New Classical Cepheids in the Inner Part of the Northern Galactic Disk, and Their Kinematics

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Abstract

The characteristics of the inner Galaxy remain obscured by significant dust extinction, hence infrared surveys are useful for finding young Cepheids whose distances and ages can be accurately determined. A near-infrared photometric and spectroscopic survey was carried out and three classical Cepheids were unveiled in the inner disk, around 20° and 30° in Galactic longitude. The targets feature small Galactocentric distances, 3–5 kpc, and their velocities are important, as they may be under the environmental influence of the Galactic bar. While one of the Cepheids has a radial velocity consistent with the Galactic rotation, the other two are moving significantly slower. We also compare their kinematics with that of high-mass star-forming regions with measured parallactic distances.

Key words: Galaxy: disk – Galaxy: kinematics and dynamics – stars: variables: Cepheids

Supporting material: machine-readable table

1. Introduction

The inner part of the Galaxy is a crossroad of various stellar populations, and different components of the Galaxy, like the bulge and the disk, are mixed. Within ~250 pc around the supermassive black hole, Sgr A*, stars with a wide range of age and interstellar gas form a disk known as the nuclear stellar disk or the central molecular zone (Launhardt et al. 2002). This relatively small component of the Galaxy (∼10^8 M⊙ in mass) is surrounded by the bulge that is more massive, ∼2 × 10^10 M⊙ (Velenti et al. 2016), and more extended. Further out, the disk of stars and interstellar matter is extended, the main component of the Galaxy (∼10^12 M⊙, Bland-Hawthorn & Gerhard 2016). In the rest of the Introduction, we review the stellar populations present in the components of the inner Galaxy and describe the goal of this study, in which we use Cepheids as tracers of stellar kinematics at the innermost part of the disk.

The trouble in studies of the inner Galaxy is interstellar extinction. It is therefore natural that the earliest studies on stellar populations of the bulge were focused on stars found in the low-extinction regions represented by the Baade window and the outer parts at higher Galactic latitudes (see the review by Rich 2013). The development of infrared instruments enlarged the window for studying the bulge and other regions in the inner Galaxy thanks to the significantly reduced effect of interstellar extinction. For example, in the early 1990s, the bulge was found to be elongated, showing a bar-like structure (e.g., Nakada et al. 1991) together with the elongated distribution of interstellar gas observed in the radio regime (Binney et al. 1991).

Besides the main bar-like bulge that dominates the surface brightness distribution at |l| < 10°, some additional structures have been suggested to explain the distribution of red clump giants in the inner part, |l| < 4° (e.g., Nishiyama et al. 2005), and in the outer part, 10° < l < 30° (e.g., Hammersley et al. 1994, 2000). It is, however, unclear if there is more than one bar or if the structural parameters of the bar(s) show a smooth variation when traced by stellar populations with different ages (Wegg et al. 2015). In any case, the presence of the extended bar-like distribution of relatively young populations represented by red clump giants is an interesting feature of the inner Galaxy, and it may be related to the presence of even younger stellar clusters, from a few to ~50 Myr, that seem to be preferentially located near the end of the extended bar (Davies et al. 2009, 2012). With Galactocentric distances of 3–5 kpc, many of these clusters are located at around the interface of the bar/bulge and the disk.

As a matter of fact, the interface between the Galactic bulge and the innermost part of the disk has not been explored well compared to the bulge itself. The bulge has a steep radial profile that falls down to a density lower than the disk component at around a couple of kiloparsecs (e.g., Sofue 2013), while the Galactic disk is suggested to have a hole in the central region (Einasto 1979; Robin et al. 2003). Radio observations of H II regions and high-mass star-forming regions (HMSFRs) with maser emission seem to support such a hole by finding the drop in density of these objects toward the central region of the disk (Anderson et al. 2011, 2012; Jones et al. 2013; Sanna et al. 2014). Identifying stellar populations in such a central region of the disk, however, is challenging and entails several observational difficulties. For example, various stellar populations are overlaid along the line of sight. Distances can be determined only for limited kinds of objects. Above all, interstellar extinction makes it hard to detect objects in the optical and
complicates interpretations even if they are visible at longer wavelengths.

The goal of this study is to find Cepheids located at the interface of the bar/bulge and the disk, and to study their kinematics. Cepheids follow the famous period–luminosity relation (PLR, hereinafter), which works as a fundamental step of the cosmic distance scale (see, e.g., Freedman & Madore 2010) and the stars also adhere to a period–age relation (Bono et al. 2005). They are therefore useful as a tracer of young stellar populations (10–300 Myr) in dust-obscured regions of the Galaxy. However, surveys of distant Cepheids are incomplete because of extreme extinction toward the Galactic disk. Recent developments of near-infrared observing facilities and their systematic surveys have opened a new path to such obscured Cepheids as demonstrated by recent works (Matsunaga et al. 2011b, 2016; Feast et al. 2014; Dékány et al. 2015a, 2015b). In particular, Matsunaga et al. (2016) reported that the density of Cepheids located within ∼2.5 kpc from the Galactic center is lower than the surrounding part, except for the nuclear stellar disk, which is consistent with the aforementioned radio observations.

In this paper, we report the results of our new survey for small regions toward the inner disk, 20° and 30° in Galactic longitude, and spectroscopic follow-up observations for the discovered Cepheids. While the new Cepheids are located in a different region of the disk compared to those previously found in the series of our near-infrared searches for Cepheids (Matsunaga et al. 2011b, 2016), an important step that we take in this paper is the demonstration of a method of comparing the radial velocities of Cepheids with the Galactic rotation with relevant uncertainties, e.g., in distance, taken into account.

## 2. Photometric Observations

### 2.1. Data and Analysis

We used the IRSF telescope and the SIRIUS camera to conduct our survey. The IRSF (InfraRed Survey Facility) is a 1.4 m telescope and the SIRIUS (Simultaneous 3-color InfraRed Imager for Unbiased Survey) is a near-infrared camera that can take images in three photometric bands (JHK) simultaneously. The field of view is about 7′ × 7′, with a pixel scale of 0″45/pix. Details of the instrument can be found in Nagashima et al. (1999) and Nagayama et al. (2003).

We observed three different lines of sight within the Galactic plane (b = 0°): l = +40°, +30° and +20°. We hereby denote the three regions Lp40, Lp30, and Lp20, respectively. At around each Galactic longitude, we observed nine fields-of-view covering 20′ × 20′. Time-series observations were performed for approximately 45 times between 2007 and 2012. For each set of monitorings, we took five exposures with 8 sec integration in total.

To search for Cepheids, the methods in previous studies (Matsunaga et al. 2009, 2013) are adopted. The limiting magnitudes are 15.5, 15.1, and 14.3 mag in JHK, for the Lp20 region, and slightly deeper, by up to 0.3 mag, in the other two regions, probably due to stellar blending caused by the higher stellar density for Lp20. The saturation limits are around 8.5, 8.5, and 8.0 mag in JHK. We detected approximately 45,000, 30,000, and 25,000 stars in the regions Lp20, Lp30, and Lp40, respectively, although the numbers of stars detected in J are roughly half of those in the other two bands. Among 300 candidates of variable star identified based on their large standard deviations of time-series photometric results, we have identified roughly 50 variables whose periods are shorter than 60 days.

### 2.2. Our Targets

In this paper, we report 3 classical Cepheids, one in the Lp20 and two in the Lp30 region, for which high-resolution spectra were obtained as we describe in Section 3.

Table 1 lists their coordinates, periods, and mean magnitudes. The mean magnitudes were obtained as intensity means of maximum and minimum from fourth-order Fourier periods. The mean magnitudes in J, H, and K from IRSF/SIRIUS, and [3.6] and [4.5] magnitudes taken from the GLIMPSE catalog (see the text).

| R.A. (J2000) | Decl. (J2000) | l (°) | b (°) | P (days) | (J) (mag) | (H) (mag) | (K) (mag) | [3.6] (mag) | [4.5] (mag) |
|-------------|--------------|-------|-------|----------|----------|----------|----------|-----------|-----------|
| Lp20A       | 18:28:11.47  | 18:45:28.56 | 18:45:48.01 |
| Lp30A       | 11:37:32.4   | -02:44:40.5 | -02:27:30.1 |
| Lp30B       | 19.9541      | 29.8099   | 30.1015  |
| Lp20A       | -0.2073      | +0.0738   | +0.1325  |
| Lp30A       | 10.79        | 12.72     | 42.70    |
| Lp30B       | ...          | 11.72     | ...      |

Note. Listed for the three target Cepheids are positions (R.A. and decl. in J2000, together with the Galactic coordinate l, b), period P, mean magnitudes in J, H, and K, from IRSF/SIRIUS, and [3.6] and [4.5] magnitudes taken from the GLIMPSE catalog (see the text).

11 This research has made use of the VizieR catalog access tool, CDS, Strasbourg, France. The original description of the VizieR service was published in Ochsenbein et al. (2000).

12 The effective wavelengths of these mid-infrared bands are: 3.35 and 4.60 μm for W1 and W2 (Wright et al. 2010), and 3.55 and 4.48 μm for [3.6] and [4.5] (Hora et al. 2008).
coefficients in the respective bands. As discussed in Matsunaga et al. (2016), in the case of heavily reddened objects through the Galactic disk, the largest source of error on the obtained distances will be the uncertainty on the adopted extinction law, which provides the extinction coefficients. In order to quantify the impact of such uncertainty on the derived distances, we devised a new technique, presented in L. Inno et al. (2017, in preparation). In summary, we adopt the PLR of classical Cepheids from Matsunaga et al. (2013) for $H$ and $K_s$, while the log $P$–[3.6] relation is taken from Marengo et al. (2010):

\[ M_H = -3.256 \log P - 1.3 - 6.562 \]  
\[ M_{K_s} = -3.295 \log P - 1.3 - 6.685 \]
\[ M_{3.6} = -3.16 \log P - 1.0 - 5.74. \]

All of these relations were calibrated based on trigonometric parallaxes of Cepheids in the solar neighborhood (Benedict et al. 2007; van Leeuwen et al. 2007). Then, we use the extinction coefficients, $A_K/E_{H-K}$ or $A_K/E_{3.6}$, the observed magnitudes and the PLR in two bands, either $H$ and $K_s$, or $K_s$ and [3.6], to estimate the distance modulus $m_0$ and foreground extinction $A_K$. Note that the [4.5] magnitudes are not used because the log $P$–[4.5] relation shows a metallicity dependence related to the presence of the CO absorption at this wavelength (Hackwell & Gehrz 1974; Majaess et al. 2013; Scowcroft et al. 2016). In contrast, the metallicity effect on the PLR in the range of $H$, $K_s$, and [3.6] is minimal if any (Bono et al. 2010; Scowcroft et al. 2016). While the characterization of the infrared PLR to a very high precision is important and still in progress, e.g., in a cosmological context (Riess et al. 2016), the accuracy of our analysis is limited by the reddening correction as we see below. Finally, a comparison of the multiple estimates using both near- and mid-infrared magnitudes and using two different extinction laws allows us to evaluate such errors in a robust manner.

We consider two $A_K/E_{H-K}$ values: 1.44 from Nishiyama et al. (2006) and 1.83 from Cardelli et al. (1989). These values are at around two extremes of the extinction law for the near-infrared range among previous investigations (see, e.g., Table 1 of Nishiyama et al. 2006). For $A_K/E_{3.6}$, we adopt 2.01 from Nishiyama et al. (2009) and 1.76 predicted by the power law with the index of 1.61 (Cardelli et al. 1989). 3.6 $\mu$m is slightly outside the near-infrared regime considered by Cardelli et al. (1989, 0.9–3.3 $\mu$m), but we only use these $A_K/E_{3.6}$ values for comparing the effect of two substantially different extinction laws.

It should be noted that the results of Nishiyama et al. (2006, 2009) were obtained with giants in the Galactic bulge, while those of Cardelli et al. (1989) were based on stars in the solar neighborhood. There can be a spatial variation of the reddening law in a rather complicated manner (see, e.g., Nataf et al. 2016, and references therein). Unfortunately, the extinction law toward the regions of our interest, $l \approx 20^\circ$–$30^\circ$ at several kiloparsecs, is not well established. The anonymous referee pointed out that most of the recent results (e.g., Alonso-García et al. 2015; Majaess et al. 2016) on the extinction law in the infrared regime are different from that of Cardelli et al. (1989; see also reviews and discussions by Damineli et al. 2016; Nataf 2016). Some works, however, suggest that the extinction laws show variations depending on sightlines and/or the amount of extinction (Nishiyama et al. 2006; Fitzpatrick & Massa 2009; Gosling et al. 2009). It is hard to give a robust range of its

![Figure 1](image-url) Light curves of our classical Cepheids. The vertical dashed lines indicate the phases of the IRCS spectroscopic observations (Section 3).

### Table 2

| Object | MJD   | $J$ (mag) | $H$ (mag) | $K_s$ (mag) |
|--------|-------|-----------|-----------|-------------|
| Lp20A  | 54226.02957 | ... | 13.54     | 11.68       |
| Lp20A  | 54229.06910 | ... | 13.80     | 11.86       |
| Lp20A  | 54231.08360 | ... | 13.78     | 11.87       |
| Lp20A  | 54231.18865 | ... | 13.81     | 11.88       |
| Lp20A  | 54232.02653 | ... | 13.73     | 11.82       |

Note. These are the first five lines of 162 $JHK_s$ measurements in total for three objects, Lp20A, Lp30A, and Lp30B.

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

### 2.3. Distances and the Effect of the Extinction Law

The $H$- and $K_s$-band mean magnitudes and the [3.6] single-epoch magnitudes can be used to determine the distances to our newly discovered Cepheids by adopting PLR and extinction
uncertainty, and here we use the two extreme laws, Nishiyama et al. (2006) and Cardelli et al. (1989), to give likely maximum uncertainties.

Table 3 lists the estimates of \((\mu_0, A_K)\) obtained with different combinations of photometric bands and different extinction laws (rows 1–4). Also given are the combined values (row 5) which are simple means and standard errors of the four estimates, and we use them in the discussions in Section 4. The error budgets of these combined values are dominated by the uncertainty of the extinction law. The different \(A_K, \mu_0\), values from Nishiyama et al. (2006) and Cardelli et al. (1989) lead to significantly different \(A_K\) and \(\mu_0\) values, e.g., ~0.8 mag for Lp30B (Table 3). Typical peak-to-valley amplitudes \(\Delta[3.6]\) of 0.2 mag in the [3.6] band (Monson et al. 2012) result in errors of ±0.1 mag because we used single-epoch magnitudes of [3.6], but those errors are smaller than the uncertainty introduced by the extinction law for Lp20A and Lp30B. The effect of \(\Delta[3.6]\) is comparable to the uncertainty due to the extinction law in case of Lp30A, whose reddening is not so large. Figure 2 plots the extinction \(A_K\) against the distance \(D\) based on the estimates with the different data sets and the extinction laws (Nishiyama versus Cardelli). The large scatters of the estimates clearly illustrate the impact of the extinction law.

Table 3 and Figure 2 include estimates under the assumption that our targets are type II Cepheids. Such an assumption, however, can be rejected even if the choice of the extinction law has a large impact on the distance estimates (rows 6–7). Because of similar colors but distinctly different absolute magnitudes for classical Cepheids and type II Cepheids\(^{13}\) at a given period, assuming the two different types of Cepheids would lead to similar reddenings but totally different distances (Table 3). This allows us to determine the types of Cepheids (Matsunaga et al. 2011b; Matsunaga 2014; Matsunaga et al. 2016). Lp20A and Lp30B are much redder than intrinsic colors of Cepheids and obviously affected by very large extinctions, 2.5–3 mag in \(A_K\) or even larger. The reddening of Lp30A is moderate, slightly larger than \(A_K = 1\) mag. Their distances would be estimated to be within 4 kpc if they were type II Cepheids (Figure 2), but at these short distances such large extinctions are far from expected. The \((D, A_K)\) values obtained by assuming that these stars are classical Cepheids are closer to the three-dimensional extinction map provided by Marshall et al. (2006), who gives \(A_K = 1.8\) mag at 10 kpc toward the redder two, Lp20A and Lp30B, and 0.9 mag at 5.5 kpc toward Lp30A. With the short distances obtained with the PLR of type II Cepheids, \(D \lesssim 3\) kpc, their extinction map gives \(A_K \sim 0.5\) mag, which much smaller than the values in Table 3.

Further investigations of spectra may be useful for supporting the classification as classical Cepheids. Type II Cepheids are, for example, relatively metal-poor compared to classical Cepheids in general. While some type II Cepheids are as metal-rich as the Sun (Maas et al. 2007), classical Cepheids in the inner disk are expected to be more metal-rich (e.g., Genovali et al. 2014).

\(^{13}\) We used the PLR of type II Cepheids taken from Matsunaga et al. (2011a), as described in the supplementary information of Matsunaga et al. (2011b).

Table 3
| Object   | Lp20A        | Lp30A        | Lp30B        |
|----------|--------------|--------------|--------------|
| (1) \(H, K\), and N06 | 15.00 (2.59) | 13.81 (1.15) | 14.86 (2.89) |
| (2) \(H, K\), and C89 | 14.30 (3.29) | 13.50 (1.46) | 14.08 (3.67) |
| (3) \(K, [3.6]\), and N09 | 14.98 (2.61) | 13.50 (1.46) | 15.00 (2.76) |
| (4) \(K, [3.6]\), and C89 | 15.31 (2.29) | 13.68 (1.28) | 15.34 (2.42) |
| (5) Combined | 14.90 ± 0.25 | 13.62 ± 0.09 | 14.82 ± 0.31 |

Assumption: Classical Cepheid

| Object   | Lp20A        | Lp30A        | Lp30B        |
|----------|--------------|--------------|--------------|
| (6) \(H, K\), and N06 | 12.58 (2.63) | 11.31 (1.19) | 11.78 (2.99) |
| (7) \(H, K\), and C89 | 11.87 (3.34) | 10.98 (1.52) | 10.97 (3.80) |

Assumption: Type II Cepheid

Note. For each Cepheid there are four estimates (1–4) of distance modulus \(\mu_0\) and extinction \(A_K\), with different combinations of two photometric magnitudes, either \(H\) and \(K\), or \(K\) and [3.6], and the extinction laws, C89 (Cardelli et al. 1989), N06 (Nishiyama et al. 2006), or N09 (Nishiyama et al. 2009). The raw (5) gives the means and standard errors of the four estimates, which are used in the discussions (double signs correspond to one another for each object). The rows (6) and (7) give the estimates under the assumption of type II Cepheids, which are used for Figure 2.

Figure 2. The three panels present a comparison of the current estimates of extinction and distance for the three targets (Lp20A, top; Lp30A, middle, Lp30B, bottom), with the three-dimensional extinction map (solid curve) provided by Marshall et al. (2006). The open and filled symbols indicate estimates based on the \(H, K\), data, and those based on the \(K, [3.6]\), data, respectively. The triangles and star symbols indicate the estimates from adopting the extinction laws of Cardelli et al. (1989) and the law of Nishiyama et al. (2006, 2009), respectively. The symbols located at \(D > 4\) kpc are obtained by assuming that the objects are classical Cepheids, while the others are obtained by assuming that they are type II Cepheids. The thick gray lines mark the “combined” estimates with the assumption of classical Cepheids listed in Table 3.
The Astrophysical Journal, 842:104 (8pp), 2017 June 20

Tanioka et al.

Table 4
Log of Spectroscopic Observations and Measured Radial Velocities of the Cepheids

| Date (UTC) | Timea (UTC) | MJDb | Phase | Integrationsc | S/N | σf, (km s⁻¹) | ΔV (km s⁻¹) | Vhelio (km s⁻¹) | VLSR (km s⁻¹) |
|------------|-------------|------|-------|---------------|-----|-------------|------------|---------------|-------------|
| 2012 Jul 28 | 11:20 | 56136.47 | 0.56 | 300° × 16 | 10 | 1.1 | -3 | 7 | 22 |
| 2012 Jul 27 | 10:45 | 56135.45 | 0.64 | 120° × 8 | 100 | 0.7 | 3 | 93 | 109 |
| 2012 Jul 27 | 11:40 | 56135.48 | 0.72 | 300° × 12 | 25 | 1.3 | 15 | 32 | 49 |

Notes. The heliocentric velocities (Vhelio) and velocities relative to the LSR (VLSR) were calculated from measurements over five echelle orders with the standard error σV, and are after the correction of pulsational velocity ΔV subtracted.  
a Coordinated Universal Time at around the middle of the observation.  
b Modified Julian Date calculated from the given time.  
c Duration of each integration (t1) and the number of integrations N.

3. Spectroscopic Observations

We observed the three Cepheids with the Infrared Camera and Spectrograph (IRCS) equipped with the adaptive optics system, AO188, and attached to the Subaru 8.2 m telescope (Kobayashi et al. 2000; Hayano et al. 2010). This instrument allowed us to obtain high-resolution (λ/Δλ = 20,000) H-band spectra. The observation log is given in Table 4. The signal-to-noise ratios, S/Ns, are significantly different among the three targets, as listed in the table (also see the spectra in Figure 3).

The data reduction and radial velocity measurements were carried out following the steps described in Matsunaga et al. (2015). In short, a spectrum with N raw spectra combined after the normalization was prepared for each object (Figure 3), and cross-correlated with synthetic spectra that include both stellar absorption lines and telluric lines, to search for the velocity that best explains the shift between the stellar and telluric lines. We estimated the velocity with five echelle orders and for each target these orders gave us self-consistent values leading to a small standard error of mean, σV, listed in Table 4, even for Lp20A, whose spectrum has a rather low S/N.

It is necessary to make corrections of the pulsational effect to investigate the kinematics of the Cepheids in the disk. This was done following the same method described in Matsunaga et al. (2015) but using templates of velocity and light curve constructed for Cepheids in each period range of a target. The detail of the templates will be given in L. Inno et al. (2017, in preparation). Table 4 lists the estimated offsets ΔV in velocity to be added for the correction. Thus, corrected radial velocities were transformed into the heliocentric values Vhelio and the velocities relative to the local standard of rest, VLSR, assuming the standard solar motion (Crovister 1978; Reid et al. 2009). The errors of the VLSR are dominated by the uncertainty in the correction of the pulsational effect, and are estimated to be 10 km s⁻¹.

4. Discussion

It is known that classical Cepheids show a narrow distribution with a scale height of about ~100 pc around the Galactic plane, and our Cepheids are found within 0°.25 in Galactic latitude, also due to the limited survey area. We compare their distribution and kinematics with those of the HMSFRs with parallaxes measured by Reid et al. (2014). The latter group is also located in a similarly small range around the Galactic midplane, within 0°.5 except for a few nearby objects.

Figure 4 plots the distributions of the Cepheids and the HMSFRs in the range of l = 10°–35° projected onto the Galactic plane. We draw, as a guide, the spiral arms and Galactic bars that are also adopted from Reid et al. (2014), except for the Outer arm, which is not relevant to this work. Lp30A is clearly located along the Scutum arm; its distance error is relatively small, at least comparable to the parallax-based distances to nearby HMSFRs, and has little effect on the proximity of Lp30A in the tangential direction of the Scutum arm. Although the other two Cepheids seem to be located near the inner part of the Scutum arm, the larger errors of their distances make it hard to draw a firm conclusion on their locations. Spiral arms in the Galactic disk have not been established at around 10 kpc from the Sun and beyond, even with gas and star-forming components like H II regions.

Figure 5 plots VLSR against distance from the Sun for the Cepheids and the HMSFRs grouped into three ranges of Galactic longitude. Assumimg the circular rotation of the disk, we expect

\[ V_{\text{LSR}} = \left( \frac{\Theta}{R} - \frac{\Theta_0}{R_0} \right) R_0 \sin I, \]

where Θ and R are the circular orbital speed and the distance from the Galactic center (Θ0 and R0 for the solar position), and the distance from the Sun, D, can be translated to the Galactocentric distance as

\[ R = \sqrt{D^2 + R_0^2 - 2DR_0 \cos I}. \]

The solid curve in Figure 5 shows the calculated VLSR in each direction where the solar values are adopted from Reid et al. (2014): Θ0 = 240(±8) km s⁻¹ and R0 = 8.34(±0.16) kpc. It has been suggested that the Galactic rotation is slower in the innermost part of the disk (see, for example, Figure 4 in Reid et al. 2014). The dashed curve in Figure 5 indicates how the expected VLSR changes if Θ gets smaller by 15%, i.e., 36 km s⁻¹, within 5 kpc of the Galactic center.

Some objects show offsets from the predicted curve of VLSR in Figure 5. A method of Monte-Carlo simulation is used to judge whether VLSR is different from the prediction of the Galactic rotation and to estimate how large the drift from the rotation curve is, in a statistical manner, as follows. We consider the distance and VLSR as well as their errors for each object, and generate the trial values, d and ν, with simulated Gaussian errors added in each run. Then, a VLSR at the distance d is predicted based on the Galactic rotation model but with simulated values of R0 and (Θ0 + ν)/R0 taking their errors into account. The solar motion in the direction of the Galactic rotation, V⊙, is fixed as the standard value of 15.4 km s⁻¹, which is used for the translation from Vhelio to VLSR in this work. The (Θ0 + ν)/R0 parameter, 30.75 ± 0.43 km s⁻¹ kpc⁻¹ (Reid et al. 2014), is used as an independent variable instead of Θ0 itself because the measurements of R0 and Θ0 may be correlated (Reid et al. 2009, 2014). Thus, simulated VLSR value, V', at the distance of d is compared with ν, and the difference V'–ν is taken as a simulated value of the drift. The drift has a positive value if the object is moving away from us at a speed
slower than expected with the Galactic rotation. We repeat such a run $10^6$ times and check how the simulated $(d, v^\prime - v)$ are distributed. Figure 6 plots such distributions for the three Cepheids as contours. Table 5 lists the median values of the simulated drifts, $v - v^\prime$ and the ranges of $\pm 1\sigma$. We also calculated how much a deviation from the zero drift is significant by counting the simulation runs that gave zero or negative (or instead positive) drift if the object has a positive (negative) median drift. For example, less than $\sim 0.1\%$ of the $10^6$ runs returned a drift of zero or smaller for Lp20A for which the median drift was estimated as 117 km s$^{-1}$, which rules out the null hypothesis that this object is moving as expected by the Galactic rotation (or even faster) by the $3.1\sigma$ significance. Lp30B also has a significant positive drift. In contrast, Lp30A has a negligible drift and follows the Galactic rotation. Together with the comparisons to the Galactic rotation, the Monte-Carlo simulations provide us with estimates of the Galactocentric distances of Cepheids taking various errors into account; we obtained $R_{GC} = 3.3^{+0.7}_{-0.4}$ kpc, $4.6 \pm 0.16$ kpc and

Figure 3. Part of the Subaru/IRCS spectra in the $H$-band for our Cepheids, (a) Lp20A, (b) Lp30A, and (c) Lp30B. The gray horizontal strip for each spectrum indicates the continuum, with the width of $\pm 1\sigma$ according to the S/N in Table 4. The vertical dotted lines indicate telluric lines. With an eye check on raw data, we found that the seeming emission line at around 16730 Å for Lp30A and other less prominent positive features are not real.

Figure 4. The distributions of our three Cepheids are indicated by the red star symbols. The locations of high-mass star-forming regions, between 10° and 35° in $l$, with trigonometric parallaxes measured, are taken from Reid et al. (2014) and indicated by circles with different colors according to the spiral arms or other components to which the objects are assigned: inner Galaxy sources, green; Scutum arm, cyan; Sagittarius arm, blue; others, black. The short and long Galactic bars are also adopted from Reid et al. (2014) and indicated by gray ellipses. Circles are drawn to mark the Galactocentric distances of 4, 8, and 12 kpc.

Figure 5. $V_{LSR}$ of the Cepheids and those of high-mass star-forming regions from Reid et al. (2014) are plotted against distance. The filled curve indicates the velocity predicted by the flat rotation with $\Theta_0 = 240$ km s$^{-1}$, while the dashed curve adopts the velocity that is 15% smaller within 5 kpc of the Galactic center. The symbols are the same as those in Figure 4, but encircled are objects whose $V_{LSR}$ are significantly different from the filled curve (see the text, Table 5, and Figure 6).
4.6$^{+0.8}_{-0.3}$ kpc for Lp20A, Lp30A, and Lp30B, respectively. Our three classical Cepheids are among those nearest to the Galactic center (Dékány et al. 2015b; Matsunaga et al. 2016), except the ones found in the nuclear stellar disk (Matsunaga et al. 2011b, 2015).

We performed the same kind of Monte-Carlo simulations for HMSFRs from Reid et al. (2014) within the range of $10^5$–$35^5$ (Table 5). As pointed out by Reid et al. (2014), some HMSFRs show significant drifts, or peculiar motions, from the Galactic rotation. While the position and kinematics of Lp30A are perfectly consistent with those of surrounding HMSFRs in the Scutum arm, we found large drifts for the other two Cepheids. For Lp20A, there are no comparable young tracers, due to the absence of HMSFRs with maser parallaxes measured in its direction. At its Galactocentric distance, $\sim$3.5 kpc, the Galactic rotation may be deviating from the flat rotation. There are two HMSFRs that are located even nearer to the Galactic center: G010.47$+$0.02 is assigned to the Connecting arm and G012.02$-$0.03 is assigned to the Far 3 kpc arm (Sanna et al. 2014). These arms are considered to be related to the Galactic bar(s), in particular the long thin bar, and their extensions in Galactic longitude are between $-12^5$ and $+13^5$ (Dame & Thaddeus 2008; Sanna et al. 2014). Lp20A is located away from these inner structures. Lp30B has an even larger Galactocentric distance, $\sim$5 kpc; a few SFRs relatively close to it seem to show a $v_{LSR}$ more-or-less consistent with the Galactic rotation but the measurements of their parallaxes leave larger uncertainties than that for Lp30B. The two Cepheids with large drifts are located at around the interface between the disk and the bulge where the non-axisymmetric gravitational perturbations may have strong effects on gas and stellar orbits. The very limited statistics of Cepheids in such an inner region of the Galaxy and the lack of their proper motions prevent us from drawing conclusions on the general features of stellar kinematics. Tracers like Cepheids in such regions, nevertheless, would give important constraints on the stellar kinematics in the inner Galaxy, and the drift considered in this work would be a useful indicator for such studies.

5. Summary

The three classical Cepheids we have reported here are located at $3$–$5$ kpc from the Galactic center. Although the uncertainty in the extinction law leaves large errors in distance (up to 15%), we found that the radial velocities of two of the Cepheids are significantly different from those expected from the Galactic rotation, possibly being influenced by the
Galactic bar, based on a method utilizing Monte-Carlo simulations. Only a small number of Cepheids have been identified so far in such an inner part of the Galactic disk (Dékány et al. 2015b; Matsunaga et al. 2016), and thus the new objects are interesting for follow-up investigations. For example, their abundances will provide further insight into chemical evolution in the inner Galaxy. In the future, significantly more Cepheids are expected to be found in near-infrared variability surveys like VISTA Variables via Lactea (Minniti et al. 2010; Dékány et al. 2015a, 2015b). The uncertainty in the extinction law, however, introduces large errors in distances to the Cepheids deeply obscured in the Galactic disk. It is necessary to determine the extinction law in each direction of the disk in order to construct an accurate map of Cepheids and other objects in such obscured regions.

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