THE MEGAMASER COSMOLOGY PROJECT. VIII. A GEOMETRIC DISTANCE TO NGC 5765b

F. Gao$^{1,2,3}$, J. A. Braatz$^2$, M. J. Reid$^4$, K. Y. Lo$^2$, J. J. Condon$^2$, C. Henkel$^{5,6}$, C. Y. Kuo$^7$, C. M. V. Impellizzeri$^{2,8}$

D. W. Pesce$^9$, and W. Zhao$^1$

1 Key Laboratory for Research in Galaxies and Cosmology, Shanghai Astronomical Observatory, Chinese Academy of Science, Shanghai 200030, China
2 National Radio Astronomy Observatory, 520 Edgemont Road, Charlottesville, VA 22903, USA
3 Graduate School of the Chinese Academy of Sciences, Beijing 100039, China
4 Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
5 Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany
6 King Abdulaziz University, P.O. Box 80203, Jeddah, Saudi Arabia
7 Academia Sinica Institute of Astronomy and Astrophysics, P.O. Box 23-141, Taipei 10617, Taiwan
8 Joint Alma Office, Alonso de Cordova 3107, Vitacura, Santiago, Chile
9 Department of Astronomy, University of Virginia, P.O. Box 400325, Charlottesville, VA 22904, USA

Received 2015 June 18; accepted 2015 November 25; published 2016 January 27

ABSTRACT

As part of the Megamaser Cosmology Project, here we present a new geometric distance measurement to the megamaser galaxy NGC 5765b. Through a series of very long baseline interferometry observations, we have confirmed the water masers trace a thin, sub-parsec Keplerian disk around the nucleus, implying an enclosed mass of $4.55 \pm 0.40 \times 10^8 M_\odot$. Meanwhile, from single-dish monitoring of the maser spectra over two years, we measured the secular drifts of maser features near the systemic velocity of the galaxy with rates between 0.5 and 1.2 km s$^{-1}$ yr$^{-1}$. Fitting a warped, thin-disk model to these measurements, we determine a Hubble Constant $H_0$ of 66.0 $\pm$ 6.0 km s$^{-1}$ Mpc$^{-1}$ with an angular-diameter distance to NGC 5765b of 126.3 $\pm$ 11.6 Mpc. Apart from the distance measurement, we also investigate some physical properties related to the maser disk in NGC 5765b. The high-velocity features are spatially distributed into several clumps, which may indicate the existence of a spiral density wave associated with the accretion disk. For the redshifted features, the envelope defined by the peak maser intensities increases with radius. The profile of the systemic masers in NGC 5765b is smooth and shows almost no structural changes over the two years of monitoring time, which differs from the more variable case of NGC 4258.

Key words: cosmological parameters – dark energy – distance scale – galaxies: individual (NGC 5765b) – galaxies: nuclei – masers

Supporting material: machine-readable table

1. INTRODUCTION

Recent measurements of the cosmic microwave background (CMB) anisotropies have provided dramatic confirmation of the “standard” ΛCDM model (e.g., Hinshaw et al. 2013). However, degeneracies between parameters such as the dark energy equation of state, the Hubble constant, and the neutrino mass limit the determination of each quantity from the CMB data alone. One way to break this degeneracy is to conduct high-precision measurements of $H_0$ (better than a few percent), as pointed out in Hu (2005). This motivation has reinvigorated efforts to measure $H_0$ and has driven the development of better methods of measuring $H_0$ over the past few years. For a general review on this topic, please see Freedman & Madore (2010) and references therein.

So far, measurements of $H_0$ have achieved about 3% precision. Riess et al. (2011) derived $H_0 = 73.8 \pm 2.4$ km s$^{-1}$ Mpc$^{-1}$ by using both SNe Ia and Cepheids. Meanwhile, by improving the calibration of the period–luminosity (P–L) relation of Cepheids using mid-infrared observations, Freedman et al. (2012) obtained $H_0 = 74.3 \pm 2.1$ km s$^{-1}$ Mpc$^{-1}$ from the Carnegie Hubble Program.

On the other hand, with the flat geometry assumption, the model-dependent prediction of $H_0$ from the most recent Planck result has a lower $H_0$ of $67.8 \pm 0.9$ km s$^{-1}$ Mpc$^{-1}$ (Planck Collaboration et al. 2015), while the recent complete WMAP nine-year observations constrain $H_0$ to be 70.0 $\pm$ 2.2 km s$^{-1}$ Mpc$^{-1}$ (Hinshaw et al. 2013). Both of these predictions are in tension with the directly measured $H_0$ from SNe Ia and Cepheids, as mentioned above. It is not clear so far whether this tension means new physics are needed, adding to the basic six-parameter ΛCDM model, or any unknown systematic errors exist in either of the measurements. In either case, a direct measurement of $H_0$ independent of the methods mentioned above is highly desired.

As one of the direct distance measurement methods, the “disk maser” method has demonstrated its capability for precise distance measurement through the work on the archetypal disk megamaser galaxy NGC 4258 (e.g., Herrnstein et al. 1999; Humphreys et al. 2013). This method utilizes the 22 GHz water maser emission, which traces a sub-parsec thin accretion disk in Keplerian rotation at the center of a galactic nucleus, to obtain the angular-diameter distance. The maser distance to NGC 4258 provides an anchor point for the distance ladder using Cepheids and SNe Ia in Riess et al. (2011). When applied to more distant galaxies well into the Hubble flow, the disk maser method provides a simple, one-step measurement of $H_0$ that does not involve secondary calibrations, which may introduce extra systematic errors.

With this motivation, the Megamaser Cosmology Project (MCP) aims to make an independent measurement of $H_0$ to a few percent uncertainty by measuring the angular-diameter distances to disk megamaser galaxies well into the Hubble flow (between 50 and 200 Mpc). So far, the MCP group has published results on three galaxies, UGC 3789 with $H_0 = 68.9 \pm 7.1$ km s$^{-1}$ Mpc$^{-1}$ (Reid et al. 2013), NGC 6264 with $H_0 = 68.0 \pm 9.0$ km s$^{-1}$ Mpc$^{-1}$ (Kuo et al. 2013), and NGC 6323 with $H_0 = 73^{+26}_{-22}$ km s$^{-1}$ Mpc$^{-1}$ (Kuo et al. 2015).
The measurement of distances for other megamaser-host galaxies and the search for more suitable distance measurement candidates are ongoing.

As part of the MCP effort, here we present a new geometric distance measurement to the megamaser galaxy NGC 5765b. NGC 5765b is an Sa-b galaxy in a galaxy pair together with NGC 5765a. It harbors a Seyfert 2 active galactic nucleus. The 22 GHz water maser emission was discovered in 2012 February during our survey observations using the Robert C. Byrd Green Bank Telescope (GBT). Figure 1 shows a representative GBT single-dish spectrum, which has a typical disk maser profile showing three sets of emission lines, indicating a rotation speed about 600 km s\(^{-1}\). The recession velocity of NGC 5765b is \(\sim 8345\) km s\(^{-1}\), which is well into the Hubble flow. In this paper, we use optical velocity defined in the LSR frame throughout. To convert to Heliocentric for NGC 5765b, subtract 12 km s\(^{-1}\) from the LSR velocity.

This paper focuses solely on the distance measurement to NGC 5765b and some physical properties of the maser disk specific to this galaxy. In a forthcoming paper, we will summarize the results from the four published galaxies measured by the MCP, present a combined \(H_0\) measurement, and summarize plans to complete the project. We will compare \(H_0\) from masers to that measured from other methods, and present updates on constraints of other cosmological parameters in the final summary paper.

This paper is arranged as follows: we report the very long baseline interferometry (VLBI) observations and results in Section 2. Section 3 describes our single-dish monitoring observations and the acceleration measurements. In Section 4 we describe the distance measurement with a Bayesian approach and give the fitting results and error budgets. In Section 5 first we discuss some essential requirements for good distance measurement based on the case of NGC 5765b. Then we focus on some physical properties seen in NGC 5765b, including the clumpiness of the redshifted features, the correlation between maser flux and radius seen in the redshifted features, and the variability of the systemic maser profile compared to the case of NGC 4258. We present our conclusions in Section 6.

2. VLBI OBSERVATIONS

To map the spatial distribution of maser spots in NGC 5765b, we conducted a series of VLBI observations between 2012 April and 2014 January, with the 10 antennas of the Very Long Baseline Array (VLBA), augmented by the 100 m GBT, the Effelsberg 100 m telescope (EB), and the Karl G. Jansky Very Large Array (VLA). We list all the basic observing information in Table 1, including project code, date observed, duration, antennas used, beam size, sensitivity, and the observing mode.

2.1. VLBI Absolute Position Measurement for NGC 5765b

Following the detection of maser emission in NGC 5765b by the GBT, we conducted phase referencing VLBI observations (project code BB313AC and BB321Y5) to measure the maser’s sky position. Based on our experience, to maintain good phase coherence and calibration, we require an absolute position measurement for the NGC 5765b maser good to \(\sim 10\) mas (see details in Appendix A). We followed the observation setup and data reduction process for phase referencing observations as described in Reid et al. (2009). Two nearby quasars, J1448

---

\(^{10}\) The Green Bank Telescope is a facility of the National Radio Astronomy Observatory.

\(^{11}\) The VLBA is a facility of the National Radio Astronomy Observatory, which is operated by the Associated Universities, Inc. under a cooperative agreement with the National Science Foundation (NSF).
Table 1

| Project Code | Date       | Antennas | Synthesized Beam (mas x mas, degree) | Track Length (hr) | Sensitivity (mJy) | Observing Mode |
|--------------|------------|----------|--------------------------------------|-------------------|-------------------|----------------|
| BB313 J      | 2012 Apr 14| VLBA+GB+EB | 1.04 x 0.27, -10.49                  | 10                | 1.10              | Self-cal.      |
| BB313 AC     | 2012 Nov 09| VLBA+GB+EB | 1.00 x 0.26, -11.94                  | 12                | 1.25              | Phase-ref.     |
| BB321 C      | 2013 Feb 16| VLBA+Y     | 1.42 x 0.47, -16.66                  | 6                 | 0.72              | Self-cal.      |
| BB321 E1     | 2013 Feb 17| VLBA+Y     | 1.37 x 0.40, -18.05                  | 7                 | 0.78              | Self-cal.      |
| BB321 F      | 2013 Feb 21| VLBA+Y     | 1.97 x 0.56, -16.08                  | 6.25              | 0.93              | Self-cal.      |
| BB321 L      | 2013 Mar 13| VLBA+GB+Y  | ...                                  | 7                 | ...               | Self-cal.      |
| BB321 N      | 2013 Mar 14| VLBA+GB+Y  | 1.90 x 0.49, -6.68                   | 5                 | 0.59              | Self-cal.      |
| BB321 S      | 2013 Apr 13| VLBA+GB+Y  | ...                                  | 7                 | ...               | Self-cal.      |
| BB321 T      | 2013 Dec 03| VLBA+GB+Y  | 1.00 x 0.32, -8.93                   | 6                 | 0.83              | Self-cal.      |
| BB321 Y2     | 2014 Jan 12| VLBA+GB+Y  | 1.49 x 0.36, -14.00                  | 6                 | 0.52              | Self-cal.      |
| BB321 Y3     | 2014 Jan 13| VLBA+GB+Y  | 1.52 x 0.38, -12.33                  | 6                 | 0.53              | Self-cal.      |
| BB321 Y4     | 2014 Jan 16| VLBA+GB+Y  | 1.51 x 0.41, -9.55                   | 6                 | 0.42              | Self-cal.      |
| BB321 Y5     | 2014 Jan 17| VLBA      | 0.69 x 0.23, -13.19                  | 6                 | 2.00              | Phase-ref.     |

Note. VLBI observation details. Data for BB321L and BB321S were affected by bad weather and instrument problems, so we did not make the VLBI map from these two tracks.

Table 2

| Name          | R.A.       | decl.         | Uncertainty in R.A. (mas) | Uncertainty in decl. (mas) |
|---------------|------------|---------------|---------------------------|----------------------------|
| J1448+0402    | 14°48′50″36′1110 | +04°02′19″89244 | 1.68                      | 2.05                       |
| J1458+0416    | 14°58′59″35′215 | +04°16′13″82056 | 0.03                      | 0.05                       |
| NGC 5765b     | 14°50′51″51′950 | +05°06′52″2502 | 0.1                       | 0.7                       |

Note. Positions for J1448+0402 and J1458+0416 are from the VLBA Calibrator Survey. Position for NGC 5765b is measured in reference to J1458+0416.

+0402 and J1458+0416, were chosen as phase reference calibrators and we cycled the observations between these two calibrators and NGC 5765b.

The data reduction was done with NRAO’s Astronomical Image Processing System (AIPS) software. From BB313AC we derived the sky position of the peak maser emission at velocity 8294.0 km s⁻¹, which is R.A. = 14°50′51″51′950 and decl. = +05°06′52″2502. We use this position in correlating later VLBI observations. The position difference we measured between BB313AC and BB321Y5 is 0.1 mas in R.A. and 0.7 mas in decl., which is quoted as the measured absolute position uncertainty. We list the sky positions for all these three sources in Table 2.

2.2. New VLBI Capability Starting 2013 February

In general, our ability to measure the relative positions of megamaser spots with the VLBI is limited by sensitivity, with the position uncertainty of each maser spot approximately given by 0.5θ/⟨S/N⟩, in which θ is the synthesized beam size and S/N is the signal-to-noise ratio. To reduce the noise level would require a longer integration time and/or larger array collecting area. The typical intensity of maser emission in our targets is a few tens of mJy and line widths are ~2 km s⁻¹. Based on our experience, mapping 10 mJy maser line requires a ~10 hr VLBI observation using the VLBA+GBT+EB. The case of NGC 6323 further demonstrates the necessity of VLBI sensitivity, in which 13 12 hr VLBI tracks were conducted to map the <10 mJy systemic masers in NGC 6323 (Kuo et al. 2011), but in the end their sensitivity-limited VLBI measurement is still the limiting factor for determining H₀ as concluded in Kuo et al. (2015).

Our VLBI observations benefit from two significant upgrades which were implemented in 2013 February.

1. The VLBI observations were joined by the VLA in the phased array mode, following the completion of the expanded VLA project. The phased VLA is a key component in our VLBI observations as it improves our sensitivity by up to 40%.

2. As part of the VLBA sensitivity upgrade project, the new ROACH Digital Backend (RDBE), together with the Mark 5C recording system, replaced the old VLBA legacy system for all stations included in our observations. The new recorder increases the data-recording rate from 512 Mbit s⁻¹ to 2 Gbit s⁻¹, allowing us to use two 128 MHz bands to cover the entire maser spectrum contiguously, with dual polarization and 2 bit sampling. For comparison, with the recording rate of 512 Mbit s⁻¹ and maximum bandwidth of each baseband limited to 16 MHz as before, we could barely cover the entire spectrum of NGC 5765b with the eight available basebands, as both the blueshifted and redshifted features span over 20 MHz in frequency. So the new system increases the sensitivity by increasing observation efficiency. For data correlation, in addition to the default “continuum-like” correlation pass with 0.5 MHz channel size over the entire band, we obtained a second correlation pass with three narrow bands of 32 MHz bandwidth centered on the three sets of maser lines using the new zoom-bandmode offered in the DiFX software.
correlator. The spectral resolution in our raw data is 25 kHz (~0.3 km s⁻¹), which is comparable to that of our GBT single-dish spectrum (24.4 kHz). This is five times finer than what we could achieve with the legacy system and it allows higher accuracy of matching between the single-dish and VLBI spectra.

Except for the two VLBI tracks conducted in phase referencing mode when measuring the absolute position of NGC 5765b, all other VLBI observations were observed in the “self-cal” mode, in which we use the strongest maser line as the phase calibrator. Our observation setup and data reduction process are similar to previous MCP observations, so please refer to earlier papers (Reid et al. 2009; Kuo et al. 2013) for more details. Here we only describe differences from earlier work.

For the phased VLA, we need to “phase it up” prior to each VLBI scan. The “phase up” was done by observing J1448+040 (>200 mJy, 12°1 away from NGC 5765b) for one minute between each VLBI scan. To maintain good phase coherence for the VLA, we set the maximum VLBI scan length to be 10 mins with the VLA in B or C configuration. We also added a flux calibration scan for the VLA to get the combined system temperature for the phased array. For all self-calibration tracks, we used the hourly observed delay calibrator to solve for the change of multi-band delay in time rather than using geodetic blocks as we do for phase-referenced tracks. After removing the instrumental delay, we ran FRING in AIPS on delay calibrators to solve for the multi-band delays and apply this correction to the target source.

In our 2013 and 2014 data, we noticed a fast fringe phase drifting over time and lower fringe amplitude on all GBT baselines on calibrator scans, after all calibrations were applied. To quantify this issue, we fit the fringe phase, delay, and rate using the strongest maser lines in NGC 5765b (at a velocity between 8294 and 8301 km s⁻¹, with flux >100 mJy) on the GBT-VLA baseline with an integration time of 30 s. Then we smoothed the fitted results with a boxcar window of five minutes and got a residual fringe rate (RFR) of ~4 mHz on the GBT over the entire observation. We repeated this measurement in all our VLBI data sets and found this RFR appears on all calibrator scans and target scans, and it remains constant over the entire track and also between tracks. Finally, we corrected the RFR using AIPS task CLCOR by adding in the rate correction before splitting the data for self-calibration.

After calibrating each of the tracks and doing preliminary imaging, we identified the best tracks and combined them in the following way: for data observed in early 2013, we combined data from BB321C, BB321E1, BB321F, and BB321N in UV space, as they were observed within two months of each other. Likewise, for data observed in late 2013 until early 2014, we combined BB321T, BB321Y2, BB321Y3, and BB321Y4 in UV space. Then we combined these two maps in the image plane by applying a weighted average to their positions for each velocity channel, with each velocity channel matched within 0.3 km s⁻¹ between the two data sets. The channel size of the final data sets is ~1.7 km s⁻¹. The two maps were aligned by referencing to the position of the strongest feature in the systemic part of the spectrum, assuming they are the same feature with no position change (if we assume a Keplerian rotation velocity of 600 km s⁻¹ for the strongest feature, the sky position change of this feature over one year is only ~0.001 mas). This gives the final VLBI map we use in the following analysis, as shown in Figure 2.

2.3. VLBI Observation Results

In general, our VLBI map (Figure 2) shows a linear configuration of all maser features along the position angle (P. A.) of 145° (defined with respect to the redshifted masers, as measured from due north to the east). The position for each maser spot is referenced to the strongest line in the systemic part of the spectrum. By assuming a Hubble constant of 70 km s⁻¹ Mpc⁻¹ and recession velocity of 8345 km s⁻¹ for NGC 5765b, we get a nominal distance of 119 Mpc. The high-velocity masers extend between 0.5 to 2.0 mas from the coordinate origin, which corresponds to ~0.3 to 1.2 pc. We note the blueshifted and redshifted features are distributed asymmetrically with respect to the systemic features, and the disk shows a clear warp in P. A. Maser spots on the redshifted side are concentrated into five clumps, while the blueshifted spots are more evenly distributed and are roughly divided into two parts. We discuss such clumpiness in more detail in Section 5.

The spatial distribution of maser spots in NGC 5765b is consistent with a thin-disk model. To check the kinematics of the maser disk, we construct the position–velocity (P–V) diagram by defining the impact parameter as \( r = \sqrt{(x-x_0)^2 + (y-y_0)^2} \), in which \( x_0 \) and \( y_0 \) are the VLBI position for the strongest maser spot at 8295.91 km s⁻¹. Then we fit the high-velocity data with a Keplerian rotation curve, assuming an edge-on disk (\( i = 90° \)) with no inclination warping and also assuming that all the high-velocity maser...
spots are located along the midline (defined as the radial line through the disk perpendicular to the line of sight). The best fit yields an enclosed mass of $4.4 \pm 0.44 \times 10^7 M_\odot$ with the fitted recession velocity $8304 \text{ km s}^{-1}$ and a position offset of the dynamic center of $0.011 \text{ mas}$ in R.A. and $-0.162 \text{ mas}$ in decl. from the coordinate origin. In Figure 3 we show the P–V diagram, which is centered on the fitted dynamic center. The best-fit Keplerian curve is overplotted as the dotted lines. Most of the high-velocity features deviate from the best-fit Keplerian curve by less than 5% of their rotation velocity. We treat this as the main contributor to the uncertainty on the black hole mass measurement since this simple model does not include fitting the inclination warp of the disk. So the final uncertainty for the black hole mass is about 10%.

While this simple model does not account for any inclination warping on the maser disk, the VLBI map and P–V diagram together still confirm that masers in NGC 5765b trace a thin, sub-parsec Keplerian disk. We treat these results as an initial guess for the central black hole mass, recession velocity, and position of the dynamic center in the more detailed modeling of the maser disk (Section 4).

3. ACCELERATION MEASUREMENTS

3.1. Monitoring Observations

To measure the secular drift of maser velocities in NGC 5765b over time, we obtained monthly GBT monitoring observations. Each observation lasted $\sim 3 \text{ hr}$, from which we reach an rms noise of $\sim 1.2 \text{ mJy}$, at a channel size of $24.4 \text{ kHz}$ with Hanning smoothing. All together we obtained 18 epochs of observations from 2012 February to 2014 May, which bracket our VLBI observations. We list the details on the monitoring observations in Table 3. We note that because of a scheduling issue, we did not get monitoring observations in 2014 January. Since our 2014 VLBI observation took place at this time, we used the VLBI spectrum to fill in that epoch. In this regard, we have 19 epochs of data used in the acceleration measurements.

### Table 3

| Epoch | Date Observed | Day Number | Tsys (K) | rms noise (mJy) |
|-------|---------------|------------|----------|------------------|
| 1     | 2012 Feb 26   | 0          | 53.0     | 1.93             |
| 2     | 2012 Apr 08   | 42         | 40.0     | 1.23             |
| 3     | 2012 May 11   | 75         | 48.3     | 1.38             |
| 4     | 2012 Oct 20   | 237        | 48.9     | 1.33             |
| 5     | 2012 Nov 13   | 261        | 36.2     | 1.15             |
| 6     | 2012 Dec 13   | 291        | 35.7     | 1.07             |
| 7     | 2013 Jan 08   | 317        | 38.5     | 1.18             |
| 8     | 2013 Feb 25   | 365        | 35.4     | 1.71             |
| 9     | 2013 Mar 04   | 372        | 39.1     | 1.21             |
| 10    | 2013 Apr 06   | 405        | 46.1     | 1.38             |
| 11    | 2013 May 03   | 432        | 42.4     | 1.17             |
| 12    | 2013 May 25   | 454        | 41.1     | 1.38             |
| 13    | 2013 Nov 23   | 636        | 46.4     | 1.65             |
| 14    | 2013 Dec 24   | 667        | 45.0     | 1.38             |
| 15    | 2014 Jan 03   | 677        | ...      | 1.29             |
| 16    | 2014 Feb 09   | 724        | 65.5     | 2.18             |
| 17    | 2013 Mar 08   | 741        | 53.5     | 1.64             |
| 18    | 2014 Apr 06   | 770        | 38.0     | 1.05             |
| 19    | 2014 May 09   | 803        | 60.9     | 1.69             |

Note.

Due to the lack of a GBT observation, here we use the spectrum from the combined VLBI data of BB321T Y2 Y3 and Y4.

3.2. Acceleration of the Systemic Masers

3.2.1. Measuring “By Eye”

We show all 19 epochs of monitoring spectra in Figure 4, from which we can see the overall trend for line profile drifting and trace each individual component. As a first approximation, we use the peak of each distinct maser feature to trace the underlying acceleration. Those peaks were identified by eye and the results plotted in Figure 5. From this, we get an initial estimate of the number of Gaussian components associated with the spectrum and the magnitude of the accelerations. From Figure 5 it is clear that the systemic features can be traced easily over the two-year monitoring period, and show distinct accelerations. The features between 8260 and 8290 km s$^{-1}$ all have similar accelerations of $\sim 0.6 \text{ km s}^{-1} \text{ yr}^{-1}$. Features outside that velocity range show more varied accelerations, between 0.5 and 1.2 km s$^{-1} \text{ yr}^{-1}$.

The “by eye” method does not adequately distinguish blended features. We also note that some systemic features (e.g., $\sim 8300 \text{ km s}^{-1}$ in the middle epochs) show a “negative” slope, which we believe is not a sign of “negative” acceleration, but may have resulted from several lines blending together and the emerging of new peaks at different velocities, as the overall spectral profile shows a clear change (which is better illustrated in Figure 4).
So we get initial estimates of line accelerations using the “by eye” method. We then use these estimates (only the positive ones) as the initial values in a least squares determination of accelerations, as described in the next section.

Figure 4. Stacked spectra from GBT monitoring data, zoomed on the systemic part, with the date referenced to 2012 February 26. Data from epoch 15 comes from VLBI tracks BB321T, Y2, Y3, and Y4 combined, as a complement to the unscheduled GBT monitoring observation.

Figure 5. Acceleration plots show velocities of the maser line peaks in both the systemic and high-velocity parts. Each cross marks a peak velocity at the given epoch, identified by eye. The date on the X-axis is referenced to the first GBT monitoring observation data, 2012 February 26. The “negative” slope seen in several systemic features (e.g., \( \sim 8300 \, \text{km s}^{-1} \) in the middle epochs) appears to result from lines blending together and the emerging of new peaks at adjacent velocities. This is better illustrated in Figure 4.

3.2.2. Method 1

To determine the best-fit accelerations for each maser component, we decompose the overall profile into a series of
Gaussian components and measure the drift of each component as the acceleration, using a least squares fitting algorithm. This is the so-called "Method 1" in previous MCP papers.

We follow the fitting process described in Reid et al. (2013), in which for the first step we specify the velocity and acceleration for each component at a reference epoch, keep the line width fixed to 2 km s$^{-1}$ (the typical line widths for the systemic masers in NGC 5765b are between 2 and 3 km s$^{-1}$, and here we use 2 km s$^{-1}$ as an initial guess), and let the program set the amplitude of each component at the corresponding velocity from the real data. After this step, we have an initial mask of the Gaussian decomposition. We minimize the residual $\chi^2$ between our Gaussian decomposition model and the real data by doing the fitting iteratively. In the second step, we fit the amplitude, width, and velocity together for each component, but keep the acceleration unchanged. Finally, we include the acceleration in the fitting and stop when the residual $\chi^2$ reaches a stable minimum.

Visual inspection shows the systemic maser spectrum divides mainly into two parts around 8290 km s$^{-1}$, with the features between 8260 and 8290 km s$^{-1}$ (named "clump 1") more distinct, while features between 8290 and 8340 km s$^{-1}$ (named "clump 2") more blended, especially around 8295 km s$^{-1}$. So we fit the accelerations in the two clumps separately, with the procedure mentioned above. The final reduced $\chi^2$ for the two clumps are 1.673 and 1.758, respectively. We note that since we have used Hanning smoothing for our data, the optimal reduced chi-squared value will not be unity.

We list the acceleration results from method 1 in Table 4 below.

3.2.3. Method 2

To check whether the results from Method 1 depend on the initial velocity and acceleration values, here we fit the accelerations using the more automated Method 2 (see a description in Reid et al. 2013) in which the algorithm explores a wider range of initial parameters. Instead of specifying the number of components and the initial guess of velocity/width/acceleration for each component, here we only specify the velocity range for the fitting, the average width for each component, and the average separation in velocity between each component. The program will generate multiple trials and do the fitting separately, with each trial using a set of initial values generated randomly for each of the components. We run the program with 100 trials to explore different starting points and keep the few best solutions with small $\chi^2$ and consistency with the results measured by eye. We show the fitting results in Figure 6.

3.3. Error Floor for Accelerations of Systemic Masers

From previous MCP experience, to account for more realistic uncertainties in cases where the formal fitting uncertainty from method 1 is unrealistically small (e.g., less than 0.05 km s$^{-1}$ yr$^{-1}$ in the case of NGC 5765b), we use an "error floor" on the acceleration result and add that in quadrature to the formal fitting error to get the final uncertainty for each measured acceleration. However, a single value for the "error floor" might not be suitable for all maser features in the case of NGC 5765b. It is clearly shown in both Figure 4 and Table 4 that the spectral features in clump 1 are more distinct and accurately measured, while those in clump 2 are more blended and show larger scatter. Since line blending is an important contributor to the uncertainties, a large error floor here which may accurately represent the errors in clump 2 would down-weight results from clump 1, while a small error floor will overweight results from clump 2 in the other way. So for this galaxy we use the difference between the results from method 1 and method 2 for each measured maser spot as an estimate of the error floor for each component.

We plot the acceleration fitting results from both methods in Figure 6 for comparison.

3.4. Accelerations of the High-velocity Masers

The high-velocity features are not as highly blended as the systemic ones. Considering their relative weakness and their short lifetime (some of the blueshifted features are only evident for two to three epochs), we measured their accelerations using only the "by eye" method. We list these results in Table 5.

Besides the formal fitting error, we also calculate the rms scatter in both the redshifted and blueshifted results, which are 0.155 km s$^{-1}$ yr$^{-1}$ (red), 0.275 km s$^{-1}$ yr$^{-1}$ (blue), 0.200 km s$^{-1}$ yr$^{-1}$ (combined). Overall, most of the measured results are within this rms level, with only maser features at 8856.32 and 7582.95 km s$^{-1}$ showing clear offsets from zero acceleration. For a high-velocity feature with rotation velocity of 600 km s$^{-1}$ in NGC 5765b, an acceleration of 0.2 km s$^{-1}$ yr$^{-1}$ along the line of sight (LOS) direction requires a 16° deviation from the midline on the disk. Thus, we conclude that most of the high-velocity features are located on the midline (the diameter

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|}
\hline
Velocity & Epochs & Line Width & Acceleration & $A_v$ \\
(km s$^{-1}$) & & (km s$^{-1}$ yr$^{-1}$) & (km s$^{-1}$ yr$^{-1}$) & \\
\hline
8261.36 & 1-19 & 2.52 & 0.48 & 0.018 \\
8264.05 & 1-19 & 2.02 & 0.54 & 0.014 \\
8267.48 & 1-19 & 3.14 & 0.57 & 0.025 \\
8269.31 & 1-19 & 2.25 & 0.64 & 0.011 \\
8271.96 & 1-19 & 3.49 & 0.50 & 0.015 \\
8275.06 & 1-19 & 2.08 & 0.66 & 0.009 \\
8277.74 & 1-19 & 2.55 & 0.60 & 0.010 \\
8280.81 & 1-19 & 2.97 & 0.46 & 0.031 \\
8283.88 & 1-19 & 3.24 & 0.37 & 0.033 \\
8286.92 & 1-19 & 2.43 & 0.51 & 0.022 \\
8291.61 & 4-19 & 3.33 & 0.62 & 0.041 \\
8293.12 & 4-19 & 1.72 & 0.91 & 0.020 \\
8294.91 & 4-19 & 2.75 & 0.92 & 0.026 \\
8297.61 & 4-19 & 3.05 & 0.84 & 0.039 \\
8299.79 & 4-19 & 2.46 & 0.75 & 0.036 \\
8302.12 & 4-19 & 2.37 & 0.61 & 0.048 \\
8303.95 & 4-19 & 2.05 & 0.61 & 0.054 \\
8305.70 & 4-19 & 2.09 & 0.43 & 0.068 \\
8307.81 & 4-19 & 2.41 & 0.44 & 0.063 \\
8309.84 & 4-19 & 2.33 & 0.55 & 0.101 \\
8311.42 & 4-19 & 2.30 & 0.52 & 0.096 \\
8313.23 & 4-19 & 2.25 & 0.82 & 0.084 \\
8315.25 & 4-19 & 2.15 & 0.45 & 0.117 \\
8317.04 & 4-19 & 2.02 & 0.23 & 0.104 \\
8318.75 & 4-12 & 1.81 & 1.12 & 0.063 \\
8320.76 & 4-12 & 1.83 & 0.98 & 0.064 \\
8323.24 & 4-12 & 2.98 & 0.76 & 0.167 \\
8326.08 & 4-12 & 1.92 & 1.30 & 0.060 \\
8328.69 & 4-12 & 3.04 & 0.52 & 0.310 \\
\hline
\end{tabular}
\caption{Acceleration Measurements for the Systemic Masers from Method 1}
\end{table}
through the disk perpendicular to the LOS) of the maser disk with deviations less than \(\sim 16^\circ\), with few exceptions.

4. DETERMINATION OF \(H_0\)

4.1. Model Fitting of the Accretion Disk

To reconstruct the geometry and spatial distribution of maser spots from the observed data, here we fit a warped disk model to the VLBI and acceleration data using a Bayesian approach. This model can accommodate 14 global parameters describing the disk geometry, including the Hubble constant \(H_0\), the central black hole mass \(M\), the position of the dynamic center on the sky \(X_0\) and \(Y_0\), the recession velocity and peculiar velocity of the galaxy \(V_0\) and \(V_p\), the position angle and first/second order of warping on the P.A. direction \(\theta_A\), \(\partial \theta_p / \partial \theta\), \(\partial^2 \theta_p / \partial \theta^2\), the inclination angle and first/second order of warping on the inclination direction \(\theta_i\), \(\partial \theta_i / \partial \theta\), \(\partial^2 \theta_i / \partial \theta^2\), and two additional parameters describing the eccentricity of the disk \(e\) and the change of the azimuth angle for the major axis of the elliptical with radius \(\partial \eta_c / \partial \theta\). Apart from these global parameters, there are also two parameters \(\alpha\) and \(\phi\) describing the coordinates on the disk for each maser spot. The input data for the model consists of the sky position, velocity, and acceleration for each maser spot. The program uses a Markov Chain Monte-Carlo (MCMC) approach to sample the parameter space and applies the Metropolis-Hastings algorithm to explore the probability distribution function for each of the global parameters. To better sample parameter space, the program allows multiple “strands,” defined as independent runs of the MCMC with different starting conditions, to run simultaneously. A more detailed description about the disk model and fitting process can be found in Reid et al. (2013) and Humphreys et al. (2013).

All together there are 212 maser spots mapped for NGC 5765b. We list the input data in Table 6. We estimated the initial value for the position angle, black hole mass, recession velocity, and black hole position from our fitting of the P–V diagram in Section 2, while the initial value for \(H_0\) in each strand was evenly selected between 60 and 80 km s\(^{-1}\) Mpc\(^{-1}\). Except for recession velocity and peculiar velocity, we did not include a prior uncertainty in any other global parameters as we try to keep our fitting result away from any existing bias. We also note that even though the initial value for \(H_0\) was chosen between 60 and 80 km s\(^{-1}\) Mpc\(^{-1}\), \(H_0\) could vary to any number as there are no constraints on it during each trial of fitting.

NGC 5765b sits in a galaxy pair together with NGC 5765a, and the recession velocity for each of them are (a) 8469 km s\(^{-1}\) and (b) 8345 km s\(^{-1}\). Assuming the dynamic center of this galaxy pair has the averaged recession velocity of 8401 km s\(^{-1}\), then the additional uncertainty in peculiar velocity caused by this galaxy pair is \(\sim 70\) km s\(^{-1}\), which is less than 1% of the recession velocity of NGC 5765b. Apart from this, we do not
have any constraints on whether NGC 5765b deviates from the Hubble flow. Nevertheless, we include the peculiar velocity in our fitting so that the uncertainty of peculiar velocity contributes appropriately to our final uncertainty in $H_0$. As a conservative treatment, we use a peculiar velocity of zero with prior uncertainty of 250 km s$^{-1}$ in our final fitting.

In our final model fitting we use 10 global parameters, where we have excluded the second order of warping in both the P.A. and inclination directions, and the two parameters for eccentricity, as they were insignificant to the final result. We use 10 strands in our fitting, with each strand containing $2 \times 10^3$ trials, which is sufficient to reach convergence. The convergence is indexed by the autocorrelation (AC) function for each model parameter. We require the AC function to drop near zero before 40% of the largest lag number. The largest lag number is defined as 25% of the maximum number of MCMC trials that have been recorded for each strand. Usually if 6 or 7 out of the total 10 strands have converged, we consider the total fitting result as converged. We show an example plot of the $H_0$ versus trial iteration number for several strands in Figure 7. Another example of the AC function with lag number and also the $H_0$ probability distribution for the same strands are shown in Figure 8.

To come to our final result, we dropped the first 20% of trials in each strand to avoid using any unconverged trials in the final probability distribution. For each of the global parameters, we quote the mean value in the probability distribution function as the fitted result, and 68% confidence range as the error. All uncertainties listed here have been scaled by $\sqrt{\chi^2/N}$, i.e., $\sqrt{1.575}$. For $H_0$, we determine $66.0 \pm 5.0$ km s$^{-1}$ Mpc$^{-1}$. We list the full set of final fitting results in Table 7. We also plot the probability distribution for each global parameter in Figure 9, and show the distribution of maser features on the disk in Figure 10.

### 4.2. Systematic Uncertainty in $H_0$

Apart from the formal fitting uncertainty for $H_0$, here we investigate several factors that might cause systematic uncertainty.

To test for human bias in the acceleration measurement, here we fit the maser disk using accelerations determined using method 2, rather than method 1, while still using the difference between the two methods as the error floor for acceleration data. This fit gives $H_0 = 68.5 \pm 6.0$ km s$^{-1}$ Mpc$^{-1}$, which is consistent within 1$\sigma$ of our original result.

For the systemic features, the error floor we used for the acceleration data is the measured difference between results using method 1 and method 2 for each maser spot independently. To test the robustness of our measurement against the value of the error floor, we also tried setting the error floor to the mean difference between method 1 and method 2, calculated separately for clump 1 and clump 2. The mean difference in clump 1 is $0.045$ km s$^{-1}$ yr$^{-1}$, and for clump 2 the value is $0.20$ km s$^{-1}$ yr$^{-1}$.

We re-run the Bayesian fitting with other parameters unchanged and get $H_0 = 68.0 \pm 6.4$ km s$^{-1}$ Mpc$^{-1}$, consistent with our original result.

### Table 6

Input Data for the Disk Fitting Program

| Velocity (km s$^{-1}$) | $X$ (mas) | $X_c$ (mas) | $Y$ (mas) | $Y_c$ (mas) | $A$ (km s$^{-1}$ yr$^{-1}$) | $A_c$ (km s$^{-1}$ yr$^{-1}$) |
|------------------------|-----------|-------------|-----------|-------------|---------------------------|-----------------------------|
| 8329.78 | 0.0140 | 0.0036 | −0.0156 | 0.0099 | 0.520 | 0.310 |
| 8327.99 | 0.0108 | 0.0019 | −0.0268 | 0.0052 | 0.520 | 0.310 |
| 8326.21 | 0.0161 | 0.0020 | −0.0355 | 0.0051 | 1.300 | 0.152 |
| 8324.43 | 0.0245 | 0.0029 | −0.0249 | 0.0078 | 0.760 | 0.318 |
| 8322.65 | 0.0351 | 0.0020 | −0.0416 | 0.0055 | 0.760 | 0.318 |
| 8320.86 | 0.0428 | 0.0012 | −0.0312 | 0.0032 | 0.980 | 0.127 |
| 8319.08 | 0.0371 | 0.0016 | −0.0262 | 0.0040 | 1.120 | 0.070 |

Note. Input data for the Bayesian fitting program for NGC 5765b. No error floor for the position data has been added. An error floor of 0.2 km s$^{-1}$ yr$^{-1}$ was added for the acceleration data of the high-velocity masers.

(This table is available in its entirety in machine-readable form.)

5. DISCUSSION

### 5.1. Essential Requirements for Good Distance Measurements

Combined with our previous experience, we note that a good distance measurement (with uncertainty less than 10%) using the “disk maser” method requires both a well-defined rotation curve from the high-velocity maser components and well-measured accelerations over a wide velocity range for the systemic masers. In principle, only one systemic feature with a perfectly measured acceleration could provide the distance, since the rotation curve defined by the high-velocity features measures the enclosed mass, the dynamic center, and recession velocity. In practice, a large spread of systemic features over a
wide velocity range not only reduces the mean acceleration measurement uncertainty, but also traces the inclination warping with masers at different radii. The case of NGC 5765b fulfills such requirements in the following aspects.

1. The system has bright maser lines, benefiting VLBI calibration and imaging.

A minimum maser line flux of \( \sim 100 \text{ mJy} \) is required to get a solid fringe detection for the VLBA+GBT array, within one to two minutes integration time and 125 kHz channel size under moderate atmospheric conditions. For the VLBA+GBT+VLA array, this limit goes down to \( \sim 50 \text{ mJy} \). In the case of NGC 5765b, the strongest maser line is about 200 mJy, which is ideal for providing sufficient calibration of the atmospheric and instrumental effects.

As mentioned in Section 2.2, the relative position uncertainty of each maser spot is approximately given by \( 0.59/(S/N) \). For NGC 5765b, the blueshifted features are the faintest, with most of them being below 15 mJy (as shown in Figure 1). The systemic masers for which the acceleration has been measured are almost all above 20 mJy. The 1\( \sigma \) noise level from our VLBI map is 0.3 mJy beam\(^{-1} \) channel\(^{-1} \) (with a channel width of 125 kHz), providing a 10\( \sigma \) measurement of features at 3 mJy. Compare this to the Kuo et al. (2015) result on NGC 6323, where the systemic masers (which are weaker than the high-velocity masers in that galaxy) are all below 10 mJy. The authors conclude their final uncertainty (\( \sim 30\% \)) on the distance measurement is dominated by the low precision of the maser position measurements, even though their VLBI map has a noise level similar to that in our study.

It is also advantageous that our VLBI observations were scheduled closely in time (within two months) in both 2013 and 2014, which limits the impact of maser variability when combining tracks.

2. The maser covers a wide velocity range in both the systemic and high-velocity masers.

As mentioned in Section 2.2, the rotation curve traced by the high-velocity features defines \( M/D \), where \( M \) is the enclosed mass and \( D \) is the distance, while the slope of the systemic features on the P–V diagram constrains \( M/D^3 \). So a wider velocity coverage on both the systemic and high-velocity features provides better leverage and hence better constraints on \( M \) and \( D \). In the case of NGC 5765b, the redshifted and blueshifted masers span over 350 and 250 km s\(^{-1} \), respectively, and sample the rotation curve very well, as shown in Figure 3.

The systemic masers in NGC 5765b span 90 km s\(^{-1} \), and we are able to measure the acceleration of each line with a typical uncertainty of \( \sim 10\% \) within 70 km s\(^{-1} \) velocity range. For comparison, in NGC 4258 the systemic features span over 110 km s\(^{-1} \) (Humphreys et al. 2008), contributing to the 3\% distance measurement (Humphreys et al. 2013).

3. Accelerations of the systemic features are measured accurately.

In NGC 5765b, the low variability among the systemic features and relatively low (<1.5 km s\(^{-1} \) yr\(^{-1} \)) but similar drift rate for the majority of features allows us to trace them through all observing epochs and contributes to our precise acceleration measurements. However, the monitoring must span a longer time to measure these low accelerations. The lifetimes of
individual maser components in other galaxies varies from a few months to a few years. In NGC 5765b, the systemic masers have shown little structural changes over the observed 2.5 years, which has allowed us to utilize all 2.5 years of monitoring data to analyze each component. We also note that the low variability and small accelerations in NGC 5765b reduce the impact of the summertime gap with GBT monitoring data. For maser galaxies with high accelerations or variability, it would be better to fill the summer gap for the best acceleration measurements.

5.2. Improving the $H_0$ Estimate with Future NGC 5765b Observations

In this section, we investigate chances to improve the $H_0$ measurement with observations of NGC 5765b in the future. The constraint on $H_0$ from this work is 9.1%, with random uncertainties dominating the final result rather than systematic uncertainties, as listed in Table 8. So, in principle, the final result could be improved by more observations. Since we use the same methodology for our distance measurement as Humphreys et al. (2013) for NGC 4258, which reached a 2.2% formal fitting uncertainty and a 3% total uncertainty, we compare the input data for both NGC 4258 and NGC 5765b quantitatively in this section.
The input data for the Bayesian fitting program we used here are the sky position, velocity, and acceleration with individual uncertainties for each maser spot. The input data can be improved in two ways, by observing more maser spots covering a wider velocity range or by smaller uncertainties for each type of data.

We list the details of input data for both NGC 4258 and NGC 5765b in Table 9 for comparison. Regarding the velocity coverage, the most noticeable difference is the velocity range for the systemic part with accelerations measured: 110 km s\(^{-1}\) in NGC 4258 versus 70 km s\(^{-1}\) in NGC 5765b. For the high-velocity features, the velocity coverage is similar, which means a similar sampling range of the Keplerian rotation curve as NGC 4258 and NGC 5765b have similar black hole masses. Due to the relatively high intensity of the systemic masers in NGC 5765b and the noise level we reached here (\(1\sigma\) of 0.3 mJy beam\(^{-1}\) channel\(^{-1}\) (125 kHz) for the VLBI map, and <2 mJy channel\(^{-1}\) (24.4 kHz) for the single-dish monitoring spectra), increasing either VLBI or single-dish observing sensitivity will not substantially cover new velocities. So, as a practical matter, it would be difficult to improve the overall fitting result by including more maser spots.

On the other hand, regarding the uncertainty for each type of data, the most noticeable difference between NGC 5765b and NGC 4258 lies in the acceleration data. For NGC 4258, the uncertainty on acceleration for each measured maser component is less than 4\% (Humphreys et al. 2008), while for NGC 5765b the typical uncertainty is 10\% for each maser component. The VLBI position uncertainties are similar between NGC 4258 and NGC 5765b, after adding the position...
error floor. So we conclude that future improvement of the $H_0$ uncertainty with NGC 5765b depends on measuring accelerations with better precision.

5.3. Clumpiness of the High-velocity Masers

A visual inspection of the GBT spectrum (insets in Figure 1) of the high-velocity components reveals the maser lines are regularly clustered into several clumps. This is especially obvious on the redshifted features, in which there are mainly five clumps evenly distributed between 8740 and 8980 km s$^{-1}$, spaced by $\sim 50$ km s$^{-1}$. Beyond this, there is another clump centered at 9075 km s$^{-1}$.

The VLBI map (Figure 2) shows that the redshifted masers are also spatially clustered into several clumps, with a typical spacing between clumps of $\sim 0.3$ mas (0.18 pc). The blueshifted masers, meanwhile, are distributed more smoothly and mainly appear in two clumps.

Such clumpiness of the high-velocity masers has been seen in several disk maser systems (e.g., NGC 4258 by Humphreys et al. 2008, 2013; UGC 3789 and NGC 2960 by Kuo et al. 2011), but only discussed in detail for NGC 4258. We note that the spacing of clumps appears to be similar between the red and blue sides of the disk only in the case of NGC 4258. Also of note is that the features in NGC 4258 appear clumped in radial arcs as shown in Humphreys et al. (2013), while for NGC 5765b, they appear clumped in both radius and azimuthal angles, as shown in Figure 10.

Several models have been proposed to explain the generation of such clumpiness, including a spiral density wave model (Maoz 1995) and a spiral shock model (Maoz & McKee 1998).

The spiral shock model proposed that masers are generated in spiral shock regions and this could explain the asymmetry of the intensity between the redshifted and blueshifted features, as first seen in NGC 4258. This model also predicts that the redshifted features will have negative accelerations, while the blueshifted features have positive accelerations. In the case of NGC 5765b, the weighted average accelerations of the high-velocity features are (redshifted) $0.008 \pm 0.155$ km s$^{-1}$ yr$^{-1}$ and (blueshifted) $-0.049 \pm 0.275$ km s$^{-1}$ yr$^{-1}$. These results are consistent with zero acceleration, though with large measurement uncertainties. One particular blueshifted feature at 7582.95 km s$^{-1}$ has an acceleration of $-0.528 \pm 0.110$ km s$^{-1}$ yr$^{-1}$, which is inconsistent with predictions from the spiral shock model. So even though the redshifted features are brighter than the blueshifted features in NGC 5765b, our acceleration results do not support the spiral shock model. In a parallel MCP paper, Pesce et al. (2015) systematically examine the predictions from this model using all the disk maser spectra obtained from the MCP, and they do not find clear evidence supporting this model.

The spiral density wave model proposed that spiral structures are generated from nonaxisymmetric perturbations on the accretion disk and maser clumps are located at the intersection of the spiral arms and the disk midline. So the high-velocity masers would be distributed within a few degrees from the midline and would have very small LOS accelerations that can be slightly positive or negative. This model works well for NGC 4258, where the maser clumps for both the redshifted and blueshifted features are periodic in disk radius with the same characteristic scale of $\sim 0.75$ mas (e.g., Humphreys et al. 2008). In the case of NGC 5765b, even though the redshifted features are clustered into several clumps with a spacing of $\sim 0.3$ mas, the blueshifted features do not show the same spacing (as shown in Figure 2). So more precise measurements are needed to test the spiral density wave model in NGC 5765b.

5.4. Amplitude Versus Position for the High-velocity Masers

Bragg et al. (2000) compared the maser flux with maser position in NGC 4258, where no dependence between line amplitude and radius was found. Instead, they found that the maser amplitude peaks around the midline. This was interpreted as that masers originate in aligned clumps of material that amplify each other, so the observed amplitude is largely independent of radius.

To test these results for NGC 5765b, we plot the maser amplitude versus disk radius and versus deviation from the midline for the high-velocity masers in NGC 5765b in Figure 11. The flux comes from the VLBI map, which represents the mean maser intensity over our VLBI observations. The radius comes from the Bayesian fitting result for each maser spot.

It is interesting that for the redshifted lines, the peak intensities of maser lines are proportional to their radius, and masers peak away from the midline. We use a power-law function to fit the outline of the peak intensities versus radius for the redshifted features and the best fit yields a power index of $0.70 \pm 0.050$ (1$\sigma$), as shown by the solid line on the plot.

To see whether our fitted results are specific to the VLBI data only, we also use the GBT monitoring data for a consistency check: we measure the peak intensity closest (within 1 km s$^{-1}$) to the velocities where the VLBI intensity peaks, namely 8753.8 km s$^{-1}$, 8856.0 km s$^{-1}$, 8968.5 km s$^{-1}$, 9077.5 km s$^{-1}$, 9079.0 km s$^{-1}$, and 9081.3 km s$^{-1}$, and use these data to re-fit the power index for each epoch of the
monitoring observations. The mean power-law index is 0.75 ± 0.014 (1σ). So the power index we measured from the VLBI data is consistent with this result to within 3σ.

Intuitively, this positive flux-radius dependency seems natural. The LOS velocity of the high-flux masers goes as \( V_{\text{rot}} \cdot \cos(\phi) \), where \( V_{\text{rot}} \) is the Keplerian rotation speed and \( \phi \) is the angular deviation from the midline. To maintain a velocity coherence of ~1 km s\(^{-1}\) required for maser amplification, maser spots with higher rotation velocities (thus closer to the dynamic center) would have shorter gain length. This would result in masers at higher rotation velocity having lower intensity by assuming the maser intensities are proportional to the gain length. If we assume the maser is saturated, a detailed calculation (see Appendix B) shows that the flux goes with radius as \( f \propto r^{1.5} \) with the maser flux being linearly proportional to the gain length. For comparison, we plot the fitted curve with the power index fixed to 0.5 (dotted line) and 1.5 (dashed line) in Figure 11(a).

Since the fitted power index is inconsistent with the calculation above, a better explanation is needed. The maser flux may not scale with the gain length linearily, as the maser might be partially saturated. Also, we did not include the disk warping in our calculation, which would re-shape the regions where maser flux peaks. The disk warping may also cause the line peaks to deviate from the midline. Another factor that should be taken into account is the different gas and dust temperatures at different radii, which would have a significant effect on the maser pumping efficiency (e.g., Yates et al. 1997).

Pesce et al. (2015) compiled a list of 32 clean\(^{12}\) megamaser disk systems discovered so far and present their time-averaged single-dish spectra. Six of these maser systems show a similar dependency of maser flux on radius as we have seen in the redshifted part of NGC 5765b here. They are J0437+2456 (blueshifted), UGC 3789 (blueshifted), ESO269-G012 (blue-shifted), UGC 9639 (blueshifted), NGC 6264 (redshifted), and CGCG498-038 (redshifted).

### 5.5. Beaming Angle of the Systemic Masers

The slope of the systemic features on the P–V diagram is related to the physical radius of those spots to the dynamic center (\( \sqrt{GM/r^2} \)). From the P–V diagram, we fit a slope of 435.7 km s\(^{-1}\) mas\(^{-1}\). Combined with the black hole mass of \( 4.4 \times 10^7 M_\odot \) and nominal distance of 119 Mpc, this result corresponds to 0.68 pc. The Keplerian rotation velocity at this radius is about 530 km s\(^{-1}\).

The systemic masers span 90 km s\(^{-1}\) in NGC 5765b (from 8240 to 8330 km s\(^{-1}\)). For simplicity, if we assume all the systemic features are located at the same radius, this would give a beaming angle of 9°8 on the azimuth direction for the systemic masers. However, since not all the systemic masers lie on the same radius, as shown by our Bayesian fitting result, here instead we use the velocity range of 8260–8290 km s\(^{-1}\), in which masers are located at a similar radius of about 1 mas on the disk, to estimate the lower limit of the beaming angle. This gives an azimuthal beaming angle of 3°3.

For comparison, among the other published megamaser disk systems, only two have azimuthal beaming angles estimated. NGC 4258 has a beaming angle of 7°, measured both by the slope of the systemic features (Miyoshi et al. 1995) and by monitoring the drift of systemic features with time (Moran 2008). For UGC 3789, based on the slope of the systemic features on the P–V diagram by Braatz et al. (2010), we estimate the beaming angle to be 4°4 and 2°5, respectively, for the two maser rings, as described in Braatz et al. (2010).\(^{12}\)

\(^{12}\) Here “clean” disk means that maser emission generated from the Keplerian disk dominates over that generated from jets or outflows, and the disk itself displays Keplerian rotation.

---

**Table 8**

| Systematic uncertainties | Value in Base Model | \( H_0 \) (km s\(^{-1}\) Mpc\(^{-1}\)) | Difference from base model | \( H_0 \) (km s\(^{-1}\) Mpc\(^{-1}\)) | (%) |
|--------------------------|---------------------|--------------------------------------|---------------------------|--------------------------------------|-----|
| Different systemic feature acceleration error floor | ... | 68.0 | 2.0 | 66.0 | 3.00 |
| Different hv-feature acceleration error floor | 0.2 km s\(^{-1}\) yr\(^{-1}\) | 66.5 | 0.5 | 66.0 | 0.75 |
| Different method for measurement of systemic accelerations | ... | 68.5 | 2.5 | 66.0 | 3.8 |
| Unmodeled spiral structure | ... | ... | 0.66 | ... | 1.0 |
| Systematic uncertainties added in quadrature | | | 3.31 | ... | 5.0 |
| Uncertainty in the \( H_0 \) based on NGC 5765b maser distance | | | 6.0 | ... | 9.1 |

**Note.** The final uncertainty is calculated by adding individual sources of uncertainty in quadrature.

**Table 9**

| Name         | Redshifted | Systemic | Blueshifted |
|--------------|------------|----------|-------------|
| Number of data points | 151        | 187      | 32          |
| NGC 4258     | 71         | 71       | 70          |
| NGC 5765b    | 354        | 90 (70)  | 253         |

**Note.** Comparison of the input data for the Bayesian fitting between NGC 4258 and NGC 5765b. For the velocity range of systemic masers, the number listed in the brackets are velocity ranges with valid accelerations measured.
5.6. The Profile and Variability of Systemic Masers in NGC 5765b Compared to NGC 4258

The profile of the systemic masers in NGC 5765b is smooth compared to the “spiky” high-velocity masers. This contrast is more obvious than the case of NGC 4258. One might consider whether the blended/“spiky” difference arises because the systemic features are amplifying the background radio continuum emission. Also, since the systemic features all have similar LOS velocity, their velocities overlap and the total spectral profile is likely the sum of weak maser emission coming from numerous gas clouds in the accretion disk. The high-velocity masers, meanwhile, are self-amplified, and the spikiness may reflect a sparse availability of seed photons and different gain paths.

Another feature of the systemic maser spectrum is that there is little change of the overall profile across the observed 2.5 years as shown in Figure 4, unlike the case of NGC 4258, which has shown clear structural changes on a timescale of a few months (e.g., Argon et al. 2007). The “notches” and “dents” formed between strong features in the systemic part in NGC 5765b (especially between 8260 and 8290 km s$^{-1}$) co-drift with the maser peaks. This means the masing gas clouds are distributed closely with each other spatially, and they lie on a similar radius, which will have similar accelerations. This is consistent with the Bayesian fitting results, in which masers in the velocity range of 8260 and 8290 km s$^{-1}$ are all located at radii between 0.895 and 1.126 mas on the disk.

The black hole masses for NGC 4258 ($4.0 \times 10^7 M_\odot$ from Humphreys et al. 2013) and NGC 5765b ($4.55 \times 10^7 M_\odot$ from this work) are similar. The systemic maser spots in NGC 4258 are distributed around 0.14 pc in radius on the disk, while for NGC 5765b, systemic masers cover a larger range of radii, from 0.39 to 0.64 pc. As mentioned by Wallin et al. (1999), the change of the velocity field on the LOS direction may be the main reason for the spectral variability, so maser spots at larger radii would have a smaller change in the LOS velocity field in a certain amount of time according to the Keplerian rotation, thus showing less spectral variation. Qualitatively, the variabilities seen in NGC 4258 and NGC 5765b are consistent with this explanation.

Other explanations for maser variability include the change of the local physical conditions for pumping the masers and variability of the background continuum source, which is particularly important if the masers are unsaturated. The persistence of the systemic masers in NGC 5765b might therefore be a result of a less variable background source, or an indication that the maser is saturated.

Figure 11. Modeled radius and angle vs. peak intensity for the high-velocity masers in NGC 5765b. The upper left plot shows the radius vs. peak intensity for the redshifted features, and the solid line shows the best fit to the outline of the maser line peaks, with flux $\propto \rho^{0.7}$. For comparison, the dotted line has flux $\propto \rho^{0.5}$, while the dashed line has flux $\propto \rho^{1.5}$. The upper right panel shows the angle off the midline vs. maser peak intensity for the redshifted features. The maser peaks appear away from the midline. Plots for the blueshifted features are on the bottom panel. The blueshifted features show no such dependencies as seen in the redshifted features.
If the change of the LOS velocity field is the main reason for maser variability, future observations might be able to detect a correlation between maser variability and acceleration for the systemic features in all disk maser systems, since the acceleration depends on the radius.

5.7. Searching for the Background Radio Continuum Emission

As mentioned above, systemic masers in NGC 5765b may amplify the background radio continuum emission. We searched for radio continuum emission from the line-free channels in our VLBI data set, but did not detect continuum emission at an upper limit of 0.1 mJy at 22 GHz. However, our recent VLA observation of NGC 5765b reveals a continuum flux of 5 mJy at 22 GHz. Also, a point source is detected with an integrated flux of 13.45 mJy at 1.4 GHz from the FIRST survey. So either the 22 GHz radio continuum emission associated with NGC 5765b is compact and variable, falling below our detection limit during the VLBI observations, or the emission has been resolved by the VLBI observations.

6. CONCLUSIONS

We present here the geometric distance measurement to the megamasers in NGC 5765b, as part of the MCP. Owing to the relatively strong maser emission (>200 mJy), new VLBI capabilities, and slow but discrete accelerations of the systemic masers, we are able to measure the distance with very high precision, from which we determine 

\[ H_0 = 66.0 \pm 6.0 \text{ km s}^{-1} \text{ Mpc}^{-1} \]

and an enclosed mass of \(4.55 \pm 0.40 \times 10^7 \text{ M}_\odot\). The case of NGC 5765b demonstrates essential requirements for good distance measurements (<10% uncertainty), which can serve as guidelines for future distance measurement work.

We also investigate some of the physical properties of the maser disk in NGC 5765b: the redshifted and blueshifted features are spatially clustered into several clumps with different characteristic scales on the red and blue sides. Combined with the acceleration measurements, these results favor the spiral density wave model, while the spiral shock model is not supported. We find that the peak maser amplitude depends on radius in the redshifted features. NGC 5765b shows little variation of the systemic maser profile over the two years of observation. This is quite different compared to the case of NGC 4258. If variability is dominated by the change of the LOS velocity field due to Keplerian rotation, we expect to see a positive correlation between systemic maser variability and acceleration. This hypothesis could be tested within current disk maser systems.

We thank the anonymous referee for valuable comments on the paper. F.G. gratefully acknowledges support provided by the National Radio Astronomy Observatory (NRAO) through the Grote Reber Doctoral Fellowship, and support in part by the Major Program of National Natural Science Foundation of China (grants 11590780 and 11590784) and the Strategic Priority Research Program “The Emergence of Cosmological Structures” of the Chinese Academy of Sciences, grant No. XDB09000000. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. This research has made use of the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

Facilities: GBT, VLA, VLBA, Effelsberg.

APPENDIX A

REQUIREMENT ON ABSOLUTE SOURCE POSITION ACCURACY IN MCP VLBI OBSERVATIONS

For a given baseline \(B\), the interferometric phase of a target source at direction \(S\) and observing frequency \(\nu_0\) is given by \(\phi_0 = \frac{2\pi\nu_0 B S}{c}\). During data cross-correlation, the estimated source position is taken into account to remove the source geometric phase. After this step, the phase becomes \(\phi = \frac{2\pi\nu B S}{c}\), where \(S_0\) is the true source position, and \(S_e\) is the estimated source position used in data cross-correlation. For VLBI observations of masers, the phase of a target maser spot at frequency \(\nu = \nu_0 + \Delta\nu\) is:

\[
\phi = 2\pi B \left( S_0 - S_e + S \right) \frac{c}{\nu} = 2\pi \left( \nu_0 + \Delta\nu \right) \frac{B \left( S_0 - S_e + S \right)}{\nu} = 2\pi \frac{B \cdot S}{c} \left( \frac{S_0 - S_e + S}{S_0 - S_e} \right)
\]

where \(S\) is the projected position difference between the maser spot at frequency \(\nu\) and the reference position \(S_0\).

Subtracting the phase corresponding to the reference position from the phase of a given maser spot, we got the relative phase difference \(\Delta\phi\), which is what we actually measured. \(\Delta\phi\) is given by:

\[
\Delta\phi = \phi - \phi_0 = 2\pi \frac{B \cdot (S_0 - S_e + S)}{c} - 2\pi \nu_0 \frac{B \cdot S}{c} = 2\pi \frac{B}{c} \left( \nu_0 + \Delta\nu \right) (S_0 - S_e + S) - \nu_0 (S_0 - S_e)
\]

The second term in the bracket contains the additional phase caused by absolute source position uncertainty \(\Delta\nu \left( S_0 - S_e \right)\). To neglect this term’s effect would require \(\frac{\Delta\nu}{\nu_0 (S_0 - S_e)} \gg 1\).

For NGC 5765b, the frequency for the reference feature is \(\nu_0 = 21636\ \text{ MHz}\), and all high-velocity features are within 64 MHz of the reference feature. Based on our initial VLBI map, the position difference of the high-velocity features and the reference feature in the systemic part is greater than 0.3 mas. Putting these numbers in the equation above, if we require the additional phase to be less than one-tenth of the original phase, we have \(\left( S_0 - S_e + S \right) \sim (S_0 - S_e) \approx 10\ \text{ mas}\), so the absolute source position uncertainty should be within 10 mas. For other maser targets, the required position accuracy depends on the maser frequency coverage and the size of the maser disk. For targets in the MCP, 10 mas is usually sufficient.

APPENDIX B

DERIVATION OF THE RELATION BETWEEN MASER INTENSITY AND RADIUS ON THE DISK

Suppose maser clouds are located on the disk with position \((r, \phi)\), in which \(\phi\) is measured relative to the LOS direction, and on the midline redshifted masers have \(\phi = +90\), while blueshifted masers have \(\phi = -90\). For an arbitrary maser cloud, the LOS velocity is given by \(V_1 = V_r \cdot \cos(90 - \phi_1)\),
where \( V_r \) is the Keplerian rotation velocity defined by \( V_r = \sqrt{GM/r} \). For another maser cloud located at \((r, \phi_2 = \phi_1 + \Delta \phi)\), the LOS velocity is given by \( V_2 = V_r \cdot \cos(90 - \phi_1 - \Delta \phi) \). Maintaining the velocity coherence required for maser amplification would require \( \Delta V = V_2 - V_1 \leq 1 \text{ km s}^{-1} \). If \( \Delta \phi \) is infinitesimal, \( \Delta V \) can be written as \( \Delta V = \sqrt{GM/r} \cdot \cos(\phi_1) \cdot \Delta \phi \leq 1 \text{ km s}^{-1} \).

For the same maser clouds, we define the gain length as the position difference projected on the LOS direction \( \Delta L = r \cdot (\cos \phi_2 - \cos \phi_1) = r \cdot \sin(\phi_1) \cdot \Delta \phi \). If we assume maser emission could be generated and amplified through the two maser clouds along the LOS direction and the maser intensity is proportional to the gain length by multiplying a constant, \( g \), then the maser flux is \( F = g \cdot \Delta L = g \cdot r \cdot \sin(\phi_1) \cdot \Delta \phi \). Replacing \( \Delta \phi \) from above, finally we have \( F = g \cdot r \cdot \sin(\phi_1) \cdot \Delta \phi = g \cdot \tan(\phi_1) \cdot r^{1.5} / \sqrt{GM} \).

REFERENCES

Argon, A. L., Greenhill, L. J., Reid, M. J., Moran, J. M., & Humphreys, E. M. L. 2007, ApJ, 659, 1040
Bragg, A. E., Greenhill, L. J., Moran, J. M., & Henkel, C. 2000, ApJ, 535, 73

Braatz, J. A., Reid, M. J., Humphreys, E. M. L., et al. 2010, ApJ, 718, 657
Freedman, W. L., & Madore, B. F. 2010, ARA&A, 48, 673
Freedman, W. L., Madore, B. F., Scowcroft, V., et al. 2012, ApJ, 758, 24
Herrnstein, J. R., Moran, J. M., Greenhill, L. J., et al. 1999, Natur, 400, 539

Hinshaw, G., Larson, D., Komatsu, E., et al. 2013, ApJS, 208, 19
Hu, W. 2005, in ASP Conf. Ser. 339, Observing Dark Energy, ed. S. C. Wolff, & T. R. Lauer (San Francisco, CA: ASP), 215
Humphreys, E. M. L., Reid, M. J., Greenhill, L. J., Moran, J. M., & Argon, A. L. 2008, ApJ, 672, 808
Humphreys, E. M. L., Reid, M. J., Moran, J. M., Greenhill, L. J., & Argon, A. L. 2013, ApJ, 775, 13
Kuo, C. Y., Braatz, J. A., Condon, J. J., et al. 2011, ApJ, 727, 20
Kuo, C. Y., Braatz, J. A., Lo, K. Y., et al. 2015, ApJ, 800, 26
Kuo, C. Y., Braatz, J. A., Reid, M. J., et al. 2013, ApJ, 767, 155
Maoz, E. 1995, ApJ, 455, L131
Maoz, E., & McKee, C. F. 1998, ApJ, 494, 218

Miyoshi, M., Moran, J. M., Herrnstein, J. R., et al. 1995, Natur, 373, 127
Moran, J. M. 2008, ASPC, 395, 87
Pesce, D. W., Braatz, J. A., Condon, J. J., et al. 2015, ApJ, 810, 65
Planck Collaboration Ade, P. A. R., Aghanim, N., et al. 2015, arXiv:1502.01589
Reid, M. J., Braatz, J. A., Condon, J. J., et al. 2009, ApJ, 695, 287
Reid, M. J., Braatz, J. A., Condon, J. J., et al. 2013, ApJ, 767, 154
Riess, A. G., Macri, L., Casertano, S., et al. 2011, ApJ, 730, 119
Suyu, S. H., Auger, M. W., Hilbert, S., et al. 2013, ApJ, 766, 70
Wallin, B. K., Watson, W. D., & Wyld, H. D. 1999, ApJ, 517, 682
Yates, J. A., Field, D., & Gray, M. D. 1997, MNRAS, 285, 303