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2016 J. Phys.: Conf. Ser. 728 022003
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Atmospheric structure and mass loss in Miras

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Abstract.
The cool molecular region of late-type stellar atmospheres, the ‘MOLsphere’ located between the photosphere and expanding circumstellar shell, is explored by using time series of near-IR spectra of one large amplitude AGB (Mira) variable. The ~1400 K MOLsphere of the Mira R Cas is shown to undergo large amplitude velocity changes that are aperiodic with time scales many times longer than the photospheric pulsation. The mass of the MOLsphere is ~3 × 10^{-5} M⊙. Initial analysis suggests that MOLsphere is thin compared to the stellar radius.

1. Introduction
For low mass stars the majority of the mass loss occurs during the AGB evolutionary phase. Near the tip of the AGB mass rates are typically ~10^{-6} M⊙ yr^{-1}. Initial-to-final mass relations show that solar mass stars lose about 0.45 M⊙ before becoming a white dwarf. The total mass loss exceeds 2 M⊙ for a 3 M⊙ star [1]. There is broad agreement on the basic mass loss mechanisms. Mechanical energy from the stellar pulsation enlarges the star and results in a cool, extended outer atmosphere. This allows dust to form and mass is lost due to radiation pressure on the grains [2].

Arguably the least understood subprocess in mass loss is the transfer of matter from the photosphere to the expanding circumstellar region. A number of theoretical studies show that dissipation of shocks from the stellar pulsation plays a critical role [3]. It is known that SiO masers are formed in the non-expanding circumstellar region and mid-IR and microwave interferometry techniques are also starting to probe the region. Here we discuss spectroscopy of near-IR lines that originate in the photospheric-circumstellar boundary.

2. The MOLsphere
Hinkle [4] discovered that the low excitation 2-0 CO lines of Miras are asymmetric. The asymmetric line profiles result from blending between photospheric lines and lines formed in a cooler, ~1000 K, atmospheric component. Tsuji [5] found similar lines in non-variable cool stars and attributed the origin of these lines to a cool, molecular region he called the MOLsphere. Initial observations [4, 6] of the bright, unobscured Miras R Leo and χ Cyg suggested that the Mira MOLsphere was stationary. The photospheres of all Miras, observable in many features in the near-IR spectra, undergo large amplitude velocity pulsations at the period of the optical light curve. There are a number of papers describing the photospheric pulsation as observed...
Figure 1. A 3 year time series of velocities is shown CO lines in the Mira R Cas. The filled symbols are CO second overtone lines formed in the photosphere. The velocities of these lines follow the 431 day Mira pulsation of R Cas [7]. The open symbols are low-excitation CO first overtone (2.3 $\mu$m) lines formed in the MOLSphere. The MOLSphere velocities are decoupled from the stellar pulsation.

Figure 2. Two spectra of the low excitation CO first overtone lines in R Cas at different dates. Upper spectrum has blended photospheric and MOLSphere components but these are widely separated on the lower spectrum. JD 2445864=1984 Jun 12.

in CO second overtone lines [8]. A stationary MOLSphere was contrary to expectations from models that did not produce any stationary layers [3].

Additional observations of a small sample of typical Miras show that the early observations suffered from unfortunate sampling. The MOLSphere lines can have brief periods of near constant velocity but in fact undergo velocity changes over much longer periods than the stellar pulsation period. This is seen in Figure 1 for R Cas. The aperiodic MOLSphere velocity changes
Figure 3. Curve of growth for the MOLSphere lines. The excitation temperature was selected by forcing high and low excitation lines onto a single curve of growth. Data filled symbols, simple model fit pluses.

observed in R Cas are similar to model predictions. Comparison with models suggests that the lines originate at several stellar radii.

As a consequence of changing velocities for both the MOLSphere and photospheric lines (Figure 1) there are some times when the spectral lines originating in these components are unblended (Figure 2). This greatly simplifies the measurement of the MOLSphere excitation temperature and permits curve of growth determination of the MOLSphere column density (Figure 3). For R Cas on 1984 Jun 12 \( T_{\text{exc}} = 1400 \) K. The CO curve of growth is well fit by a plane-parallel isothermal model with log \( N_L = 21.3 \) and a microturbulence of 3.1 km s\(^{-1}\). The fit implies that the MOLSphere region is thin compared to the stellar radius. Dynamic model atmospheres place gas at this temperature at \( \sim 2 R_\star \) with dust condensation at similar or slightly larger radii (\( \sim 3 R_\star \) [9]). An \( \sim 2 R_\star \) radius is in excellent agreement with mid-IR interferometry of a cool molecular region [10]. A simple model of the MOLSphere shell assuming a typical Mira radius of 400 \( R_\star \) gives a total MOLSphere mass of \( \sim 3 \times 10^{-5} M_\odot \).

3. Mira Masses

In a recent paper [11] we discuss the determination of main sequence masses of Mira progenitors from isotopic abundances. The atmospheric carbon and oxygen isotopic ratios are altered by the CNO cycle, He burning, and mixing processes that take place in the stellar interior over the lifetime of the star [12]. For instance, in a region where an incomplete CNO cycle takes place \(^{13}\)C and \(^{17}\)O increase whereas \(^{12}\)C and \(^{18}\)O are depleted. In the heart of an H-burning zone, where the temperature is higher and the CNO cycle attains the equilibrium, \(^{13}\)C and \(^{17}\)O are also consumed. On the other hand, the \(^{12}\)C is the main product of He burning through the
well-known $3\alpha$ reaction. The products of these fundamental nucleosynthesis processes appear at the stellar surface as a result of deep mixing events that produce substantial modification of the atmospheric abundances of carbon and oxygen. The values of $^{12}\text{C}/^{13}\text{C}$ and $^{16}\text{O}/^{17}\text{O}$ are both very dependent on the main-sequence mass of the progenitor stars.

By measuring carbon and oxygen isotopic ratios we demonstrate that most unobscured Miras in the solar neighborhood had progenitor masses $\leq 2\, M_\odot$ [11]. While we were not able to determine the oxygen isotopic ratios for R Cas, the low $^{12}\text{C}/^{13}\text{C}$ strongly suggests a low progenitor mass. In future studies it will be interesting to see how the structure of the MOLsphere is related to various inputs such as the surface abundances, mass loss rate, luminosity, etc. ultimately stemming from the nature of the progenitor.

Acknowledgments
TL acknowledges support by FWF project P23737.

4. References