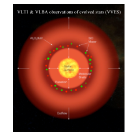
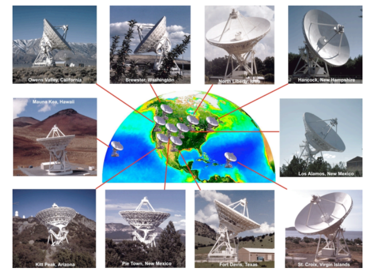


Coordinated Studies of AGB stars with the VLTI and the VLBA

Markus Wittkowski (ESO) , D. A. Boboltz (USNO), and Iva Karovicova (ESO) *

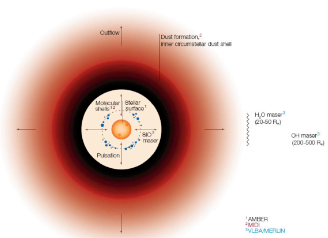
Program Summary

- Goal: use two of the highest resolution interferometers in the world, the VLTI and the VLBA, to study Asymptotic Giant Branch (AGB) stars and their circumstellar envelopes from near-infrared to radio wavelengths.
- Such stars are interesting because they are the precursors to planetary nebulae; objects that are well studied, but with formation mechanisms that are not well understood.
- Figure 1 shows the advantage of a polychromatic approach to the study of AGB stars where we can observe:
  1) The photosphere in the near-infrared (VLTI-AMBER).
  2) The molecular shell in the near- and mid-infrared (VLTI-AMBER and VLTI-MIDI).
  3) The SiO maser shell at 7-mm (VLBA-SiO masers).
  4) The circumstellar dust in the mid-infrared (VLTI-MIDI).
  5) The circumstellar wind region at 1.3-cm (VLBA-H_2O masers).
- Such an approach allows the development of a more complete picture of the entire circumstellar envelope.
- Because AGB stars are long-period (~1 yr.) variables with significant variations within a pulsation cycle and from cycle to cycle, it is important to obtain near-simultaneous observations over time in order to relate the various regions to each other as a function of stellar phase & cycle.



Source Selection and Observations

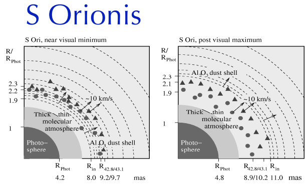
- Thus far we have concentrated on 6 stars: S Ori, GX Mon, RR Aql, R Cnc, X Hya (all Mira variables) and AH Sco (a supergiant).
- All of the stars except S Ori have both SiO and H_2O masers (S Ori only has SiO).
- Numerous proposals to both ESO and NRAO have been submitted and have been well received by the scheduling committees for both facilities.
- Our first observations were concentrated on VLTI-MIDI and VLBA-SiO maser observations. More recent observations include more VLTI-AMBER observations, and we have expanded the VLBA observations to include the H_2O masers. We have begun using phase referencing to try to register the locations of the SiO masers relative to the H_2O masers.
- Recent VLTI&VLBA observations of R Cnc and X Hya were also coordinated with NIR photometry at the SAAO.



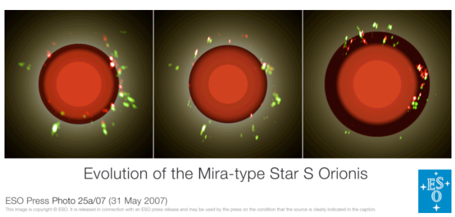
Modeling

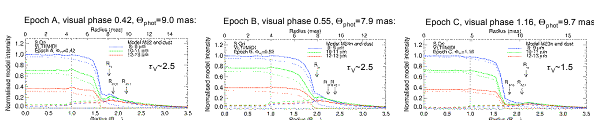
- We have developed an overall modeling approach that describes the VLTI-AMBER, VLTI-MIDI, and VLBA-SiO maser observations.
- We describe the photopshere and geometrically extended molecular layers (sometimes called the MOLsphere) by the self-excited dynamic model atmospheres by Ireland, Scholz, & Wood (2004, MNRAS, 352, 318) and Ireland, Scholz, Tuthill, and Wood (2004, MNRAS, 355, 444).
- We add a radiative transfer model of the dust shell to these dynamic model atmospheres using the Monte Carlo radiative transfer code mcsim_mpi by Ohnaka et al. (2006, A&A, 45, 1015). Following Lorenz-Martins & Pompeia (2000), we use Al_2O_3 and/or silicate grains.
- Gray et al. (2009, MNRAS, 394, 51) combined the dynamic model atmosphere and dust shell model (see above) with a maser propagation model of the SiO maser emission.

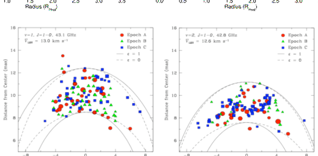
S Orionis



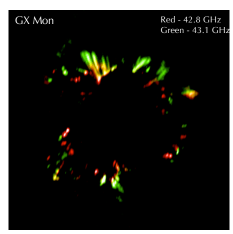
S Ori at Minimum and Maximum

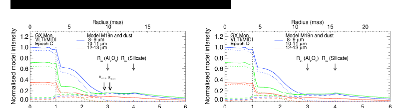




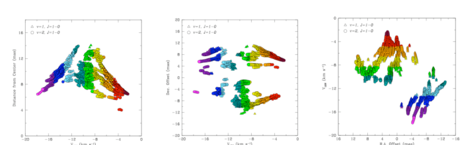


GX Monocerotis





Model Fits to VLTI-MIDI Data



Maser Kinematics

Summary of Results

- Pilot study (VLTI-VINCI near-IR + VLBA) showed that the maser shells lie at 2.0 (43.1 GHz) and 1.9 (42.8 GHz) photospheric radii (Boboltz & Wittkowski 2005, ApJ, 618, 953). Figs. here are from Wittkowski et al. 2007, A&A, 470,191

  Al_2O_3 dust grains *and* SiO masers form at relatively small radii of ~1.8–2.4 photospheric radii. Silicon does not appear to be bound in silicates.

  The masers and the circumstellar dust are **co-located near visual minimum.**

  The kinematics of the SiO masers suggest some kind of expansion, most likely accelerated. However, uniform expansion cannot be ruled out. There is no preferred axis of symmetry for the velocity structure of the masers.

  Our MID results suggest increased mass-loss and dust formation close to the surface near minimum and a more expanded dust shell after maximum.

Preliminary Results

- Al_2O_3 grains at relatively small radii -again co-located with the SiO masers- *and* silicate grains at larger radii can be seen (unlike S Ori, which shows only Al_2O_3).
- Many of the maser **features change position as a function of velocity** (channel) giving the features a cometary appearance in the integrated total intensity images.
- There appears to be a **gradient in the velocity as a function of radius** with features closer to the center of the distribution at higher speeds (relative to the LSR velocity) and features at greater distances having lower velocities. Such a gradient may imply **expansion of the SiO masers**.
- There appears to be a **preferred axis of symmetry which runs nearly north-south** with red-shifted masers lying mostly to the east of this axis and blue-shifted masers to the west.

  This separation of blue- and red-shifted masers about the N-S axis may be a signature of **rotation of the SiO maser shell**.

Outlook

- A MIDI monitoring study of RR Aql covering 4 pulsation cycles is presented by Iva Karovicova (-> talk on Thursday).
- Scheduled AMBER observations of RR Aql aim at reconstructing a NIR image concurrent with new SiO and H_2O maser images.
- We have a scheduled APEX run to study the variability of high-frequency SiO masers, and plan to image them with ALMA.

* This project includes contributions by D. A. Boboltz (USNO), T. Driebe (MPIfR), M.D. Gray (U. Manchester), E.M.L. Humphreys (ESO), I. Karovicova (ESO), K. Ohnaka (MPIfR), A. Richards (U. Manchester), M. Scholz (U. Heidelberg, U. Sydney), F. van Wyk (SAAO), P. Whitelock (SAAO/UCT), M. Wittkowski (ESO)