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

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Outline

Introduction

Miras as tracers of the Milky Way

Case study 1

Miras in the bulge and the distance to the GC

Case study 2

Carbon-rich Miras in the bulge

Concluding remarks
What Miras can tell us.
What are Miras?

- Long period (P>100 days)
- Large amplitude (ΔV>2.5 mag)
- Late-type stars in the last stage of AGB

Related variable stars:
  - Semi-regulars, Irregulars

Refer to “GCVS Variability Types” and “Variable Star Type Designations in AAVSO VSX”

A part of long-term light curve of Mira (o Cet) with P=332 days (Taken from AAVSO, https://www.aavso.org/).
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)
P-L relation of Miras and SRs

- Miras can be classified with relative ease.
  - Regularity of the light curves
  - Large Amplitudes: $Amp(I\text{-band}) > 1$ mag
- A single sequence of PLR is found in $K_s$ (not in $I$).

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Pioneering studies on Miras P-L relation:

Their studies became possible thanks to IR data.

P-L relation of Miras

- No tight correlation in the optical
- Tight PL relation found in the near-IR (or in bolometric mag.)
- Many long-period Miras ($P>350$ days) get fainter than the linear relation because of thick circumstellar dust.

P-L relation of Miras

- Bolometric magnitudes, $M_{bol}$, measure integrated brightness; energy absorbed by circumstellar dust is re-emitted in the mid- to far-infrared.

- $M_{bol}$ give robust distances of Miras even with circumstellar dust.

Reach of Miras’ distance

- Previous results include only 2 galaxies w. D>1Mpc.
- JWST may greatly extend the frontier.

NGC5128@4Mpc

NGC4258@7Mpc
Ages of Miras

• Younger Miras have longer periods, although the relationship is not established like Cepheids.
  • Evolutionary and pulsational models of Miras are very difficult because of their very extended atmospheres.

• Some facts supporting the period-age relation:
  • Correlation between period and kinematics
  • Old globular clusters host only Miras with short P (100–300 days).

Mirases as tracers

- Distances can be determined based on P-L relation.
  - Infrared observations are required.
- They are low- and intermediate-mass stars in the AGB phase representing old and intermediate-age populations.
- C-rich/O-rich dichotomy gives insights into subgroups of intermediate-age populations.
- Many Mirases have circumstellar dust shells making themselves important contributors to interstellar dust and integrated IR emissions of galaxies.
Two important phenomena

- Dredge up
- Mass loss

Some references:

Evolution around the AGB

A evolutionary track of low-mass stars.
Structure of the AGB

- C+O core with double burning shells are surrounded by the extended envelope.

From the textbook “AGB stars”
Thermal pulse and Dredge up

- He-shell burning occurs violently—"thermal pulse"
- 3rd dredge up events after thermal pulses brings up processed materials to the surface.
- Important elements enhanced by 3rd dredge up:
  - $^{12}$C
  - s-process elements (Y, Ba, La, etc)

From the textbook “AGB stars”
An evolutionary track of low-mass stars.

Carboxy-rich stars (red) produced by 3rd dredge up are more common in metal-poor systems and appear in the last stage of intermediate-mass AGB stars.

Evolutionary tracks of AGB stars (Marigo et al. 2008)

Herwig, F. 2005

An evolutionary track of low-mass stars.
Dependency on age and metal

- The frequency of C-rich evolved stars can be considered as a population indicator.
- Being applied to nearby galaxies (e.g., Boyer et al. 2013).

Old AGB stars don’t evolve into C-rich stars.

Intermediate-age stars become C-rich AGB stars (especially if metal-poor).

C-rich/O-rich ratio at the AGB phase (Boyer et al. 2013, ApJ, 774, 83)

Metal-rich stars tend to avoid evolving into C-rich stars.

Ratio of C-rich AGBs to O-rich ones:

- ~8.5 for SMC Miras
- ~2.5 for LMC Miras
- zero for Bulge Miras?
Period distribution (O-rich/C-rich)

- Metallicity: MW (~1 $Z_{\text{solar}}$) > LMC (~0.3 $Z_{\text{solar}}$) > SMC (~0.1 $Z_{\text{solar}}$)
- C-rich frequency: Milky Way < LMC (~2.5) < SMC (~8.5)
C-rich and O-rich dichotomy

- Some AGB stars have more C than O at the surface.
- 3\textsuperscript{rd} dredge-up from the stellar interior
- Mass transfer from the binary companion

From the textbook “AGB stars”
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From the textbook “AGB stars”
Mass loss

- Mass loss of AGBs (especially Miras) are large, \( \sim 10^6 \, M_{\text{Solar}}/\text{yr} \) or more, thanks to:
  - Pulsation—shock pushing up gas into higher layers.
  - Dust formation—giving higher opacity
  - High luminosity and low gravity are also crucial.

Freytag et al. (2017) Nowotny et al. (2010)
Section summary

• AGB stars evolved from low-mass (~10 Gyr old) to intermediate-mass (100 Myr–5 Gyr) stars.

• Miras are large-amplitude ($\Delta V > 2.5$ mag) and long-period ($P > 100$ days) variables.

• Miras have particular characteristics, due to mass loss and dredge up phenomena, which poses interesting problems.
Case Study 1

Miras in the bulge and the distance to the Galactic Center

Matsunaga et al. 2013, IAUS, 289, 109
Distribution of stellar populations in and around the Bulge

How old is the Nuclear Bulge?

Age distribution of (intermediate to young) bulge stars
IRSF + SIRIUS

1.4-m telescope in Sutherland (SAAO)

SIRIUS:

FOV: about 7.7’ x 7.7’
Pixel Scale: 0.453”/pix,
Simultaneous $JHK_s$ images.

It has been steadily working for over 17 years since 2000, during which 170+ papers were published. 24+ PhD theses (20 in JP, 3 in SA)
IRSF survey towards the GC

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

- Total number: 1364
- Period is obtained for 549.
Example light curves of Miras
Period distribution

• Near-IR surveys provide comprehensive samples of Miras from short to long periods.
• The broad period range indicates a wide parameter range (age and/or metallicity).

Bulge Miras selected among IRAS objects. Mass-losing objects were selected.

Bulge Miras found in OGLE-II survey. Biased against mass-losing objects.
Estimating distance and extinction

- P-L relations in JHKs.
  - Intrinsic colors and absolute magnitudes

- Extinctions and distances can be derived at the same time.

P-L relation of the LMC Miras, using data from Ita et al. (2004)
Samples of Miras for distances

- We derived distances of Miras with:
  - Period $< 350$ d
  - with more than two of $JHK$s

- Colors are necessary to estimate the extinction.
  - Longer-P Miras are affected by circumstellar dust.

It may be possible to estimate the circumstellar extinction from colors (Ita & Matsunaga, 2011), but probably not for the objects towards the Galactic Centre.

Structure of interstellar extinction

- Locations of individual Miras and their extinction
- Integrated extinction between the Sun and the bulge
Extinction toward GC

• In the optical wavelengths, objects around the GC are invisible (even bright stars like Miras are not detected by Gaia).

• Infrared surveys are crucial in the central part of the Galaxy.

Distance to the Galactic Center

- $\mu_0 (\text{GC}) = 14.58 \pm 0.02 \pm 0.15 \text{ mag}$
  - $R_0(\text{GC}) = 8.24 \pm 0.08 \pm 0.42 \text{ kpc}$
  - $\mu_0 (\text{LMC}) = 18.45(\pm 0.05)$ is assumed.

- Agreement with estimates based on other methods including stellar orbits around Sgr A* (e.g. Gillessen et al. (2017): $R_0(\text{GC}) = 8.32 \pm 0.07 \pm 0.14 \text{ kpc}$).

A review of previous estimates of $R_0(\text{GC})$ is given in de Grijs & Bono (2016, ApJS, 227, 5)
Section summary

- Near-IR surveys are effective to look for comprehensive samples of Miras from short-period Miras to long-period Miras with thick circumstellar dust.

- Using short-period Miras (P<350 days), we obtained the distance to the Center to be 8.24 kpc, but the systematic error is still large, ~0.4 kpc.

Matsunaga et al. 2013, IAUS, 289, 109
Case Study 2

Carbon-rich Miras in the Galactic bulge

Previous works on bulge C stars

• Azzopardi et al. (1991) identified 34 carbon stars.
  • Too faint to be carbon AGB stars after the 3rd dredge up.
  • Probably evolved in binary systems (or accreted from a dwarf galaxy, Sgr dSph?)

• Cole & Weinberg (2002) considered the stars with \((J-Ks)_0 > 2\) (because such red ones are C stars in the LMC). This is not true.

• Ishihara et al. (2010) used \((J-Ks)\) and AKARI (9-18) colors to classify between O-rich/C-rich stars. Their C-rich stars seem to be located also in the bulge. Spectorsorsopic follow-ups are necessary.

• Miszalski et al. (2013) serendipitously discovered a C-rich symbiotic Mira towards the bulge. They considered that it is nearer than the bulge, and our near-IR photometry supports their conclusion.
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No C-rich stars in the bulge were confirmed and this has been understood as a result of the metal-rich and old population.
Dependency on age and metal

- The frequency of C-rich evolved stars can be considered as a population indicator.
  - Being applied to nearby galaxies (e.g. Boyer et al. 2013).

Old AGB stars don’t evolve into C-rich stars.

Intermediate-age stars become C-rich AGB stars (especially if metal-poor).

C-rich/O-rich ratio at the AGB phase (Boyer et al. 2013, ApJ, 774, 83)

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No C-rich AGB stars had been confirmed in the bulge. ⇔
The dominant population of the bulge is old and metal-rich.

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C-rich/O-rich ratio at the AGB phase (Boyer et al. 2013, ApJ, 774, 83)
Stellar populations in the bulge

- Almost all bulge stars were thought to be old (~10 Gyr).
- Recent supports for intermediate-age stars (~a few Gyr).
  - The presence of such younger stars is still controversial.
  - Does the bulge have C-rich AGBs aged a few Gyr?

Age-metal relation for microlensed stars in the bulge (Bensby+13)

Metal-rich stars should be younger to explain the bulge CMD? (Haywood+16)
How to search for bulge C stars?

- AKARI(IRC)+2MASS colors for several groups of objects including AGB stars, YSOs and extragalactic sources.

Teaching samples based on SIMBAD classification
Spectral features for the difference colors

- **Mid-IR: [9]—[18]**
  - O-rich: Silicate 9.8 + 18 μm
  - C-rich: SiC 11.3 μm

- **Near-IR: J—Ks**
  - O-rich: H$_2$O dominates both J/Ks
  - C-rich: strong C$_2$, CN bands in J

*O-rich stars get redder in [9]—[18].*

Ita et al. (2010)

Lancon & Wood (2000)
Distribution of O-rich/C-rich AGBs in Ishihara et al. (2011)

- More C-rich AGBs in the outer Galaxy
- This trend has been known (eg. Noguchi et al. 2004).
Questions left from Ishihara+11

• Are there really so many C-rich stars in the bulge?
• Some caveats in Ishihara et al. (2011)
  • Contaminations of non-AGB stars/misclassification
  • Large errors in distance
    • They used the empirical relation between [9] and Ks-[9]
      (assuming that AGBs form a sequence in the CMD).
  • Interstellar reddening and extinction is not taken into account.
The goal of our work

- Identify candidates of C-rich Miras in the bulge
  - Miras are evolved AGB stars (their evolutionary stages are constrained).
  - The distances can be estimated based on period-luminosity relation.
- Confirm its type (as C-rich) based on spectroscopy
- If any confirmed, discuss their implications on stellar populations in the bulge
Targets selection

- 66 candidates of 6528 Miras in Soszynski+13 (OGLE-III)
- 4 candidates of 643 Miras in Catchpole+16

Candidates of C-rich Miras from the OGLE-III catalog and Catchpole+16

70 candidates of C-rich Miras
Spectroscopy w. SAAO/74inch

- SpUpNIC spectrograph at 74 inch (1.9m) in Sutherland
- 5600—9200 Å with $\lambda/\Delta\lambda \sim 1,200$ (Grating GR8)
- Observation on 13—19 July, 2016
- 300—1200 sec exposures for 36 targets ($I=12—17^{\text{mag}}$)
8 C-rich Miras confirmed

- 6 C-rich Miras among OGLE-III bulge Miras and 2 additional C-rich Miras from Catchpole+2016
- Emission lines from two objects
- $JHK_s$ photometry collected with IRSF 1.4m (SAAO)

IRSF $JHK_s$-band photometry also obtained, showing some offsets from 2MASS colors.
Distances to the C-rich Miras

• Relatively large errors remain due to the mix of interstellar and circumstellar extinction.
• 4 Miras (and maybe another) are within the bulge.
  • representing a rare population: 4–5/7000~0.1%

3 foreground (including a symbiotic C-rich Mira in Miszalski+13)

4 members

1 background?
One would expect $\sim 5 \times 10^4$ Miras in the bulge. Roughly, $\sim 50$ C-rich Miras to be found.
The origin of C-rich Miras

• Intermediate-age stars (around 0.5—3 Gyr) ??
  • If they become C-rich stars after the 3rd dredge-up process.
  • They should be not-so-metal-rich and less oxygen enhanced.

• Still old objects ??
  • If the origin is mass transfers or mergers in binary systems.
  • (Possibly related) Blue stragglers exist in the bulge (e.g. Clarkson et al. 2011).
  • Even a rare evolutionary path may be important to explain a rare object like the bulge C-rich Miras.

• Accretion from a (merged) dwarf galaxy ??

• Kinematics and chemical information may help uncover their origin(s).
Section summary

• 4—5 C-rich Miras are identified in the bulge for the first time.

• Representing a rare population in the bulge, but their origins are unclear.
  • May be intermediate-age stars (0.5—3 Gyr).
  • May be old stars affected by binary evolution.
  • May be accreted from a (merged) dwarf galaxy.

• Further candidates selection using the AKARI color will be useful for finding more C-rich stars in the bulge.
