Resolving the extended atmosphere and the inner wind of Mira (ο Cet) with long ALMA baselines

Ka Tat Wong
Max Planck Institute for Radio Astronomy (MPIfR)

Tomasz Kamiński (ESO/Chile; MPIfR)
Karl M. Menten (MPIfR)
Friedrich Wyrowski (MPIfR)

10 June 2016
The 19th Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun (Cool Stars 19)
Outline

• Extended atmosphere, previous obs.
• ALMA long baseline observation
  ➢ images + spectra
• Radiative transfer modelling
  ➢ molecular abundances
  ➢ inner dust shells
  ➢ kinematics
• Comparison with hydrodynamical models
Circumstellar Environments

- **He**
- **Convective Envelope**
- **Optical Photosphere (R_★)**
- **SiO maser**
- **H_2O maser**
- **H_2O maser**
- **OH maser**
- **Radio Photosphere** $R_{\text{radio}} \approx 2R_★$
- **Extended Atmosphere**
  - **Pulsations + shocks**
  - **Shock-induced non-TE chemistry**
  - **Dust nucleation**
- **Dust condensation and wind acceleration zone**
- **Circumstellar Envelope**
- **Interstellar Medium**
- **SiO maser**
- **H_2O maser**
- **H_2O maser**
- **OH maser**
- **• Shock-induced non-TE chemistry**
- **• Dust nucleation**
- **• Grain-surface chemistry**
- **• Photodissociation**
- **• Ion-neutral reactions**
- **Fully accelerated stellar wind** $V_{\text{exp}} \approx 10 – 30 \text{ km s}^{-1}$

**Extended Atmosphere**

- **Optical Photosphere (R_★)**
- **Convective Envelope**
- **e – H/H_2**

**Diagram Details**

- **Radius** $R$ (AU)
  - 0
  - 2
  - 4
  - 6
  - 8
  - 10
- **Temperature** $T$ (K)
  - 2500
  - 1500
  - 1000
  - < 500
- **Gas Density** $n_{H_2}$ (cm$^{-3}$)
  - 10$^{14}$
  - 10$^{12}$
  - 10$^{10}$
  - < 10$^7$
Hydrodynamical Models

• **CODEX** model series  (Ireland, Scholz, Wood 2008; 2011; 2014)
• O-rich Mira IRC –20197  (Jeong et al. 2013)
• **DARWIN** models  (e.g. Liljegren et al. 2016; Höfner et al. 2016)
Probing the Extended Atmosphere

• Molecular absorption spectroscopy (ISO)
  ➔ “MOLsphere”  (e.g. Tsuji+ 97, Tsuji 00; Woitke+ 99)

• SiO/H$_2$O maser emission (VLA/VLBA)
  (e.g. Reid & Menten 97, 07; Cotton+ & Perrin+ 04, 09, 10, 15)

• Mid-IR interferometry (VLTI)
  (e.g. Ohnaka et al. 2005; Karovicova et al. 2011)

High spatial resolution images
(Sub)millimetre thermal line emission & absorption
2014 Long Baseline Campaign

HL Tau
ALMA (NRAO/ESO/NAOJ)

Mira AB system
ALMA (NRAO/ESO/NAOJ)  K.T. Wong et al. (MPIfR)

3 Juno
ALMA (NRAO/ESO/NAOJ)

beam @230 GHz ≤ 30 mas

SDP.81
ALMA (NRAO/ESO/NAOJ)  B. Saxton (NRAO/AUI/NSF)

longest baseline = 15.24 km

antennae on short spacings
nominal LBC antennae
Band 6 Data

• 229.6 GHz (1.3 mm) continuum  
  (Matthews et al. 2015; Vlemmings et al. 2015; Planesas et al. 2016; this work)

• SiO  \( \nu = 0, 1, 2 \)  \( J = 5 - 4 \)

• \(^{29}\text{SiO} \)  \( \nu = 0 \)  \( J = 5 - 4 \)

• \( \text{H}_2\text{O} \)  \( \nu_2 = 1 \)  \( J(K_a,K_c) = 5(5,0) - 6(4,3) \)

• H30\( \alpha \) (Radio Recomb. Line)  \( \text{(no detection)} \)

• Angular resolution: 30 – 32 mas

• Velocity resolution: 0.08 – 0.17 km/s
Band 6 Data

- 229.6 GHz (1.3 mm) continuum
- $\Delta V = 20.5$ km/s
- Bandwidth = 2 GHz

T. Kamiński, K. T. Wong et al.
- multi-epoch spectral line obs. (1965 – 2015; mm – optical)
- clumpy, inhomogeneous distribution of AlO
- irregular temporal variation

$\Rightarrow$ A&A 592, A42

Fig. 3, Kamiński et al. (2016)
SiO $v = 0$ $J = 5-4$

Credit: Wong et al., A&A 590, A127, 2016, reproduced with permission © ESO
Channel Maps: SiO & $^{29}$SiO $\nu = 0$

$^{28}$SiO $\nu = 0 J = 5 - 4$

$E_{up}/k = 31$ K

$^{29}$SiO $\nu = 0 J = 5 - 4$

$E_{up}/k = 31$ K

Credit: Wong et al., A&A 590, A127, 2016, reproduced with permission © ESO
Channel Maps: SiO & $^{29}$SiO $\nu = 0$

$^{28}$SiO $\nu = 0 \, J = 5 - 4 \quad E_{\text{up}}/k = 31 \, \text{K}$

$^{29}$SiO $\nu = 0 \, J = 5 - 4 \quad E_{\text{up}}/k = 31 \, \text{K}$

Credit: Wong et al., A&A 590, A127, 2016, reproduced with permission © ESO
Channel Maps: SiO $v = 2$ & H$_2$O $v_2 = 1$

$^{28}$SiO $v = 0 \ J = 5 – 4$

$E_{up}/k = 31 \ K$

$^{28}$SiO $v = 2 \ J = 5 – 4$

$E_{up}/k = 3552 \ K$

H$_2$O $v_2 = 1 \ J(K_a,K_c) = 5(5,0) – 6(4,3)$

$E_{up}/k = 3462 \ K$

Credit: Wong et al., A&A 590, A127, 2016, reproduced with permission © ESO
SiO & H$_2$O Spectra

without continuum subtraction!

SiO $\nu = 1$ masers

emission

saturated absorption

Credit: Wong et al., A&A 590, A127, 2016, reproduced with permission © ESO
Inverse P-Cygni Profile

Evans, N.J. II (1999) Annu. Rev. Astron. Astrophys. 37: 311–62
SiO $v = 0 \ J = 5-4$

radial dist. = 32, 64, 96, 128, 160 mas
pos. angle = 0°, 90°, 180°, 270°

Flux density (Jy/beam)

Credit: Wong et al., A&A 590, A127, 2016, reproduced with permission © ESO
From an intense, southern (~26 mas) SiO-emitting clump

Credit: Wong et al., A&A 590, A127, 2016, reproduced with permission © ESO
$\text{SiO } \nu = 2 \ (5-4)$
SiO depletion radius \( \geq 4R \star \approx (8.0 \times 10^{13} \text{ cm} \approx 1200R_{\odot}) \)

\( T_{\text{kin}} \lesssim 600 \text{ K} \)

Credit: Wong et al., A&A 590, A127, 2016, reproduced with permission © ESO
inner dust shells may not be pure silicates (e.g., corundum Al$_2$O$_3$ – Perrin et al. 2015)

$T_{\text{kin}} \lesssim 600$ K

SiO depletion radius $\geq 4R_*$

$(8.0 \times 10^{13}$ cm $\approx 1200 R_\odot)$

Credit: Wong et al., A&A 590, A127, 2016, reproduced with permission © ESO
shock front $\Delta V \lesssim 12 \text{ km s}^{-1}$

pseudo-continuum

infall-only models $\Rightarrow$ excessive blueshifted emission

additional shock fronts ($\Delta V \lesssim 5 \text{ km s}^{-1}$) possible

Credit: Wong et al., A&A 590, A127, 2016, reproduced with permission © ESO
$\text{H}_2\text{O} \nu_2 = 15(5,0)–6(4,3)$

Credit: Wong et al., A&A 590, A127, 2016, reproduced with permission © ESO
A higher H$_2$O ($\sim$10$\times$) abundance near the radio photosphere is needed to fit the redshifted end of the spectrum.
Testing **CODEX** Models

- o54 series: 6 cycles (Ireland et al. 2008; 2011)
- predict $\rho(r)$, $T(r)$, $v(r)$
- select models near phase $\sim 0.45$ (SV obs.)
- reproduce SiO & H$_2$O spectra

We thank M. J. Ireland, M. Scholz, and P. R. Wood for providing the results of the o54 model series.
• CODEX models reproduce the observed SiO & H$_2$O spectra very well.

Credit: Wong et al., A&A 590, A127, 2016, reproduced with permission © ESO
\textbf{CODEX Models}

- $n_{\text{H}_2}(r) \gtrsim 10^{12} \text{ cm}^{-3}$ near radio photosphere to reproduce enough absorption (consistent with Reid \& Menten 1997 \& Yamamura et al. 1999)

- $\rho(r) \rightarrow n_{\text{H}_2}(r)$: gas density underestimated by $10^2 – 10^4$ times
Summary

1. ALMA long baselines clearly resolve SiO & H$_2$O line absorption against Mira's radio continuum.
2. Gas-phase SiO starts to deplete significantly at radius $\geq 4R_\star$ & temperature $T_{\text{kin}} \lesssim 600$ K.
3. The extended atmosphere generally shows infall motion, with shock velocity $\Delta V \lesssim 12$ km s$^{-1}$.
4. Hydrodyn. models from CODEX can predict the atmospheric structures in remarkable detail.