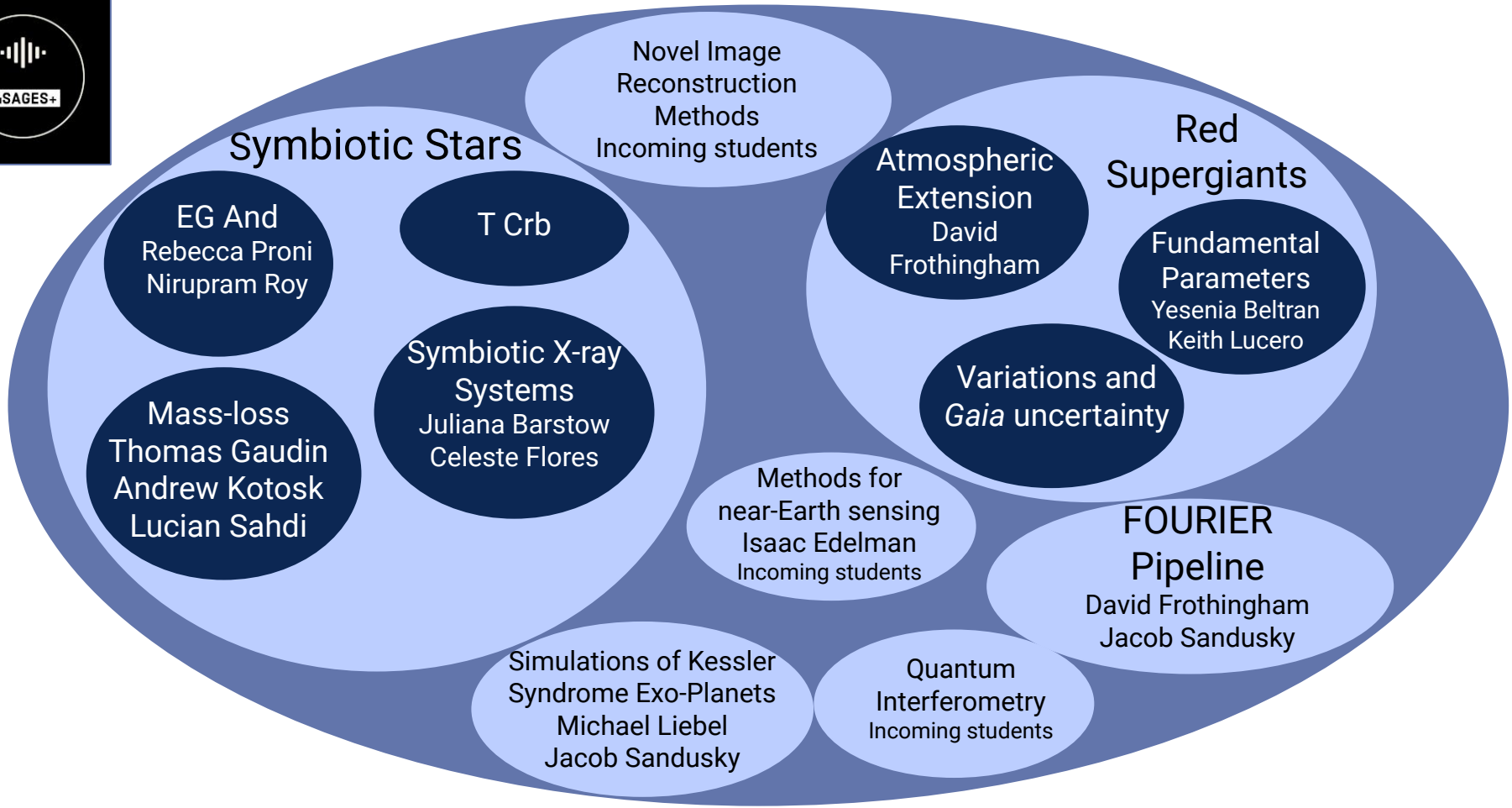
Student Science at NMT: Learning Optical Interferometry Through Projects on Evolved Stars

Updates from the Interferometry for Stellar and Galactic Evolution and Space Sensing (I4SAGES+) Group

Ryan Norris

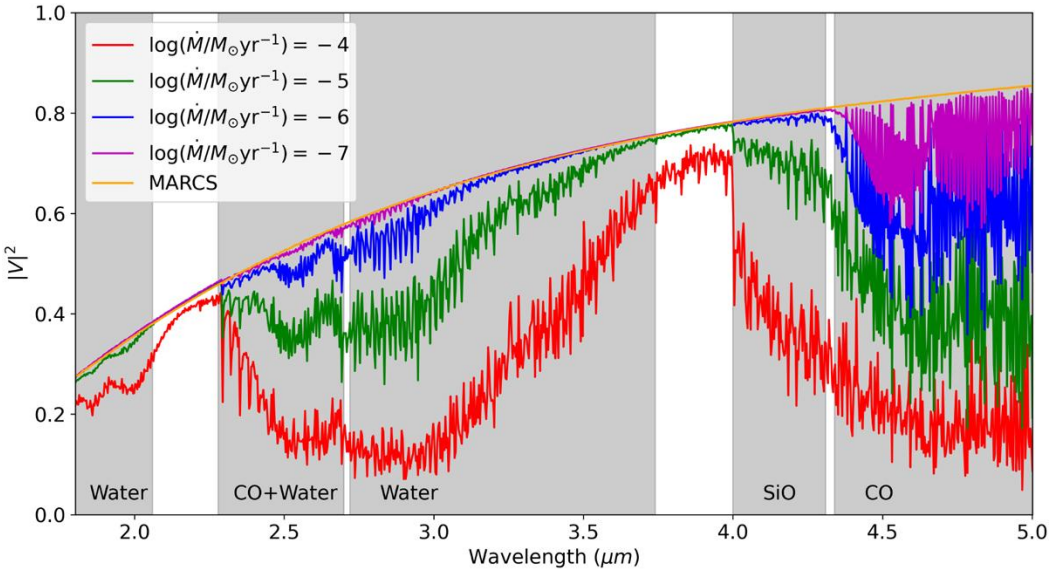
3-12-202


Novel Image Reconstruction Methods
Incoming students
Symbiotic Stars
EG And
Rebecca Proni
Nirupram Roy
T Crb
Symbiotic X-ray Systems
Juliana Barstow
Celeste Flores
Mass-loss
Thomas Gaudin
Andrew Kotosk
Lucian Sahdi
Red Supergiants
Atmospheric Extension
David Frothingham
Fundamental Parameters
Yesenia Beltran
Keith Lucero
Variations and *Gaia* uncertainty
Methods for near-Earth sensing
Isaac Edelman
Incoming students
FOURIER Pipeline
David Frothingham
Jacob Sandusky
Simulations of Kessler Syndrome Exo-Planets
Michael Liebel
Jacob Sandusky
Quantum Interferometry
Incoming students

Red Supergiants

High Mass Loss Red Supergiants (David Frothingham-GS)

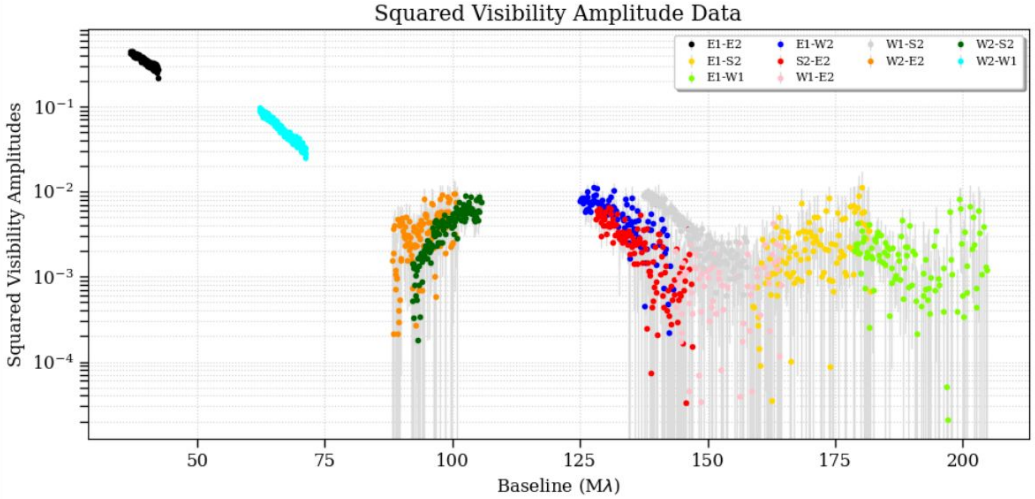
- MARCS models with winds produce atmospheric extension observed in RSGs but not yet reproduced in models
- The best objects for testing this would be high-mass loss or late type RSGs
  - RW Cep: 3.6x10^{-6} M$_{\odot}$/yr (Mauron and Johnson 2007)
  - SW Cep: 1.15x10^{-6} M$_{\odot}$/yr (Kee et al. 2021)
  - PZ Cas: 8.36x10^{-6} M$_{\odot}$/yr (Mauron and Johnson 2007)
  - V356 Cas
  - [NB54] 371



González-Torà et al. 2023

High Mass Loss Red Supergiants (David Frothingham-GS)

- Observations with MIRCX+MYSTIC and PAVO in Sep 2022
  - Poor weather! But thanks to generosity of CHARA we got some data on alternate night
  - PZ Cas on right
- Preliminary results show some disagreement with existing literature values



Target	Gaia Distance (pc)	Radii ($R_\odot$) Literature	Radii ($R_\odot$) this work
SW Cep	3010^{+218}_{-348}	234	1035^{+75}_{-120}
PZ Cas	2586^{+254}_{-286}	1940 (V band) 1190 (K band)	1585^{+160}_{-180}

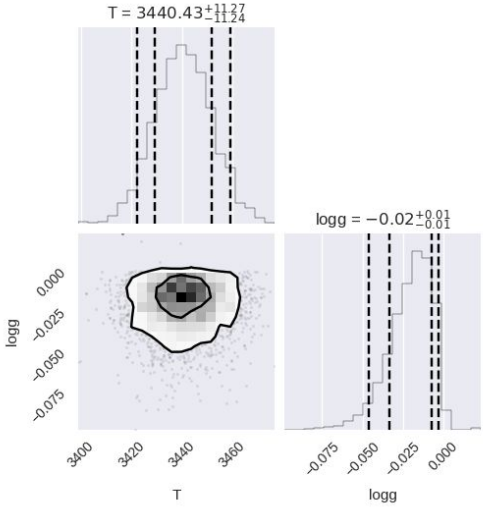
Fundamental Parameters of Red Supergiants (Yesenia Beltran-UG, Keith Lucero-UG)

- Using MIRC 2015, 2016 and IRTF SpeX 2015, 2016 observations
- Angular diameter fits using UltraNest within OITOOLS.jl
- Using *Gaia* distances derived in Bailer-Jones et al. 2021

Object	θ_{UD}	χ^2_{UD}	ln Z_{UD}	θ_{LD}	α	χ^2_{LD}	ln Z_{LD}	Radius ($R_\odot$)
V366 AND	$2.48^{+0.07}_{-0.05}$	3.28	−6.96	$2.60^{+0.12}_{-0.09}$	$0.39^{+0.32}_{-0.24}$	3.28	−6.96	492^{+39}_{-29}
XX PER	$2.93^{+0.13}_{-0.1}$	7.37	−8.73	$3.11^{+0.13}_{-0.13}$	$0.61^{+0.26}_{-0.31}$	7.37	−8.73	718^{+80}_{-56}
KK PER	$2.30^{+0.04}_{-0.04}$	3.69	−7.66	$2.45^{+0.11}_{-0.1}$	$0.43^{+0.3}_{-0.25}$	3.69	−7.66	513^{+22}_{-18}
PP PER	$1.60^{+0.12}_{-0.08}$	0.74	−5.61	$1.74^{+0.17}_{-0.12}$	$0.53^{+0.33}_{-0.35}$	0.74	−5.61	372^{+35}_{-23}
BU PER	$2.82^{+0.15}_{-0.12}$	24.20	−17.05	$2.75^{+0.12}_{-0.11}$	$0.84^{+0.12}_{-0.19}$	24.20	−17.05	686^{+75}_{-57}
AD PER	$2.60^{+0.13}_{-0.1}$	5.91	−7.78	$2.76^{+0.14}_{-0.13}$	$0.61^{+0.26}_{-0.35}$	5.91	−7.78	594^{+49}_{-37}
FZ PER	$1.82^{+0.04}_{-0.02}$	23.60	−18.08	$2.13^{+0.06}_{-0.06}$	$0.89^{+0.08}_{-0.15}$	23.60	−18.08	496^{+32}_{-28}
PR PER	$2.22^{+0.14}_{-0.09}$	26.68	−18.36	$2.44^{+0.09}_{-0.09}$	$0.81^{+0.13}_{-0.21}$	26.68	−18.36	603^{+57}_{-47}
SU PER	$5.30^{+0.25}_{-0.46}$	30.05	−18.81	$3.53^{+0.09}_{-0.09}$	$0.78^{+0.16}_{-0.19}$	30.05	−18.81	1259^{+95}_{-129}
RS PER	$2.98^{+0.02}_{-0.02}$	19.89	−16.51	$3.34^{+0.07}_{-0.09}$	$0.79^{+0.14}_{-0.21}$	19.89	−16.51	775^{+110}_{-85}
S PER	$4.95^{+0.21}_{-0.18}$	19.07	−13.82	$5.13^{+0.24}_{-0.23}$	$0.69^{+0.21}_{-0.28}$	19.07	−13.82	1298^{+64}_{-57}
W PER	$2.97^{+0.04}_{-0.04}$	8.97	−10.56	$3.24^{+0.11}_{-0.11}$	$0.64^{+0.25}_{-0.24}$	8.97	−10.56	558^{+49}_{-30}
TV GEM	$6.45^{+0.13}_{-0.11}$	45.03	−27.6	$4.57^{+0.12}_{-0.14}$	$0.95^{+0.04}_{-0.08}$	45.03	−27.60	1627^{+972}_{-388}
WY GEM	$2.70^{+0.08}_{-0.07}$	4.02	−7.23	$2.85^{+0.13}_{-0.12}$	$0.48^{+0.32}_{-0.27}$	4.02	−7.23	522^{+45}_{-34}
6 GEM	$7.16^{+0.39}_{-0.26}$	61.23	−34.47	$4.67^{+0.09}_{-0.09}$	$0.95^{+0.03}_{-0.06}$	61.23	−34.47	1353^{+346}_{-241}
NR VUL	$3.09^{+0.05}_{-0.04}$	6.17	−8.65	$3.34^{+0.14}_{-0.16}$	$0.54^{+0.3}_{-0.36}$	6.17	−8.65	923^{+62}_{-50}
BD+354077	$3.25^{+0.06}_{-0.05}$	7.88	−9.58	$3.61^{+0.12}_{-0.16}$	$0.72^{+0.2}_{-0.31}$	7.88	−9.58	627^{+31}_{-30}
BI CYG	$5.51^{+0.09}_{-0.07}$	2.02	−6.40	$5.98^{+0.26}_{-0.28}$	$0.57^{+0.3}_{-0.37}$	2.02	−6.40	1528^{+140}_{-135}
RW CYG	$6.31^{+0.26}_{-0.26}$	22.28	−15.25	$6.00^{+0.14}_{-0.14}$	$0.82^{+0.12}_{-0.17}$	22.28	−15.25	1119^{+96}_{-85}
AZ CYG	$3.82^{+0.06}_{-0.05}$	16.08	−13.75	$3.96^{+0.09}_{-0.08}$	$0.45^{+0.17}_{-0.16}$	16.08	−13.75	941^{+55}_{-49}
KSI CYG	$5.41^{+0.12}_{-0.06}$	0.30	−5.68	$5.84^{+0.28}_{-0.29}$	$0.49^{+0.34}_{-0.33}$	0.30	−5.68	206^{+9}_{-10}
LW CYG	$4.25^{+0.08}_{-0.07}$	15.83	−13.18	$4.52^{+0.21}_{-0.2}$	$0.48^{+0.35}_{-0.33}$	15.83	−13.18	445^{+13}_{-11}
V424 LAC	$3.83^{+0.08}_{-0.08}$	13.85	−12.32	$4.0^{+0.15}_{-0.13}$	$0.7^{+0.2}_{-0.25}$	13.85	−12.32	288.0^{+26}_{-21}

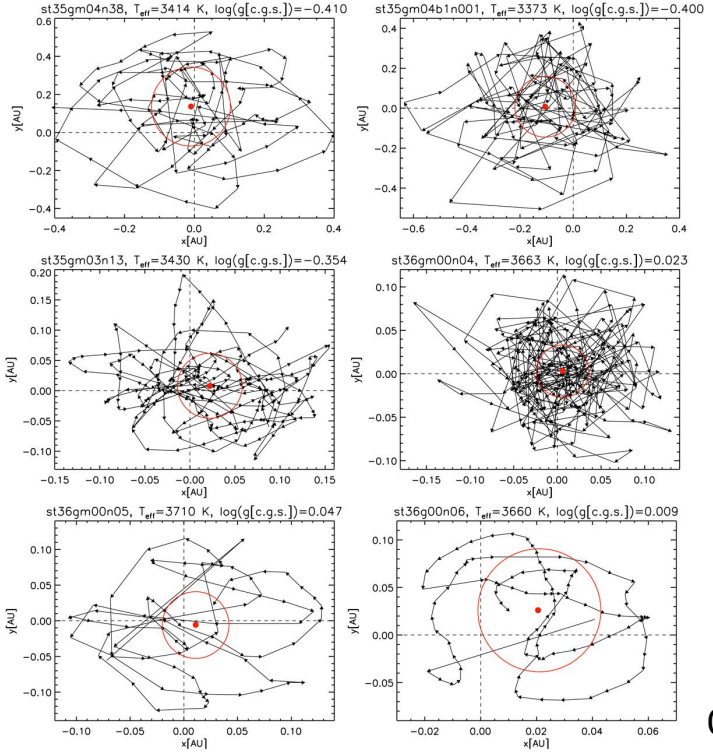
Fundamental Parameters of Red Supergiants (Yesenia Beltran-UG, Keith Lucero-UG)

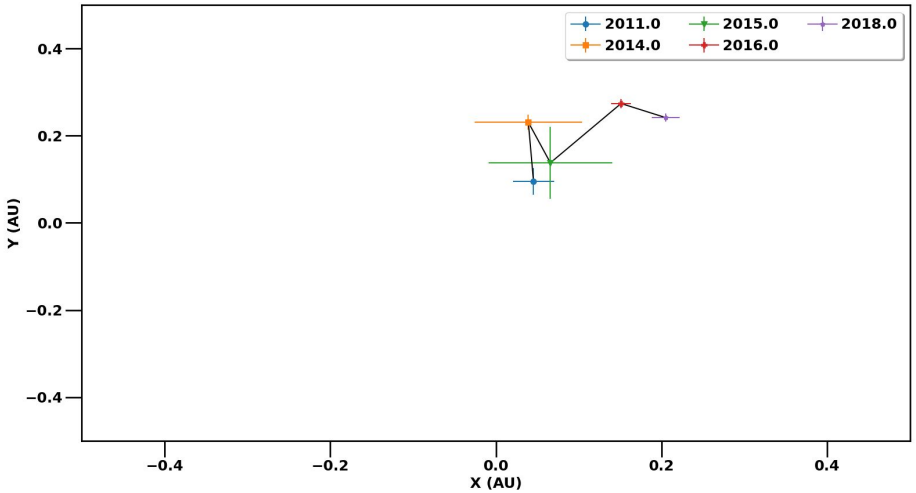
- Using MIRC 2015, 2016 and IRTF SpeX 2015, 2016 observations
- Temperatures derived using Starfish code with synthetic spectra from PHOENIX (values below; RSG grid from Lancon et al. 2007), MARCS, and SATLAS models



Object	Temperature (K)	Levesque 2005 Temperature (K)	Gazak et al. 2014 Temperature (K)
XX PER	3440^{+13}_{-14}	NA	NA
KK PER	3443^{+12}_{-13}	NA	4030 ± 25
RS PER	3440^{+11}_{-11}	3550	3690 ± 50
SU PER	3467^{+13}_{-13}	3575	NA
TV GEM	3278^{+27}_{-26}	3700	NA
WY GEM	3306^{+21}_{-22}	NA	NA
6 GEM	3396^{+15}_{-014}	3800	NA

Centro-symmetry variations compared to Gaia errors

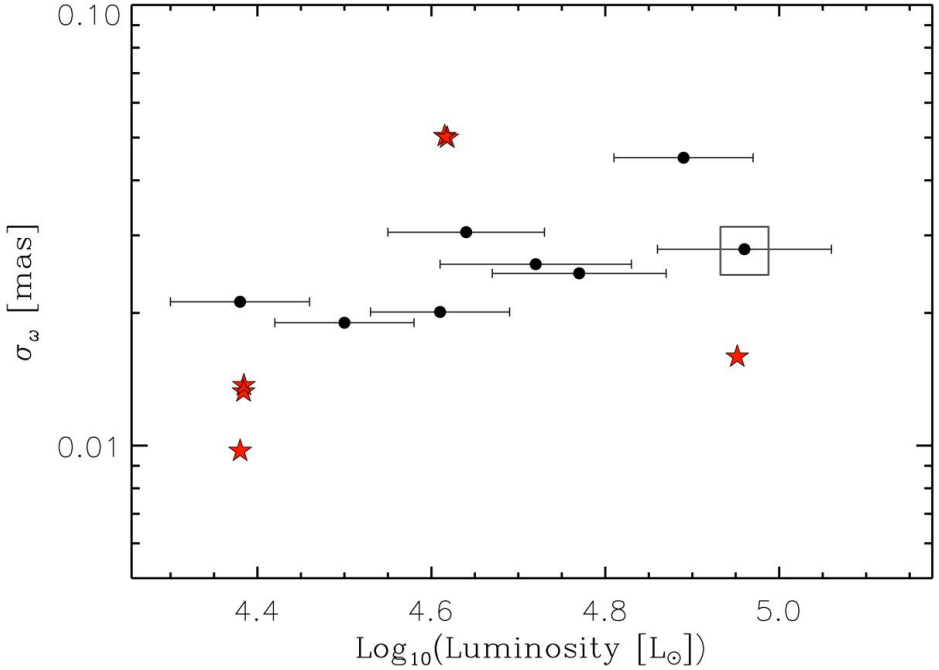




Variations in center of mass location scaled to distance used in Chiavassa et al. 2022

Chiavassa et al. 2022

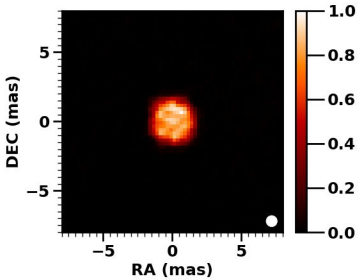
Centro-symmetry variations compared to *Gaia* errors



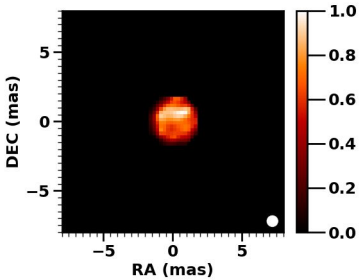
Chiavassa et al. 2022

- Spread in photo-center shift for SU Per : 0.03 mas (Chiavassa et al. 2022)
- *Gaia* uncertainty for SU Per (in square): 0.03 mas

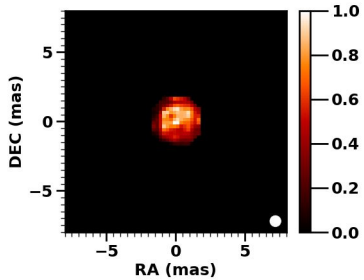
Imaging SU Per



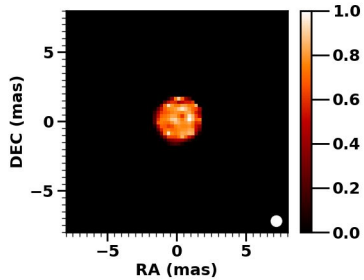
2015



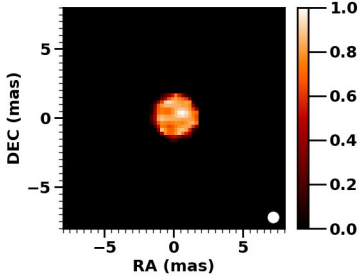
2016



2019



2020



2021

On-going work (Norris et al. in prep) studying both long and short-term observations

Images shown here made with squeeze using total variation and laplacian regularizers with 3.5 mas masks

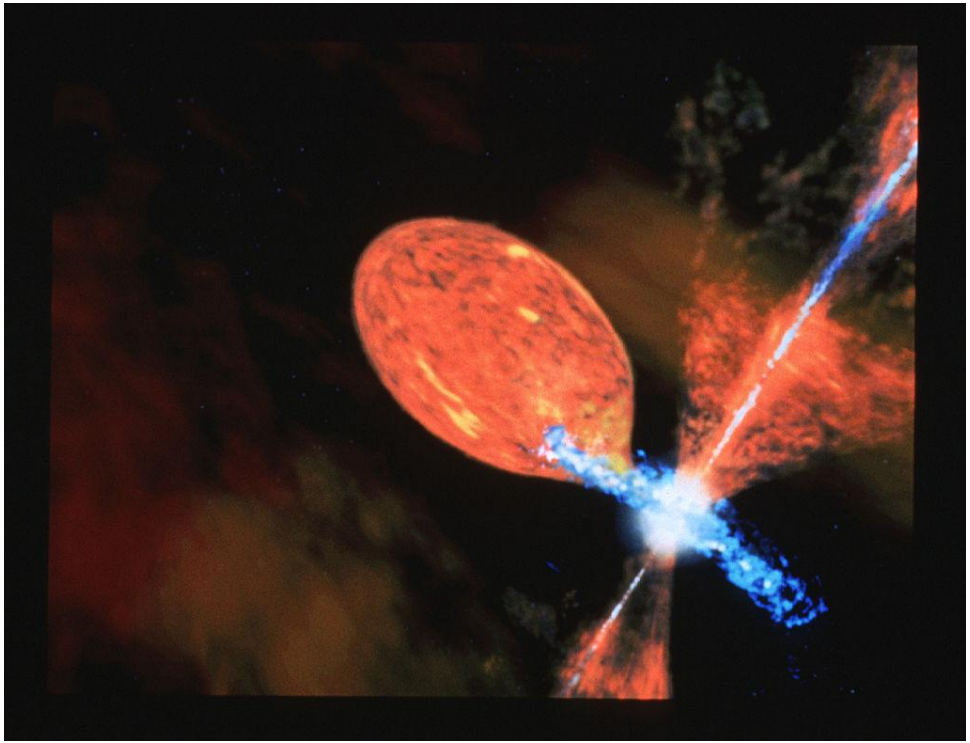
Symbiotic Stars

This material is based upon work supported by the National Science Foundation under Grant 2213518 (LEAPS-MPS)

And in collaboration with Magdalena Otulakowska-Hypka

What are symbiotic stars?

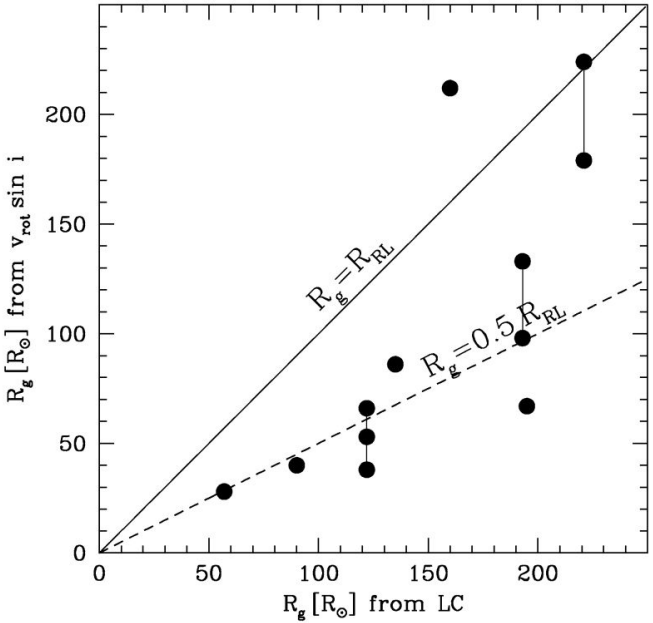
- Wide orbit interacting binaries with cool (M type usually) and hot, compact (usually white dwarf) object
- Compact object accretees mass
  - Type Ia Supernovae Progenitor?



NASA, ESA, and D. Berry (STScI)

How does mass get to an accretion disk in symbiotic stars?

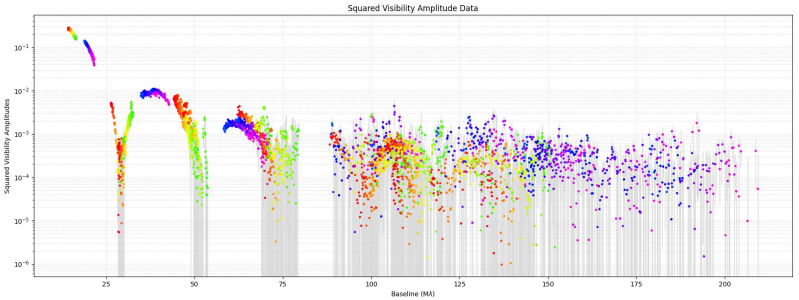
- Observations show a discrepancy in determined radii of red giant
- Ellipsoidal variations in light curves suggest Roche lobe overflow
- But radii derived from rotational velocities suggest otherwise
- We need interferometric radii!

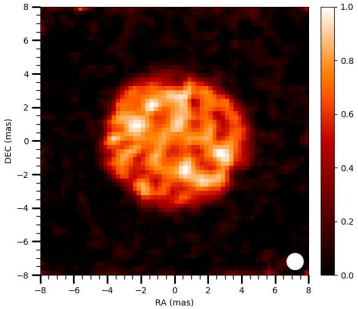


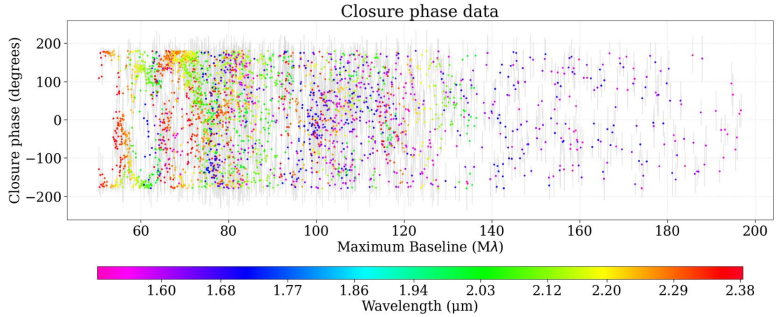
Mikolajewska (2007)

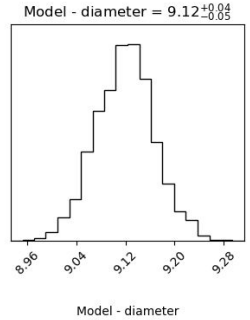
Interferometry of Symbiotic Stars (Thomas Gaudin-GS)

- Imaging and model fitting of giant in systems
  - EG And, BD Cam, V1472 Aql, SU Lyn
  - Gaudin et al. in prep.
- Models include uniform disk, elongated disk and hybrid model
- Other stars in program too
  - Right: CH Cyg



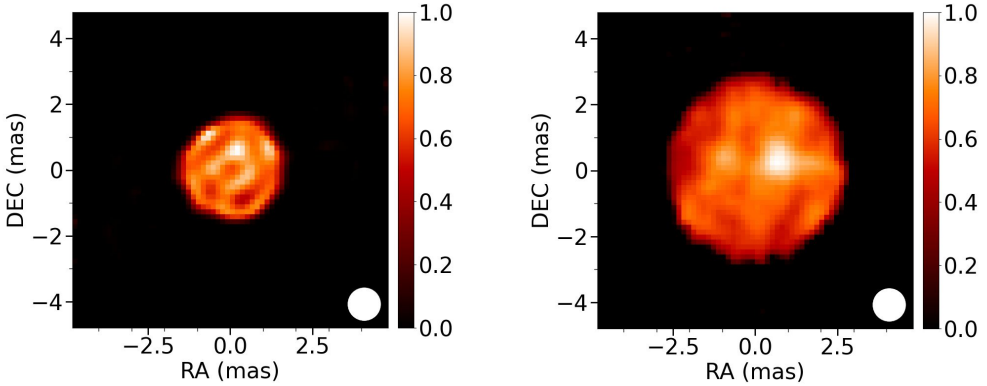






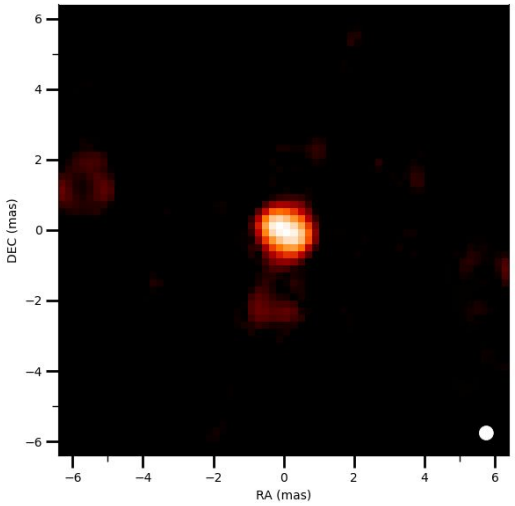
Interferometry of Symbiotic Stars (Thomas Gaudin-GS)

- SU Lyn (L) and BD Cam (R)
  - Gaudin et al. in prep
- SU Lyn is likely transitioning toward an early stage AGB (Ilkiewicz et al. 2022)
- BD Cam is a giant



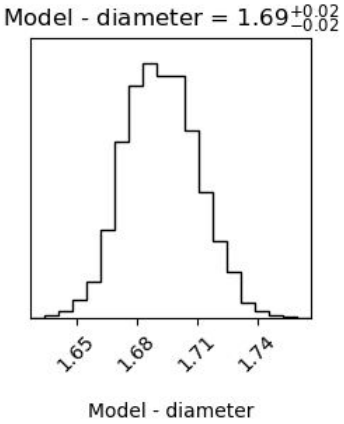
Imaging EG And (Rebecca Proni-GS)

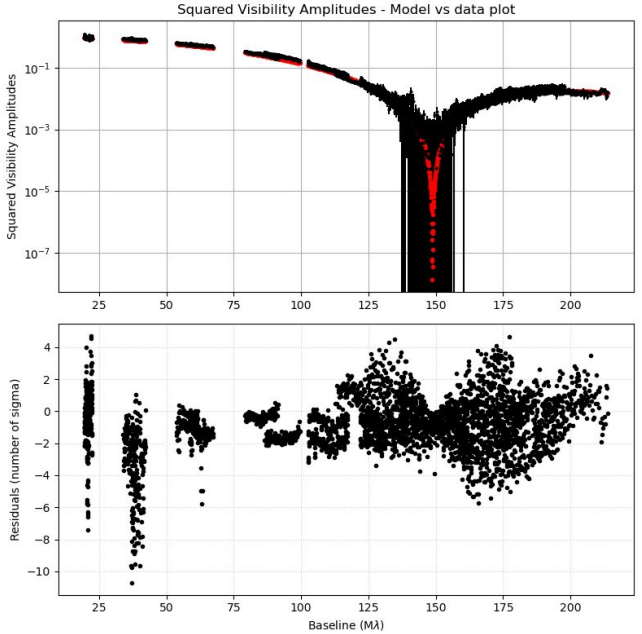
- Data spanning 2016-2022, more if using archival data
- An interesting target because it exhibits ellipsoidal light curves
- BUT! Interferometric radius combined with dynamical mass suggests star is not filling Roche radius (Gaudin et al. in prep)
- Image on right: July 2022 with OITOOLS.jl
- Rebecca is working on imaging each epoch
- Inclination 60° (Sion, E.M et al. 2017)



Modelling EG And (Nirupam Roy-GS)

- Data spanning 2016-2021, more if using archival data
- An interesting target because it exhibits ellipsoidal light curves
- BUT! Interferometric radius combined with dynamical mass suggests star is not filling Roche radius
- Nirupam is working on investigating changes in radii and/or shape across different points in the orbit





4U +1954

- Long Period X-Ray Binary (symbiotic?) with Neutron Star
- *Recently identified as containing a supergiant:*
  - *M4 I (Hinkle et al. 2020)*
  - *NOT a traditional symbiotic system*
- *Spectra gave T=* $3450^{+100}_{-50} K$
- *SED* and *Gaia* distance (3295^{+985}_{-631} pc) give
  - L= $43880^{+3470}_{-15900}\ L_\odot$ R= $586^{+188}_{-127}\ R_\odot$
    - Hinkle et al. 2020

V934 Her

- X-Ray Symbiotic with Neutron Star

4U +1954

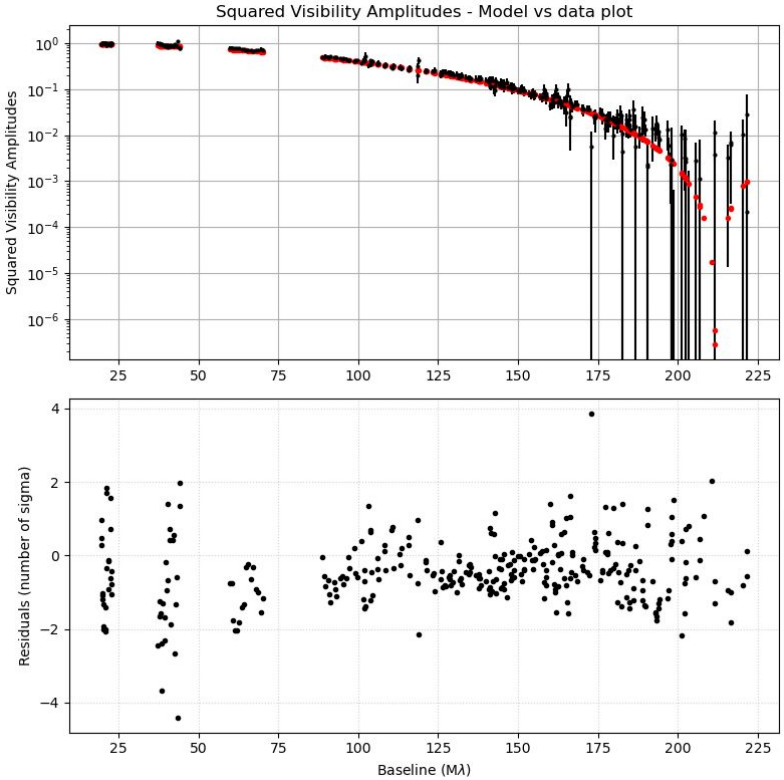
Fitting with UltraNest within OITOOLS.jl

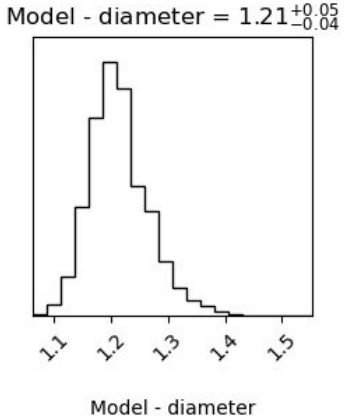
$$R = 447^{+15}_{-35}\ R_\odot$$

with parallax from Bailer-Jones et al. 2021

$$R = 428^{+129}_{-83}\ R_\odot$$

with parallax used in Hinkle et al. 2020





$$\chi^2 = 0.99$$

V934 Her

Fitting with UltraNest within OITOOLS.jl

$$R = 79^{+4}_{-4}\ R_\odot$$

with parallax from Bailer-Jones et al. 2021

$$R = 80^{+4}_{-3}\ R_\odot$$

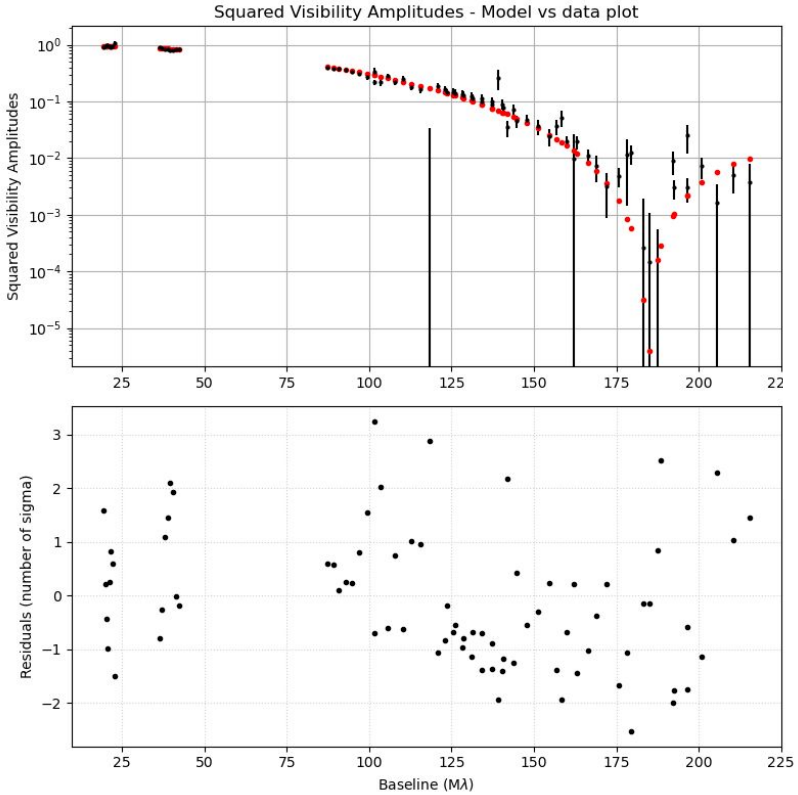
with parallax used in Hinkle et al. 2019

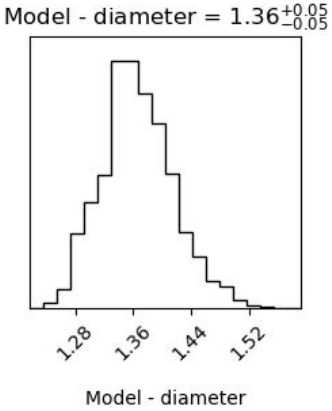
$$71\ R_\odot$$

in Hinkle et al. 2019 and

$$90\ R_\odot$$

in Van Belle et al. 1999





$$\chi^2 = 1.58$$

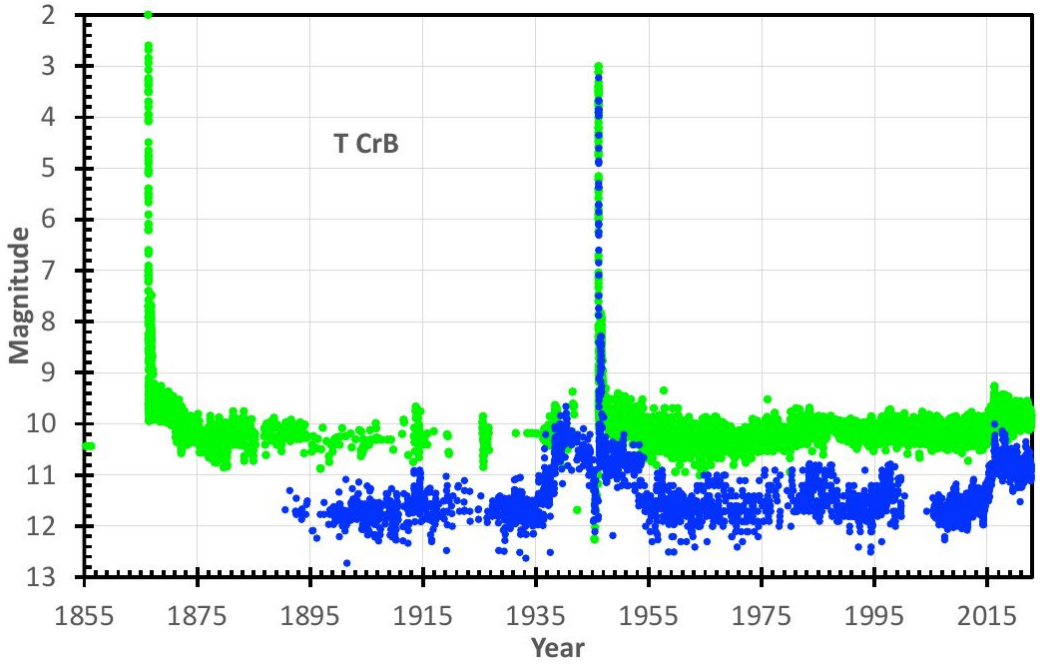
T Crb: An upcoming recurrent nova

- Closest recurrent nova
- Eruption in 1866 and 1946
- XMM-Newton observations suggest increased accretion in the past five years
- Brightness increases similar to that of past events
- Previous Predictions:

$$2023.6 \pm 1$$

$$2026 \pm 3$$

(Schaefer, B.E 2019; Luna et al. 2020)



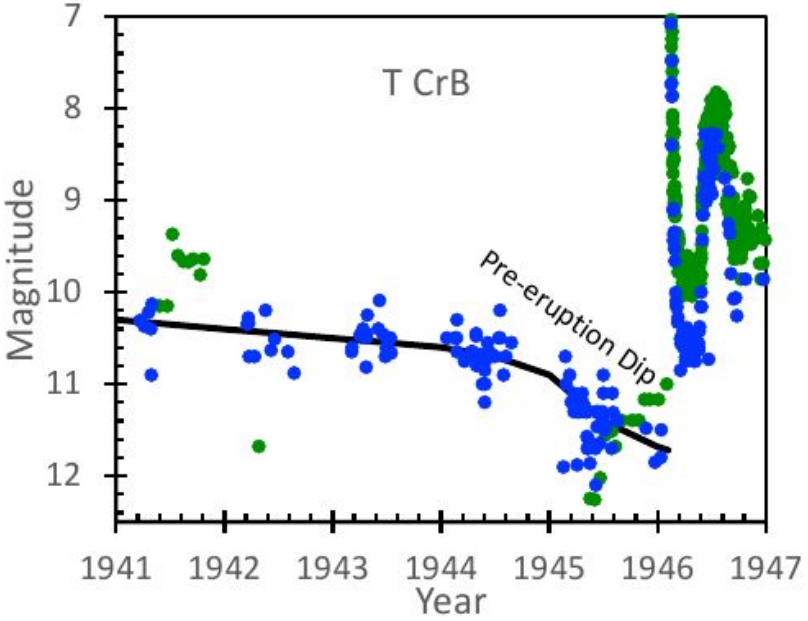
Schaefer, B.E. 2023

T Crb: An upcoming nova

- Nova in 1866 and 1946

  In 1946, a decrease in brightness happened roughly one year before nov

- Cause?
  - Possibly related to circumstellar dust
  - P Cygni profile observed prior to 1946 eruption



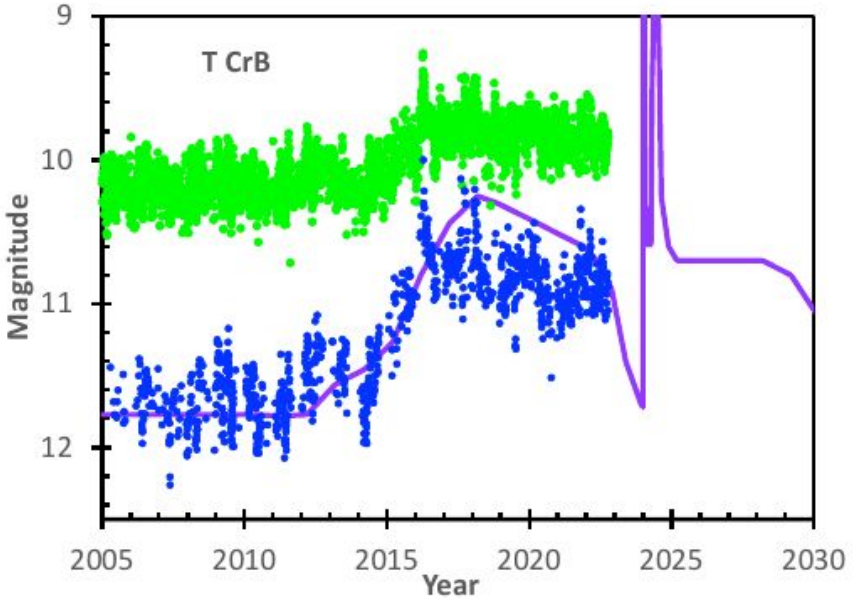
Schaefer, B.E. 2023

T Crb: An upcoming nova

Newest prediction based on comparison to previous eruptions

$$2025.5 \pm 1.3$$

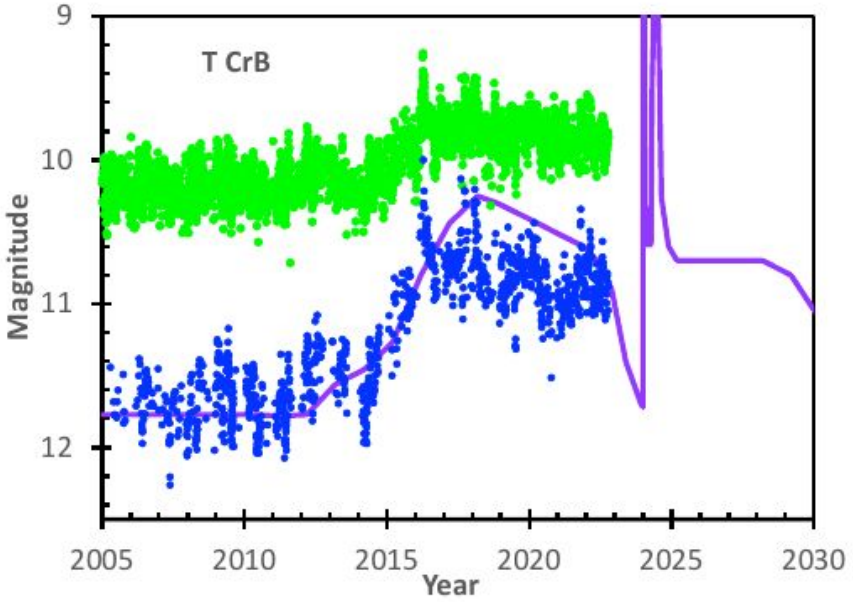
Schaefer, B.E. 2023



Schaefer, B.E. 2023

T Crb: An upcoming nova

- Multi-discipline collaboration
  - X-Ray, Radio, novae experts
- Goals: Monitor in time leading up to eruption
  - Aide in interpreting nova observations
  - Understand pre-eruption dip?
- Determine mass-transfer mechanism
  - Inclination 60° (Belczynski & Mikolajewska 1998)
  - Estimated angular diameter 0.9 mas

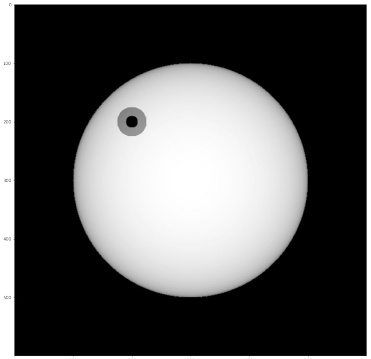


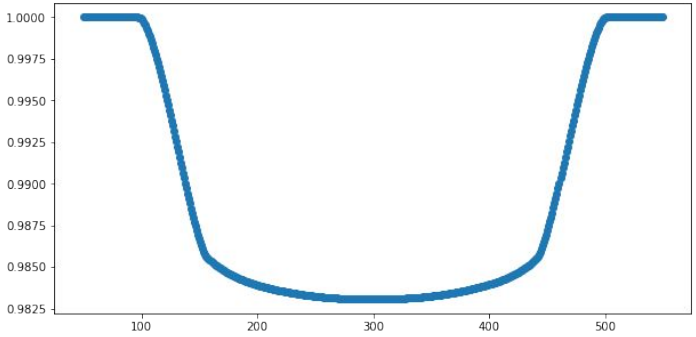
Schaefer, B.E. 2023

Other Projects

Simulating Light Curves of Exoplanets with Satellite Debris (Michael Liebel-UG and Jacob Sandusky-UG)

- Currently making models of limb darkened disks and atmosphere approximated via gradient
- Next step is to model debris

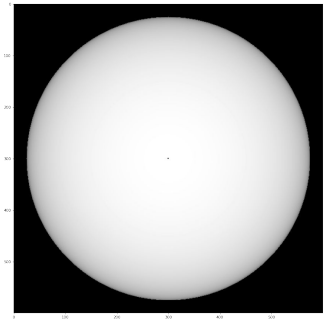




Upper Left: Star and plane with exaggerated atmosphere

Upper Right: Light curve for upper left model

Lower Right: Scale simulation of Mercury around Sun



Summary

- Six undergraduates learning optical interferometry and/or simulation techniques
- Three graduate students learning optical interferometry and studying evolved stars, all using CHARA data/conducting observations via NOIRLab
  - Many others are contributing to MROI development outside of my group
- Looking ahead to MROI: Larger RSGs, including very evolved objects that are faint in optical wavelengths; additional symbiotic and other interacting binaries; numerous other object classes!