Puzzles of the young massive binary θ1 Ori C

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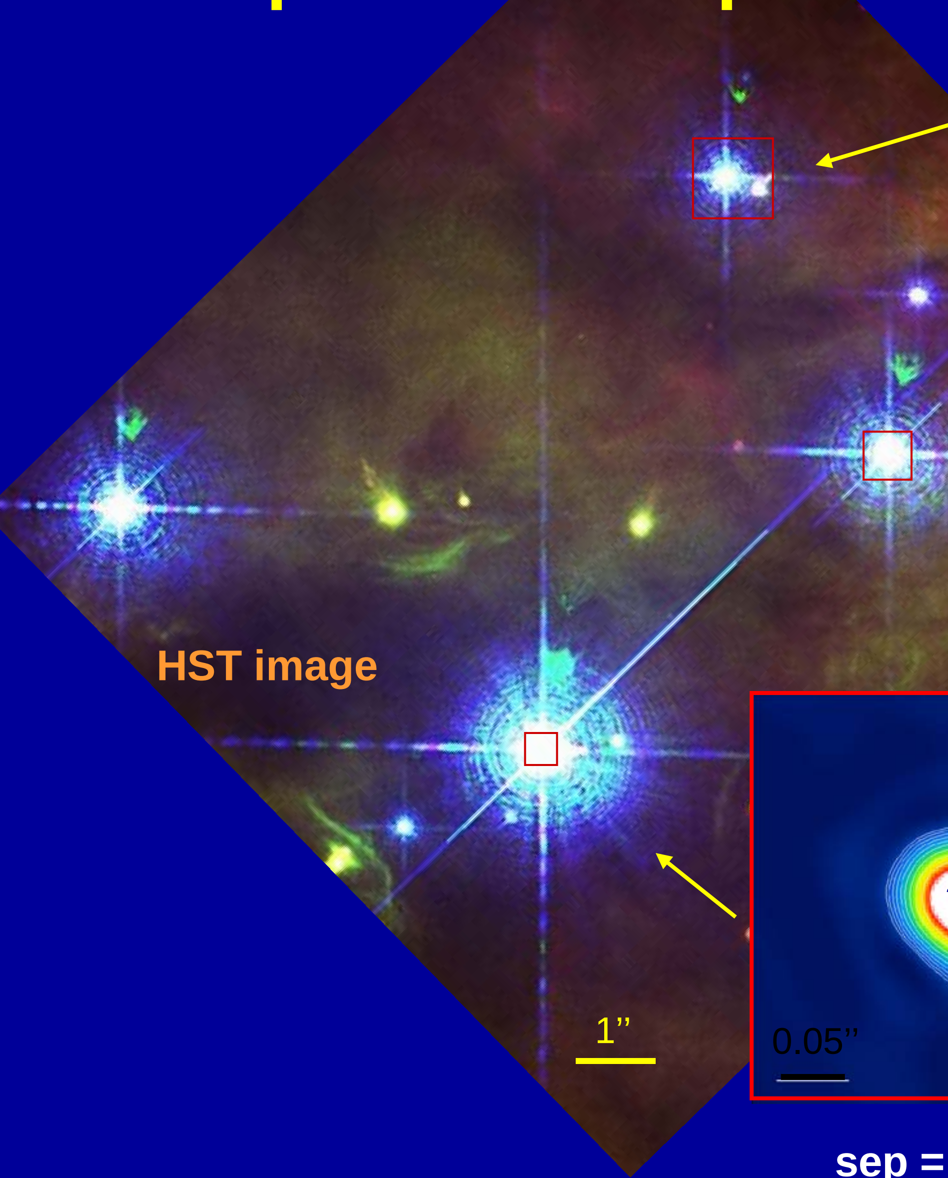
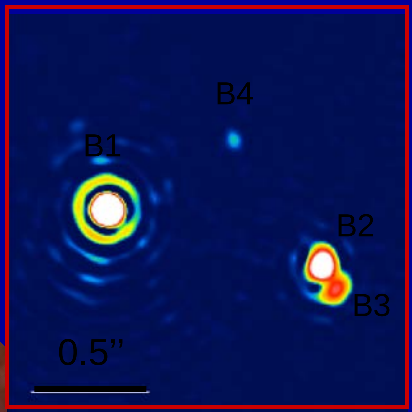
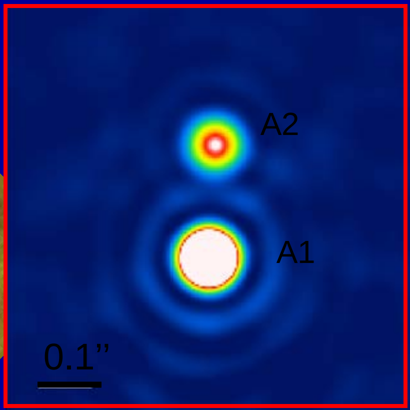
Young, massive Orion Trapezium multiples





B2-3:
sep = 117 mas



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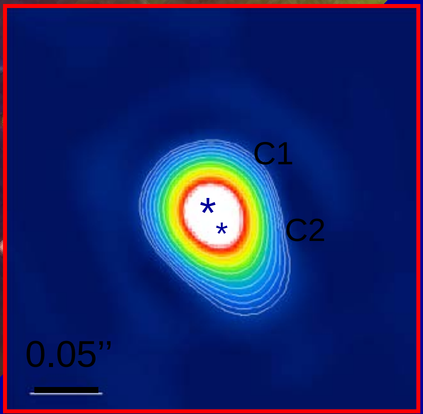

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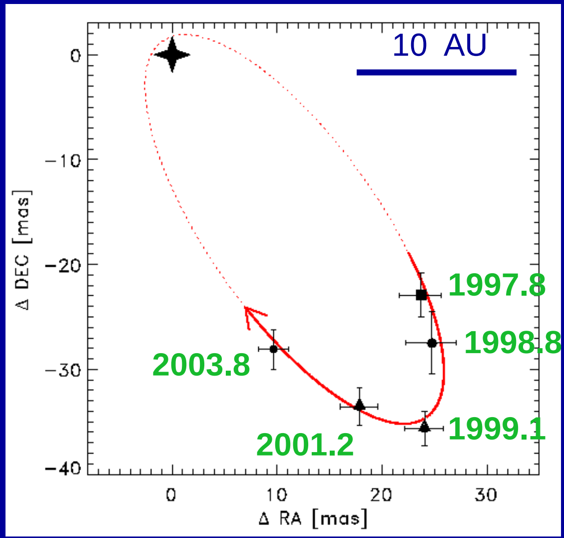
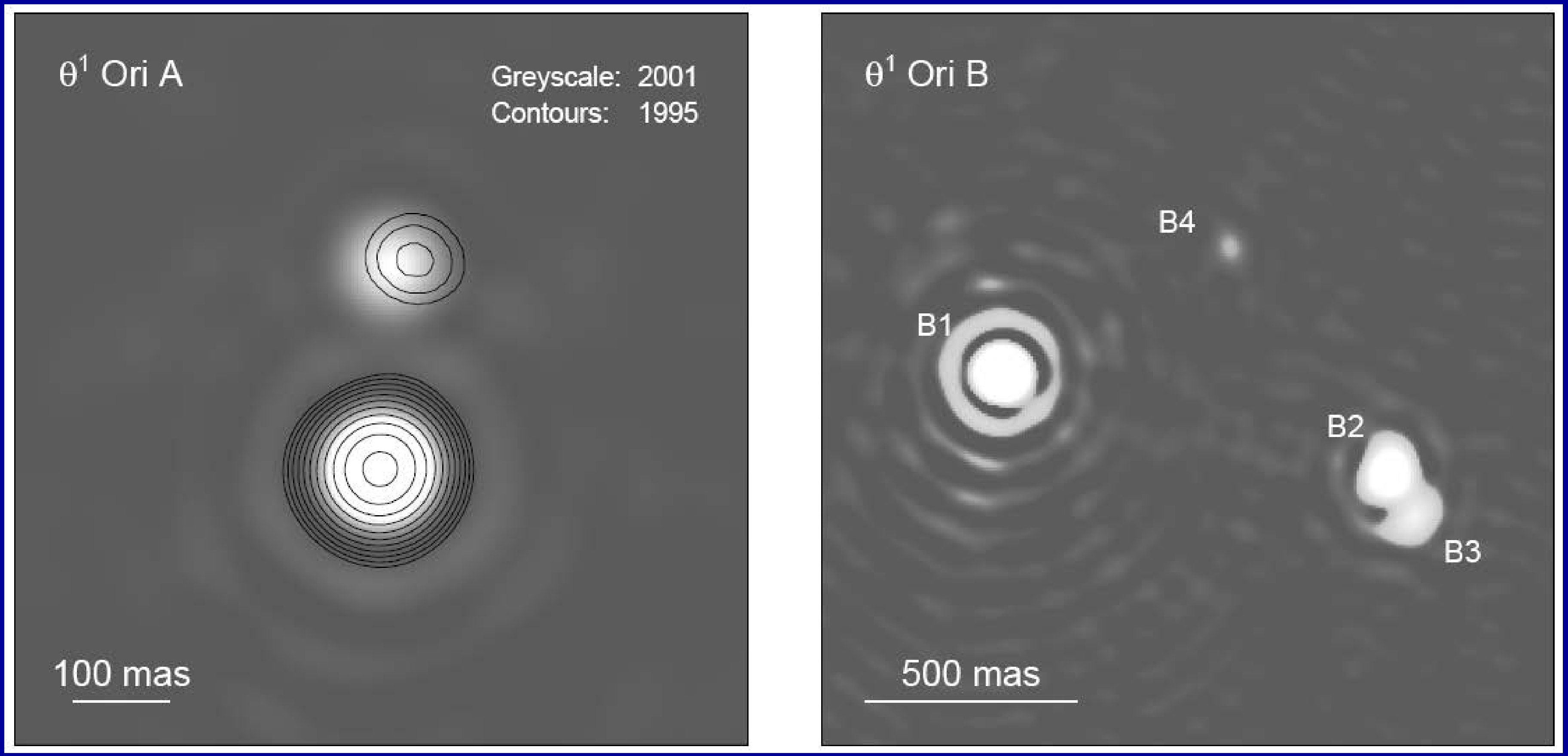


Θ^1 Ori A and B infrared speckle interferometry



M_{tot} ~ 20, P~200 yr

B2-B3: M_{tot} ~ 10, P~150 yr

Θ1 Ori C – the youngest and the nearest high-mass star

P = 11.26 yrs

T = 2002.57

e = 0.592

a = 43.6 mas

i = 99

Ω = 26.5

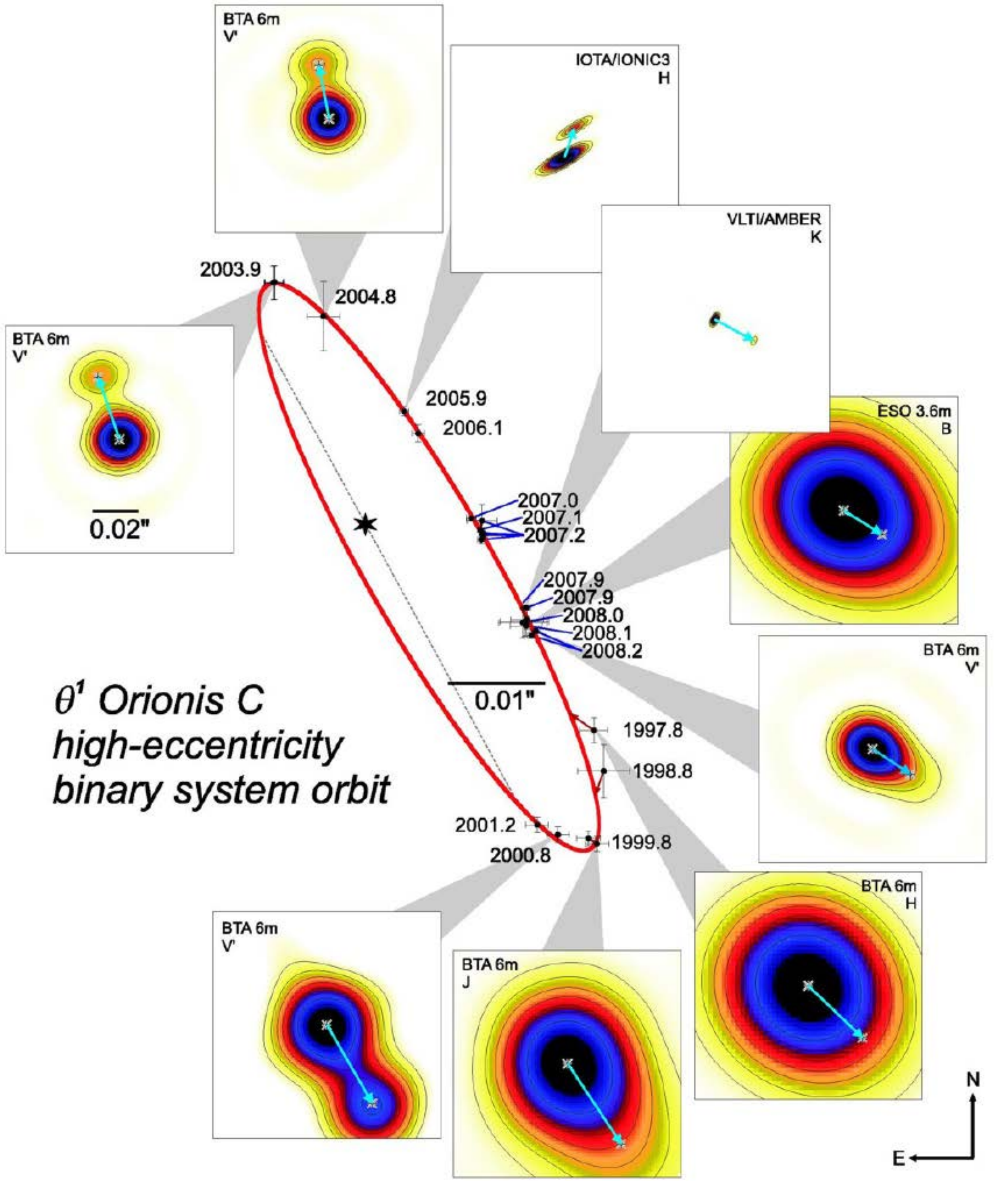
γ = 23.6 km/s

$M_1 + M_2 = 39M_0 + 8M_0$

O5.5 + B2

dist = 410 ± 20 pc

(S.Kraus et al. 2009)



PRINCIPAL PROBLEMS:

- **How do they form?**
- **Is their chemical composition different from a present-day cosmic matter in the solar vicinity ?**
- **Can the global magnetic field of the θ^1 Ori C slow down its rotation ?**
- **Was the runaway infrared source, the Becklin-Neugebauer (BN) object, ejected from the θ^1 Ori C system ?**

COMPONENTS PARAMETERS FROM INTERFEROMETRY

- *S.Kraus et al.* (2009):

  Comp. 1 - T_{eff} = (37000 - 40000 K)
  $\log L_1/L_\odot$ = (5.21 – 5.29)
  M_1= (34.0 - 39.0) $M_\odot$

  Comp. 2 - T_{eff} = (30000 - 33000 K)
  $\log L_2/L_\odot$ = (4.68 – 4.76)
  M_2= (8.0 – 15.5) $M_\odot$

- **Large spread of fundamental parameters complicates the analysis of the spectrum**

MODEL ATMOSPHERES

θ^1OriC 1 **:** ***Teff* = 39000 K, *log L/L*⊙ = 5.41 , *M* = 34.0, *R* = 10.7, *log g* = 3.91**

θ^1OriC 2 **:** ***Teff* = 31900 K, *log L/L*⊙ = 4.68, *M* = 15.5, *R* = 7.2, *log g* = 3.92**

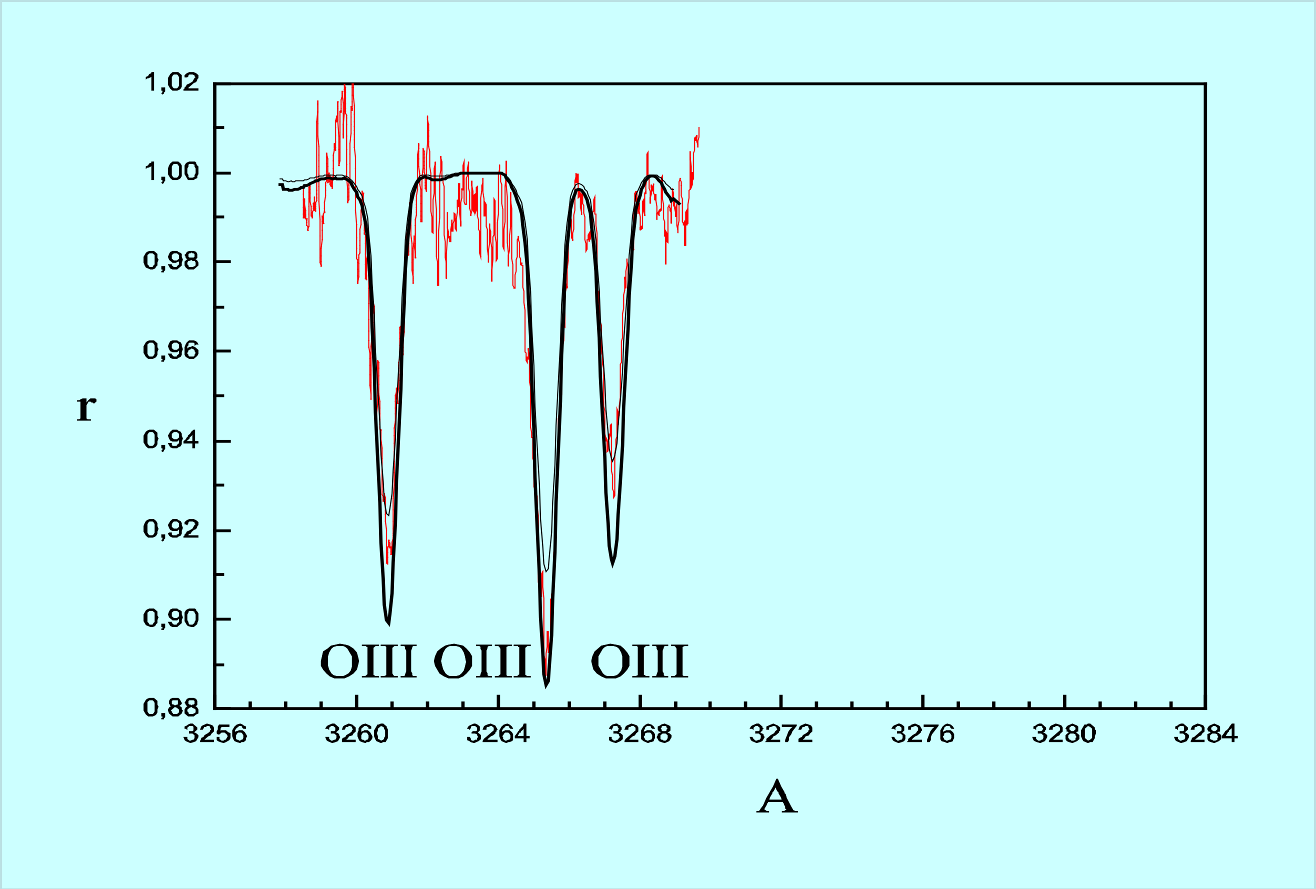
- For these parameters we used ***Vt* = 15 km/s** and the solar chemistry:
  H = 1.00, He = 0.089 – by mass
  logN(H)=12.00, *logN*(He) = 10.95 – by number of atoms

  logN for the remaining elements:
  C 8.52, N 8.01, O 8.89, Ne 8.05, Mg 7.54,
  Si 7.51, Fe 7.63

ABSORPTION PROFILES

- HI, HeI, HeII, CII - CIV, NII - NIV, OII – OIV, NeII, SiIII – SiIV и MgII ion absorption lines are observed in the spectrum between 3000 and 9000 AA. All H and He lines are contaminated by emission components, therefore the atmospheric parameters of the two stars were defined from the weak profiles of C, N, O, Ne, Si, and Mg lines.

OBSERVED (red) AND SYNTHETIC (black) PROFILES FOR OIII LINES IN THE SPECTRUM



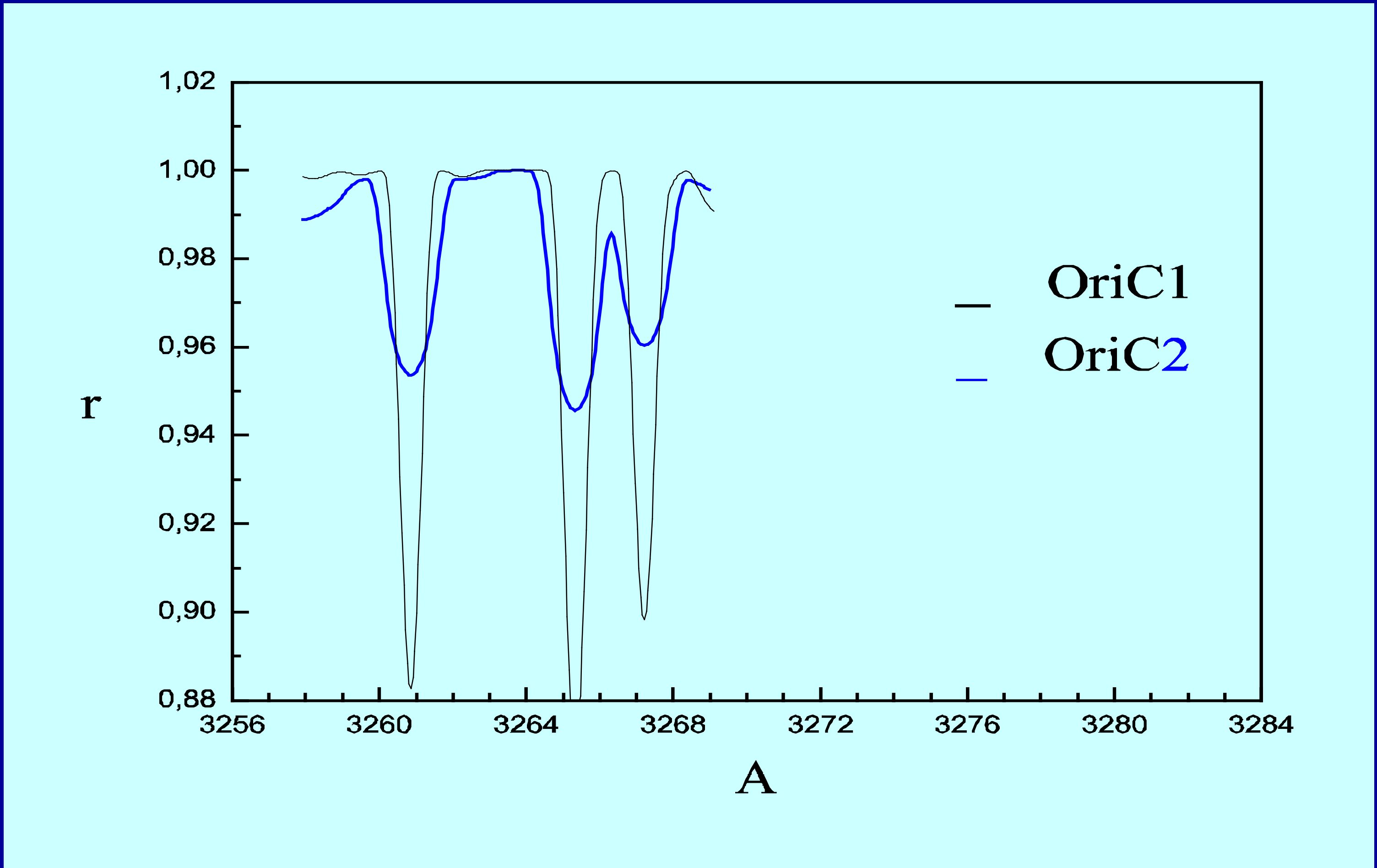
Orbital phase 0.55. Corresponding Vr_1 =26 km/s и Vr_2=14 km/s (relative to the Sun),

ROTATION VELOCITY FOR OF THE PRIMARY STAR

- ***v* sin*i*** for the primary star was defined in the range 24 to 140 km/s (Vitrichenko, 2003; Simon-Dias et al., 2006).

  From our equivalent widths: ***v* sin*i* = 35 *km/s*** (the equatorial value is $\boldsymbol{v_{1rot}}$ **= 35.4 km/s)** for the primary. The rotation period of θ^1 OriC1 is $15^d.422$ (Stahl et al., 2008), which gives the equatorial velocity 33 km/s for the radius R_1 = 10 R⊙. Using ***i***=105^o , we obtain ***v* sin*i* = 32 km/s**.

OIII PROFILES FOR TWO COMPONENTS SEPARATELY



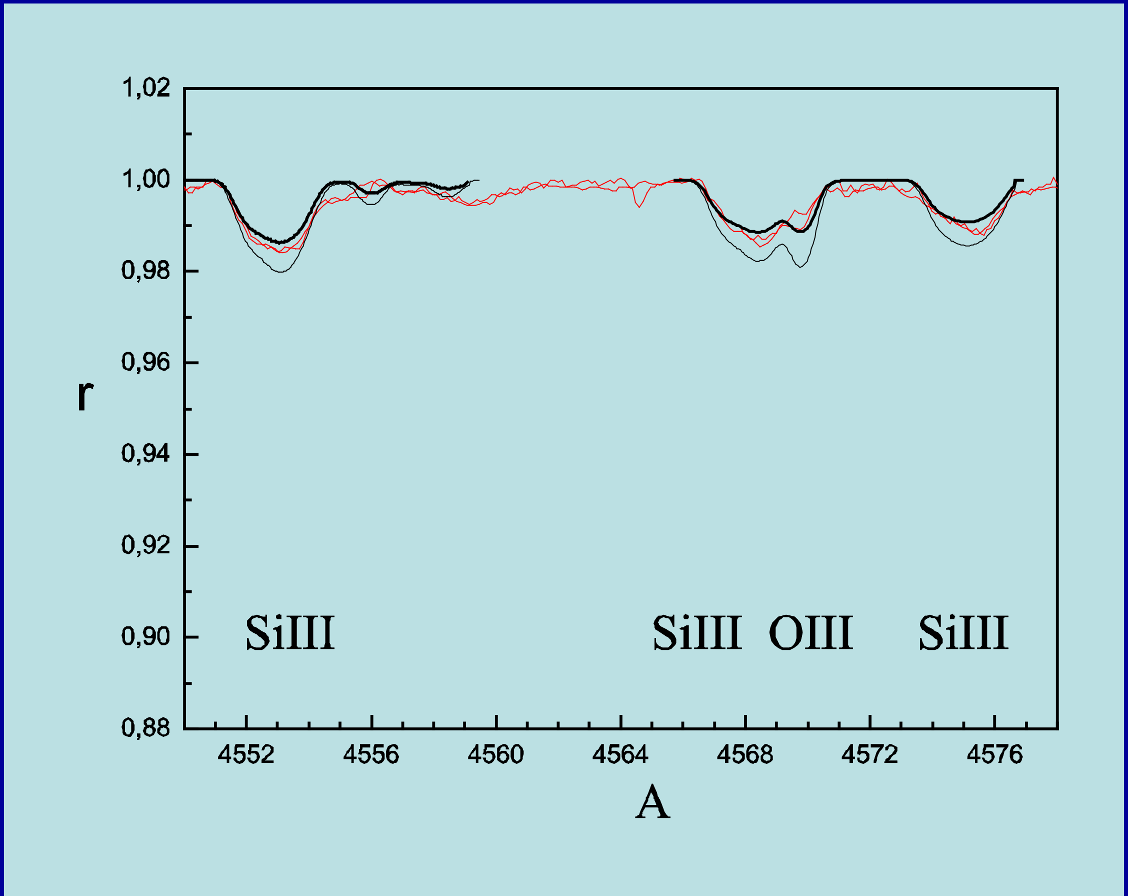
The primary star rotation velocity corresponds to *Vsin i* = 35 km/s

LINE PARAMETERS FOR THE SYNTHETIC SPECTRUM CALCULATION NEAR Si III TRIPLET

Ion	λ, A	ε, eV	log gf
FeIII	4548.99	20.88	-1.66
NII	4552.94	23.48	0.33
SiIII	**4552.62**	**19.02**	**0.18**
CaIII	4553.29	45.06	0.05
NeII	4553.40	34.83	-0.80
SiIII	**4554.00**	**28.12**	**-0.16**
OIII	4555.38	46.92	-0.41
OII	4557.73	31.37	-0.32
OII	4557.91	46.92	-0.89
FeIII	4558.85	55.11	-0.53

Ion	λ, A	ε, eV	log gf
NeI	4565.55	34.82	1.59
VIII	4567.59	20.18	0.95
SiIII	**4567.84**	**19.02**	**-0.04**
NeII	4569.06	34.93	0.14
OIII	4569.26	45.99	0.07
NeII	4574.42	34.84	-1.16
SiIII	**4574.76**	**19.02**	**-0.51**
VIII	4574.92	20.18	-0.27
NeII	4575.72	36.18	-1.64
NeII	4576.32	37.48	-1.71

OBSERVED (red) AND SYNTHETIC (black) SPECTRA IN THE REGION 4550-4578 AA



SNR=2000. Orb. phase = 0.653, 0.691. Corresponding radial velocities:

Vr1=29 km/s and Vr2=3 km/s (relative to the Sun), or Vr1= 45 km/s and Vr2= 19 km/s (relative to the Earth).

Rotation of the secondary

- Rotation velocity for θ^1 OriC2 was estimated from the width of atmospheric triplet Si III 4552.62, 4567.84, 4574.76 AA formed mainly in the atmosphere of the secondary.
- The BTA spectra give: $\Delta\lambda$ = 5.10, 4.62, 4.27 AA.

  From the width of the lines we obtain $\boldsymbol{v} \sin \boldsymbol{i}$ **= 147 km/s**. The lower limit is $\boldsymbol{v}_{\mathbf{2rot}}$ **= 96 km/s**.

Chemical abundances for θ^1 Ori C

Element	*log **N*** I,2	*log **N*** B	*log **N*** N	*log **N*** Sun
H	12.00	12.00	12.00	12.00
He	10.95	10.98	10.98	10.93
C	8.38	8.35	8.52	8.50
N	7.93	7.80	7.73	7.85
O	8.97	8.75	8.73	8.75
Ne	8.05	8.10	8.05	7.95
Mg	7.54	7.55		7.65
Si	7.51	7.50		7.55

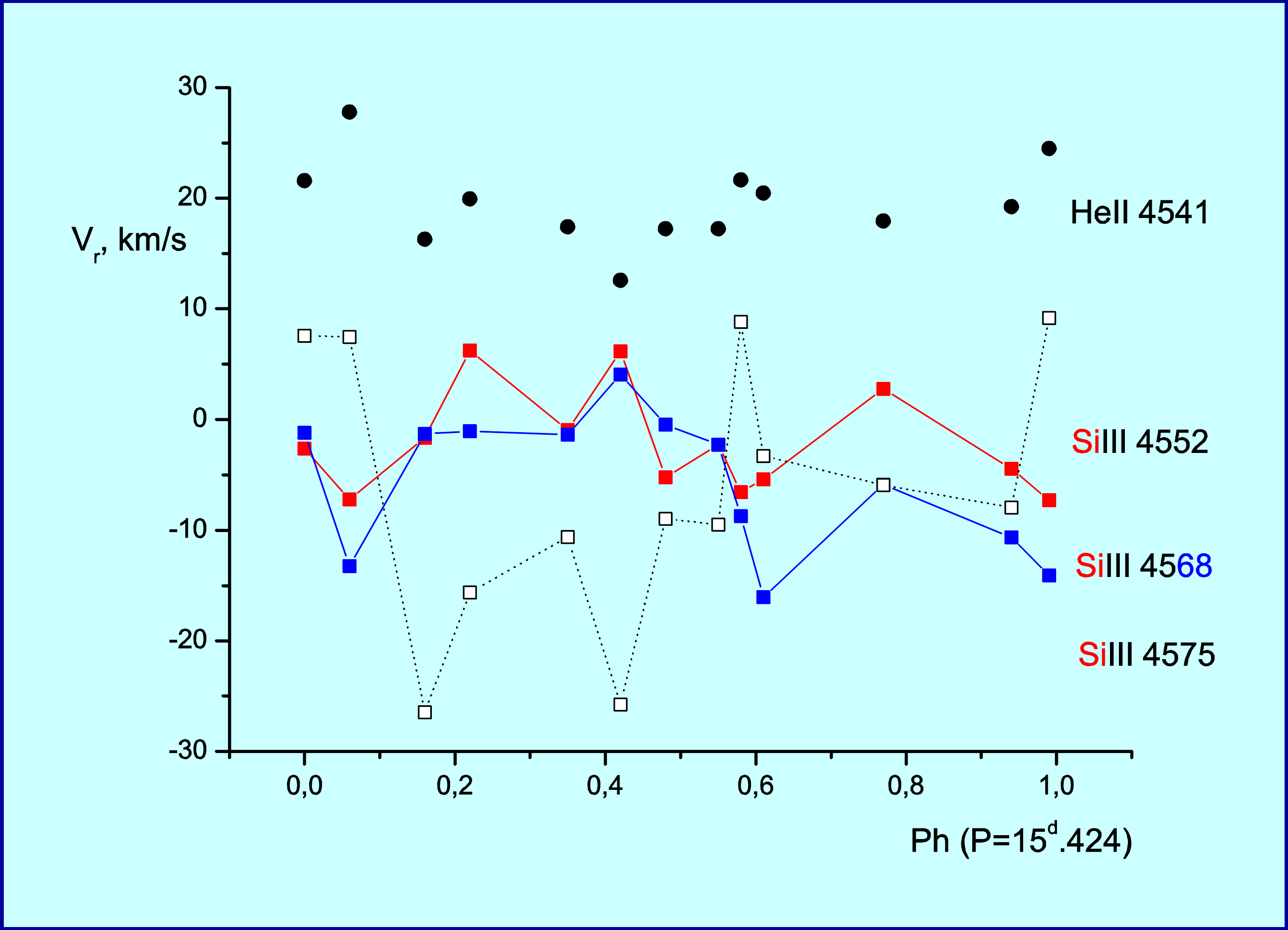
No clear indication of contamination by SNII nucleosynthesis products

Questions the origin of the Sun

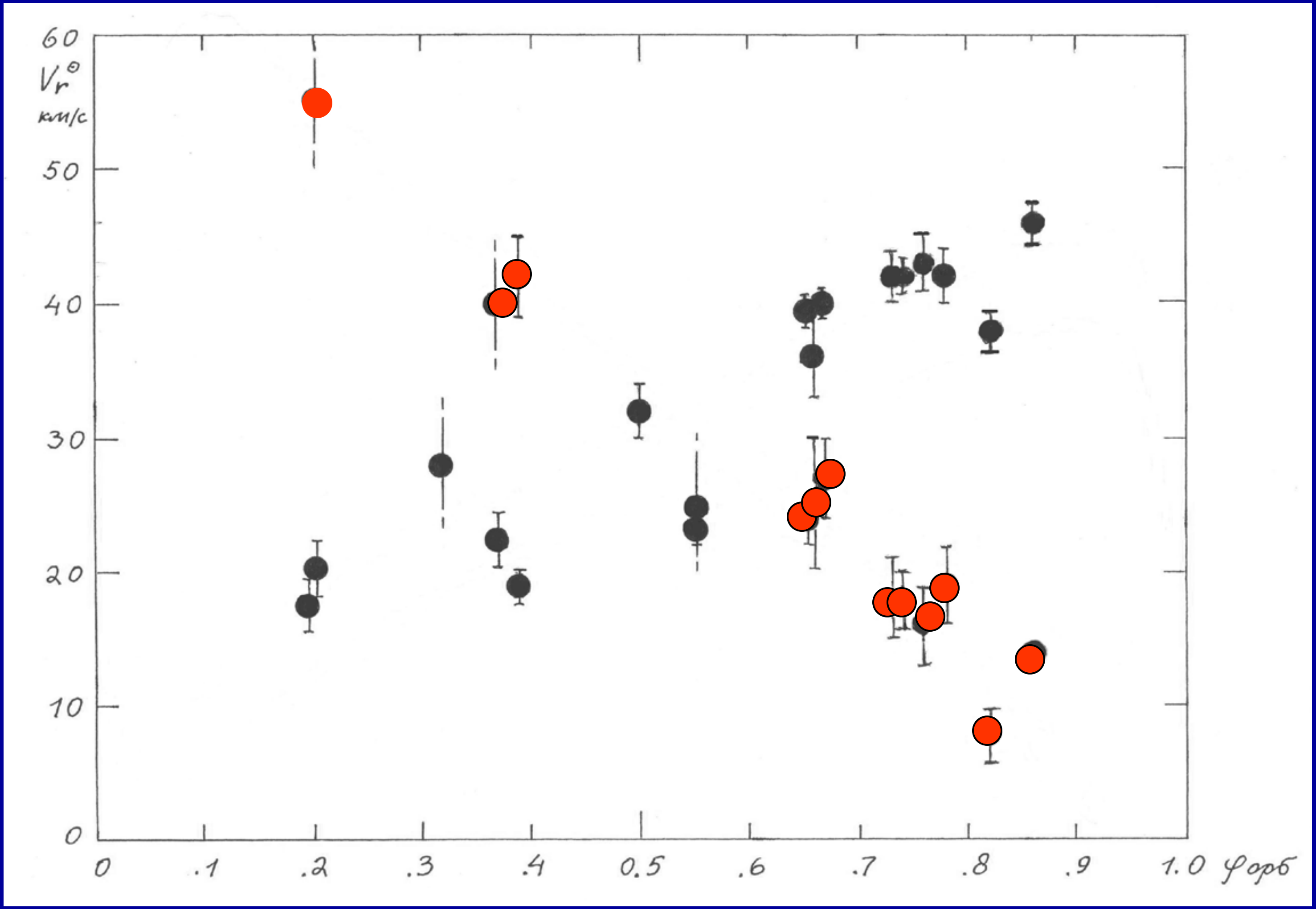
BEST MODEL FIT

	θ^1OriC 1	θ^1OriC 2
• Mass, *M*⊙	35.8	10.0
• Luminosity, *log L*⊙	5.20	4.69
• Radius, *R*⊙	10.0	8.2
• Teff, K	37000	30000
• *log g*	4.01	3.60
• Equatorial rotation velocity, km/s	35.4	96.2
• Magnetic field, *G*	500-1500	

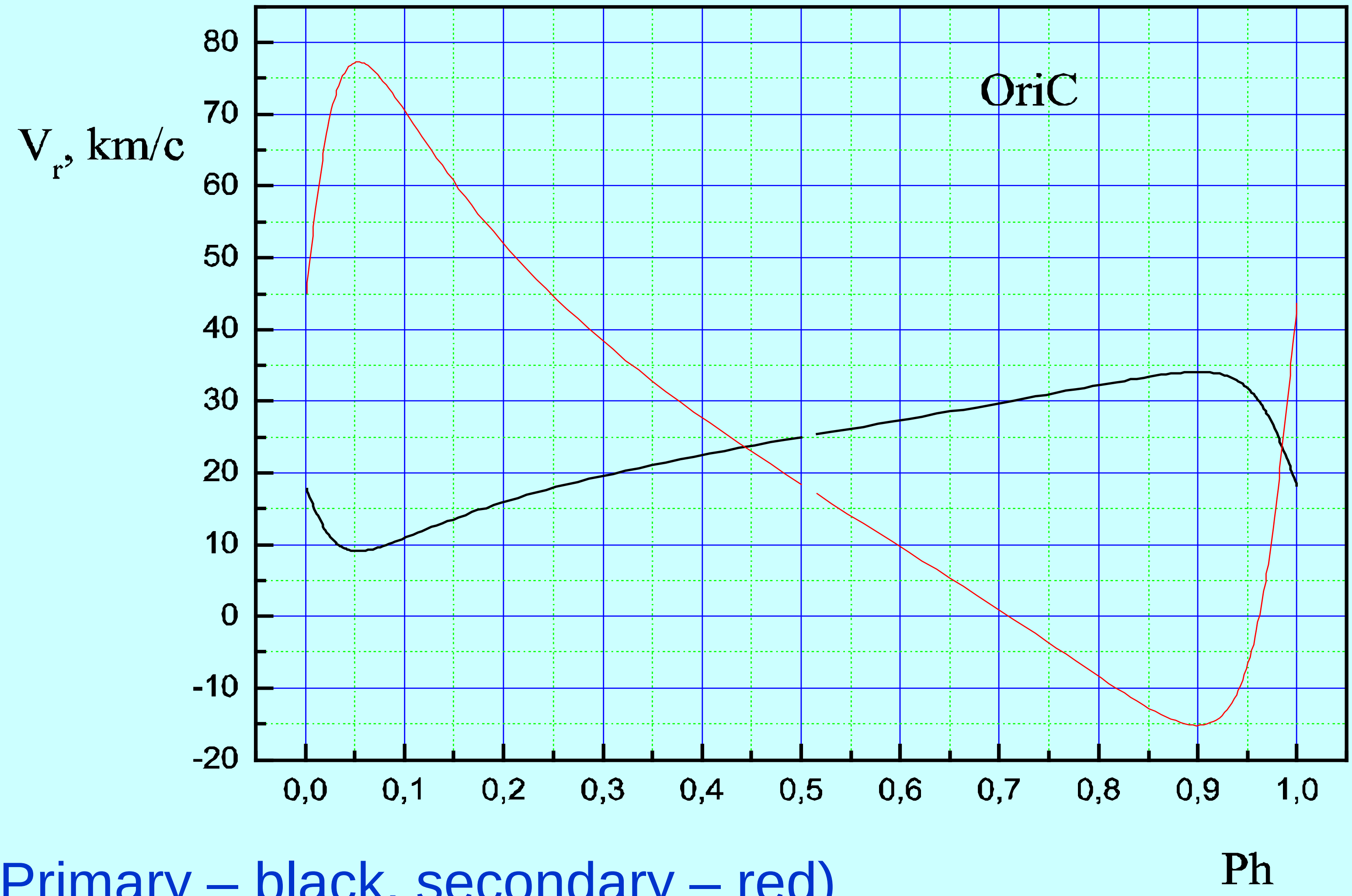
RADIAL VELOCITIES OF THE COMPONENTS FROM He II and Si III lines



Radial velocities of the components

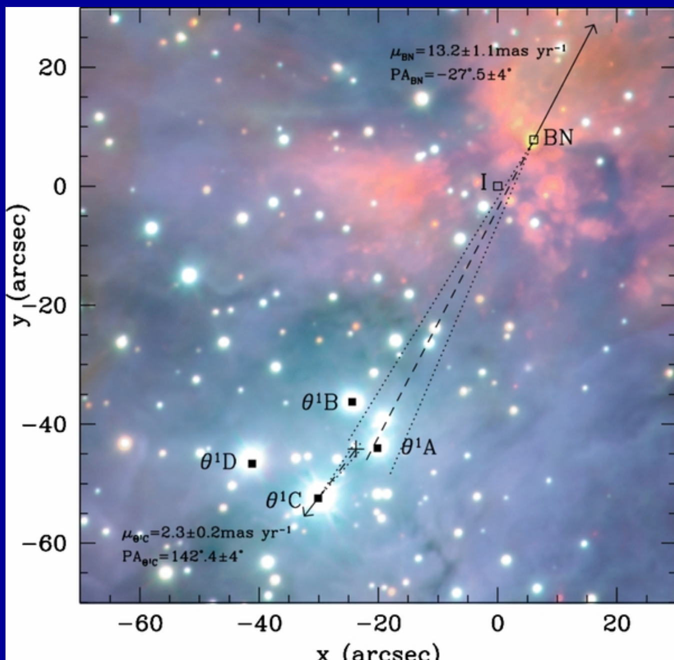


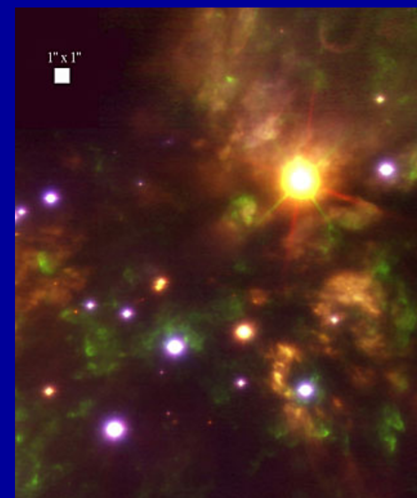
θ¹ OriC RADIAL VELOCITIES



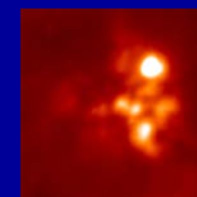
Primary – black, secondary – red)

ESO 2.2 µm NAOS-CONICA false color image of the region around the Becklin-Neugebauer object





BN



KL

Is θ1 Ori C a gravitational slingshot ?

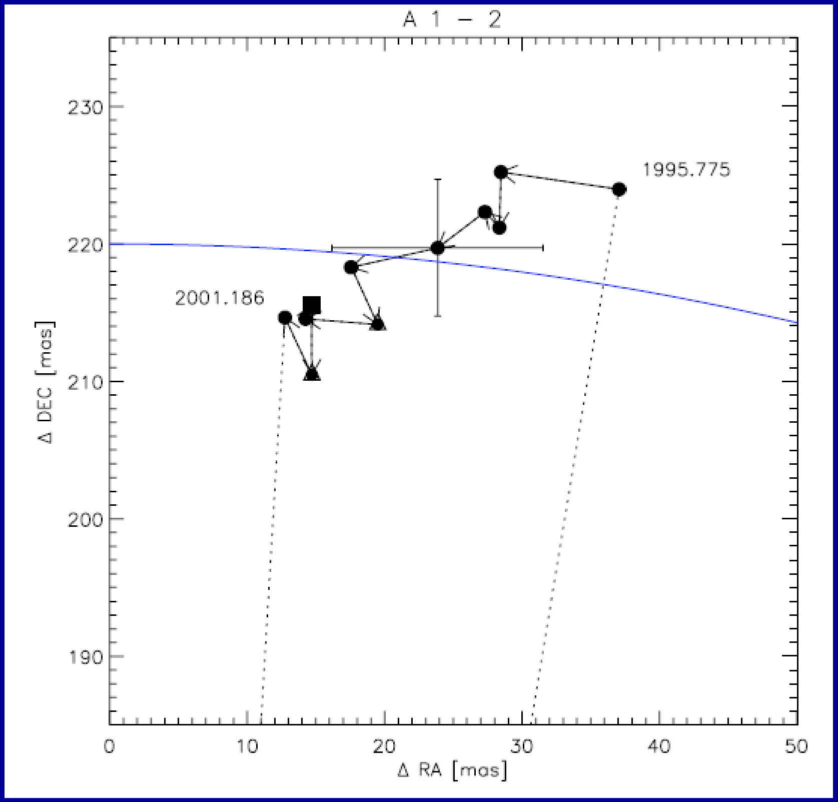
Missing stellar mass required for virial equilibrium in the innermost region of ONC

Mass of secondary, $M_{\theta 1OriC2} > M_{BN}$

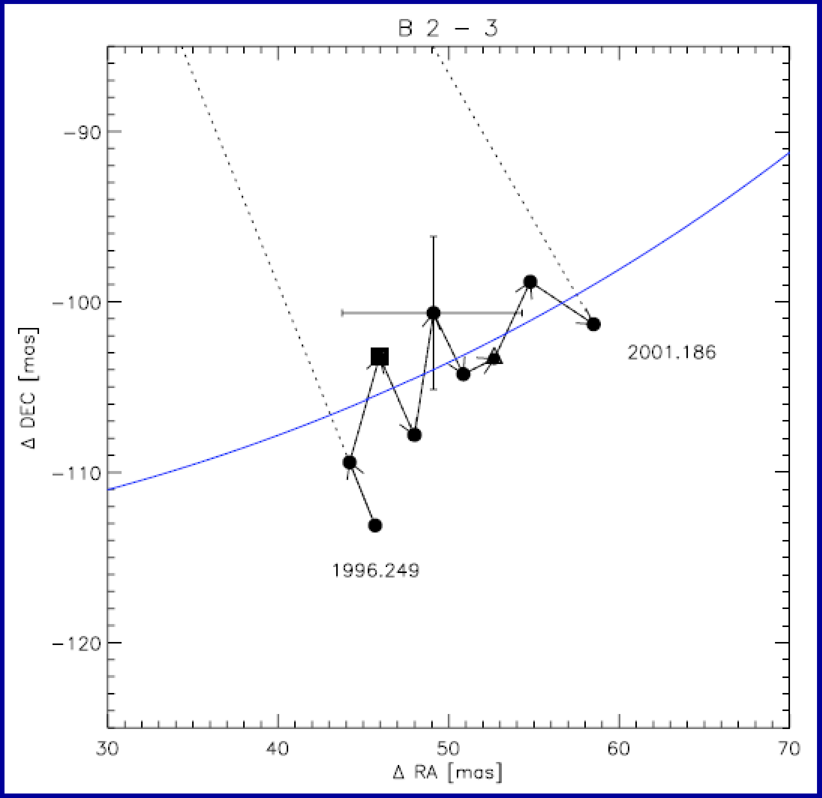
Ratio of ejection kinetic energy to binary total energy, (1.1-3.5) × 10^{47} *erg*

Eccentricity (e(θ1C)) = 0.6

Relative motions in the systems θ1 Ori A and θ1 Ori B



A1-2



B2-3

MAGNETIC BRAKING ?

Magnetic braking due to the momentum carried away by the electromagnetic radiation from the rotating magnetic field gives the following period change (Longair 1994):

$$\frac{\dot{P}}{P} = \frac{8\pi^2 R^4 B_0{}^2}{3\eta c^3 M P^2}$$

here B_0 is the surface magnetic field.

For θ1 OriC1 parameters with B_0 = 1 - 1.5 kG (Wade et al. 2006), it gives

P/P ~ 2 X 10^{-13} yr^{-1} - a negligible effect.

The upper estimate for the magnetic energy of θ1 OriC1 is:

$$E_{magn} = H^2/8\pi \cdot 4/3\pi R^3 = 1.72 \cdot 10^{40} \div 2.75 \cdot 10^{41} erg$$

which is a very small part of its rotational energy:

$$E_{rot1} = 0.2 M_1 \omega_1{}^2 R_1{}^2 = 1.9449 \cdot 10^{47} erg.$$

Hypothesis

- Both components of θ^1 OriC were formed as a result of fragmentation of a non-magnetic (or weakly magnetic) cloud. We assume that θ^1 OriC 2 has constant rotation velocity V2. Then, the primary star θ^1 OriC 1 after the formation had

$$V^0_{rot1} = \frac{R_1}{R_2} V^0_{rot2} = \frac{10.70}{7.94} 96.2 = 129.64 km/s.$$

- Its original rotation energy was $E^0_{rot\ 1} = 2{,}61 \times 10^{48}$ erg.

- The rate of the energy dissipation for the age 250 000 yrs is $0.51 \cdot 10^{36}$ erg/s for the total luminosity of the star $7.46 \cdot 10^{38}$ erg/s.

SCENARIO

Fast rotating magnetic star generates a toroidal component ***Bt*** of the magnetic field. There is a continuous outflow of gas from θ1 Ori C 1 in the form of magnetically confined wind. The magnetic field lines force the highly conducting gas to corotate with the star. Even a moderate rate of mass loss leads to a disproportionately large rate of loss of angular momentum (Mestel 1999).

Angular momentum dissipation for a simple monopole magnetic field is (Weber & Davis 1967):

$$\dot{J} = \frac{2}{3} \dot{M} \Omega R_A^2$$

R_A is the Alfven radius.

Ud-Doula et al. (2009) modified the momentum loss equation for the case of dipolar magnetic field:

$$\dot{J}_{dWD} = \frac{2}{3}\dot{M}\Omega R_A^2 = \frac{2}{3}\dot{M}\Omega R_*^2 \left[0.29 + (\eta_* + 0.25)^{1/4}\right]^2$$

where the wind confining parameter is

$$\eta_* \equiv \frac{B_{eq}^2 R_*^2}{\dot{M} v_\infty}$$

Spin-down time for a magnetic dipole star (strong-confinement limit) is:

$$\tau_{spin} \approx \tau_{mass} \frac{\frac{3}{2}k}{\sqrt{\eta_*}} \approx \frac{\frac{3}{2}kM}{B_{eq}R_*}\sqrt{\frac{v_\infty}{\dot{M}}}$$

With the θ[1]Ori C1 parameters derived above we obtain the spin-down time

T_{spin} = 10 Myr (an order too much!)

for moderate magnetic confinement, $\eta = 30$,

mass-loss rate $\dot{M} = 4\mathrm{x}10^{-7}\, M_{sun}$ /yr,

wind terminal speed 2500 km/s (Donati et al. 2006).

Note:

$$\frac{\tau_{spin}}{\tau_{mass}} \approx \frac{\frac{3}{2}k}{\left[0.29 + (\eta_* + 0.25)^{1/4}\right]^2}$$

Another examples are HD 191612, P=538 d (Donati et al. 2006) and HD 108, P=15 yr ? (Martins et al. 2010). The spin-time for HD 191612 is only 0.4 Myr for $\dot{M} = 6\mathrm{x}10^{-6}\, M_{sun}$ /yr.