論文内容の要旨

論文題目

H_2O maser observations of massive star forming region

IRAS 06058+2138, IRAS 19213+1723 and AFGL 2789 with VERA

（VERAによる大質量星形成領域 IRAS 06058+2138,

IRAS 19213+1723, AFGL 2789での水メーザー観測）

氏 名 : 呉 忠植

Massive stars are fundamental in determining the appearance and evolution of galaxies. Throughout their life cycle, they produce a dominant fraction of the heavy elements, generate significant amounts of energy and momentum with stellar winds, molecular outflows, UV radiation, and eventually supernova explosions. Massive stars and their associated molecular clouds trace the spiral arms of The Galaxy. In principle, one can construct a simple model of the rotation speed of stars and gas as a function of distance with respect to the center of the Galaxy. Since the Galactic rotation depends on the distribution of mass, rotation curves of galaxy, plotted with rotation velocities as functions of distance from galaxy centers, play a very important role in studies of the mass distributions in disk galaxies. For instance, rigid-body rotation near the Galactic center implies that the mass must be roughly spherically distributed and the density nearly constant. On the other hand, flat rotation curves suggest that the bulk of the mass in the outer region of the Galaxy are spherically distributed with a density law that is proportional to r^{-2}. On the other hand, observations of rotation curves in external galaxies revealed that they are basically flat within optical disks of spiral galaxies. These flat rotation curves observed in external galaxies provided strong evidences for the dark matter, which can not detect with observations, in outer regions of galaxy. In contrast, although a large number of observations and simulations have been made to determine it of the Galaxy, the outer rotation curve is still crude because first, in case of our galaxy, it is difficult to determine its spiral structure because of our view from the interior of the Galaxy. Second, if the observations are performed with 1-dimension, only the line of sight component of spatial velocity, it is difficult to determine accurate distances (that is, a kinematic distance) of the Galactic objects which can be trace the rotation curve, such as bright stars and molecular clouds enough to observable at the far distance. Another reason is a difficulty to measure proper motions of Galactic objects, a low spatial resolution of observation system gives large uncertainties to study of the Galaxy. Besides, the large scatter in the data from observation, not only caused by the different methods but also due to the different parameters can be reason of difficulties to determine the rotation velocities.

In spite of numbers of observational studies on massive star-formation processes, the formation of massive stars is poorly understood. There are two scenarios to explain the formation of massive stars. The first is the accretion scenario, similar to process for low-mass star, of which a accreting process result in a formation disk and outflow then stellar core is formed with these process. Another scenario, the coalescence scenario proposes that massive stars are formed by merging of stars with low or intermediate masses. Massive stars are born in the dense cores of giant molecular clouds and deeply embedded. In addition, massive stars are usually born in clusters, and hence their individual studies are usually affected by confusion, which is more serious for distant massive star forming regions than for nearby low-mass sources. Moreover, the time scale of high-mass stars which much shorter than low-mass stars also cause the lack of knowledge in massive star forming process. The presence of maser emission represents the physical conditions of star forming region, in all case, the maser spots are not only extraordinarily bright, but also small in size and narrowly confined in frequency. Therefore masers act as powerful signposts of active star formation and as unique tool to probe the physical conditions and kinematics of these regions.

The distance to source is one of the most fundamental physical properties, if it is estimated with high accuracy then can be applied to study a structure of the Galaxy, to luminosities and masses of stars in massive star forming regions, and eventually one can determine the type of stars. The direct method to obtain distance to objects is to measure the annual parallax. As the Earth orbits around the Sun with a period of one year, star positions show seasonal modulations. By measuring this apparent displacement of star positions (annual parallax) which nearby objects have a larger parallax than more distant objects, one can determine the distance. For instance, the Hipparcos satellite has used this technique for over 100,000 nearby stars, and has reached distances of ~300 pc by parallax measurements. However, this is much smaller than the size of the Galaxy which radius of the Galactic disk is thought about 15 kpc. Hence, present astrometry in the optical domain also has the difficulties to study a distant stars and structure of the Galaxy. At radio wavelengths, however, high precision astrometry have been made with VLBI (Very Long Baseline Interferometry), while VLBI observations suffer from the fluctuation of atmosphere, which mainly due to the water vapor in the troposphere, this problem can be eliminated by phase-referencing method which has been developed to cancel out the tropospheric fluctuations. In phase-referencing observations, one target and nearby reference sources of one or more are observed by rapidly switching the telescope, where reference sources have been known their absolute position already. After correcting for the influence of troposphere, relative position of the target source with respect to the reference sources can be determined. By performing VLBI observation with phase-referencing method, therefore one can measure the absolute positions, parallaxes, and proper motions of target sources with high accuracy of sub milliarcsecond (mas) or a few μas. VERA (VLBI Exploration of Radio Astrometry) is a VLBI array aimed for obtaining 3-dimensional map of the Galaxy. Most unique aspect of VERA is 'dual-beam' receiver system, which can observe two nearby sources at the same time. VERA's dual-beam observations more effectively cancel out the atmospheric fluctuations than single-beam VLBI system, and can measure the absolute positions of target sources with high accuracy of ~10μas.

In this thesis, we report the studies of the Galactic rotation curve and massive star-forming regions performed H_2O maser (22GHz) observations with phase-referencing by VERA. Three massive star-forming region of IRAS 06058+2138, IRAS 19213+1723, and AFGL 2789 are selected, these are thought that locate in the different position of the Galaxy and different distance with respect to the Galactic center, and trace slightly different evolution phase and stellar type. The galactic coordinates of IRAS 06058+2138, IRAS 19213+1723 and AFGL 2789, (l, b)=(188°.95, 0°.89), (52°.10, 1°.04) and (94°.60, −1°.80), respectively. For these massive star forming regions, the first astrometric observations are performed, therefore we can understand the importance of this study, as defining the kinematics of sources in massive star-forming region and the Galactic plane as well as determining the absolute position of the celestial sources on the sky plane. In previous studies for IRAS 06058+2138, IRAS 19213+1723 and AFGL 2789, kinematic distances have uncertainties significantly greater than their parallax distances. However, by performing VLBI observation with phase-referencing method of VERA, the absolute positions of target sources are measured with high accuracy of sub-mas or several μas. Therefore our parallaxes and proper motions yield full space motions accurate to the order of a few to sub km s^{-1}. The parallaxes of IRAS 19213+1723 and AFGL 2789 are 0.569±0.0344 mas (1.76±0.106 kpc) and 0.326±0.0314 mas (3.07±0.295 kpc), and these are located in the Perseus spiral arm. The parallax of IRAS 19213+1723 is 0.569±0.0344 mas (1.76±0.106 kpc), placing it in the Carina-Sagittarius arm.

In chapter 6, we present the studies of the rotation curve of outer Galactic plane and earlier phase of stellar evolution in massive star forming regions by using distributions and proper motions of H_2O masers. The rotation curves of the Galaxy are determined with 3-dimensional velocity components of H_2O maser features, we show that the flat rotation curve in the range of 6.4 kpc$\leq R \leq$ 13 kpc as combining with S269 which observed with VERA, and overall rotation curves of the Galaxy are not depending on the rotation velocity of LSR, Θ_0. However, if one pay attention to detailed profile of rotation curve, there are some inconsistency from flat rotation curve. Our results as well as the previous observations of HI and CO molecular emission show a dip profile from ~8.5 to 11 kpc although those show the flat rotation curve as overall range of outer region. Dip profile, due to slower than the Galactic rotation, can be explain either that another structure except the galactic bulge, disk and dark halo in outer region of the Galaxy is exist and provides gravitational influence, or dip profile trace the peculiar motion of the Perseus arm itself. In addition, IRAS 06058+2138, IRAS 19213+1723, and AFGL 2789 are moving systematically toward the Galactic center, it is difficult to explain as their random motions described by the Schwarzschild distribution function. Thus we suggest that this peculiar motions of IRAS 06058+2138 and AFGL 2789 located in the Perseus arm may be trace the peculiar motion of the Perseus arm, and IRAS 19213+1723 in the inner Galaxy are affected by the gravitational potential of the central bar. Alternatively, this peculiar motion toward the Galactic center can be explain that LSR is moving to the opposite of Galactic center direction.

On the other hand, from the studies of the kinematics and earlier phase of stellar evolution in massive star forming regions, we determined the luminosities of IRAS 06058+2138 (MM1, MM2), IRAS 19213+1723 and AFGL 2789 with new distances determined by phase-referencing VLBI observations, and estimated stellar type are early B type for all sources. From proper motions and LSR velocities of the H_2O masers, we found that MM1 of IRAS 06058+2138 accompanied with an outflow and a rotating expanding disk. Then, we have calculated the disk size to be 90 mas (~160 AU at the distance of 1.76 kpc) and the mass of the central star to be about 11 $M_\odot$. The estimated stellar mass is comparable to early B type star, that is consistent with the stellar type determined with the luminosity. The H_2O masers in AFGL 2789 and IRAS 19213+1723 may trace the bipolar outflow with wide angle and outflow with expanding, respectively. In the case of IRAS 19213+1723, the maser features are concentrated in compact region of less than only 1 mas and have high velocity difference between the H_2O emission and CO emission, we suggest that these high velocity maser features may be appeared from relatively less dense region of ambient gas. And finally, by comparing the previous observational results of MM1 and MM2 in IRAS 06058+2138, IRAS 19213+1723 and AFGL 2789 to our results of phase-referencing VLBI observations, the evolutionary status can be determined and suggested that the H_2O masers of MM2 trace the earlier evolutionary phase than the methanol masers, therefore MM2 represents the earliest evolutionary phase among these sources, and IRAS 19213+1723 represents the latest one.