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## *Abstract of recently accepted papers*

### Small scale structure in circumstellar envelopes and the origin of globules in planetary nebulae

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We analyze the small scale structure in the circumstellar envelopes of NGC 7027 and IRC+10216, using high resolution optical images in dust scattered light. We use the observations to test the proposal that globules in planetary nebulae, typified by globules in the Helix nebula, originate in high density contrast proto-globules in the atmosphere of the progenitor AGB star and are carried out in the circumstellar wind (Dyson et al. 1989). We find no evidence for the presence of proto-globules in the extended envelopes of NGC 7027 and IRC+10216 with the expected sizes and masses $\geq 10^{-5}$ $M_\odot$ which are needed to produce globules like those in the Helix nebula. We do find azimuthal structure in the envelopes on size scales of $l \geq 0.1d$ where $d$ is the radial distance, consistent with the smoothing out of small scale structure by thermal motions in the wind acceleration region. Unless globules require special conditions not found in NGC 7027 or IRC+10216, which are among the most likely precursors of Helix-like nebulae, our results argue against their origin in the atmosphere of the central star. We suggest alternative scenarios for globule formation, including the fragmentation of the neutral circumstellar gas at the transition phase by directed outflows or jets.

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*or via WWW on* http://physics.nyu.edu/~pjh1
*or via anonymous ftp at* ftp.dstu.univ-montp2:pub/GRAAL/mauron/globules.ps.gz

### Mass loss rates of a sample of irregular and semiregular M-type AGB-variables

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We have determined mass loss rates and gas expansion velocities for a sample of 69 M-type irregular (IRV; 22 objects) and semiregular (SRV; 47 objects) AGB-variables using a radiative transfer code to model their circumstellar CO radio line emission. We believe that this sample is representative for the mass losing stars of this type. The (molecular hydrogen) mass loss rate distribution has a median value of $2.0\times10^{-7}\,M_\odot\,yr^{-1}$, and a minimum of $2.0\times10^{-8}\,M_\odot\,yr^{-1}$ and a maximum of $8\times10^{-7}\,M_\odot\,yr^{-1}$. M-type IRVs and SRVs with a mass loss rate in excess of $5\times10^{-7}\,M_\odot\,yr^{-1}$ must be very rare, and among these mass losing stars the number of sources with mass loss rates below a few $10^{-8}\,M_\odot\,yr^{-1}$ must be small. We find no significant difference between the IRVs and the SRVs in terms of their mass loss characteristics. Among the SRVs the mass loss rate shows no dependence on the period. Likewise the mass loss rate shows no correlation with the stellar temperature.

The gas expansion velocity distribution has a median of $7.0\,km\,s^{-1}$, and a minimum of $2.2\,km\,s^{-1}$ and a maximum of $14.4\,km\,s^{-1}$. No doubt, these objects sample the low gas expansion velocity end of AGB winds. The fraction of objects with low gas expansion velocities is very high, about 30% have velocities lower than $5\,km\,s^{-1}$, and there are objects with velocities lower than $3\,km\,s^{-1}$: V584 Aql, T Ari, BI Car, RX Lac, and $L^2$ Pup. The mass loss rate and the gas expansion velocity correlate well, a result in line with theoretical predictions for an optically thin, dust-driven wind.

In general, the model produces line profiles which acceptably fit the observed ones. An exceptional case is R Dor, where the high-quality, observed line profiles are essentially flat-topped, while the model ones are sharply double-peaked.

The sample contains four sources with distinctly double-component CO line profiles, i.e., a narrow feature centered on a broader feature: EP Aqr, RV Boo, X Her, and SV Psc. We have modelled the two components separately for each star and derive mass loss rates and gas expansion velocities.

We have compared the results of this M-star sample with a similar C-star sample analysed in the same way. The mass loss rate characteristics are very similar for the two samples. On the contrary, the gas expansion velocity distributions are clearly different. In particular, the number of low-velocity sources is much higher in the M-star sample. We found no example of the sharply double-peaked CO line profile, which is evidence of a large, detached CO-shell, among the M-stars. About 10% of the C-stars show this phenomenon.

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## Detection of Water Vapor in the Photosphere of Arcturus

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We report detections of pure rotation lines of OH and $H_2O$ in the K1.5 III red-giant star Arcturus ($\alpha$ Boötis) using high-resolution, infrared spectra covering the regions $806-822\,cm^{-1}$ ($12.2-12.4\,\mu m$) and $884-923\,cm^{-1}$ ($10.8-11.3\,\mu m$). Arcturus is the hottest star yet to show water-vapor features in its disk-averaged spectrum. We argue that the water vapor lines originate from the photosphere, albeit in the outer layers. We are able to predict the observed strengths of OH and $H_2O$ lines satisfactorily after lowering the temperature structure of the very outer parts of the photosphere ($\log\tau_{500}=-3.8$ and beyond) compared to a flux-constant, hydrostatic, standard MARCS model photosphere. Our new model is consistently calculated including chemical equilibrium and radiative transfer from the given temperature structure. Possible reasons for a temperature decrease in the outer-most parts of the photosphere and the assumed break-down of the assumptions made in classical model-atmosphere codes are discussed.

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## The light curve of the semiregular variable $L_2$ Puppis: I. A recent dimming event from dust

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The nearby Mira-like variable $L_2$ Pup is shown to be undergoing an unprecedented dimming episode. The stability of the period rules out intrinsic changes to the star, leaving dust formation along the line of sight as the most likely explanation. Episodic dust obscuration events are fairly common in carbon stars but have not been seen in oxygen-rich stars. We also present a 10-$\mu$m spectrum, taken with the Japanese IRTS satellite, showing strong silicate emission which can be fitted with a detached, thin dust shell, containing silicates and corundum.

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## Multiple Collimated Outflows in the Proto-planetary Nebula GL 618

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We present narrow-band H$\alpha$, [S II], and [O I] Hubble Space Te lescope images of the young planetary nebula GL 618. This object is a compact, bipolar nebula that is currently undergoing the transition from asymptotic giant branch star to planetary nebula. Our images confirm the presence of at least three highly collimated outflows emanating from the central regions of GL 618. We also detect H$\alpha$ emission close to the central dust lane and in an extended scattered light halo. The three outflows are occurring simultaneously in this object, as opposed to being the result of a precessing jet. We derive an inclination for the brightest outflow in the East lobe of $39° \pm 4°$. This differs from the previous estimate of $45°$. In addition, our results indicate that the outflows seen in GL 618 are probably not coplanar. Line strengths derived from the narrow-band images indicate a shock velocity in the range of $40 - 100$ km s$^{-1}$. Based on the shock velocity we estimate that the age of the outflows is less than 500 years. The outflows seen in the optical images of GL 618 are related to features seen in near-IR, CO and CS maps of this object. This relationship indicates that the outflows are playing a major role in the morphological evolution of this young planetary nebula, interacting with and shaping the neutral envelope surrounding GL 618. We discuss the implications of these jets and their interaction with the neutral envelope in the context of current models of planetary nebula formation.

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# The Structure of Winds in AGB Stars

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Most dusty winds are described by a set of similarity functions of a single independent variable that can be chosen as $\tau_V$, the overall optical depth at visual. The self-similarity implies general scaling relations among the system parameters, in agreement with observations. Dust drift through the gas has a major impact on the structure of most winds.

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*Preprints can be obtained by contacting* moshe@uky.edu
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# On the origin of the 19.5 $\mu$m feature. Identifying circumstellar Mg-Fe-oxides

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We report the detection of a broad, prominent 19.5 $\mu$m dust emission feature in ISO-SWS spectra. It is especially conspicuous in the spectra of low mass-loss AGB stars with relatively high photospheric temperatures belonging to the variability classes SRb and Lb. The feature carrier is proposed to be $Mg_{0.1}Fe_{0.9}O$, a solid solution of MgO (periclase) and FeO (wustite). This dust species has cubic crystal symmetry like spinel, the carrier of the 13, 16.8 and 31.8 $\mu$m spectral features, together with which the 19.5 $\mu$m feature is being observed. A broad emission plateau between 11 and 15 $\mu$m, which is attributable to amorphous $Al_2O_3$, is also detected together with the 19.5 $\mu$m and the spinel features. As a consequence of our discovery, we postulate the existence of a distinct class of circumstellar shells, dominated by oxide and not by silicate dust.

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# The binary central star of the planetary nebula Abell 35

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Using new Far Ultraviolet Spectroscopic Explorer (FUSE) observations in conjunction with Space Telescope Imaging Spectrograph (STIS) and International Ultraviolet Explorer (IUE) archive data, we have modeled both components of the binary central star of the planetary nebula Abell 35. The white dwarf (the ionizing star) was modeled using the non-LTE, plane-parallel code TLUSTY. We find its parameters to be $T_{eff} = 80\pm3$ kK, $\log g = 7.70^{+0.13}_{-0.18}$ cm s$^{-2}$, [He/H] = $-4\pm1$ and C, N ,O , Si, and Fe to be under-abundant by two orders of magnitude with respect to their solar values. This confirms its classification as a DAO white dwarf, and using the Hipparcos distance $D = 163$ pc, we derive a radius of $R_{WD} \simeq 1.65\,\mathrm{x}10^{-2}$ $R_\odot$ and a mass of $M \simeq 0.5$ $M_\odot$.

The modeling of the far-ultraviolet (FUV) spectra also constrains the extinction value; $E_{\rm B-V} = 0.04 \pm 0.01$. Furthermore, the FUSE and STIS data allow us to measure the molecular hydrogen ($H_2$) and neutral hydrogen ($H_{\rm I}$) column densities along the sight-line, the majority of which we believe is associated with the circumstellar material. The FUSE spectrum is best fit with a two-component model for $H_2$, consisting of a cool component ($T = 200$ K) with $\log N({\rm H_2, cool}) = 19.6^{+0.1}_{-0.2}$ cm$^{-2}$, and a hot component ($T \simeq 1250$ K) with $\log N({\rm H_2, hot}) = 17.4^{+0.3}_{-0.4}$ cm$^{-2}$. The $H_{\rm I}$ column density is $\log N({\rm H_I}) = 20.9 \pm 0.1$ cm$^{-2}$. Assuming a typical gas/dust ratio for the interstellar medium, our value of $E_{\rm B-V}$ implies that $\log N({\rm H_I}) = 20.8$ cm$^{-2}$ of this is circumstellar. Our low extinction value and the measured column densities imply that there is essentially no dust in the nebula. Assuming that the neutral and molecular hydrogen is contained in a sphere of comparable dimensions to the ionized shell, we derive the combined mass of the circumstellar $H_{\rm I}$ and $H_2$ to be $\sim 2.7$ M$_\odot$. Other geometries, such as a shell surrounding the ionized region, can be excluded. The mass of the ionized hydrogen is $\lesssim$ 1 % that of the neutral material. From comparison with evolutionary calculations, we estimate the progenitor mass to be $\sim 3.2$ M$_\odot$.

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## Bispectrum speckle interferometry of IRC+10216: the dynamic evolution of the innermost circumstellar environment from 1995 to 2001

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We present new near-infrared ($JHK$) bispectrum speckle-interferometry monitoring of the carbon star IRC+10216 obtained between 1999 and 2001 with the SAO 6 m telescope. The $J$-, $H$-, and $K$-band resolutions are 50 mas, 56 mas, and 73 mas, respectively. The total sequence of $K$-band observations covers now 8 epochs from 1995 to 2001 and shows the dynamic evolution of the inner dust shell. The present observations show that the appearance of the dust shell has considerably changed compared to the epochs of 1995 to 1998. Four main components within a 0.2 arcsec radius can be identified in the $K$-band images. The apparent separation of the two initially brightest components A and B increased from $\sim 191$ mas in 1995 to $\sim 351$ mas in 2001. Simultaneously, component B has been fading and almost disappeared in 2000 whereas the initially faint components C and D became brighter (relative to peak intensity). The changes of the images can be related to changes of the optical depth caused, for instance, by mass-loss variations or new dust condensation in the wind. Our recent two-dimensional radiative transfer model of IRC+10216 suggests that the observed relative motion of components A and B is not consistent with the outflow of gas and dust at the well-known terminal wind velocity of 15 km s$^{-1}$. The apparent motion with a deprojected velocity of 19 km s$^{-1}$ on average and of recently 27 km s$^{-1}$ appears to be caused by a displacement of the dust density peak due to dust evaporation in the optically thicker and hotter environment. The present monitoring, covering more than 3 pulsation periods, shows that the structural variations are not related to the stellar pulsation cycle in a simple way. This is consistent with the predictions of hydrodynamical models that enhanced dust formation takes place on a timescale of several pulsation periods. The timescale of the fading of component B can well be explained by the formation of new dust in the circumstellar envelope.

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## IRC+10216 in action: present episode of intense mass-loss reconstructed by two-dimensional radiative transfer modeling

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We present two-dimensional (2D) radiative transfer modeling of IRC+10216 at selected moments of its evolution in 1995–2001, which correspond to three epochs of our series of 8 near-infrared speckle images (Osterbart et al. 2000, Weigelt et al. 2002). The high-resolution images obtained over the last 5.4 years revealed the dynamic evolution of the subarcsecond dusty environment of IRC+10216 and our recent time-independent 2D radiative transfer modeling reconstructed its physical properties at the single epoch of January 1997 (Men'shchikov et al. 2001). Having documented the complex changes in the innermost bipolar shell of the carbon star, we incorporate the evolutionary constraints into our new modeling to understand the physical reasons for the observed changes. The new calculations show that our previous static model is consistent with the brightness variations seen in the near-infrared images, implying that during the last 50 years, we have been witnessing an episode of a steadily increasing mass loss from the central star, from $\dot{M} \approx 10^{-5}\ M_{\odot}\,\mathrm{yr}^{-1}$ to the rate of $\dot{M} \approx 3 \times 10^{-4}\ M_{\odot}\,\mathrm{yr}^{-1}$ in 2001. The rapid increase of the mass loss of IRC+10216 and continuing time-dependent dust formation and destruction caused the observed displacement of the initially faint components C and D and of the bright cavity A from the star which has almost disappeared in our images in 2001. Increasing dust optical depths are causing strong backwarming that leads to higher temperatures in the dust formation zone, displacing the latter outward with a velocity $v_T \approx 27\ \mathrm{km\,s^{-1}}$ due to the evaporation of the recently formed dust grains. This self-regulating shift of the dust density peak in the bipolar shell mimics a rapid radial expansion, whereas the actual outflow has probably a lower speed $v < v_{\infty} \approx 15\ \mathrm{km\,s^{-1}}$. The model predicts that the star will remain obscured until $\dot{M}$ starts to drop back to lower values in the dust formation zone; in a few years from that moment, we could be witnessing the star reappearing.

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## Probing the mass loss history of carbon stars using CO line and dust continuum emission

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An extensive modelling of CO line emission from the circumstellar envelopes around a number of carbon stars is performed. By combining radio observations and infrared observations obtained by ISO the circumstellar envelope characteristics are probed over a large radial range. In the radiative transfer analysis the observational data are consistently reproduced assuming a spherically symmetric and smooth wind expanding at a constant velocity. The combined data set gives better determined envelope parameters, and puts constraints on the mass loss history of these carbon stars. The importance of dust in the excitation of CO is addressed using a radiative transfer analysis of the observed continuum emission, and it is found to have only minor effects on the derived line intensities. The analysis of the dust emission also puts further constraints on the mass loss rate history. The stars presented here are not likely to have experienced any drastic long-term mass loss rate modulations,

at least less than a factor of ~5, over the past thousands of years. Only three, out of nine, carbon stars were observed long enough by ISO to allow a detection of CO far-infrared rotational lines.

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## ISO-SWS calibration and the accurate modelling of cool-star atmospheres - II. General results

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The fine calibration of the ISO-SWS detectors (Infrared Space Observatory - Short Wavelength Spectrometer) has proven to be a delicate problem. We therefore present a detailed spectroscopic study in the $2.38 - 12\,\mu$m wavelength range of a sample of 16 A0 – M2 stars used for the calibration of ISO-SWS. By investigating the discrepancies between the ISO-SWS data of these sources, the theoretical predictions of their spectra, the high-resolution FTS-KP (Kitt Peak) spectrum of $\alpha$ Boo and the solar FTS-ATMOS (Atmospheric Trace Molecule Spectroscopy) spectrum, both *calibration* problems and problems in *computing the theoretical models and the synthetic spectra* are revealed. The underlying reasons for these problems are sought for and the impact on the further calibration of ISO-SWS and on the theoretical modelling is discussed extensively.H

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## ISO-SWS calibration and the accurate modelling of cool-star atmospheres - III. A0 to G2 stars

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Vega, Sirius, $\beta$ Leo, $\alpha$ Car and $\alpha$ Cen A belong to a sample of twenty stellar sources used for the calibration of the detectors of the Short-Wavelength Spectrometer on board the Infrared Space Observatory (ISO-SWS). While general problems with the calibration and with the theoretical modelling of these stars are reported in Decin et al. (2002), each of these stars is discussed individually in this paper. As demonstrated in Decin et al. (2002), it is not possible to deduce the effective temperature, the gravity and the chemical composition from the ISO-SWS spectra of these stars. But since ISO-SWS is absolutely calibrated, the angular diameter ($\theta_D$) of these stellar sources can be deduced from their ISO-SWS spectra, which consequently yields the stellar radius (R), the gravity-inferred mass ($M_g$) and the luminosity (L) for these stars. For Vega, we obtained $\theta_D = 3.35 \pm 0.20$ mas, R$= 2.79 \pm 0.17\,R_\odot$, $M_g = 2.54 \pm 1.21\,M_\odot$ and L$= 61 \pm 9\,L_\odot$; for Sirius $\theta_D = 6.17 \pm 0.38$ mas, R= $1.75 \pm 0.11\,R_\odot$, $M_g = 2.22 \pm 1.06\,M_\odot$ and L= $29 \pm 6\,L_\odot$; for $\beta$ Leo $\theta_D = 1.47 \pm 0.09$ mas, R= $1.75 \pm 0.11\,R_\odot$, $M_g = 1.78 \pm 0.46\,M_\odot$ and L= $15 \pm 2\,L_\odot$; for $\alpha$ Car $\theta_D = 7.22 \pm 0.42$ mas, R= $74.39 \pm 5.76\,R_\odot$, $M_g = 12.80^{+24.95}_{-6.35}\,M_\odot$ and L= $14573 \pm 2268\,L_\odot$ and for $\alpha$ Cen A $\theta_D = 8.80 \pm 0.51$ mas, R= $1.27 \pm 0.08\,R_\odot$, $M_g = 1.35 \pm 0.22\,M_\odot$ and L= $1.7 \pm 0.2\,L_\odot$. These deduced parameters are confronted with other published values and the goodness-of-fit between observed ISO-SWS data and the corresponding synthetic spectrum is discussed.

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## ISO-SWS calibration and the accurate modelling of cool-star atmospheres - IV. G9 to M2 stars

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A detailed spectroscopic study of 11 giants with spectral type from G9 to M2 is presented. The 2.38 – 4.08 $\mu$m wavelength-range of band 1 of ISO-SWS (Short-Wavelength Spectrometers on board of the Infrared Space Observatory) in which many different molecules — with their own dependence on each of the stellar parameters — are absorbing, enables us to estimate the effective temperature, the gravity, the microturbulence, the metallicity, the CNO-abundances, the $^{12}C/^{13}C$-ratio and the angular diameter from the ISO-SWS data. Using the Hipparcos' parallax, the radius, luminosity and gravity-inferred mass are derived. The stellar parameters obtained are in good agreement with other published values, though also some discrepancies with values deduced by other authors are noted. For a few stars ($\delta$ Dra, $\xi$ Dra, $\alpha$ Tuc, H Sco and $\alpha$ Cet) some parameters — e.g. the CNO-abundances — are derived for the first time. By examining the correspondence between different ISO-SWS observations of the same object and between the ISO-SWS data and the corresponding synthetic spectrum, it is shown that the relative accuracy of ISO-SWS in band 1 (2.38 – 4.08 $\mu$m) is better than 2 % for these high-flux sources. The high level of correspondence between observations and theoretical predictions, together with a confrontation of the estimated $T_{\rm eff}$(ISO) value with $T_{\rm eff}$ values derived from colours — which demonstrates the consistency between $V - K$, $BC_K$, $T_{\rm eff}$ and $\theta_D$ derived from optical or IR data — proves that both the used MARCS models to derive the stellar quantities and the flux calibration of the ISO-SWS detectors have reached a high level of reliability.

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## MULTI-EPOCH INTERFEROMETRIC STUDY OF MIRA VARIABLES I. Narrowband diameters of RZ Peg and S Lac

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As part of the long-term monitoring of Mira variables at the Palomar Testbed Interferometer, we report high-resolution narrowband angular sizes of the oxygen-rich Mira S Lac and the carbon-rich Mira RZ Peg in the near-infrared. The dataset spans three pulsation cycles for S Lac and two pulsation cycles for RZ Peg (a total of 1070 25-sec observations), and represents the first study to correlate multi-epoch narrowband interferometric data of Mira variables. When the calibrated visibility data are fit using a uniform disk brightness model, differences are seen in their angular diameters as a function of wavelength within the $K$ band (2.0 - 2.4 $\mu$m); the source of which is believed to be molecular absorptions in or above the photospheres of the two chemically different Miras. Using visible photometric data provided by the AFOEV, the continuum minimum size of RZ Peg lags this by 0.28 $\pm$ 0.02 in pulsation, similar to the phase lag found in CORAVEL radial velocity data. However, for S Lac, the continuum minimum size tracks the visual maximum brightness. Based on the mean of the continuum angular diameter cycloids, basic stellar parameters are computed for both RZ Peg and S Lac, with both showing maximum atmospheric extension with respect to the 2.0 and 2.4 $\mu$m diameters near phase 0.9. Using the mean value of the fitted cycloids, RZ Peg has a radius $R_{mean} = 377 \pm 111\ R_\odot$ and a mean $T_{eff} = 2706 \pm 36$ K ; S Lac has a radius $R_{mean} = 292 \pm 73\ R_\odot$ and a mean $T_{eff} = 2605 \pm 47$ K . The dominant source of error in the radii is the large uncertainty in the distances to these two stars.

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*Thesis Abstract*

# Spectral Angular Diameters of Mira Variables Using Long-Baseline Near-Infrared Interferometry

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This dissertation (i) reviews the capabilities of the Palomar Testbed Interferometer (PTI), and (ii) the use of PTI to investigate angular diameters of Mira variables stars within narrow spectral bands i n the near-infrared as a function of pulsational phase. PTI is a three-aperture Michelson stellar interfero meter with two non-simultaneous baselines with sensitivity to resolved sources with angular diameters in th e range of 1.0 - 6.0 milliarcseconds. In preparation for this disseration, over 60 Mira variables were obse rved for a total of 12,000 wavelength-dependent angular diameters. Diameters of non-Mira control stars were also measured, and are compared to the extended atmospheres of their chemical counterparts. It is establis hed that the oxygen-rich and carbon-rich Miras behave differently with respect to their phase-dependent dia meters, as evidenced in the near-infrared narrowband channels, and is a result of the differing molecular m akeup of their outer atmospheres. Effective temperatures and linear sizes are established, and evidence for departures from spherical symmetry are reported. The data contained herein will be useful to in verifying theoretical limb-darkening laws and pulsation modes for these highly evolved and enigmatic stars.