Scientific Justification

The detection of molecules at radio frequencies has considerably improved our knowledge of circumstellar chemistry. One object that has been studied extensively over the years is IRC+10216, a carbon-rich asymptotic giant branch (AGB) star approximately 8 $M_\odot$ and a mass loss rate of 3×10^{-5} $M_\odot$ yr^{-1} (Agundez & Cernicharo, ApJ, 650, 374, 2006). The inventory of molecules, together with high angular resolution images of their spatial distribution (Trung & Lim, ApJ, 678, 303, 2008; also available at: http://casaguides.nrao.edu/index.php?title= EVLA_Spectral_Line_Calibration_IRC%2B10216), have lead to sophisticated chemical models of the circumstellar envelope (CSE) of this object. However, few studies have been conducted on the oxygen-rich counterparts. This is because early chemical equilibrium models (Tsuji, A&A, 23, 411, 1973) on oxygen-rich envelopes showed that all the carbon within these oxygen-rich stars should be contained in CO and the nitrogen trapped in N_2. As such, it was presumed that the CSEs of oxygen-rich stars would be poor in complex molecules (Olofsson, in Proc. of the Dusty Molecular Universe: a Prelude to Herschel and ALMA, 223, 2005). However, recent observations have shown that this is clearly not the case. In 2010, Tenenbaum and coworkers (ApJ, 720, L102) conducted a 1 mm survey of IRC+10216 simultaneously with VY CMa, an oxygen-rich super-giant star approximately 25 $M_\odot$ with a mass loss rate of 3×10^{-4} $M_\odot$ yr^{-1} (Smith et al., ApJ, 121, 1111, 2001). The observations yielded a total of 18 different species in the envelope of VY CMa suggesting a complex chemistry does take place in the CSEs of these stars. The molecular species detected included SO_2 and SiS as well as the more unique inorganic species AlO, AlOH and PO (Tenenbaum et al. 2010).

It is clear that much is still not understood concerning the chemistry of oxygen-rich stars. Two different types of models have been used in an effort to explain the chemistry within. Chemical equilibrium modeling by Tsuji (1973) stated that gas phase constituents freeze out at some equilibrium value in or near the photosphere. This leads to a very molecule poor CSE whereas observations clearly show a rich molecular inventory. Non-equilibrium chemical models allow for reactions in the outflowing gas from processes of mass loss (Willacy & Millar, A&A, 324, 237, 1997; Nejad & Millar, MNRAS, 230, 79, 1988; Scalo & Slavsky, ApJ, 239, L73, 1980). It is well known that the mass-loss from evolved stars governs the evolution and structure of the surrounding molecular envelope and it has been estimated that these objects contribute ∼85% of the total mass returned to the interstellar medium (Dorschnery & Henning, A&A Rev., 6, 271, 1995). From these models, large amounts of OH are predicted to form as a result of the photodissociation of H_2O by interstellar UV radiation. The formation of OH has a big impact on the chemistry as reactions involving OH have a small activation barrier. Both SO and SO_2 are formed through reactions with this radical (Willacy & Millar 1997; Sahai and Wannier, ApJ, 394, 320, 1992).

$$S + OH \rightarrow SO + H \tag{1}$$

$$SO + OH \rightarrow SO_2 + H \tag{2}$$

Therefore, the predicted increase in abundance of these molecules compared to the equilibrium value can be as much as two orders of magnitude (Scalo & Slavsky, 1980).

Sahai & Wennier (1992) conducted a survey of SO towards 23 oxygen-rich envelopes; detecting the molecule in 13 of the objects targeted. Given the high detection rate, it was confirmed that the circumstellar abundance of SO is significantly enhanced over what was predicted by the equilibrium models of the photospheres of the oxygen-rich stars. In addition, for stars with mass loss rates less than 5×10^{-6} $M_\odot$ yr^{-1}, the interstellar UV radiation has the opportunity to penetrate deeper into the CSE, producing a large $[OH]/[H_2]$ abundance. Since the production of SO is directly related to the presence of OH, the expected $[SO]/[H_2]$ ratio should be much larger. For stars with these smaller mass-loss rates, observations have shown that the derived SO abundances are significantly larger than the peak values even determined by the non-equilibrium models (which already predict an enhanced abundance by 2 orders of magnitude). Also, in most cases, the radius of the SO shell in the CSE was actually **larger** than that of the OH shell; opposite of what was expected (Sahai & Wannier 1992). It is well established that that SO is readily detectable in many oxygen-rich stars.

Non-equilibrium models also predict that other species such as NS, SH and H_2S should be equally abundant to that of SO and species such as S_2, SO_2, CS and SO^+ should also be present but in lower abundance (Scalo & Slavsky, 1980). Yet, SO_2, SO and CS are the only species whose detection have been reported in multiple oxygen-rich stars (Sahai & Wannier 1992; Ziurys et al., Nature, 447, 1094, 2007). Furthermore, while predicting a large abundance, non-equilibrium models also suggest that SO should contain only a small fraction of the total sulfur available within the CSE. The current fractional abundance of SO determined by the observations of Sahai & Wannier (1992) already exceeds the upper limit predicted if the cosmic S/H abundance ratio is assumed with all sulfur contained in SO. The over abundance of SO could be due to a deficiency in hydrogen within the CSEs of these cool stars that models are not considering (Sahai & Wannier 1992). Though no compelling evidence, albeit the over abundances of SO, was provided to support this claim.

It is quite clear that sulfur chemistry plays an important role in the CSEs of oxygen-rich stars. Sulfur is considered an important source of electrons in some regions of the CSE, having an impact on ion-molecule reactions. In fact, removing role of sulfur in the chemical models resulted in a 60% increase in the abundance of $CH_3{}^+$ within the CSE, causing a corresponding overabundance of other carbon bearing species (Willacy & Millar 1997). To date, a total of six sulfur-bearing molecules have been reported in oxygen-rich stars (Tenenbaum et al. 2010) with the ubiquitous presence of SO_2 and SO. Further still, the abundances of these sulfur-bearing species, including those of SO_2 and SO, are about an order of magnitude smaller in super-giant stars than in AGBs.

W Hya is a young AGB star of about 1 $M_\odot$, estimated at a distance of ~80 pc, with a relatively low mass loss rate estimated at 2.5×10 $M_\odot$ yr^{-1} (Justtanont et al., A&A, 439, 627, 2005). It has a relatively high $^{12}CO/^{13}CO$ ratio of 35 as compared to other oxygen-rich AGBs such as IK Tau at ~10 (Milam et al., ApJ, 690, 837, 2009). Additionally, W Hya contains many SiO, H_2O and OH masers in its CSE. Figure 1 shows the H_2O and SiO maser emission observed using the VLA toward W Hya (Reid & Menten, ApJ, 671, 2068, 2007). The radio emission (green), appears slightly elongated as opposed to more spherical emission observed in objects such as o Ceti. This observed elongation could be of some significance in understanding the elongated structures of post-AGB phase planetary nebulae (Reid & Menten 2007). Yet, no further investigation has taken place on this observed elongation.

An investigation of the infrared emission at 60 and 100 microns, which traces the cool dust grains making up the CSE of W Hya, also yielded surprising results (Hawkins, A&A, 229, L5, 1990). These observations revealed one of the largest mass loss envelopes around an evolved star at 30-40′ in diameter (see Figure 2). W Hya was also found to exhibit an abnormally low gas-to-dust ratio of ~10-20 (Hawkins 1990) as compared to the average value for oxygen rich stars of ~100 (Sopka et al., ApJ, 294, 242, 1985). Futhermore, a recent survey studying the CO and HCN emission from five different oxygen-rich stars showed the abundance of CO in W Hya was $\sim 3.0 \times 10^{-4}$. While this number compares very nicely to the abundances found in the two AGB stars IK Tau and TX Cam, the estimated sources size for W Hya in CO was found to be 14″, whereas IK Tau and TX Cam were found to be 40″ and 100″, respectively. Finally, the [HCN]/[CO] ratio for W Hya is an order of magnitude smaller than that of TX Cam and IK Tau (Ziurys et al., ApJ, 695,1604, 2009). It is clear that W Hya is a unique oxygen-rich AGB star that warrants further extensive study.

Technical justification

To provide further insight to the sulfur chemistry, kinematics and dynamics of the CSE of this very unique oxygen-rich AGB, we propose to map W Hya using the eVLA in SO and SO_2. SO_2 has been observed toward W Hya in the infrared using the Infrared Satellite Observatory (Figure 3) and at submillimeter wavelengths using the Arizona Radio Observatory Submillimeter Telescope (Figure 4) (Justtanont et al., A&A, 417, 625, 2004; Pulliam, Dissertation, University of Arizona, 2010). An additional unique feature of this object is the narrow line widths of molecular transitions. In Figure 4 the emission from W Hya shows an SO_2 feature sitting directly adjacent to the J=3-2 transition of HCO^+. The line width ($\Delta V_{1/2}$) of SO_2 in W Hya is $\sim$12 km s^{-1} as compared to $\sim$35 km s^{-1} found in the source IK Tau and TX Cam.

Also, very little is understood about the chemical and kinematic structure of W Hya. From previous studies, it is assumed that the source size of HCN and CO are $5''$ and $14''$, respectively (Ziurys et al. 2009). The model of Willacy & Millar (1997) predict that both SO and SO_2 are expected to peak at a similar radius from the star and are formed in the inner envelope, comparable to HCN. The narrow linewidth of SO_2 compared to HCO^+ in W Hya shown in Figure 4 (Pulliam 2010) provides some evidence of SO_2 as an inner shell species. Still, the problem remains: **With no current chemical maps of SO or SO_2 in oxygen-rich CSEs to support these claims, much is left to speculation**. SO is expected to be more abundant in oxygen-rich stars than SO_2 (Willacy & Millar 1997). However, recent observations of IK Tau, an oxygen-rich star of approximately 1 $M_\odot$ with a mass loss rate of 4.6×10^{-6} $M_\odot$ yr^{-1} (Justtanott 2004), indicates that SO_2 is nearly twice as abundant as SO (Kim et al., A&A, 516, 68, 2010). Moreover, the abundance determined for inner winds of SO is 10 times higher than predictions (Willacy & Millar 1997; Kim et al. 2010). The non-equilibrium chemical models are clearly missing crucial information of the overall picture with unknowns rapidly accumulating. By mapping SO and SO_2 towards the oxygen-rich star W Hya, valuable information concerning the dynamics and kinematics of the source will be obtained and improved constraints placed on models. Theorist will be able to refine their chemical models, providing a more complete picture of the chemistry within these once uninteresting oxygen-rich stars. Additionally, using these molecular maps, we will be able to follow up on the initial speculation of Reid & Menton (2007) and begin to trace the dynamical evolution of AGB stars to planetary nebula.

We propose to image the CSE of W Hya in SO and SO_2 using Ka band. We will observe the $J_{Ka,Kc}$ = $4_{0,4}$ -$3_{1,3}$ transition of SO_2 at $\sim$29.32 GHz and and the J_N =1_0 -0_1 for SO at $\sim$30.00 GHz (frequencies available at www.splatalogue.net). For these observations, we will utilize the high spatial resolution of C configuration which gives a synthesized beam size of $\sim0.8''$. Since this project depends not only on the detection of these transitions but also the image quality of the molecular envelope, we require as complete uv-coverage as possible. W Hya can be observed for approximately 7 hours per day. Setting up the WIDAR correlator in DUAL polarization mode in 1 subband over 32 MHz of bandwidth (a velocity resolution of 1.25 km s^{-1}), in a 5 hour track, we can achieve an rms of $\sim$36 mJy which should be adequate to detect each of these transitions. Therefore, we require 2 full tracks on W Hya in order to complete these observations.

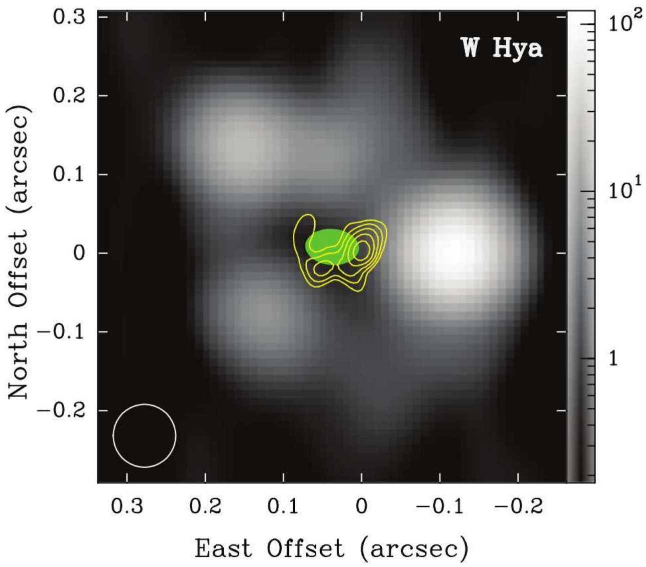

Fig. 1.— Image of H_2O maser emission (gray scale), SiO maser emission (yellow contours) and radio continuum emission (green filled ellipse) of W Hya. Observations completed using the VLA. Figure from Reid and Menton 2007.

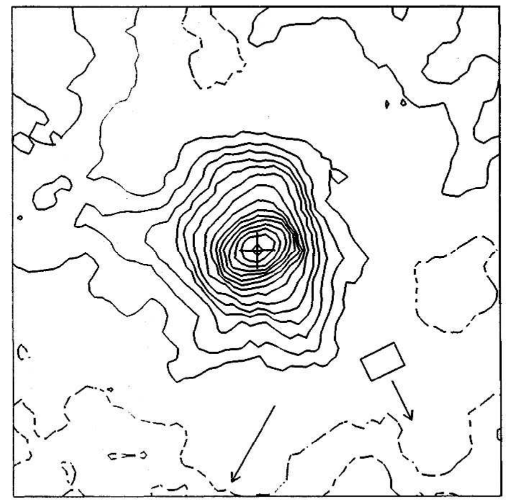

Fig. 2.— IRAS 100 micron continuum emission of W Hya. The image above is 1 degree by 1 degree. The detector size is shown to scale ($3' \times 4.5\ '$) as the square box in the lower right. The emission from W Hya is $\sim$30-40$'$ in diameter, implying a CSE on the order of 1 pc. From Hawkins 1992.

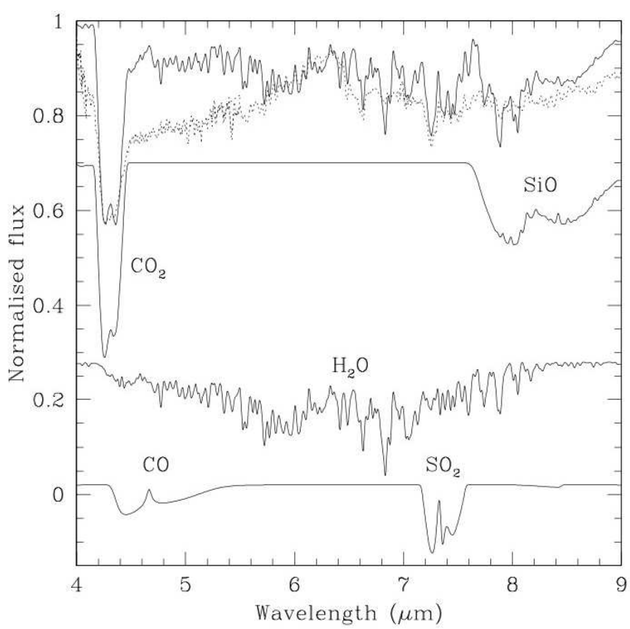

Fig. 3.— ISO SWS observations of W Hya demonstrating the SO_2 stretching mode. Figure from Justtanont 2004

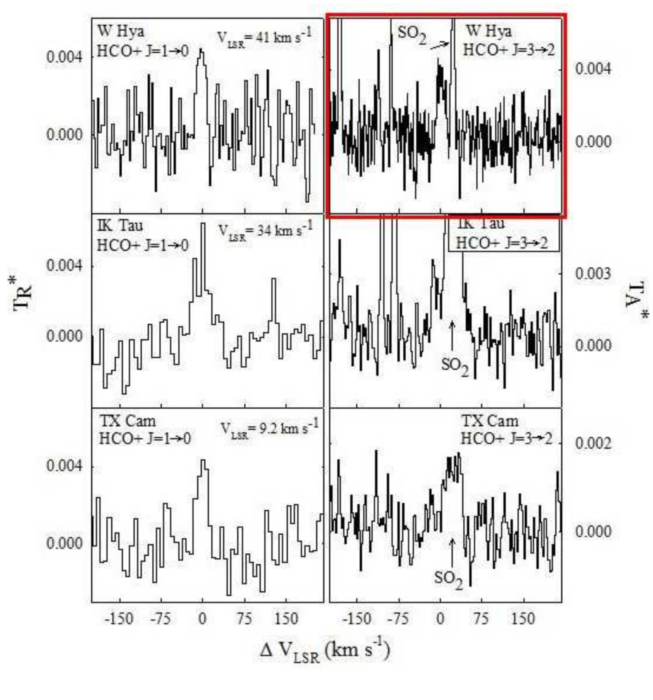

Fig. 4.— Millimeter and submillimeter observations of HCO^+ and SO_2 in oxygen-rich stars using the ARO 12m and Submillimeter Telescope. SO_2 in W Hya is shown in the upper right (highlighted by the red box) directly to the right of HCO^+ which is centered at $\Delta V_{1/2}$=0 km s^{-1}. Figure from Pulliam 2010.