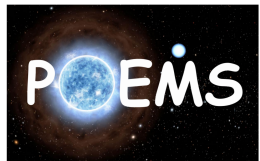


# Stellar outflows with the NOT



Tiina Liimets (ASU, Czech)

R. Corradi (GTC, Spain)  
 M. Santander-García (OAN, Spain)  
 B. Balick (UW, USA)  
 M. Kraus (ASU, Czech)  
 D. Jones (IAC, Spain),  
 A. Djupvik (NOT)

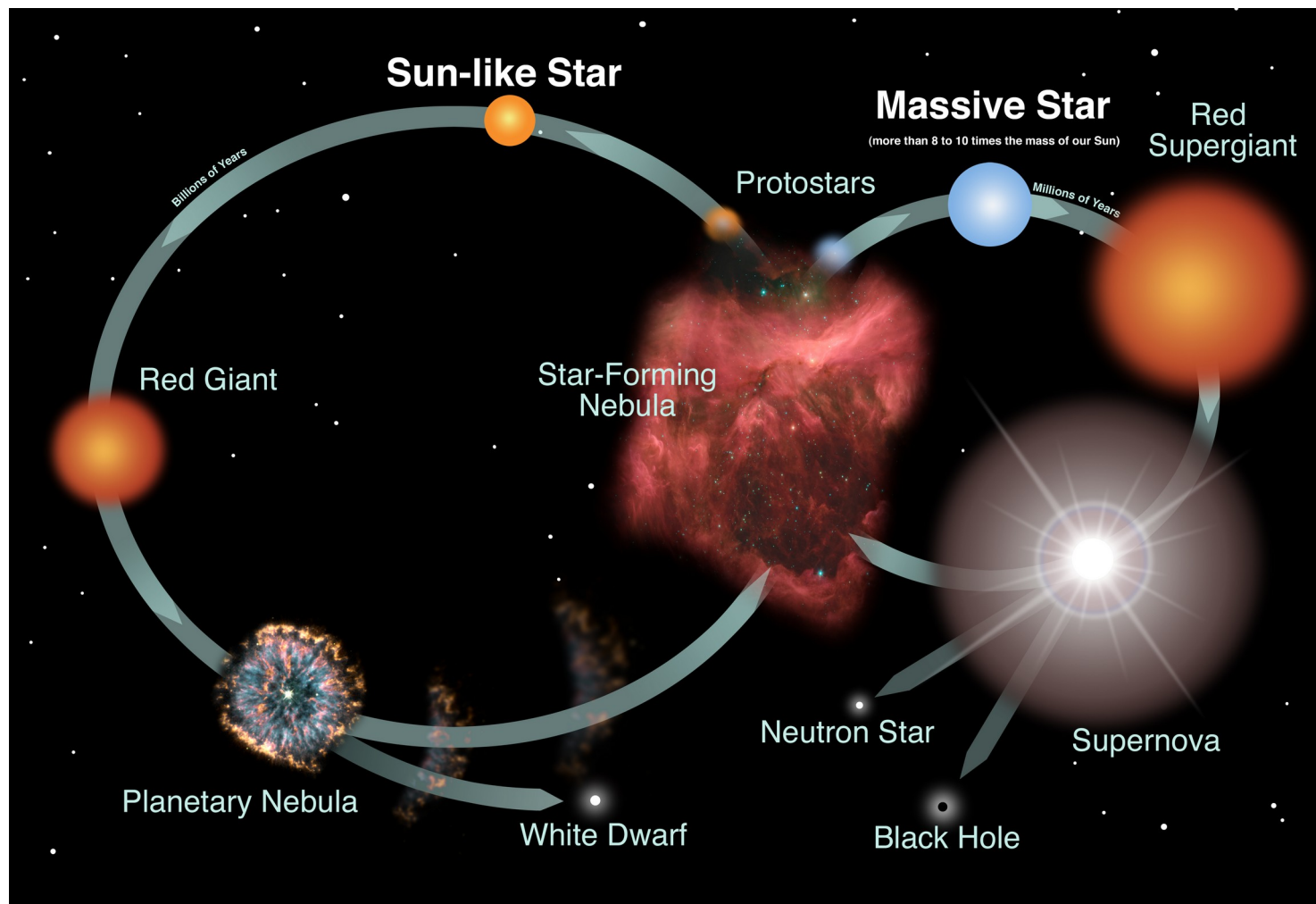


Physics of Extreme  
 Massive Stars  
 Marie-Curie-RISE project  
 funded by the European Union



# It all starts with a nebula and ends with a nebula!

Most of stars are binaries!



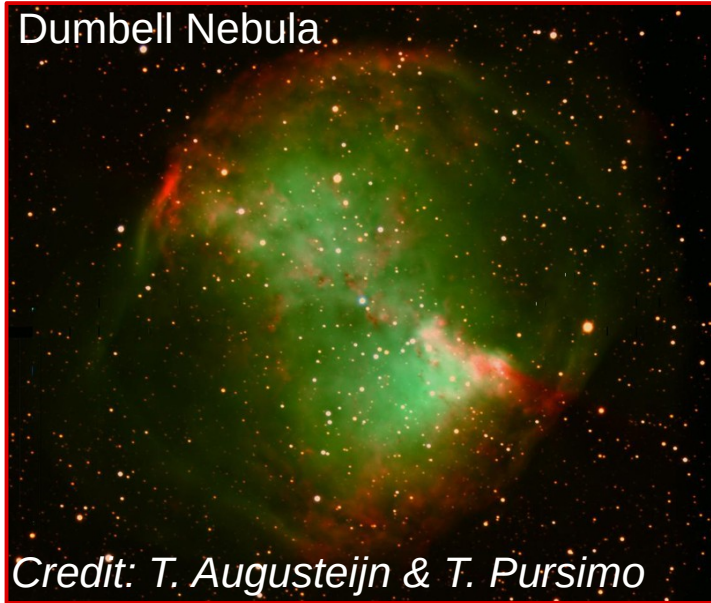
*Credit: NASA and the Night Sky Network*

# WHY study stellar outflows?

**Astronomy in real time!**

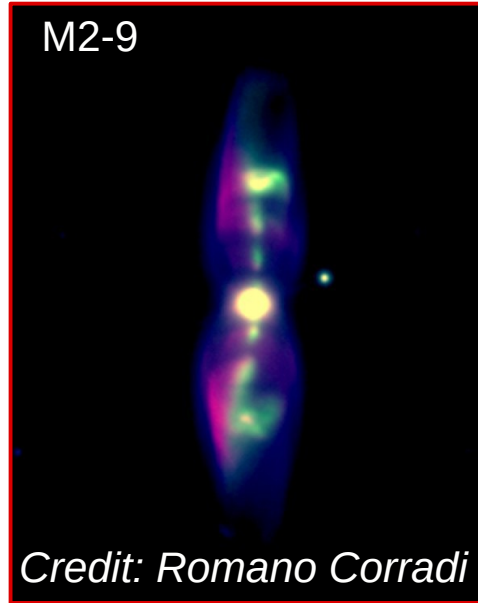
Proper motions! + spectra = 3D

Dumbell Nebula



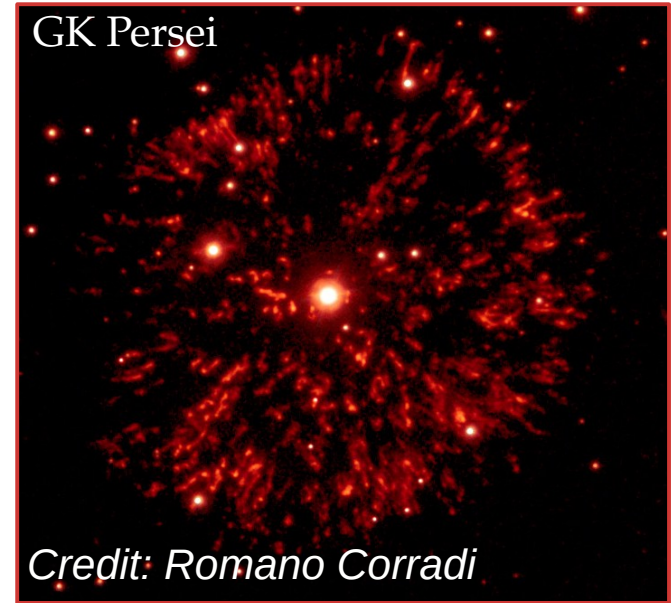
*Credit: T. Augusteijn & T. Pursimo*

M2-9



*Credit: Romano Corradi*

GK Persei



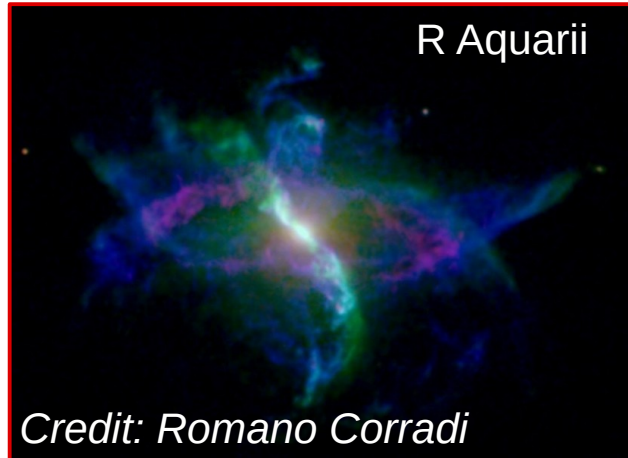
*Credit: Romano Corradi*

Little Dumbbell Nebula



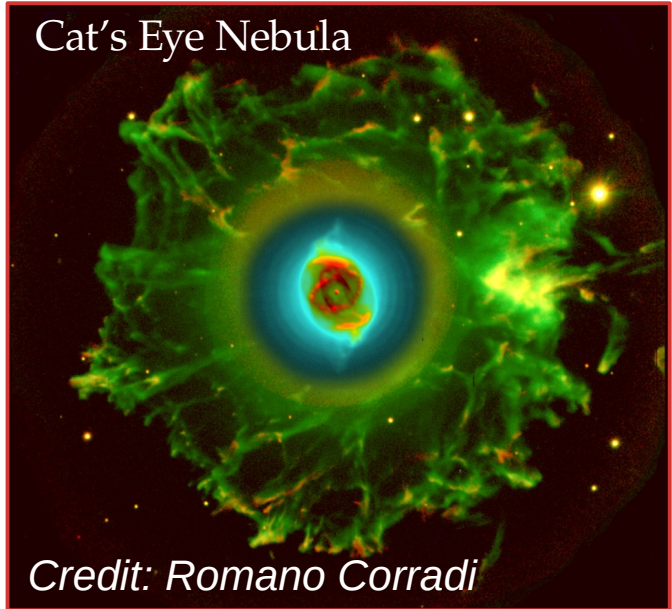
*Credit: J. Näränen & K. Torstensson*

R Aquarii



*Credit: Romano Corradi*

Cat's Eye Nebula

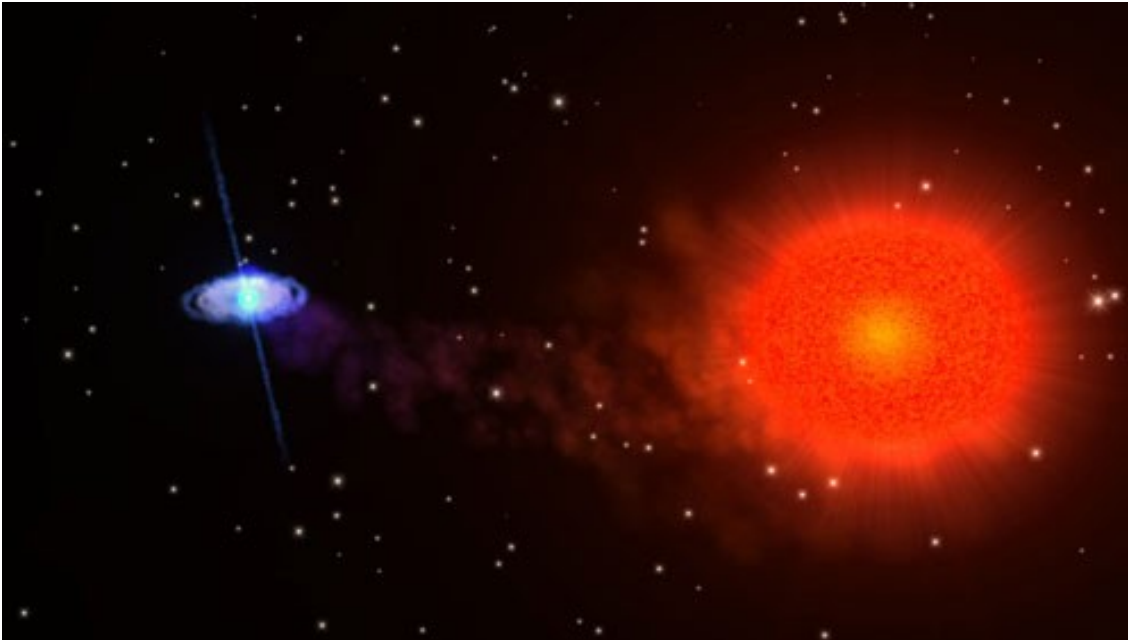


*Credit: Romano Corradi*

Most of the images from the NOT archive



# Symbiotic nebulae



*Credit: NASA*

★ Interacting wide binary system:  
white dwarf + red giant

★ Mass transfer mechanisms:  
stellar winds,  
wind-Roche-lobe overflow.

★ Nebulosities:  
stellar winds, jets,  
nova-like explosions,  
...

★ Symbiosis: absorption lines (red giant)  
+  
nebular emission lines (hot component)

# Symbiotic nebulae: Legacy of the NOT

~ 30 yrs of NOT

3 generations of  
astronomers.

*“A narrowband imaging survey of symbiotic stars”*

R.L.M. Corradi, E. Brandi, O. E. Ferrer, and **H. E. Schwarz**

A&A, 1999, 343, 841



Survey of symbiotic nebulae: NOT was the main telescope to observe the Northern targets.

Before: only 3 known symbiotic nebulae (2 discovered by Hugo and Romano)

During 1<sup>st</sup> observing night at the NOT, 3 more nebulae were discovered!

Result: enlarged ~4 times the known extended nebulae around Symbiotic stars.

# Symbiotic binary R Aquarii

A&A 612, A118 (2018)  
<https://doi.org/10.1051/0004-6361/201732073>  
© ESO 2018

**Astronomy  
&  
Astrophysics**

## New insights into the outflows from R Aquarii

T. Liimets<sup>1,2</sup>, R. L. M. Corradi<sup>3,4</sup>, D. Jones<sup>4,5</sup>, K. Verro<sup>1,6</sup>, M. Santander-García<sup>7</sup>, I. Kolka<sup>1</sup>,  
M. Sidonio<sup>8</sup>, E. Kankare<sup>9</sup>, J. Kankare<sup>9</sup>, T. Pursimo<sup>10</sup>, and P. A. Wilson<sup>11,12</sup>

<sup>1</sup> Tartu Observatory, Observatooriumi 1, Tõravere 61602, Estonia  
e-mail: [tiina@obs.ee](mailto:tiina@obs.ee)

<sup>2</sup> Institute of Physics, University of Tartu, Ravila 14c, Tartu 50411, Estonia

<sup>3</sup> GRANTECAN, Cuesta de San José s/n, 38712 Breña Baja, La Palma, Spain

<sup>4</sup> Instituto de Astrofísica de Canarias, 38200 La Laguna, Tenerife, Spain

<sup>5</sup> Departamento de Astrofísica, Universidad de La Laguna, 38206 La Laguna, Tenerife, Spain

<sup>6</sup> Kapteyn Instituut, Rijksuniversiteit Groningen, Landleven 12, 9747AD Groningen, The Netherlands

<sup>7</sup> Observatorio Astronómico Nacional (OAN-IGN), C/ Alfonso XII, 3, 28014 Madrid, Spain

<sup>8</sup> Terroux Observatory, Canberra, Australia

<sup>9</sup> Astrophysics Research Centre, School of Mathematics and Physics, Queen's University Belfast, Belfast BT7 1NN, UK

<sup>10</sup> Nordic Optical Telescope, Apartado 474, 38700 Santa Cruz de La Palma, Spain

<sup>11</sup> Leiden Observatory, Leiden University, Postbus 9513, 2300 RA Leiden, The Netherlands

<sup>12</sup> CNRS, UMR 7095, Institut d'Astrophysique de Paris, 98bis Boulevard Arago, 75014 Paris, France

Received 10 October 2017 / Accepted 23 January 2018

PoS

PROCEEDINGS  
OF SCIENCE

## Nebulosities of the Symbiotic Binary R Aquarii - A Short Review

**Tiina Liimets\***

*Astronomický ústav, Akademie věd České republiky, v.v.i., Fričova 298, 251 65 Ondřejov, Czech Republic*

*Tartu Observatory, University of Tartu, Observatooriumi 1, 61602 Tõravere, Estonia*

*E-mail: [tiina.liimets@asu.cas.cz](mailto:tiina.liimets@asu.cas.cz)*

**Romano M. L. Corradi**

*GRANTECAN, Cuesta de San José s/n, E-38712, Breña Baja, La Palma, Spain*

*Instituto de Astrofísica de Canarias, E-38200 La Laguna, Tenerife, Spain*

NOT: [OI] [OII] [OIII]

Distance: 180 pc  
*Liimets+ 2018*

# R Aquarii

Cool Mira + hot WD

Hourglass  
nebula  
~670 yrs  
*Liimets+ 2018*

Jet  
~300 to 0 yrs  
*Liimets+ 2018*  
*Schmid+ 2018*

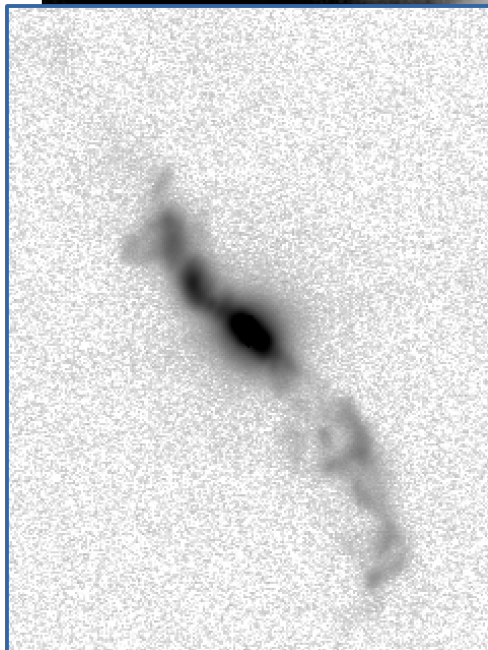
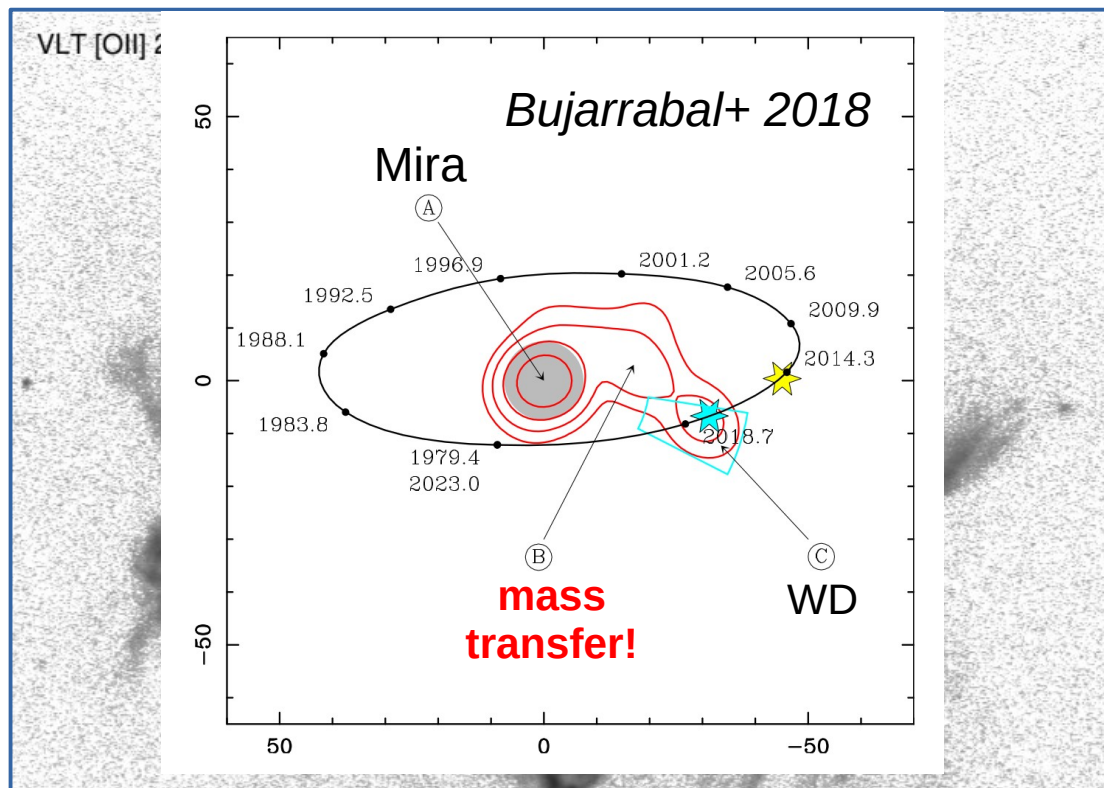
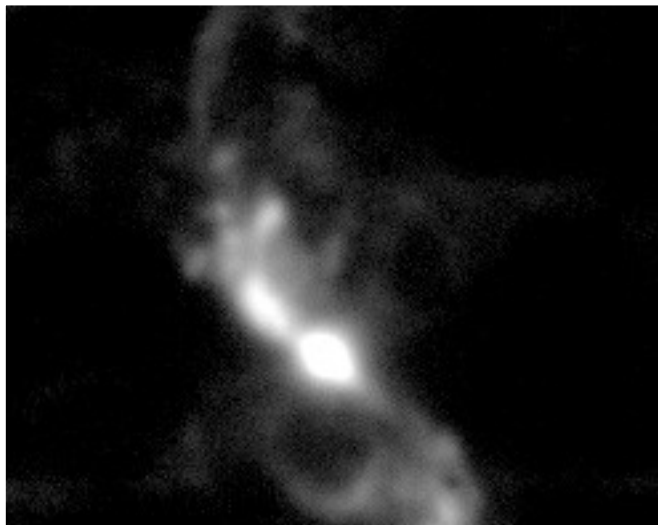
MAIN MOTIVATION: Jet  
- Continuous/clumpy?  
- Alternates between poles?

NOT: [OI] [OII] [OIII]

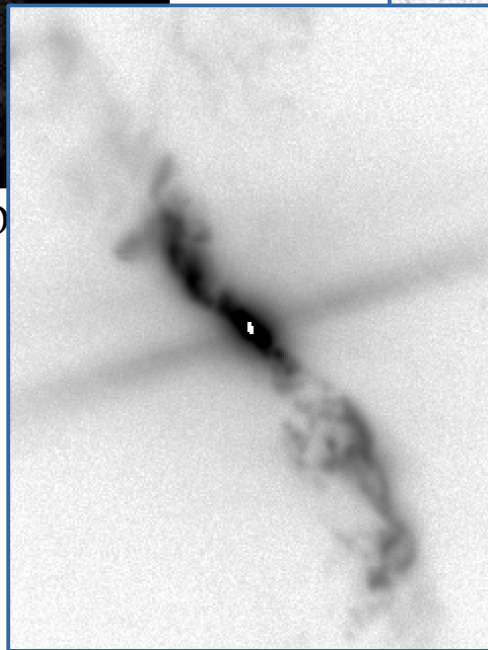
3 decades of IMAGING (**mostly NOT!**)  
 $\text{H}\alpha$ +[NII], [OIII]5007Å, [OII]3727Å, [OI]6300Å



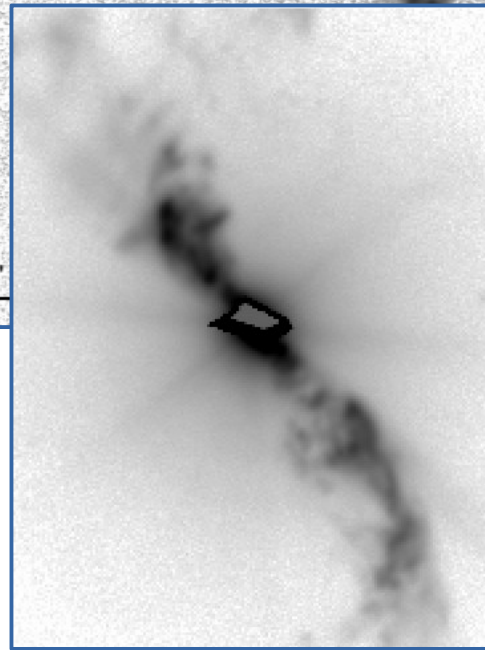
# The Jet I (R Aquarii)



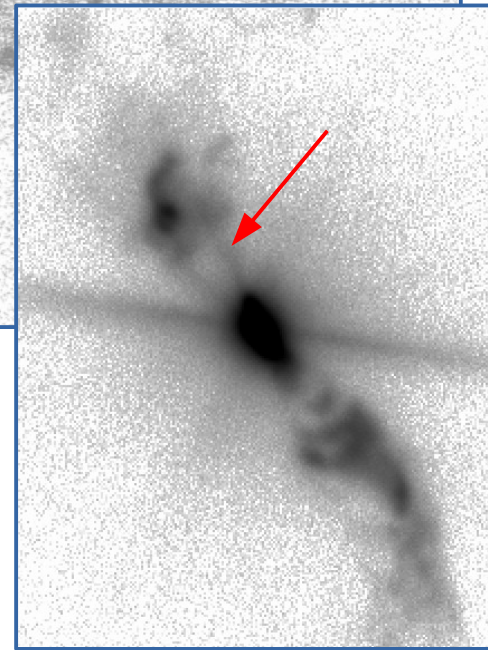
2002 NOT [OIII]



2007 NOT [OIII]



2012 VLT [OIII]



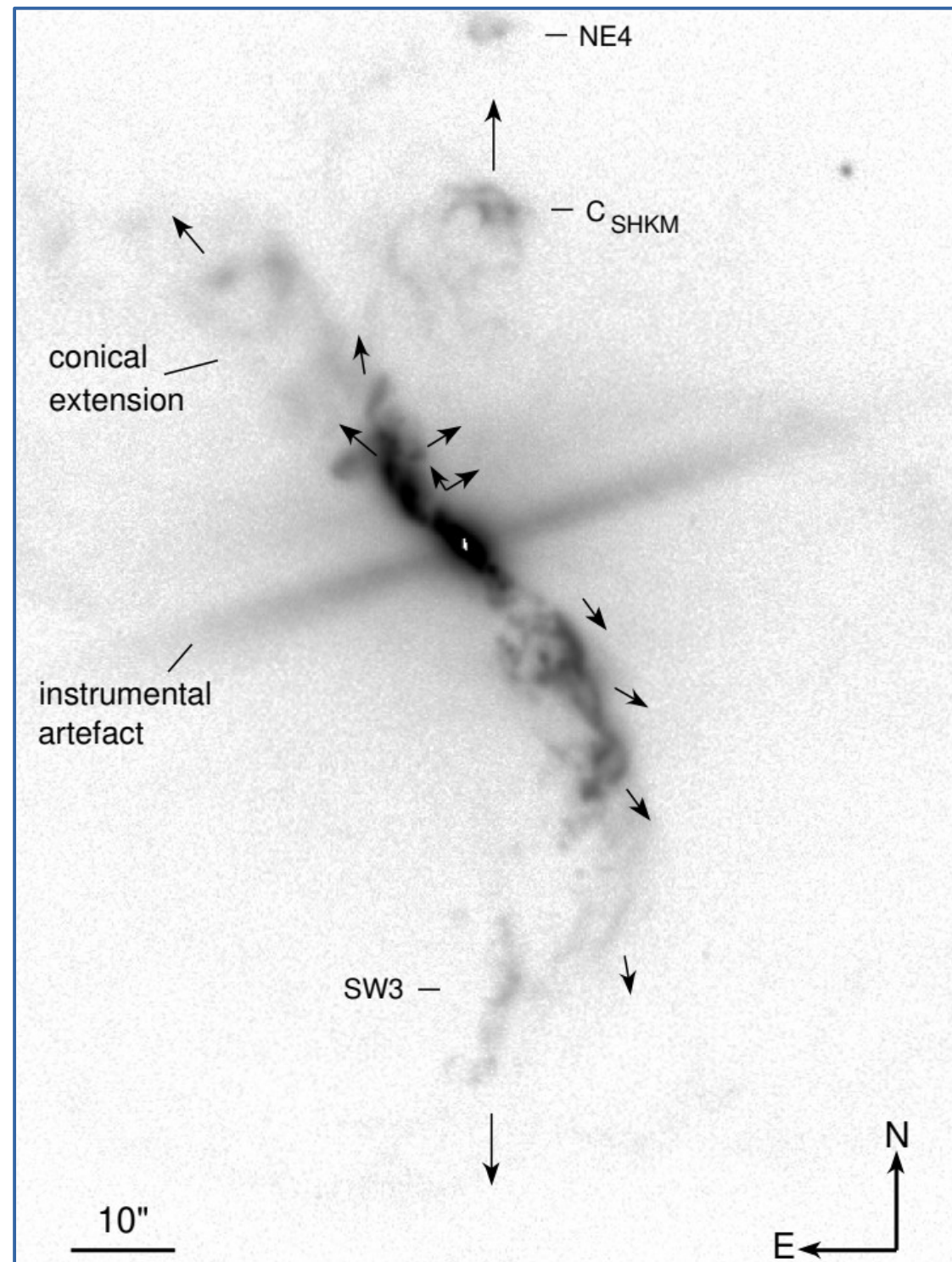
2019 NOT [OIII]



# The Jet II (R Aquarii)

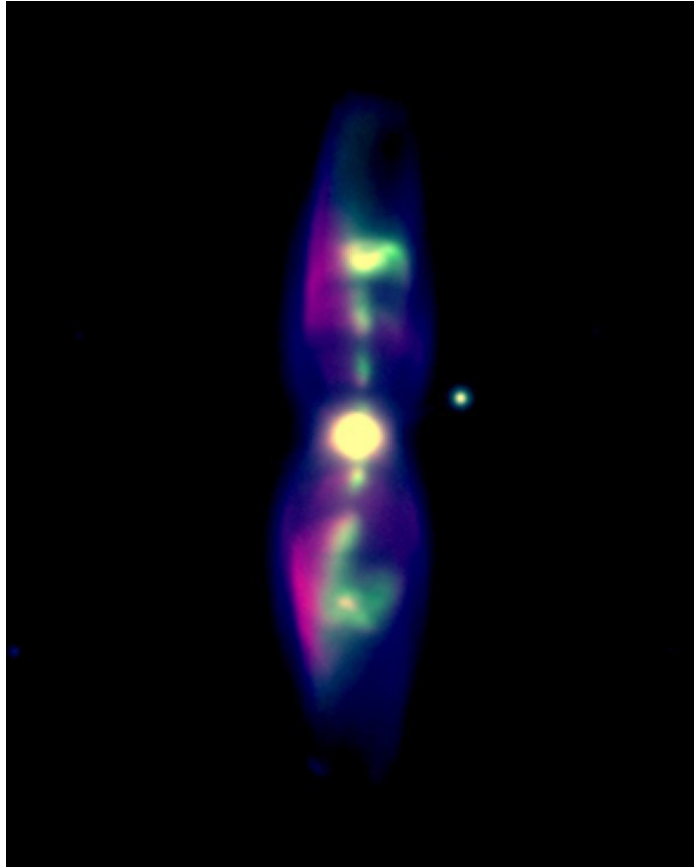
- ★ Overall ballistic expansion
- ★ Fast moving lateral features.  
Up to 900 km/s
- ★ The evolution of the jet is complex:
  - physical matter moving,
  - changing ionisation,
  - changing illumination,
  - shocks,
  - precession, ...

*Liimets et al. 2018, A&A, 612, 118*  
*Liimets et al. 2021, Pos-SISSA, 41*



# M 2-9 (Butterfly Nebula)

## Symbiotic / planetary nebula?



Credit: R. Corradi (NOT: *H $\alpha$*  *H $\alpha$*  [OIII]) 2006

~4 decades of IMAGING  
(large part with the NOT!)  
 $H\alpha + [NII], [OIII]5007\text{\AA}$

Astron. Astrophys. 319, 267–273 (1997)

ASTRONOMY  
AND  
ASTROPHYSICS

### M 2-9: moving dust in a fast bipolar outflow\*

Hugo E. Schwarz<sup>1,2</sup>, Colin Aspin<sup>1,3</sup>, Romano L.M. Corradi<sup>1</sup>, and Bo Reipurth<sup>2</sup>

<sup>1</sup> Nordic Optical Telescope, Apartado 474, Sta. Cruz de La Palma, Canarias, Spain

<sup>2</sup> ESO, Casilla 19001, Santiago 19, Chile

<sup>3</sup> Joint Astronomy Centre, 660 A'ohoku Pl., Hilo, Hawaii 96720, USA

<sup>4</sup> IAC, Via Lactea, E-38200 La Laguna, Tenerife, Canarias, Spain

Received 29 April 1996 / Accepted 30 July 1996

THE ASTRONOMICAL JOURNAL, 119:1339–1344, 2000 March  
© 2000. The American Astronomical Society. All rights reserved. Printed in U.S.A.

### THE EVOLVING MORPHOLOGY OF THE BIPOLAR NEBULA M2-9

SEAN DOYLE<sup>1</sup> AND BRUCE BALICK<sup>2</sup>

Department of Astronomy, University of Washington, Box 351580, Seattle, WA 98195

R. L. M. CORRADI<sup>3</sup>

Instituto de Astrofísica de Canarias, Calle Vía Láctea, E-38200 La Laguna, Tenerife, Spain

AND

H. E. SCHWARZ<sup>4</sup>

Nordic Optical Telescope, Apdo. 321, E-38780 Santa Cruz de la Palma, Spain

Received 1999 October 6; accepted 1999 December 3

A&A 529, A43 (2011)  
DOI: [10.1051/0004-6361/201016361](https://doi.org/10.1051/0004-6361/201016361)  
© ESO 2011

Astronomy  
&  
Astrophysics

### The evolution of M 2–9 from 2000 to 2010\*,\*\*

R. L. M. Corradi<sup>1,2</sup>, B. Balick<sup>3</sup>, and M. Santander-García<sup>1,2,4</sup>

<sup>1</sup> Instituto de Astrofísica de Canarias, 38200 La Laguna, Tenerife, Spain  
e-mail: [rcorradi@iac.es](mailto:rcorradi@iac.es)

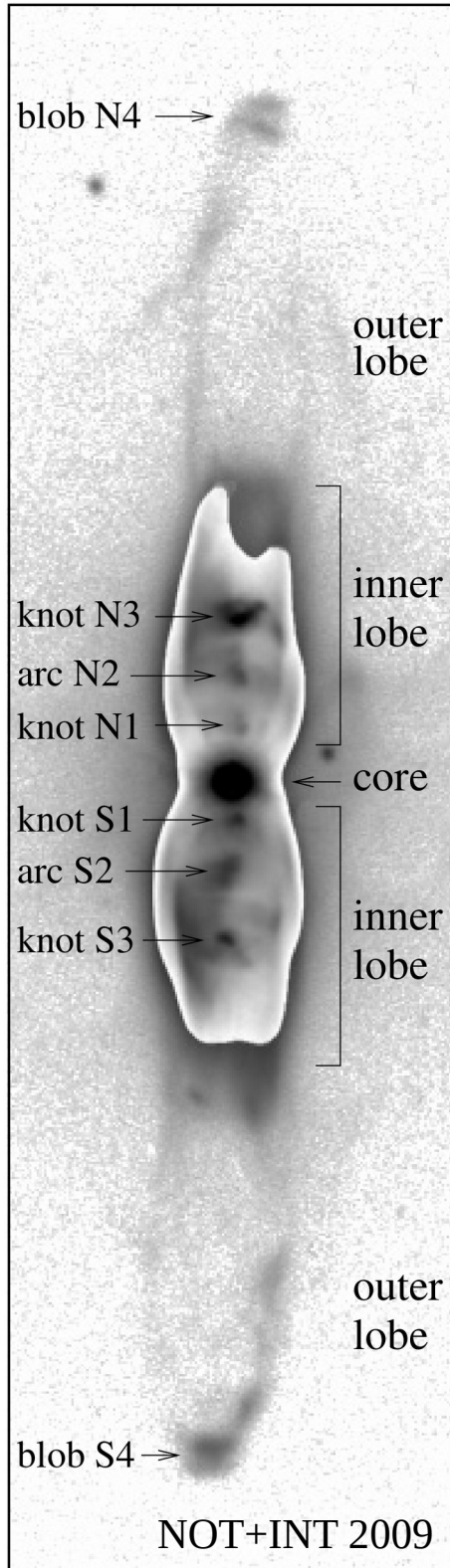
<sup>2</sup> Departamento de Astrofísica, Universidad de La Laguna, 38206 La Laguna, Tenerife, Spain

<sup>3</sup> Astronomy Department, University of Washington, Seattle, WA 98195, USA

<sup>4</sup> Isaac Newton Group of Telescopes, Apart. de Correos 321, 38700 Santa Cruz de la Palma, Spain

Received 20 December 2010 / Accepted 4 February 2011

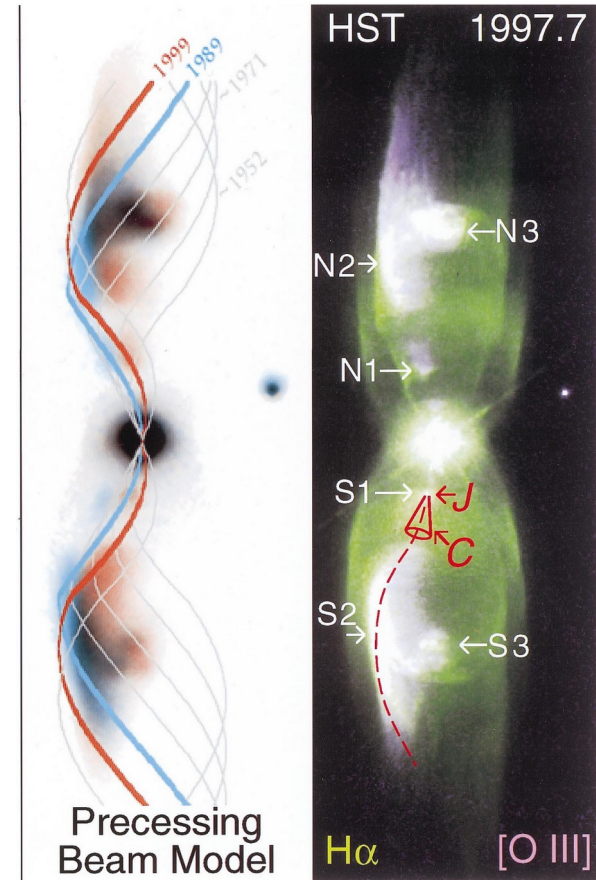
# M 2-9: main results



## ★ Nested system of lobes:

- Neutral shell > outer lobes + dusty blobs  
(distance  $1.3 \pm 0.2$  kpc  
inclination  $i=18^\circ$ )
- Inner lobes + knots/arcs  
(ionized gas)

## ★ Corkscrew geometry of the inner rotating features.

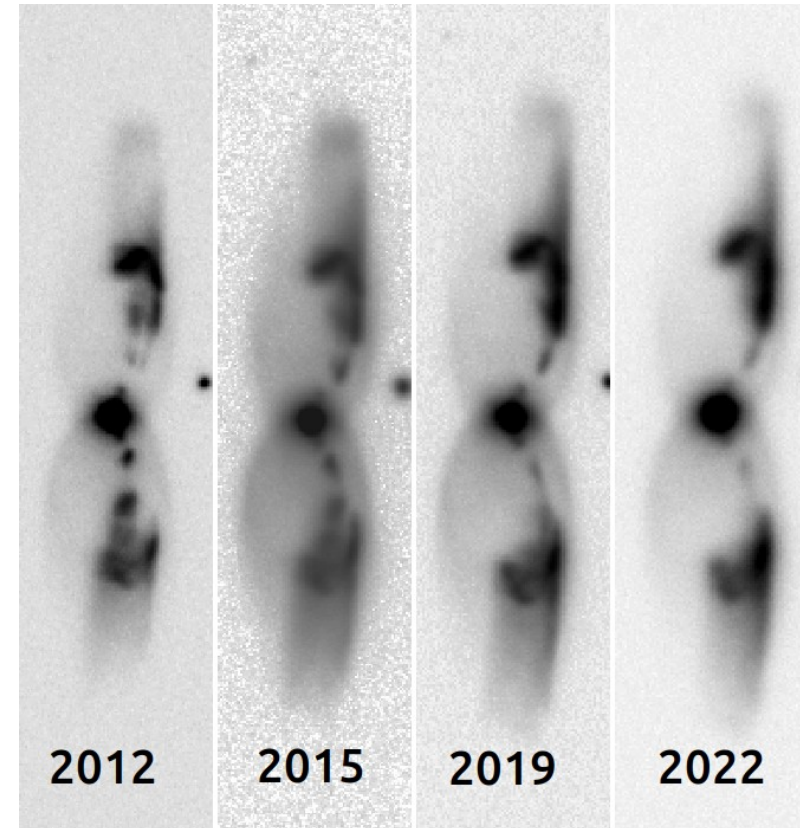
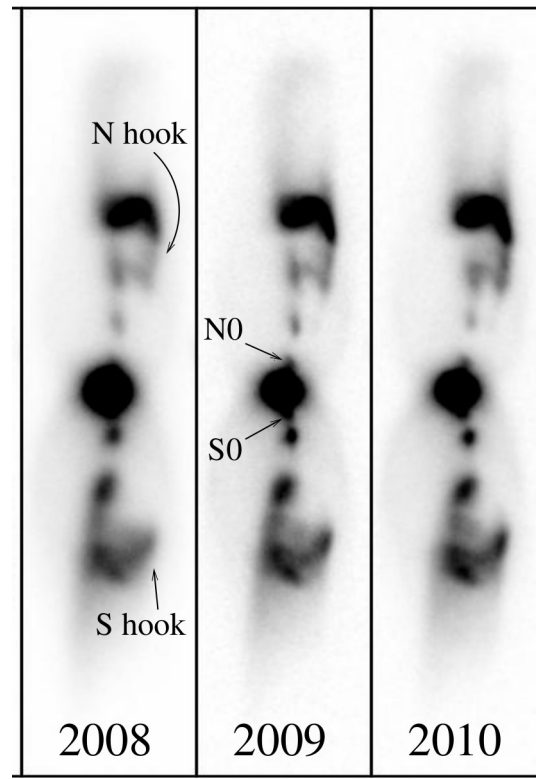


*Doyle, Balick, Corradi, Schwarz*  
*AJ, 2000, 119, 1339*

*Corradi, Balick, and Sandander-Garcia*  
*A&A, 2011, 529, A43*



# The lighthouse effect



- ★ Delay of the propagation of the pattern with latitude > spray of high velocity particles (11 000 – 16 000 km/s)
- ★ No other ionizing mechanism needed!
- ★ Mirror symmetry of the rotating pattern!
- ★ The pattern rotates  $P \sim 90$  years.

ALFOSC: Ha Ha [OIII]

Corradi, Balick, and Sandander-Garcia A&A, 2011, 529, A43

1997

# Extended shells around B[e] stars.



*Galaxies* 2022, 10, 41



Article

## Follow-Up of Extended Shells around B[e] Stars

Tiina Liimets <sup>1,\*</sup> , Michaela Kraus <sup>1</sup> , Alexei Moiseev <sup>2</sup>, Nicolas Duronea <sup>3</sup>, Lydia Sonia Cidale <sup>3,4</sup> and Cecilia Fariña <sup>5,6</sup>

<sup>1</sup> Astronomical Institute, Czech Academy of Sciences, Fričova 298, 25165 Ondřejov, Czech Republic; michaela.kraus@asu.cas.cz

Ha survey  
+  
individual targets

NOT + ALFOSC (NOTCAM)

THE ASTRONOMICAL JOURNAL, 162:150 (14pp), 2021 October  
© 2021. The American Astronomical Society. All rights reserved.

<https://doi.org/10.3847/1538-3881/ac1355>



## Resolving the Circumstellar Environment of the Galactic B[e] Supergiant Star MWC 137. II. Nebular Kinematics and Stellar Variability\*

Michaela Kraus <sup>1</sup> , Tiina Liimets <sup>1,2</sup> , Alexei Moiseev <sup>3</sup> , Julieta P. Sánchez Arias <sup>1</sup> , Dieter H. Nickeler <sup>1</sup> ,  
Lydia S. Cidale <sup>4,5</sup>, and David Jones <sup>6,7</sup>

<sup>1</sup> Astronomical Institute, Czech Academy of Sciences, 251 65 Ondřejov, Czech Republic; michaela.kraus@asu.cas.cz

<sup>2</sup> Tartu Observatory, University of Tartu, Observatooriumi 1, 61602 Tõravere, Estonia

THE ASTRONOMICAL JOURNAL, 154:186 (16pp), 2017 November  
© 2017. The American Astronomical Society. All rights reserved.

<https://doi.org/10.3847/1538-3881/aa8df6>



## Resolving the Circumstellar Environment of the Galactic B[e] Supergiant Star MWC 137 from Large to Small Scales\*

Michaela Kraus <sup>1,2</sup> , Tiina Liimets <sup>2,3</sup> , Cristina E. Cappa <sup>4,5</sup>, Lydia S. Cidale <sup>5,6,7</sup>, Dieter H. Nickeler <sup>1</sup> ,  
Nicolas U. Duronea <sup>4</sup>, Maria L. Arias <sup>5,6</sup>, Diah S. Gunawan <sup>7</sup>, Mary E. Oksala <sup>8,9</sup>, Marcelo Borges Fernandes <sup>10</sup>,  
Grigoris Maravelias <sup>7</sup>, Michel Curé <sup>7</sup>, and Miguel Santander-García <sup>11</sup>

<sup>1</sup> Astronomický ústav, Akademie věd České republiky, v.v.i., Fričova 298, 251 65 Ondřejov, Czech Republic; michaela.kraus@asu.cas.cz

<sup>2</sup> Tartu Observatory, 61602 Tõravere, Tartumaa, Estonia



# Protostellar jets in Serpens

Astronomy  
&  
Astrophysics

Amanda Djupvik (NOT)

## Proper motions of embedded protostellar jets in Serpens<sup>★</sup>

A. A. Djupvik<sup>1</sup>, T. Liimets<sup>2,3</sup>, H. Zinnecker<sup>4,5</sup>, A. Barzdis<sup>6</sup>, E. A. Rastorgueva-Foi<sup>7</sup>, and L. R. Petersen<sup>8</sup>

<sup>1</sup> Nordic Optical Telescope, Rambla José Ana Fernández Pérez, 7, 38711 Breña Baja, Spain  
e-mail: amanda@not.iac.es

<sup>2</sup> Tartu Observatory, 61602 Tõravere, Estonia  
e-mail: tiina@obs.ee

<sup>3</sup> Institute of Physics, University of Tartu, Ravila 14c, 50411 Tartu, Estonia

<sup>4</sup> SOFIA Science Center, NASA Ames Research Center, 94035 Moffett Field, USA  
e-mail: hzinnecker@sofia.usra.edu

<sup>5</sup> Deutsches SOFIA Institut (DSI), University of Stuttgart, 70569 Stuttgart, Germany

<sup>6</sup> Institute of Astronomy, University of Latvia, Raina bulv. 19, Riga, LV 1586, Latvia

<sup>7</sup> School of Maths & Physics, University of Tasmania, 7001 Hobart, Australia  
e-mail: efoi@utas.edu.au

<sup>8</sup> Niels Bohr Institute, University of Copenhagen, Juliane Maries Vej 30, 2100 Copenhagen, Denmark

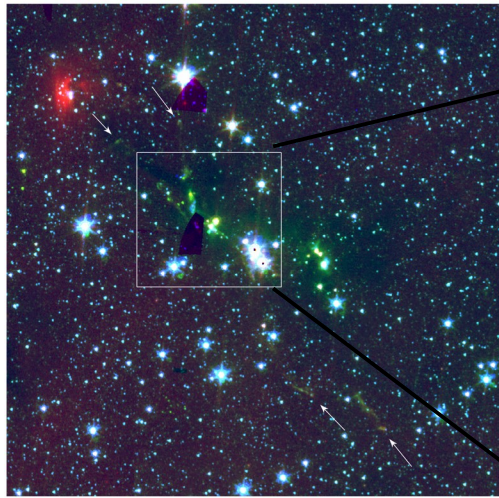
Received 14 May 2015 / Accepted 18 December 2015

Two decades of NOTCAM H<sub>2</sub> imaging  
+ K-band long-slit spectra (2011, 2014)

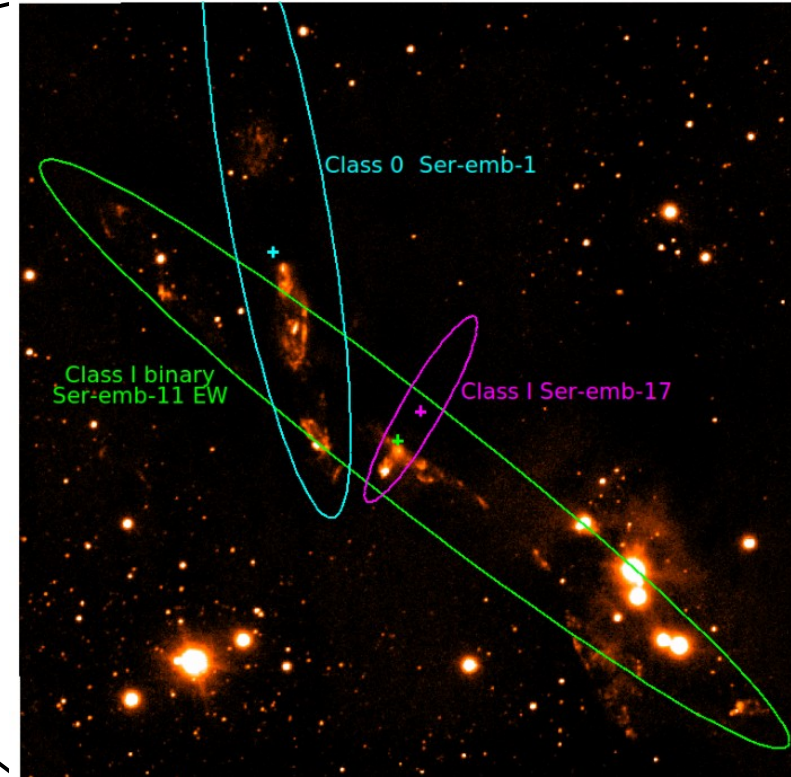
Image: IRAC/Spitzer: 3.6  $\mu\text{m}$ , 4.5  $\mu\text{m}$ , 8  $\mu\text{m}$



# Serpens / G3-G6 region



IRAC/Spitzer:  
3.6  $\mu\text{m}$ , 4.5  $\mu\text{m}$ , 8  $\mu\text{m}$



NOTCam: H<sub>2</sub> 2.12  $\mu\text{m}$  line of shocked  
molecular hydrogen

- ★ 3 partly overlapping deeply embed flows.
- ★ Mass flow rate is two order of magnitude higher in Class 0 compared to Class I jets, while their bolometric luminosities are equal.
- ★ Episodic behaviour: appearing, disappearing, time-variable velocities.

M 2-9

# To take home

- ★ Scientific legacy of the NOT.
- ★ Johannes Andersen Student Programme.
- ★ NOT family.

1997



The end