Multi-epoch VERA observations of SiO masers toward R Aquarii

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Abstract

We carried out multi-epoch phase-referencing VERA (VLBI Exploration of Radio Astrometry) observations of v=1,2 J=1-0 SiO masers toward R Aquarii (R Aqr) covering about three stellar pulsation periods from Oct. 2011 to Jun. 2014. Overall distributions of the SiO masers show clumpy and partial ring-like structures dominant in NE (2012) and SE (2013, 14) regions. The v=2 J=1-0 SiO maser rings is located closer than v=1 J=1-0 SiO maser consistent with previous VLBI observations. The SiO maser rings appear to be contracting for the v=1 transition but expanding after contraction for v=2 transition due to shock propagations.

Introduction

- **AGB (Asymptotic Giant Branch) stars**
  - Late-stage of a few solar mass stellar evolution
  - Pulsation with **Large mass-loss rate** ($\sim 10^{-6}\ M_{SUN} yr^{-1}$)
    - Main source for chemical enrichment of universe
    - Driving mechanism not well understood

- **R Aquarii (R Aqr)**
  - The closest **symbiotic star** (Mira + WD binary system)
  - Pulsation period : 387 days
  - Hour-glass like inner & outer nebulae
  - Bipolar jet feature - powered by accretion disk on the WD
  - **Circumstellar SiO maser** source associated with Mira variable

- **SiO masers in AGB stars**
  - Formed mostly in Oxygen-rich ([O]/[C] >1) AGB stars
  - Perfect target for VLBI observations with a high spatial resolution
  - Useful for astrometry : distance (parallax) and proper motions
  - **Tracer of inner most region of circumstellar envelope (CSE)**
    - Formed between photosphere and dust formation region
    - Important probe for studying structures and dynamics of the CSE
  - Many vibrational/rotational transitions
  - Appears as a ring-like structure
    - Tangential amplification

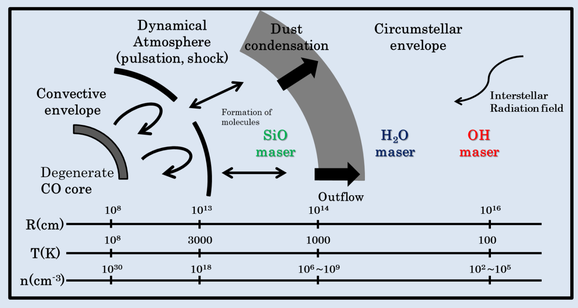

Fig 1. Schematic structure of a typical AGB circumstellar envelope

Observations

- Multi-epoch phase-referencing VERA observations (4 stations)
- Period : From Oct. 2011 to 2014 Jun. – total 21 epochs
- Frequency : ^{28}SiO masers of v=1,2 J=1-0 (43.112, 42.820 GHz)
- Simultaneous observations for the target (R Aqr) and reference source (J2348-16) – separation ~ 1.6 degree

Targets	R.A. (J2000)	Dec.(J2000)
R Aquarii	23h 43m 49.4616s	-15° 17' 04.202"
J2348-1631	23h 48m 02.6085s	-16° 31' 12.022"

- Record : DIR2000 16IF x 16MHz
- Correlation : Mitaka FX correlator
- Velocity resolution : 0.21 km s^{-1}
- Data reduction : NRAO AIPS software
  - Phase-referencing & Imaging done : 16 epochs
  - Synthesis beam : 1.00 mas × 0.43 mas P.A. −27.22 deg

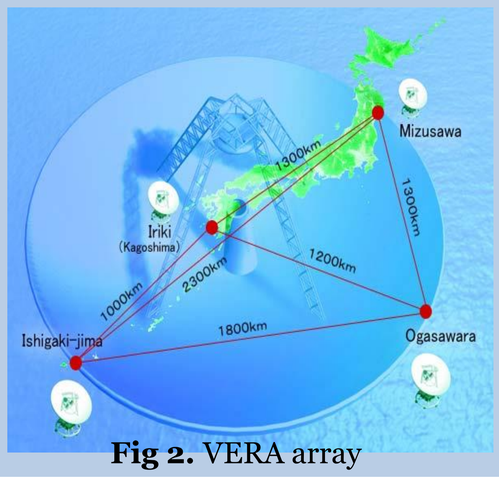

Fig 2. VERA array

Results

❖ *SiO masers distributions* (Fig 3)

- Clumpy and Partial ring-like distributions

- Asymmetric distributions – dominant in NE(2012) and SE(2013,2014) regions
- Mean maser radii : $R_{v=2}$~14.68 mas < $R_{v=1}$~15.39 mas
  ($R_{v=2}$~ 3.20 AU < $R_{v=1}$~ 3.35 AU @ 218 pc[1])
  - v=2 SiO maser is closed to the star than v=1 SiO maser
- SiO masing region R_{SiO} = 2.79 ~2.93 R_{MIRA} (R_{MIRA} = 1.14 AU[2])

- Spike-like features

- East region in 2012 / South-West region in 2014

❖ *Maser ring variations* (Fig 4)

- Contraction and Expansion

- Ballistic contraction of the v=1 SiO maser region (gravitational effect)
  - Mean acceleration : $g_{SiO} \sim 3.9 \times 10^{-7}$ km s^{-2}
    ($g_{SiO} \sim 1.5 \times 10^{-7}$ km s^{-2} for TX Cam[3])
    ($g_{SiO} \sim 3.3 \times 10^{-7}$ km s^{-2} for R Cas[4])
- Contraction → Expansion of the v=2 SiO maser region (shock effect)
  - Contraction : Before encountering the propagated shock
  - Expansion : After shock encountering – following shock propagation

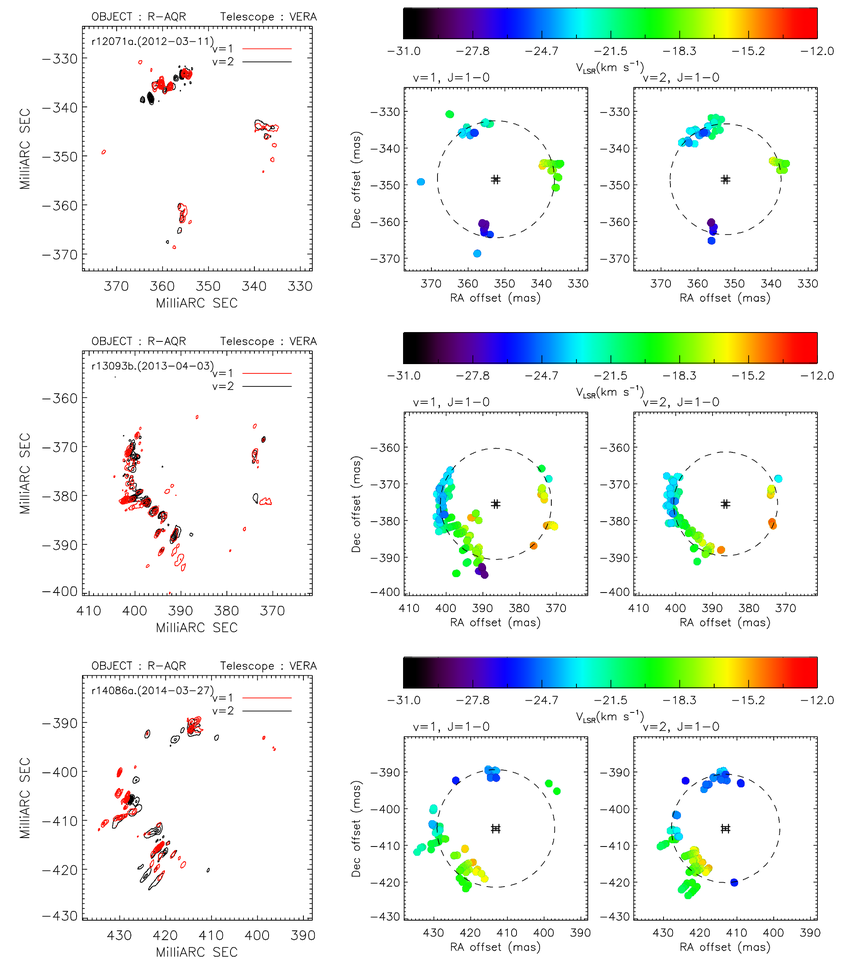

Fig 3. VLBI map of SiO masers toward R Aqr
(Left) Velocity integrated contour map of SiO masers
(Right) Distributions of SiO maser spots in LSR velocity field

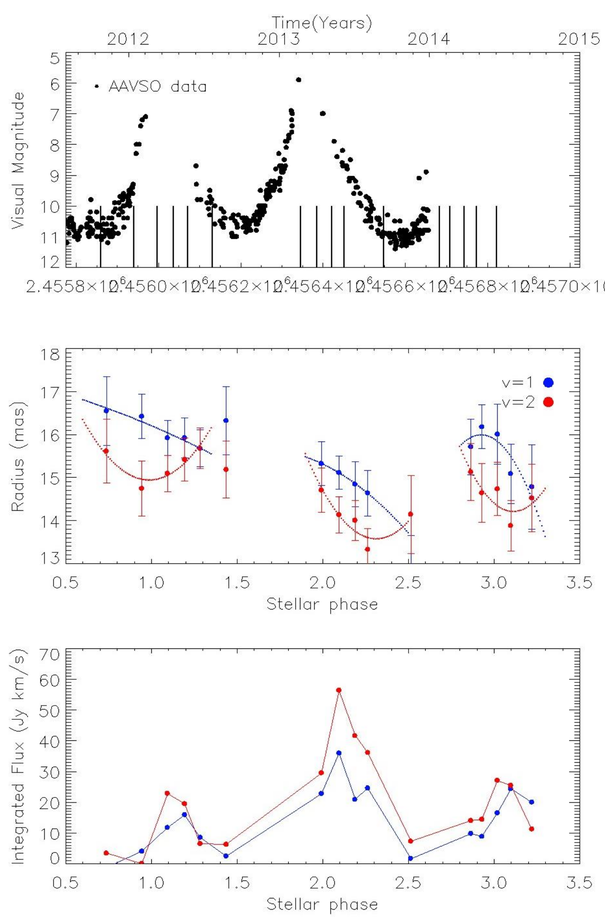

Fig 4. (Top) Optical light curve of R Aqr (AAVSO)
(Middle) Variations of the SiO maser ring radii
(Bottom) Integrated XC spectra of SiO masers

❖ *SiO masers flux variations* (Fig 4,5)

- Following the pulsation period of the Mira variable
  - correlation with optical light curve (phase lag ~0.1)
- Slightly coincidence maximum radio flux with optical maximum between 2012 and 2013
- Correlation SiO maser radii and flux variations
  - smaller radius (closed to the star) being more intense

❖ *Future Works*

- Compare with SiO maser models and dynamic atmospheric models of the oxygen-rich Mira variables
  - SiO maser pumping mechanism
  - confine SiO maser emitting region
  - correlation masing radius with its intensity
  - non-uniform shock propagation
- Linked to other observational results for CES in AGB stars

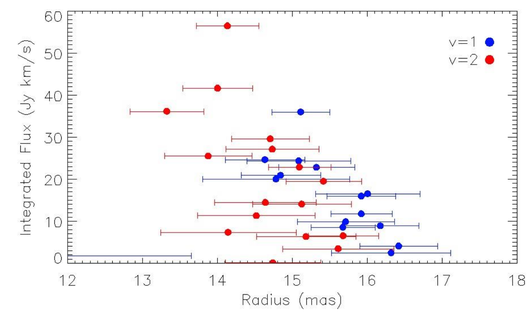

Fig 5. Integrated SiO maser spectra plotted with respect to the ring radii

References

[1] Min et al., 2014, PASJ 66, 38
[2] van Leeuwen et al., 1997, MNRAS 287, 955
[3] Gonidakis et al., 2010, MNRAS 406, 395
[4] Assaf et al., 2011, MNRAS 415, 1083