New Distance and Revised Natures of High Mass Star Formation in G5.89-0.39

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Abstract

We report on the astrometric observations of the 22 GHz H$_2$O masers in the high mass star-forming region G5.89-0.39 with VERA (VLBI Exploration of Radio Astrometry). Newly derived distance of 1.28\textpm0.08 kpc is the most precise and significantly nearer than previous values. We revised physical parameters and reconsidered nature of G5.89-0.39 based on the new distance as follows. (1) The ionizing star of the ultra compact (UC) H\textsc{ii} region is a late O-type (O8 – 8.5) zero age main sequence (ZAMS) star, consistent with previously established limits based on its infrared spectral line emission. (2) Crescent-like maser alignment at the position of the O type ZAMS star may trace accretion disk (or its remnant), which suggests that the star is still young and before complete evaporation of circumstellar materials. (3) Although the revised mass for the east-west outflow has been reduced, it still quite large (100 $M_{\odot}$) which indicates that a significant fraction of the mass is entrained material and that the dynamical age significantly underestimates the actual outflow age. Our newly-derived distance emphasizes that G5.89-0.39 is one of the nearest targets to investigate ongoing high-mass star formation and evolution in a compact cluster containing a young O-type star.

Key words: Astrometry — ISM:masers (H$_2$O) — ISM:individual (G5.89-0.39, W28A2) — ISM:H\textsc{ii} regions — ISM:jets and outflows

1. Introduction

A systematic and consistent scenario of high mass star formation has not been constructed yet. In spite of enormous and intense works, there are many hypotheses and unsolved issues (e.g., Zinnecker & Yorke 2007 and reference therein). But, several recent theoretical studies have suggested that high mass star formation can be achieved via mass accretion (e.g., Krumholz et al. 2009). This hypothesis seems to be consistent with observational signatures of massive accretion disk and torus around high mass protostellar object (HMPO) or protocluster (e.g., Beuther et al. 2009). Upcoming Atacama Large Millimeter / submillimeter Array (ALMA) will be able to resolve such a circumstellar structure enough and provide us more quantitative information about a specific accretion mechanism onto an individual HMPO.

Precise distance of a source is essential to quantitative discussions. However, most of the high mass star-forming regions, which will be targets for ALMA, are even located on the inner Galactic plane, where source distances often contain significant uncertainty. Direct distance measurements by astrometric observations are quite important for such regions, in especial, highly accurate VLBI (Very Long Baseline Interferometry) astrometry is the only technique suitable for deeply embedded high mass star-forming regions where optical measurements are almost impossible. Hachisuka et al. (2006) has been first demonstrated great performance of VLBI astrometry using H$_2$O maser in W3(OH) region, and since then, several studies have achieved 10 micro-arcsecond (\textmu as) accuracy for northern star-forming region (e.g., Moellenbrock et al. 2009; Sato et al. 2010b). In this paper, we report on an annual parallax measurement of H$_2$O masers in the high mass star-forming region G5.89-0.39 with VERA (VLBI Exploration of Radio Astrometry; Kobayashi et al. 2008).

G5.89-0.39 (also known as W28A2) is one of the most famous, shell type ultra compact (UC) H\textsc{ii} region (e.g., Wood & Churchwell 1989). The O-type ionizing star has been detected as a near-infrared (NIR) point source by Feldt et al. (2003) inside the shell (hereafter Feldt’s star). Acord, Churchwell & Wood (1998) (hereafter ACW98) have directly measured dynamic angular expansion of the radio shell. Observed supersonic expansion and short dynamical age (600 yr) indicate that this small UCH\textsc{ii} region is just after the birth. G5.89-0.39 is also known to be a host of an extremely massive outflow which is centered on the shell (e.g., Acord, Walmsley & Churchwell 1997). The whole part of the shell is completely inside the outflow extent (e.g., Watson et al. 2007). This also gives further
support on a remarkable youth of the UCHII region.

Previously reported distances for G5.89-0.39 vary over a wide range (1.9 - 3.8 kpc; Hunter et al. 2008, and reference therein). Almost all of them are measured through kinematic distance method, but at the Galactic longitude of 5°.89, this method intrinsically contains large systematic error of kpc order. Although ACW98 tried to estimate the distance from the shell expansion without any Galactic rotation models, they still have adopted several assumptions for their modeling of the data. In this point of view, our direct distance measurement is very important to confirm the physical parameters of G5.89-0.39.

2. VERA Observations

VERA observations of the H$_2$O masers ($J_{K_a,K_c} = 6_{16}^{-}-5_{23}$) at 22.23508 GHz associated with G5.89-0.39 have been carried out at 9 epochs between 2007 November and 2009 May. A summary of all observations is listed in table 1, which contains observing dates, synthesized beam sizes in milli-arcsecond (mas), beam position angles (PA) east of north, spectral resolutions, typical noise levels and dynamic ranges of synthesized images and brief comments, if any, about system noise temperatures ($T_{sys}$).

Each observation was made in VERA’s dual-beam mode in which targeted maser source and phase calibrator (or position-reference source) were observed simultaneously (Kawaguchi et al. 2000; Homma et al. 2003). The real-time, instrumental phase difference between the two beams was measured for a calibration using the artificial noise sources during the observations (Homma et al. 2008a). We chose J1755-2232 ($\alpha_{2000}=17^h55^m26^s2848, \delta_{2000}=-22^\circ32^\prime10^\prime61656; \text{Petrov et al. 2005}$) as a paired calibrator. This source is separated from G5.89-0.39 by 1°.92 at a position angle of -140° east of north. The flux density of J1755-2232 is about 150 mJy. No significant structure is seen in this point-like calibrator. A bright calibrator, NRAO530 (=J1733-1304; Ma et al. 1998), was also scanned every 120 minutes as a delay and bandpass calibrator. Each observation was made for about 6 hours, but total scan time for the targeted source pair was only about 2.5 hours because we observed not only G5.89-0.39–J1755-2232 pair but also another maser–calibrator pair alternately. We will describe another source pair in forth coming paper.

Left-handed circular polarized signals were quantized at 2-bit sampling and filtered with the VERA digital filter unit (Iguchi et al. 2005), after that, data were recorded onto magnetic tapes at a data rate of 1024 Mbps. There were 16 IF channels with 16 MHz band width where one IF was assigned to the maser lines and other 15 IF of total 240 MHz were assigned to J1755-2232 and NRAO530. The data correlation was performed with the Mitaka FX correlator (Chikada et al. 1991). Correlated data were divided into 512 and 64 spectral channels for the maser and calibrators, respectively. For the maser lines, the full 16 MHz data were used only in the fourth epoch, and in other cases, we used 8 MHz which is covering whole maser emissions to achieve sufficient velocity resolution (0.21 km s$^{-1}$).

The system noise temperatures were depended on weather conditions in each station and elevations. Typical $T_{sys}$ value at a averaged elevation angle was varied 200 to 500 K for each station in a case of normal weather. Sometimes it exceeded 1000 K in a bad case for Ogasawara and Ishigaki station. There was very high $T_{sys}$ value (~5000 K) at Iriki station in the first epoch, and hence, we performed phase-referenced imaging using other three stations in this epoch. Phase-referenced images of the targeted maser source were successfully obtained in 8 epochs without the final epoch, where significant phase fluctuations were still remained after the fringe fitting for J1755-2232, and then, all maser spots were completely defocused.

3. Data reduction

Data reduction was carried out using the NRAO Astronomical Imaging Processing System (AIPS) package. Amplitude and bandpass calibrations were made for the targeted maser and J1755-2232 independently. We calibrated clock parameters for each station using the residual delay of NRAO530. The tropospheric zenith delay offset was also calibrated by the modified delay-tracking data which were calculated based on the actual measurements of the atmospheric zenith delay with the global positioning system (GPS) at each station (Homma et al. 2008b).

There were two different paths of the analysis depending on a purpose. The one was phase-referencing (or 2-beam) analysis for a measurement of the annual parallax and another was single-beam analysis which was suitable for searching all maser spots and studying internal motions of them. Here, the term 'maser spot' indicates a maser component seen in a single velocity channel, and by contrast, the term 'maser feature' represents physical gas clump which is consist of several maser spots which are detected in successive velocity channels and closely located each other. We define it in the same way as Motogi et al. (2008).

In the single beam analysis, we simply performed fringe fitting and self-calibration using the brightest maser spot in the feature O1 (see section 4.3). We then searched for all maser spots by a wide-field mapping under a 7-$\sigma$ detection limit. Total explored area was 5 × 5 arcsec$^2$ of each channel map centered on the ionizing star in G5.89-0.39. Annual aberration was also corrected for several masers which were significantly distant ($\gg 3''$) from the phase-referenced maser spot in this analysis.

In the phase-referencing analysis, fringe fitting and self-calibration for J1755-2232 were done, and then, obtained delay, rate and phase solutions were applied to the target visibilities following the correction of measured instrumental phase difference between the two beams (see above). The modified delay-tracking mentioned above was re-calculated with respect to each maser feature for accurate position measurement. New delay-tracking center was always located within 10 mas from relevant maser feature.

The coherence in phase-referenced images were still sig-
nificantly degraded at this stage. Because of the low brightness and large separation angle of J1755-2232, and the low elevation angle during observations, significant atmospheric zenith delay residuals, which is a main cause of the coherence loss, still remain. We, therefore, estimated and corrected this residuals with the image optimizing method described in Homma et al. (2007, 2008b). Estimated residuals were found to be within ±3 cm in whole epochs (~1.5 cm on average). This is consistent with a typical case seen in VERA observations (Homma et al. 2008b). The dynamic ranges (or signal to noise ratios) of phase-referenced images showed dramatic improvement with this correction. But, even after this improvement, limited coherence and defocusing made several faint spots undetectable.

After these calibrations, synthesized image cube was finally made with all maser features in both analyses. Each cube had a field of view of 25.6 × 25.6 mas² centered on relevant feature. Imaging and deconvolution (CLEAN algorithm) was done in uniform weighting which provided the highest spatial resolution. The synthesized beam was about 2.2 × 0.9 mas² with the position angle of -20°. Typical image noise level was ~400 mJy beam⁻¹ (1-σ) in the case of the single-beam analysis (see table 1). It was significantly increased in phase-referenced case by a factor of 2 or 3, and up to 10 in the worst case. The absolute and relative positions of each maser spot were determined by an elliptical Gaussian fitting. The formal error in this fitting was typically 50 μas in RA and 100 μas in Dec. This value is approximately equal to a uncertainty of relative positions between each maser spots. Overall discussion about the accuracy of absolute positions in each measurement is given in section 4.2.

4. Result

4.1. Parallax Measurement

There were two strong maser features (feature O1 and C6 in section 4.3) successively detected for 8 epochs in phase-referenced maps. We measured their absolute motions referenced on J1755-2232. These motions can be expressed by the sum of the annual parallax π and proper motion of each feature μ. The latter is usually assumed to be a linear and constant motion for simplicity (e.g., Nakagawa et al. 2008). This seems to be applicable for our case, because the relative proper motion between two features are actually fitted by a linear motion (see section 4.3 and figure 2) and the drifts of their line of sight velocities are well negligible (<0.2 km s⁻¹) during the two years.

A least square fitting was made with π plus μ to the right ascension offsets (X ≡ Δα × cosδ) from the first epoch. We performed our fittings in the same way as Hirota et al. (2008). Here, whole detected maser spots in each feature (7 maser spots per feature) were distinctly used and an initial position of each maser spot, X₀ and Y₀, was included as a fitting parameter. Reduced χ² was calculated as

$$\chi^2 = \frac{1}{m} \sum \omega_i (X_i - f(t_i))^2,$$

where m and ωᵢ were the degree of freedom and a fitting weight for each data point, respectively. We adopted a dynamic range of phase-referenced image (DN) as a fitting weight, since it was a rough measure of the coherence loss caused by residual delay which was difficult to estimate directly. A weight for i-th data point was to be ωᵢ ∝ DNᵢ and scaled to make the total reduced χ² to be ~1. If we assume the normal distribution, 1/√ωᵢ is equal to the error variance of i-th data point.

Figure 1 shows the examples of the parallax measurement for G5.89-0.39. Note that only a linear proper motion was fitted to the declination offsets (Y ≡ Δδ), since G5.89-0.39 was located on the ecliptic plane (β ~-0.6°), where the parallax in the declination degenerated into an order of 10 μas. It is just comparable with the maximum accuracy of VERA’s dual beam astrometry (Homma et al. 2007) and hard to detect. In each figure, the associated error bars indicate 1/√ωᵢ values. The X were well fitted by a linear motion (dashed line) and parallax (solid curve), by contrast, large dispersion from the best-fit linear motion is clearly seen in cases of Y. The error in Y

| Date       | Synthesized Beam (mas × mas) | PA (°) | Resolution (km s⁻¹) | 1-σ Noise (Jy beam⁻¹) | DNᵢ / DNₛ (σ) | Comments for Tₛyst |
|------------|-----------------------------|-------|---------------------|-----------------------|---------------|-------------------|
| 2007/11/5  | 1.92 × 0.71                 | -24.33| 0.21                | 0.82                  | 9 / 32        | ~5000 K at IR²     |
| 2008/1/12  | 1.88 × 1.02                 | -16.23| 0.21                | 0.35                  | 11 / 166      | ~1000 K at IS      |
| 2008/3/14  | 2.15 × 0.88                 | -20.15| 0.21                | 0.22                  | 15 / 402      | -                 |
| 2008/5/7   | 2.32 × 0.88                 | -24.48| 0.42                | 0.63                  | 14 / 530      | 500 - 2000 K at OG |
| 2008/7/1   | 2.14 × 0.81                 | -23.04| 0.21                | 0.42                  | 8 / 128       | -                 |
| 2008/11/11 | 2.62 × 0.84                 | -26.16| 0.21                | 0.29                  | 11 / 144      | 800 - 3000 K at OG |
| 2009/2/6   | 2.02 × 0.92                 | -16.82| 0.21                | 0.17                  | 15 / 255      | -                 |
| 2009/5/18  | 2.26 × 0.84                 | -23.32| 0.21                | 0.28                  | 15 / 43       | -                 |
| 2009/9/13  | 2.21 × 0.78                 | -19.95| 0.21                | 0.25                  | - / 54        | -                 |

a Typical value in self-calibrated images.
b The maximum dynamic ranges for phase-referenced (DNᵢ) and self-calibrated image (DNₛ).
c IR, IS, OG:Iriki, Ishigaki, Ogasawara station, respectively.
rors of the elliptical Gaussian fittings. This can be seen motion measurement are much larger than the formal error range is still significantly nearer than previously reported parallax measurement. We also emphasize that even if we 

\[ \pi \approx 0.78 \pm 0.04 \text{ mas} \]

This fact suggests that \( \pi \) is the variability of maser feature structures in our case, which we have ignored above, cannot be negligible. This type of error is another important error source for VERA observations (e.g., Hirota et al. 2007). Moreover, it can be actually dominant error source in some cases (e.g., Sato et al. 2008). If we attribute dominant part of the post-fit variance to this effect, instead of the atmospheric error, expected error of the parallax can be reduced by the additional factor of \( 1/\sqrt{N} \), where \( N \) is the number of maser spots in single feature. Since both of the feature O1 and C6 are consist of 7 maser spots in our case, the conclusive error of parallax is to be \( 0.33/\sqrt{7 \times 2 \times (8-1)} \sim 0.03 \text{ mas} \), where the numerator of 0.33 mas is averaged value of the post-fit residual in \( X \). This is just comparable to the actual fitting error. Therefore, we conclude that the dominant error source is the variability of maser feature structures in our case, although the contribution from atmospheric zenith delay residuals is also nonnegligible. The proportion of their contributions is, more quantitatively, to be \( \sim 2:1 \), if we use averaged atmospheric delay residuals of \( \sim 1.5 \text{ cm} \) which has been evaluated from the image optimizing method.

4.3. Kinematics and Spatial Distribution of Masers

Absolute proper motions of feature O1 and C6 shown in table 2 are motions respect to the Sun, and hence, include the contribution of solar motion and the Galactic rotation. If we assume the solar motion relative to the LSR based on the Hipparcos data (Dehnen & Binney 1998), the contribution of solar motion is calculated to be \( 0.69 \text{ mas yr}^{-1} \) and -1.19 mas yr\(^{-1}\) for \( X \) and \( Y \), respectively. The contribution of the Galactic rotation is estimated to be -0.04 mas yr\(^{-1}\) and -0.07 mas yr\(^{-1}\) based on a \( R_0 \) of 8.4 kpc and \( \Theta_0 \) of 254 km s\(^{-1}\) (Reid et al.
Fig. 1. The examples of parallax fitting for the brightest maser spot of feature O1 (left) and C6 (right). Here, X and Y axis shows elapsed days from the first epoch and positional offsets from $\alpha_{2000}=18^h00^m30^s3066$, $\delta_{2000}=-24^\circ04^\prime04^\prime48649$ in mas, respectively. The annual parallax (solid curve) and linear proper motion (dashed line) were successfully fitted in X direction (upper two panels). On the other hand, only a linear proper motion was fitted in Y direction because of the location of G5.89-0.39 (see text). The errors in each panel are calculated from the fitting weights which have been scaled to make the total reduced $\chi^2$ to be $\sim 1$.

Table 2. Summary of simple parallax fittings

| Feature | V$_{LSR}$ (km s$^{-1}$) | $\pi$ (mas) | D (kpc) | $\sigma^a$ (mas) | $\mu^b$ (mas yr$^{-1}$) |
|---------|----------------|-------------|---------|-----------------|---------------------|
| O1      | 9.4            | $X$ 0.79 $\pm$ 0.05  | 1.27 $\pm$ 0.08 | 0.27 $\pm$ 0.09 | -0.43 $\pm$ 0.09 |
|         |                | $Y$ --       | --       | 0.78 $\pm$ 0.29 | -1.43 $\pm$ 0.29   |
| C6      | 11.0           | $X$ 0.77 $\pm$ 0.09 | 1.30$^{+0.17 -0.14}$ | 0.39 0.77 $\pm$ 0.14 | 0.39 0.77 $\pm$ 0.14 |
|         |                | $Y$ --       | --       | 0.94 $\pm$ 0.30 | -0.47 $\pm$ 0.30   |
| Combined|                | 0.78 $\pm$ 0.04 | 1.28$^{+0.07 -0.06}$ | $\pm$ 0.06 |

$^a$ The rms deviations of the post-fit residuals.
$^b$ 1 mas yr$^{-1} = 6.1$ km s$^{-1}$ at the distance.
$^c$ The weighted means of those for two features.

Table 3. Gaussian Parameters of $\pi$ distributions from Bootstrap Analysis

| Feature | Median (mas) | Standard Deviation | D (kpc) | 3-$\sigma^a$ |
|---------|--------------|--------------------|---------|--------------|
| O1      | 0.80 $\pm$ 0.005 | 0.06 $\pm$ 0.005 | 1.25$^{+0.11 -0.09}$ | $+0.38 -0.24$ |
| C6      | 0.75 $\pm$ 0.008 | 0.10 $\pm$ 0.008 | 1.33$^{+0.15 -0.14}$ | $+0.87 -0.38$ |
| Combined| 0.78         | 0.05               | 1.28$^{+0.09 -0.08}$ | $+0.33 -0.22$ |

$^a$ 3-$\sigma$ (> 99 % confidence) error ranges in kpc.
$^b$ The weighted means of those for two features.
2009). This value is well negligible and do not change in the common range of $R_0$ and $\Theta_0$ (220 – 254 km s$^{-1}$, 8.0 – 8.5 kpc; Hou et al. 2009). Here, we assumed flat rotation and adopted our newly determined distance of 1.28 kpc. The intrinsic proper motions of the maser features, where these two contributions are subtracted, is represented in table 4. We note that these motions are still include the peculiar motion of their natal cloud and the internal motions of each maser feature. Since only two features are detected in 2-beam analysis, we cannot divide these two components at this section, but brief presumption will be provided in section 5.2.2 based on the model fitting of the maser kinematics.

Additional 12 maser features were detected in the single beam analysis. All parameters of detected features are listed in table 5. Total 14 maser features can be divided into 4 maser sites. We name these sites as origin (O), center (C), north (N) and south (S) based on their positions. These four maser sites are widely spread around the UCH II region. We estimated internal proper motions relative to the phase-referenced feature O1 for the features which were detected in at least three observing epochs. Figure 2 shows the example of feature C6. Their internal motion was well fitted by linear motion. Estimated motions are also summarized in table 4. Overall distributions and proper motions of maser features are represented in figure 3, where black and grey arrows show relative and converted absolute proper motions, respectively. Relative positions and internal proper motions of all maser features are converted to absolute values using the position and motion of the feature O1. The converted motion of C6 is actually coincide with the directly estimated one within the error.

Each of the sites O, N and S, which is located on outside of the ionized shell, contains only one or two maser features. This limited number of maser features can be related to a life time of H$_2$O maser activity. They are generally believed to disappear along with a evolution of UCH II region (e.g., Beuther et al. 2002b, Breen et al. 2010), in attributing to a dispersion of dense gas which required to excite masers. All of these sites are associated with SiO $J = 8 - 7$ emission detected by Sub-Millimeter Array (SMA) (Hunter et al. 2008). SiO $J = 8 - 7$ emission is a moderate shock tracer and frequently observed in post-shock gas which is associated with a protostellar outflow (e.g., Takami et al. 2006). Such a spatial relationship may indicate that H$_2$O maser and SiO emission trace same shock fronts. This is not so surprising case because H$_2$O masers are also associated with strong outflow shock frequently (e.g., Motogi et al. 2008; Torrelles et al. 2010).

On the other hands, line of sight velocities of maser features in the site O and N are not consistent with that of SiO emission. The velocity offsets are larger than 5 km s$^{-1}$. These offsets may reflect the difference of precise locations where each emission comes from. This can be simply attributed to the different excitation conditions of SiO and H$_2$O. The critical density of SiO $J = 8 - 7$ emission are $n_{H_2} \approx 10^7$ cm$^{-3}$ based on the database in Schöier et al. (2005). It is actually 2 orders of magnitude smaller than that of H$_2$O maser and comparable with pre-shock density of the maser (Elitzur 1992). H$_2$O maser is, hence, probably excited in the most strongly compressed part such as a head part of a bow shock. Emission from that region cannot dominate the integrated SiO emission, since such a region should have quite limited volume compared to total post-shock gas.

The site C, by contrast to other site, is not associated with SiO emission. There are 9 maser features and almost all of them (7 of 9) are highly variable and only detected in a single epoch. This maser site had been reported in the past VLA observation (Hofner & Churchwell 1996), but observed position and line of sight velocity was slightly different from our detection. Whole maser features, including the one detected by VLA, closely located at the position of Feldt’s star (< 200 mas). Their line of sight velocities are little red-shifted from systemic velocity of 9 km s$^{-1}$ (e.g., Hunter et al. 2008) and clearly different from that of OH masers seen in the same position (Stark et al. 2007).

Highly blue shifted (~ 35 km s$^{-1}$) OH masers are thought to be excited in expanding neutral shell or strong outflow (the former in Stark et al. 2007, the latter in Zijlstra et al. 1990). They seem to be located on the forefront of the ionized shell in either cases. The kinematic difference strongly invokes the distinct origins of OH and H$_2$O masers. Such a nearly located, but strictly distinct displacement of these two maser was quite natural if we considered different excitation conditions again, and it had been actually observed for several regions (Forster & Caswell 1989). Taking into account these situation, we propose that this H$_2$O maser site is just located inside a ionized shell and excited in a remnant of dense circumstellar structure such as an accretion disk. Extremely young dynamical age of UCH II region (~ 600 yr) well support the presence of such a remnant and their crescent-like distribution and velocity field can be actually explained by a simple ring model (see section 5.2.2).

5. Discussion

5.1. Validity of New Distance

The newly estimated distance of 1.28 kpc is well smaller than the previously reported distances (> 1.9 kpc). This is mainly because almost all of past measurements have been done kinematically. Kinematic distance essentially depends on the Galactic rotation model and accuracy of determining rotation velocity of the source. If it is the case that target source has unknown, non-negligible velocity component aside from the Galactic rotation, kinematic distance is no longer reliable in principle. This type of systematic error is more and more significant especially for the source near the Galactic center direction. In the case of our source ($i = 5^\circ.89$), only a few km s$^{-1}$ offset along the line of sight can cause an error of ~ 1 kpc.

Reid et al. (2009) had first analyzed the Galactic rotation based on the distances of 18 star-forming regions which are estimated only from trigonometric parallaxes of masers derived from VLBA and VERA observations.
### Table 4. Intrinsic Proper Motions

| Feature | Absolute Proper Motion$^a$ | Relative Proper Motion$^a$ |
|---------|---------------------------|---------------------------|
|         | $\mu_X$ | $\mu_Y$ | $\mu_X$ | $\mu_Y$ |
| O1$^b$  | -1.08 ± 0.24 | -0.16 ± 0.40 | – | – |
| C6      | 0.12 ± 0.29 | 0.79 ± 0.47 | – | – |
| O2$^c$  | -1.02 ± 0.33 | -0.46 ± 0.43 | 0.06 ± 0.09 | -0.29 ± 0.03 |
| C6      | -0.21 ± 0.29 | 1.31 ± 0.48 | 0.87 ± 0.05 | 1.47 ± 0.08 |
| C9      | -1.51 ± 0.27 | 0.72 ± 0.53 | -0.43 ± 0.03 | 0.89 ± 0.13 |
| N       | -3.38 ± 0.43 | -1.79 ± 1.56 | -2.3 ± 0.19 | -1.63 ± 1.16 |
| S1      | -0.12 ± 0.40 | -1.03 ± 0.93 | 0.96 ± 0.16 | -0.86 ± 0.53 |

$^a$ All values are in the units of mas yr$^{-1}$.

$^b$ The upper 2 rows are from the parallax fitting.

$^c$ The lower 5 rows are from the internal proper motions relative to O1.

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**Fig. 3.** Overall distribution of maser features. Lower left panel: The locations of 4 maser site (O,C,N,S) are presented by color points with dashed circle. The coordinate origin is $\alpha_{2000}=18^{h}00^{m}30^{s}3$, $\delta_{2000}=-24^{d}04^{m}09^{s}$. Here, background color scale, black crosses and contour shows the first moment map of SiO $J = 8–7$ emission, 875 $\mu$m dust cores and 3 mm continuum image ($0.1$ Jy beam$^{-1}$) from Hunter et al. (2008), respectively. The star marks the positions of Feldt’s star $\alpha_{2000}=18^{h}00^{m}30^{s}44$, $\delta_{2000}=-24^{d}04^{m}09^{s}$. Other 4 panels: Detailed distributions of maser features are shown. Here, each point indicates detected maser feature. Each axis shows the relative coordinate from the phase-referenced maser feature O1 in the units of mas. Absolute and internal proper motions are written in black and grey arrows, respectively. Red triangle with error bar in site C (upper right panel) is the maser detected by Hofer & Churchwell (1996). Here, the star marks the position of Feldt’s star again and its error is presented by dashed circle of 250 mas diameter (200 from positional error and 50 from PSF, see Feldt et al. 2003). The color represents $V_{\text{LSR}}$ (km s$^{-1}$) for all of 5 panels in the scale of associated color bars.
Table 5. Detected Maser Features

| Feature | Epoch | $V_{\text{LSR}}$ (km s$^{-1}$) | $\Delta V^a$ | Offset$^b$ (mas) | Peak Intensity (Jy beam$^{-1}$) |
|---------|-------|-----------------|------------|-----------------|----------------------------------|
|         |       |                 | $X$ (err)  | $Y$ (err)       |                                  |
| O1      | 1     | 9.36            | 1.26       | 0.00 (0.03)     | 0.00 (0.08)                      | 74.0                             |
|         | 2     | 9.34            | 1.69       | -0.20 (0.01)    | -0.03 (0.02)                     | 75.6                             |
|         | 3     | 9.26            | 1.90       | -0.38 (0.01)    | -0.06 (0.01)                     | 80.3                             |
|         | 4     | 9.50            | 2.11       | -0.54 (0.01)    | -0.08 (0.02)                     | 72.1                             |
|         | 5     | 9.37            | 1.47       | -0.71 (0.02)    | -0.11 (0.04)                     | 63.6                             |
|         | 6     | 9.33            | 1.26       | -1.12 (0.02)    | -0.17 (0.05)                     | 32.0                             |
|         | 7     | 9.30            | 1.26       | -1.36 (0.01)    | -0.21 (0.02)                     | 19.6                             |
|         | 8     | 9.39            | 1.05       | -1.65 (0.04)    | -0.25 (0.11)                     | 21.7                             |
|         | 9     | 9.26            | 1.26       | -2.01 (0.04)    | -0.31 (0.11)                     | 14.2                             |
| O2      | 1     | 8.72            | 0.63       | -15.90 (0.06)   | 2.33 (0.17)                      | 10.1                             |
|         | 2     | 8.70            | 0.84       | -16.24 (0.06)   | 2.30 (0.10)                      | 5.5                              |
|         | 3     | 8.63            | 1.05       | -16.51 (0.04)   | 2.25 (0.10)                      | 7.0                              |
|         | 4     | 8.65            | 0.84       | -16.63 (0.06)   | 2.12 (0.15)                      | 5.9                              |
|         | 5     | 8.74            | 0.63       | -16.85 (0.07)   | 2.08 (0.17)                      | 5.1                              |
|         | 6     | 8.48            | 0.63       | -17.16 (0.08)   | 1.87 (0.25)                      | 3.4                              |
|         | 7     | 8.46            | 0.84       | -17.20 (0.06)   | 1.76 (0.14)                      | 3.2                              |
|         | 8     | 8.76            | 0.63       | -17.69 (0.09)   | 1.78 (0.23)                      | 2.7                              |
| C1      | 8     | 17.19           | 0.63       | 1954.03 (0.05)  | 3852.79 (0.14)                   | 5.1                              |
| C2      | 2     | 15.45           | 0.63       | 1984.14 (0.07)  | 3745.18 (0.12)                   | 4.2                              |
| C3      | 7     | 12.67           | 1.69       | 1944.75 (0.04)  | 3732.56 (0.08)                   | 3.3                              |
| C4      | 7     | 12.67           | 0.84       | 1946.13 (0.09)  | 3736.36 (0.21)                   | 1.3                              |
| C5      | 3     | 11.58           | 0.63       | 1998.60 (0.07)  | 3665.11 (0.17)                   | 2.8                              |
| C6      | 1     | 11.04           | 1.05       | 2001.86 (0.03)  | 3689.41 (0.09)                   | 27.9                             |
|         | 2     | 11.02           | 1.26       | 2001.77 (0.03)  | 3689.77 (0.06)                   | 19.8                             |
|         | 3     | 11.16           | 1.47       | 2001.63 (0.01)  | 3690.14 (0.03)                   | 43.0                             |
|         | 4     | 11.18           | 1.68       | 2001.60 (0.03)  | 3690.50 (0.07)                   | 56.0                             |
|         | 5     | 11.27           | 1.26       | 2001.54 (0.03)  | 3690.75 (0.08)                   | 46.9                             |
|         | 6     | 11.22           | 1.26       | 2001.37 (0.02)  | 3690.98 (0.07)                   | 39.8                             |
|         | 7     | 11.19           | 1.47       | 2001.49 (0.02)  | 3691.23 (0.04)                   | 28.3                             |
|         | 8     | 11.08           | 1.47       | 2001.48 (0.03)  | 3691.79 (0.09)                   | 13.7                             |
|         | 9     | 10.94           | 1.05       | 2001.48 (0.06)  | 3692.09 (0.16)                   | 4.7                              |
| C7      | 7     | 10.56           | 0.63       | 1944.66 (0.09)  | 3732.89 (0.21)                   | 1.9                              |
| C8      | 3     | 10.74           | 0.63       | 1990.50 (0.05)  | 3662.93 (0.11)                   | 5.1                              |
|         | 1     | 9.78            | 0.63       | 1978.74 (0.03)  | 3668.10 (0.08)                   | 22.1                             |
|         | 2     | 9.76            | 0.84       | 1978.48 (0.06)  | 3668.15 (0.10)                   | 9.9                              |
|         | 3     | 9.90            | 0.84       | 1978.20 (0.03)  | 3668.34 (0.08)                   | 8.2                              |
|         | 5     | 10.00           | 0.63       | 1977.75 (0.08)  | 3668.60 (0.20)                   | 3.9                              |
| N       | 2     | 3.65            | 1.05       | 3932.54 (0.05)  | 4185.95 (0.09)                   | 6.7                              |
|         | 3     | 2.95            | 2.95       | 3932.14 (0.02)  | 4186.54 (0.04)                   | 18.0                             |
|         | 7     | 3.82            | 1.26       | 3929.04 (0.05)  | 4184.55 (0.11)                   | 2.9                              |
| S1      | 4     | 8.23            | 1.26       | 4898.62 (0.07)  | -1070.77 (0.19)                  | 8.0                              |
|         | 5     | 8.11            | 1.05       | 4898.48 (0.04)  | -1070.66 (0.10)                  | 13.7                             |
|         | 6     | 8.06            | 1.47       | 4898.27 (0.05)  | -1071.59 (0.15)                  | 12.6                             |
|         | 7     | 8.03            | 1.47       | 4898.35 (0.03)  | -1071.68 (0.07)                  | 11.3                             |
|         | 8     | 8.13            | 1.05       | 4898.50 (0.05)  | -1071.14 (0.14)                  | 4.7                              |
| S2      | 8     | 8.13            | 0.63       | 4897.28 (0.09)  | -1075.02 (0.24)                  | 2.4                              |

$^a$ Full width at zero intensity (FWZI) for each maser feature.

$^b$ The positions relative to (18$^h$00$^m$30.3066, −24°04′4.48649) (J2000.0).
Their new analysis indicates that commonly used kinematic distances are generally overestimated, sometimes by factors greater than 2, which is just in our case. Similar result has already been reported in other VERA observation (G14.33-0.64, the measured distance $\sim 1.1$ kpc, $l = 14^\circ.33$ (Sato et al. 2010a)). Our result seems to be well consistent with the hypothesis in Sato et al. (2010a) that the Sagittarius spiral arm, in which G5.89-0.39 and G14.33-0.64 are thought to be located, lies at the closer distance ($\sim 1$ kpc) from the sun compared to the previous value ($2 - 3$ kpc). Of course, more large samples must be required to confirm it.

Fig. 2. The internal proper motion of feature C6. Y axes in each panel show the positional offset relative to the phase-referenced feature O1. Both of Dashed lines indicate the best-fit linear proper motions.

Progressive Galactic simulation in Baba et al. (2009) also suggests that star-forming regions and young stars in a spiral arm have significant non-circular motions up to $30$ km s$^{-1}$. If their calculation is correct, a kinematic distance intrinsically has large systematic error of $\sim 2 - 3$ kpc. With these contexts, the significant difference between the kinematic distance and our new distance can be attributed to the systematic error in the kinematic distance.

ACW98 have been derived the source distance of 2.0 kpc from the expansion of the ionized shell, but it is still highly model dependent (see section 5.2.3). Consequently, our new distance which has no model dependency is thought to be the most reliable distance of G5.89-0.39.

5.2. Physical Parameters and High Mass Star Formation in G5.89-0.39

Because of significant modification of the distance to G5.89-0.39, we first recalculated physical parameters which had been previously reported based on the new distance. Table 6 to 9 summarize recalculated parameters. Each table contains both of original and modified values with the reference papers. Detailed explanations for listed parameters are given in related subsections and captions.

5.2.1. Evolution of the O-type Protostar

Table 6 show the properties of Feldt’s star. We derived stellar spectral type in the same manner in Wood & Churchwell (1989). We first estimated excitation parameter of the source from radio continuum emission (see also Krutz et al. 1994). This was simply converted to the flux of Lyman continuum photons ($N_L$) and spectral type (Sp type) comparing the stellar models in Panagia (1973). In the second, we used total far-infrared luminosity ($L_{\text{FIR}}$). $L_{\text{FIR}}$ can be a good measure of bolometric luminosity for deeply embedded sources. Because of the low spatial resolution, $L_{\text{FIR}}$ may include several contributions from other objects around the UCH II region, and hence, this gives upper limit of the source luminosity.

Derived spectral types are almost consistent and indicate late O-type star (O8 – O8.5 ZAMS). Expected stellar mass $M_*$ is about $25 M_\odot$ (e.g., Vacca et al. 1996). This is a roughly half value of previously reported O5 ZAMS (or O5V) star. Feldt et al. (2003) tested such an early spectral type by a model fitting of mid-infrared color ($K_s$ and $L'$ bands). But their fitting is based on the distance of 1.9 kpc, and if we adopt new distance and appropriate extinction value, all of O type stellar models which are later than O5 can move into the range of $L'$ band excess reported in Feldt et al. (2003).

The line ratio of He I triplet at 2.11 $\mu$m to Br$\gamma$ also supports the existence of late O-type star. Hanson, Luhman, & Rieke (2002) have observationally determined upper limit of this ratio as 0.02 for G5.89-0.39 and indicated that this value is clearly smaller than a value expected for a star earlier than O7 type. Puga et al. (2006) actually detected 2.11 $\mu$m HeI emission with VLT. Although they suggested rather early O star ($< O7$), the detection only at the location of Feldt’s star also ruled out a star earlier than O7, because such an early type star could fully ionize whole He atoms and provide constant line ratio throughout a UCH II region (e.g., Osterbrock 1989).

This seems to be a reliable constraint, since the line ratio is fully independent of the source distance. Consequently, new spectral type of O8 – O8.5 seems to be reasonable.

As seen in table 6, we also estimated the momentum rate of stellar wind ($\dot{P}_{\text{wind}}$). It has been calculated from pressure balance at the inner surface of ionized shell. We simply assumed that spherically-symmetric wind and then thermal pressure of ionized gas was balanced with $\dot{P}_{\text{wind}}$ per unit area. Although detailed properties of mass loss activity at the ZAMS stage are still unknown, estimated $\dot{P}_{\text{wind}}$ is ten times larger than that of a dwarf star which
### Table 6. Recalculated Stellar Parameters

| Parameter               | Original value | Modified value | Reference |
|-------------------------|----------------|----------------|-----------|
| $N_L$ ($s^{-1}$)        | $4.5 \times 10^{48}$ | $1.6 \times 10^{48}$ | (1)       |
| $L_{\text{FIR}}$ ($L_\odot$) | $3.0 \times 10^5$ | $7.3 \times 10^4$ | (1)       |
| Sp Type (radio)         | O7             | O8.5           | (1), (2)  |
| Sp Type (FIR)           | O6             | O8             | (1), (2)  |
| $M_*$ ($M_\odot$)      | $\sim 40$      | $\sim 25$      | (3)       |
| $P_{\text{wind}}$ ($M_\odot$ km s$^{-1}$ yr$^{-1}$) | –              | $2.5 \times 10^{-3}$ | (4)       |

References.– (1):Wood & Churchwell 1989, (2):Panagia 1973, (3):Vacca et al. 1996, (4):this work.

### Table 7. Recalculated Parameters of UCH II region

| Parameter      | Original value | Modified value | Reference |
|----------------|----------------|----------------|-----------|
| $n_e$ (cm$^{-3}$) | $2.4 \times 10^5$ | $3.2 \times 10^5$ | (1)       |
| $R_i / R_e$ (au) | 1900 / 5200     | 1200 / 3300    | (2)       |
| $v_\text{shell}$ (km s$^{-1}$) | 39             | 25             | (2)       |
| $t_{\text{dyn}}$ (yr) | 600          | 600            | (2)       |
| $E_{\text{therm}}$ (10$^{45}$ erg) | –            | 0.7            | (3)       |
| $E_{\text{kin}}$ (10$^{45}$ erg) | –            | 1.2            | (3)       |
| $P_{\text{shell}}$ ($M_\odot$ km s$^{-1}$) | –            | 5.6            | (3)       |
| $M_{\text{env}}$ ($M_\odot$) | 300           | 123            | (4)       |
| $n_{\text{env}}$ (cm$^{-3}$) | $5.3 \times 10^6$ | $8.0 \times 10^6$ | (4)       |
| $T_{\text{env}}$ (K) | 40 – 140       | 40 – 140       | (5)       |

$a$References.– (1):Wood & Churchwell 1989, (2):ACW98, (3):this work, (4):Tang et al. 2009, (5):Su et al. 2009.

$b$ Tangential expansion derived from the angular expansion rate.

### Table 8. Parameters of the E-W Outflow ($CO$ $J = 1 - 0$) from Watson et al. (2007)

| Parameter          | Original value | Modified value |
|--------------------|----------------|----------------|
| $t_{\text{dyn}}$ (yr) | 7700          | 5000           |
| $v_\text{flow}$ (km s$^{-1}$) | Blue lobe Red lobe | Blue lobe Red lobe |
| $M$ ($M_\odot$)    | 123            | 116            |
| $E_{\text{kin}}$ (10$^{46}$ erg) | 6.4          | 5.3            |
| $P$ ($10^2 M_\odot$ km s$^{-1}$) | 9.0          | 8.0            |
| $M$ ($10^{-3}$ $M_\odot$ yr$^{-1}$) | 16.0        | 15.0           |
| $\dot{M}$ ($10^{-2}$ $M_\odot$ km s$^{-1}$ yr$^{-1}$) | 12.0        | 10.0           |
| $L_{\text{mech}}$ ($L_\odot$) | 68.0         | 56.0           |

$a$ Integrated velocity range.

### Table 9. Parameters of the inner high velocity Outflow ($CO$ $J = 3 - 2$) from Klaassen et al. (2006)

| Parameter          | Original value$^a$ | Modified value |
|--------------------|---------------------|----------------|
| $t_{\text{dyn}}$ (yr) | 2000               | 1300           |
| $v_\text{flow}$ (km s$^{-1}$) | Blue lobe Red lobe$^b$ | Blue lobe Red lobe$^c$ |
| $M$ ($M_\odot$)    | 2.7                | 0.6            |
| $E_{\text{kin}}$ (10$^{46}$ erg) | 1.5          | 0.3            |
| $P$ ($M_\odot$ km s$^{-1}$) | 55.9         | 12.0           |
| $M$ ($10^{-4}$ $M_\odot$ yr$^{-1}$) | 13.5        | 3.0            |
| $\dot{M}$ ($10^{-2}$ $M_\odot$ km s$^{-1}$ yr$^{-1}$) | 2.8           | 0.6            |
| $L_{\text{mech}}$ ($L_\odot$) | 59.0         | 11.5           |

$a$ Inclination of outflow axis which has been originally assumed as $45^\circ$ is ignored.

$b$ The maximum velocities.

$c$ Absorption features seen in the red lobe have not been corrected in Klaassen et al. (2006).
has $\sim 25$ $M_\odot$ (Sternberg et al. 2003 and reference therein). A wind velocity is generally determined by gravitational force at the launching point of a wind, and it is thought to be same order between ZAMS and dwarf stage. This is about $2.0 \times 10^4$ km s$^{-1}$ for $25$ $M_\odot$ dwarf (e.g., Smith et al. 2002). In this case, mass loss rate is order of $10^{-6}$ $M_\odot$ yr$^{-1}$, and of course, ten times larger than the value of dwarfs. One possible explanation for this excess may be larger stellar radius of very young ZAMS star which is still under contraction. This could cause relatively weak surface gravity and might help mass loss activity.

Recent theoretical works in Hosokawa & Omukai (2009) calculated detailed stellar evolution via spherically-symmetric mass accretion. They have shown that large entropy supply under high accretion rates ($> 10^{-4}$ $M_\odot$ yr$^{-1}$) onto a proto-stellar surface prevent contraction of protostar and, at some stage, cause far large stellar radius ($\sim 100 R_\odot$). Hosokawa, Yorke, & Omukai (2010) has been treated the case of cold-disk accretion, and they have suggested that expected evolution is qualitatively same as spherically-symmetric case after $10$ $M_\odot$. Realistic mass accretion should correspond to some intermediate state between these two extreme cases as they pointed out.

The most important product of their evolutionary track is delayed hydrogen burning. Resultant young high mass (proto-)star with large radius and limited UV photons can explain highly luminous but low-effective temperature (proto-)star with large radius and limited UV photons between these two extreme case as they pointed out. This assumption may mean that Feldt’s star is quite rare sample, but it seems to be well consistent with extraordinarily young dynamical age of UCHII region. If this is the case and we assume steady mass accretion, the time required to form Feldt’s star is simply $\sim 2.5 \times 10^4$ yr.

### 5.2.2. Maser Morphology Near the Feldt’s Star: a Possible Partial Ring

Newly detected crescent-like structure of water maser may also suggest youth of the source. As we mentioned above, the maser clumps in the site C can be associated with circumstellar remnant gas. Their alignment and velocity field are actually fitted by the Keplerian rotating and expanding ring model in Uscanga et al. (2008). The fitting parameters are central position of a ring $(x_0, y_0)$, radius $R$, inclination from the cephalus plane $i$, position angle of apparent major axis measured from east toward north $\theta$, expansion (or infalling) velocity $v_{\text{exp}}$ and velocity of the source $(v_x, v_y, v_z)$. Here, $z$ means a line of sight direction. We regarded Feldt’s star as a central source of ring, in turn, its mass was fixed to be $25 M_\odot$. Thus, Keplerian rotation velocity depended on $R$ only.

We performed the model fit with a standard $\chi^2$ fitting. First, the spatial distribution of 9 (our detection) + 1 (VLA detection) maser features was fitted by $x_0, y_0, R, i, \theta$, and then, $v_z, v_y, v_x$ were determined from the velocity field of masers. It should be noted that $v_x$ and $v_y$ are more uncertain than $v_z$, because there are only 2 available proper motion vectors. Table 10 and figure 4 show the best fitted parameters and estimated ring superposed on the maser alignment, respectively.

The best fitted ring is almost edge-on and its position angle is roughly north – south direction. It is noteworthy that this geometry matches well the largest outflow which has a position angle of nearly linear alignment from east (red lobe) to west (blue lobe) (see below). The center of the ring is slightly offset from Feldt’s star (1826 mas, 3587 mas), but it can be within the ring if we take into account $\sim 200$ mas error. The small and negative expansion velocity means that the ring is slowly infalling.

### Table 10. The best fit parameters of the ring model

| Parameter | Best Fit (err$^a$) |
|-----------|------------------|
| $x_0$ (mas) | 1914.6 (0.5) |
| $y_0$ (mas) | 3877.2 (0.8) |
| $R$ (mas) | 235.2 (1.2) |
| $\theta$ (°) | 110.5 (0.2) |
| $i$ (°) | 83.0 (0.2) |
| $v_{\text{exp}}$ (km s$^{-1}$) | -1.2 (0.8) |
| $v_x$ (km s$^{-1}$) | -6.5 (1.5) |
| $v_y$ (km s$^{-1}$) | 6.4 (1.1) |
| $v_z$ (km s$^{-1}$) | 18.6 (0.4) |

$^a$ Formal 4 $\sigma$ error of $\chi^2$ fittings.

Western edge is on the far side.
be eventually divided into the migration motion of Feldt’s star and systemic peculiar motion of G5.89-0.39. These divided values are presented in Table 11, where the line of sight component of the peculiar motion ($\sim 4.7$ km s$^{-1}$) was also extracted from $V_{\text{LSR}}$ using the Galactic rotation model in Hou et al. (2009).

The peculiar motion of the system have also been shown in ($U$, $V$, $W$) frame at the same time. Here, $U$ is toward the Galactic center from the source position, $V$ is along the Galactic rotation at the local place, $W$ is perpendicular to the Galactic plane and toward the north Galactic pole. Magnitude of the non-circular component $\sim 14$ km s$^{-1}$ is enough within theoretically predicted range (see section 5.1 again).

5.2.3. Anisotropic Expansion of UCH II Region

Table 7 summarizes the parameters of the UCH II region. Upper seven rows present the electron density $n_e$, inner / outer radius of the radio shell $R_i / R_o$, expansion velocity $v_{\text{shell}}$, dynamical age $t_{\text{dyn}}$, thermal energy of ionized gas $E_{\text{therm}}$, kinetic energy $E_{\text{kin}}$ and total momentum of shell expansion $P_{\text{shell}}$. Lower three rows contain the parameters of surrounding dense envelope. Envelope mass $M_{\text{env}}$ and density $n_{\text{env}}$ are obtained from SMA observation of submillimeter dust continuum (Tang et al. 2009) and its size scale is roughly $2 \times 10^4$ au. In especial, envelope temperature $T_{\text{env}}$ have been derived from an excitation analysis of the CH$_3$CN ($J = 12 - 11$) line by Su et al. (2009), and hence, do not depend on a distance. They have found a temperature gradient in the range shown in the table.

Overall properties of the ionized region are not changed drastically except for the expansion velocity which is calculated from angular expansion rate of $4 \pm 1$ mas yr$^{-1}$ in ACW98. Even if ionized gas is in a free expansion state, its expansion velocity should be almost equal to a sound speed of ionized gas ($\sim 13$ km s$^{-1}$ at $10^4$ K). This suggests that only a half of total momentum can be thermally provided and the shell must require another source of momentum input. If we attribute it to a spherically symmet-

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**Table 11.** Divided velocity components

|                  | Migration velocities of Feldt’s star | Non-circular motion of G5.89-0.39 |
|------------------|-------------------------------------|----------------------------------|
| $(v_x, v_y, v_z)$| 6.3$^a$ (0.3) 6.0 (0.3) 9.6 (0.0)  | -12.8 (1.8) 0.4 (1.4) 4.7 (0.4)  |
| $(U', V', W')$   | 5.4 (1.6) -5.5 (2.4) 11.3 (2.4)    |                                  |

$^a$ Velocities are in the units of km s$^{-1}$.

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**Fig. 4.** Left panel shows the best-fit ring model superposed on the maser distribution in figure 3. Curved arrow represents rotational direction. The red and blue arrows show a same geometry as red and blue lobe of E-W outflow. The inclination of the ring is consistent with this outflow geometry. Right panel shows velocity field of the ring. Red and black arrows show expected proper motion vectors of the ring and observed vectors, respectively. These motions contain both of the systemic velocity of G5.89-0.39 offset from the Galactic rotation and migration velocity of the ring.
Anisotropic stellar wind discussed in section 5.2.1, required time is about 1000 yr. Moreover if the momentum of photons from Feldt’s star is added, the total momentum of the shell could be provided during $t_{\text{dyn}}$.

ACW98 have determined the source distance in comparison between angular expansion rate and the line width of radio recombination lines under several assumptions about how the shell expansion contributes to the line width. Now we have more accurate distance, and in turn, we can estimate a residual contribution to the line width which offsets from spherical expansion. This value is $\sim 50$ km s$^{-1}$ based on their analysis. This is twice as large as tangential expansion and nearly consistent with highly blue shifted OH masers in front of the shell.

This highly anisotropic expansion could be explained by the idea proposed by Hunter et al. (2008), where an outflow from SMA1, which is the luminous dust core near Feldt’s star, had been going across north to south and it was disrupted after the formation of the UCHII region. If this is the case, ionization of intrinsically expanding gas within the outflow can give a plausible explanation for high velocity ionized gas, and hence, observed anisotropy.

### 5.2.4. Outflow Nature

The revised properties of the outflowing gas in G5.89-0.39 are listed in tables 8 and 9. Table 8 shows the parameters of CO ($J = 1 - 0$) emission which trace the outer extended flow (Watson et al. 2007), and table 9 presents that of the inner high velocity flow which has been detected in CO ($J = 3 - 2$) emission (Klaassen et al. 2006). Each table contains the dynamical age $t_{\text{dyn}}$, outflow velocity ($v_{\text{flow}}$), outflow mass $M$, kinetic energy $E_{\text{kin}}$, momentum $P$, outflow rate $\dot{M}$, momentum rate $\dot{P}$ and mechanical luminosity $L_{\text{mech}}$. We note that an effect of inclination is not corrected in these tables, although Klaassen et al. (2006) have originally assumed inclination of 45°.

The largest outflow in table 8 is thought to be driven by Feldt’s star and extends just east – west direction (see figure 2 in Watson et al. 2007). Total mass measured from CO ($J = 1 - 0$) is $\sim 100 M_\odot$ and greatly exceeds the source mass. Such an extremely massive outflow is often observed toward a high mass star-forming region (e.g., López-Sepulcre et al. 2009). The origin of large mass is unsolved problem (e.g., Churchwell 1997).

A detailed driving mechanism of a protostellar outflow is still under discussion, however Machida, Inutsuka, & Matsumoto (2008) have shown that high velocity jet and molecular outflow (hereafter called intrinsic outflows) are distinctly driven in their MHD simulation as natural products of magnetized core collapse and mass accretion via rotating disk. This is consistent very well with a case of nearby low mass star formation, and seems to be applicable for high mass case as long as objects are formed by gravitational collapse and mass accretion. The energy source of intrinsic outflows is gravitational energy which is transformed into outflow energy mediated by magnetic fields. In this point of view, total outflow mass of intrinsic outflows cannot exceed that of central object at a driving point. Clearly, much of the outflow mass arises from material entrained far from the driving source. Quantitatively, observations of outflows from massive young protostellar objects show that the entrained mass is on the order of 4% of the core mass surrounding the central protostar (e.g., Beuther et al. 2002a). This relation suggests that the parent core for the forming cluster containing Feldt’s star contained about $\sim 2500 M_\odot$.

On the other hand, if we assume the ratio of the outflow to the accretion rate as $\sim 10\%$ from theoretical works (e.g., Pelletier & Pudritz 1992), total mass of intrinsic outflows for Feldt’s star is $\sim 2.5 M_\odot$ following the discussion in section 5.2.1. This is comparable with the mass of the CO ($J = 3 - 2$) outflow which traces inner hot and high velocity outflow (see table 9). If we consider a momentum transport from the CO ($J = 3 - 2$) outflow to the CO ($J = 1 - 0$) outflow, required time is $2.3 \times 10^4$ yr. This is consistent with a formation time of Feldt’s star estimated above and clearly larger than the dynamical age of outflow which is obtained from an extent divided by a current velocity. We note that this time scale should be a lower limit, since the mass and momentum of the CO ($J = 3 - 2$) outflow is the sum of the east – west flow from Feldt’s star and north – south flow from SMA1. They have been unresolved in the single dish data in Klaassen et al. (2006), and actually, significant fraction of high velocity emission arises from the latter (see high resolution images in Hunter et al. 2008).

The fact that a commonly used dynamical time underestimates actual outflow age has already been pointed out in the case of low mass objects (Parker et al. 1991) and we suggest that it can occur in the case of too massive outflow in high mass star formation which includes large entrained mass. It should be, consequently, careful that an observationally estimated outflow rate, which often reaches $10^{-2} M_\odot$ yr$^{-1}$ for high mass star, is also overestimated by an order of magnitude. This looks reasonable because Hosokawa & Omukai (2009) have predicted that large accretion luminosity must prevent steady accretion in the case of such a too large accretion rate. Detailed information about a termination of high velocity inner flow is quite useful to confirm these discussions. This would be obtained from direct measurement of proper motions of outflow lobes with ALMA.

### 6. Conclusion

The distance of G5.89-0.39 is newly estimated to be $1.28^{+0.05}_{-0.08}$ kpc from the annual parallax measurement with VERA. This is 2/3 of the previously known value, but it is well reasonable if we take into account the small galactic longitude of $\sim 5.89^\circ$ and recent theoretical prediction about non-circular motions of star-forming regions.

Rescaled physical parameters based on the new distance give us several in-depth natures of high mass star formation in G5.89-0.39 as follows.

1. The ionizing star is rather later type ZAMS than previously believed type of O5. Spectral type of O8.5 – O8 means that the UCHII region are excited by not so massive and standard O-type object. Expected accretion
rate is $\sim 10^{-3} \ M_\odot \ yr^{-1}$ based on the extremely young age of the ionized shell and detailed evolutionary track of massive protostar under a high accretion rate. Resultant formation time is about $2.5 \times 10^4 \ yr$ in this case.

(2) Detected maser alignment at the O-star can be fitted by infalling Keplarian ring and its inclination and position angle are also consistent with east-west orientation of the strong outflow. It seems to be trace accretion disk (or its remnant) and suggest remarkable youth of the O-star which is before complete evaporation of circumstellar structure.

(3) Reconsideration of outflow nature suggests that the large portion of outflow mass should be entrained from massive envelope. A commonly used dynamical time should significantly underestimate actual outflow age same as low mass cases (Parker et al. 1991). This also causes an overestimate of outflow rate by an order of magnitude. Direct observation of momentum transportation from intrinsic outflow to outer entrained flow is required to confirm this. This may be able to be achieved with the proper motion measurement of outflow lobe with ALMA.

We finally emphasize that G5.89-0.39 is one of the nearest target to investigate individual high mass star formation and evolution of core scale cluster including an O-type object.

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