Evidence for very extended gaseous layers around O-rich Miras and M giants

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ABSTRACT

Nine bright O-rich Mira stars and five semi-regular variable cool M giants have been observed with the IOTA (Infrared and Optical Telescope Array) interferometer in both K'($\sim 2.15\,\mu m$) and L'($\sim 3.8\,\mu m$) broad-band filters, in most cases at very close variability phases. All of the sample Mira stars and 4 of the semi-regular M giants show strong increases, from $\simeq$ 20 to $\simeq$ 100%, in measured uniform disk diameters between the K' and L' bands. (A selection of hotter M stars does not show such a large increase.) There is no evidence that K' and L' broad-band visibility measurements should be dominated by strong molecular bands, and cool expanding dust shells already detected around some of these objects are also found to be poor candidates for producing these large apparent diameter increases. Therefore we propose this must be a continuum or pseudo-continuum opacity effect. Such an apparent enlargement can be reproduced using a simple 2-component model consisting of a warm (1500 K-2000 K) extended ($\simeq$ up to 3 stellar radii) optically thin ($\tau \simeq 0.5$) layer located above the classical photosphere. The Planck weighting of the continuum emission from the two layers will suffice to make the L' uniform disk (UD) diameter appear larger than the K' UD diameter. This 2-layer scenario could also explain the observed variation of Mira UD diameters versus infrared wavelength - outside of strong absorption bands - as already measured inside the H, K, L and N atmospheric windows. This interpretation is consistent with the extended molecular gas layers (H_2O, CO ...) inferred around some of these objects from previous IOTA K' band interferometric observations obtained with the Fiber Linked Unit for Optical Recombination (FLUOR), and from ISO and high resolution ground-based FTS infrared spectra. The two component model has immediate implications. For example, the Mira photosphere diameters are smaller than previously recognized - this certainly implies higher effective temperatures, and may favor fundamental mode pulsation. Also, the uniform disk model fails generally to represent the brightness distribution and has very limited applicability for Mira stars. The presence of a very extended gas layer extending up to $\simeq$ 3 stellar radii seems now well established on a fair sample of AGB stars ranging from late type giants to long period variables, with some probable impact on stellar model atmospheres and mass loss mechanisms.

Subject headings: stars:variables:general –stars:atmospheres, circumstellar matter – –instrumentation: interferometers –stars:individual: R Aquarii, R Cassiopeiae, U Herculis, Chi Cygni, R Cancri, R Leonis Minoris, U Orionis, o Ceti, R Leonis, SW Virginis, RT Virginis, RX Bootis, g Herculis, RS Cancri

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1. Introduction

Due to their large angular scale and unusually high infrared brightness, late type stars, and particularly Miras, have been extensively observed in the near to thermal infrared using high angular resolution imaging techniques. Many such observations have been reported lately, either using single-telescope aperture masking (Tuthill, Haniff, & Baldwin 1995; Tuthill et al. 2000b; Haniff, Scholz, & Tuthill 1995; Tuthill, Haniff, & Baldwin 1999), direct near IR long baseline interferometry e.g.(Perrin et al. 1999; Young et al. 2000) or mid-infrared heterodyne interferometry (Danchi et al. 1994; Lopez et al. 1997; Weiner et al. 2000). From this body of work emerges a very complex description of the stellar photosphere and near-in environments of Miras, with repeated occurrences of strong asymmetries, large chromatic size variations - particularly pronounced in regions of deep molecular absorption by species such as TiO or VO - evidence for clumps, hot spots, and of course phase variability of the whole structure. Consequently the modeling of generally partial (in azimuth or spatial frequency) visibility measurements is very delicate and many fundamental aspects of Mira variables still remain unclear. This is illustrated by the continuing debate on the pulsation mode of these objects (Willson 2000; Whitelock & Feast 2000; Wood 1999) and the difficulties to fit the data with existing limb darkening models. As already stated (Hofmann, Scholz, & Wood 1998), one major problem arises from the difficulty to retrieve accurate Rosseland diameters and corresponding physical characteristics - such as effective temperatures or modes of pulsation - from interferometric observations at monochromatic wavelengths or in various broad-band filters. The effects of limb darkening, atmospheric extension and variability phase are very difficult to implement in the models, especially close to strong molecular absorption lines (see for instance the effect of TiO at 710 nm in Haniff et al. 1995). One hope was that infrared measurements would be less sensitive to limb darkening effects and should provide less contaminated or true "photosphere" size estimates, commensurate with Rosseland diameters and rather constant versus wavelength or phase (Tej et al. 1999). Unfortunately angular diameters measured in the infrared show complex behaviors similar to optical diameters, as already suggested by previous measurements of individual stars (Tuthill, Monnier, & Danchi 1999; Mennesson et al. 1999b; Tuthill, Monnier, & Danchi 2000) and extensively reported in this paper. Yet we believe that the chromatic dependence of Mira star apparent uniform disk diameters in the near infrared, specially in the 2-4 micron region, can be efficiently used to constrain the near-in stellar atmospheric structure. This is illustrated by the following analysis of our K'/L' band data, related to other high angular or spectral resolution measurements when available.

In the next section we briefly describe our observational set-up. We present the experimental results in Sect. 3 and give a general interpretation of these in Sect. 4, in comparison with relevant models and observations.

2. Observations

All measurements presented here were acquired on the Infrared and Optical Telescope Array IOTA (Traub 1998) with baselines ranging from 15 to 38 m. They used the FLUOR single-mode guided optics instrument (Perrin 1996; Coudé du Foresto et al. 1998) in the K' or K band (2.0 to 2.4 microns) and "TISIS" (Thermal Infrared Stellar Interferometric Set-up,) FLUOR's extension to the L' band (3.4 to 4.1 microns). The L' band experiment saw first light in April 1998 (Mennesson et al. 1999a). All L' data reported here were obtained in 2000 with an upgraded version using a dedicated L' single-mode coupler and slow background chopping (0.01 to 0.1 Hz, which was found to be sufficient for bright objects) with IOTA tertiary mirrors. November 2000 data used both complementary interferometric outputs and are of better quality than those obtained in March 2000 with a single photometer. FLUOR monitors both the incoming flux coming from each telescope and the interferometric fluxes. In contrast to FLUOR, TISIS uses a simple single-

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mode fluoride glass coupler and only measures the interferometric signals. Owing to this lack of absolute photometric calibration, TISIS achieves a mean relative accuracy of 1 to 5% on visibility measurements, to be compared to 1% or better with FLUOR.

Unless specified in the results, the characteristics of these K' and L' filters are the following: K' (λ_{mean}=2.16 μm, FWHM=0.32 μm, λ_{eff}=2.13 μm) and L' (λ_{mean}=3.79 μm, FWHM=0.54 μm, λ_{eff}=3.77 μm). FLUOR measurements carried out before 2000 used a regular K filter (λ_{mean}=2.20 μm, FWHM=0.44 μm, λ_{eff}=2.15 μm). The effective wavelength λ_{eff} sets the observing spatial frequency at a given baseline. For a definition of λ_{eff} and of the general data reduction of broadband interferograms obtained with single-mode waveguides, please refer to Coudé du Foresto, Ridgway, & Mariotti (1997) and Perrin et al. (1998).

3. Experimental results

The azimuth coverage of the observations is small (below 30^0) in all cases. In addition, we generally do not fully resolve the stars in L', with the sole exception of χ Cygni. Therefore we chose to represent the data set by UD best fits. They should just be regarded as raw parameters for a preliminary diagnosis and analysis of the atmospheric structure. Using UD fits also avoids the modeling difficulty encountered when deriving Rosseland diameters from visibility measurements (Hofmann et al. 1998), mostly in this case where only first lobe measurements are available, i.e. low resolution information on the center to limb variation. Besides, chromatic variations in UD diameters are obviously related to true physical variations in stellar atmospheric structure with wavelength. Tables 1 and 2 show a summary of the results obtained in the two observing runs of February/March 2000 and October/November 2000. Note that in some cases - R Cassiopeiae, Chi Cygni, o Ceti, R Leonis, and RS Cancri in November 2000 - the quoted error bars on the UD diameters are assymetric and much larger than the formal error bars deduced from a least squared fit of the visibility data. That is because these stars were found to depart strongly from UD models, and we prefered to give L' band UD diameter *intervals* in that case. The mean UD diameter is computed using all spatial frequencies available. The UD diameter "error bar" is given by the smallest and largest UD diameters obtained when fitting each visibility point individually. For the other stars in the sample, either a single spatial frequency was observed (R Aquarii, U Herculis, R Cancri, R Leonis Minoris, RT Virginis, RX Bootis, g Herculis, RS Cancri in March 2000), or no significant departure from UD models was detected (U Orionis and SW Vir), which seems to be the exception. In these two cases, the quoted error bar on the UD diameter comes directly from the least squared fit residuals, using all visibility points available. Luminosity phases were determined using the AFOEV [7] database. For each observing campaign, all stars have been observed in the two spectral channels within 25 days maximum, with the exception of R Leonis and RS Cancri. Additional measurements obtained at other phases or in different filters with FLUOR/TISIS are also given for R Leonis and o Ceti.

3.1. General results

An exhaustive list of L' visibility measurements obtained with TISIS on Miras, supergiants and semi-regular variable red giants will be given in a forthcoming paper (Chagnon et al. in preparation). We concentrate here on the observational results obtained on evolved stars. Yet, owing to the importance of the chromatic size variations reported here, it is worthwhile noting that no similar variations with phase or wavelength has been detected by the FLUOR and TISIS instruments on any giants or supergiants with a type earlier than M5. This is illustrated for instance by K'/L' measurements of the M5II supergiant α Herculis, showing no variation in UD diameters at the 1% level (Perrin et al. in preparation). We also note that conversely to Miras, these earlier type stars show L' band visibility curves in very good agreement with UD models.

3.1.1. UD diameter vs wavelength

All of the O-rich Mira stars in the sample (8 of spectral type M and one, χ Cygni, of spectral type S) and four of the M giant semi-regular variables

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[7] AFOEV: Association Francaise des Observateurs d'Etoiles Variables

Table 1: UD diameter best fits (ϕ) obtained for 9 Miras variables using K' and L' FLUOR/TISIS measurements. Variability phases are averaged over the time of the observations. For o Ceti narrow band measurements around 2.03, 2.15, 2.22 and 2.39 microns, the filters FWHM is $\simeq 100\,\text{nm}$.

Star	Spectral Type	Date (yy/mm/dd)	Variab. phase	Filter	ϕ (mas)
R Aquarii	M7IIIpevar (Mira)	00/10/18	0.41	K'	16.88 ± 0.56
		00/11/20	0.51	L'	34.32 ± 1.09
R Cassiopeiae	M7IIIe (Mira)	00/10/14-15	0.09	K'	24.78 ± 0.09
		00/11/14-23	0.17	L'	$31.09^{+2.58}_{-4.31}$
U Herculis	M7III (Mira)	00/02/19-26	0.23	K'	10.98 ± 0.01
		00/03/10	0.27	L'	14.26 ± 0.47
Chi Cygni	S (Mira)	00/05/15-24	0.38	K'	23.24 ± 0.08
		00/11/14-23	0.81	L'	$30.40^{+3.30}_{-7.28}$
R Cancri	M7IIIe (Mira)	00/02/26	0.34	K'	11.58 ± 0.02
		00/03/11	0.37	L'	16.59 ± 0.42
		00/10/16	0.96	K'	10.04 ± 0.08
		00/11/20	1.06	L'	13.39 ± 2.45
R Leonis Minoris	M7e (Mira)	00/02/19	0.37	K'	11.85 ± 0.01
		00/10/16	0.97	K'	10.48 ± 0.05
		00/11/20	1.08	L'	21.44 ± 0.70
U Orionis	M8III (Mira)	00/10/15-18	0.88	K'	15.59 ± 0.06
		00/11/15-20	0.96	L'	25.66 ± 0.69
o Ceti	M7IIIe (Mira)	97/12/19	0.94	K	28.79 ± 0.10
		00/10/18	4.02	$2.03\mu m$	25.73 ± 0.09
		00/10/18	4.02	$2.15\mu m$	25.13 ± 0.08
		00/10/18	4.02	$2.22\mu m$	25.19 ± 0.12
		00/10/18	4.02	$2.39\mu m$	29.22 ± 0.12
		00/10/18	4.02	K'	24.40 ± 0.11
		00/11/14-23	4.11	L'	$35.21^{+2.75}_{-1.27}$
R Leonis	M8IIIe (Mira)	96/04/17-18	0.24	K	28.18 ± 0.05
		97/03/04	1.28	K	30.68 ± 0.05
		00/03/10-14	4.81	L'	$36.02^{+0.43}_{-0.52}$
		00/11/14-22	5.62	L'	$39.08^{+1.49}_{-3.30}$

Table 2: UD diameters best fits (ϕ) obtained for 5 semi-regular variables (b type) using K' and L' FLUOR/TISIS measurements. By definition one can not give accurate luminosity phases for these objects.

Star	Spectral Type	Date (yy/mm/dd)	Filter	ϕ (mas)
SW Virginis	M7III (SR b)	00/02/29	K'	16.24±0.06
		00/03/09-14	L'	22.88±0.33
RT Virginis	M8III (SR b)	00/02/18	K'	12.38±0.13
		00/03/11	L'	16.24±0.73
RX Bootis	M7.5III (SR b)	00/02/29	K'	17.48±0.13
		00/03/10-12	L'	21.00±0.27
g Herculis	M6III (SR b)	00/02/27	K'	12.67±0.04
		00/03/12	L'	20.84±0.59
RS Cancri	M6IIIase (SR b)	96/04/17	K'	14.27±0.09
		00/03/14	L'	21.71±1.09
		00/11/17-22	L'	$14.81^{+3.22}_{-2.93}$

(SW Virginis, RT Virginis, RX Bootis and g Herculis) show the same trend (tables 1 and 2): a large (> 20%) increase in UD diameter between K' and L'. The amplitude of the effect varies strongly with the star. R Aquarii and R Leonis Minoris clearly stand out in the sample with enlargements from K' to L' of $\simeq$ 100% at variability phases only differing by 0.10. The detailed circumstellar structure obviously differs from one star to another, with peculiar characteristics in some cases - e.g. R Aquarii is a symbiotic star - but there could be a common simple cause for such a systematic effect.

Note that for R Leonis and RS Cancri, the K' and L' observations were not conducted at close variability phases. Each of the R Leonis K' measurements provides size estimates noticeably smaller than in L though, implying that this effect is real. For RS Cancri, more observations will be required to reach a conclusion about the K'/L' behavior.

3.1.2. UD diameters vs variability phase

Four Mira stars have been observed at different variability phases in K' and/or L': R Cancri, R LMi, o Ceti and R Leo. In all cases the apparent UD diameter is larger when the star is observed closer to its luminosity minimum. This effect is also observed in L' on the only semi-regular variable that was observed at two different epochs: RS Cancri. Although these first results may indicate a trend, the time-coverage is not yet sufficient to draw conclusions.

3.1.3. Study of possible correlations

The L' to K' UD diameter ratio was investigated for possible correlation with a number of parameters, namely the star variability phase, variability period, infrared excess, spectral type, visible magnitude variation amplitude (as provided by the records of the AFOEV) and mass loss rate. We used the stellar physical parameters listed in table 3. Magnitude differences between 12 and 25 μm were derived from IRAS measurements (Beichman et al. 1988) using the same relation as in Walker & Cohen (1988), i.e. [12]-[25] = 1.56 - 2.5 $\log(F_{12}/F_{25})$, with F_{12} and F_{25} the IRAS fluxes in Janskys at 12 and 25 μm. Phases given are mean visible luminosity phases at the time of K' or L' observations. For R Leonis and RS Cancri no K'/L' observations at close phases are available, and diameter error bars reflect measurements at different epochs of the cycle. Mass-loss rates estimates are taken from Loup et al. (1993) or from Lebertre & Winters (1998).

The conclusion is that no strong correlation was found between the UD diameter ratio and any of these parameters. A possible exception is the mass loss rate, for which a weak correlation was found. Note however that for different authors and methods of computation (radio observations of CO emission lines, empirical photometric relations , etc...), there is a large scatter of mass loss rate estimates in the literature (generally within a factor of 3 or more) so that correlation with this parameter is difficult to assess.

3.2. Individual stars results

As representative examples of the effects reported here, we present the visibility curves and UD diameter estimates obtained in K' and L' for o Ceti, R Aquarii and R Leonis, three very well known Mira stars that have been observed extensively at high resolution from the near infrared to the radio domain.

3.2.1. o Ceti

Figure 1 shows visibilities measurements and best UD fits in K' (October 2000) and L' (November 2000) bands for o Ceti. o Ceti is the Mira prototype star with a spectral type M7IIIe and a period of 332 days. We observed it close to its maximum variability phase in October/November 2000, yielding UD diameter fits of 24.40±0.11 mas in K' and $35.21^{+2.75}_{-1.27}$ mas in L'. The observed enlargement with increasing wavelength is then 44% for variability phases only differing by 0.09. The K band UD diameter previously measured in December 1997 is also consistent with a much smaller apparent size in K band, although no L' measurements were available at the same epoch. Data obtained in December 1998 with an earlier less accurate version of TISIS also confirm the larger L' diameter (Mennesson et al. 1999b), so that the chromatic effect is now well established. The ISO spectrum (Yamamura, de Jong, & Cami 1999) of o Ceti does not show any significant absorption features in the region covered by the L' filter: only the very edges are contaminated by residual OH and SiO absorptions. Similarly our FLUOR narrow band data (table 1, and Perrin et al. in preparation) show a small difference between K' broad-band UD diameter and narrow band UD diameters measured in the "continuum" around 2.15 and 2.22 μm. This shows that o Ceti broad-band K' diameter estimates are fairly unaffected by substantial molecular absorption. The strong effect of CO and H_2O only appears in the 2.39 μm narrow-band measurements, at the very edge of the K' filter.

3.2.2. R Aquarii

Figure 2 shows visibility measurements and best UD fits in K (October 2000) and L' (November 2000) bands for R Aquarii, a mass-losing long period ($\simeq$ 387 days) Mira variable, with a spectral type M7III. R Aquarii is believed to be in a symbiotic system. Recent aperture masking measurements (Tuthill et al. 2000b) placed an upper limit of around $\Delta_M > 5mag$ for the relative infrared (J to K) brightness of the potential companion. We observed R Aquarii close to its minimum variability phase in October/November 2000, yielding UD diameter fits of 16.88±0.56 mas in K and 34.32±1.09 mas in L', which represents a relative enlargement of 103% for variability phases only differing by 0.10. This enlargement may be due to the continuum emission of an upper layer contributing a significant fraction of the stellar flux as wavelength increases - our favored model discussed at greater length below - or may indicate the presence of a cold companion, only visible at longer infrared wavelength. This last assumption is consistent with the significant deviation from circular symmetry found by aperture masking at 3.08μm and not at shorter wavelengths.

3.2.3. R Leonis

R Leonis is a Mira star of spectral type M8IIIe with a period of 310 days. This is the only case in our sample, where UD diameter measurements in K' and L' were taken at substantially different phases. Yet they show the same trend as the other stars: a marked increase in size from K to L', of the order of 20-30%. K band data recorded in April 1996 and March 1997 were analyzed previously (Perrin et al. 1999). These data showed

Table 3: Physical properties of Miras and semi-regular variable stars observed with FLUOR/TISIS. The last line indicates the correlation coefficient between the measured L' to K' UD diameter ratios ($\phi_{L'}/\phi_{K'}$) at a given luminosity phase, and the various stellar parameters. For R Leonis and RS Cancri measurements are not obtained at close phases, so all observations are used to derived UD diameter ratios. [12]-[25] magnitude differences are derived from IRAS measurements (see text). dM/dt is the stellar mass-loss rates estimates from (a): Loup et al. 1993 or (b): Lebertre & Winters 1998. Δm_V is the typical stellar visible magnitude variation during one luminosity cycle.

Star	Period (days)	[12]-[25]	dM/dt ($M_\odot$/yr)	Δm_V	phase	$\phi_{L'}/\phi_{K'}$
R Aquarii	387	0.40	[b]$3.0\,10^{-7}$	5	0.46± 0.05	$2.03^{+0.14}_{-0.12}$
R Cassiopeiae	431	0.60	[a]$1.1\,10^{-6}$	7	0.13 ± 0.04	1.25±0.01
U Herculis	405	0.45	[a]$2.6\,10^{-7}$	6.5	0.25 ± 0.02	1.30±0.05
Chi Cygni	408	0.15	[a]$5.6\,10^{-7}$	8.5	0.59± 0.22	1.31±0.01
R Cancri	362	0.49	[b]$2.0\,10^{-8}$	5	0.36 ± 0.02	1.43±0.04
					0.01± 0.05	1.33±0.12
R Leonis Minoris	372	0.60	[a]$2.8\,10^{-7}$	5.5	0.03± 0.05	2.04±0.05
U Orionis	372	0.51	[b]$3.0\,10^{-7}$	6.5	0.92±0.04	1.65± 0.02
o Ceti	332	0.72	[a]$5.0\,10^{-7}$	7	0.06± 0.05	1.44±0.01
R Leonis	310	0.26	[a]$1.0\,10^{-7}$	5.5	-	1.28±0.11
SW Virginis	150	0.81	[a]$5.7\,10^{-7}$	2.5	-	1.41±0.02
RT Virginis	-	0.77	[a]$7.4\,10^{-7}$	1	-	1.31±0.06
RX Bootis	195	0.80	[a]$8.1\,10^{-7}$	1.5	-	1.20±0.01
g Herculis	89	0.39	[a]$2.6\,10^{-7}$	1	-	1.64±0.05
RS Cancri	120	0.66	[a]$5.2\,10^{-7}$	1.5	-	$1.28^{+0.33}_{-0.27}$
Correlation factor	0.145	-0.133	-0.344	0.084	0.114	

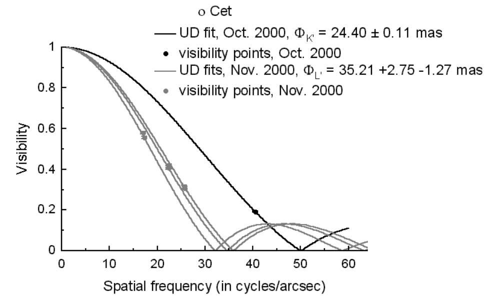

Fig. 1.— o Ceti observations: October (K') and November (L') 2000. Visibility measurements and best uniform disk fits. A significant departure from the UD model is visible in the L' data. The mean UD L' diameter is computed using the 3 available spatial frequencies. The L' UD diameter error bar is given by the smallest and largest UD diameters obtained when fitting each visibility point individually.

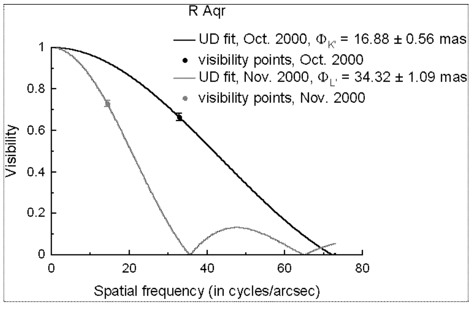

Fig. 2.— R Aquarii observations: October 2000 (K') and November 2000 (L'): visibility measurements and best uniform disk fits.

size variability with phase and residual visibilities at high spatial frequency. They were best fitted using an extended brightness distribution, as derived in models of molecular scattering by CO and H_2O (Hofmann, Scholz, & Wood 1998). We also note that the apparent UD diameter in L' increases by 9% between phases 0.81 and 1.62 during the 2000 observations. These fluctuations with phase may be due to changes in the spatial extent - and/or in opacity- of the outer atmospheric layers, as already deduced for R Leonis and Chi Cygni from COAST interferometric observations (Burns et al. 1998; Young et al. 2000) at 830 nm and 910 nm. K' visibility variations may trace actual variations in the size of the deeper continuum forming layers, while L' variations may reflect opacity or temperature variations in an extended envelope. Accurate modeling of the Center to Limb Variation at each wavelength, and improved spatial frequency coverage in the interferometric measurements, is necessary to disentangle these two effects.

The March 1997 and November 2000 data, which provide the best spatial frequency coverage in each of the K' and L' bands are presented and modeled in more detail in section 4.1.3.

3.2.4. RS Cancri

Uniquely among our observations of semi-regular variables, RS Cancri shows a large change in the L' visibility and implied UD diameter, and this is for observations at similar "phase" separated by two full cycles. Although the variation is much larger than the estimated errors, such a large variation does seem surprising, and this result should be confirmed before drawing conclusions.

4. Discussion

4.1. Interpretation

We are seeking here to advance one general explanation for the observed diameter changes between the K' and L' bands.

4.1.1. General

Substantial absorption lines of molecular H_2O, CO, SiO and CO_2 are visible in some O-rich Miras near infrared spectra (Yamamura, de Jong, & Cami 1999;

Tsuji et al. 1997), but they appear outside the K' and L' filters. Even though some wing absorption features may still be present, the overall stellar flux remains largely overwhelmed by continuum emission for broad-band observations in any of the H, K' and L' filters (Scholz 2001). There is no evidence for molecular bands strong enough to produce large opacity difference between the K' and L' broad-band regions, so that broad-band diameters measured in these filters should be very close to continuum size measurements.

In the absence of obvious strong molecular absorption, the effective opacity in the broad filter bandpasses may be determined by the continuum, or possibly by a large number of weak, overlapping and blended lines which form a pseudo-continuum. This leads us to an interpretation based on a continuum effect. We propose a model consisting of a cool, semi-transparent gaseous shell extending far above the classical photosphere, typically 3 stellar radii away (figure 3). We suggest that the Planck weighting of the emission from the two layers will suffice to make the L' UD diameter appear larger than the K' UD diameter. Owing to the wavelength dependence of the Planck function, the extended cooler ($\simeq 1500\,$K to $2000\,$K) gas layer contributes a larger fraction to the overall stellar flux at $3.8\,\mu m$ than at 2.2 μm for instance. More generally when the star is observed in infrared regions that are beyond the peak emission of the "classical" photosphere ($\lambda > 1-1.5\,\mu$m), emission from this extended region can become important. The variation in apparent size with wavelength is then a temperature effect modulating the relative contribution from the extended atmosphere. Aside from a general increase in apparent size with wavelength, the detailed variation with wavelength should be diagnostic of the opacity source. Thus a molecular pseudo-continuum would be effective only in wavelength regions where line opacity was important.

4.1.2. The example of R Leonis

Interestingly, the circumstellar gas layer does not need to be optically thick to produce a substantial apparent diameter increase between the K' and L' atmospheric windows. This is illustrated by simple models for R Leonis. The physi-

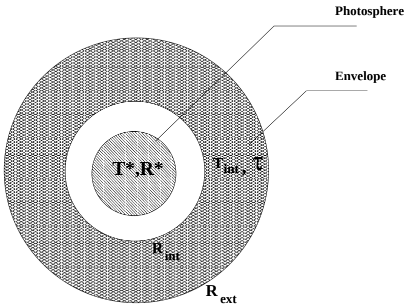

Fig. 3.— Adopted spherically symmetric model. It consists of a central photosphere with radius R^* and effective temperature T^*, surrounded by an envelope with inner radius R_{int}, outer radius R_{ext}, inner temperature T_{int} and optical depth τ, common to both K' and L' bands.

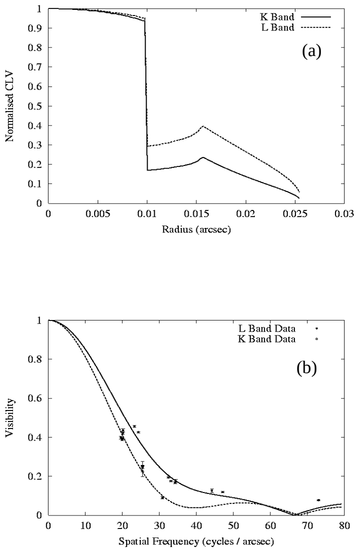

Fig. 4.— Results of R Leonis observations modeling using a 2-layer model (see text). Predicted CLV and visibility curves are given in full line in K and dashed line in L'. (a) Center to Limb Variation. (b) Model visibility and observations: March 1997 (K') and November 2000 (L').

cal model consists of the central photosphere considered as a black-body with effective temperature T^* and radius R^*, and a spherically symmetric surrounding envelope characterized by inner radius R_{int}, outer radius R_{ext}, inner temperature T_{int} and optical depth τ common to both K' and L' bands (figure 3). That is 6 free parameters, to be compared with the 11 true independent R Leonis visibility measurements we have. To keep the model simple, we assumed radiative equilibrium and mass flux conservation inside an assumed expanding envelope, so that the temperature there varies as $1/\sqrt{r}$, and the density goes as $1/r^2$. The numerical code solves for the one-dimensional radiative transfer equation for each line of sight separately, and sums the resulting intensities to provide the Center to Limb Variation (CLV).

As an example, figure 4 shows the CLV and visibility curves obtained when fitting the K' (March 1997) and L' (November 2000) R Leonis data with such a model. A reasonably good fit (χ^2 per point of 2.2) is found with a 10 mas radius uniform photosphere at an effective temperature of 2700 K, surrounded by a spherical layer extending from 15 to 27 mas, with an inner temperature of 1730 K and an optical depth of $\simeq 0.5$ in both K' and L'. Figure 4a shows the increased relative contribution of the upper layer flux at $3.8\,\mu$m. Looking at the visibility curves (figure 4b), the outer layer affects the mid spatial frequencies but has no influence on the first visibility null location, which is fixed by the size of the photosphere. In that sense CLV curves appear as a good tool to disentangle between opacity variations in the outer atmosphere, and actual photospheric pulsation. We note that the large visibility residual observed in K' at the highest spatial frequency remains poorly fitted. More observations in the [50-70] cycles/ arcsec spatial frequency range would obviously be very helpful to determine whether the visibility effectively bounces after a first minimum or monotonically decreases in a more gaussian fashion. This is part of an on-going work with FLUOR/TISIS.

In the fit, the upper layer was not assumed at thermal equilibrium with the central photosphere, so that its inner temperature was left as a free parameter. This is consistent with recent models of molecular gas layers around Miras (Willson 2000) and better fits the data than in the case where thermal equilibrium is assumed. Good fits with similar χ^2 were obtained with different combinations of photospheric and inner layer radii. But the layer extension (up 2 to 3 stellar radii) and optical depth (0.4 to 1) seemed to be well constrained by the data. The actual source of opacity (dust or molecules) was not discussed and no scattering was included, so that this crude model obviously needs more work. Yet its merit is to easily reproduce the observed L' enlargements with few parameters.

4.1.3. Issues raised by the 2-layer model

There are two main issues brought up by such a model: the physical interpretation of the "gap" region between the 2 layers, and the impact of the model on the stellar Spectral Energy Distribution (SED).

We did not force the inner radius of the surrounding layer to coincide with the stellar radius. The resulting apparent gap (figure 3), which is required to better fit the R Leonis visibility data, could arise from several sources, but is most easily understood as a drop of opacity with depth. Either the continuum opacity or a pseudo-continuum opacity could vary with depth due to changing abundances of molecules, ionization, or excitation. Though we do not have a specific hypothesis to explain a continuum drop, we note that the layers are observed to have molecular abundance and temperature differences. A layer of reduced gas density inside R_{int}, while conceivable, may not be plausible hydrodynamically.

The extended, partially transparent shell of the two component model may have both absorption and scattering opacity - both will result in an increased apparent UD diameter. The absorption opacity, however, (likely to be dominant in K' or L') will lead to thermal reemission at a lower temperature. This will result in an increased flux at longer wavelengths, and the SED will deviate from a blackbody spectrum. However, the flux in the longer wavelength region available to be absorbed and reemitted is small. Miras differ strongly from blackbodies anyway, and the changes in the SED may not be dramatic. Simulation of the SED is behind the scope of this paper, but it clearly sets an upper limit to the broad-band opacities in the envelope.

It is already well known that supergiant stars have angular diameter variation within strong molecular bands (Quirrenbach et al. 1993) and even within single strong atomic lines (Schmidtke 1987). Higher spectral resolution diameter measurements in the L' band, and more detailed modeling, would be required to confirm whether or not such a wavelength dependent opacity effect could give the large visibility changes that are observed averaged over the K' and L' bands. Our limited measurements and modeling suggest that isolated band and line opacity may not suffice. Therefore, in our modeling we have assumed a continuum opacity effect - of course, the physical phenomenon could arise due to an effective pseudo-continuum of many blended spectral lines. H_2O is a natural candidate for this opacity, as discussed in section 4.3.1 and 4.3.2.

Our model is simple, but it has the advantage of capturing and parameterizing the basic physical phenomena - two layers with a Planck weighting - with minimal additional complication. It is inspired by and maintains qualitative consistency with the latest detailed Mira studies. At the same time, it avoids complex and possibly incomplete physics which is necessarily included in state-of-the art modeling.

4.1.4. The issue of azimuthal asymmetry

The FLUOR measurements at K' and L' are showing very clearly that a uniform disk model does not represent the actual brightness distribution across Mira stars. The UD diameter can only have limited usefulness - here, we have used it as an index to parameterize visibility curves recorded at different wavelengths, but otherwise nearly constant parameters. For example, the approximately N-S baselines of IOTA, with near-transit observations, give nearly constant position angle. At IOTA, multiple baselines are observed by moving telescopes - not by super synthesis - hence at nearly constant position angle. If super synthesis were used to observe multiple baselines, as has been done elsewhere, the different position angles would correspond to different baseline lengths and different spatial frequencies. In that case, use of a UD model would appear to give evidence for an azimuthal variation in stellar diameter even for a symmetric disk. Azimuthal asymmetry is certainly not ruled out for Mira stars, but sparse UV coverage and UD model fitting cannot demonstrate asymmetry, which may be merely an artifact of adopting the UD model.

4.2. Comparison to existing models

The “2-layer Planck weighting effect” described above has been recently and independently proposed (Scholz 2001) to produce strong chromatic dependency in some Mira CLV and corresponding visibility models. One of these models -P74200- (Hofmann, Scholz, & Wood 1998; Bedding et al. 2001) predicts strong (up to a factor of 2, depending on measured spatial frequency) apparent UD diameter increases between H, K and L bands due to a “tail” in the CLV of Mira stars observed close to maximum variability phase. The effect of this “tail” is very important at mid-spatial frequencies of the first visibility lobe, where most of our observations are conducted. This tail would be mainly due to an extended H_2O layer extending far above the classical photosphere, which is consistent with our interpretation. The parameters for this model are the following: pulsation mode=fundamental, period=332 days, stellar mass=$1M_{\odot}$, non pulsating parent star radius R_p=$241\,R_{\odot}$, “surface radius”=$5\,R_p$, luminosity L=$4960\,L_{\odot}$, stellar radius=$1.04\,R_p$, effective temperature=3060 K. One should note however that a strong cycle to cycle variation is predicted by these models, and that the expected K' to L' discrepancy varies considerably from one luminosity maximum to the following for instance. The visibility curves predicted by these models are so distinctive that a few measurements at well chosen spatial frequencies could test them efficiently. This will be the aim of future observations. The essential element of this model is then consistent with our interpretation: the K to L (and H to K) apparent diameter enlargements are evidence for a “tail” in the CLV, due in this case to an extended atmospheric molecular layer.

Recent dynamical models of Mira atmospheres (Willson 2000) allow the formation of molecules (out of radiative equilibrium) and dust in a so-called refrigerating region as close as 2 stellar radii, also making the near-in molecular layer scenario plausible.

4.3. Comparison to other observations

Infrared spectra of some Mira stars and other M giants show extended molecular (mostly H_2O) regions whose size and temperatures are fully consistent with the extended layer invoked in our model. Thermal infrared measurements show that dust alone should not strongly affect near infrared (J to L') diameters of late type stars. Also, they show UD diameters around 11.15 microns even larger than those measured at near IR wavelengths. This is also in agreement with our interpretation.

4.3.1. ISO spectra

Warm molecular envelopes have been revealed by ISO infrared spectra of several Miras (o Ceti, S Virginis) and semi-regular variables (SW Virginis, RT Virginis) of our sample. Of particular interest is the o Ceti ISO spectrum (Yamamura et al. 1999) taken between 2.4 and 5.3 μm close to its maximum phase. These authors found a remarkably accurate fit to the observed spectrum using two spherically symmetric molecular gas layers located above the classical photosphere and placed on top of each other. The first envelope contains hot H_2O (2000 K) and SiO (2000 K), whereas the outer colder one is composed of H_2O (1400 K) and CO_2(800 K). Other molecular species such as OH and CO are also visible in the spectrum but were not included in the model since their parameters are less constrained. The hot optically thick H_2O molecular envelope extends out to two stellar radii. It is seen in emission in the 3.4-4 microns region (our L' filter), whereas the 2.6-3.3 μm radiation is absorbed by the outer cold (1400 K) H_20 layer, extending out to 2.3 stellar radii.

Like o Ceti, SW Virginis has been observed by ISO in the 2.4 to 5.3 μm region. Tsuji (Tsuji et al. 1997) found the spectrum compatible with absorption or emission due to H_2O, CO, SiO and CO_2 extended envelopes. The 2.7 μm absorption feature would be due to an H_2O envelope extending to 2 stellar radii with an excitation temperature of 1250 K, whereas excess emission in the 3.95-4.55 μm region is mainly explained by extended 2000 K CO and 1250 K CO_2 envelopes.

4.3.2. Ground based FTS spectra

Further independent evidence for extended gas layers around late type stars comes from excess absorption in first overtone CO bands. It was measured by high resolution FTS spectra of a few late M giants, including RX Bootis, SW Virginis, g Herculis, ρ Per (Tsuji 1988), and interpreted as the effect of a quasistatic molecular formation zone, an extra molecular component distinct from the photosphere and characterized by excitation temperatures in the 1000 K to 2000 K range.

There is also strong indication of an analogous 2-layer H_2O extended structure around R Leonis. This comes from high resolution spectroscopy of the 1.9 μm H_2O band (Hinkles & Barnes 1979). These authors derived excitation temperatures of 1700 K and 1150 K for the two components, i.e. somewhat similar to the hot and cold layers inferred around o Ceti (Yamamura, de Jong, & Cami 1999).

4.3.3. Aperture masking observations

Near infrared narrow-band (generally 1 to 3% wide) aperture masking observations on the Keck telescope were recently reported for o Ceti (Tuthill et al. 1999b) and R Aquarii (Tuthill et al. 2000b), two of our targets, as well as for W Hya (Tuthill et al. 2000a), another Mira.

When observed in the continuum, these 3 stars show a substantial ($\simeq$ 10 to 20%) increase in apparent diameter between H and K. This is much more than what conventional differential limb darkening between H and K may account for, and consistent with what would be expected from a 2-layer model.

In all cases again, measurements conducted around 3.08μm show much larger objects than in K: the 3.08μm UD best fit diameter is 59.9 mas for o Ceti observed close to maximum phase in December 1997, and around 34 mas for R Aquarii observed at two different epochs (June 1998, and January 1999). This may be interpreted by substantial molecular absorption in the upper atmosphere (possibly by water vapor, in the wings of the 2.7 μm feature visible in o Ceti ISO spectra).

The aperture masking observations also appear consistent with the presence of a very extended molecular gas layer around these stars.

4.3.4. Thermal infrared interferometry

Early 11.15 μm observations with the Infrared Spatial Interferometer (ISI) 13 m baseline were carried out on a sample of 13 late type stars

(Danchi et al. 1994). As expected from infrared excesses previously detected around Mira variables by IRAS (Little-Marenin & Little 1990), the ISI measurements showed extended dust shells around a sample of bright Miras and also allowed modeling of the dust characteristics. Radiative transfer models (Lopez et al. 1997) were used to retrieve physical parameters for the star itself (effective temperature and photospheric radius) and its surrounding dust envelope (inner/outer radius, inner radius temperature, optical depth). Five of the observed stars (R Leonis, o Ceti, Chi Cygni, U Orionis and R Aquarii) are common to our sample. In all cases the dust shells detected by ISI around these stars are too cold at the condensation radius, and in any event too optically thin, to explain the variations we observe between K and L' (Mennesson 1999), (Salomé et al. in preparation). So if dust layers are involved in the observed K' to L' discrepancy, they are different from the ones observed by the ISI, and there is no current evidence for their existence. Besides we find large UD diameters increases between K' and L' even when no dust is detected close to the star by the ISI (Danchi et al. 1994), as in the case of Chi Cygni and U Orionis. So we do not think that dust is likely to explain our results. Recent theoretical models do not predict a strong influence of dust on interferometric measurements at near infrared wavelengths (Bedding et al. 2001).

Physical stellar diameters derived by the ISI measurements at 11.15 microns before 1999 were still quite model dependent, because the 13 m baseline visibilities were dominated by the dust shell emission. More direct and accurate stellar diameter measurements were obtained in October/November 1999 on o Ceti close to maximum (average phase of 0.9) with a 56 m baseline. This baseline should completely resolve out the extended cool dust shell. Yet the derived UD stellar diameter of 48.2±0.6 mas (Weiner et al. 2000) is much larger than what near infrared measurements indicate: $\simeq$ 23 to 35 mas from J, H (Tuthill et al. 1999b), K' to L' (this work). This result is consistent with thermal emission from a hot extended (up to 2-3 stellar radii) region around the central photosphere, that still contributes a significant part of the 11.15 microns mid-infrared coherent flux once the outer colder regions have been resolved out by the interferometer. It will be very interesting to compare our L' measurements to the ISI largest baseline observations of the same objects, as they become available.

5. Conclusions

We have reported the first long baseline interferometric measurements obtained in the 3.4 to 4.1 micron region on a sample of 14 AGB stars, among which nine are Miras. They yield a systematic and rather surprising result: a strong increase in the apparent UD diameters of all the Miras from K' to L' bands. In the absence of obvious strong molecular absorption, the effective opacity in the broad filter bandpasses may be determined by the continuum, or possibly by a pseudo-continuum of weak lines. The observed diameter shift is therefore interpreted as a continuum effect. We suggest that a very extended ($\simeq$ 3 stellar photospheric radii) gas layer is responsible, as its contribution to the overall stellar flux increases with IR wavelength.

We also suggest that this 2-layer scenario explains the UD diameter chromatic variations already detected around a few of our sample objects by the Keck aperture masking experiment from 1.5 to 3.08 μm, and the yet larger diameter measured at 11.15μm by heterodyne interferometry on o Ceti. IR spectra of many of our sample stars indicate that the outer layer is rich in molecular H_2O, so that H_2O could be an important source of opacity. But we still detect some chromatic size variations on one S-type (Chi Cygni). Interestingly, the K' to L' apparent UD diameter increase also occurs for four non-Mira stars, which suggests that large amplitude pulsation is not required to produce the very extended, warm and dense envelopes around Miras. Some other mechanism must be capable of producing this extension. If correct, the 2-layer interpretation also means that Mira photospheres are significantly smaller than has been estimated from previous high angular resolution measurements. This could favor a fundamental mode of pulsation (Wood 1990).

Ground-based interferometric observations of late type stars in the L' atmospheric window are of particular interest: they seem well suited to reveal and probe the extended layer in the upper atmosphere of these stars. At shorter wavelengths the warm stellar photospheric emission, and/or strong molecular absorption/diffusion dominate. At longer wavelengths the cooler extended dust shell contaminates visibility measurements.

Finally, the warm extended layer discussed here could be of major interest for the understanding of mass loss mechanisms at the end of the AGB phase. This intermediate extended region located between the hot photosphere and the cool outer dust shell provides ideal temperature and density conditions for complex chemistry to occur, including the slow nucleation of dust, driven further away by stellar radiation pressure.

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