VSOP-2 KSP Proposal from Japan: Deep Exploration of the Dynamics of the Milky Way Based on High Precision Water Maser Astrometry

Hiroshi Imai (Kagoshima University) and KSP Maser Working Group in Japan
High precision maser astrometry

• Diagnosing extragalactic circumnuclear disks/torii (see Greenhill’s talk)

• Exploring the 3D dynamics of the Local Group of Galaxies
  – Orbits of H$_2$O maser sources and (nuclear) continuum sources in nearby (D<20 Mpc) galaxies

• Dark matter distribution of the Milky Way Galaxy (R$_{gal}$<50 kpc)
  – H$_2$O masers in the LMC/SMC (orbits)
  – H$_2$O masers in the Milky Way (rotation curve)
  – SiO masers? (see Colomer’s talk)
Current astrometric achievements

Distance to S269
D=5.28^{+0.24}_{-0.22} kpc
(Honma et al. 2007) (VERA)

Exploration of the Galactic rotation curve
Current astrometric achievements

Distance to IRAS 19134+2131 (VLBA)

\[ D = 8.0^{+0.9}_{-0.7} \text{ kpc} \] (Imai, Sahai & Morris 2007)
Current astrometric achievements

Exploration of stellar evolution in the Galaxy

Kpc-scale astrometry is technically and scientifically feasible.
Scientific themes on maser astrometry

• The Galactic dynamics: **up to 50 kpc**
  Statistical analysis of source distances and orbits
  – Galactic center
    • Formation of the central star cluster and the nuclear disk
  – Thick/ spherical components
    • co-evolution of the bulge and the massive BH (Sgr A*)
    • halo/ globular clusters:
      ancient Galactic dynamics and star formation
  – Thin components
    • disk: formation of spiral shocks/ warp kinematics
    • inner ring and bar: inner Lindblad resonance, etc.
    • Galactic rotation curve: dark matter distribution
  – Outer region
    • dynamics of the whole Galactic system (**LMC/SMC**)
Scientific themes on maser astrometry

• Stellar evolution in the Galactic system

Deep exploration of individual sources
  – Star formation (high mass stars)
    • Coalescence or massive accretion
    • Star formation in low metallicity environments
  – Stellar mass loss
    • Stellar pulsation in Mira variables
    • High velocity flows in super giants and water fountains

• Standard candles for stellar astrometry
  – Cold stars visible in only long wavelength emission
  – Stars visually extended and variable:
    invalid for high precision astrometry
  – Some stellar maser sources linked to
    astrometric space missions:
    c.f. GAIA, SIM, JASMIN
Crowded maser spot distribution in active maser region

W3 IRS5 (Imai+ 2002)
D~2 kpc (Hachisuka+ 2006)
“Missing sky” obscured to ground radio telescopes

- **Southern sky** ($\delta<-30$ deg)
  - A small number of GRTs in the southern hemisphere
  - Large/Small Magellanic Clouds
  - Behind the Galactic Center
  - The Galactic bulge

- **Celestial equator** ($|\delta|<5$ deg)
  - ASTRO-G — GRT baselines cover (u,v)-plane much more efficiently than GRT—GRT baselines.
  - Galactic plane, Orion region, outer Milky Way
Filtering the maser sources for VSOP-2 KSP

- Filtering: angular resolution (~100 μas)
  - H$_2$O masers
    - Distant (D > 1 kpc)
    - Off Galactic plane
  - SiO masers
    - Unknown spot sizes for distant sources without VLBI observations

Gwinn (1988)
Filtering the maser sources for VSOP-2 KSP

- Filtering: temporary variability (days~months)

Annual parallax measurement during 1 year

Imai, Sahai & Morris (2007)
• Distance measurement for showing the achievement of human technology
  – Annual parallax (~20 µas)
  – Galactic rotation parallax (70 km/s ⇒ ~300 µas/yr)
  – Model fitting to internal motions (10 km/s ⇒ ~40 µas/yr)

• Dynamics of the MW/LMC/SMC system
  – Secular motions of LMC/SMC (100 km/s ⇒ ~400 µas/yr)

• Exploration of the “nearest starburst”
  – Driving sources of outflow activity
  – “Run away” from the starburst region for high-mass star formation
H$_2$O masers in LMC

- ATCA archived data (C901,C973) analyzed by Y. Katayama
- 13 fields
- 15 regions in total

http://www.noao.edu/image_gallery
H$_2$O masers in SMC

- ATCA archived data (C901, C973) analyzed by Y. Katayama
- 6 fields, 4 sources

http://apod.nasa.gov
The Milky Way Galaxy — providing “standard candles” —

Star forming regions
   (massive young stellar objects)
   - D > 2 kpc (mainly D > 10 kpc)
   - Behind the Galactic center (in the southern sky)
   - $R_{\text{gal}} \leq 20$ kpc

Evolved stars (supergiants, OH/IR stars)
   - OH/IR stars in the Galactic bulge and
     the extreme outer Galaxy
   - “Water fountain” sources (W43A-like sources)
   - $R_{\text{gal}} > 20$ kpc
The target fields

- (outer) obscured region
- Outer Galaxy
- Galactic bulge
- Celestial equator

Now in source selection
Requested hours for the KSPs (proposal to date)

1700 hours/3 years ~ 570 hours/year

• 5 hours per epoch per source
  3-4 hours per epoch per source?

• 9-15 epochs  5-8 epochs?

• 20 water maser sources  10 maser sources?
  – 10 sources in LMC/SMC
    5-7 sources in LMC/SMC?
  – 10 sources in the Milky Way
    (2-3 sources in each spiral arm)
    only the outer Galaxy and buldge?
Milestones to VSOP-2 1/2

• Maser source surveys
  – For LMC & SMC: done (ATCA archive)
  – For MW: now planning
    • IRAS point source catalog: distant high-mass star-forming regions
    • Spitzer/GLIMPSE & AKARI:
      H$_2$O masers on the Galactic plane distant sources
    • H$_2$O masers in SiO masers from ~2000 sources in Nobeyama survey

• Source selection criteria
  maser—QSO < 1–2 deg
Milestones to VSOP-2 2/2

- **Source selection/ filtering: pre-launch VLBI**
  - Time variability
    - monitoring with VERA: now processing
    - document survey: now processing
  - Brightness temperature survey: now planning
  - Reference source survey
    - VLBA (S/X) & VERA(K/Q): now processing
    - ATCA: now planning (proposing in this year)
      for candidates in Sydney University Molonglo Sky Survey (SUMSS)
    - LBA: for detected SUMSS source
  - Pre-launch astrometry: now planning
    (VERA/VLBA/LBA)
    - technical feasibility test
      (on the southern sky and the celestial equator)
    - rough estimation of kinematic distances by proper motion measurements (with 2-3 epochs)