Maser Astrometry with VLBI and Galaxy structure study

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contents

- Introduction to VLBI astrometry
- VERA and Galaxy structure
- Toward future
Introduction to VLBI astrometry
Very Long Baseline Interferometry

VLBI: interferometer with extremely long baselines

VERA (VLBI Exploration of Radio Astrometry)

VLBA 25m x 10

20m x 4, with dual-beam feeds
Toward better resolution

- Angular resolution: $\theta \sim \lambda / D$

- To obtain better resolution, go to higher frequency or have larger diameter (or both)

- To make $D$ large, separate the radio telescopes as much as possible (different continent or even space)

$\rightarrow$ VLBI (Very Long Baseline Interferometry)
Angular resolutions of VLBI

- Wavelength-resolution diagram
Good and bad about VLBI

- Good thing
  - Extremely high angular resolution
    (better than any other)

- Bad thing
  - Extremely low sensitivity
    only non-thermal emissions can be observed (synchrotron, maser)
Things to do with VLBI

With the highest angular resolution of VLBI, one can

- Obtain images with the highest angular resolution
  → compact object such as BH, masers

- Measure accurate positions of celestial objects
  → Galaxy astrometry, pulsars etc.
EHT (Event Horizon Telescope)
möffentliche VLBI to resolve the black hole shadows

First obs. with ALMA conducted in 2017
VLBI Arrays for Astrometry

- EVN, VLBA, VERA in the Northern hemisphere.
- LBA, in the Southern hemisphere
Maser astrometry with VERA & Galactic structure study
Galaxy Astrometry with VERA

- VERA to reveal the 3D structure of MWG

MWG from Ishigaki-jima station

H2O in SFR and AGB stars maser is the best target
Galaxy-scale maser astrometry

Galaxy’s center  \( D = 8 \text{ kpc} \)
\( \pi = 125 \mu\text{as} \)

Galaxy scale astrometry requires 10\(\mu\)as accuracy

Galaxy scale astrometry = frontier in 21\textsuperscript{st} century
(c.f., astrometric missions like SIM, GAIA, JASMINE)
Motion of celestial objects

parallax
(elliptical motion)
+
proper motion
(linear)

⇒ helical motion

Position astrometry can tell you both distance and source motion
What does an interferometer measure?

By comparing the voltage patterns recorded at each station.

☆ Radio source

Radio wave from the source (propagates at speed of light)

Wavefront with the same phase (which departed at the same time)

Station 2 → Station 1

By comparing the voltage patterns recorded at each station → time delay can be measured
Basic equation

- Basic observables of interferometer geometric delay: $\tau_g$

$$\tau_g = \frac{s \cdot B}{c},$$

$s$: unit vector to source  
$B$: baseline vector  
$c$: speed of light

PS Here for simplicity, we assume a point source.
Phase-referencing observation

- Target and reference sources can be observed at the same time.
- Tropospheric fluctuation can be effectively cancelled out.
Dual-beam receiving system

- Telescope
- Dual-beam receivers
- Phase-referencing
- Target source
- Reference
- Atmosphere
- VERA station
- Dual-beam platform (2.2 deg max)
Dual-beam phase compensation

W49N and OH43.8-0.1 (on 23/Jul/2002)

Phase residual: ~8 degree in RMS
Example of Astrometric results

Astrometry of H2O maser in Orion (Hirota et al+2007)

Constellation Orion

H2O maser motion against QSO

D = 440 pc
Galaxy map as of 2017

~150 sources with VERA/VLBA/EVN
Galactic constants

As of 2017 (preliminary)

144 SFRs

$R_0 = 8.16 \pm 0.26$ kpc

$\Theta_0 = 237 \pm 8$ km/s

$\Omega_0 = 28.99 \pm 0.39$ km/s/kpc

Honma+ (2012)

52 SFRs

$R_0 = 8.05 \pm 0.45$ kpc

$\Theta_0 = 238 \pm 14$ km/s

$\Omega_0 = 29.57 \pm 0.78$ km/s/kpc

Rotation curve from 144 SFRs

$(U_\odot, V_\odot, W_\odot) = (11.10, 12.24, 7.25)$ km/s (Schorich, Binney, Dehnen 2012) assumed
Rotation and mass of galaxies

• Equilibrium of centrifugal force and gravity gives a good estimate of mass

\[
\frac{mv_c^2}{r} = \frac{GM_r m}{r^2}
\]

- centrifugal
- gravity

\[
M_r = \frac{rv_c^2}{G}
\]

- mass
Flat rotation curve $\Rightarrow$ DM

An example of extra-galaxy:
HI observation of NGC 3198

Flat rotation curve suggest existence of dark halo.
More DM in the Galaxy

- $\Theta_0 = 237 \pm 8$ km/s
  (IAU standard 220 km/s)

Larger rotation velocity by 8%

$\rightarrow$ 16% larger mass

$\rightarrow$ more dark matter

(Honma et al. 2012)
Impact on Direct Dark Matter search

- Dark matter is thought to be elementary particle, and there are on-going experiments to directly detect DM (Xmass, Xenon 100, DAMA, ...).

- To reveal the nature of DM particle, Galactic parameters (galactic rotation speed and DM density) are crucial.

- High-precision VLBI astrometry can impact not only on Galactic astronomy but also on fundamental physics.

Xmass detector
Spiral structure seen with VLBI astrometry

- Systematic deviation from circular rotation seen
- Lag behind the rotation + inward motion

Comparison with theories will discriminate if the spiral arms are density wave or material wave
Future
e: EAVN

- EAVN: VLBI with China, Korea, and Japan
- Baseline doubled, and accuracy doubled with TNRT

The radio telescope project in Thailand is most welcome to join!
Future: global VLBI in cm wave

EAVN

FAST

SKA
Future: Galactic astrometry

Parallax ~ 100 uas for 10 kpc distance

GAIA and VLBI are complementary to each other
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- For more, ask students and OB here.

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