

# Science with VERA : VLBI Exploration of Radio Astrometry

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## ABSTRACT

VERA (VLBI Exploration of Radio Astrometry), being promoted by National Astronomical Observatory of Japan in collaboration with several Japanese universities, is a new VLBI array for phase referencing astrometry approved to start its construction in 2000. VERA, the first VLBI array dedicated to phase referencing VLBI, has a dual beam antenna system which enables us to observe a Galactic maser source and a nearby reference source simultaneously to remove the atmospheric fluctuation, and will measure positions of Galactic maser sources relative to reference sources (QSOs and radio galaxies) with 10 microarcsec level accuracy. With that accuracy, VERA will be able to determine parallaxes and proper motions of maser sources in the whole Galaxy. The major science targets of VERA will include 3D structure of the Galaxy and the distribution of dark matter, physics of outflow in star forming regions and stellar envelopes, precise calibration of the period-luminosity relation of Mira-type stars, and structure and evolution of QSOs and radio galaxies.

**Keywords:** VLBI, phase referencing, astrometry

## 1. INTRODUCTION

VLBI Exploration of Radio Astrometry (VERA) aims at astrometry of Galactic maser sources based on the phase-referencing VLBI technique, in which two adjacent sources are observed simultaneously to remove the atmospheric fluctuation. A position accuracy of  $\sim 100 \mu\text{arcsec}$  has been already achieved by switching differential VLBI in which an object and a reference source are observed by turns,<sup>1</sup> but the atmospheric fluctuation is not completely suppressed because of the time lag between observations of an object and a reference. In order to obtain a higher position accuracy, one needs to observe an object and a reference source at the same time. VERA, with its dual beam antenna system,<sup>2</sup> enables us to observe a Galactic maser source and an extra-galactic reference source simultaneously. With such a system, positions of maser sources relative to reference sources can be measured with 10  $\mu\text{arcsec}$  level accuracy. This accuracy allows us to determine the distance of an object at D kpc with uncertainty of D%, and the proper motion with uncertainty of 0.05D km/s. Therefore, one can obtain parallaxes and proper motions of maser sources in the whole Galaxy with VERA.

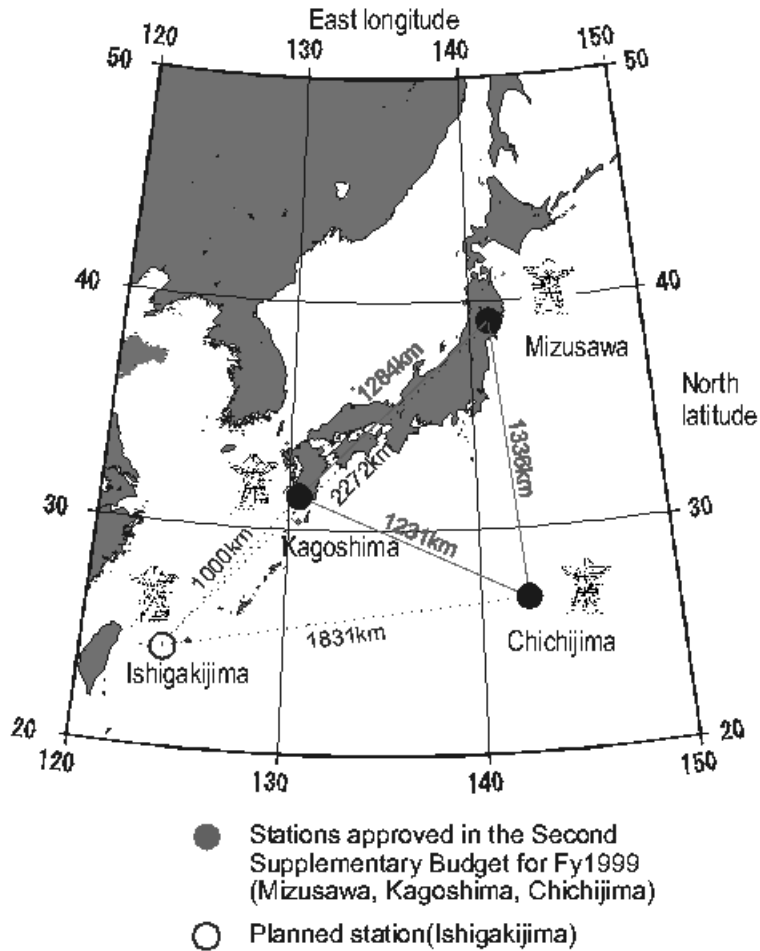
In this paper, we summarize the VERA project, in particular the sciences that can be done with VERA. First, we will briefly review the VERA system including phase referencing technique, which is the key to VERA for obtaining highest position accuracy ever achieved, and then we will describe target sources of VERA and discuss sciences that can be done with VERA.

## 2. VERA SYSTEM

### 2.1. System Overview

#### 2.1.1. Antenna

VERA is an array of four 20m $\phi$  antennas designed for observational frequency range from 2 GHz to 43 GHz, with possible extension to 86 GHz. Each antenna will be installed with dual beam system with which one can observe a target source and a reference source simultaneously to remove the atmospheric fluctuation. The dual beams on each antenna can be separated by as large as 2 degree, with minimum separation of 0.5 degree. A noise source will be mounted on the antenna aperture, and radio emissions from the noise sources will be injected into dual beam receivers during the observation of astronomical objects and used to calibrate the mechanical delay in dual beams.



**Figure 1.** VERA cite map. Filled circles are stations to be constructed in 2000. Open circle is a planned station. The longest baseline of the VERA array will be about 2300 km/s.

Based on the real time calibration of mechanical delay using the noise source, the relative path length difference in two beams will be calibrated within 50  $\mu\text{m}$ .

### 2.1.2. Receiver

Each VERA station have four receivers; S band (2 GHz), X Band (8 GHz), K band (22 GHz) and Q band (43 GHz) receivers, and all receivers will be equipped with cooled HEMT amplifiers. The receivers for S and X bands are mainly for geodetic observation to determine the baseline parameters. The receivers for K and Q bands are for  $\text{H}_2\text{O}$  and  $\text{SiO}$  masers as well as continuum sources to be used for phase-referencing. Each station will be installed with one S and X receivers, and two K and Q receivers for dual beams, respectively. The noise temperature of K band receiver will be less than 60 K, and that of Q band receiver will be less than 100 K.

### 2.1.3. Recording System

The output signals from receivers are converted to the intermediate frequency (IF) of 5 to 7 GHz, and down-converted again to the baseband before digital processing. The baseband signals will be recorded at the rate of 1 Gbps (Giga bit per second) with 2-bit quantization and with bandwidth of 256 MHz at maximum. The signals from noise source attached on the antenna aperture are mixed up with the signals from astronomical objects and recorded at the same time.

#### 2.1.4. Correlation Processing

The correlation processing will be performed with the Mitaka FX correlator, which has been developed for VSOP (VLBI Space Observatory Program).<sup>3</sup> The correlator will be modified for high speed recording system and two beam observations for phase referencing VLBI astrometry. The correlation processing of the noise sources observed with dual beams can be also done with the Mitaka FX correlator, but is mainly done on real time using delay calibration correlators installed to each station.

#### 2.2. Cites

In 1999, construction of three telescopes has been approved by the Japanese government. The three antennas will be located at Mizusawa, Kagoshima, and Chichijima island. The Mizusawa station will be located at Mizusawa Astrogeodynamics Observatory, which belongs to National Astronomical Observatory, Japan. The Kagoshima station will be located at Iriki farm of Kagoshima University, and the radio astronomy group of Kagoshima University will be in tight collaboration with NAOJ for constructing and operating the VERA antenna at Iriki station. The fourth antenna is planed to be built in Ishigakijima island in Okinawa prefecture. Figure 1 shows the antenna location as well as the baselines of VERA array. The length of six VERA baselines varies from 1000 km to 2300 km.

#### 2.3. Phase Referencing Capability

VERA aims at measuring the geometric delay difference of two sources with uncertainty of 0.1 mm. This corresponds to a visibility phase accuracy (phase of source relative to reference) of 2.6 degree at 22 GHz and 1.3 degree at 43 GHz, respectively. Atmospheric fluctuation will be suppressed by observing simultaneously a target and a nearby reference located within 2 degrees from each other.<sup>4</sup> To correct for errors in visibility phase that are caused mechanically in antennas, electrically in receivers, and digitally in recording systems, the delay difference in dual beams will be calibrated by observing the noise source mounted on the antenna aperture. Note that the noise source at each station increases the system noise temperature by only a few percent, and thus its effect on the source visibility is negligible. To calibrate the mechanical delay, each station has delay calibration correlator that performs cross correlation processing of the two beams to obtain the delay difference on real time. With such a calibration system, VERA will measure the relative delay of two objects (target and reference) with accuracy of 0.1 mm. Once the relative delay is obtained within 0.1mm, the position accuracy will be of  $\sim 10 \mu\text{arcsec}$  ( $=0.1\text{mm}/2000 \text{ km}$ , 2000 km is the baseline length).

#### 2.4. Schedule

A rough schedule of VERA is shown in table 1.

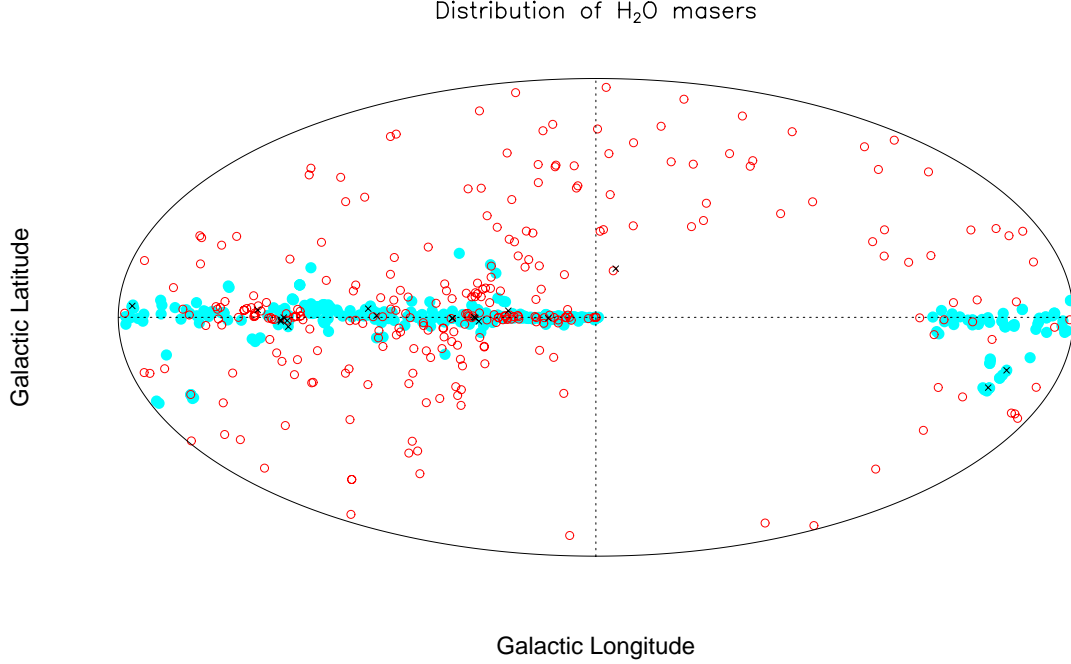
table 1: Schedule of VERA project

year	schedule
2000	construction
2001	system setup, first fringe detections
2002-3	system setup, test observations
2004(5?)-	project observations, common use observations

### 3. TARGET SOURCES OF VERA

#### 3.1. Maser Sources

The main targets to be observed with VERA are Galactic  $\text{H}_2\text{O}$  (22 GHz) and  $\text{SiO}$  (43 GHz) masers that are mainly emitted from star forming regions and Mira-type variables. Figure 1 shows the distribution of  $\text{H}_2\text{O}$  maser sources in the Galactic coordinate system.<sup>5</sup> As seen in figure 1, the  $\text{H}_2\text{O}$  masers emitted from star forming regions are concentrated to the Galactic plane, while the Mira-type variables are scattered over the whole sky area. The latter is due to the fact that the masers from Mira-type variables are mostly nearby ones. On the other hand, masers from star forming regions are much brighter than those of Mira-type stars, and so they are observable in the entire Galactic disk. In fact, according to the distance estimates of these  $\text{H}_2\text{O}$  masers<sup>5</sup>, several star forming regions with  $\text{H}_2\text{O}$  masers are found in the outermost regions of the entire Galactic disks. Thus,  $\text{H}_2\text{O}$  masers in star forming regions are good probes of the structure and dynamics of the Galactic disk.



**Figure 2.** Distribution of  $\text{H}_2\text{O}$  maser sources in the Galactic coordinate. Filled circles are maser sources in star forming regions, open circles are maser sources in Mira-type variables, and crosses are unidentified sources.

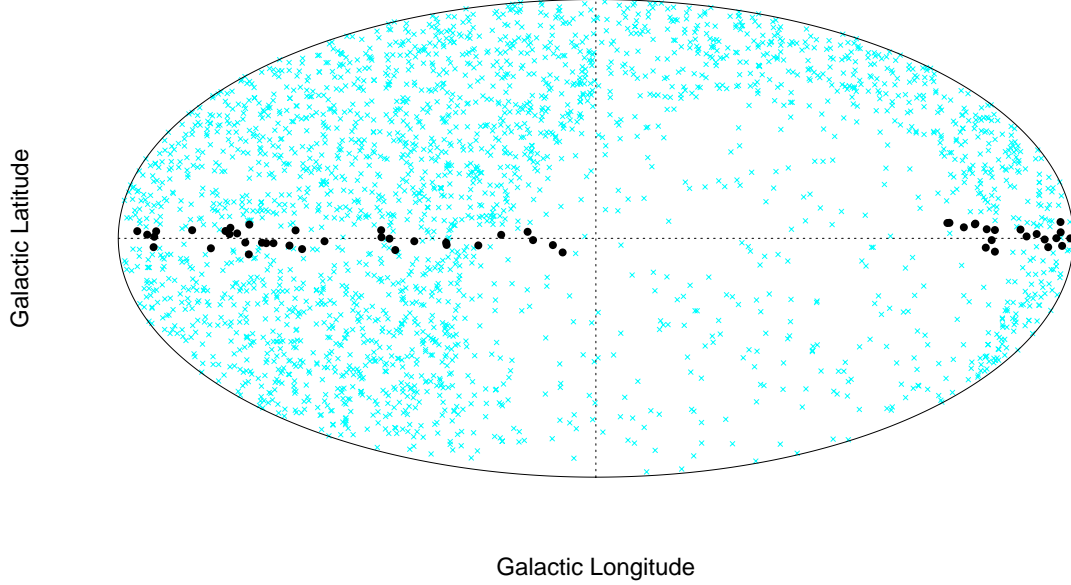
As for Mira-type variables, a number of surveys are being performed. For example, the SiO maser survey in the Galactic center region<sup>6</sup> have found several tens of Mira-type stars in the Galactic bulge. Probably a large fraction of these Mira-type stars are observable with VERA at 43 GHz band. Thus, Mira-type stars are not only useful for studying the local structure of the Galactic disk, but also useful for studying the Galactic bulge.

### 3.2. Continuum Sources

VERA also observes continuum sources that are bright at the 22 GHz and 43 GHz band for phase referencing. Continuum sources observable with VERA are radio galaxies and QSOs, and some Galactic sources such as X-ray binaries and radio emitting stars are also observed. The extra-galactic continuum sources are mostly used as phase reference sources, and positions of masers are measured relative to these reference sources. Note that Galactic continuum sources such as X-ray binaries cannot be used as a position reference because their parallaxes and proper motions are not negligible. However, those Galactic continuum sources will be also observed with VERA as target sources to study the physical mechanism of their activity.

Currently, a large number of VLBI sources (continuum sources detectable with VLBI) are known. However, most of surveys of VLBI sources have been performed in the regions with  $|b| \geq 10^\circ$ . Hence, the number of VLBI sources is much smaller in the Galactic plane. On the other hand, as seen above, many of maser sources are concentrated to the Galactic plane, and thus, one has to search for a large number of VLBI sources in the Galactic plane that can be used as reference sources. As a first step for the VLBI source surveying program, we have conducted VLBI observation of radio sources in the Galactic plane at 22 GHz<sup>7</sup> using Japanese VLBI network (J-Net). Figure 2 shows the results of the J-Net survey as well as previously known VLBI listed in ICRF catalog<sup>8</sup> and VLBA calibrator catalog.<sup>9</sup> As seen in figure 2, we have found more than 50 new VLBI sources within  $|b| \leq 5^\circ$ , and they are potential candidates for reference sources of VERA.

Distribution of Newly Detected VLBI Radio Sources



**Figure 3.** Distribution of continuum sources that are detected with VLBI. Filled circles are new VLBI sources discovered based on the J-Net survey (see text).

## 4. SCIENCE WITH VERA

### 4.1. Structure and dynamics of the Milky Way Galaxies

#### 4.1.1. Distance to the Galactic Center

The distance to the Galactic center is one of the most fundamental parameters for investigating the structure of the Milky Way Galaxy. Although a large number of studies have been made to measure the Galactic center distance, its uncertainty is still as large as 1 kpc.<sup>10</sup> One of the major reasons for this is that most of these measurements are based on indirect methods rather than using trigonometric parallax. VERA will observe the radio source Sgr A\*, thought to be the central massive black hole of the Galaxy, and directly measure its distance based on the annual parallax. With position accuracy of 10 micro-arcsec, VERA can determine the distance to Sgr A\* within 10 %. The measurement of the Sgr A\* distance will be one of the first targets for VERA.

#### 4.1.2. Galactic Rotation Velocity at the Sun

The other fundamental parameter for studying the structure of the Galaxy is the Galactic rotation velocity at the Sun,  $\Theta_0$ . The simplest way to determine  $\Theta_0$  is to measure the proper motion and distance of Sgr A\*, as the proper motion of the Galactic center  $\mu$  is related to  $\Theta_0$  as  $\mu = \Theta_0/R_0$ . However, if Sgr A\* or the Sun has local random motion in addition to the Galactic rotation, such a simple method does not work effectively. Instead, VERA can determine  $\Theta_0$  using the motions of maser sources in the Solar circle. If proper motions of a few tens of masers are obtained,  $\Theta_0$  will be determined with an accuracy of  $\sim 5$  km/s.

#### 4.1.3. Outer Rotation Curve and Distribution of Dark Matter

VERA can determine the proper motion of maser sources with unprecedented accuracy as well. The accuracy of proper motion measurement will be less than 1 km/s within 20 kpc from the Sun. With that accuracy, the rotation curve can be determined in the entire Galactic disk. The rotation curve accuracy will be of 5 to 10 km/s, depending

on the random motions of maser sources. This accuracy is much higher than that of the Galactic rotation curve currently known (typically  $\sim 30$  km/s).<sup>11</sup> Based on that rotation curve, one can reveal the distribution and total amount of dark matter in the Milky Way Galaxy.

#### **4.1.4. Testing Disk Dark Matter**

Studies on the disk structure in the Sun's neighborhood have suggested that there may be dark matter in the local disk, but this suggestion is not yet confirmed.<sup>12,13</sup> Thus, it still remains unclear if there is dark matter in the disk. By measuring three dimensional motions of nearby Mira-type variable stars with VERA, one can study the mass distribution in the local disk. Moreover, based on the motions of H<sub>2</sub>O masers perpendicular to the disk, one can also study the disk structure even at a distance of several kpc from the sun. Thus, VERA will be a powerful tool to investigate the disk dark matter, and will hopefully give a solution to that problem.

#### **4.1.5. Shape of the Milky Way Galaxy**

VERA will observe hundreds of H<sub>2</sub>O maser sources in the star forming regions distributed over the entire Galactic disk. These star forming regions are thought to be mainly located in spiral arms, as usually observed in extra-galaxies. Thus, when accurate distances are obtained for these maser sources, one may be able to know the precise shape of spiral arms in the Galaxy's disk. Also, the observations of SiO maser sources in the Galactic bulge will enable us to study the structure and dynamics of the Galactic bulge in detail. In particular, there have been several investigations suggesting that the Galaxy is a barred spiral galaxy,<sup>14-16</sup> and this can be tested with observations of bulge SiO masers with VERA. Thus, based on the observations of many H<sub>2</sub>O and SiO masers in the Galactic disk and bulge, VERA will reveal the clear shape of the Milky Way Galaxy.

### **4.2. Stellar and Star Formation Physics**

#### **4.2.1. Stellar Outflows in Mira-type variables**

One of the main targets of VERA is Mira-type star that emits H<sub>2</sub>O and SiO masers. These maser spots are in the circumstellar shell, and their physical properties are thought to be tightly related to the stellar outflow. VERA will measure the precise positions and motions of these maser spots based on the phase referencing VLBI. Thus, monitoring observations of Mira-type stars with VERA will be a powerful tool to investigate the physics and mechanism of outflows in late-type stars.

#### **4.2.2. Disk and Jet Motions in Star Forming Regions**

H<sub>2</sub>O masers emitted from star forming regions are thought to come from protoplanetary disk formed around the protostar and/or molecular outflows. Monitoring observations of these maser sources with VERA will enable us to measure the precise positions and motions relative to extra-galactic reference source such as radio sources and QSOs. Thus, VERA will enable us to obtain the absolute motion of maser spots in star forming regions for the first time, which is of great use in revealing the dynamics of star forming disk such as disk rotation and infall motion, as well as outflow motions in jets.

#### **4.2.3. Compact Active Stars in the Galaxy**

While the maser sources are the major targets of VERA, there are also several Galactic continuum sources that can be observed with VERA at 22 GHz or 43 GHz. An example of such continuum sources is an X-ray binary such as Cyg X-1 and GRO J1655-40. These X-ray binaries are thought to be a pair of a giant star and a compact object such as a neutron stars or black hole, in which the gas accretes from the giant star to the compact object. VERA can measure the precise distance to such radio emitting active stars, and also determine their orbital parameters based on the position measurement relative to extra-galactic reference sources. Once the orbital parameters are determined for the binary stars, one can obtain the mass of compact stars with high accuracy. Thus, VERA will give some fundamental information in studying the physics of compact stars.

### **4.3. Extra-galaxies and AGNs**

#### **4.3.1. Dynamics of Nearby Galaxies**

Some maser sources in nearby galaxies are also observable with VERA. Maser sources in disks of extra-galaxies can be used to study the dynamics of the galaxies. If one compares proper motions of maser sources due to galactic rotation as well as its rotation velocity obtained from its spectrum, one can obtain the distance to the galaxy directly. Such a method can be applied to M33, which has several maser sources in its disk.<sup>17</sup>

### 4.3.2. Proper Motions of Nearby Galaxies

It is common that some galaxies form a binary or group of galaxies, and are interacting with each other through their gravitational force. One of the fundamental parameters in studying the interacting galaxies is the three-dimensional velocity of galaxies. VERA will monitor nearby interacting galaxies that harbor AGNs in their central regions, and measure their three-dimensional motions. Further, systematic study of proper motions in nearby clusters of galaxies can be used to measure directly the distance to the clusters of galaxies based on statistical parallaxes. To obtain proper motion of nearby galaxies with high accuracy, monitoring for a few years is required.

### 4.3.3. Megamasers and Supermassive Black Holes

Masers are also found in the circumnuclear molecular disks of AGNs. For instance, in NGC 4258, the distribution and velocity of maser spots clearly demonstrate the existence of circumnuclear disk whose rotational motion is well fitted by Keplerian velocity, and provide the most compelling evidence for a supermassive black hole in the galaxy center.<sup>18</sup> However, such a clear evidence for supermassive black hole is only found in few galaxies. The main reason for this is that the masers in AGNs are too faint to be observed with normal VLBI. Based on the phase referencing technique, VERA will enable us to perform a long integration without coherence loss, and thus provide deeper images of AGN maser sources. Thus, with VERA, one can study systematically supermassive black holes in AGNs as well as the physics of masers in AGNs.

## 4.4. Cosmology

### 4.4.1. Period Luminosity Relation of Mira-type Variables

By combining the variation periods of Mira-type stars in the optical and/or infrared band with their accurate distances obtained with VERA, one can establish a precise period-luminosity relation for Mira-type variables. Such a relation can be used to calibrate accurately the distance of Galactic globular clusters and nearby galaxies such as Magellanic Clouds and M31. Distances to Galactic globular clusters are of great importance in studying their ages and thus the age of the Universe, and distances to nearby galaxies are also important in calibrating further steps of the cosmic distance ladder. Thus, period-luminosity relation of Mira calibrated with VERA will provide a fundamental basis for studying galaxies and cosmology.

### 4.4.2. Direct Distance Measurement to Nearby Galaxies

Distances to nearby galaxies can be directly measured with VERA based on various methods. Some examples are such as using disk rotation, statistical parallaxes and megamaser circumnuclear disks, and so on. With such distance measurements to nearby galaxies, VERA will make the basic step of the cosmic distance ladder firmer than ever.

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