A Near-Infrared Variable Star Survey in the Magellanic Clouds

Noriyuki Matsunaga (Univ. of Tokyo, Japan)
Yoshifusa Ita (Tohoku Univ., Japan)
and IRSF/SIRIUS team
Collaborators

- PI: Yoshifusa Ita (Tohoku Univ.)
- Many observers involved:
  - T. Tanabe, T. Nagayama, S. Nishiyama, etc
- Data analysis
  - Done by Y. Ita, with NM taking parts in the catalogue verification
- About Cepheids and other variable stars
  - Yoshikazu Nakada (Univ. Tokyo)
  - Giuseppe Bono, Laura Inno (Univ. Rome/ESO)
  - Michael Feast (Univ. Cape Town)
Talk Plan

- IRSF variable star survey for the LMC/SMC
  - 10 yr long monitoring survey
  - Basic survey and catalogue properties
  - Catalogue and data release plan

- Cepheids in the SMC and their light curves
  - Light curves shapes in the optical and near-IR
  - An easy way to understand the light curve shapes
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.
Observation

- >10 years, starting in 2000 Dec.
- More than 100 epochs (always with JHKs)

LMC: 3 deg$^2$ along the bar ~100 times in 10 yrs.

SMC: 1 deg$^2$ around the center ~120 times in 10 yrs.
Survey Depth

- 50 sec integration (=5sec*10dithers) for each epoch in JHKs
- 10 σ detection limits
  - 17.7, 17.0, and 15.3 mag at J, H, and K, respectively in the most crowded region.
- A Cepheid with a period ~a few days and an amplitude ~0.1 mag in the SMC (K ~ 15 mag) is detected.

Smallest amplitudes to be detected in the image subtraction as a function of brightness.
Colour-magnitude diagram (SMC)

All sources (V+nonV)

Variables Detected

log(N) in colour

Percentage in colour

90% completeness
Products

- Data reduction almost finalized for the SMC

**Photometry catalog**
- PSF fitting photometry with DAOPHOT on reference images
- JHK photometry
- ~400,000 point sources

**Variable star catalog**
- Image subtraction (ISIS by Alard)
- JHK time-series
- ~20,000 variable sources.

<table>
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<tr>
<th>R.A. (degree)</th>
<th>DEC. (degree)</th>
<th>R.A. (J)</th>
<th>DEC. (J)</th>
<th>J [mag]</th>
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<th>Name of time series data</th>
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Light curves of various objects

Some types of objects as classified in Simbad

(Carbon-rich) Mira

Emission star (Be?)

Pre-main sequence star

X-ray binary

10 years
The longest period and dust-enshrouded Miras

- The longest period found among the SMC Miras: \(~1150\) days
- We discovered several Miras not detected in the optical (OGLE)
  - Intensive mass loss producing thick circumstellar dust shells
Publication and Data release: Plan

- Basically, the data release will be accompanied by a catalogue paper for each galaxy, but please let us know if interested in earlier access to the data.
- SMC – within 2013
  - Catalog paper: almost ready (Ita et al.)
  - Science papers
    - Miras: in preparation (Ita et al.)
    - Cepheids: in preparation (Matsunaga et al.)
- LMC – expecting to release in next year
  - Catalog paper: to be written (Ita et al.)
  - Science papers: to be written
Light curve shapes of Cepheids
Light curve shapes vary with $\lambda$

- The difference in the light curve shapes are known for a long time.
  - Saw-shaped curves in the optical
  - Smaller amplitudes and more symmetric in the IR

Madore & Freedman (1991)
Two parameters

- $T_{\text{eff}}$ has a dominant effect on the optical LCs, while the radius has a stronger effect on the IR LCs.
- Freedman & Madore (2010) (see also Madore, 1985)
  - The K-band light curve is widely considered to be dominated by pure radial variations.

Freedman & Madore (2010)
Our goals

- To give a quantitative description of the differences in light curve shapes based on large datasets
- To give an (intuitive and graphic) explanation of the difference
  - Although pulsational models and SED synthesis can predict the light curves (eg Natale et al. 2008), how can we get a straightforward understanding?
Data for Cepheids in the SMC

- 912 OGLE+IRSF Cepheids
- Variations of 67% of OGLE-III Cepheids in our survey area were detected by IRSF.

<table>
<thead>
<tr>
<th>Mode</th>
<th>OGLE-III w. IRSF</th>
<th>OGLE-III w/o IRSF</th>
<th>OGLE-III Entire SMC</th>
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<td>170</td>
<td>2626</td>
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<tr>
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<td>276</td>
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Hertzsprung progression in various $\lambda$

```
<table>
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| #2751  
| ($P=33.033$) |
| #1635  
| ($P=22.151$) |
| #1385  
| ($P=15.822$) |
| #2841  
| ($P=14.713$) |
| #1377  
| ($P=13.464$) |
| #2607  
| ($P=10.757$) |
| #1753  
| ($P=9.730$)  |
| #1984  
| ($P=9.524$)  |
| #2008  
| ($P=8.826$)  |
| #2947  
| ($P=8.683$)  |
| #1454  
| ($P=5.749$)  |
| #1205  
| ($P=5.114$)  |
| #2582  
| ($P=3.606$)  |
| #2933  
| ($P=2.494$)  |
```
Hertzsprung progression in various $\lambda$

- Similar LCs in $V$ and $I$
  - Saw-shaped except P around 10 days
- More symmetric in $H$ and $K$
  - Often flat plateau around maximum

P=30d

#2751 ($P=33.033$)
#1635 ($P=22.151$)
#1385 ($P=15.822$)
#2841 ($P=14.713$)
#1377 ($P=13.464$)
#2607 ($P=9.730$)
#1984 ($P=9.524$)
#2008 ($P=8.826$)
#2947 ($P=8.683$)
#1454 ($P=5.749$)
#1205 ($P=5.114$)
#2582 ($P=3.606$)
#2933 ($P=2.494$)
Amplitudes dependent on $\lambda$

$A_V$ shows a trend depending on a period, but with a large scatter

$A_I$ is well correlated with $A_V$ (ratio $\sim 0.6$)

$A_H/A_V$ has a large scatter around a ratio of $\sim 0.3$
Mix/min phases dependent on $\lambda$

Max phase
Relative to max(V)

Min phase
Relative to min(V)

In the unit of $\pi$

$I$-band

$H$-band

$\phi_{\text{max}}(I) - \phi_{\text{max}}(V)$

$\phi_{\text{min}}(I) - \phi_{\text{min}}(V)$

$\phi_{\text{max}}(E) - \phi_{\text{max}}(V)$

$\phi_{\text{min}}(E) - \phi_{\text{min}}(V)$

$log(P)$
Mix/min phases dependent on $\lambda$

Max phase
Relative to max(V)

Min phase
Relative to min(V)

Max/min. appears at the same phase in V and I.

Max/min in the NIR are offset behind those in V.
Effects of $T_{\text{eff}}$ and radius

- Stafan-Boltzmann’s law
  \[ \delta m_{\text{bol}} = -5 \delta \log R - 10 \delta \log T_{\text{eff}} \]

- Applying bolometric correction
  \[ \delta m_\lambda = -5 \delta \log R - 10 \delta \log T_{\text{eff}} - B_\lambda \delta \log T_{\text{eff}} \]

- Linear relation unless an amplitude is large

- The $\delta \log T_{\text{eff}}$ term depends on the wavelength.
Loops on \((\delta \log T_{\text{eff}}, \delta \log R)\)

- Pejcha & Kochanek (2012)
  - (normalized) loops on \((\delta \tau \equiv \delta \log T_{\text{eff}}, \delta \rho \equiv \delta \log R)\)
  - based on observational data in literature.

\[
\begin{align*}
\delta \rho \\
\begin{array}{c}
\text{P=20d} \\
\text{One filled circle per 0.1 phases}
\end{array}
\end{align*}
\]

\[
\begin{align*}
\delta \tau \\
\begin{array}{c}
\text{P=40d} \\
\text{One filled circle per 0.1 phases}
\end{array}
\end{align*}
\]
Variations in $V$, $K$ and $m_{\text{bol}}$ inferred from a loop

$V = \text{const.}$

$m_{\text{bol}} = \text{const.}$

$K = \text{const.}$

Linear relations between magnitudes and $(\delta \log R, \delta \log T_{\text{eff}})$

\[
\begin{align*}
\delta V &= -5 \delta \log R - 13.2 \delta \log T \\
\delta m_{\text{bol}} &= -5 \delta \log R - 10.0 \delta \log T \\
\delta K &= -5 \delta \log R - 2.5 \delta \log T
\end{align*}
\]
Variations from the \((\delta \log T, \delta \log R)\) loop

The amplitude is large in \(V\) and small in \(K\).
Variations from the \((\delta \log T, \delta \log R)\) loop

- **V-band**
  - Plateau around maximum
  - Short rising branch
  - Different maximum phases

- **K-band**
  - Plateau around maximum
  - Different maximum phases
Amplitude ratios

- If the loop are round, the ratios determined by the slopes of the linear relations.
  - $\frac{AI}{AV} \sim 0.6$, $\frac{AH}{AV} \sim 0.3$
- The scatter in the ratios caused by:
  - The ellipticity of the loop
  - The phase dependency on $\lambda$

![Graph showing amplitude ratios](image)
Summary

- Near-infrared catalogue of variable stars from IRSF/SIRIUS
  - In the SMC: in this year (~20,000 variables)
  - In the LMC: next year

- Light curve shapes of Cepheids
  - Can be understood in an intuitive and graphic way by considering loops on $(\delta \log T_{\text{eff}}, \delta \log R)$ (at least to the 1st approximation).
  - The slope and opening of the loop is essential.