*, F, based on the equation

$$F=\frac{f_l-f_c}{f_c}.$$

F will be negative for absorption lines and positive for emission lines. Figure 5 shows the result of these measurements. Plotted are the relative line strengths F as a function of light–variation phase for the stars in our sample. First note that the variation in the strength of the Ca II absorption features at 8498 Å and 8542 Å mimic each other well. Second, it is apparent that the third Ca II IR line at 8662 Å does follow the trend that the other two lines display. Finally, note that the emission line strength of Hα is anticorrelated with the absorption line strength of the Ca II 8662 Å feature—when Hα is a strong emission feature, Ca II λ8662 is a weak absorption feature and when Hα has weak emission or is absent, this Ca II line is a stronger absorption feature.

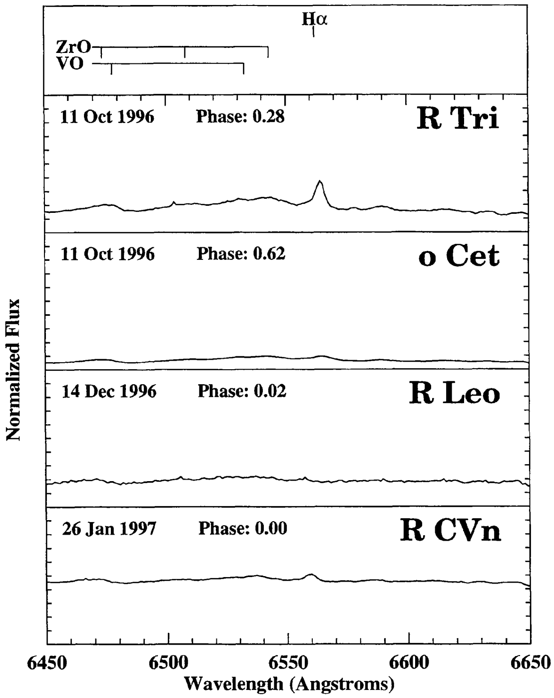

FIG. 4. Expanded view of the Hα emission feature of R Tri with the Hα emission feature of *o* Cet, R Leo, and R CVn also shown to the same scale. Note the weakness of Hα of *o* Cet, R Leo, and R CVn compared to that of R Tri.

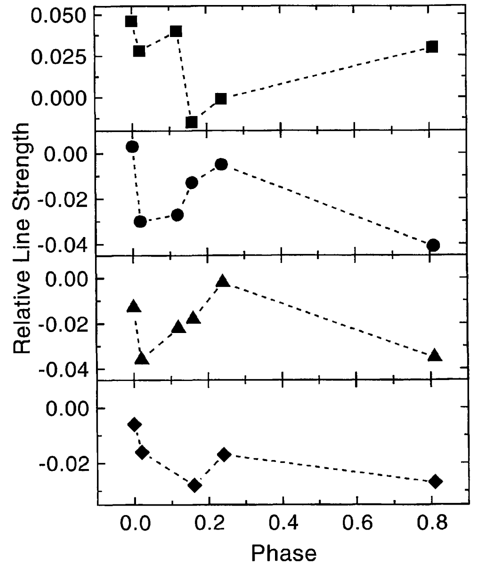

FIG. 5. Relative line strengths of Hα (filled square), Ca II lines at 8498 Å (circle), 8542 Å (triangle), and 8662 Å (diamond), as a function of light-variation phase. Variation in the Ca II lines at 8498 Å and 8542 Å mimic each other, whereas the Ca II line at 8662 Å does not follow the same trend.

The amount of data we have to date is insufficient to make any definite conclusions about the interaction between Ca II H and Hϵ. However, this preliminary data suggests that the weakness of the Hϵ line with respect to the other strong Balmer lines in Mira spectra results from the scattering of the violet Hϵ photons out to the near IR through the Ca II λ8662 line via the Ca II H line.

5. CONCLUSION

The 6000 Å to 8800 Å spectra of seven Mira variables taken at different phases suggest a possible anticorrelation between Hα emission and Ca II 8662 Å absorption. Assuming that the Hϵ line strength variations are in phase with Hα, then the apparent anticorrelation between the strength of the Hα emission line and the strength of the Ca II λ8662 line suggests that a *fluorescence* is taking place in the Ca II λ8662 line with Hϵ serving as the pump through the Ca II H line. This type of fluorescence is common in Mira type variables. The strong Fe I (42) lines at 4202 Å and 4308 Å seen in Miras are well known fluoresced features; in this case, the ultraviolet Mg II H & K lines serve as the pump via an Fe I (UV3) transition (e.g., Bidelman & Herbig 1958; Willson 1976; Luttermoser 1996).

The results of this work are preliminary. We need a much larger database to come to any firm conclusions about the anticorrelation between the Balmer line series emission line strength and the strength of the Ca II IR absorption features. We are continuing our low-dispersion spectroscopy monitoring program with the SARA and DSO telescopes of our sample of Mira stars to filling in the missing gaps of our phase space diagram of Fig. 5. We will also begin a high-dispersion ($\Delta\lambda \approx 0.1$ Å) program to monitor details in the changes of the Ca II profile at 8662 Å. We will report on this in a future paper along with the $T_{\rm eff}$ and log g determinations from the molecular features in the spectra of these stars.

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