Observational Study on Star Formation with VLBI

– Introduction to the East-Asian VLBI Network –

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Abstract

Very long baseline radio interferometry (VLBI) is a powerful tool for elucidating tiny structures (down to 1 AU) of non-thermal radio emission such as masers and synchrotron emission in very vicinity of young stellar objects and dying stars. Here I describes recent topics of study on mainly maser emission from water vapor molecules associated with young stellar objects, which are observed with VLBI. Water maser sources have been studied as signposts of the very early stage of star formation, while their characteristics have a wide variety in the spatio-kinematical structures of maser features (tiny gas clumps with bright maser spots). In fact, they are associated with not only energetic molecular outflows or hyper-compact HII regions but also accreting disks/tori. This implies that water masers are tracing fast evolution of young stellar objects. I also introduces the East-Asian VLBI network (EAVN) consisting of a great number of radio telescopes operated in Japan, Korea, and China. The EAVN has a few unique characteristics comparing with the Very Long Baseline Array (VLBA) in USA and the European VLBI network (EVN). High quality image synthesis as well as high precision astrometry and polarimetry will be effectively performed for study on water maser sources with the EAVN.

1. VLBI sources in star formation process

VLBI achieves the greatest angular resolution (up to 0.1 milliarcsec or mas) in astronomical instruments. At the same time, however, it is sensitive to only structures that are as small as the angular resolution, or more extended structures are missing in VLBI images. Therefore, non-thermal emission such as synchrotron continuum emission and maser line emission can be mapped in VLBI images because these emissions have very compact structures (apparent size smaller than 10 mas) and extremely high brightness temperatures ($T_b = S_\nu c^2/2k\nu^2\Omega >> 10^5$ K). It has been expected that mass accretion and jet/outflows occur in young stellar objects (YSOs) and excite the non-thermal emission due to release of kinematic energy in the material within very compact volumes. High angular resolution of VLBI and special properties of the non-thermal emission provides us to elucidate a series of physical processes in star formation.

1.1. Non-thermal continuum emission sources

A YSO jet seen in a YSO is driven by the magneto-hydrodynamical force on the YSO's surface (e.g. Uchida & Shibata 1985). Outer interiors of low-mass YSOs amplify a dynamo action that leads to a giant flare. Such regions should create strong synchrotron emission emitted from free electrons highly accelerated by the strong magnetic fields in these regions. Because these regions are quite tiny (<1 AU), even VLBI cannot spatially resolve the emission structure. VSOP-2, the space VLBI project planned after the VSOP project, may resolve and elucidate the detail of the emitting regions and help us to understand the magneto-hydrodynamics of YSOs.

1.2. Maser sources

In star-forming regions, water vapor, methanol, and hydroxyl maser emission are observed. All of the masers are usually composed of many maser features, or physical gas clumps. Different from continuum emission, we can measure Doppler velocities of the maser features. Together with proper motions of maser features, three-dimensional kinematical structures and (with some assumption) three-dimensional spatial structures of the maser sources may be obtained. It is expected that such spatio-kinematical structure should be tightly correlated with evolutionary status of star formation process that controls physical conditions for maser excitation. Hereafter, mainly study on water maser sources are described. Water masers are brightest and provide the highest angular resolution in the maser species mentioned above.

2. Water masers and star formation: recent results

There are about 1000 water maser sources in the Galaxy, which are catalogued in the Arcetri catalog (Valdettaro et al. 2001). Among them, about 420 sources are associated with star-forming regions. There are ∼200 and ∼50 sources that have been mapped with, respectively, connected array such as the Very Large Array (VLA) and VLBI. For statistical analysis on basis of the maser spatio-kinematics, systematic monitoring VLBI observations of the masers are highly recommended. Such VLBI observations are recently performed with the VLBI Exploration of Radio Astrometry (VERA).

2.1. Chronology of water masers in star forming process

Duration of water maser excitation is quite short, $\sim 10^5$ years in massive YSOs (Genzel & Downes 1977). Water masers are also expected to be associated with the youngest stage of star formation, massive YSOs with hot molecular cores or hyper-compact (<0.01 pc) HII regions in massive-star forming regions, or with Class 0 objects in low- and intermediate-mass star forming regions (c.f. Furuya et al. 2001). In fact, interferometric observations have revealed not only tight spatio-kinematical relation between molecular cloud cores with high density and molecular outflows but also anti-correlation of normal or even compact HII regions (Forster & Caswell 2000). Physical links between water masers and other masers have implied that water masers trace the younger stage of massive-star formation than methanol masers that are associated with either disks/tori around massive YSOs or shocks created by strong stellar winds, and hydroxyl masers that are mainly associated with compact HII regions. Figure 1 summarizes chronology of VLBI sources associated with YSOs.

2.2. Masers three-dimensional spatio-kinematics: outflows and mass accretion

Usually we can obtain theangular distribution of Doppler velocities and proper motions of maser features with monitoring VLBI observations within a few years. Three-dimensional locations of maser features are also estimated on basis of a simple assumption of a spherically symmetric velocity field of the kinematical structure or other 3-D kinematical models. When the 3-D spatio-kinematical structure is found, a distance from the Sun to the maser source is also directly estimated without any standard candles (e.g. Gwinn et al. 1992). Fig. 2 shows such an example seen in the W51 North water masers (Imai et al. 2002).

Recent VLBI observations of water masers have presented wide variety of spatio-kinematical structures of the maser sources although duration of the water maser activity much shorter than the whole process of star formation (10^6–10^7 years). Most of water maser sources are associated with molecular outflows (including W51 North) with dynamical ages (10^3–10^4 years). Some of them have much shorter dynamical age ($\sim 10^5$ years in S106 FIR, Furuya et al. 2000), implying that these maser sources are associated with births of molecular jets/outflows at the earliest phase of star formation. In massive-star forming regions, such as Cep A, a purely-spherically expanding ring was discovered and estimated its dynamical age to be only ∼50 years (Torrelles et al. 2001). These difference is likely to be difference in evolutionary status rather than environment effects. In fact, in W75 North, water masers are associated with both a spherically-expanding shell and a highly-collimated outflow, which are associated with different but similar hyper-compact HII regions (Torrelles et al. 2003).

On the other hand, water masers may also associated with Keplerian rotating or dynamically infalling disks/torii. Some of them cannot be fit to either outflows or purely Keplerian rotating disks, but expected to exhibit infall motions. One of infalling models, an impinging-clump disk model proposed by Cassen & Moosman (1981) well explains spatio-kinematical structures of water masers in L1287 and IRAS16293−2422 (Fiebig 1997; Imai et al. 1999). More strong evidence for the existence of water masers associated with accretion disks are requested; at present information on 3-D kinematical structures of the water masers are still missing. If the water masers are really associated with accretion disks, they provide very important implication for directly and more accurately estimating a mass of the central YSO, understanding the disk dynamics through transportation of angular momentum.

2.3. Massive star formation and water masers

For massive star formation, there are mainly two scenarios proposed. For the first, massive accretion through an accretion disk/torus, the spatio-kinematical structure of the innermost part of the candidate massive disk/torus and an enclosed mass of the central YSO should provide unambiguous evidence for this scenario. For the second, merging lower mass stars into a higher mass star, the existence of runaway stars is expected, which have larger momentum and angular momentum subtracted from a binary system collapsing into a massive star. Interestingly, evidences of both of the scenarios have been discovered in the same region. Orion KL/BN (Jiang et al. 2005: Gómez et al. 2005).

Our recent observational studies on water maser sources have also found maser kinematical structures supporting both of the scenario. Fig. 3 shows water masers in G192.16−3.84. The southern two water maser features exhibit fast proper motions toward the northern maser feature cluster, indicating that the two features are moving to the dynamical center located at of a YSO with a mass of $M_* = 8\ M_\odot$. The Doppler velocity distribution of maser features detected so far also support the existence of an infalling-rotating thin disk. A runaway motion was also detected in the W51 West water masers, which seems to derive from another maser source, W51 Main. However, an uncertainty of the motion is large

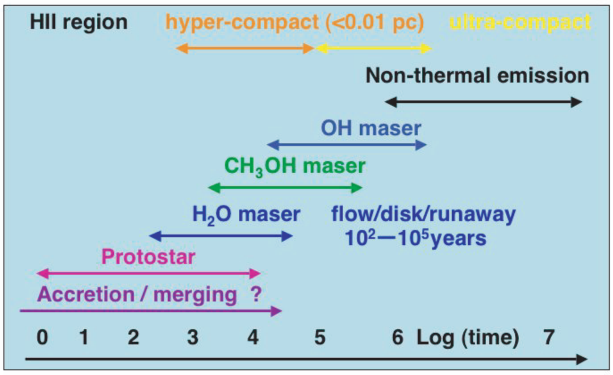

Fig. 1. Currently expected chronology of non-thermal and maser emission in star-formation process.

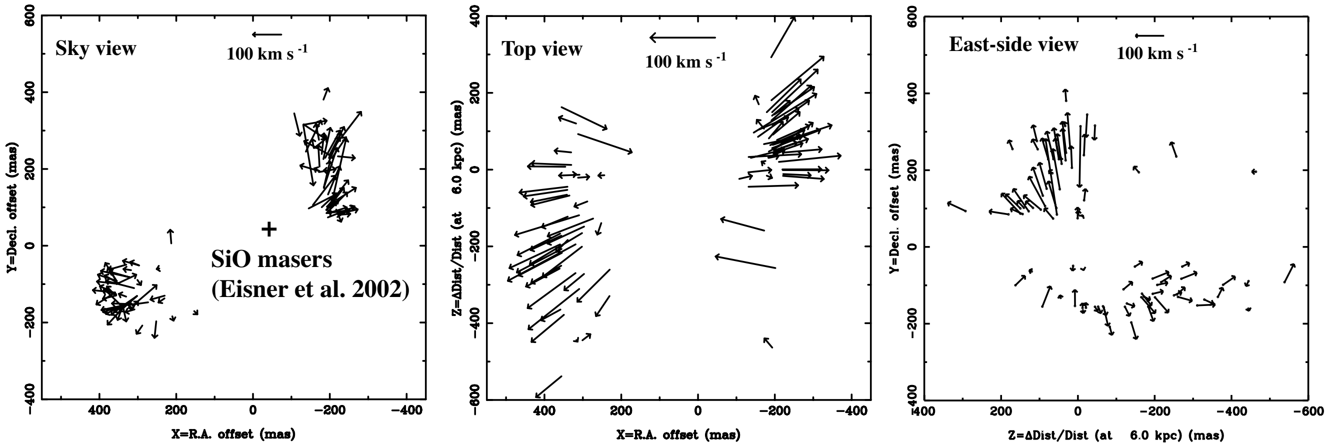

Fig. 2. Three-dimensional spatio-kinematical structure of the water masers in W51 North(Imai et al. 2002). The dynamical center of the flow is close to the location of the SiO masers in W51 North (Eisner et al. (2002), implying that the dynamical origin of the flow is located at the SiO maser source. The distance to W51 North was directly estimated to be 6.1±1.3 kpc, which is consistent with a kinematical distance (5.5 kpc) and well examined by recent photometric distance measurements.

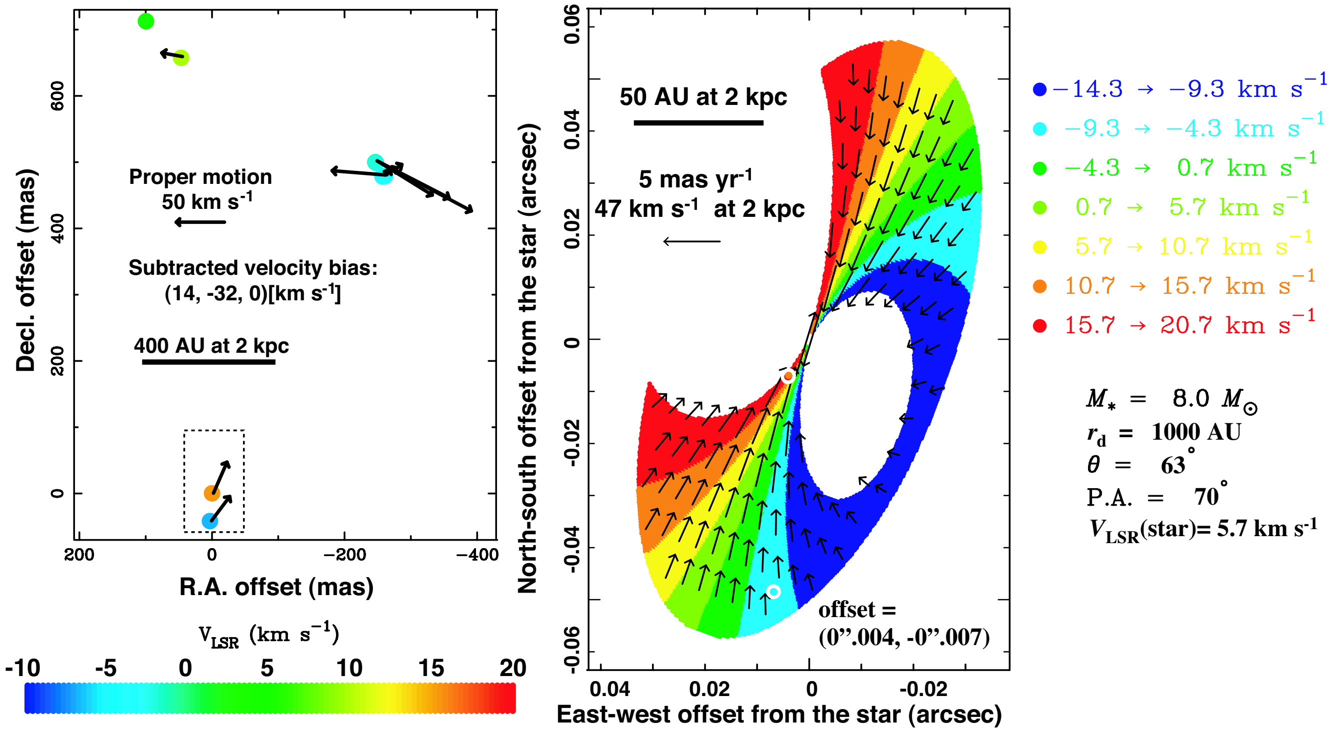

Fig. 3. Spatio-kinematical structure of the water masers in G192.16−3.84. *Left:* Locations, Doppler velocities (indicated by color), and proper motions (indicated by an arrow) of the water masers. A dotted box indicates a field of the right sub-panel.*Right:* An infalling rotating disk model and the observed two maser features seen in the southern region (circle with a white rim). The modeled Doppler velocity and proper motion field are indicated by colors and arrows, respectively.

Table 1. Parameters of telescopes in the East Asian VLBI Network.

Country	Telescope	Diameter (m)	8 GHz (Continuum)	22 GHz (water maser)	Remarks
Japan	VERA	4×20	○ ○ ○○	○ ○ ○○	2.3/6.7/43 GHz available
	NRO, NICT	45, 34, 32	x○○	○ ○ ○	Up to 150 GHz, 43 GHz available
	GSI, Yamaguchi	32, 32	○○	○x	6.7GHz available, 22 GHz planned
	Hokkaido, Gifu	11, 11	x○	○x	22 GHz planned in Gifu
	JAXA	64, 32	xx	xx	22 GHz planed for 32 m antenna
Korea	TRAO	14	x	x	Higher than 86 GHz available
	KVN	3×20	○ ○ ○	○ ○ ○	Up to 129 GHz planed
China	Shanghai	25	○	○	
	Urmqui	25	○	○	
	Delingha	14	x	x	Up to 115 GHz available
Taiwan	–	–	–	–	
Pacific	Tidbinbilla	70	○	○	
	Parks,Hobert	64, 25	○○	○○	
	Mopra	20	x	○	Up to 130 GHz
	ACTA	$6 times 25$	○	x	43/86 GHz available

($\sigma \sim$20 km s^{-1}) and the origin of the motion is still obscure. Thus study on water maser sources contribute to elucidating the formation mechanism of massive-star formation.

3. The East-Asian VLBI network (EAVN)

The EAVN is currently operated with consisting of the VLBI Exploration of Radio Astrometry (VERA) and Japanese telescopes as well as Chinese telescopes in a test observation phase. The Korean VLBI Network (KVN) will soon later join. There are 18 telescopes in tall that will join in the EAVN in different frequency bands (see table 1). The EAVN covers different sidereal times from the Very Long Baseline Array (VLBA) and the European VLBI Network (EVN), which enables us to observe transient objects in 24 hours. Because the EAVN is located slightly in the south from the VLBA and the EVN and has more compact antenna configuration, the EAVN has a better advantage for observing many maser sources around the Galactic center. One of the most important characteristics of the EAVN is that it has a unique advantage in high precision astrometry, with the dual-beam observations and the multi-frequency phase-referencing achieved by the VERA and the KVN, respectively. It provide accurate maser source distances and accurate coordinates, which enable us to accurately estimate physical parameters of the maser sources and elucidate physical links between the maser sources and other thermal/non-thermal emission sources. Higher sensitivity achieved by the EAVN also enables us to reveal clearer maser spatio-kinematics on basis of more detected maser features.

4. Summary

In the near future, the water maser chronology, mass accretion and development of molecular outflows and HII region within a short period (10^5 years) is expected to be well elucidated on basis of 3-D spatio-kinematics of water maser sources found through systematic monitoring and mapping observations of water maser sources with VLBI. EAVN will significantly contribute to such a study in term of combination of the advanced properties of VERA and KVN as well as combination of the East-Asian telescopes for higher sensitivity. Maser polarimetry also should be systematically made in the KVN with dual circular polarization system equipped in the most of the EAVN telescopes.

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