Observing Cepheids as tracers of the inner part of the Milky Way

Noriyuki Matsunaga
(The University of Tokyo)
Outline

Introduction

Cepheids as tracers of the Milky Way

Case study 1

Cepheids around the Galactic Center

Case study 2

Lack of Cepheids in the inner disk (R<3kpc)

Concluding remarks
What Cepheids can tell us.

Introduction
Tracers, for what?

- Where are they?
  - Structure of the MW
- How old are they?
  - Time and position-dependent star formation history
- How do they move?
  - Kinematics of the MW
  - The gravitational potential and dynamical evolution
- Chemical abundances?
  - Chemical evolution of the MW

Image Credit: R. Hurt (SSC), Discussed in Churchwell et al. (2009, PASP, 121, 213)

Check a review by Bland-Hawthorn & Gerhard (2016, ARA&A, 54, 529)
Variable stars as tracers

- Bright variable stars with P-L relations
  - Cepheids
  - Miras
  - RR Lyrae

- Distance indicators
- Age indicators
- Kinematic tracers
- Chemical tracers

Distribution of variable stars across the H-R diagram (Gautschy & Saio, 1995, ARA&A, 33, 75)
Classical Cepheids as tracers

• P-L relation → distance

• Ages, kinematics and chemical abundances can be accurately determined, thus working as good tracers.

Near-IR P-L relations of LMC variables (Matsunaga, 2013, IAUS 289, 109)

Division between Cepheids

10 Myr  100 Myr  1 Gyr  10 Gyr

Classical Cepheids
10-300 Myr massive stars

Type II Cepheids
~10 Gyr low-mass stars

Anomalous Cepheids
1-6 Gyr single stars, some from binary star channel (Fiorentino et al. 2012)
Application as chemical tracers

- Clear and tight metallicity gradient traced by >400 Cepheids and almost no variation in [α/Fe] (Genovali et al. 2015), but significant slopes for neutron-capture elements (da Silva et al. 2016).


MW Cepheids from optical surveys

- Distant Cepheids in the Galactic disc are obscured.
- Many remain to be discovered (by IR surveys).

The distribution of ~500 Cepheids from DDO database: overlaid on the illustration by R. Hurt (SSC)
Cepheids waiting to be found

  - A simple exponential-disc model: $f(R, z) = \exp\left(\frac{R}{3.5\text{kpc}}\right) \text{sech}\left(\frac{z}{z_0}\right)$
  - 20,000 Cepheids are predicted.
  - 9,000 Cepheids may be detected by Gaia.

Simulation of Cepheids to be detected by Gaia (Windmark et al. 2011, A&A, 530, A76)
Near-IR filters: JHKₜ

<table>
<thead>
<tr>
<th>Band</th>
<th>$\lambda_{\text{eff}}$ [μm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>J</td>
<td>1.25</td>
</tr>
<tr>
<td>H</td>
<td>1.64</td>
</tr>
<tr>
<td>Kₛ</td>
<td>2.14</td>
</tr>
</tbody>
</table>
Extinction Law

- Wavelength dependency of the extinction
  - Power law: $A_\lambda \propto \lambda^{-\alpha}$ (e.g. Nishiyama+06, $\alpha \sim 2$)
  - Cardelli’s law: $A_\lambda = a_\lambda + b_\lambda/R_\lambda$ (Cardelli+89)
Extinction in $V$ and Gaia $G$

- $A_V/A_Ks$
  - Power law: $\sim 14$ (consistent with $\sim 16$ by Nishiyama+09)
  - Cardelli law: $\sim 8$
Extinction in \( V \) and Gaia\( G \)

- \( A_V/A_{Ks} \)
  - Power law: \(~14\) (consistent with \(~16\) by Nishiyama+09)
  - Cardelli law: \(~8\)

- \( A_G/A_{Ks} \)
  - Power law: \(~8\)
  - Cardelli law: \(~6\)
  (dependent on \( A \))
  - \( G \)-band is more tolerant to extinction.
  - Bulge stars are too much obscured: \( A_{Ks} = 1.5 \sim 4 \) mag,
    \( A_G = 10 \sim 30 \) mag.
Advantages of IR data

1. Less affected by interstellar extinction.
2. Pulsating stars show more simple natures in IR. For example, PLR of classical Cepheids in the IR are:
   • Tight and less affected by metallicity.
   • Advantageous for high-precision cosmology (Riess+2016).
3. Some objects (like Miras) have circumstellar dust.


V-band (0.55 μm)
K-band (2.2 μm)
Cepheids/Miras useful in the Gaia era

• A large part of the disk cannot be seen by Gaia due to interstellar extinction.

• Cepheids and Miras are bright (especially in the infrared) and can be detected across the disk.

Gaia’s first sky map (2016 Sep, DR1)

The inner part is especially obscured, but there is massive and complex groups of stars and gas.
The inner Galaxy

- Major-axis ~ 3 kpc
- Mass ~ $2 \times 10^{10} M_\odot$
- The dominant population is old, ~10 Gyr.

(Extended) Bulge (w. bar structure)

- Major-axis ~ 3 kpc
- Mass ~ $2 \times 10^{10} M_\odot$
- The dominant population is old, ~10 Gyr.

Nuclear Bulge (Nuclear Disk+Nuclear Clusters)

- Diameter ~ 200 pc
- Mass ~ $1.4 \times 10^9 M_\odot$
- Young stars and current star formation are observed.
The Nuclear Stellar Disk

- Revealed by infrared observations in 1990s.
- A disk-like system where stars coexist with gas/dust (Central Molecular Zone)
- Relatively young stars are found to be rotating within the Disk.
  - Arches, Quintuplet (~5 Myr)
  - OH/IR stars, SiO masers (100 Myr—3 Gyr)
  - Ongoing star formation

Young stars in the Nuclear Bulge

- YSOs and massive stars: a few Myr old
  - Serabyn & Morris (1996)
  - Figer et al. (1999, 2002)
  - Yusef-Zadeh et al. (2009)
  - An et al. (2009, 2011)

Age distribution of older stars is unclear.
Distribution of stellar populations in the inner Galaxy

What will we find with Cepheids?
Section Summary

• Cepheids are some other variable stars are useful tracers of the Milky Way.
  • Their distances can be measured with P-L relations.
  • They can tell ages of stellar populations.

• A large fraction of the Milky Way, especially the inner Galaxy, is obscured by interstellar extinction.
  • Infrared surveys, like VVV, are important.
Case Study 1

Cepheids in the Nuclear Stellar Disk

Matsunaga et al. 2011, Nature, 477, 188
+Some updated materials
IRSF/SIRIUS in South Africa

InfraRed Survey Facility:
1.4 m telescope

SIRIUS:
FOV: about 7.7’ x 7.7’
Pixel Scale: 0.453”/pix,
4 times better than 2MASS
Simultaneous JHKs images.

It has been steadily working for
~15 years since 2000, during
which >100 papers were published.
IRSF survey towards the GC

- $20^{\text{arcmin}}$ by $30^{\text{arcmin}}$
- Typical limiting mag: $16.4@J, 14.5@H, 13.1@Ks$
Classical Cepheids

• 3 classical Cepheids (~25 Myr) were discovered among over 80,000 stars detected in our survey.
4th Cepheid was found

- In Matsunaga et al. (2015), we reported the 4th Cepheid.
- We measured the radial velocities which are consistent with the rotation in the NSD (Matsunaga+15).
  - Unless they belong to the disk, such velocities are unexpected.

Cepheid (a) +129 km/s

Cepheid (b) —61 km/s

Cepheid (c) —80 km/s

Cepheid (d) —11 km/s

Sgr A*

12 pc = 5′

5 arcmin corresponds to a projected distance of 12 pc at 8 kpc.
Period distribution of Cepheids

Known Cepheids in the Milky Way

The period range our survey might have missed.

4 Cepheids discovered
Color-magnitude diagram

Classical Cepheids

\begin{figure}
\centering
\includegraphics[width=\textwidth]{color_magnitude_diagram.png}
\end{figure}
Ages of Cepheids

Periood-Age relation of Cepheids (Bono et al. 2005)

Cepheids with $5<P<18$ d → 30–70 Myr

Cepheids with $P\sim20$ d → $25\pm5$ Myr
Estimating star formation rates

- Number of Cepheids
  - IMF (Kroupa 2001)
  - Lifetime of Cepheids
- SF rate within our survey field
  - Effective area of our survey
- SF rate in the entire Nuclear Bulge
## Deriving star formation rates

<table>
<thead>
<tr>
<th>Period</th>
<th>( P \approx 20 \text{ days} )</th>
<th>( 5 &lt; P &lt; 18 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>A number of Cepheids</td>
<td>( 4 \pm 2 )</td>
<td>( 0 \rightarrow &lt; 3 \ (P&gt;95%) )</td>
</tr>
<tr>
<td>Mass of Cepheid progenitors</td>
<td>( 8-10 \ M_{\text{solar}} )</td>
<td>( 6-8 \ M_{\text{solar}} )</td>
</tr>
<tr>
<td>Initial Mass Function</td>
<td>Kroupa (2001)</td>
<td></td>
</tr>
<tr>
<td>Lifetime of Cepheids</td>
<td>( 10^5 \text{ yr} )</td>
<td>( 2 \times 10^5 \text{ yr} )</td>
</tr>
<tr>
<td>Total mass of the parent population</td>
<td>( 10^5 \ M_{\text{solar}} )</td>
<td>( 10^5 \ M_{\text{solar}} )</td>
</tr>
<tr>
<td>Age range of the population</td>
<td>( 20—30 \text{ Myr} )</td>
<td>( 30—70 \text{ Myr} )</td>
</tr>
<tr>
<td>Effective survey area of the NB</td>
<td>( 13 % )</td>
<td></td>
</tr>
<tr>
<td>Star formation rate</td>
<td>( 0.1 \ M_{\text{solar}}/\text{yr} )</td>
<td>( &lt;0.01 \ M_{\text{solar}}/\text{yr} )</td>
</tr>
</tbody>
</table>
SF history from Cepheids

- SF rates, converted to consider the entire NB
  - \(0.1^{+0.2}_{-0.05}\) \(M_{\text{solar}}/\text{yr}\) for 20—30 Myr ago
  - \(0.02\) \(M_{\text{solar}}/\text{yr}\) (1σ upper limit) for 30—70 Myr ago

- Significance of the change in SFR: \(\sim 2\sigma\)

10 Gyr makes \(\sim 10^9 M_{\odot}\) comparable with \(1.4 \times 10^9 M_{\odot}\)

![Graph showing star formation rate over time](image)
SF history in the Nuclear Bulge

- Our result has a good time resolution, indicating the time-scale of the change in SF: \(~30\) Myr.

Gas infall into the Nuclear Bulge?

• through the bar structure?
• stochastic infall?

Section Summary

• We found 4 Cepheids in the Nuclear Stellar Disk.
  • First evidence of stars ~25 Myr old in this region.
• Lack of Cepheids with 5<P<18 days, suggests the quenched star formation at 30–70 Myr ago.
• Cepheids can be used to discuss star formation history.

• Matsunaga et al. 2011, Nature, 477, 188
Case Study 2

Lack of Cepheids in the inner disk

IRSF surveys toward the GC and Bulge

- IRSF 1.4-m telescope in South Africa
- SIRIUS JHKs 3-band imager

<table>
<thead>
<tr>
<th>Region</th>
<th>range</th>
<th>#(FOVs)</th>
<th>Area</th>
<th>Obs. Duration</th>
<th>#(Obs)</th>
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</thead>
<tbody>
<tr>
<td>Centre</td>
<td>$\ell = 0$</td>
<td>12</td>
<td>0.17 deg$^2$</td>
<td>2001–2008</td>
<td>~90</td>
</tr>
<tr>
<td>Bulge</td>
<td>$-10 &lt; \ell &lt; +10$</td>
<td>142</td>
<td>2.3 deg$^2$</td>
<td>2007–2012</td>
<td>~30</td>
</tr>
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</table>
Classification

<table>
<thead>
<tr>
<th>Type</th>
<th>Number</th>
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</thead>
<tbody>
<tr>
<td>Classical Cepheids</td>
<td>29†</td>
</tr>
<tr>
<td>Type II Cepheids</td>
<td>17</td>
</tr>
<tr>
<td>Eclipsing Binary Systems</td>
<td>43</td>
</tr>
<tr>
<td>Others (incl. Unclassified)</td>
<td>12</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>96</strong></td>
</tr>
</tbody>
</table>

† 4 are the Cepheids in the NSD we already discussed.
Distribution of detected Cepheids

25 classical Cepheids beyond the bulge

No classical Cepheids within 2.5 kpc of the GC except 4 in the Nuclear Stellar Disc (|l|<2 deg) → no simple exp. disc

The correction of the extinction is a crucial step of drawing this map.

4 classical Cepheids in the Nuclear Stellar Disc: previously reported in NM et al. (2011, 13, 15)
Estimating distance and extinction

- $(\mu_0, A_{K_s})$ are derived with two-band magnitudes and PLRs.

\[ A_{K_s} = \frac{A_{K_s}}{E(H-K_s)} \left\{ (H - K_s) - (M_H - M_{K_s}) \right\} \]

\[ \mu_0 = K_s - M_{K_s} - A_{K_s} \]

- $E(H-K_s) = 1.5-2$ for stars around the Galactic Center
  - $A(K_s)/E(H-K_s) = 1.44 \Rightarrow A(K_s) = 2.16-2.88$
  - $A(K_s)/E(H-K_s) = 1.61 \Rightarrow A(K_s) = 2.42-3.22 \quad \sim 0.3 \text{ mag}$
**Previous results in the ext. law**

- Recent results are mainly obtained for stars towards the bulge and give smaller values for $A_{Ks}/E(H−Ks)$, than classical values.

These works consider the direction of the bulge.

<table>
<thead>
<tr>
<th>Label</th>
<th>Reference</th>
<th>Data</th>
<th>$A_{Ks}/E(H−Ks)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C89</td>
<td>Cardelli+1989</td>
<td>Mixed</td>
<td>1.82</td>
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<tr>
<td>N06</td>
<td>Nishiyama+2006</td>
<td>IRSF</td>
<td>1.44</td>
</tr>
<tr>
<td>N09</td>
<td>Nishiyama+2009</td>
<td>2MASS</td>
<td>1.61</td>
</tr>
<tr>
<td>AG15</td>
<td>Alonso-Garcia+2015</td>
<td>VVV</td>
<td>1.28</td>
</tr>
<tr>
<td>M16</td>
<td>Majaess+2016</td>
<td>VVV</td>
<td>1.49</td>
</tr>
</tbody>
</table>

A classical value in Cardelli et al. (1989)
Nishiyama et al. (2006)

- Observed red clump in the bulge using IRSF/SIRIUS.
- Measured color and brightness for >1,000 sub-regions, which forms a sequence of RC peaks affected by different amounts of extinction.

The \( \lambda^{-2} \) law towards Bulge

Bulge red clumps split into many sub-regions give \( A_{Ks}/E_{H-Ks} = 1.44 \) (Nishiyama+06a)

The distance modulus to the GC
\( (\mu_0=14.5 \pm 0.15 \text{ mag}; \text{Nishiyama+06b}) \)

y-axis: Apparent modulus = True modulus + Extinction

x-axis: Color excess
4 Cepheids in the NSD

- One of the young stellar populations found in the NSD.
- Radial velocities also support the membership.
- These Cepheids are located at the distance of GC (8.0 ± 0.5 kpc) and give a constraint on $A_{\text{KS}}/E_{\text{H-KS}}$.

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I-v diagram for Cepheids compared with CO gas and orbits around the GC

Matsunaga et al. (2011)

Matsunaga et al. (2015)
The $\lambda^{-2}$ law towards Bulge

y-axis: Apparent modulus = True modulus + Extinction

PLRs in $H$ and $K$s can put individual Cepheids on this diagram (without assuming the extinction law or the distance).

4 NSD Cepheids

x-axis: Color excess
The $\lambda^{-2}$ law towards Bulge

The Nishiyama+06 law is consistent with that the 4 Cepheids are at the GC distance.

The y-axis: Apparent modulus = True modulus + Extinction

x-axis: Color excess

$A_{Ks}/E_{H-Ks}$

- 1.44
- 1.6
- 1.8

The diagram shows the relationship between $\mu_0 + A_{Ks}$ on the y-axis and $E_{H-Ks}$ on the x-axis.
The $\lambda^{-2}$ law towards Bulge

- y-axis: Apparent modulus = True modulus + Extinction
- 25 other Cepheids in our survey
- $A_{Ks}/E_{H-Ks}$ = 1.44
The $\lambda^{-2}$ law towards Bulge

Check these plots and discussions in Matsunaga et al. (2017, EPJ Web of Conf. 152, 1007)

Also, we found no Cepheids on the nearer side.

$A_{Ks}/E_{H-Ks}$

1.44

y-axis: Apparent modulus = True modulus + Extinction

x-axis: Color excess
A lack of young stars

• The extinction law of $A(K_{s})/E(H−K_{s})=1.44$ is used for our sample and also for Cepheids found with VVV data (Dekany et al. 2015, ApJ, 812, L29).

• Very few, if any, Cepheids are present within $\sim2.5$ kpc of the Galactic Centre except those in the NSD.

Section Summary

• A lack of young stars in the inner ~2.5 kpc except those in the NSD (< 200 pc of Sgr A*).

• The extinction law, $A(K_s)/E(H-K_s)$, has a large impact on drawing the distribution of stars in the Galactic disk.

  • Towards the Galactic bulge, $A(Ks)/E(H-Ks)$ is ~1.44 (Nishiyama+06), supported by the 4 NSD Cepheids.

Concluding remarks
Distribution of stellar populations in the inner Galaxy

- Cepheids in the disk having been discovered

Diagram:
- Age
  - 10 Gyr
  - 1 Gyr
  - 100 Myr
  - 10 Myr
  - 1 Myr
- Distance from the Centre (kpc): 0.1, 1, 10
- Nuclear Bulge
- Extended Bulge
- Disk
- Miras in the Bulge
- CEPs in the NB
- Known young stars in the NB
- Void of young stars?
VVV and OGLE are finding thousands of variables

Udalski (2017, EPJ Web of Conferences, 152, 1002)
Future prospects

• A large number of new pulsating stars across the Galaxy are expected from large surveys: VVV, OGLE, Gaia, LSST...

• Characterizing the interstellar extinction is an urgent task for mapping the wide area of disk.
  • Distance indicators with distances determined independent of extinction are valuable.

• Spectroscopic follow-up will be crucial.
  • Kinematics and chemical abundances demanded.
  • Near-IR spectroscopic observations are required to observe new ones in the obscured regions.