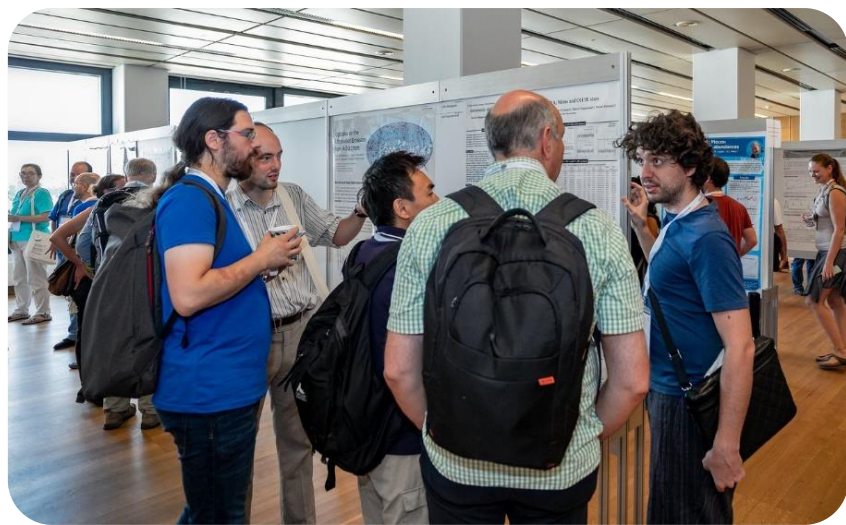


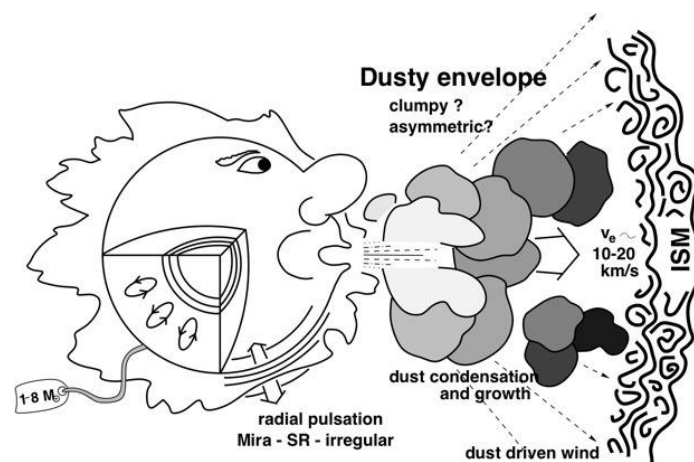
VLBIとGaiaによる長周期変光星の年周視差の比較

中川亜紀治, 濱田翔太(鹿児島大学), 須藤広志(岐阜大学), 倉山智春(帝京科学大学), 国立天文台VERAプロジェクト

1. VLBIによる位置天文の結果、周期光度関係
2. VLBIとGaiaのParallaxを比較
3. Gaiaデータを用いた周期光度関係



長周期変光星 (LPV)



<https://www.cfa.harvard.edu/~mmarengo/me/agb.html>

- Mass 1~8 M_{\odot} (Mira: 1~2.5 M_{\odot} ?)
- C/O-core, He-shell, H-rich envelope → O-rich/C-rich
- Period 100~1000 d, $P > 1000$ d
- AGB phase, Mass loss → Chemical enrichment of universe
- H₂O, SiO, OH maser → VLBI target
- Period luminosity relation → Distance indicator



天の川銀河
AGB星の
Parallax
(34天体)

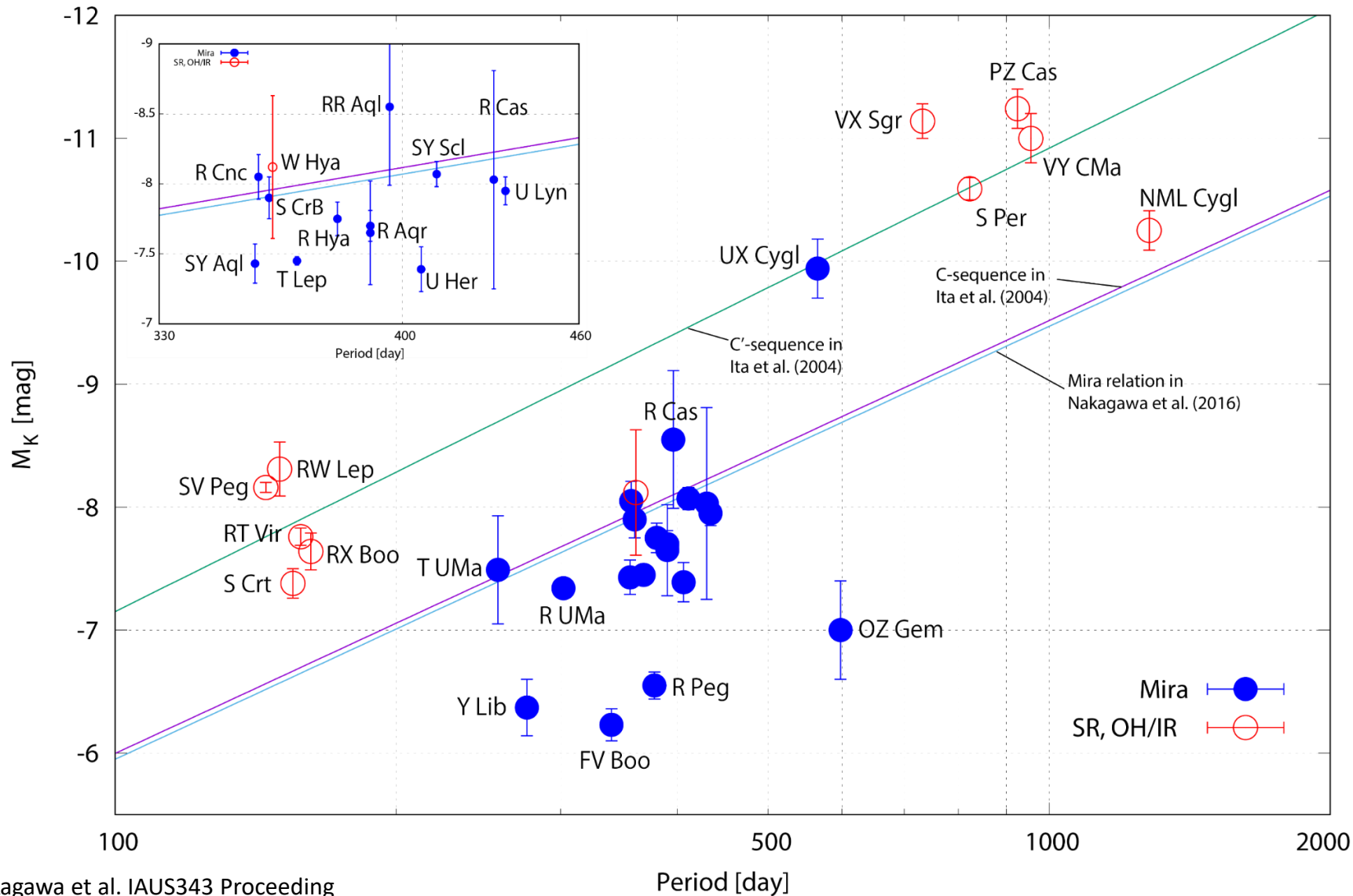
Source	Type	Π_{VLBI} [mas]	Π_{Gaia} [mas]	P [day]	$\text{Log}P$	m_K [mag]	M_K [mag]	Maser	Ref. [†] (Π_{VLBI}, m_K)
SY Scl	Mira	0.75±0.03	0.68±0.23	411	2.614	2.55	-8.07 ± 0.09	H ₂ O	nyu11,b
WX Psc	OH/IR	5.3 ^b	...	660	2.820	2.22	-4.16	OH	oro17,a
S Per	SRc	0.413±0.017	0.22±0.12	822	2.915	1.33	-10.59 ± 0.09	H ₂ O	asa10,b
OH138.0+7.2	OH/IR	0.52±0.09	...	1410	3.149	8.548	-2.87 ± 0.38	OH	oro17,a
T Lep	Mira	3.06±0.04	2.96±0.19	368	2.566	0.12	-7.45 ± 0.03	H ₂ O	nak14,c
RW Lep	SRa	1.62±0.16	2.35±0.13	150	2.176	0.639	-8.31 ± 0.22	H ₂ O	kam14,a
U Lyn	Mira	1.27±0.06	0.58±0.22	434	2.637	1.533	-7.95 ± 0.10	H ₂ O	kam16a,a
VY CMa	SRc	0.88±0.08	-5.92±0.83	956	2.980	-0.72	-11.00 ± 0.20	H ₂ O	cho08,b
OZ Gem	Mira	1.00±0.18	-0.96±0.46	598	2.777	3.00	-7.00 ± 0.40	H ₂ O	iaus336,a
OH231.8+4.2	OH/IR	0.55±0.05	0.10±0.18	548	2.739	6.546	-4.53 ± 0.11	H ₂ O	iaus336,a
R Cnc	Mira	3.84±0.29	4.43±0.55	357	2.553	-0.97	-8.05 ± 0.16	H ₂ O	iaus336,a
R UMa	Mira	1.97±0.05	2.04±0.20	302	2.480	1.19	-7.34 ± 0.06	H ₂ O	nak16,d
S CrI	SRb	2.33±0.13	2.65±0.15	155	2.190	0.786	-7.38 ± 0.12	H ₂ O	nak08,a
T UMa	Mira	0.96±0.15	0.75±0.10	257	2.410	2.60	-7.49 ± 0.44	H ₂ O	iaus336,a
RT Vir	SRb	4.417±0.134	2.05±0.29	158	2.199	-0.97	-7.76 ± 0.07	H ₂ O	zha17,a
R Hya	Mira	8.96±0.51	4.47±0.89	380	2.580	-2.51	-7.75 ± 0.12	H ₂ O	iaus336,a
W Hya	SRa	10.18±2.36	6.09±0.82	361	2.558	-3.16	-8.12 ± 0.51	OH	vle03,c
RX Boo	SRb	7.31±0.50	7.83±0.30	162	2.210	-1.96	-7.64 ± 0.15	H ₂ O	kam12,b
VF Boo	Mira	0.97±0.06	0.57±0.18	340	2.531	3.84	-6.23 ± 0.13	H ₂ O	kam16b,a
Y Lib	Mira	1.24±0.13	...	276	2.441	3.16	-6.37 ± 0.23	H ₂ O	iaus336,a
S CrB	Mira	2.39±0.17	2.32±0.29	360	2.556	0.21	-7.90 ± 0.15	OH	vle07,c
U Her	Mira	3.76±0.27	1.75±0.15	406	2.609	-0.27	-7.39 ± 0.16	OH	vle07,c
VX Sgr	SRc	0.64±0.04	0.79±0.23	732	2.865	-0.17	-11.14 ± 0.14	H ₂ O	xu18,a
RR Aql	Mira	1.58±0.40	3.15±0.30	396	2.598	0.46	-8.55 ± 0.56	OH	vle07,c
SY Aql	Mira	1.10±0.07	3.43±0.21	356	2.551	2.36	-7.43 ± 0.14	H ₂ O	iaus336,a
NML Cyg	SRc	0.62±0.047	1.53±0.57	1280	3.107	0.791	-10.25 ± 0.16	H ₂ O	zha12,a
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SV Peg	SRb	3.00±0.06	1.12±0.28	145	2.161	-0.55	-8.16 ± 0.04	H ₂ O	sud18,a
NSV25875	OH/IR	0.38±0.13	...	1748	3.243	6.857	-5.24 ± 0.77	SiO	...,a
IRAS22480+6002	SRc	0.400±0.025	0.48±0.08	2.78	-9.21 ± 0.14	H ₂ O	ima12,a
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PZ Cas	SRc	0.356±0.026	0.42±0.08	925	2.966	1.00	-11.24 ± 0.16	H ₂ O	kus13,b
R Cas	Mira	5.67±1.95	5.34±0.24	430	2.633	-1.80	-8.03 ± 0.78	OH	vle03,c

VLBIによる計測
(VERA + VLBA)

VERAによる計測

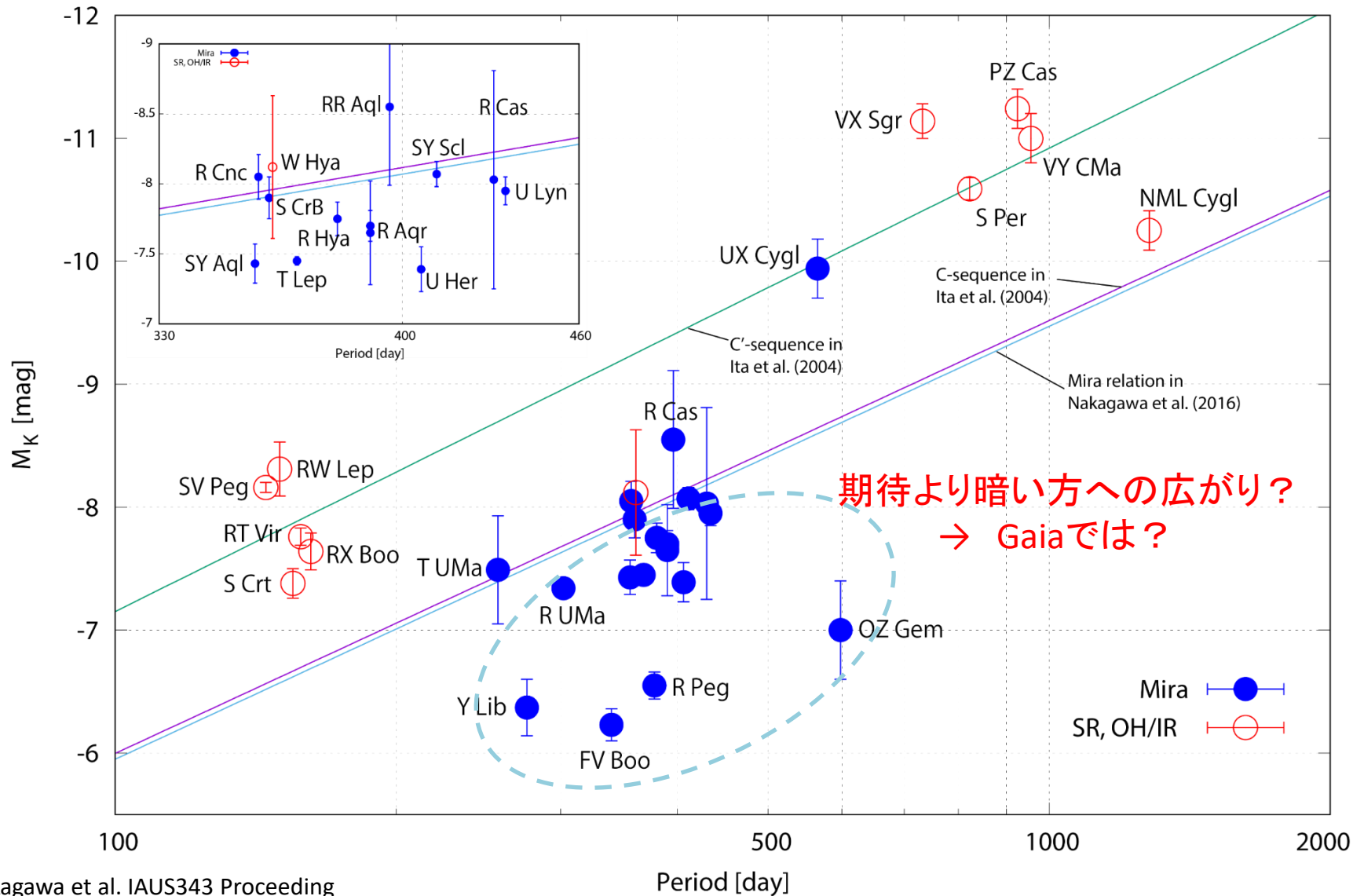
天の川銀河Mira型変光星 $M_K - \log P$

Period vs M_K of Galactic LPVs



天の川銀河Mira型変光星 $M_K - \log P$

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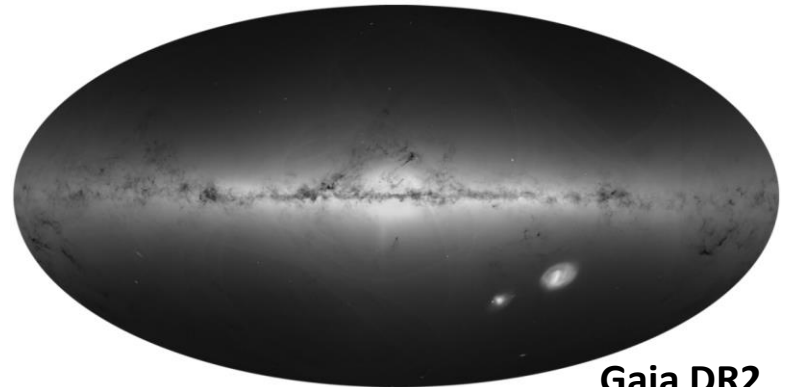


Gaia DR2

- 2018年4月25日 リリース
- 活用データ期間 2014 Aug 22 ~ 2016 May 23 (640d = 1.75yr)
- 13億天体の位置・固有運動・Parallaxなど5パラメーター ほか
- Single starとして扱い、全天体の5パラメーターを同時に解く
- $3 \text{ mag} < G < 21 \text{ mag}$
- Parallax 精度

σ_{π} (Parallax error)	G magnitude
$\sim 0.04 \text{ mas}$	$G < 14 \text{ mag}$
$\sim 0.1 \text{ mas}$	$G \sim 17 \text{ mag}$
$\sim 0.7 \text{ mas}$	$G \sim 20 \text{ mag}$

Luri et al. 2018



Gaia DR2

Summary of the contents and survey properties

Gaia Collaboration 2018

とくにAGB星について見ると...

- DR1では皆無だったが...
- DR2では多くのAGB星の結果が公開 (前出リスト 30/34 → 88%)
- DR3はバイナリーも考慮



Parallax ; VLBI vs Gaia

(34天体)

VLBIによる計測
(VERA + VLBA)

Nakagawa et al. in prep.

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R Cas	Mira	5.67±1.95	5.34±0.24	430	2.633	-1.80	-8.03 ± 0.78	OH	vle03,c

Parallax ; VLBI vs Gaia

(34天体)

VLBIによる計測
(VERA + VLBA)

精度 10%より良い

DR2 データなし

負のParallax

Nakagawa et al. in prep.

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RX Boo	SRb	7.31±0.50	7.83±0.30	162	2.210	-1.96	-7.64 ± 0.15	H ₂ O	kam12,b
VF Boo	Mira	0.97±0.06	0.57±0.18	340	2.531	3.84	-6.23 ± 0.13	H ₂ O	kam16b,a
Y Lib	Mira	1.24±0.13	...	276	2.441	3.16	-6.37 ± 0.23	H ₂ O	iaus336,a
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SV Peg	SRb	3.00±0.06	1.12±0.28	145	2.161	-0.55	-8.16 ± 0.04	H ₂ O	sud18,a
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R Aqr	Mira	4.7±0.8	3.12±0.28	390	2.591	-1.01	-7.65 ± 0.37	SiO	kam10,c
R Aqr	Mira	4.59±0.24	3.12±0.28	390	2.591	-1.01	-7.70 ± 0.11	SiO	min14,c
PZ Cas	SRc	0.356±0.026	0.42±0.08	925	2.966	1.00	-11.24 ± 0.16	H ₂ O	kus13,b
R Cas	Mira	5.67±1.95	5.34±0.24	430	2.633	-1.80	-8.03 ± 0.78	OH	vle03,c

変光周期と Parallax差の関係

- 変光周期とResidual

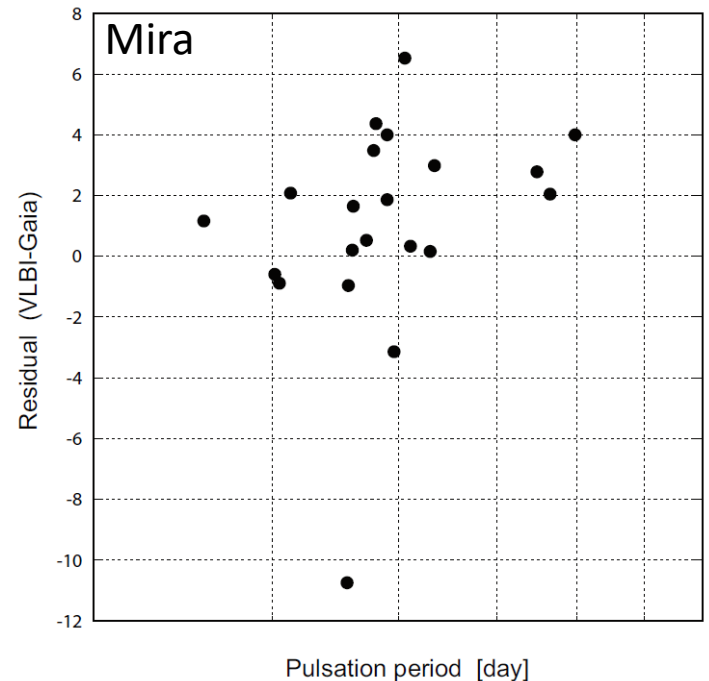
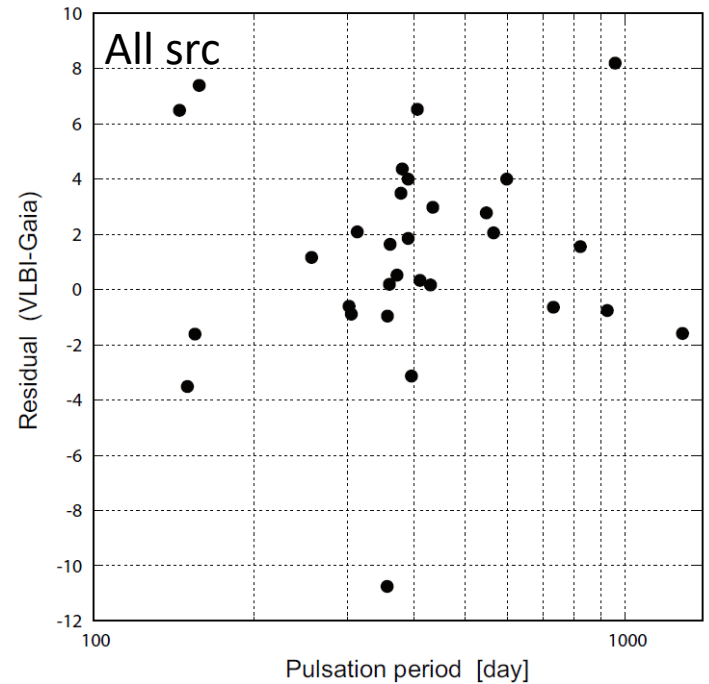
$$\text{Period vs Residual} \quad \frac{\Pi_{\text{VLBI}} - \Pi_{\text{Gaia}}}{\sqrt{\sigma_{\Pi_{\text{VLBI}}}^2 + \sigma_{\Pi_{\text{Gaia}}}^2}}$$

→ 正の相関あり？

- 変光周期と相関しそうなパラメーター

- 光球サイズ
- 光度
- 質量

- (1) VLBI parallax > Gaia parallax の傾向
- (2) Residual が周期に依存



考察1: Lutz and Kelker bias

(Lutz and Kelker 1973)

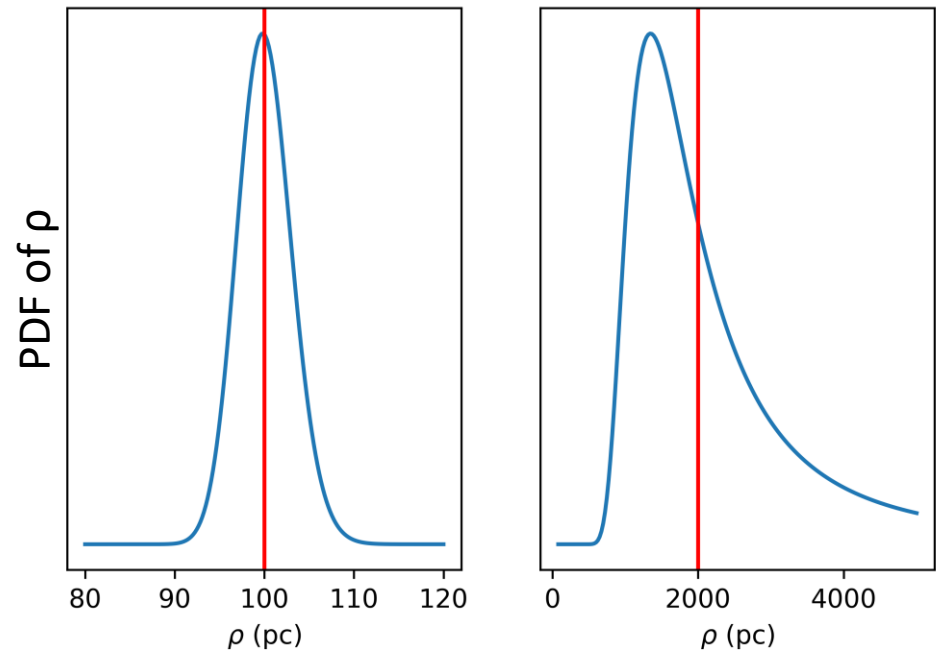
- Probability density function (PDF) of ρ

$$\begin{aligned} p(\rho | \varpi_{\text{True}}) &= p(\varpi = 1/\rho | \varpi_{\text{True}}) \cdot \left| \frac{d\varpi}{d\rho} \right| \\ &= \frac{1}{\rho^2 \sigma_{\varpi} \sqrt{2\pi}} \exp\left(-\frac{(1/\rho - \varpi_{\text{True}})^2}{2\sigma_{\varpi}^2}\right) \end{aligned}$$

ρ : distance

- もし Lutz and Kelker bias だとすると...
→ Parallax を大きく見積もりがち
- VLBI parallax > Gaia parallax
の傾向とは逆のセンス

Luri et al. 2018



$$\begin{aligned} \frac{\sigma_{\pi}}{\pi} &= \frac{0.3 \text{ mas}}{10 \text{ mas}} \end{aligned}$$

$$\begin{aligned} \frac{\sigma_{\pi}}{\pi} &= \frac{0.3 \text{ mas}}{0.5 \text{ mas}} \end{aligned}$$

Parallax measurement uncertainty σ_{π}
Parallax π

考察2: Gaia DR2 に見られる Parallax zero point のオフセット

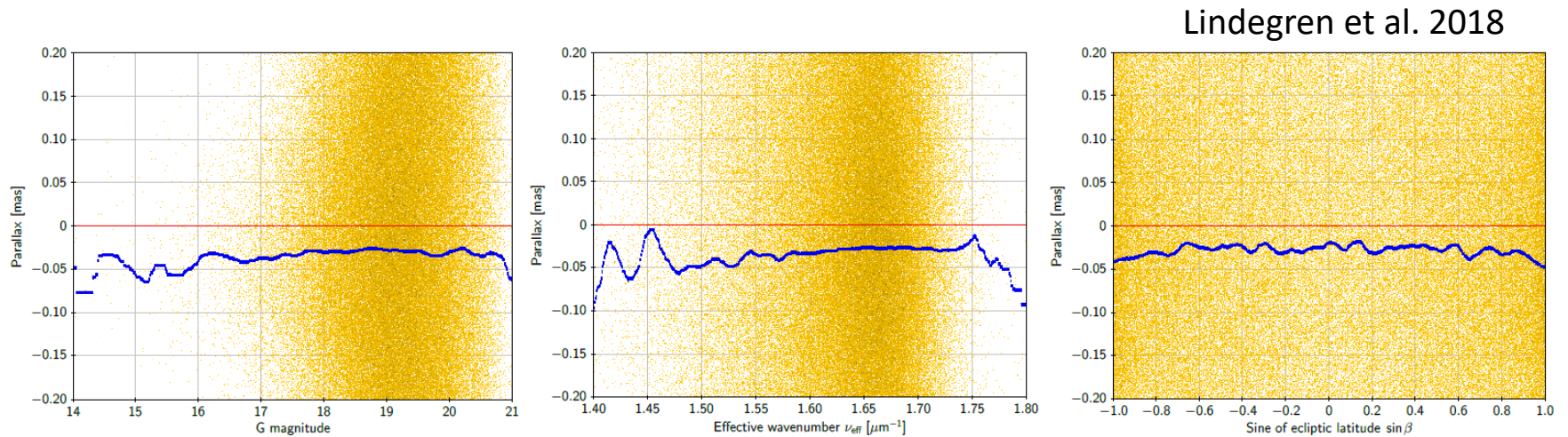


Fig. 7. Parallaxes for the full quasar sample plotted against magnitude (left), colour (middle), and ecliptic latitude (right). Because of the chosen scale, only about one-third of the data points are shown as yellow dots; the blue curves are the running medians.

- QSOを用いた内部検証
- Global zero point of the parallax
→ **-0.029 mas**
- Zero point offset に準周期的パターン
- **“-0.029 mas” はVLBI-Gaiaの差より十分小さい**

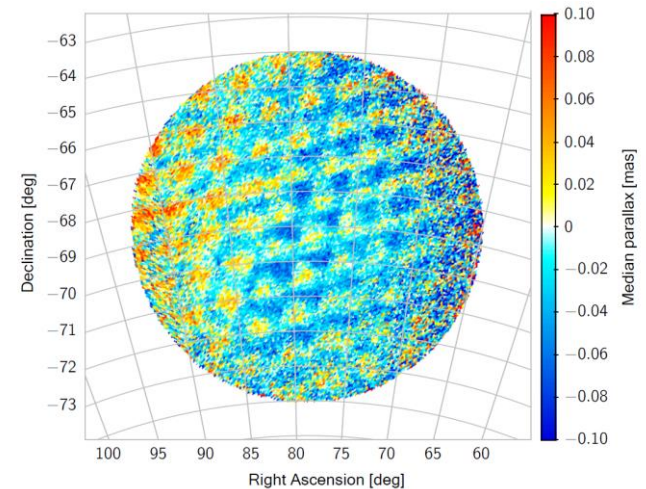
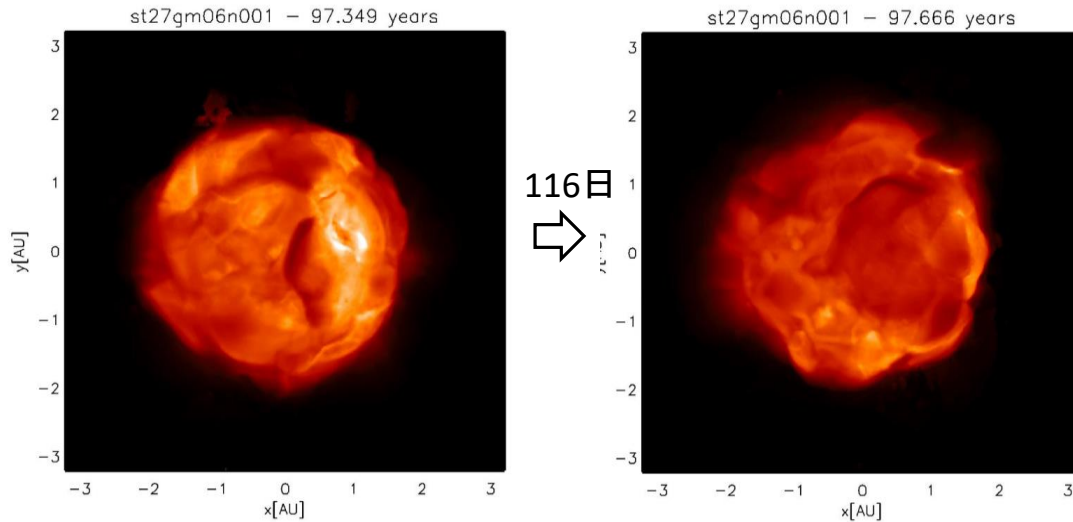


Fig. 13. Map of the median parallaxes for a sample of sources in the LMC area, showing small-scale variations of the parallax zero point. Median values are calculated in cells of about $0.057 \times 0.057 \text{ deg}^2$.

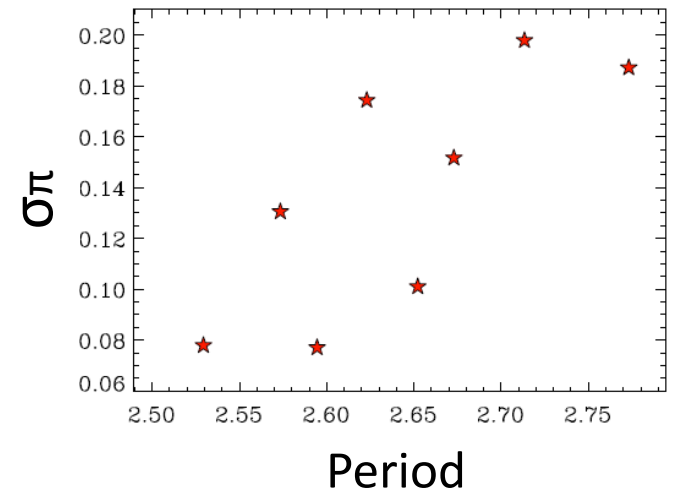
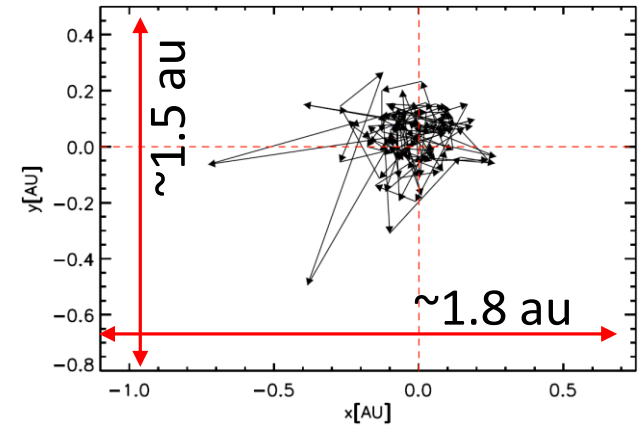
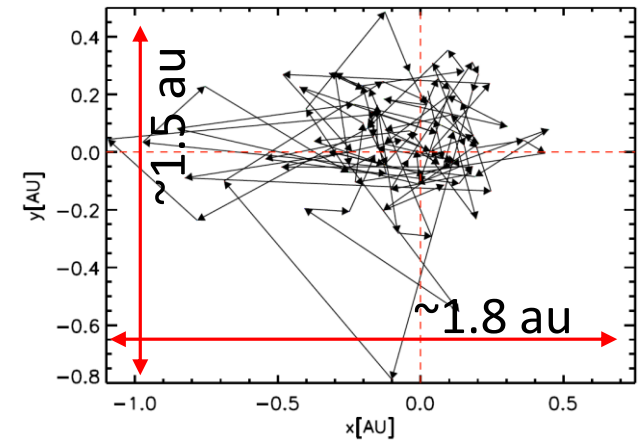
考察3: 表面輝度構造変化の影響

Chiavassa et al. 2018 (arXiv:1808.02548v1)

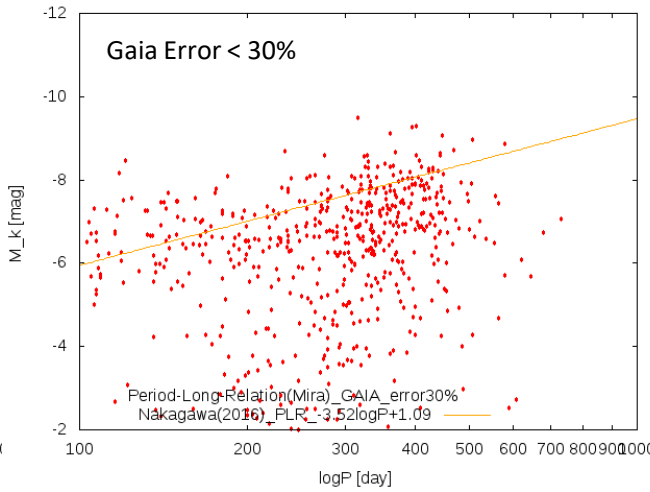
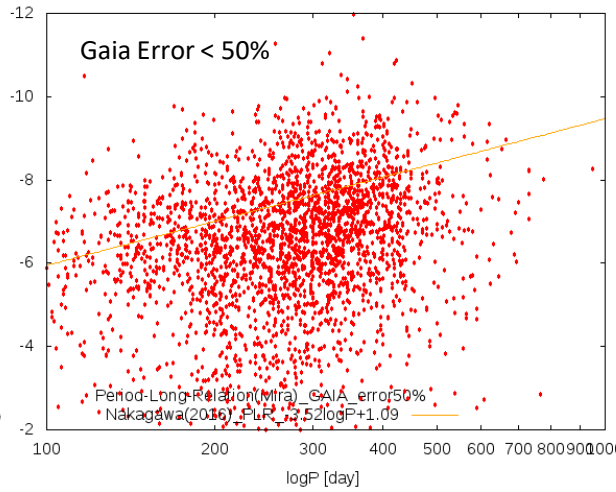
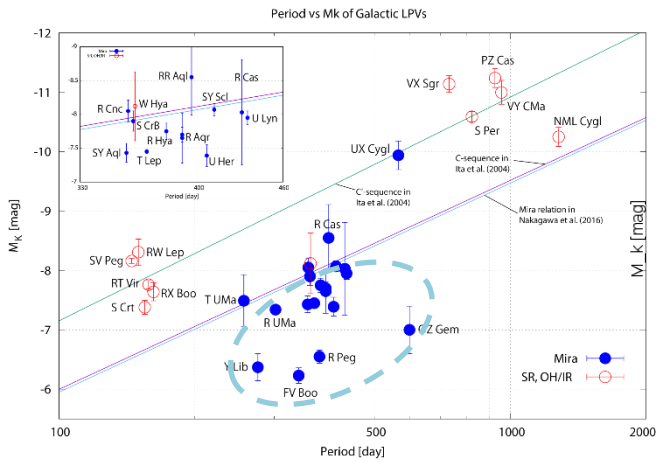
3D radiative-hydrodynamics simulations of convection



- ・シミュレーションからの見解
- ・1年より短い時間で表面輝度構造が変化
- ・数auの光球がその数十%のスケールで構造変化
- ・重心の移動 0.077 to 0.198 AU (~5 to ~11% of R_*)
- ・ σ_π の周期(P)依存も見えている
- ・影響は大きいだが VLBI parallax > Gaia parallax を説明しない

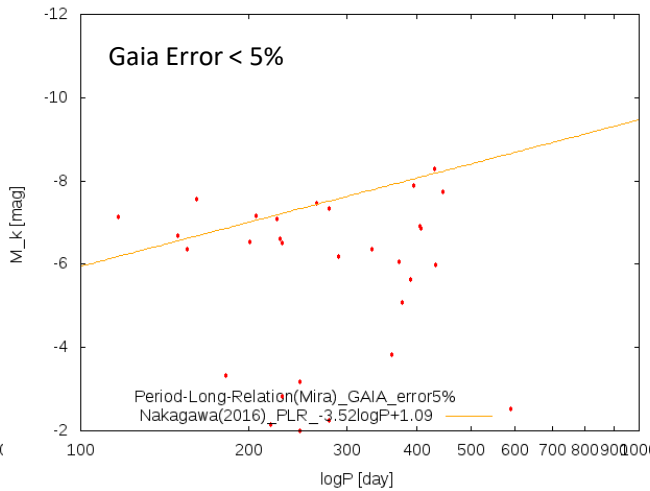
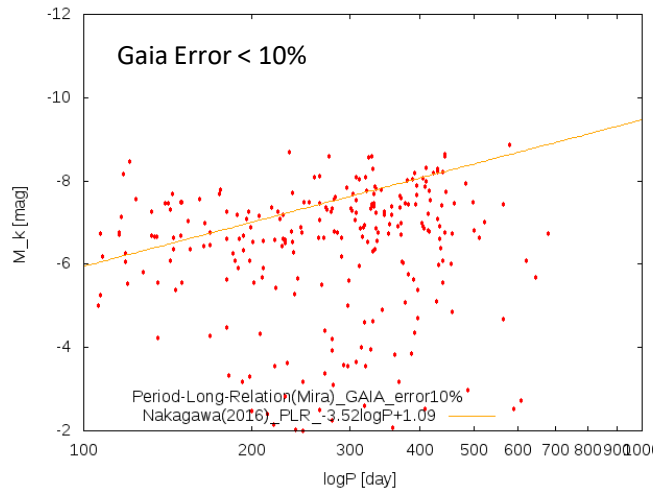


Gaiaの年周視差に基づくP-Mk分布



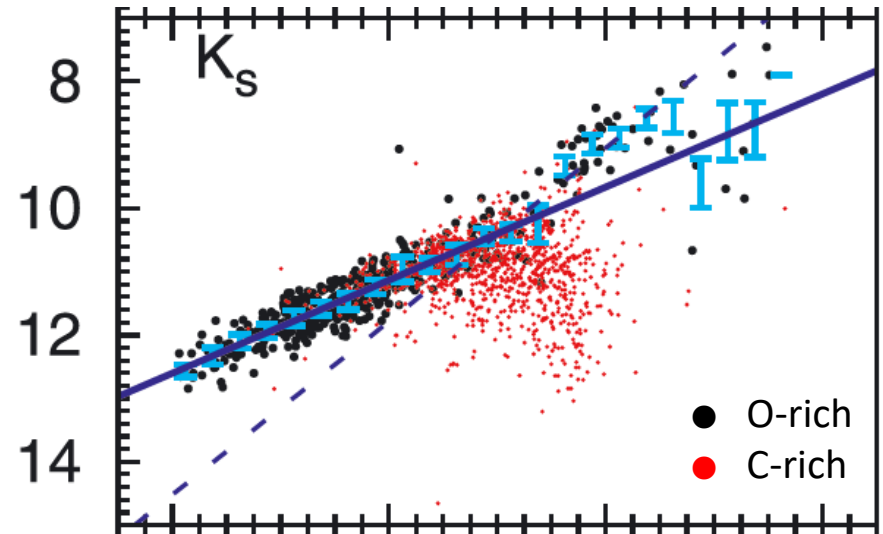
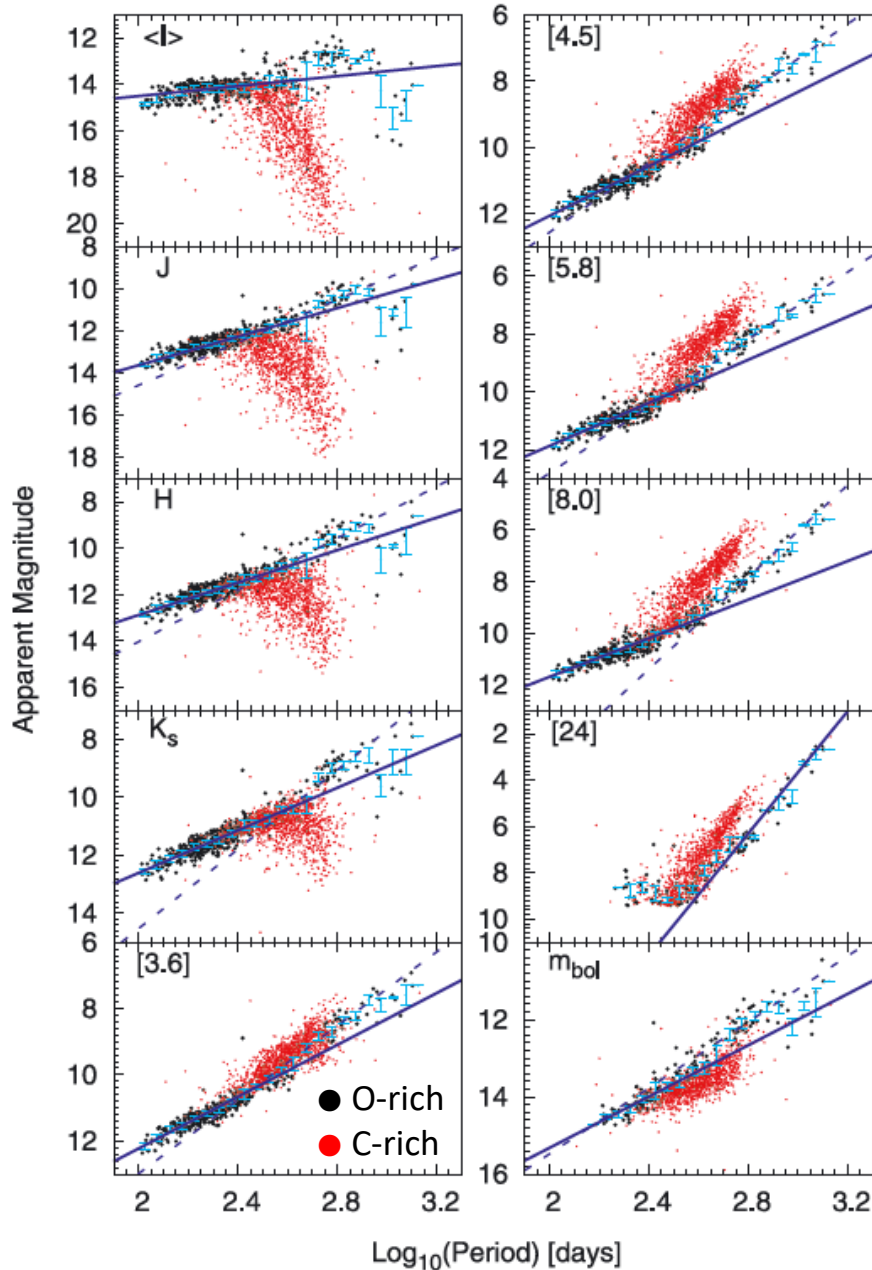
・約3000天体のLPV

・VLBIによるP-Mk分布と
同じ傾向を示すようだ



LMC のMira型星のP-Mk分布

Ita et al. 2011



- ・LMCのO-rich Mira (●) では暗い側への広がりは見られない
- ・O-rich Mira (●) の暗い側への広がりは我々の銀河に特有か
- ・天の川銀河Miraはダストによる星周減光が顕著？

VLBI位置天文はGaiaと相補的

- Gaiaで答えが出ない星もある
- OH/IR星の位置天文観測
- Extreme-OH/IR星 NSV25875
- Parallax = 0.38 ± 0.13 mas \rightarrow $D = 2.60 \pm 0.85$ kpc
- Qバンド広帯域(4Gbps)システムの活用

Method	Distance [kpc]
VERA parallax	2.60 ± 0.85
Phase-lag method	2.1 ± 0.42
Kinematic distance	2.50 ± 1.18

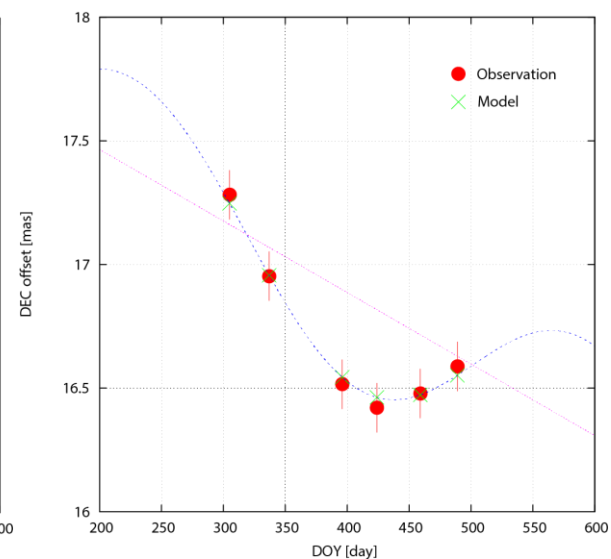
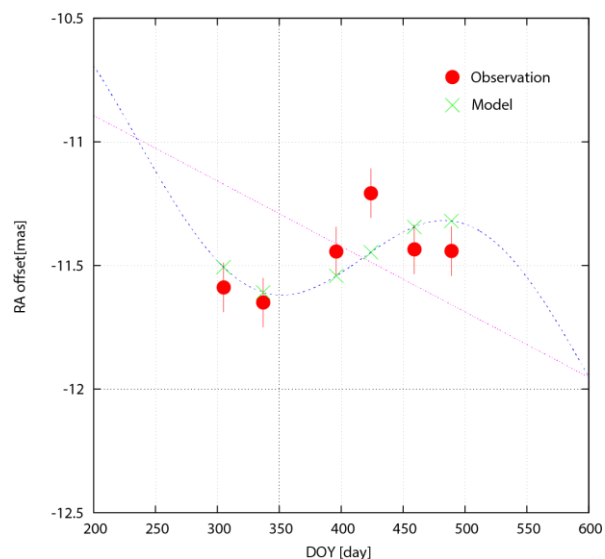
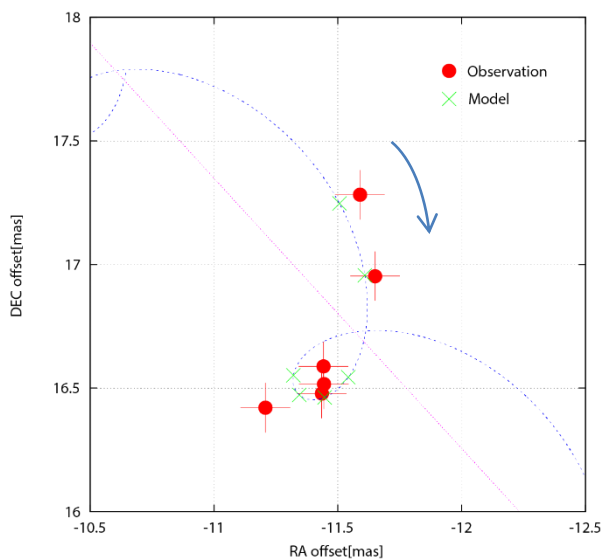
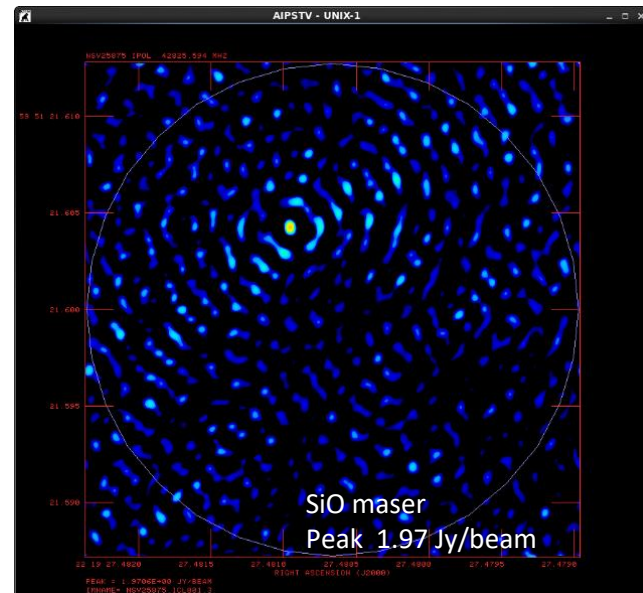


Fig : (上)43GHz SiO $v=2$ maser spot of an OH/IR star NSV25875 on 1 Nov 2017. (左)Sky plane motion of the maser spot from 1 Nov., 2017 to 4 May, 2108. (中)RA motion of the spot. Horizontal axis is days from 1 Jan., 2017. (右)DEC motion.