Periodic Changes in the K-band Spectral Angular Diameters of Mira Variables at PTI

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Abstract

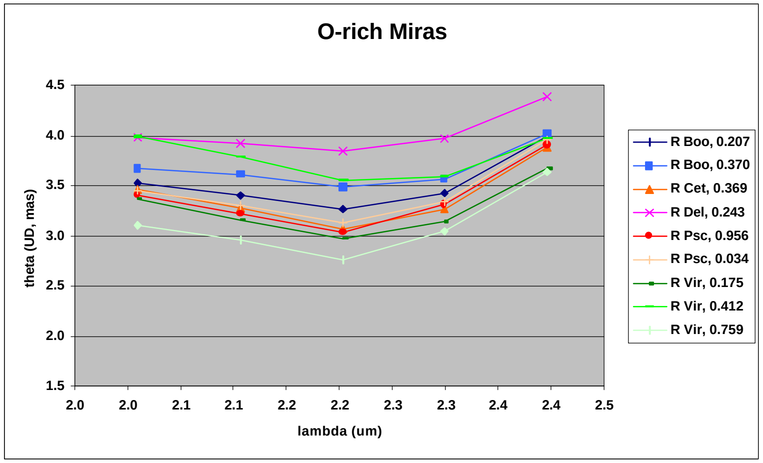
We report angular size measurements of 16 oxygen-rich, 6 carbon-rich and 4 S-type Mira variables taken at the Palomar Testbed Interferometer (PTI) as part of a long-term observational program. These data represent the first direct measurements, both spatially-resolved (1.5-4.5 mas) and spectrally-resolved in 0.1 μm bins spread over the K-band, as a function of phase. Additionally, diameters taken in 4 spectral channels spread over the H-band are presented.

Utilizing the AFOEV and AASVO databases to determine the phase in visual light, periodic changes in the 2.2um diameter with respect to the band edges are seen for O-rich Miras whereas a more uniform angular size structure is seen in C-rich Miras. Comparisons are made to O- and C-rich non-Mira giants which do not exhibit these characteristics.

This work is part of the Mira observational program at PTI to investigate the chemistry (C/O ratio, metal abundance), period length, and strength of the acoustic shock as evidence for the mode of pulsation.

Program Stars

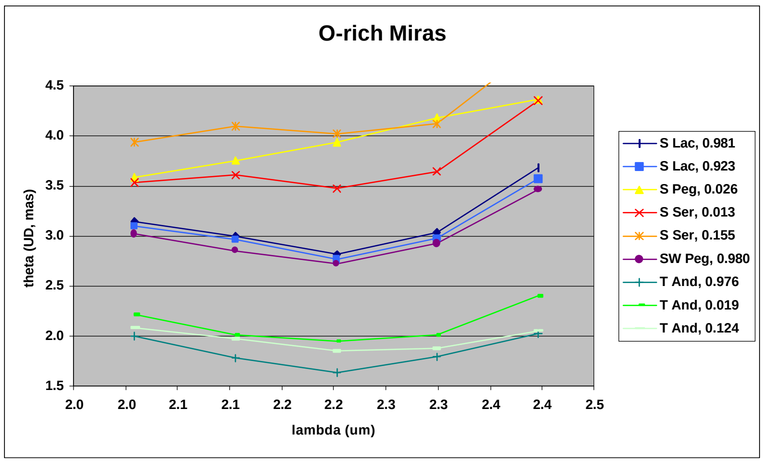
Name	HD	HIP	IRC	Latest P	V* max	V* min	K mag	Sp Type	Nights (K)	Nights (H)	Calib HD	EAS	Sp Type	Calib HD	EAS	Sp Type
R Ori	31798	23165	---------	384.84	9.1	13.4	4.05	Ce (Ne)	1		31295	0.64+/-0.03	A0V			
RZ Peg	209890	109089	+30484	437.82	7.6	13.6	2.87	Ce (Ne)	8	1	210459	1.24+/-0.15	F5III	209149	0.95+/-0.11	F5III
U Lyr	----------	95024	+40345	466.72	8.3	13.5	2.2	Ce (Ne)	1		176437	1.05+/-0.11	B9III			
V CrB	141826	77501	+40273	364.18	6.9	12.2	1.97	Ce (Ne)	2		145675	0.48+/-0.03	K0V			
VX Gem	55284	34859	+10156	368.05	8.5	12.8	2.94	Ce (Re)	5		57006	0.60+/-0.04	F8V			
Y Per	21280	16126	----------	245.07	8.1	10.9	3.25	Ce (Re)	2		20675	0.57+/-0.03	F6V			
T And	1795	----------	+30009	277.06	7.7	14.3	3.16	M3e	5		2190	0.92+/-0.09	M0III	1404	0.40+/-0.02	A2V
R Vir	109914	61667	+10256	151.05	6.2	12.1	2.24	M4.5e	2	1	115383	0.63+/-0.04	G0Vs			
R Boo	128609	71490	+30260	218.49	6.7	12.8	1.99	M4e	3		134803	0.62+/-0.04	A3V			
R Cet	15105	11350	+00032	162.21	7.2	14	3.04	M4e	1		13468	0.92+/-0.09	G9III			
R Psc	9203	----------	+00019	348.47	7.1	14.8	1.92	M4e	5		7804	0.34+/-0.02	A3V			
SW Peg	----------	----------	+20506	405.04	8	14	2.48	M4e	1	1	204642	0.85+/-0.08	K2III			
VX Aur	----------	36314	+40177	325.4	8.2	13	1.71	M4e	1		58412	0.38+/-0.03	A1V			
X Del	199170	----------	+20492	301.22	8.2	14.6	2.87	M5.5e	7	2	190406	0.51+/-0.03	G1V			
R Del	192502	99802	+10459	283.22	7.6	13.7	1.87	M5e	4		196180	1.02+/-0.05	A3V			
S Lac	213191	110972	+40512	243.4	7.6	13.9	2.51	M5e	3		207088	0.83+/-0.06	G8III			
S Ser	136695	75170	+10290	358.65	7.7	14.1	1.53	M5e	5		137510	0.43+/-0.02	G0IV-V	134323	1.20+/-0.10	G6V
TU And	2890	2546	+30012	327.63	7.8	13.1	2.05	M5e	6		7229	0.28+/-0.02	G9III+	3690	0.32+/-0.02	K0Iab
Z Cyg	190163	----------	+50314	324.22	7.6	14.7	2.44	M5e	1		185395	0.71+/-0.05	F4V			
V CMi	53847	----------	+10153	352.08	7.4	14.9	1.95	M6.5e	2		57006	0.60+/-0.04	F8V			
S Peg	220033	115242	+10533	318.32	7.4	13.8	1.59	M6e	1		222603	0.52+/-0.03	A7V			
X Gem	48912	32512	+30166	260.76	7.6	13.6	1.78	M6e	3		51834	0.92+/-0.08	K4III	45112	0.78+/-0.05	F8Ibcp
R Gem	53791	34356	+20171	356.78	6	14	2.12	Se	4		50692	0.56+/-0.02	G0V	56537	0.72+/-0.05	A3V
X And	1167	----------	+50003	394.36	8.5	15.2	3.05	Se	5		571	0.87+/-0.09	F2II	4058	0.38+/-0.03	A5Vsb
R CMi	54300	34474	+10154	350.67	7.4	11.6	2.92	Spe	1		58715	0.76+/-0.06	B8Ve			
U Cas	4350	----------	+50014	277.8	8	15.4	2.45	Sse	6		6920	0.37+/-0.03	F8V			

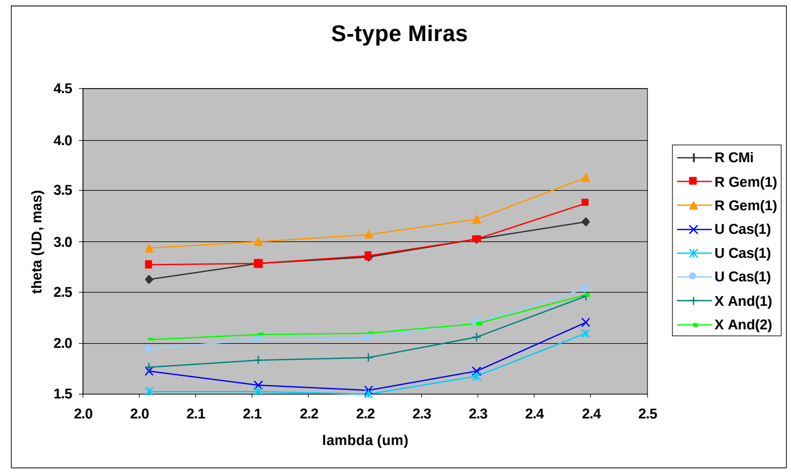


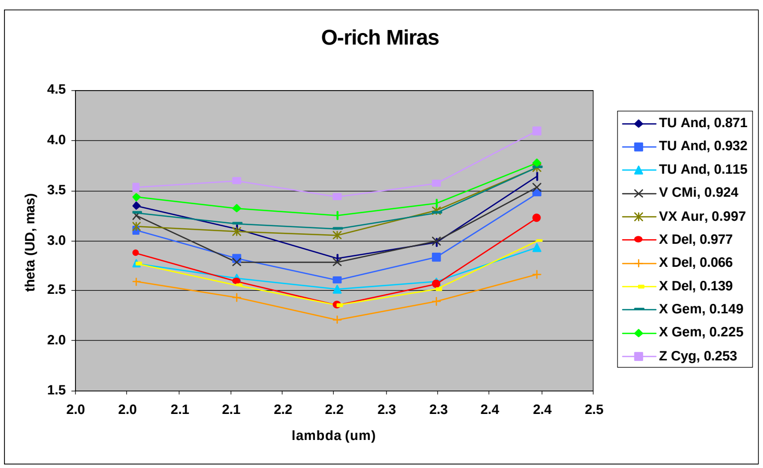
The PTI Mira data set

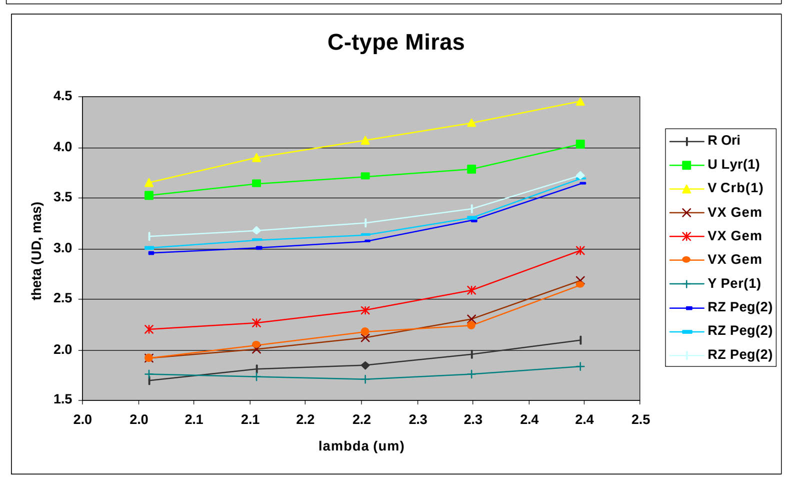
92 spectral observations, binned by phase

	P<325	P >325
M-type	10	6
C-type (R, N)	1	5
S-type	1	3



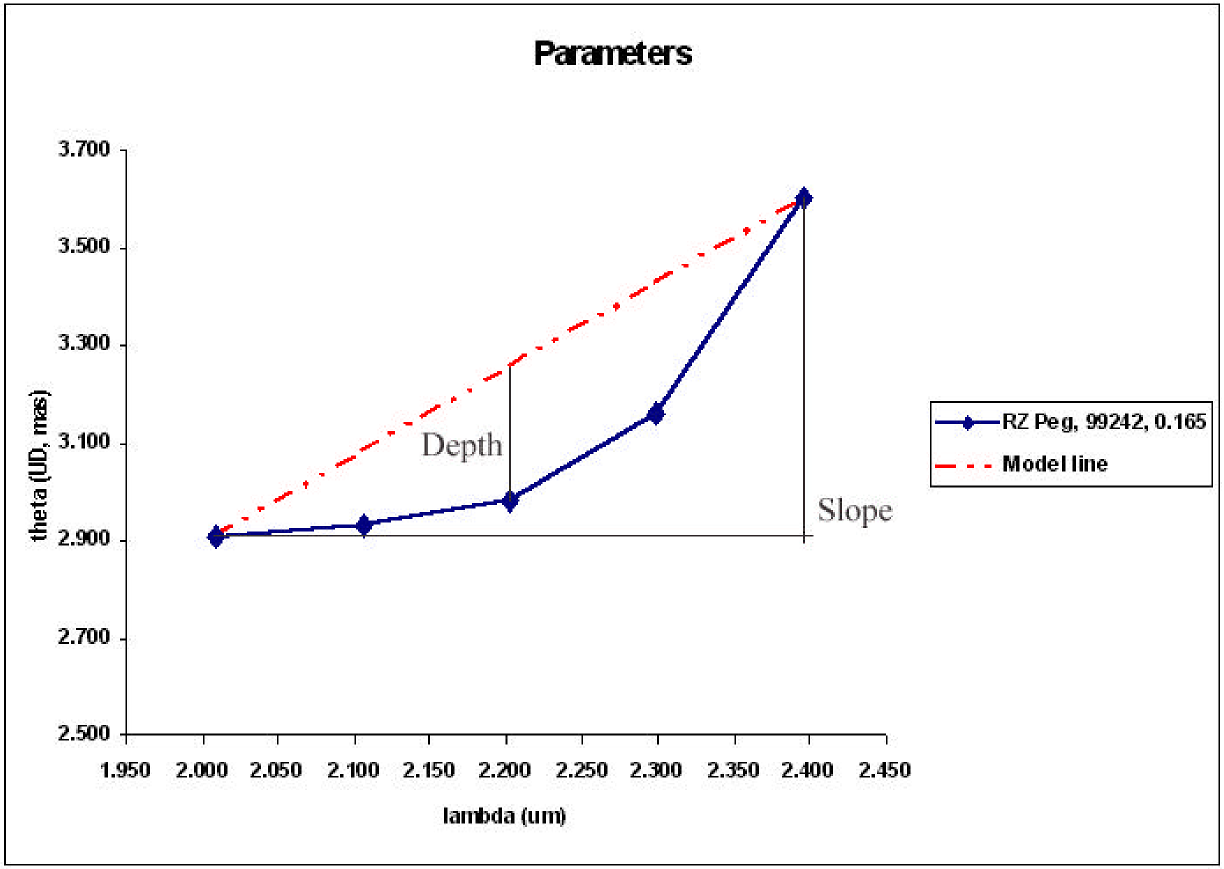






Derived Parameters

- Slope = $\Delta\theta / \Delta\lambda$
- Depth = $\theta_{model}(2.2) - \theta_{data}(2.2)$

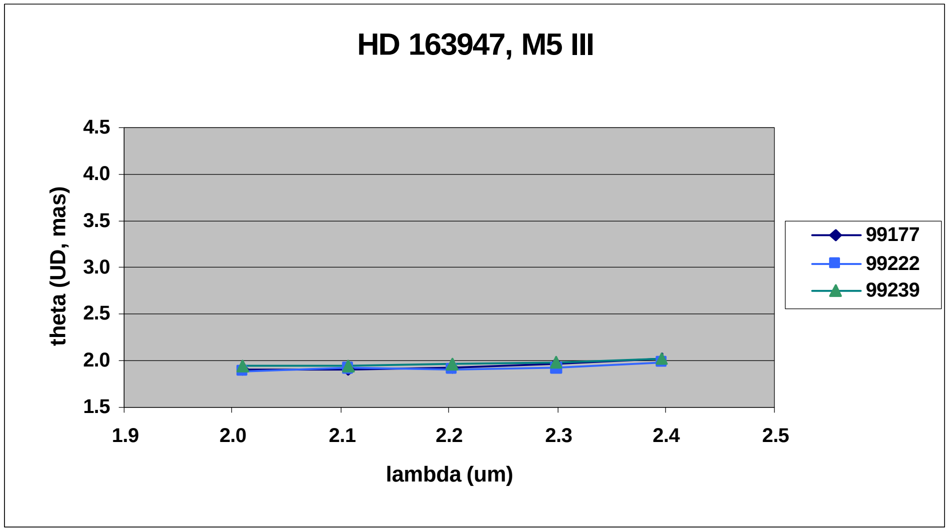


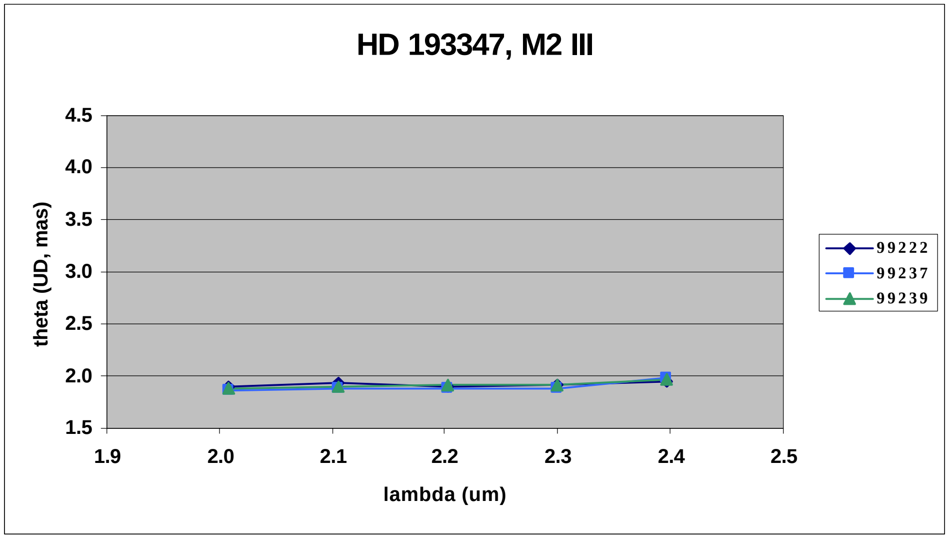
Calibration of the Visibility data

- Selection of calibrating stars based on these criteria whenever possible:
  Size (0.0 - 1.0 mas corresponds to V^2 = 1.0 - 0.9 at 2.2mm, B=100m)
  Distance from target (< 10 deg)
  MK spectral type (main sequence)
  Object type (non-variable ordinary stars)
- Calibrators taken within 15 minutes of target data
- Reduction of visibilities (V^2) considers a temporally-weighted average of the calibrator within a 2-hour window of the individual target scan under calibration. Calibrator visibilities closest to the target scan are given a higher weight than those at the edge of the +/-1 hr window.
- **Statistical errors on angular diameters per night are < 2% (< 0.05 mas).**
- **Statistical errors on all diameter ratios, slopes and depths are < 5%.**
- **All angular diameters are fitted to a uniform disk (UD) model.**

Non-Mira M-type Giants

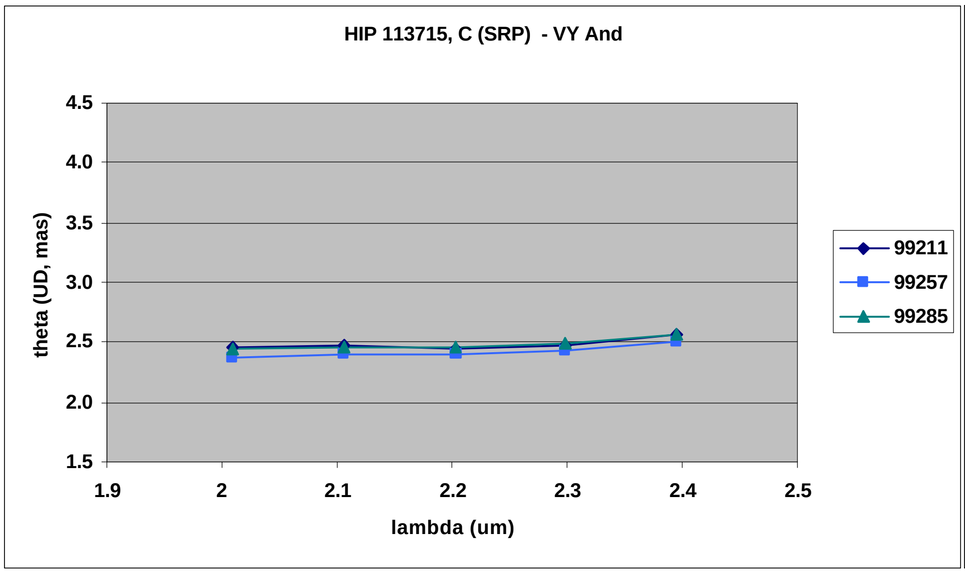
- 2 M-giant stars are shown for comparison to O-rich Miras.
- No 2.2 μm feature is detected.
- Only a very small slope across the K-band for both stars: $\Delta\theta / \Delta\lambda \sim 0.2$

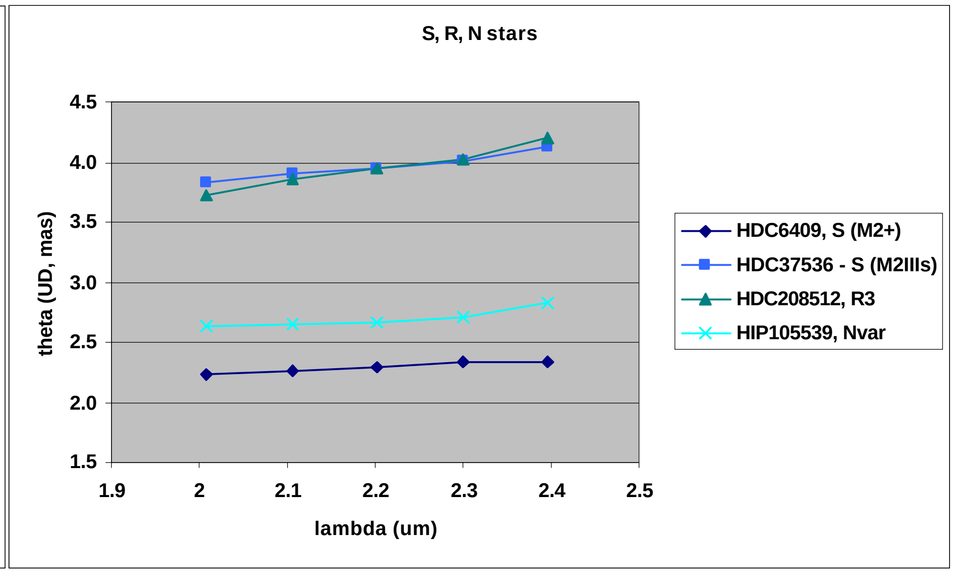




Non-Mira Carbon Giants

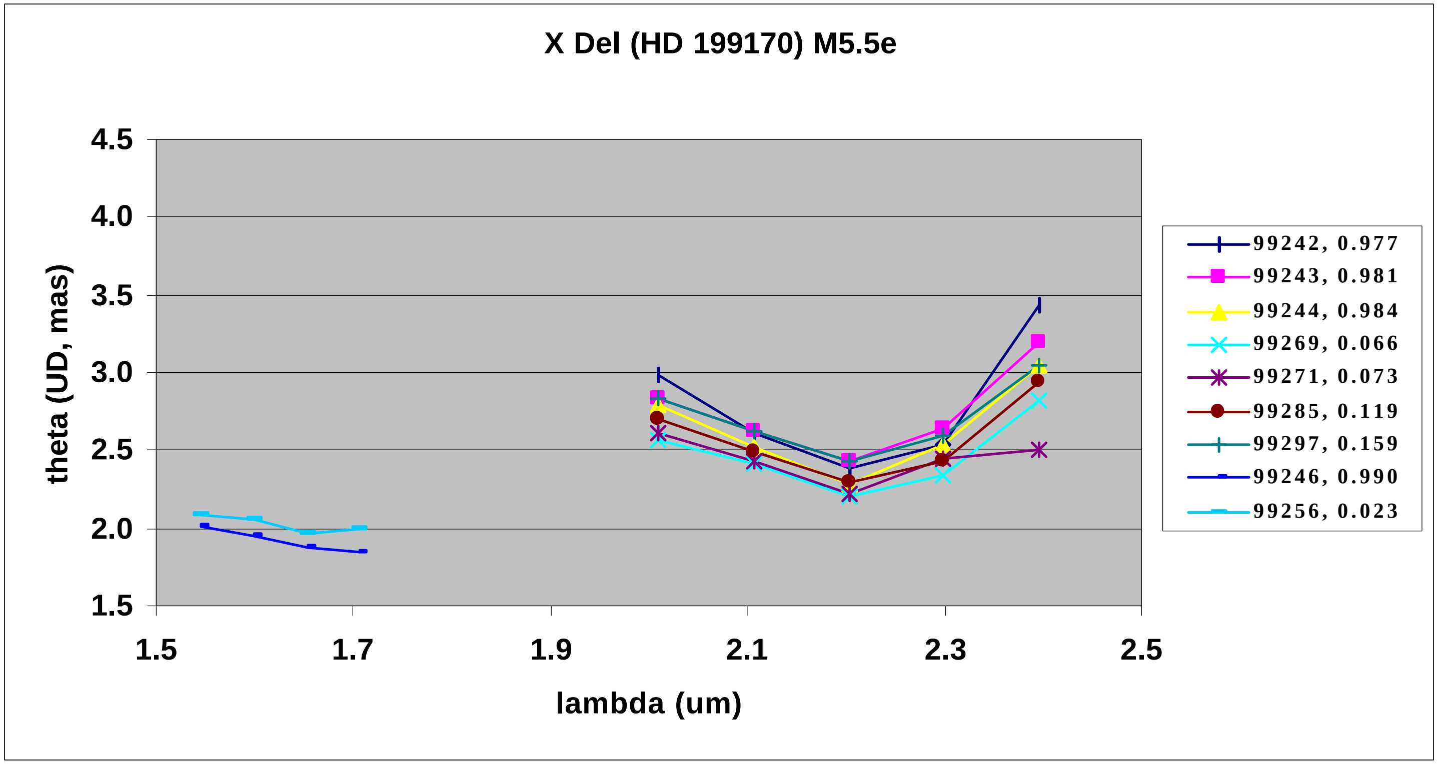
- 3 observations of VY And over 75 days show no 2.2 μm feature, with a slope ($\Delta\theta$ / $\Delta\lambda$) ~ 0.3
- 2 carbon stars show no 2.2 μm feature, with slopes ranging 0.5 – 1.2
- 2 S-type stars show no 2.2 μm feature, with slopes ranging 0.3 - 0.7





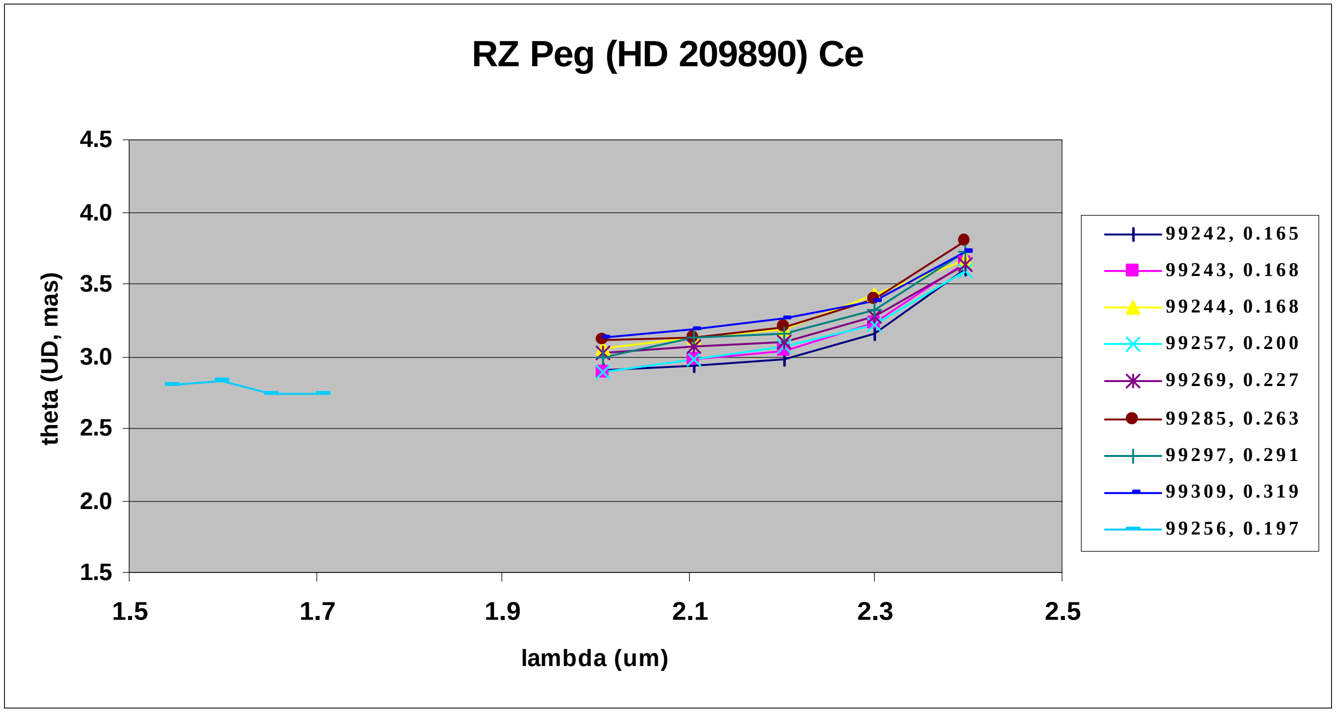
An Oxygen-rich Mira

- P = 301d, M5.5e
- Calibrated, non-normalized data shown spans 55 days, or ~ 20% of X Del's cycle.
- H-band size is ~ 15% smaller than the center 2.2 μm size.



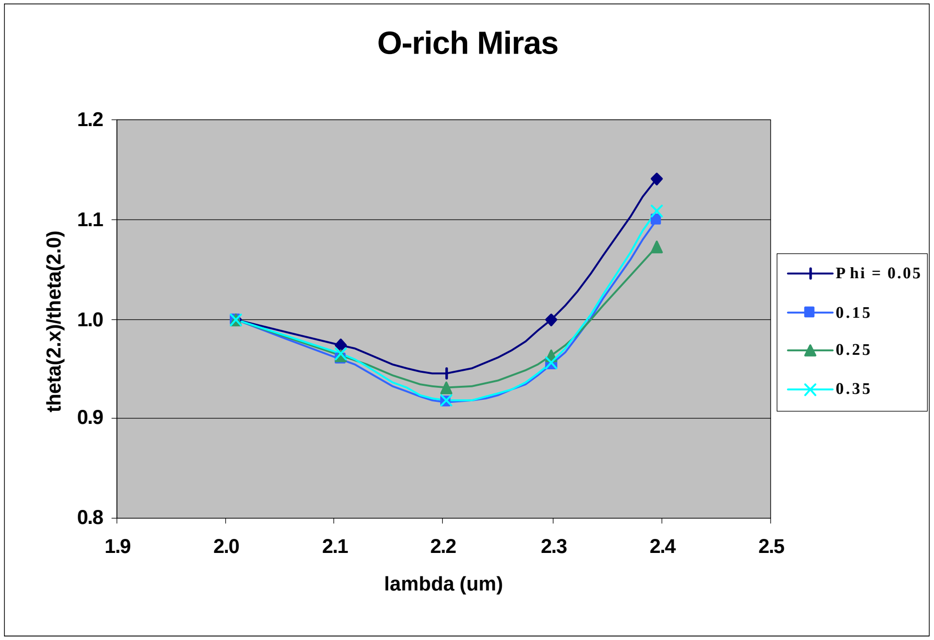
A Carbon-rich Mira

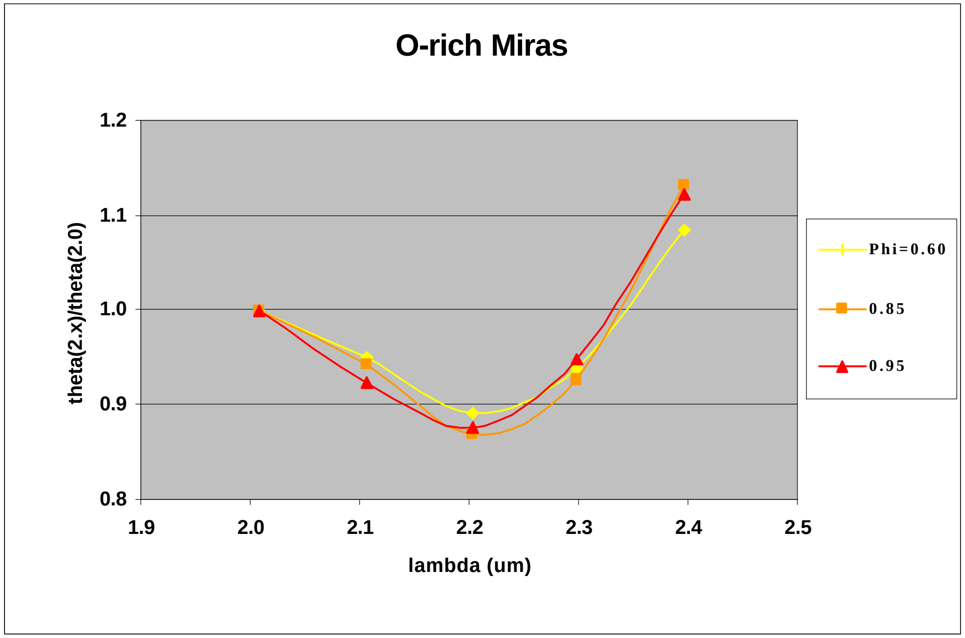
- P = 437.8d, Ce
- Calibrated, non-normalized data shown spans 67 days, or ~15% of RZ Peg's cycle.
- H-band size is 13% smaller than the center 2.2 μm size.



Composite O-rich Mira

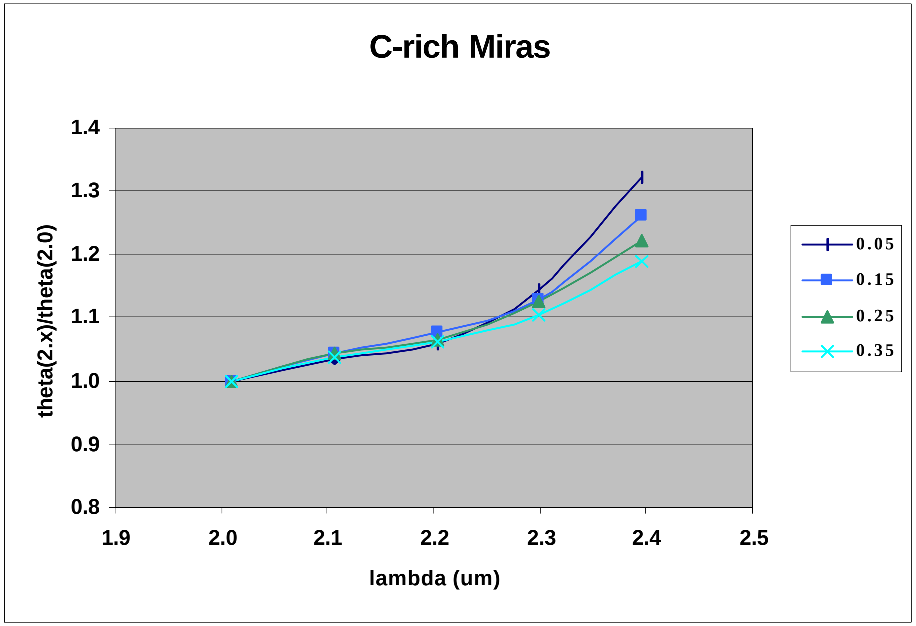
- These panels represent an ensemble average of 16 O-rich Mira stars, normalized to their 2.0 μm size. The V-shape feature centered at 2.2 μm is most pronounced before visual maximum.

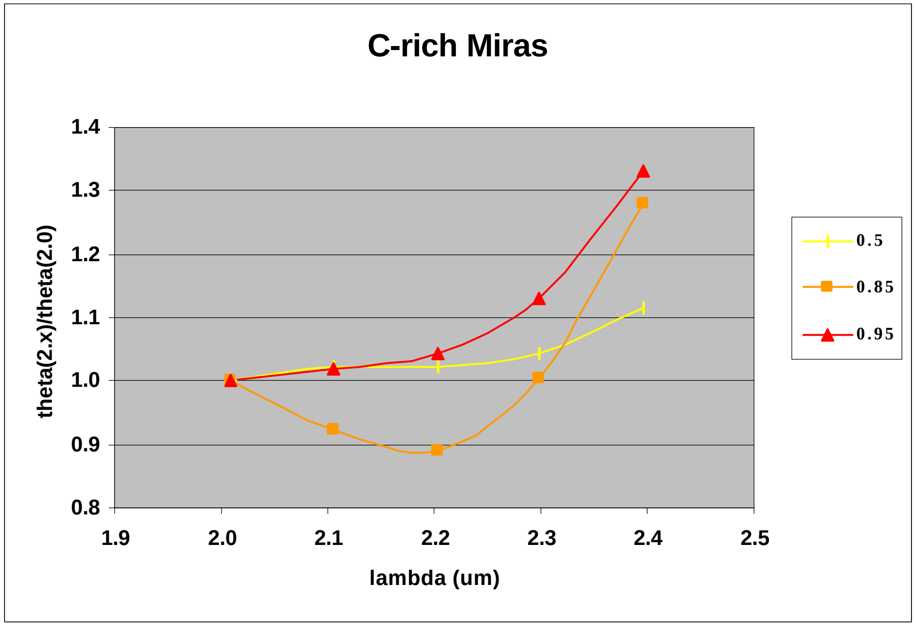




Composite C-rich Mira

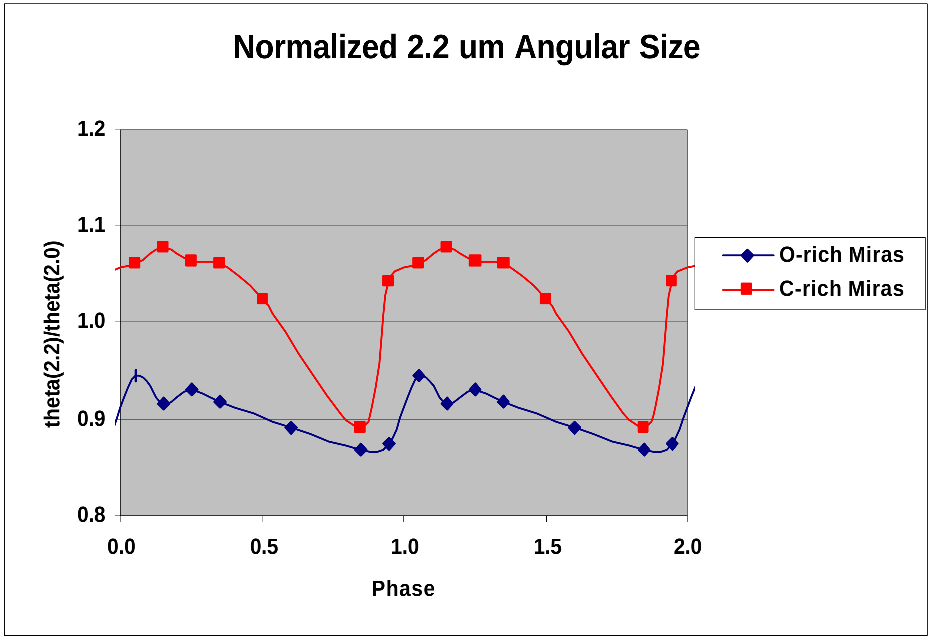
- 10 stars make up the C-rich composite Mira.
- As with the O-rich composite star, the C-rich composite Mira shows greater 2.2 μm absorption near $\phi \sim 0.9$. However, this minimum angular size effect recovers quickly after only 0.1 of phase.
- The 2.4 μm size changes markedly over the course of one cycle.

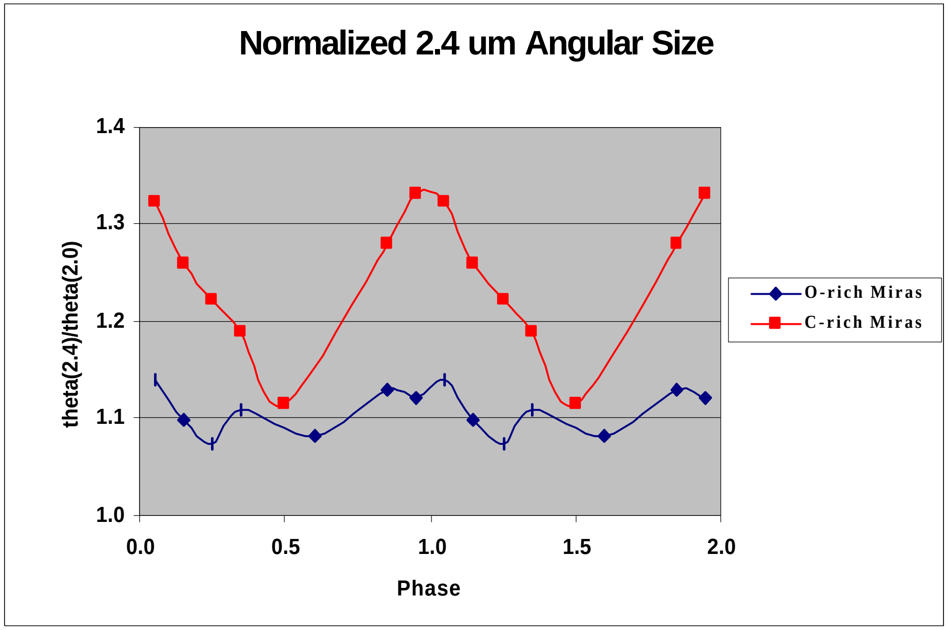




Normalized Angular Sizes

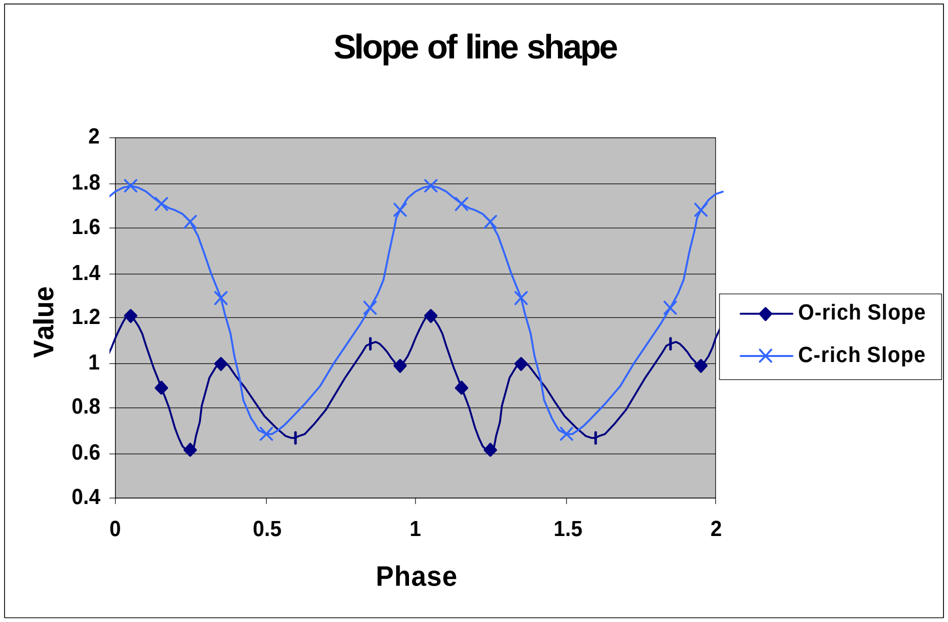
- No true continuum exists within the spectral channels; however the 2.0 μm angular size changes are the smallest. It is then taken to be the continuum in this data set.
- Changes in the 2.2 μm and 2.4 μm sizes are more pronounced in the C-rich Miras. The C-rich Miras are much more extended across the K-band than are O-rich Miras; additionally, the C-rich Miras tend to have greater amplitude variations in 2.2 μm and 2.4 μm sizes.

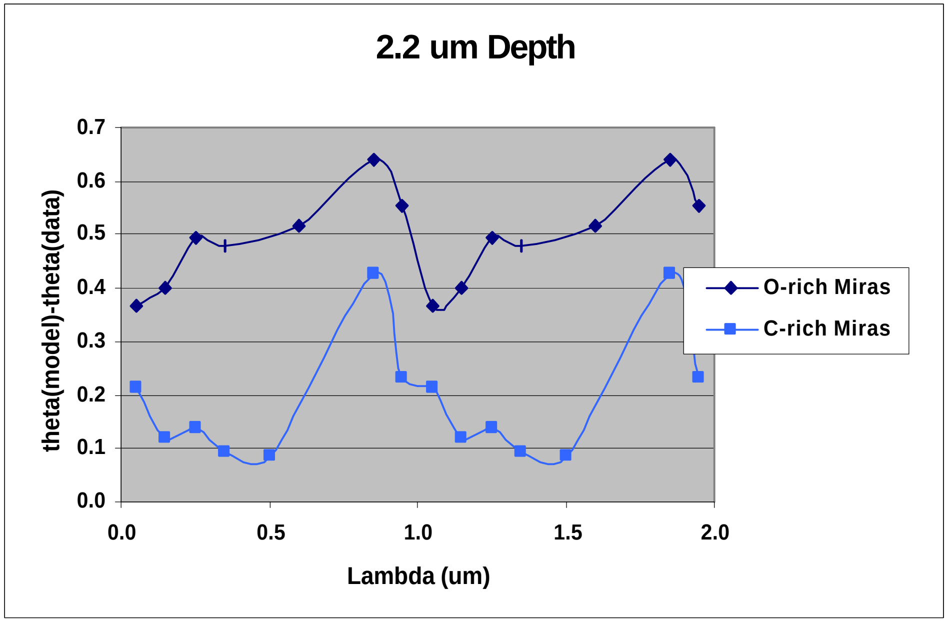




Changes in line slope and 2.2μm depth

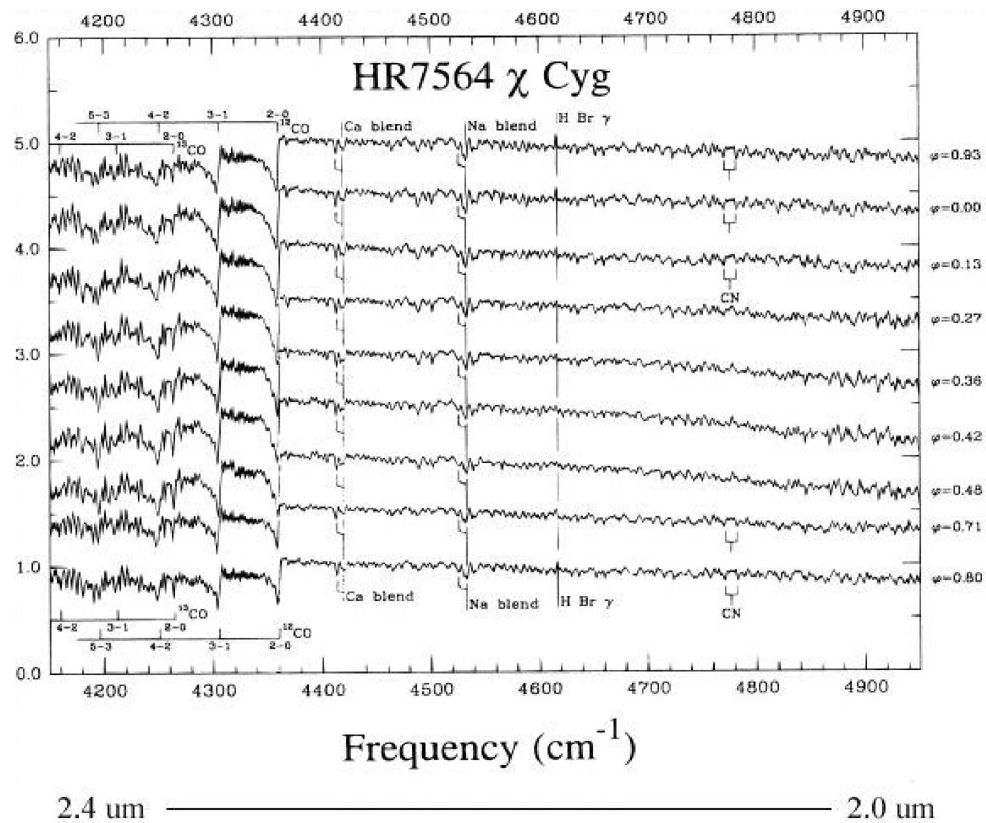
- **Line slope**: O-rich Miras have a multiple peak structure, implying intervals of expansion/compression within the K-band. The peak at $\phi \sim 0.05$ is followed by a fast compression at $\phi \sim 0.35$. C-rich Miras show a smooth interval of expansion and compression within the K-band, being widest at $\phi \sim 0.05$ and thinnest at $\phi \sim 0.50$. They are also much more extended in the K-band than their O-rich counterparts.
- **Depth**: This parameter is the deviation from the endpoint model line to the actual data. In O-rich Miras, the 2.2 μm deviation is greatest just before visual maximum, and takes a sharp dip just after this maximum. For C-rich Miras, this deviation is also a maximum near $\phi \sim 0.9$, but gradually reaches a minimum near $\phi \sim 0.5$.
- The O-rich depth curve is clearly much larger than that for C-rich Miras, and is a consequence of the “V” shape character in their diameter spectra.



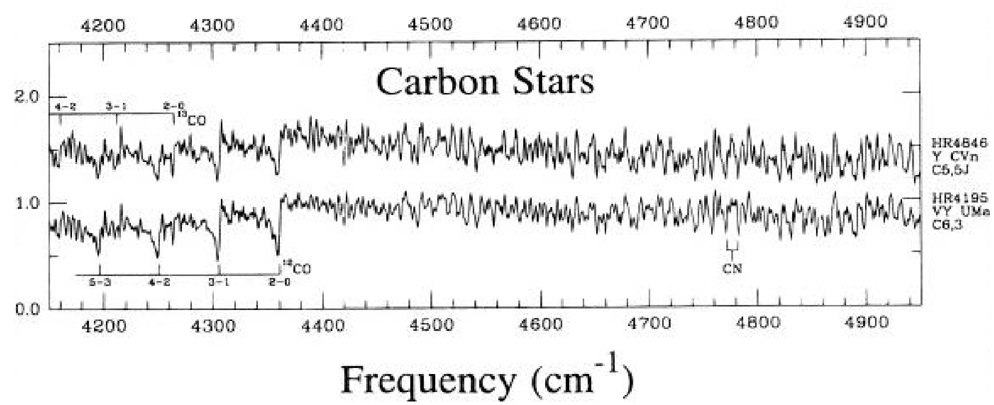


Spectroscopic Data

- K-band spectra of χ Cyg (S-type Mira) showing changes with phase along with some line identifications.



- Spectra of two non-Mira carbon stars.
- (Wallace and Hinkle, 1997)



Future Work

Further investigation is needed to see how various chemical species play a role with respect to the character of the spectral angular diameter data for O-rich, C-rich and S-type Miras:

^{12}CO and ^{13}CO, CN, OH and H_2O (stellar lines and instrumental/atmospheric effects), various metals (Si, V, Sc, Ti) and metal compounds in low-temperature (< 3000K) atmospheres using available spectroscopic data.

The IR camera (NICMOS-3) in use at PTI provides a wavelength resolution of R ~ 22. A new IR camera (HAWAII) is being developed and will be online at PTI beginning March 2000. This camera will yield a wavelength resolution of R ~ 90.

Other considerations...

Distances and Linear Radii

Period-length correlation

Radial velocity correlation

The presence/absence of Si and OH circumstellar masers

The role of acoustic shocks

Acknowledgements

This work made extensive use of the following databases: Association Francaise des Observateurs d'Etoiles Variables (AFOEV), American Association of Variable Star Observers (AAVSO), and SIMBAD (CDS/Strasbourg).

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