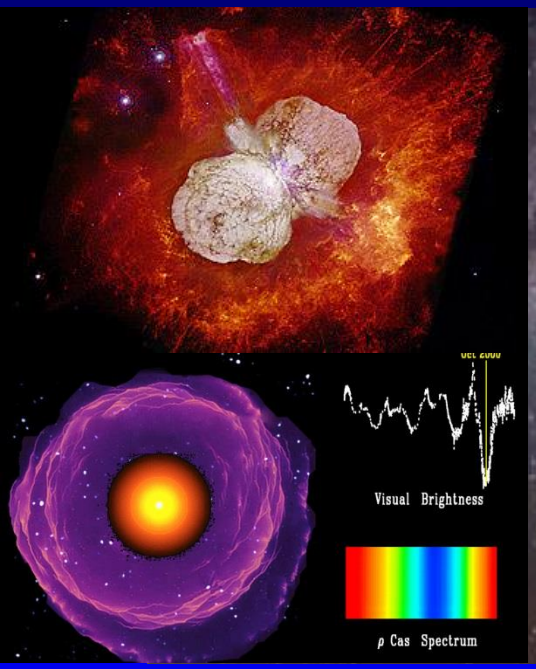
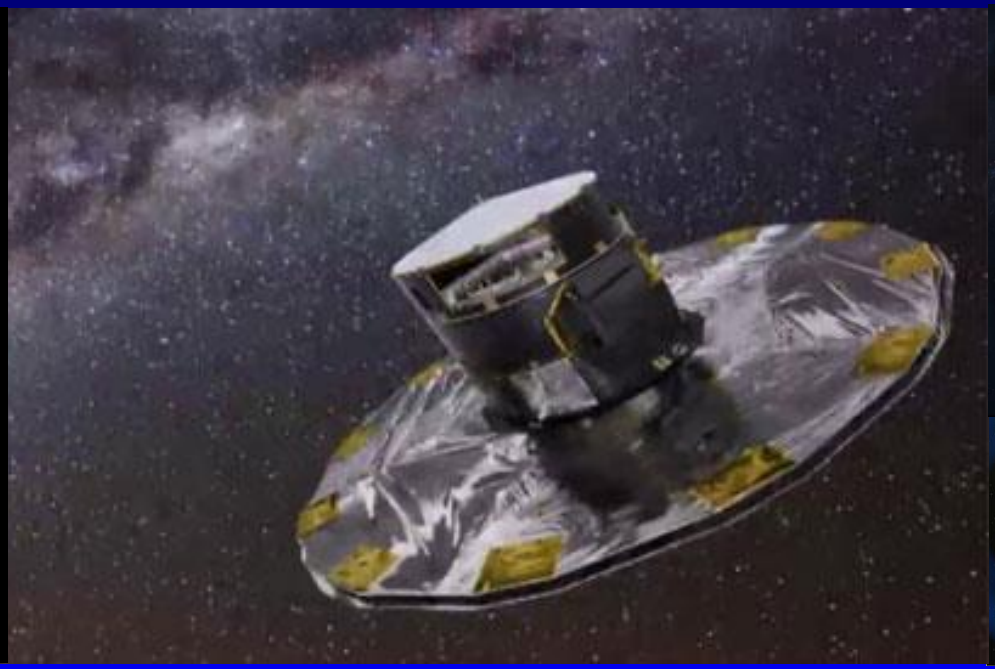
Sterrenkundige spectroscopie te KSB





Alex Lobel

Koninklijke Sterrenwacht van België

In deze lezing

- **Spectroscopie met ESA-Gaia: sterparameters en radiële snelheden.**

- **Onderzoek naar de eigenschappen en structuur van winden van zware sterren: modelisatie van spectra dmv 3-D stralingstransport.**

- **Lange termijn spectroscopische monitoring van Gele Hyperreuzen en Lichtkrachtige Blauwe Veranderlijken.**

- **Ontwikkeling van interactieve databank van hoge-resolutie spectrale atlassen voor astrofysisch onderzoek: BRASS.**

Spectroscopie met Gaia

- ESA is hoeksteen missie voor onderzoek van de Melkweg
- Astrometrische satelliet; opvolger van Hipparcos 1990-93. Inclusief optische fotometrie tot 20ste mag. & spectroscopie
- 5 jaar waarnemingen met productie van Gaia catalogus
- Astronomen betrokken bij productie van Gaia catalogus
- Wat leert Gaia ons over de vorming structuur en evolutie van ons melkwegstelsel?

gaia Lancering van dec 2013

Kourou

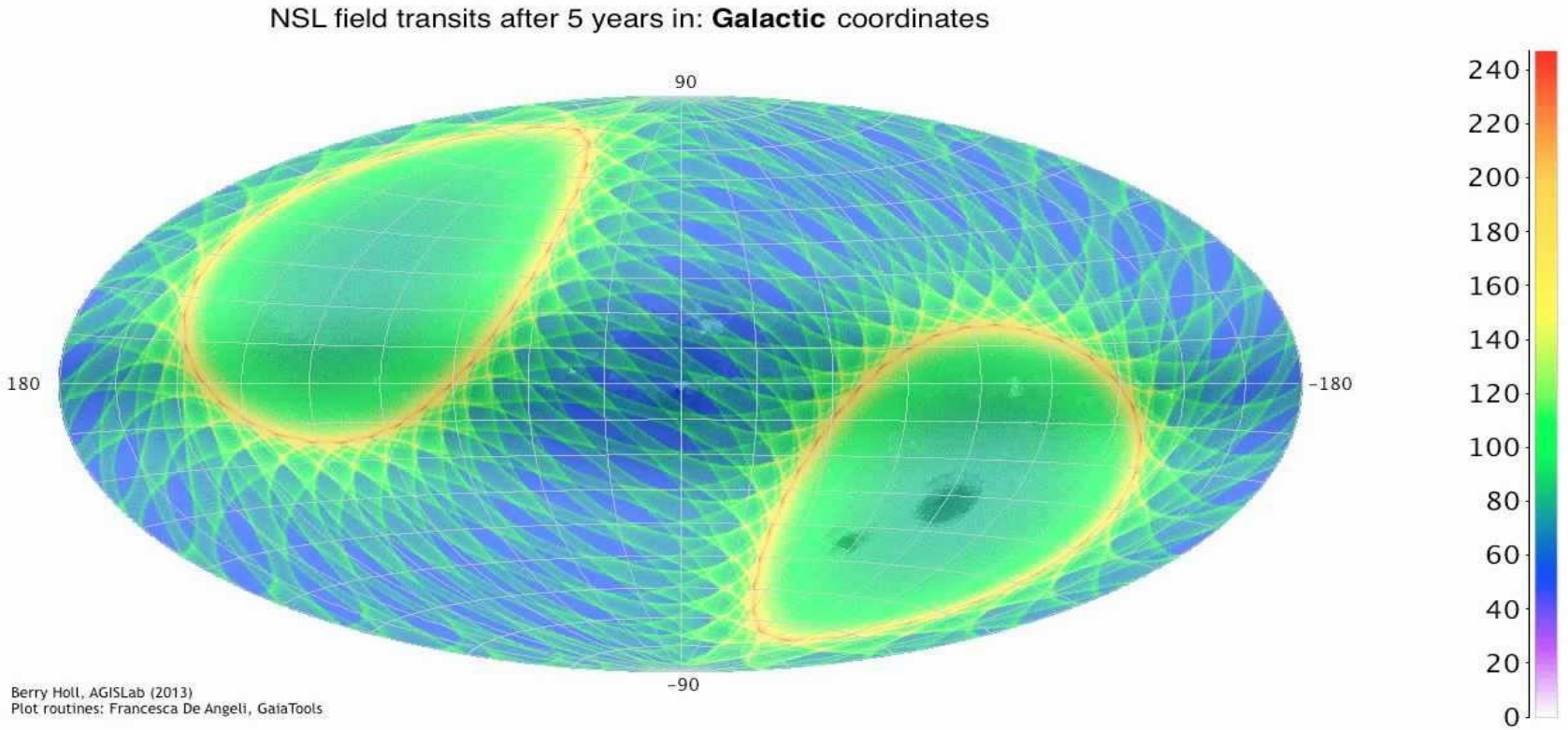
Soyuz Sz-013

Inpakking van Gaia voor Kourou

Gaia scant de ganse hemel

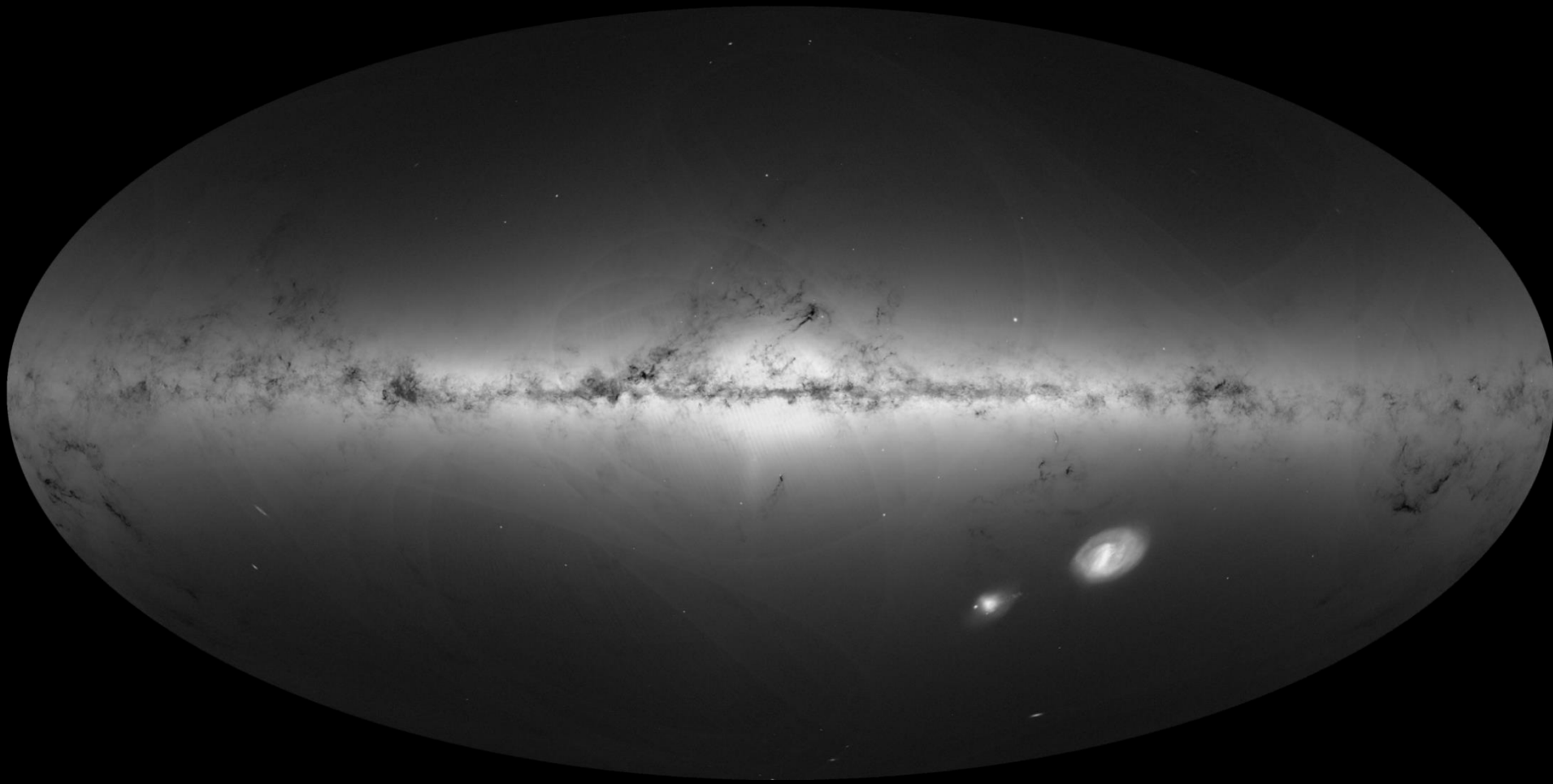
Gaia scant bronnen meerdere malen

Kaart van aantallen Gaia waarnemingen aan de hemel gedurende 5 jaar

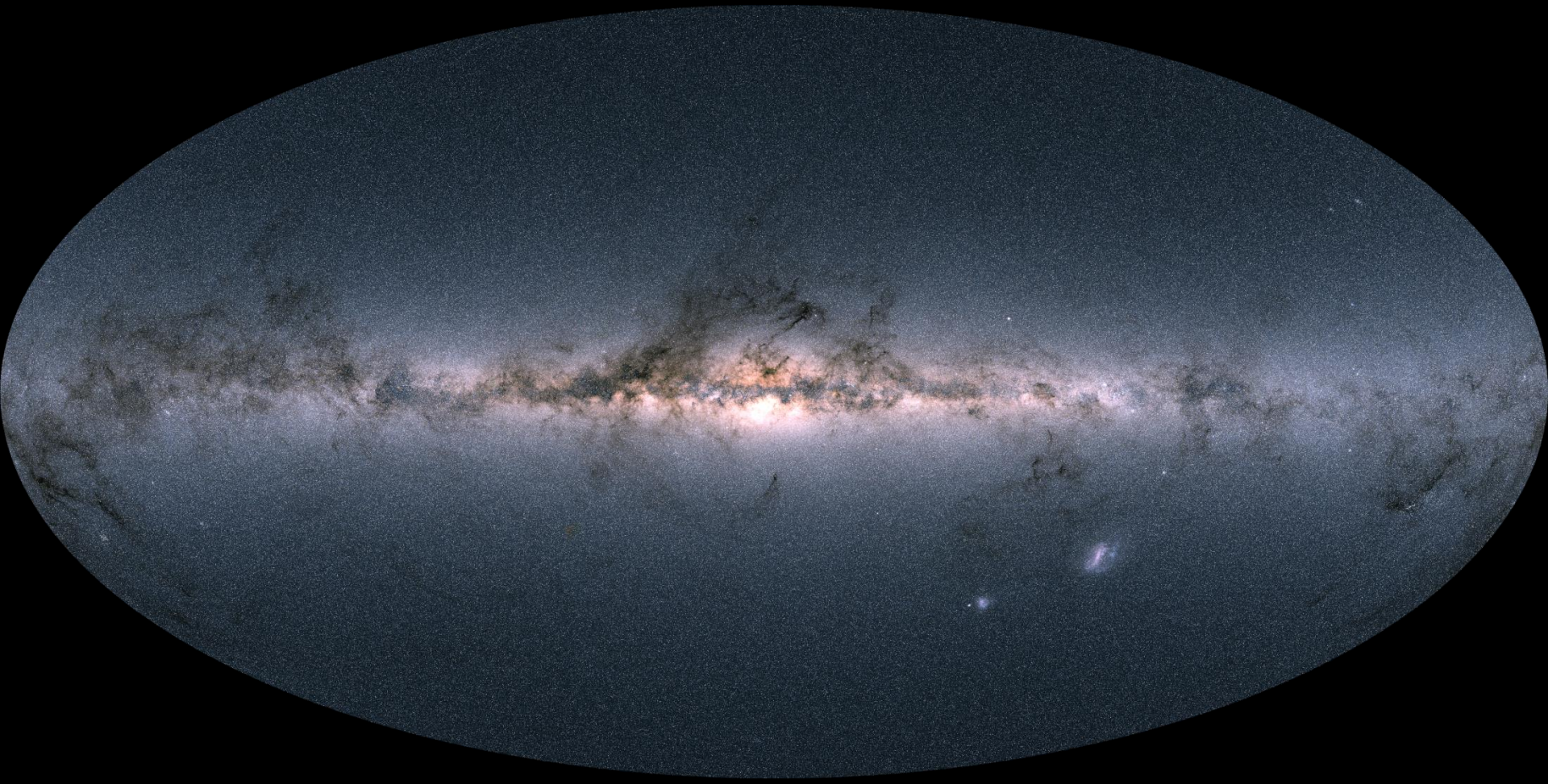


- **Waarneming van 1,69 miljard sterren elk gem. 70 maal tot *G*=20 mag.**
- **Astrometrie en blauw & rood fotometrie van elke bron.**
- **Astrometrische nauwk. in eind catalogus tot ~20 μ boogsec (*G*<15 m.)**

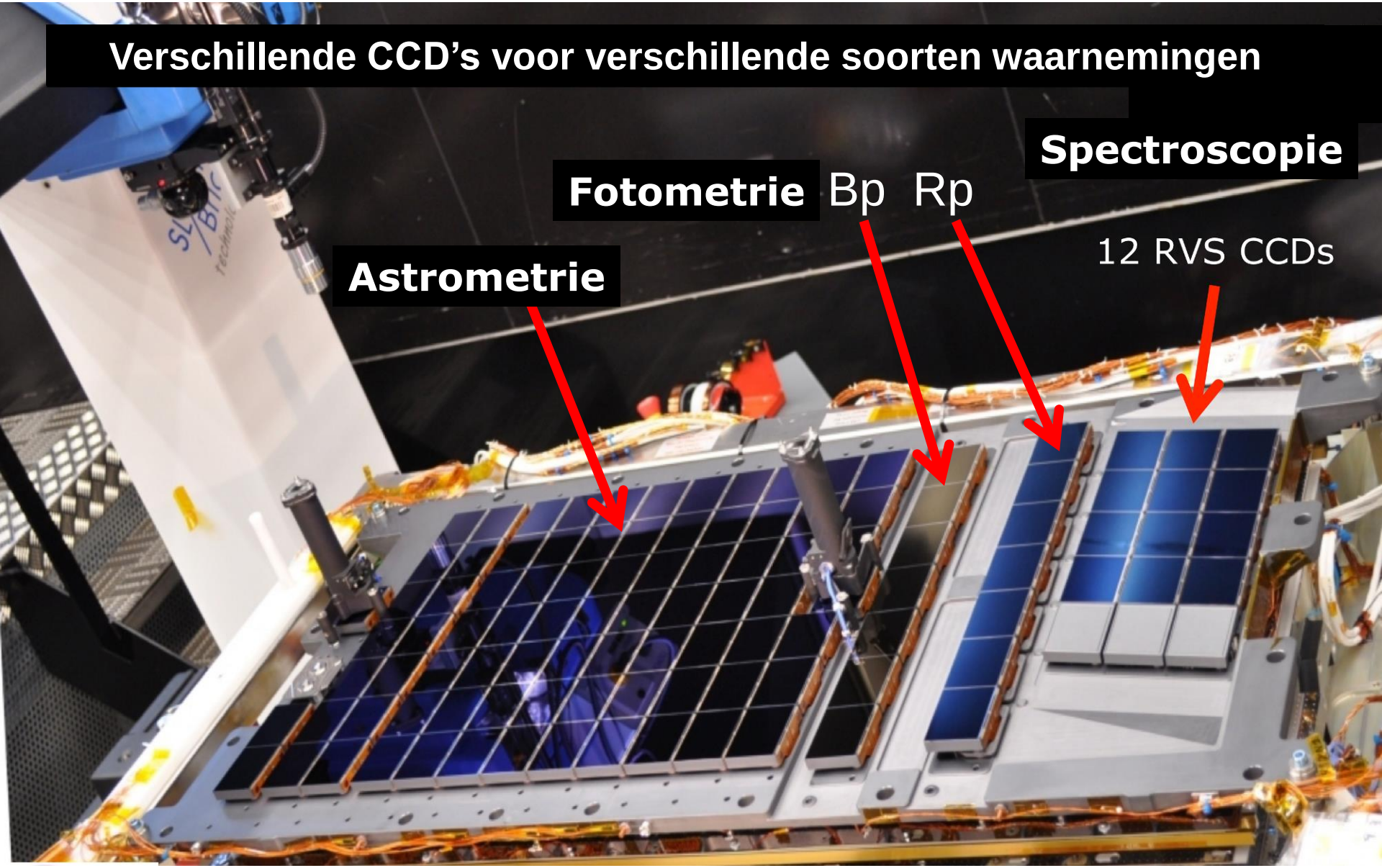
Positie en helderheid van 1,69 miljard sterren



Kleurenkaart met 1,3 miljard sterren

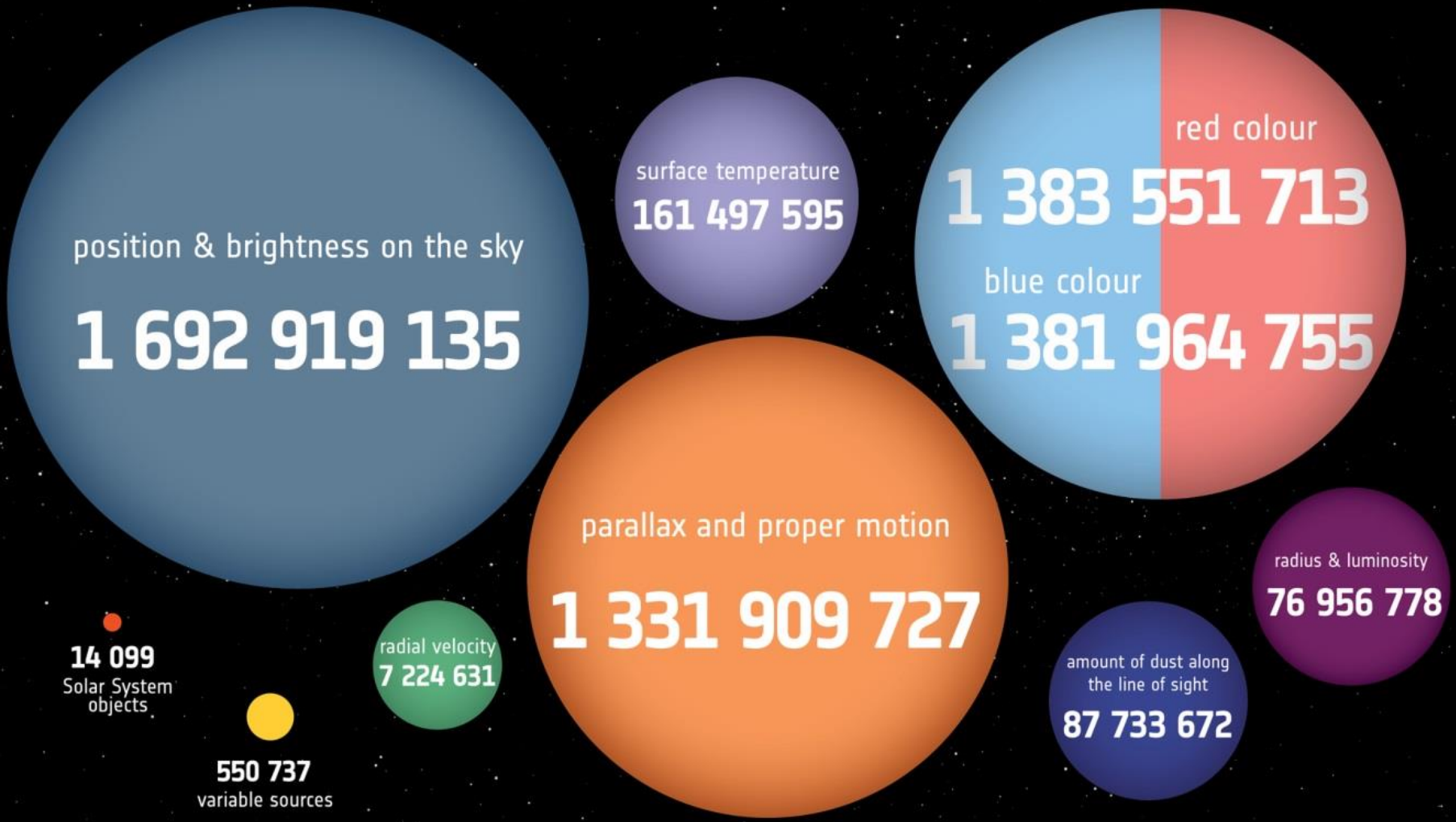


Gaia's CCD detectoren



106 CCDs ≅ 938 miljoen pixels

Aantal sterren en objecten in Gaia's tweede data uitgave

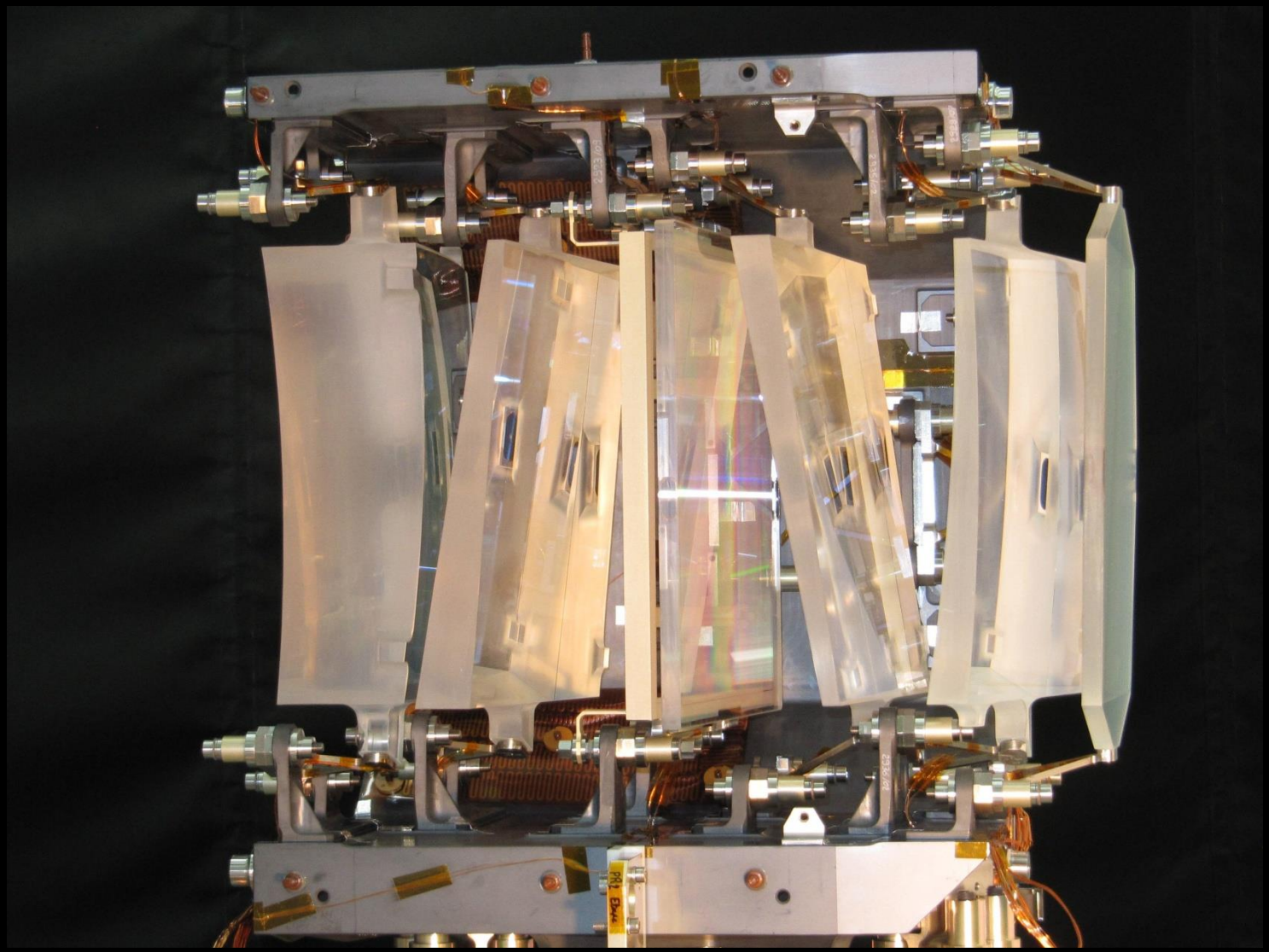


www.esa.int

The second data release of ESA's Gaia mission is scheduled for publication on 25 April 2018.

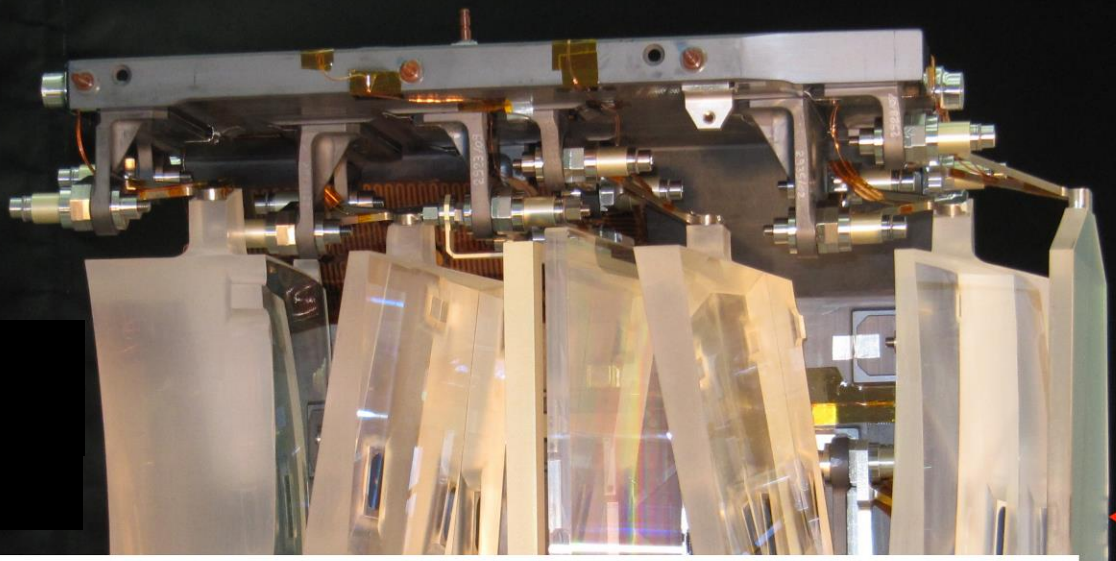
European Space Agency

Gaia spectrometer voor nabije IR

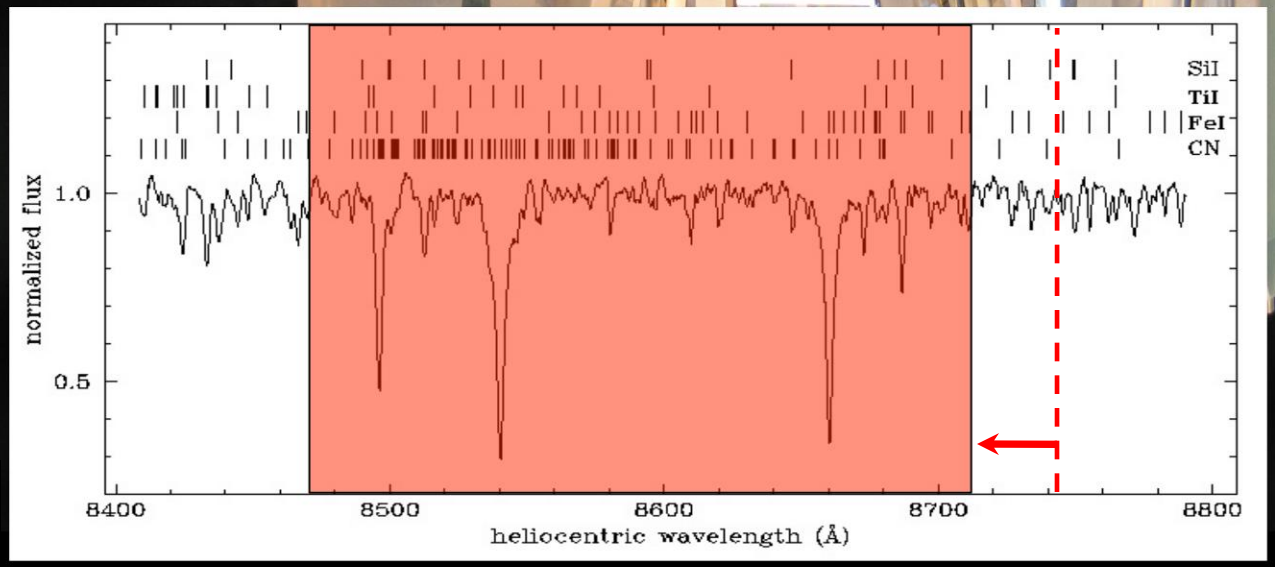


Gaia spectrometer voor nabije IR

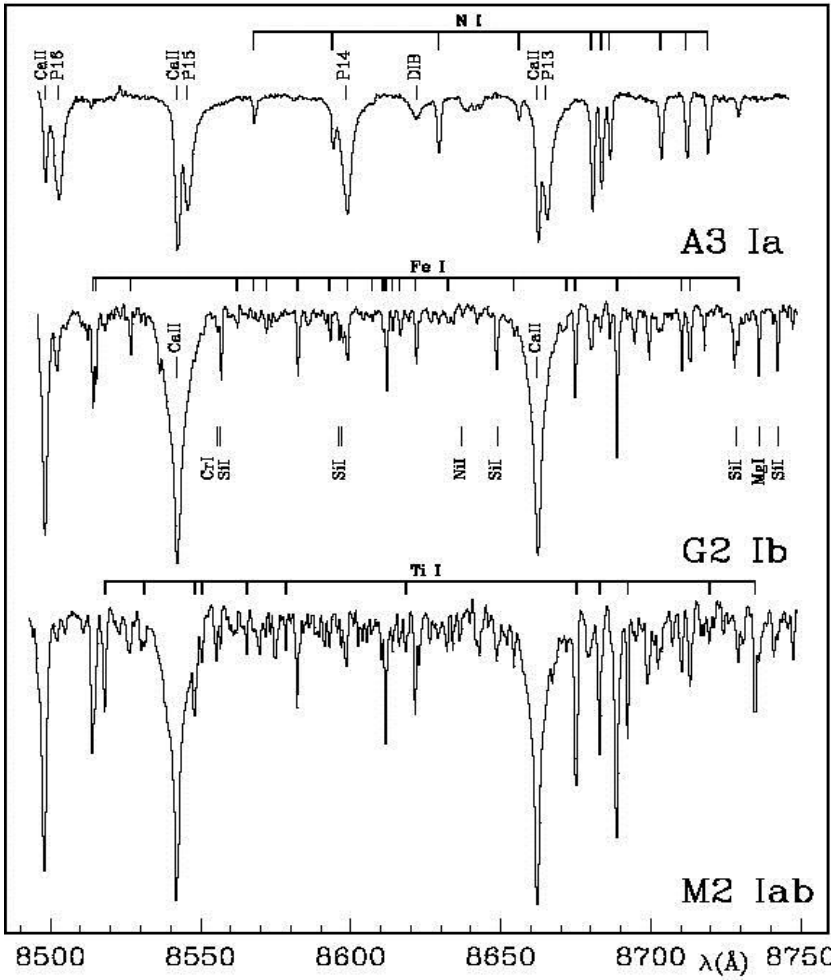
Spectrale resolutie: R=11500

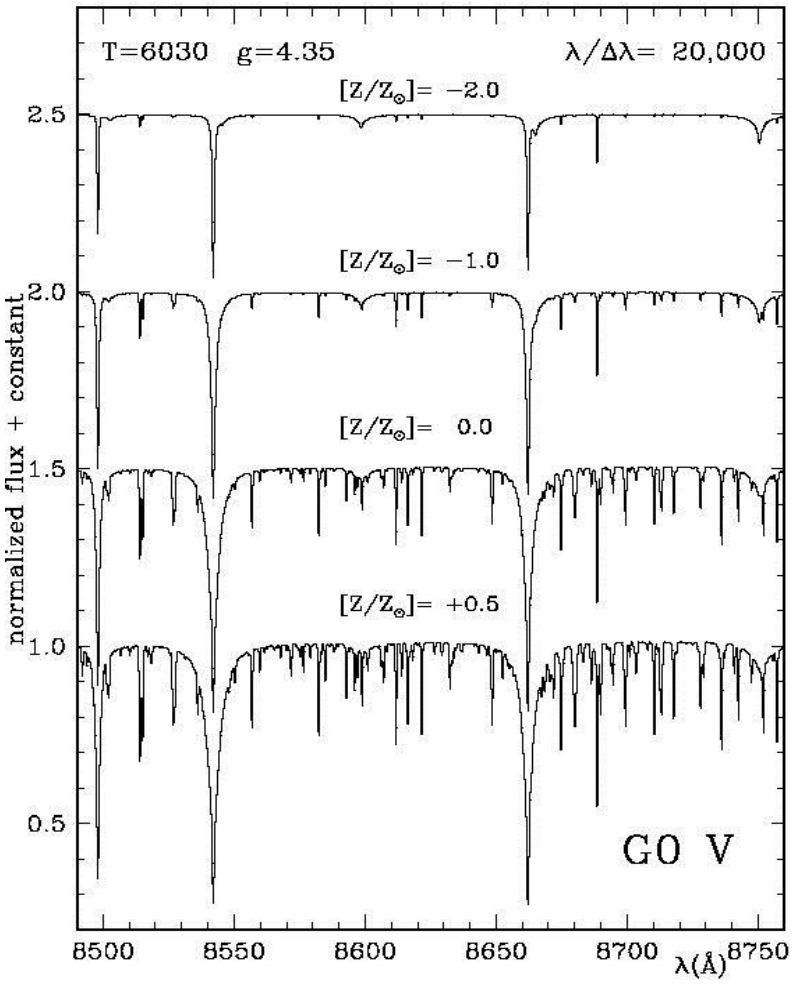


847-874 nm



Spectrale reeksen van sterren rond het Ca II triplet





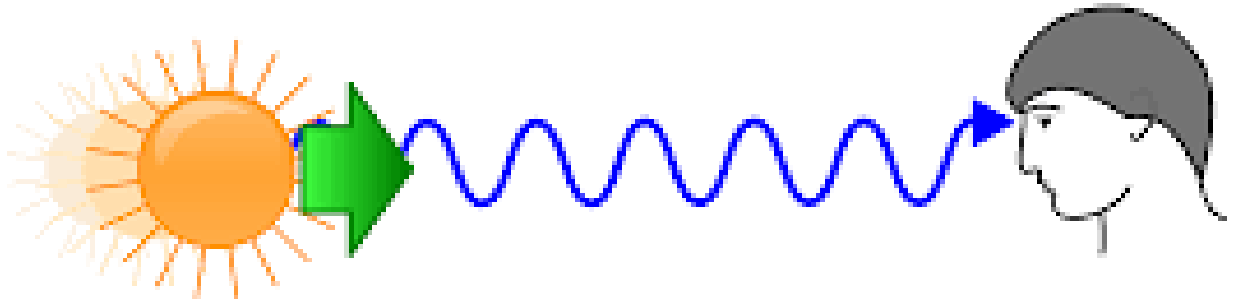
Effect van temperatuur: A tot M type

Effect van metaalgehalte in G sterren

Doppler effect voor licht

spectrale roodverschuiving

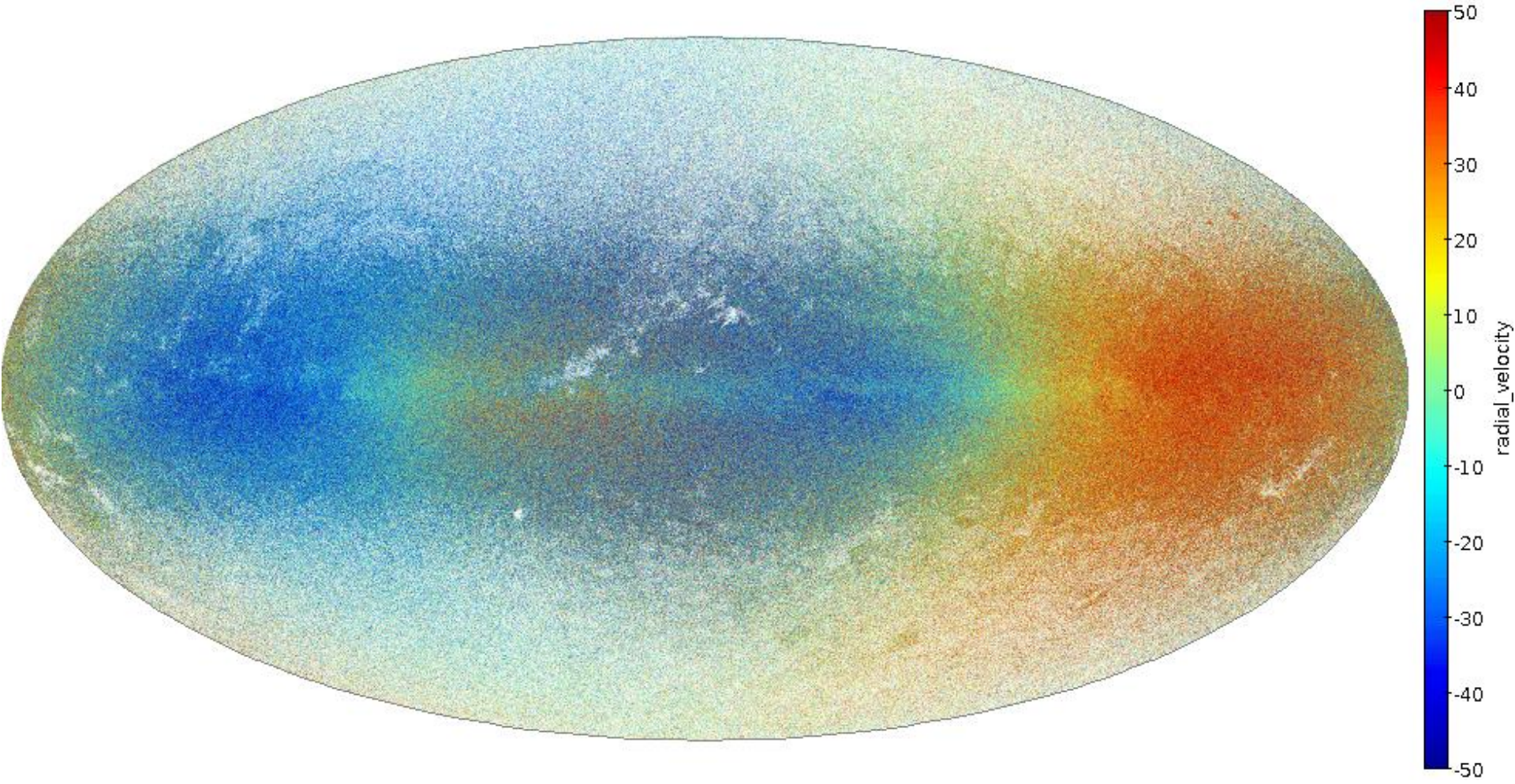
snelheid van ons weg



snelheid naar ons toe

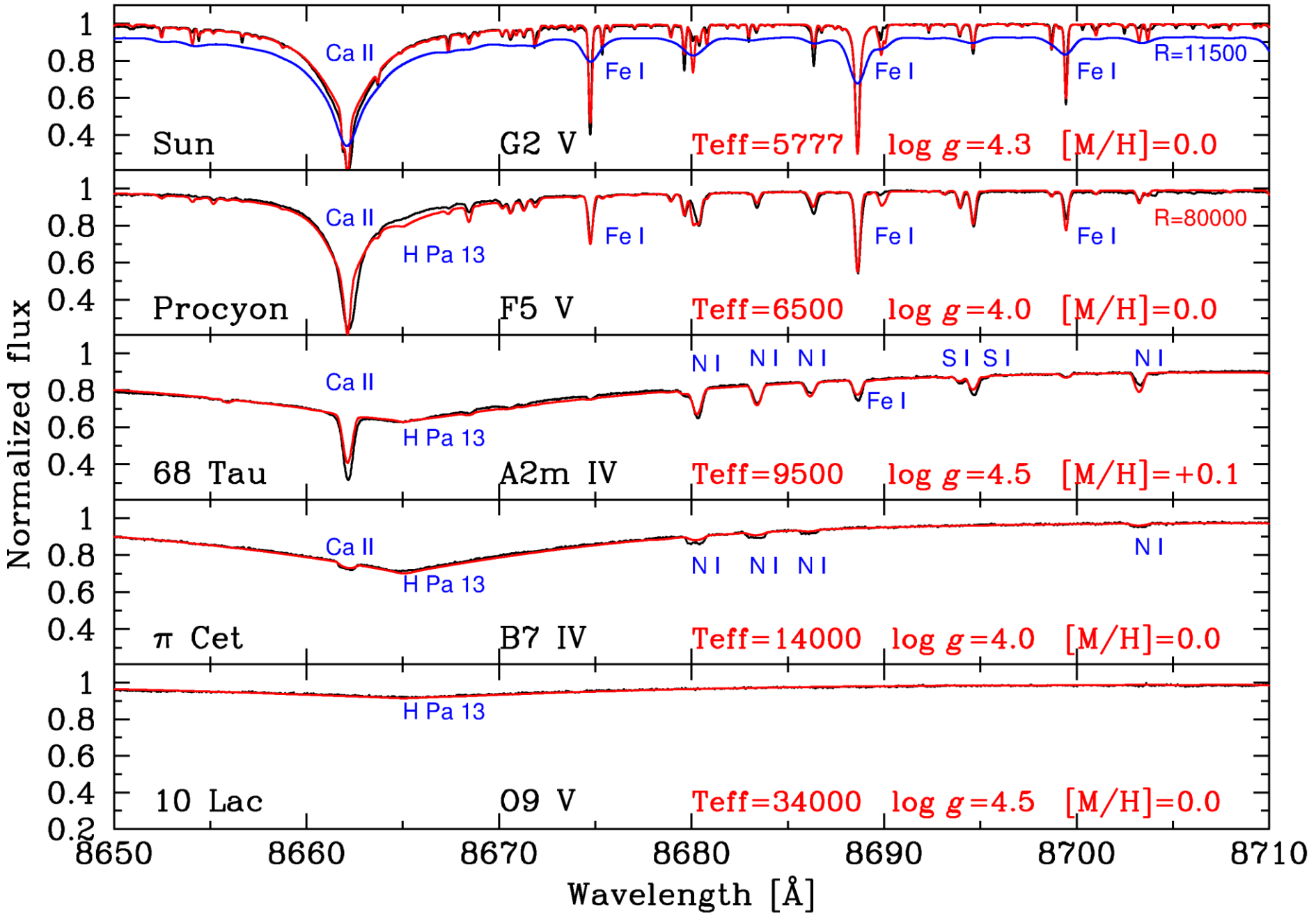
spectrale blauwverschuiving

Gemiddelde radiële snelheden van 7,2 miljoen sterren

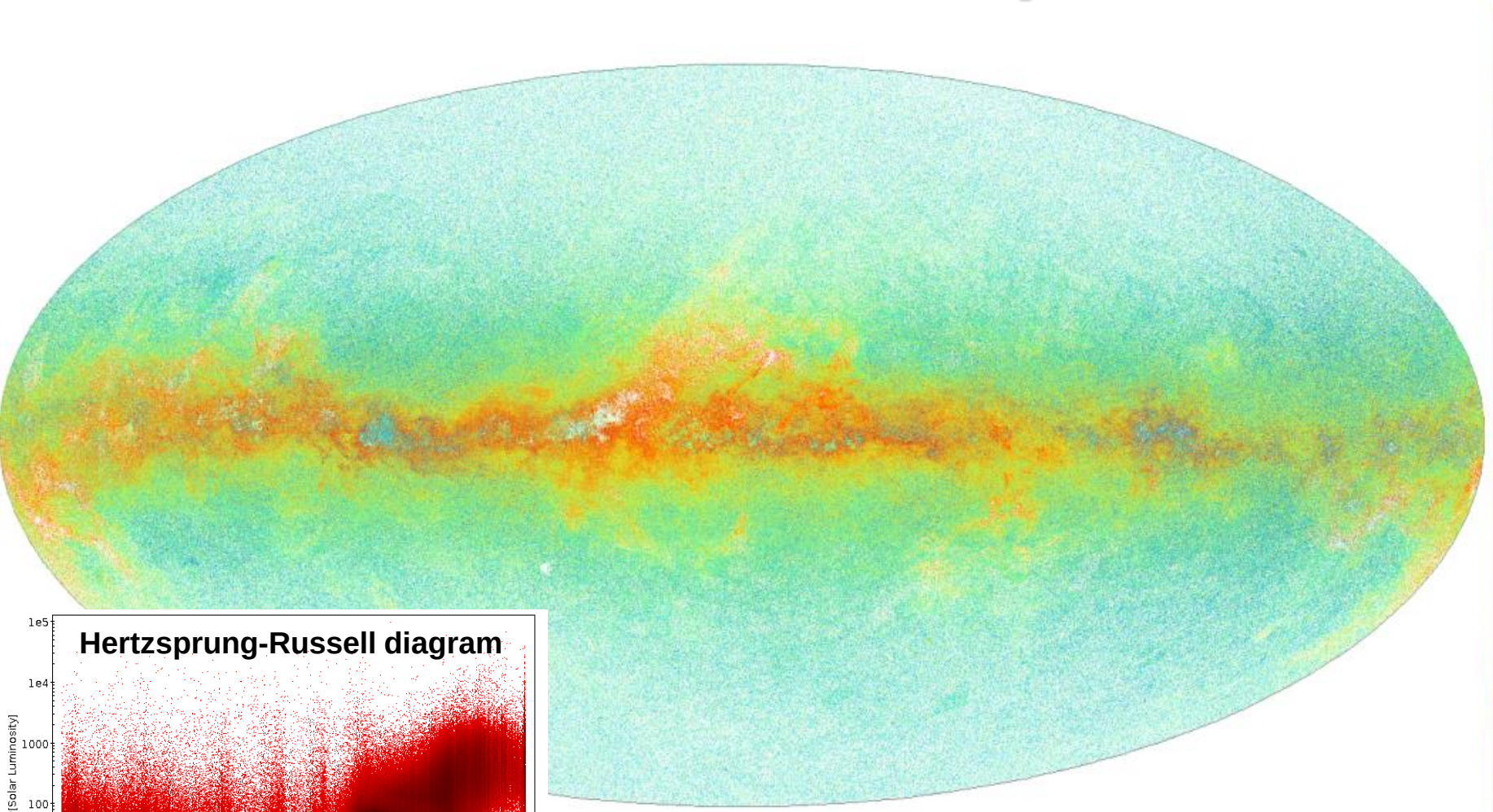


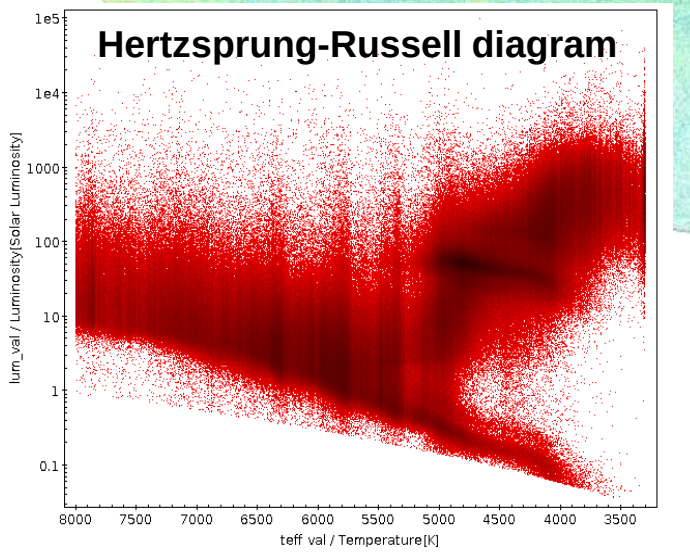
Rotatie van het melkwegstelsel en de beweging van de Zon tov de sterren

Theoretische RVS spectra voor berekening van Teff, logg, ..



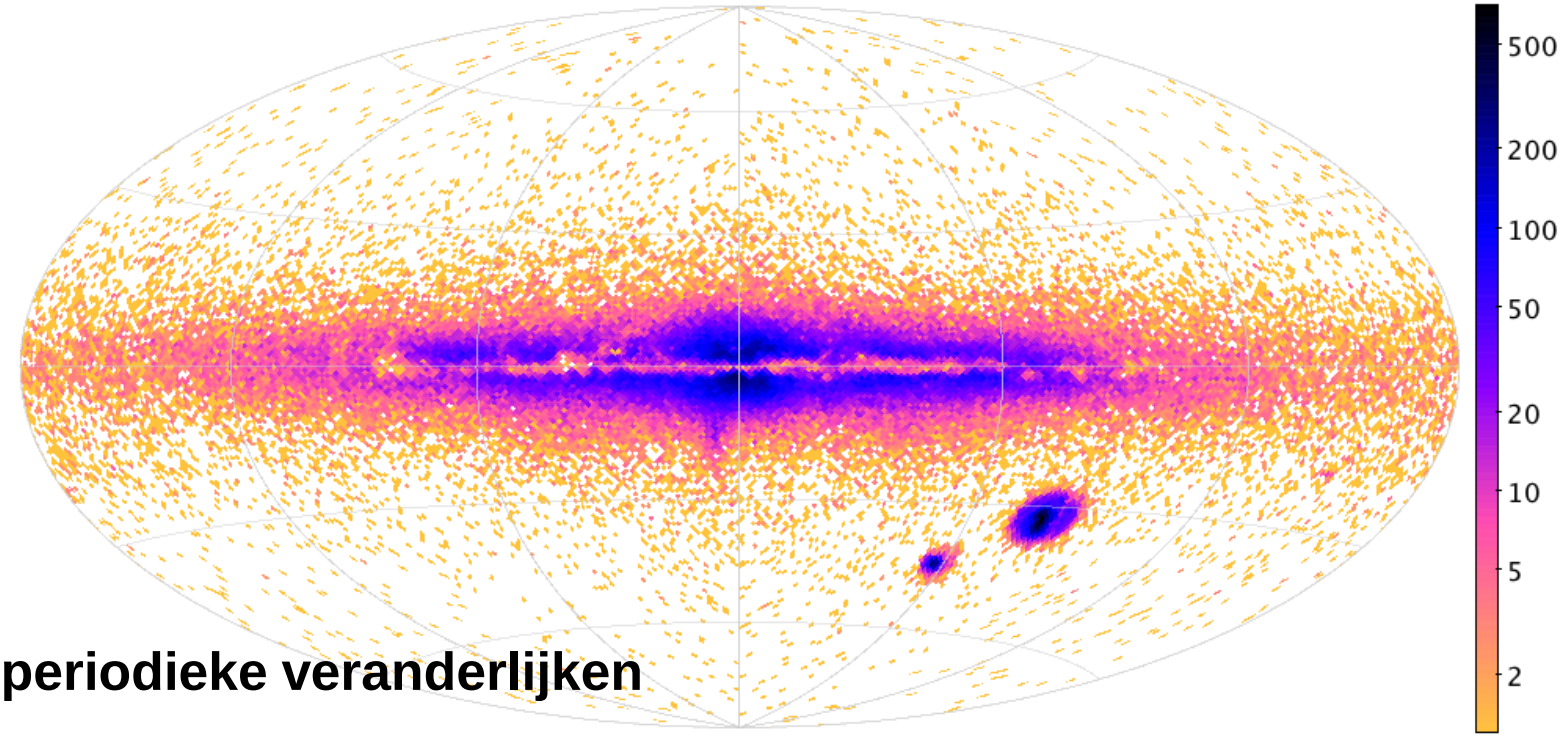
Kaart van atmosferische temperaturen Teff



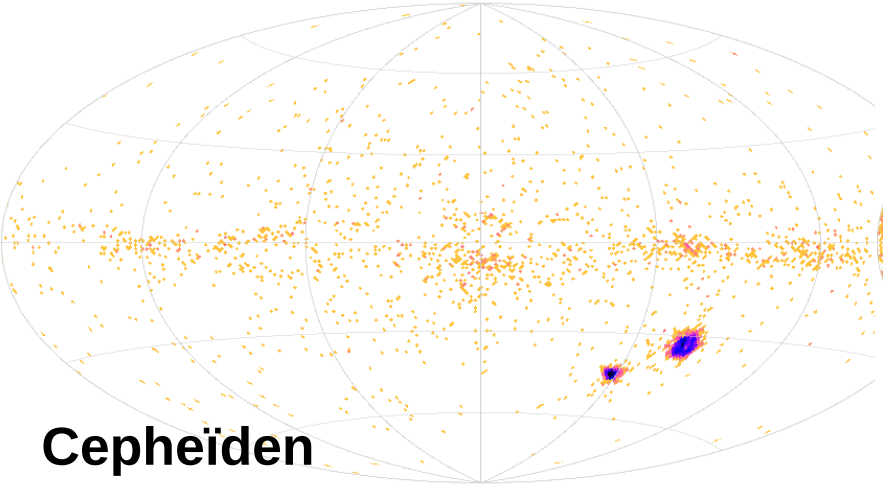


Gemiddelde meer sterren met Teff boven 5000 K waargenomen boven het Melkweg middenvlak.

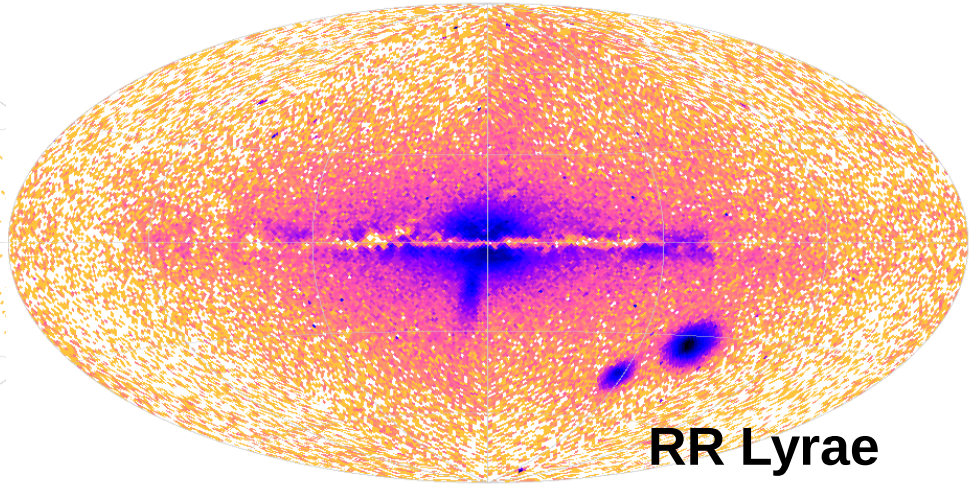
Diverse typen pulserende sterren in aantallen



Lang-periodieke veranderlijken



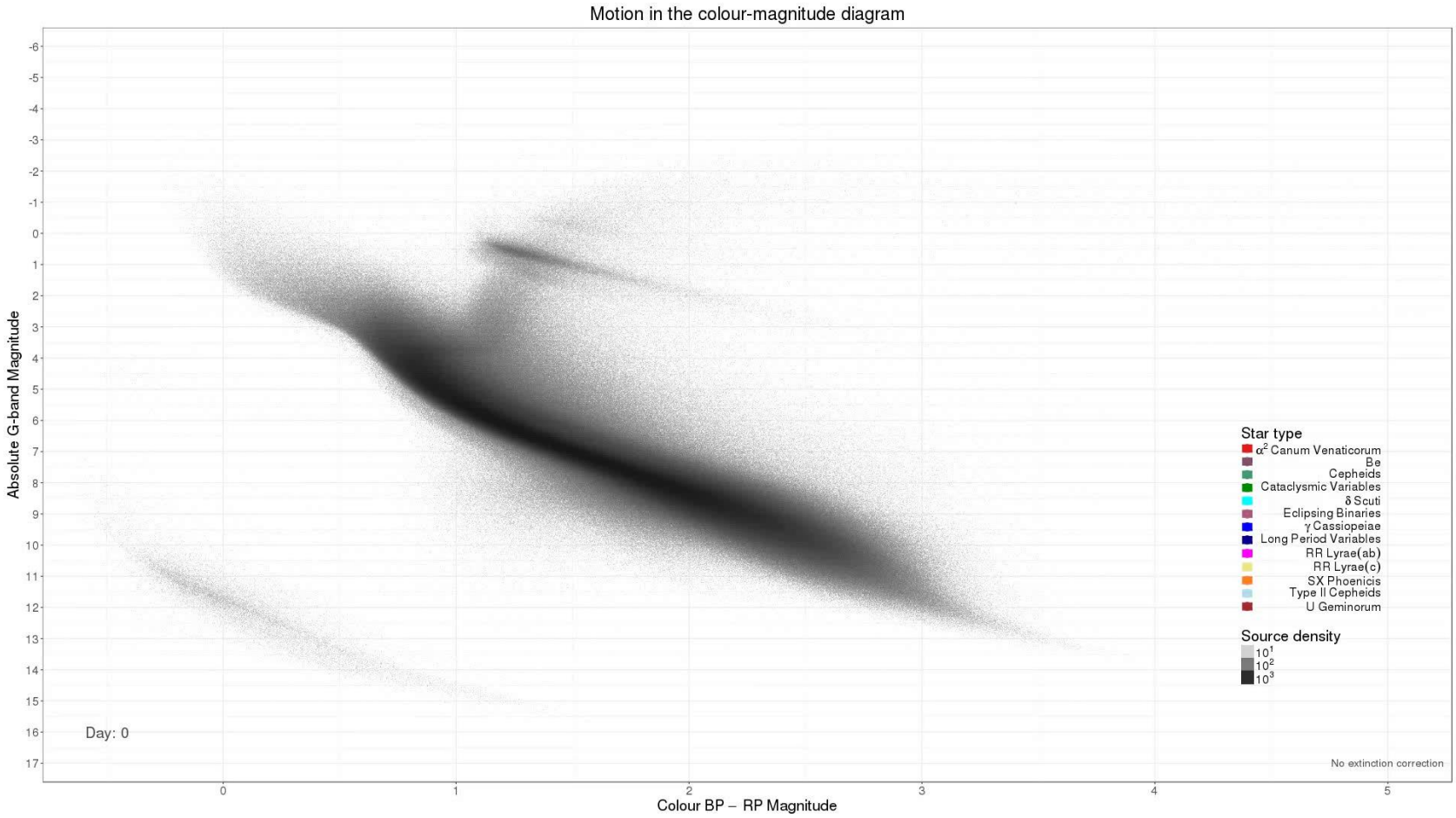
Cepheïden



RR Lyrae

Veranderlijke sterren in het H-R diagram

helder

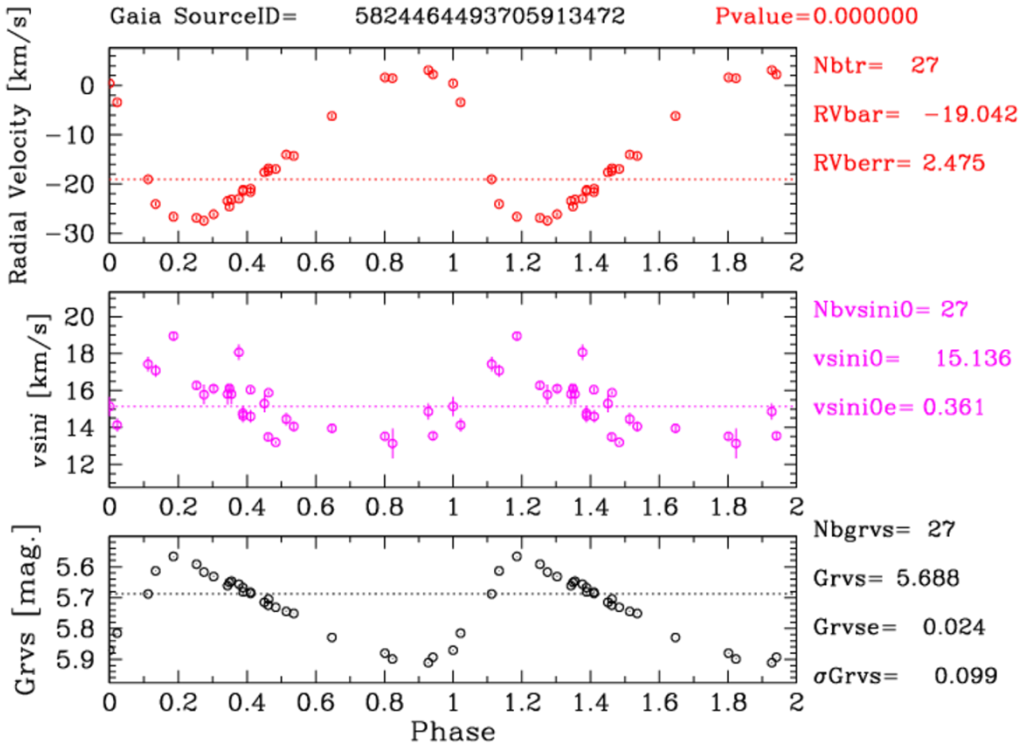


lichtzwak

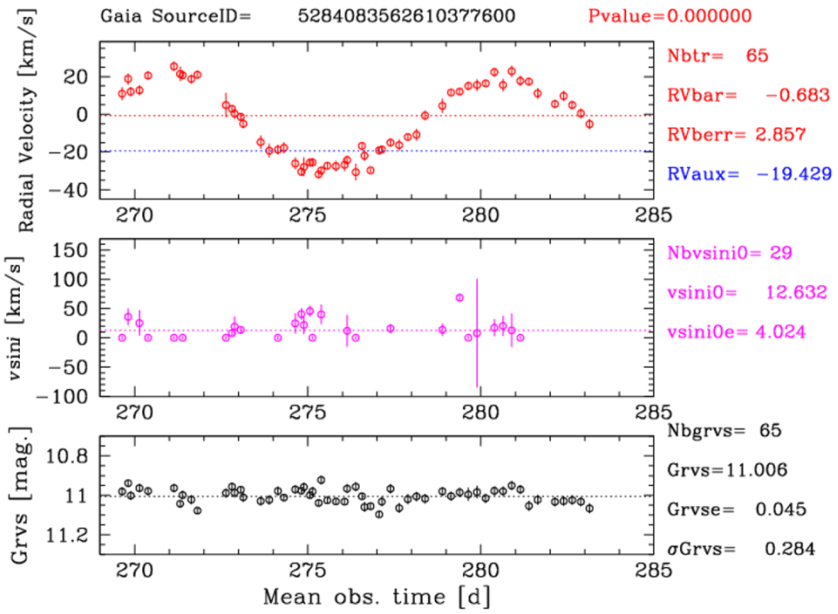
warmer ⟷ koeler

- Verschillende soorten veranderlijke sterren in het H-R diagram.
- Cyclische veranderingen in G magnitude en kleuren.
- Cepheïden zijn belangrijk voor betrouwbare afstandsbepalingen.

Gaia radiële snelheden vs. RVS magnitude

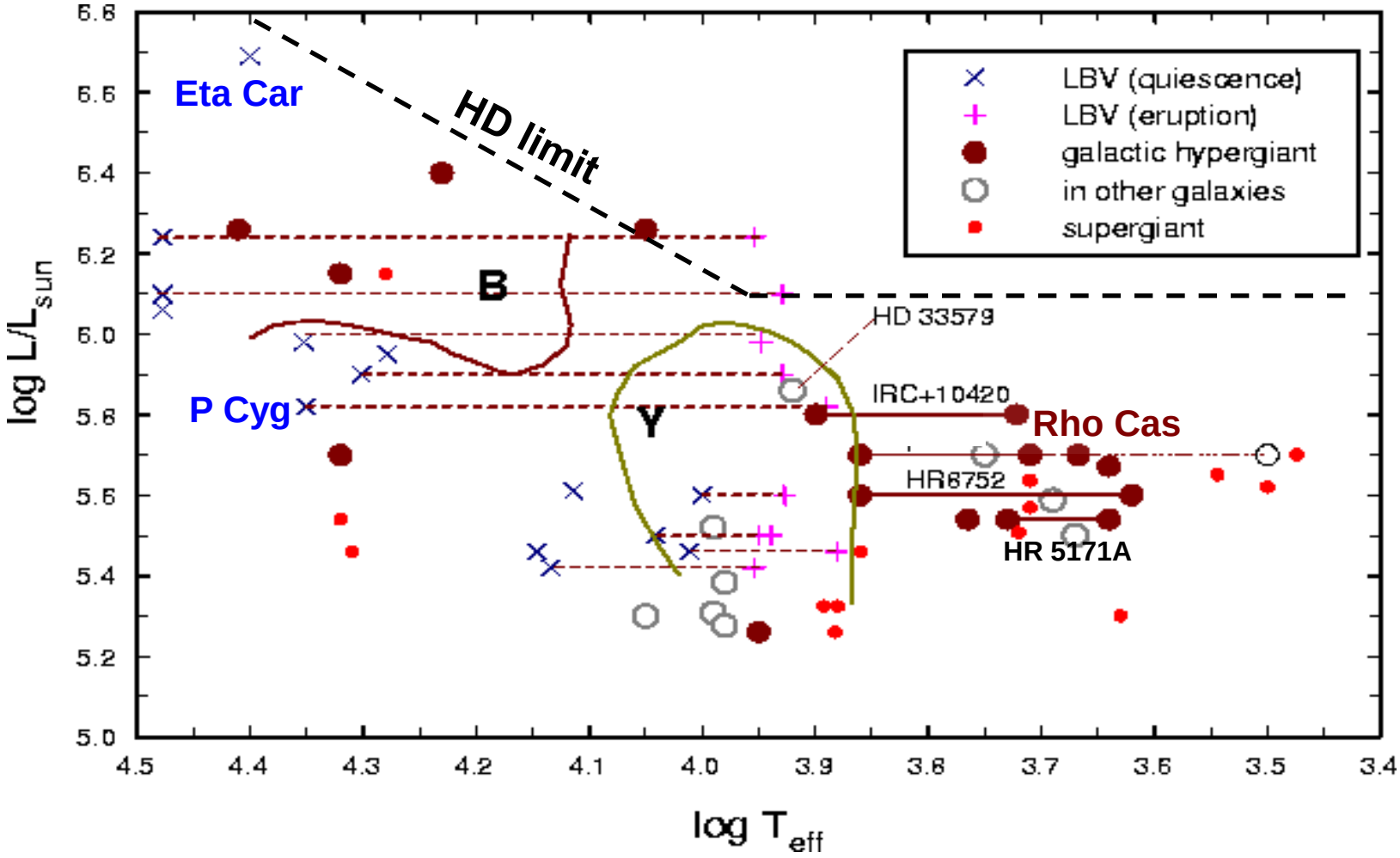


Cepheïde R TrA
Pulsatie periode = 3,389 d.



Niet-eclipserende
dubbelster TYC 8905-425-1
Orbitale periode = 10 d.

Hyperreuzen in het H-R diagram



- **Zwaarste en meest lichtkrachtige sterren nabij de grens op lichtkracht (F-G Ia^{+}).**
- **Vertonen sterke spectrale veranderingen en semi-regelmatige *V* krommen.**
- **Terugkerende uitbarstingen met sterk verhoogd massaverlies tot ~10^{-3} M$_{\odot}$ /jaar.**

LK BLAUWE VERANDERLIJKE

P Cygni B1 Ia+

T_{eff} = 19300 K Log *g* = 0.0

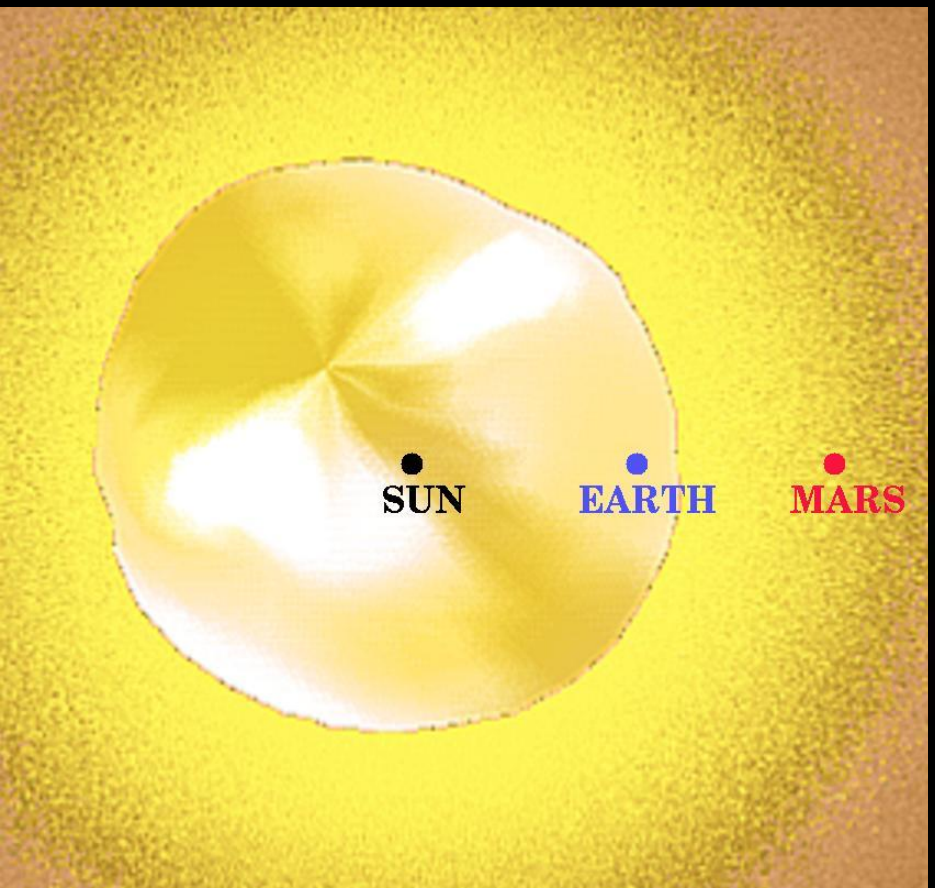
R_* = 76 $R_\odot$ L_* = 630 000 $L_\odot$

GELE HYPERREUS

Rho Cas F - G Ia+

T_{eff} = 7200 K Log *g* = 0,5

R_* = 400 $R_\odot$ L_* = 100 000 $L_\odot$



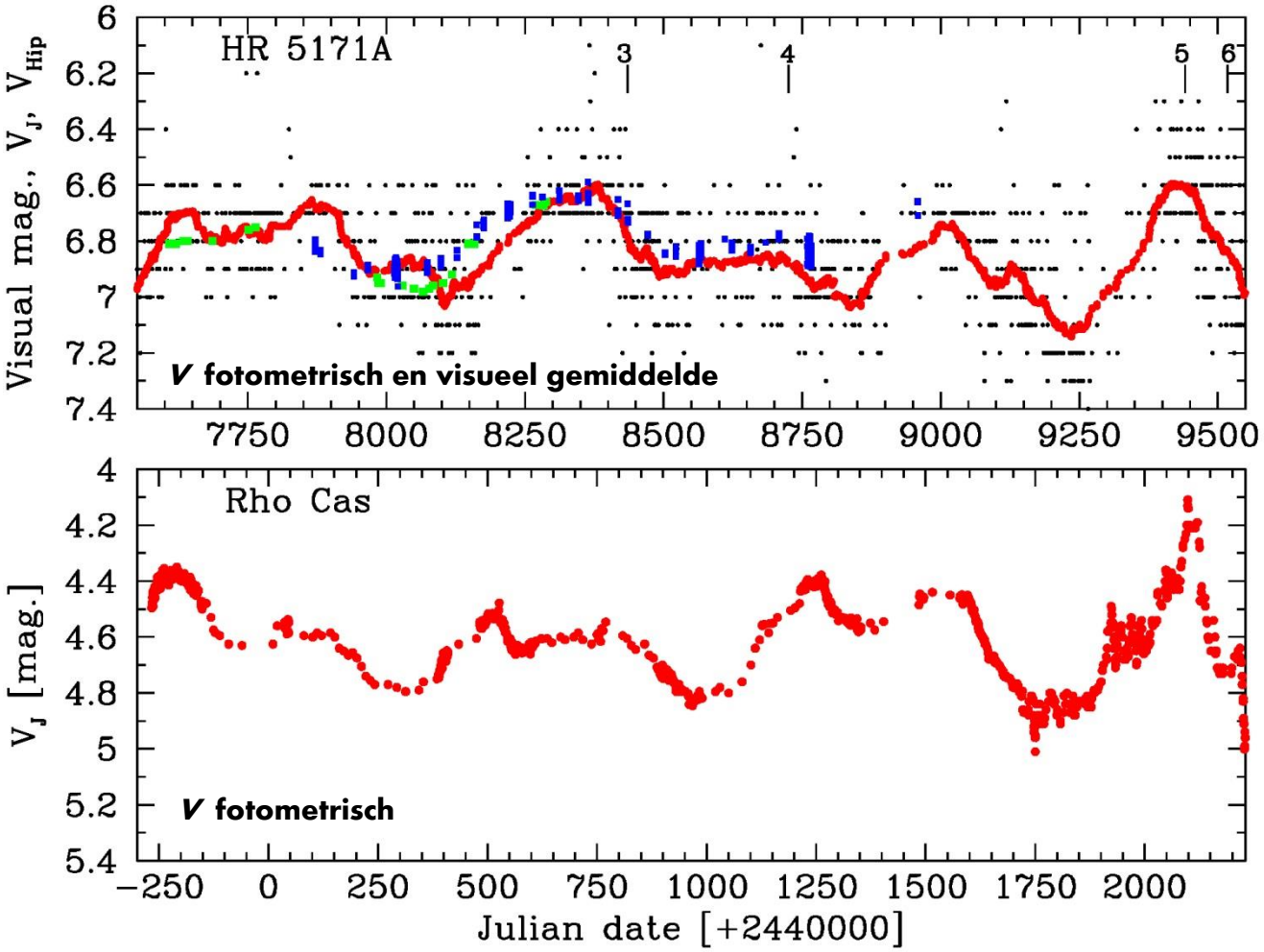
RODE SUPERREUS

Alpha Ori M2 Iab

T_{eff} = 3500 K Log *g* = - 0,5

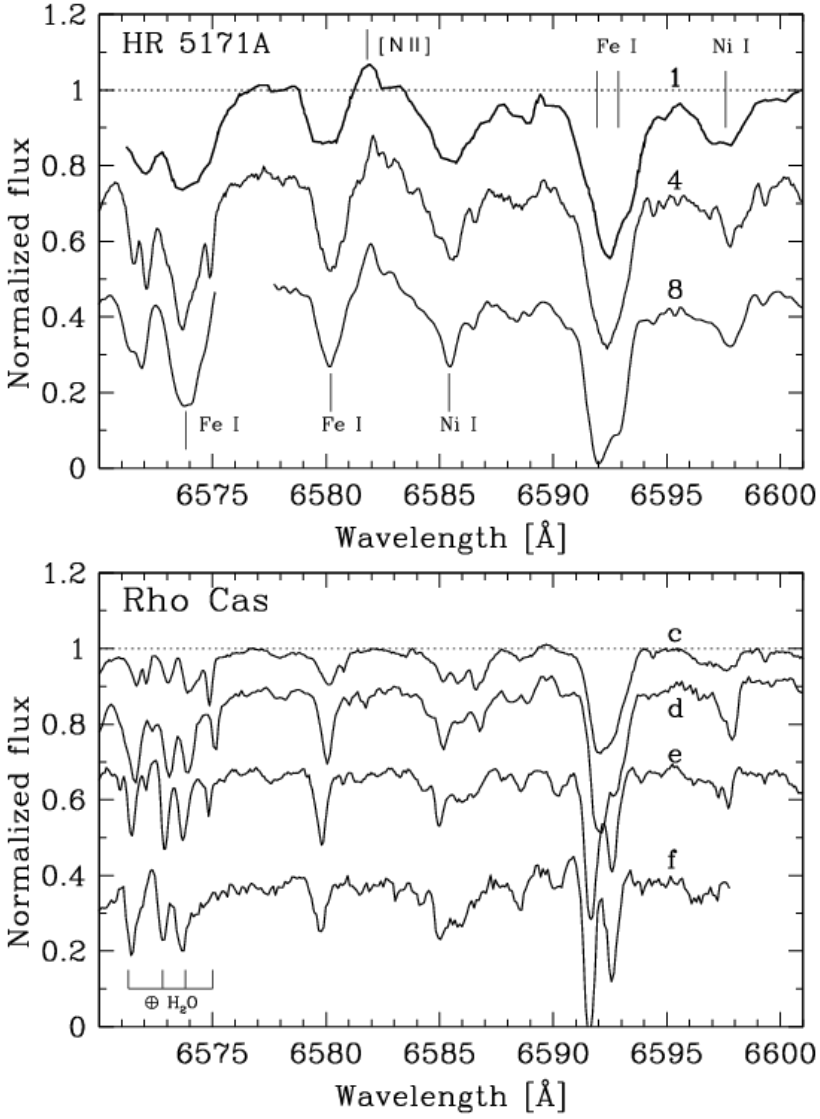
R_* = 700 $R_\odot$ L_* = 40 000 $L_\odot$

V lichtkrommen van GHRn Rho Cas en HR 5171A



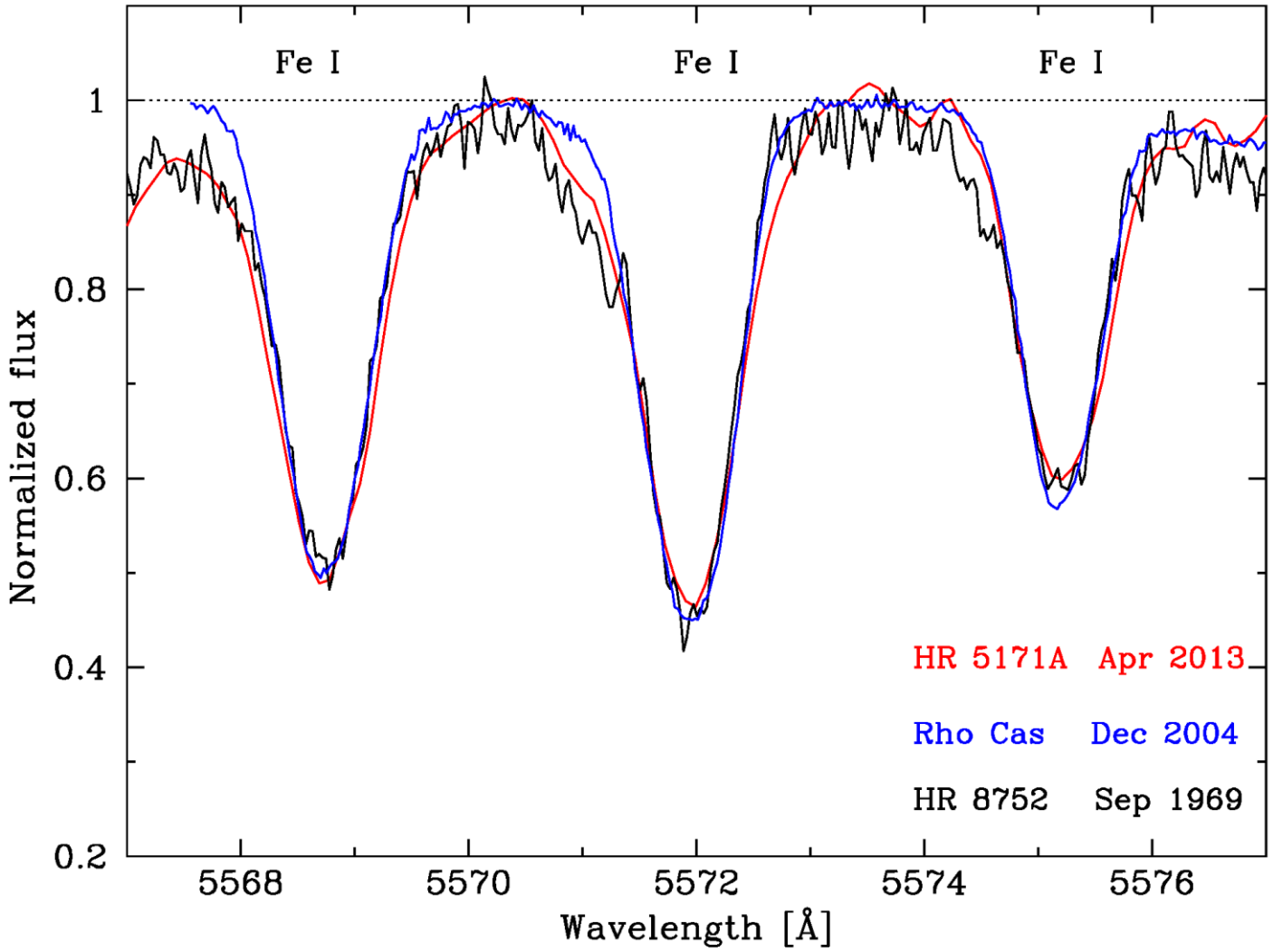
- Kwasi-periodische *V* variaties over verschillende jaren met P_q = 240 d – 520+ d.
- *V* lichtkrommen met amplituden van $0^m,2$ to $0^m,5$ tgv atmosferische pulsaties.
- *V* amplituden kunnen toe- of afnemen over jaren en overgaan in een uitbarsting.

Hoge resolutie spectra van Rho Cas en HR 5171A



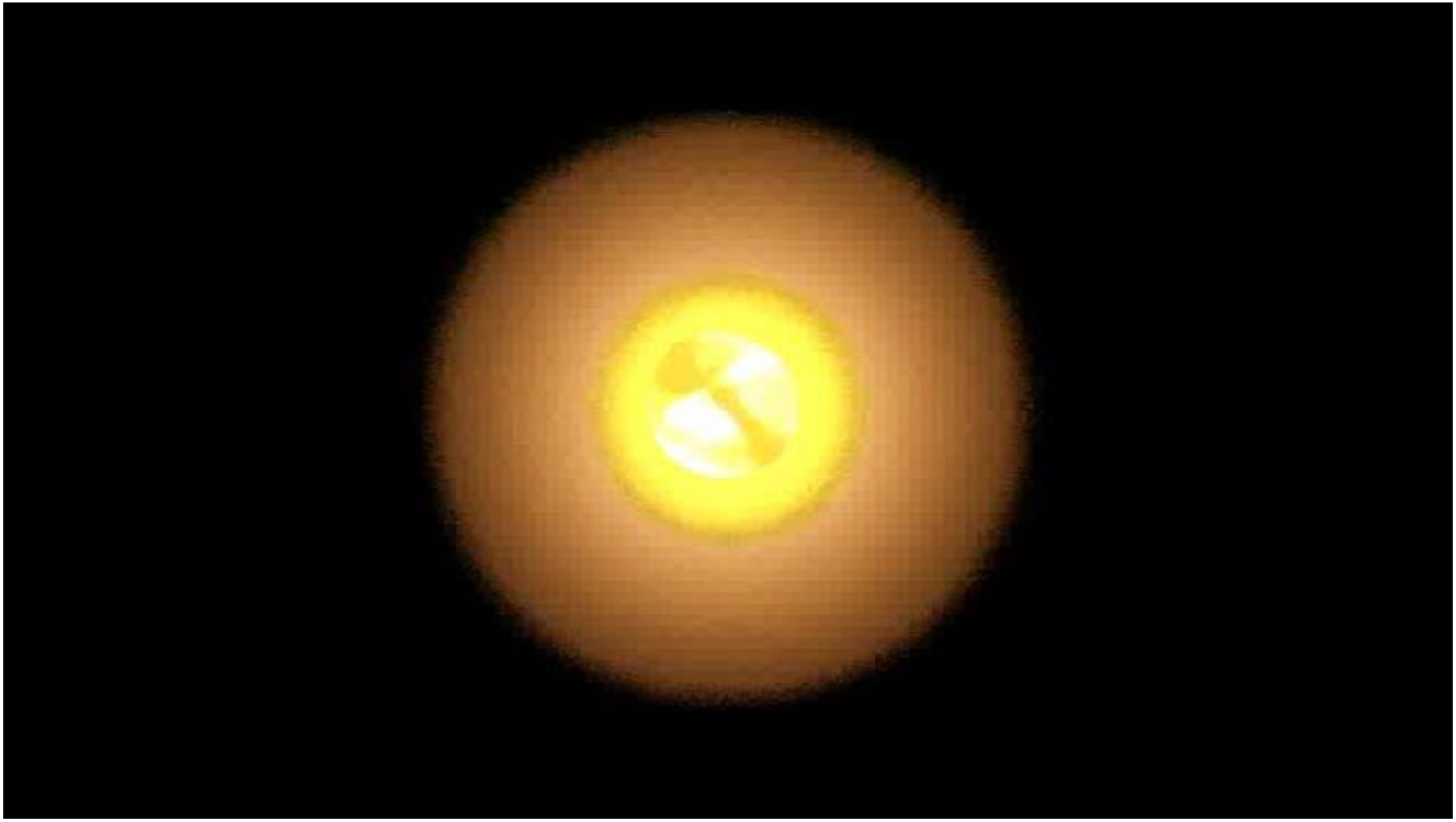
- **Gele Hyperreuzen vertonen ongewoon brede fotosferische absorptielijnen.**
- **Brede absorptielijnen als gevolg van sterke micro-turbulentie en convectie.**
- **Absorptielijnen kunnen splitsen in de kern tgv emissielijn spectrum in Rho Cas.**

Spectroscopische zustersterren Rho Cas, HR 5171A en HR 8752



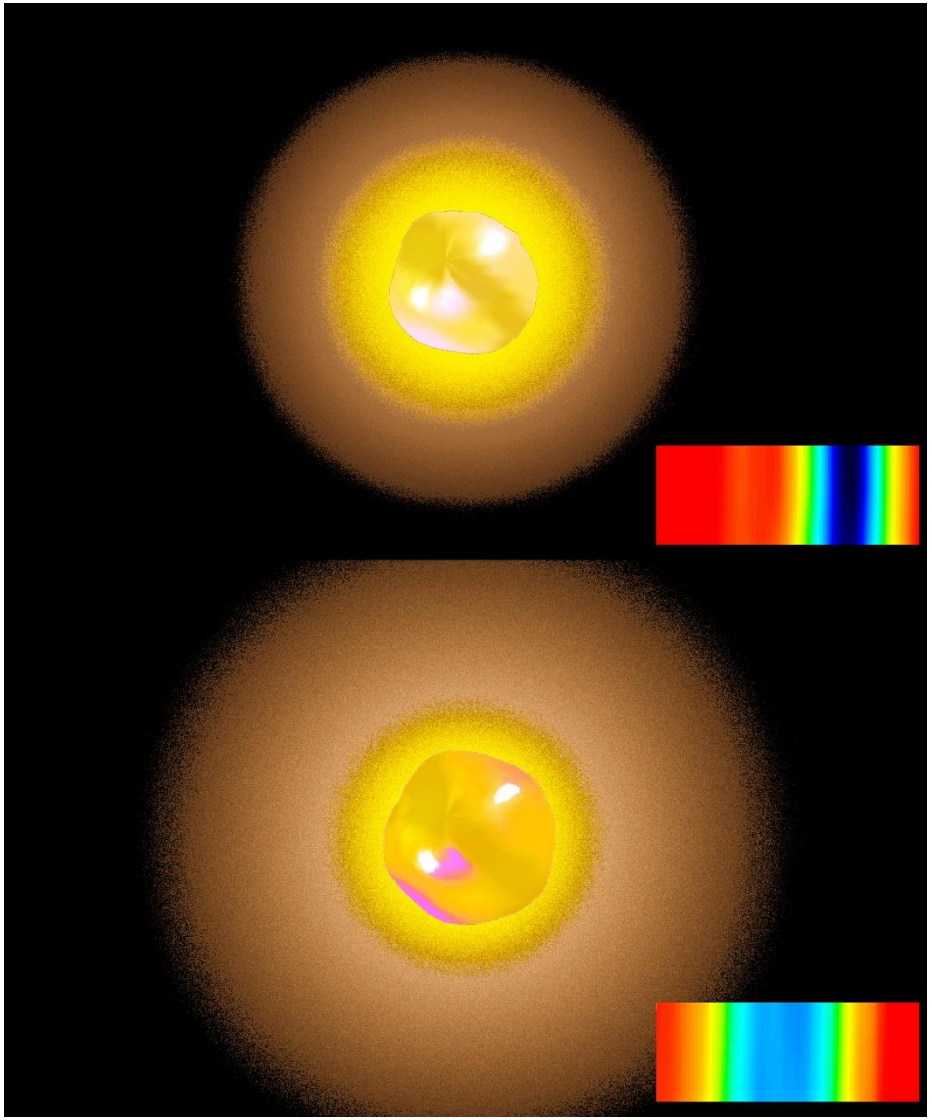
- **Fotosferische Fe absorptielijnen vertonen dezelfde vorm en breedte in 3 GHRn.**
- **Spectroscopische zustersterren tijdens perioden van vergelijkbare Teff.**

Rustige pulsaties van Rho Cas



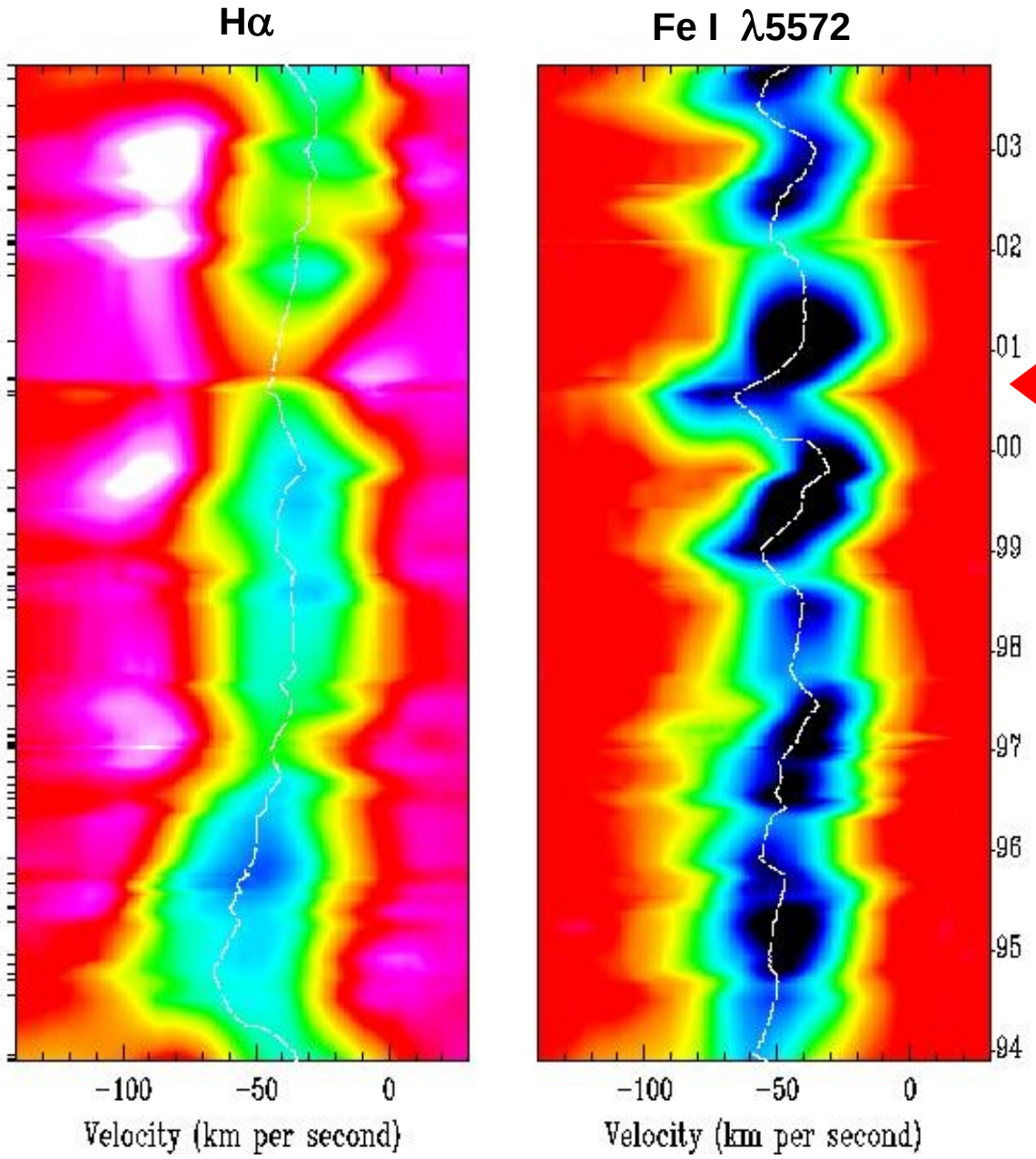
- **Atmosferische pulsaties vertonen snelheidstratificatie in metaallijnen vs. Hα lijn.**
- **Pulsaties veroorzaken sterk aangehouden massaverlies van ~10^{-5} $M_\odot$/jaar.**
- **Niet-radiële pulsaties tijdens de rustige fasen van veranderingen in *V*.**
- **Pulsaties gekoppeld aan convectieve bewegingen maken sterk verbrede lijnen.**

Rustige pulsaties van Rho Cas



- **Fotosferische metaallijnen vertonen sterke Dopplerverschuivingen.**
- ***V* lichtkromme volgt de radiële snelheidskromme na kwart van pulsatieperiode.**

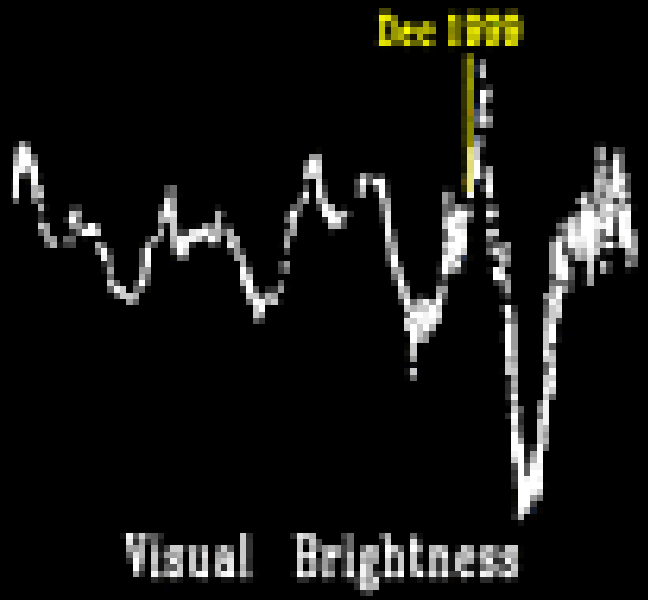
Lange termijn spectroscopische monitoring van Rho Cas



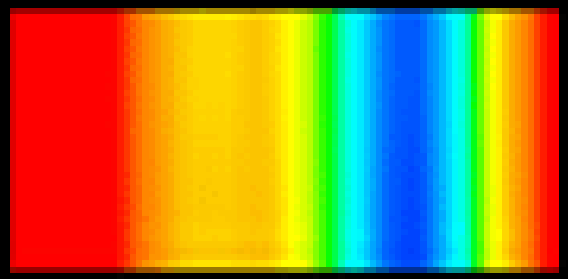
Millennium Uitbarsting

- **Uitbarsting verbonden met zeer grote amplitude van de radiële snelheid als gevolg van een ongewoon sterke pulsatie.**
- **Het reguliere massaverlies neemt sterk toe van ~10^{-5} $M_\odot$/jaar tot 5,4 10^{-2} $M_\odot$/jaar.**

Millennium uitbarsting van Gele Hyperreus Rho Cas

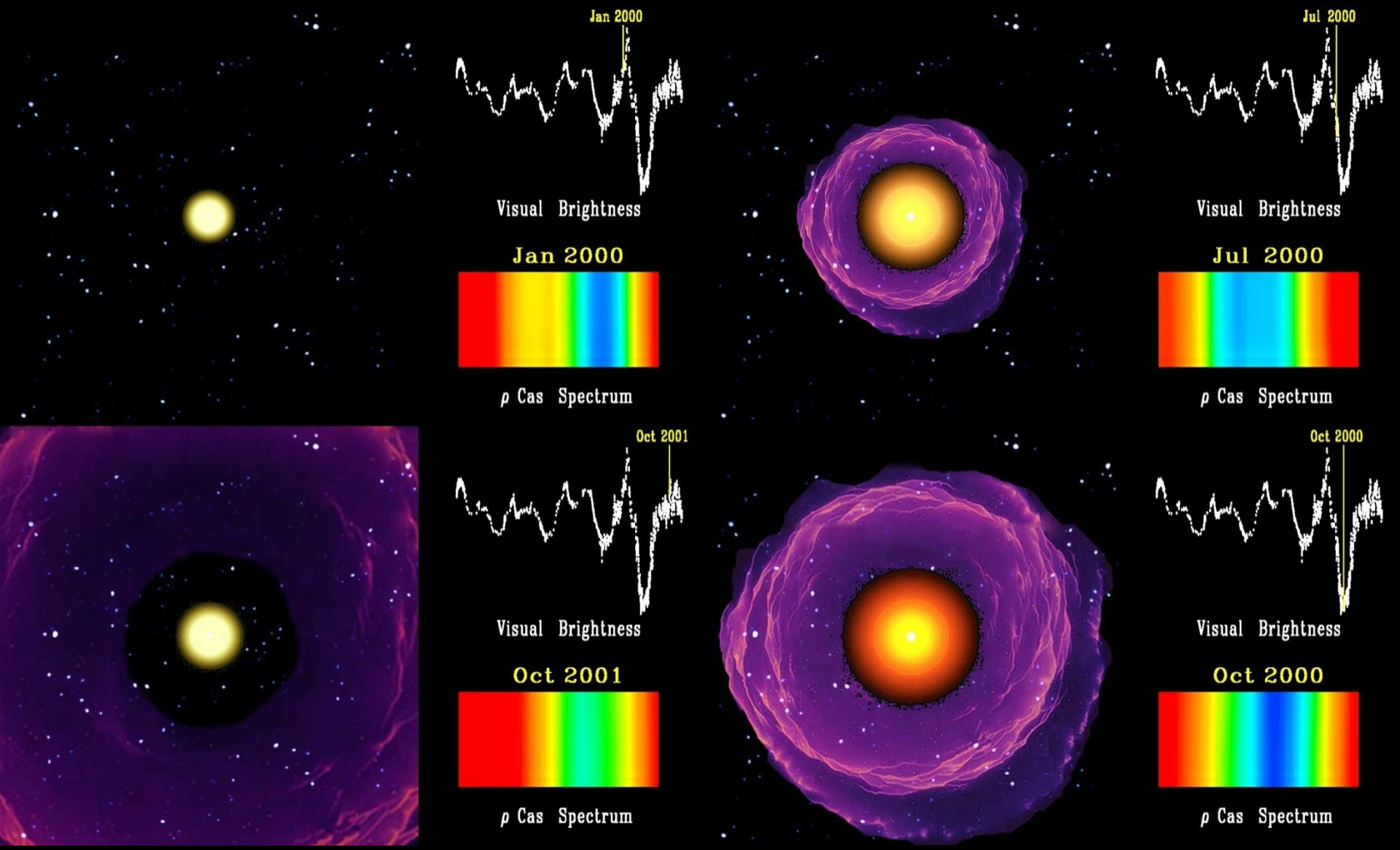


Dec 1999

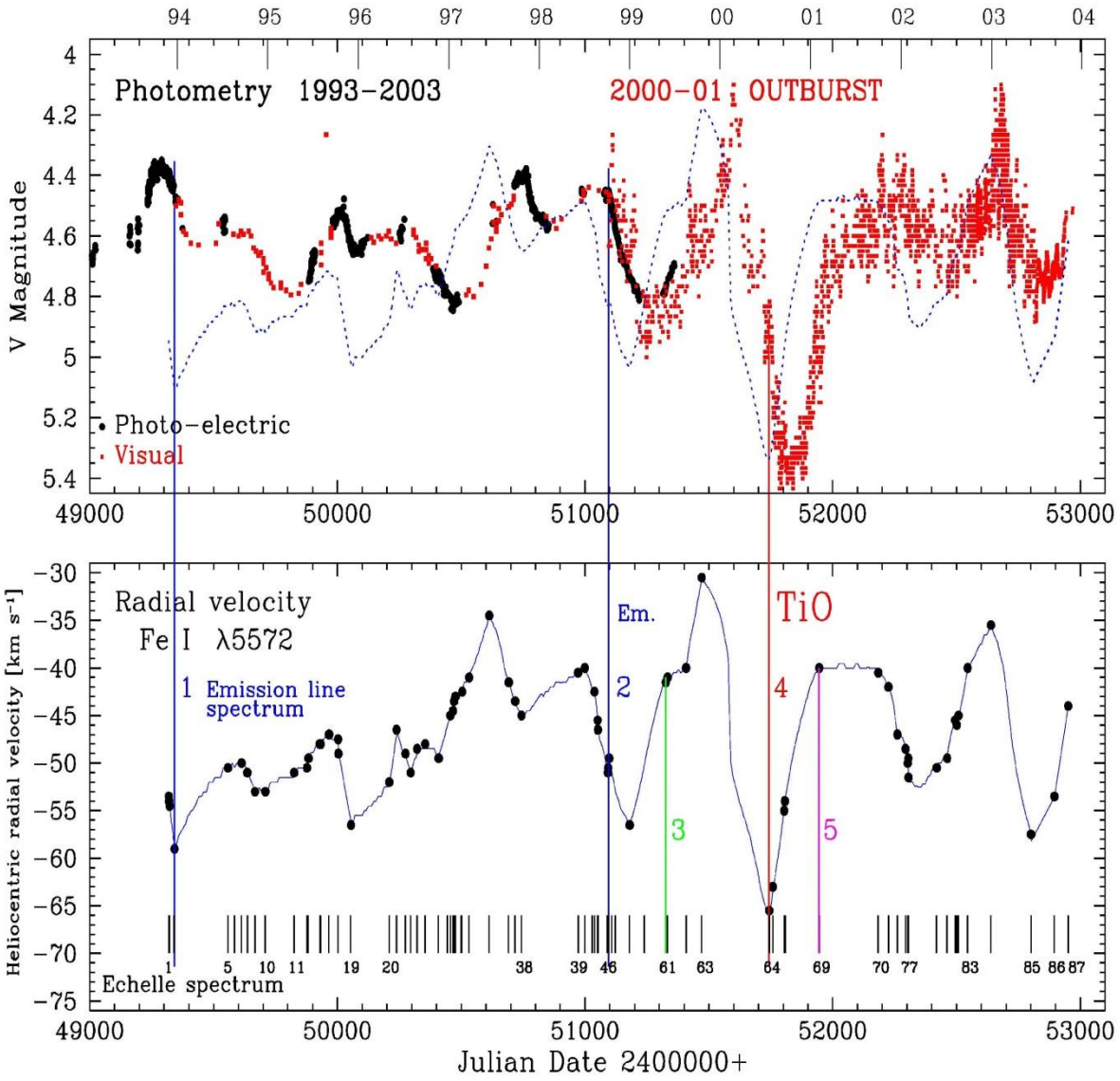


ρ Cas Spectrum

Millennium uitbarsting van Gele Hyperreus Rho Cas

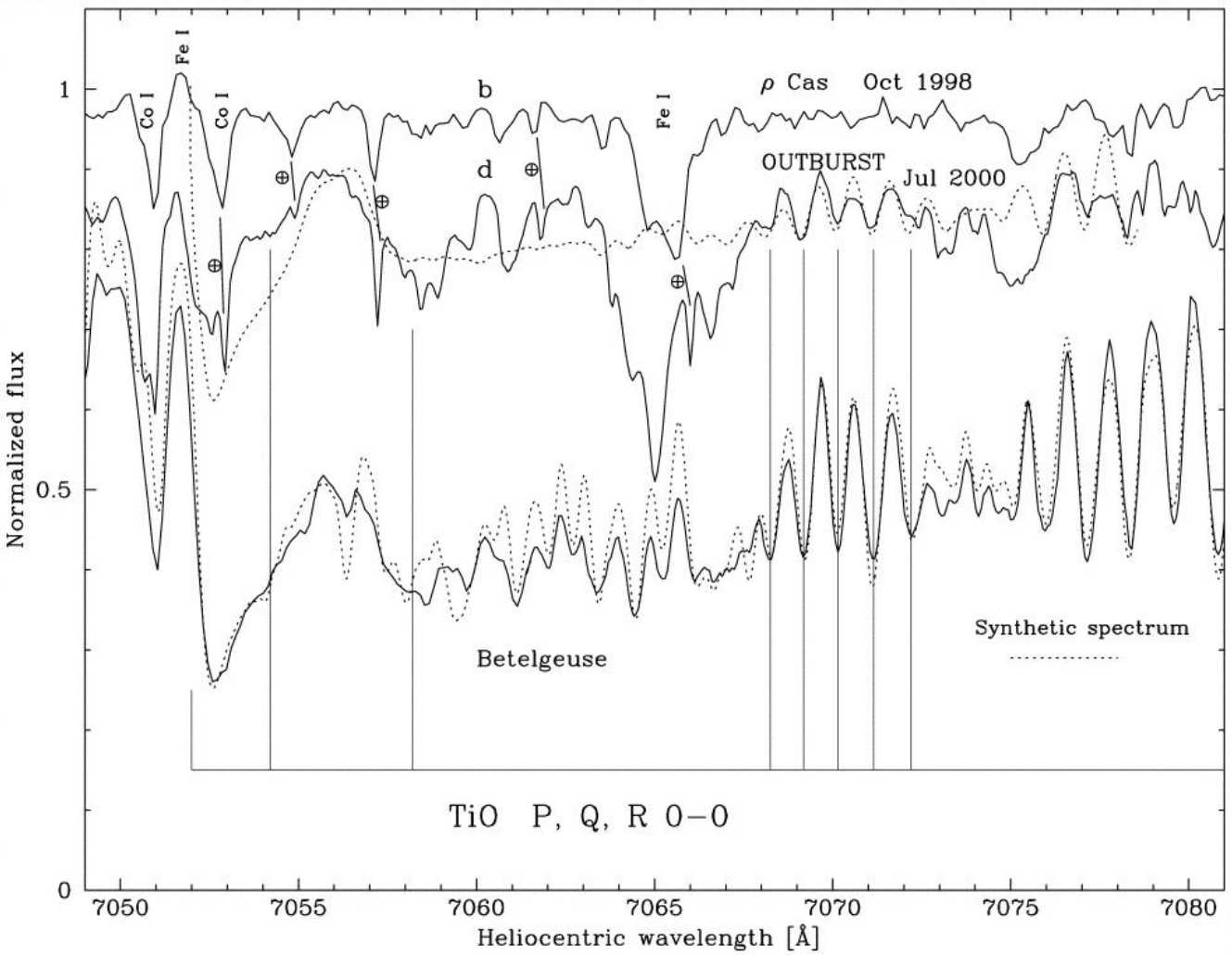


Millennium uitbarsting van Rho Cas



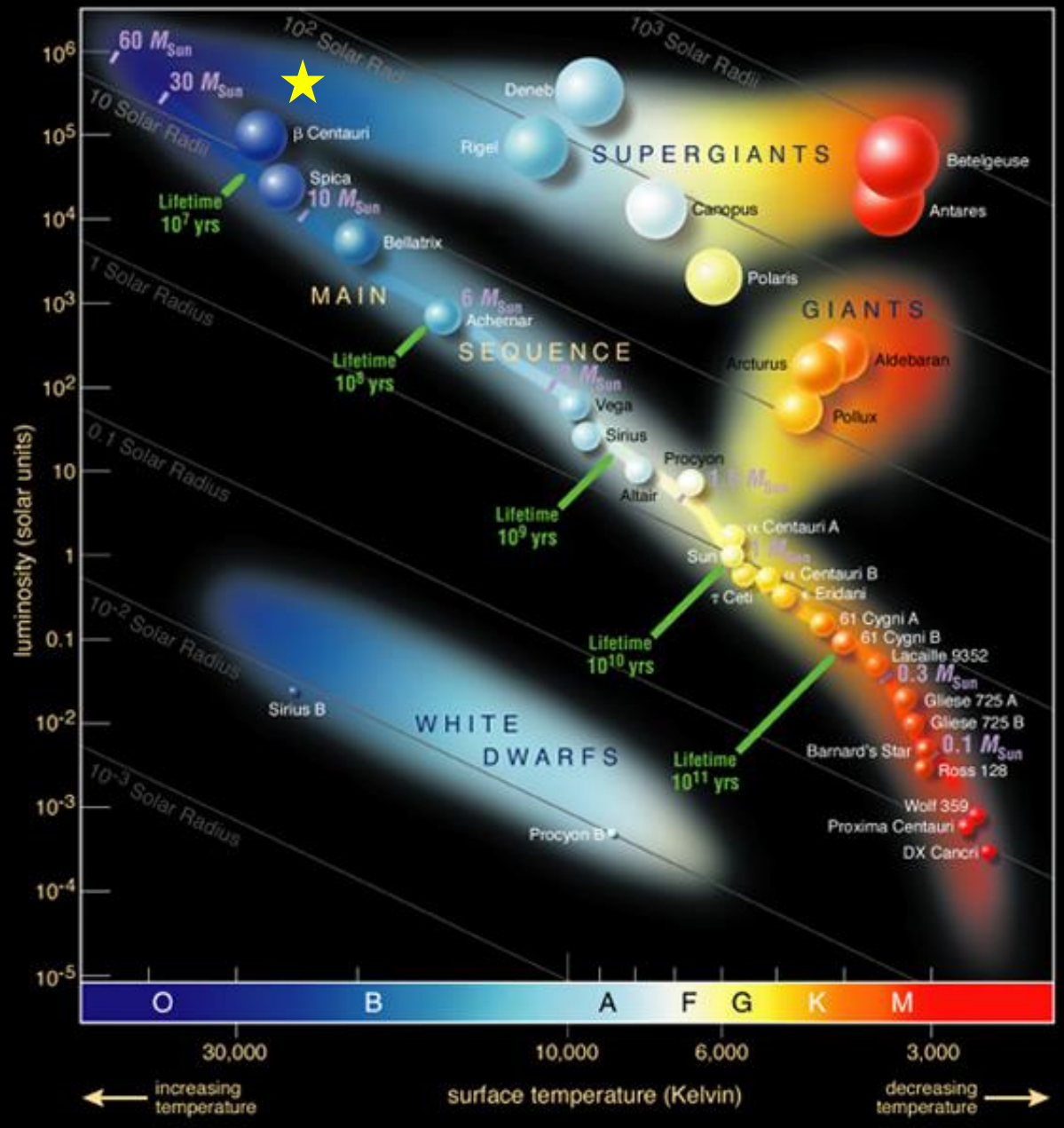
- ***V*** **verzwakt met 1,2 mag. in ca. 200 dagen.**
- **T_{eff} neemt af van ~7000 K tot beneden 4000 K.**
- **Gasschil uitgestoten met 35 ± 2 km/s waargenomen in nieuw gevormde TiO banden.**
- **Totale massa uitgestoten in gasschil is ~5 % van $M_{\odot}$ gemeten met TiO banden en blauwe windvleugels van fotosferische absorptielijnen.**

Nieuwe TiO banden in *V* minimum van de uitbarsting

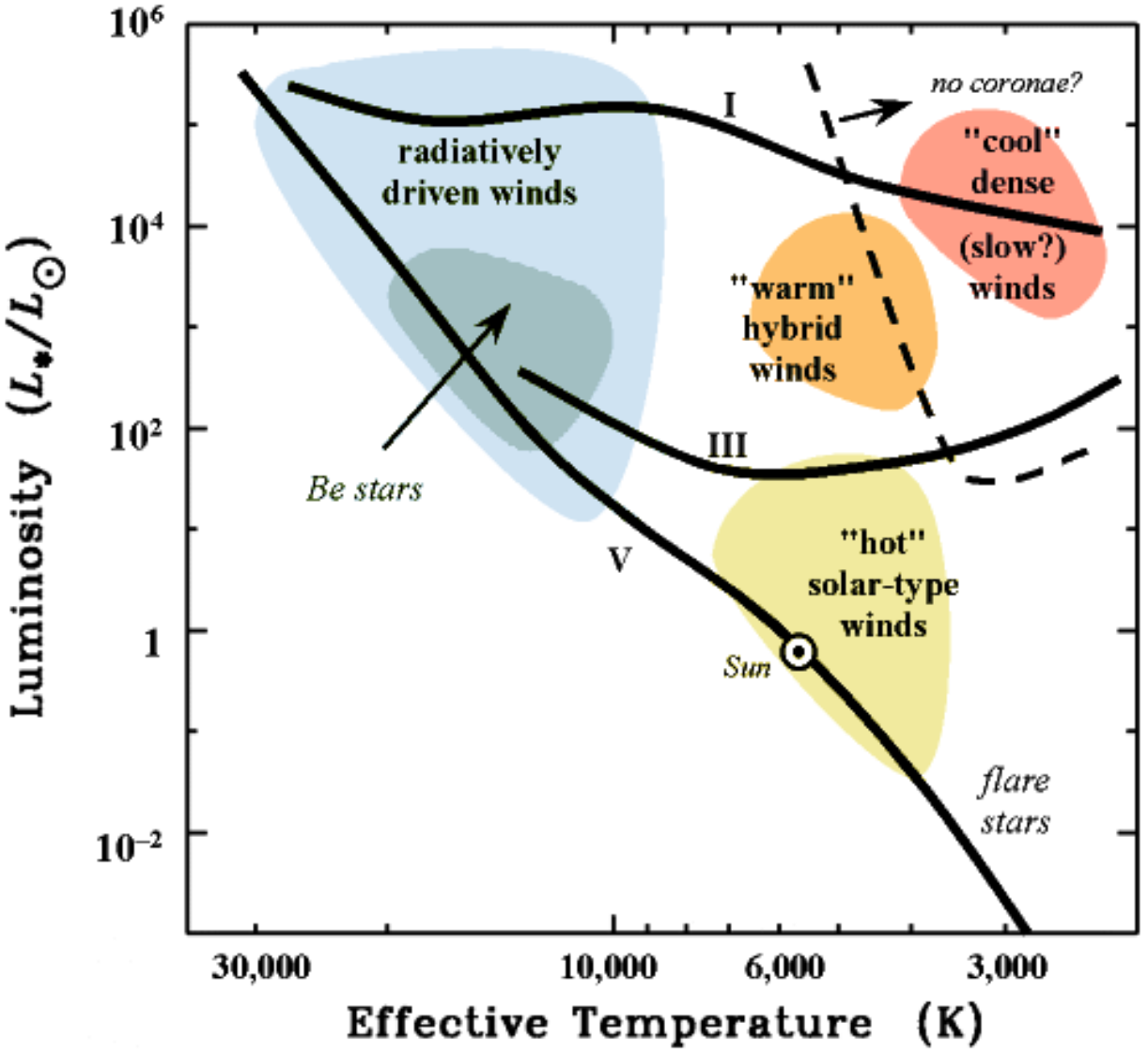


- **TiO banden verschijnen gedurende diepe *V* minima, maar verdwijnen erna.**
- **TiO banden worden alleen in M-type sterren waargenomen met Teff < 4000 K.**
- **Dopplerverschuivingen signaleren toename van massaverlies met factor > 100.**
- **Belangrijkste massaverliesmechanisme in GHRn tgv uitbarsting om ~20 - 50 jr.**

De lichtkrachtige superreus J Puppis (B0.5 Ib)

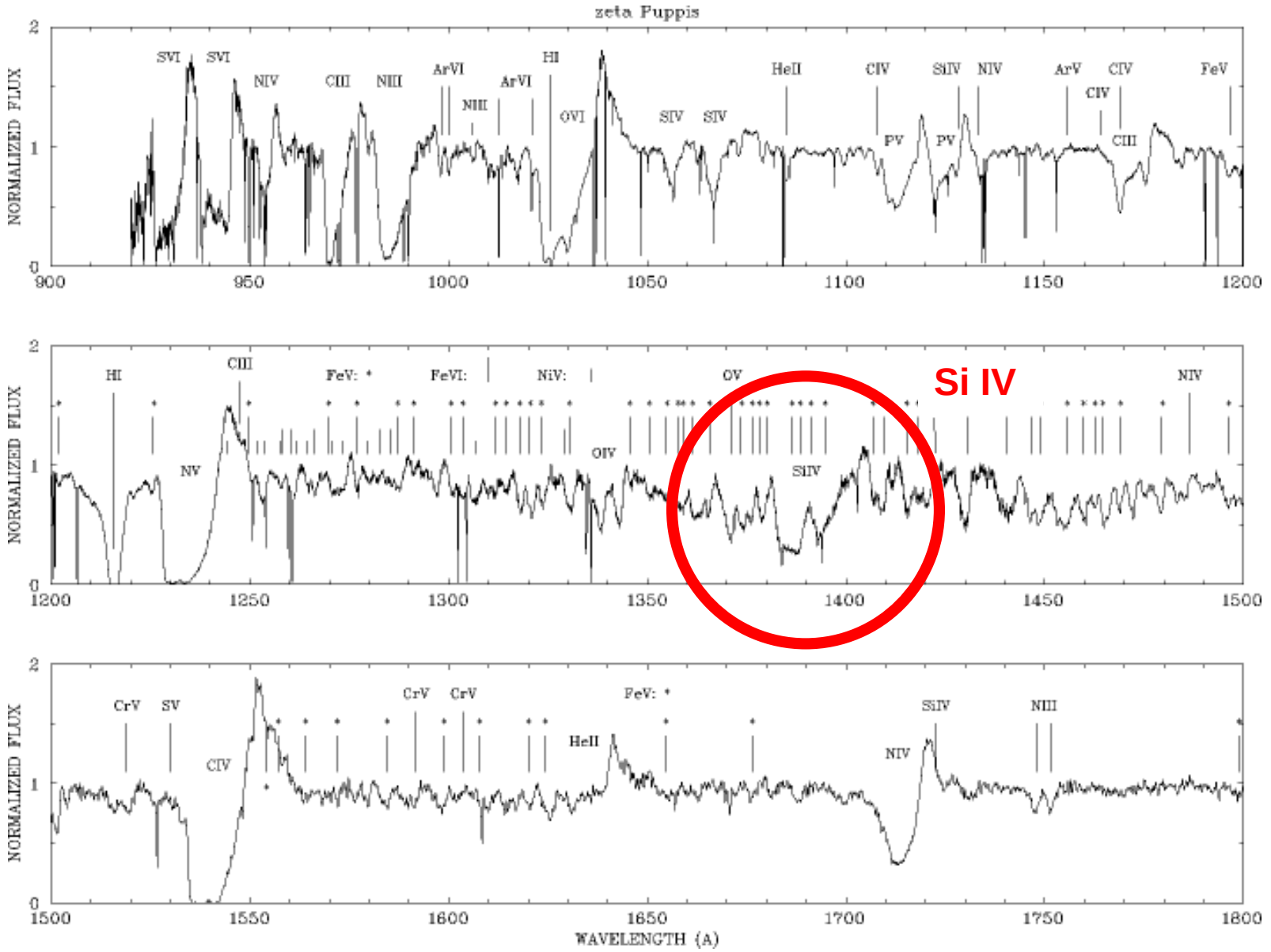


Lichtkrachtige sterren met straling aangedreven winden

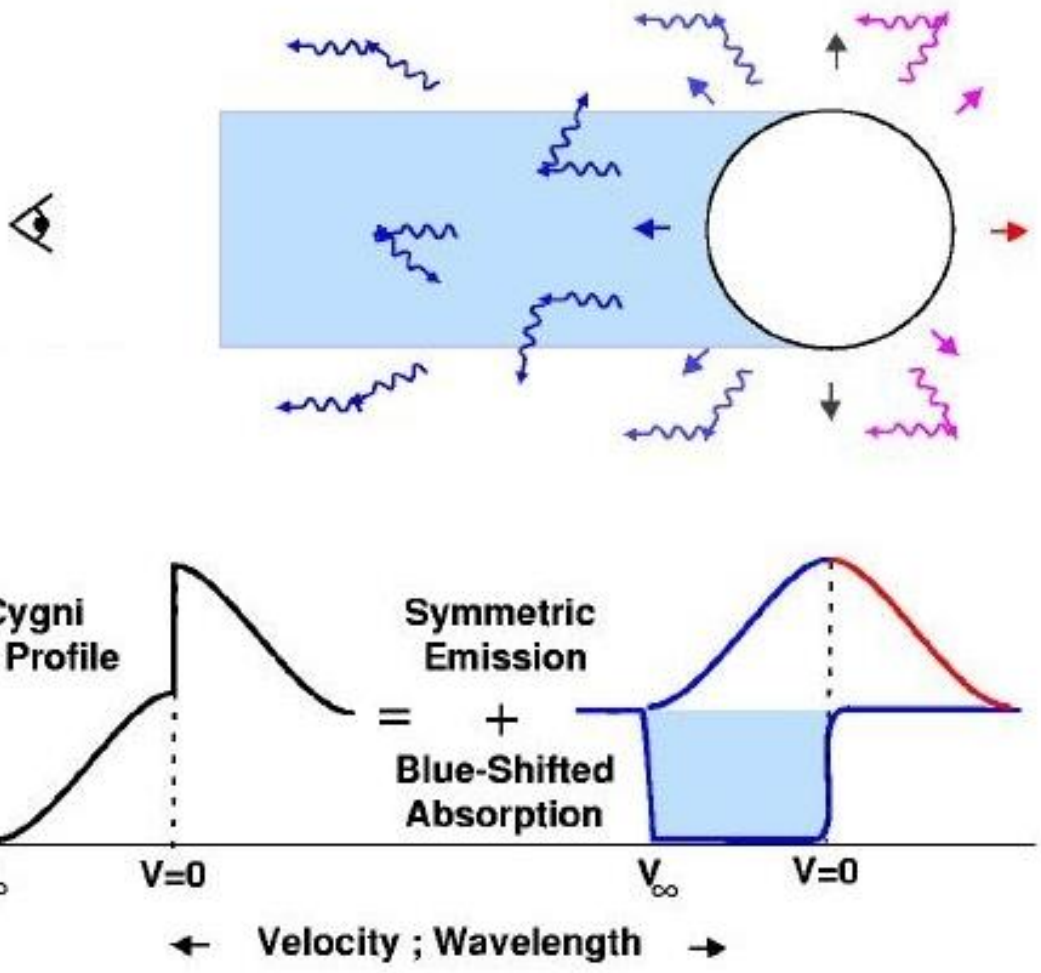


- **Straling aangedreven winden met sterk massaverlies van de ster.**
- **Zeer hoog supersonisch versnelde winden vormen P Cygni wind-lijnen.**

Ultraviolet spectra van de ruimtetelescoop IUE

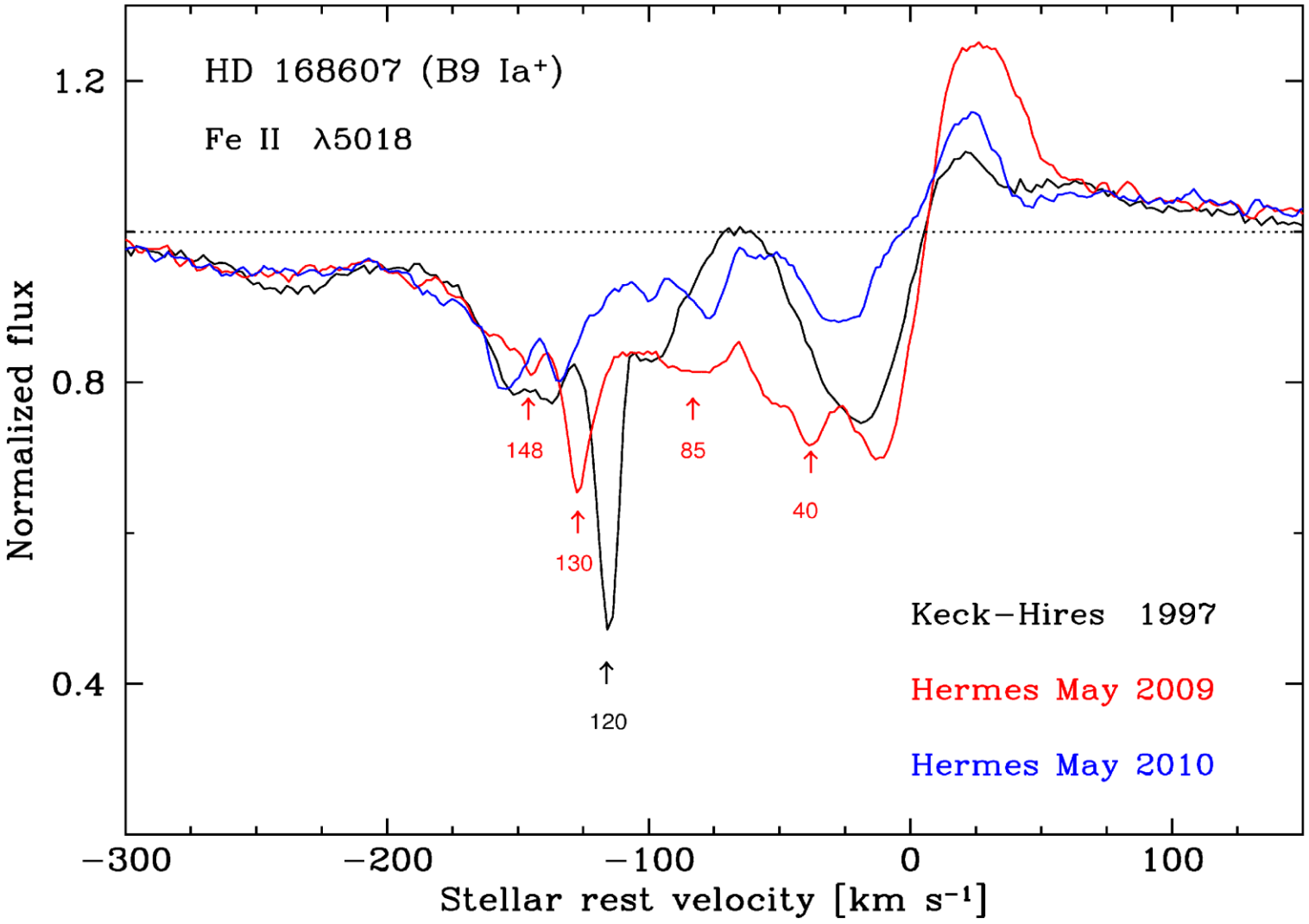


Vorming van P Cygni type lijnprofielen in sterwind



- **Absorptie gedeelte van dit profiel is een maat voor de opaciteit van de wind vóór de sterschijf.**

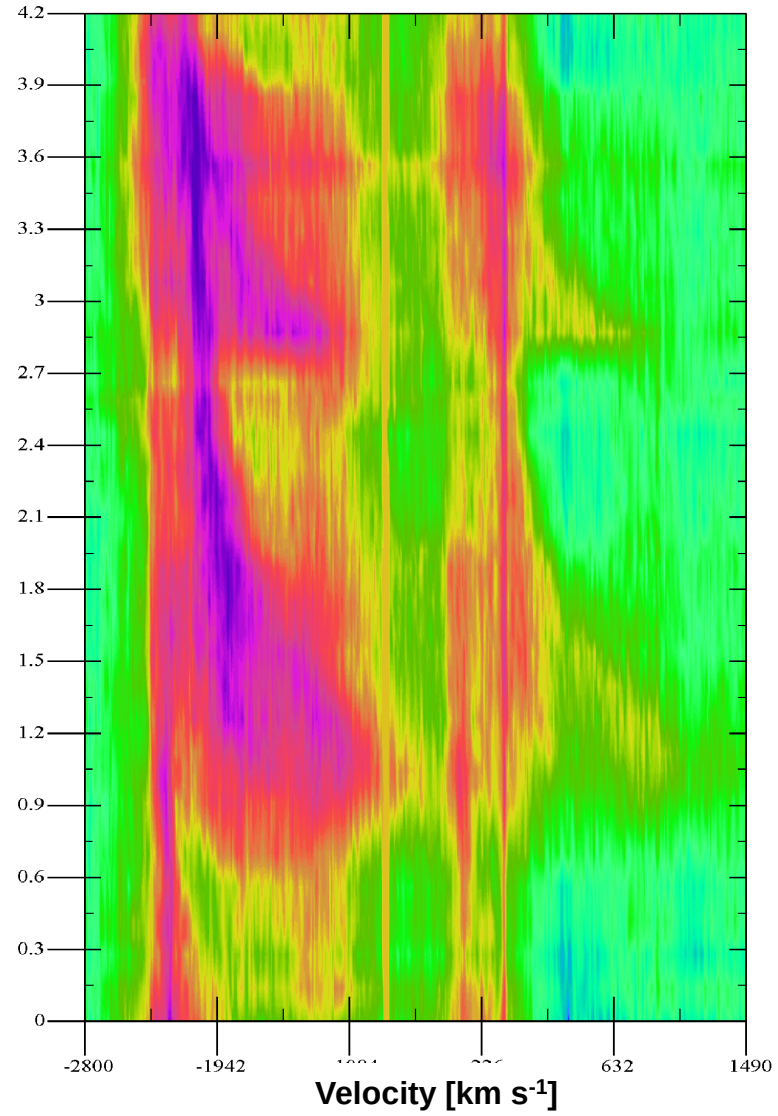
Nauwe absorptie componenten in LBV HD 168607



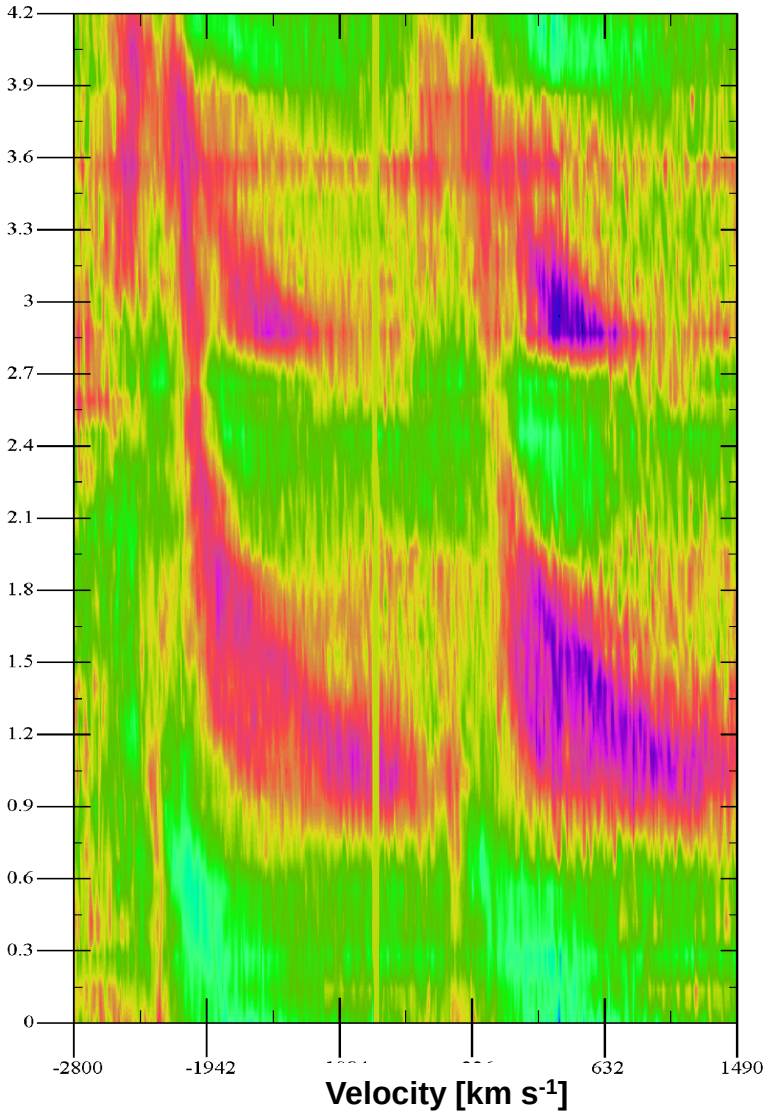
- **Smalle componenten worden waargenomen op verschillende snelheden in de sterwind met veranderlijke sterkte.**

Si IV λ1400 doublet lijnen in Xi Per van de IUE

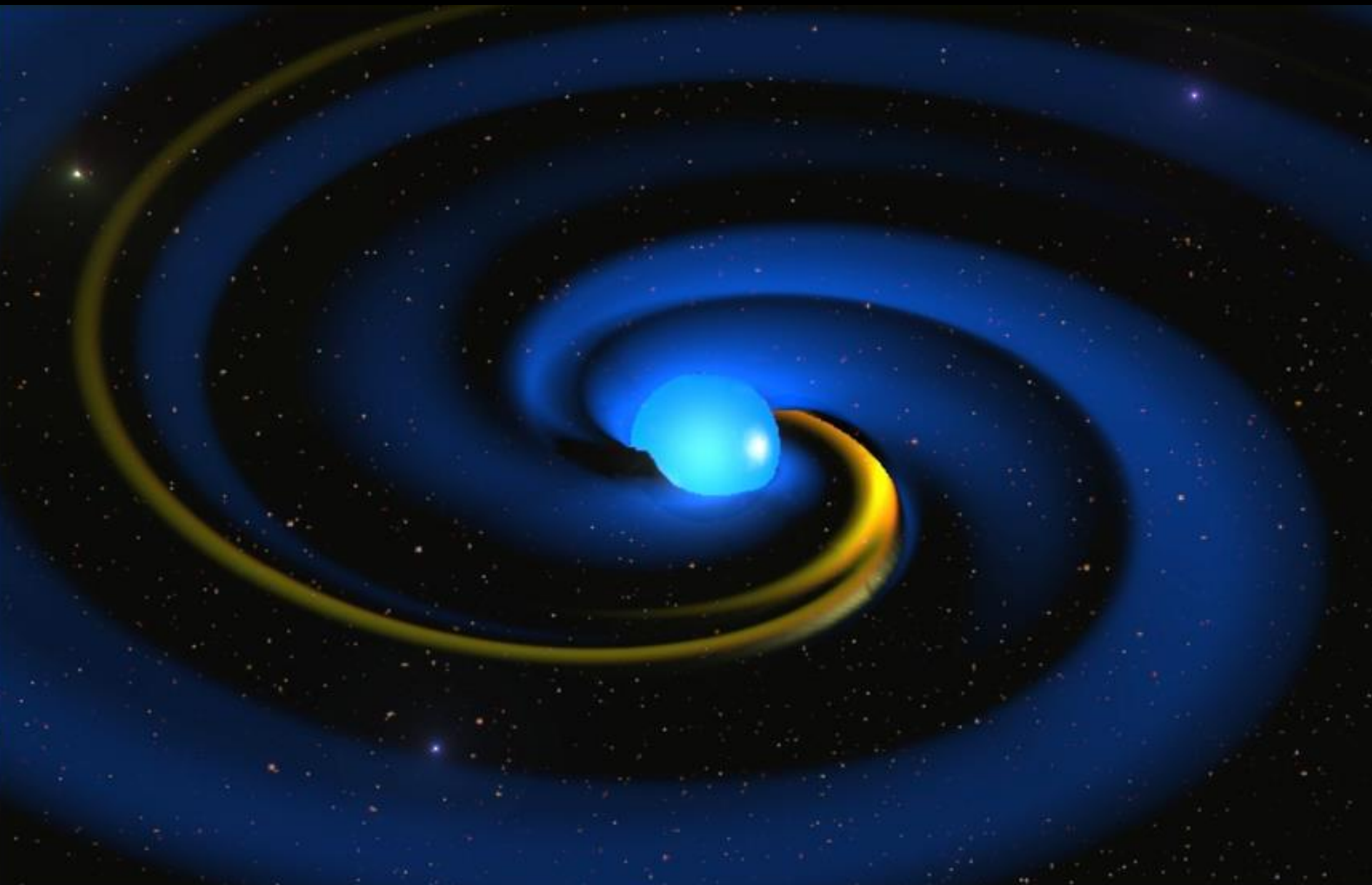
Genormaliseerde flux



Flux verschil



Roterende dichtheidsgolven in de equatoriale wind van een zware hete ster



3-D hydrodynamische simulaties met ZEUS3D code

2-spot model met

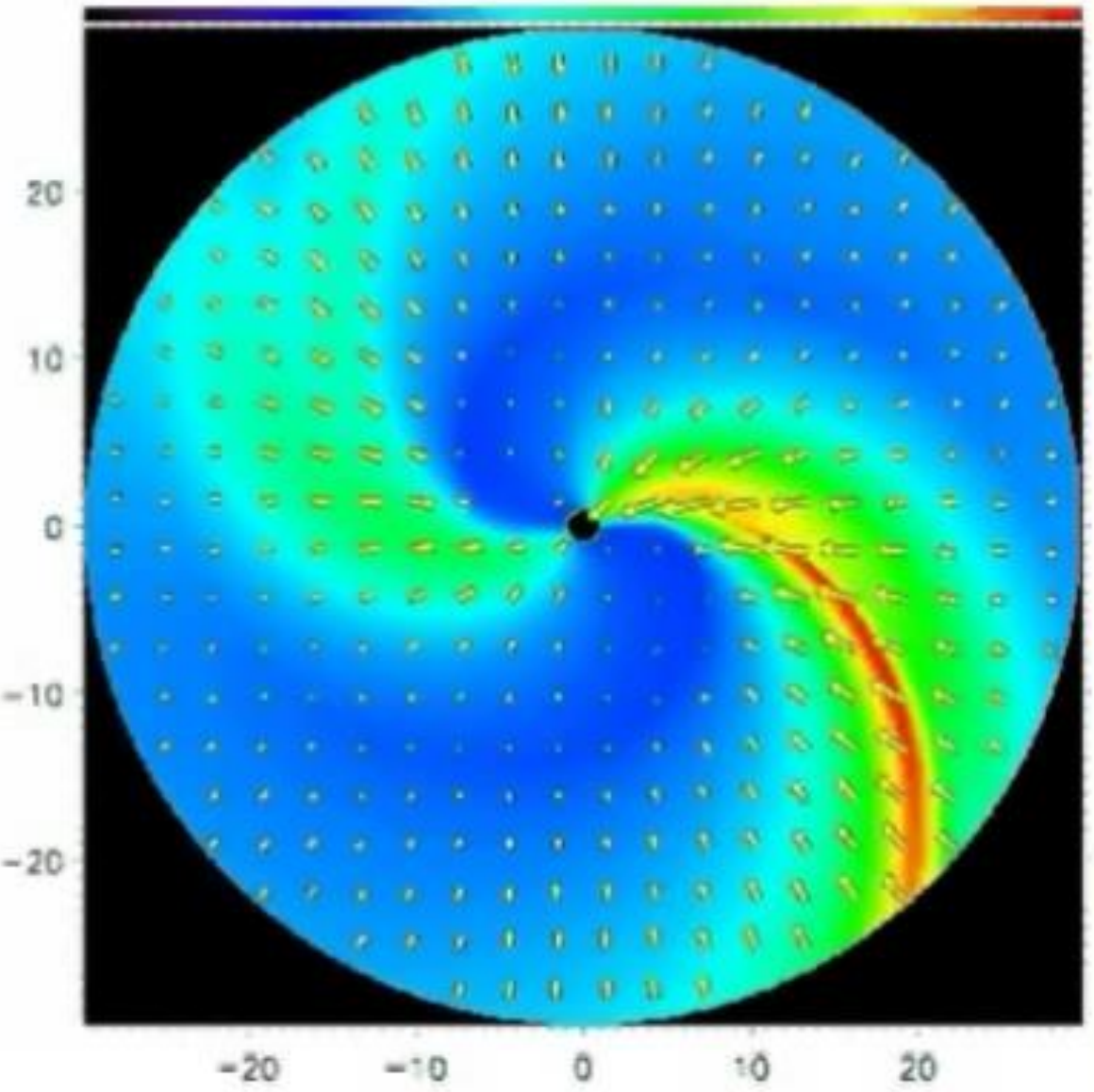
$V_{spot} = V_{rot} / 5$
$A_{spot} = 0{,}2$ & $\Phi_{spot} = 20°$
$A_{spot} = 0{,}08$ & $\Phi_{spot} = 30°$

Dichtheidscontrast:

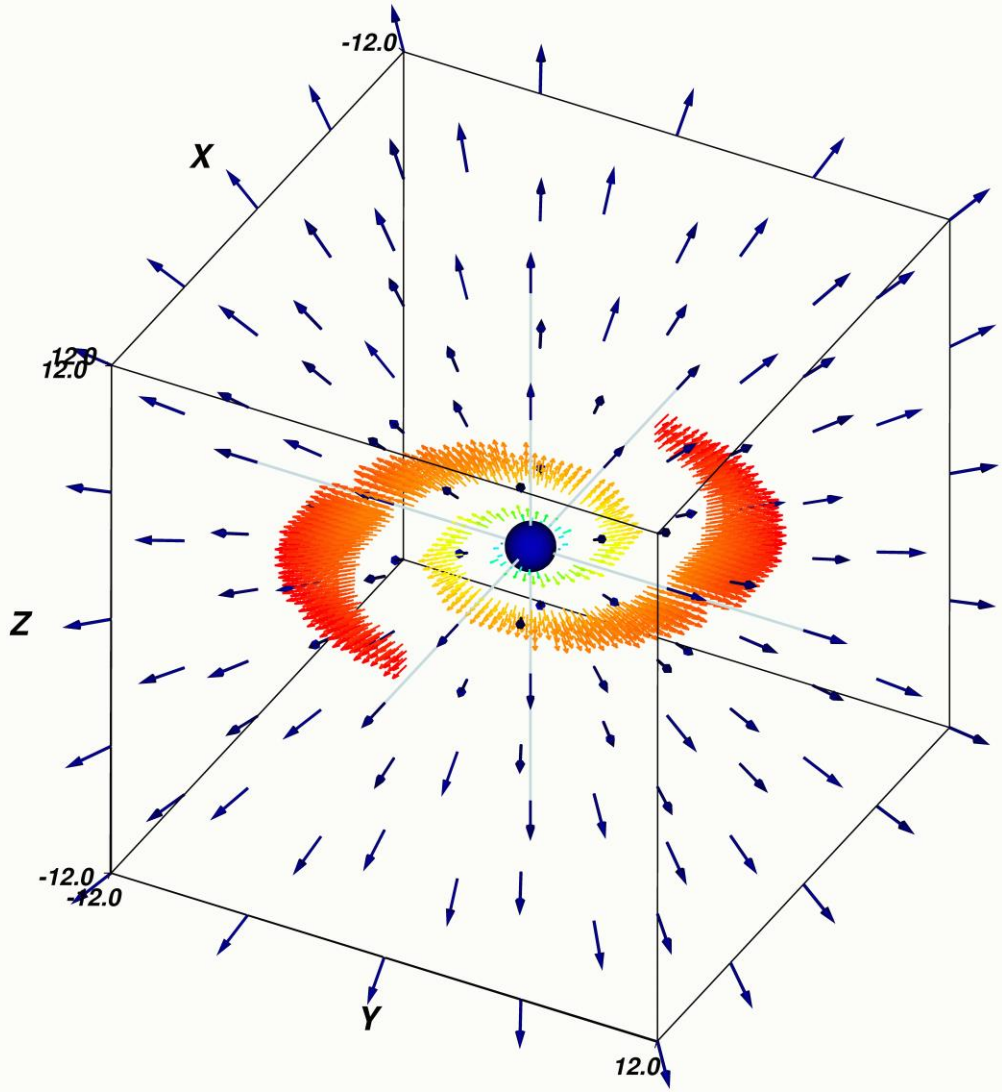
minimum $\rho / \rho_0 = 0{,}87$

maximum $\rho / \rho_0 = 1{,}31$

Twee ongelijke heldere vlekken op het ster-oppervlak aan haar evenaar



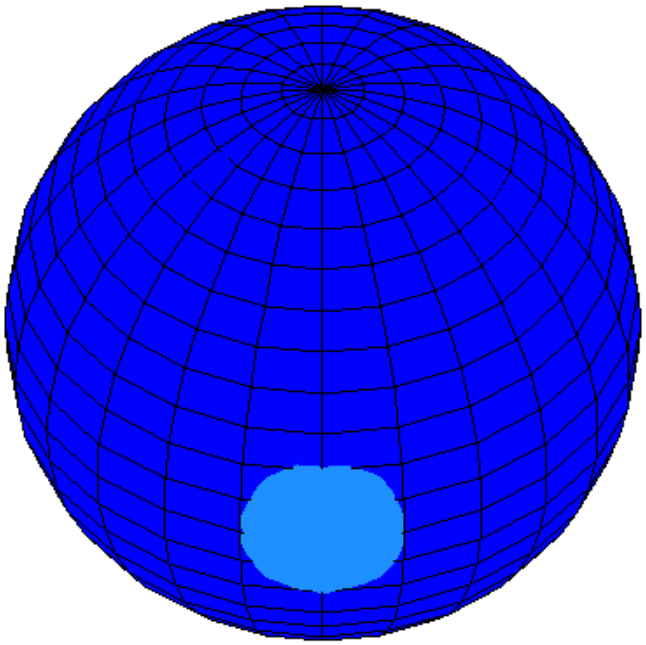
3-D stralingstransport berekeningen met Wind3D code

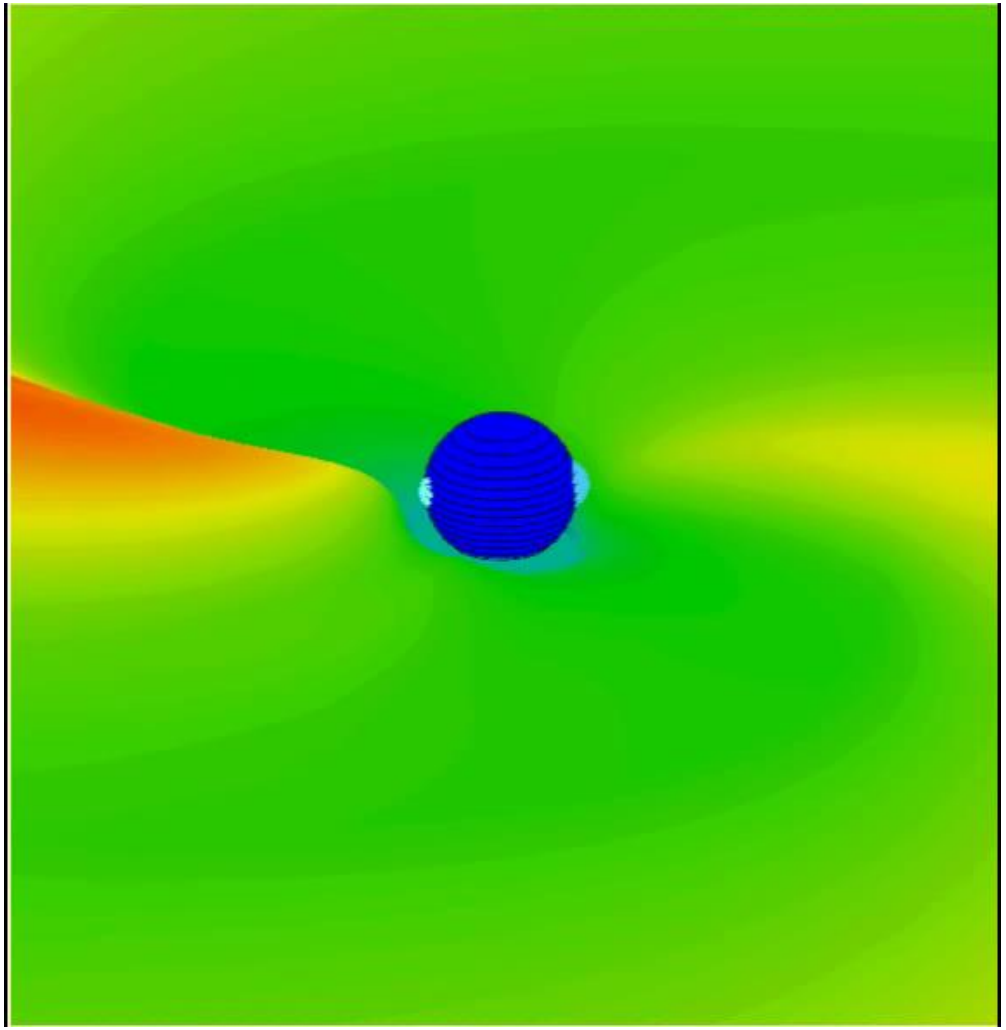


- **Code onder ontwikkeling te KSB sinds 2006.**
- **Code Accepteert 3-D wind-dichtheids- en snelheid-structuren**
- **3-D non-LTE stralingstransport iteraties in spectrale lijnen.**
- **parallelle code met zeer efficiënte CPU bezetting.**

Hete ster met versnelde wind en interne windstructuren als input voor de Wind3D code.

Hydrodynamisch windmodel van J Pup met ZEUS3D

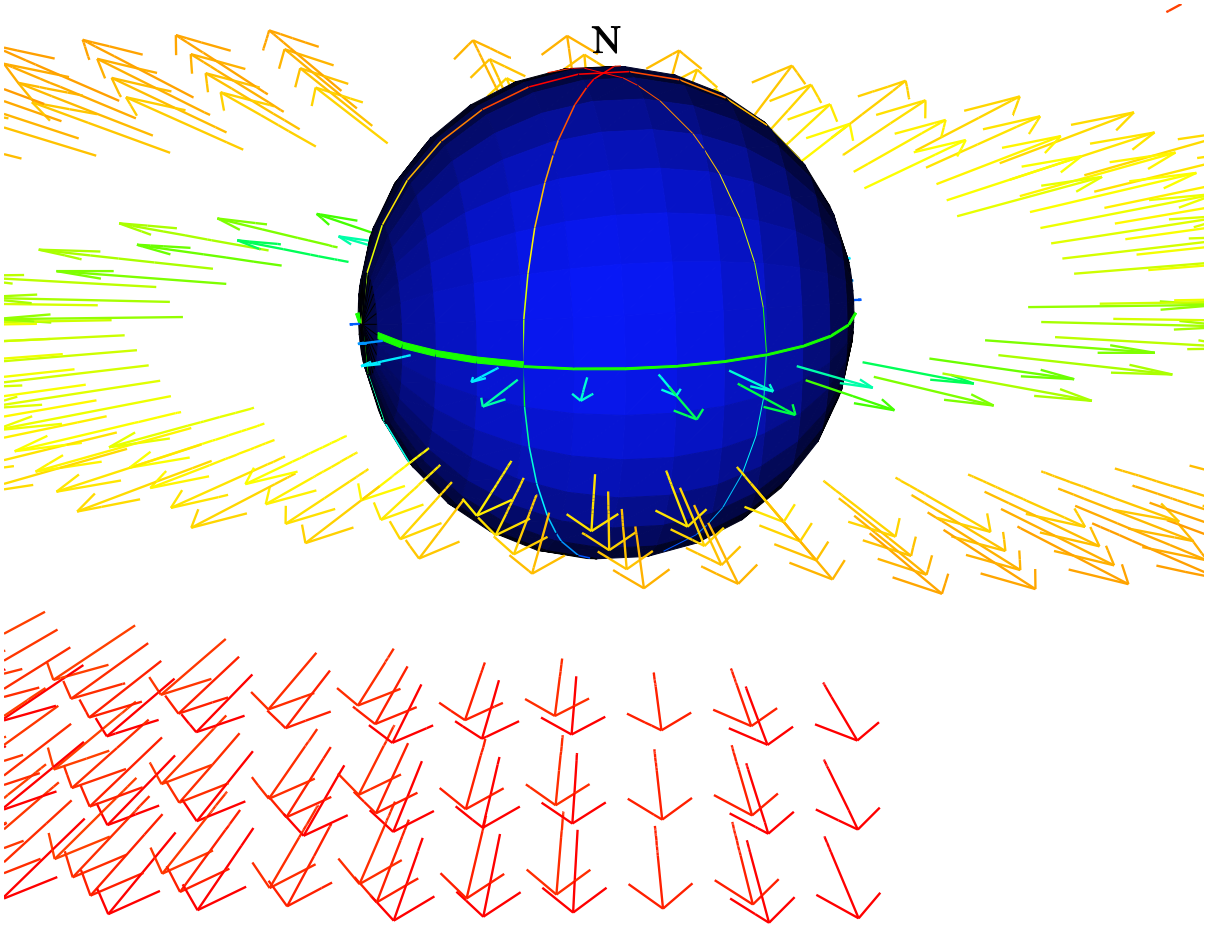


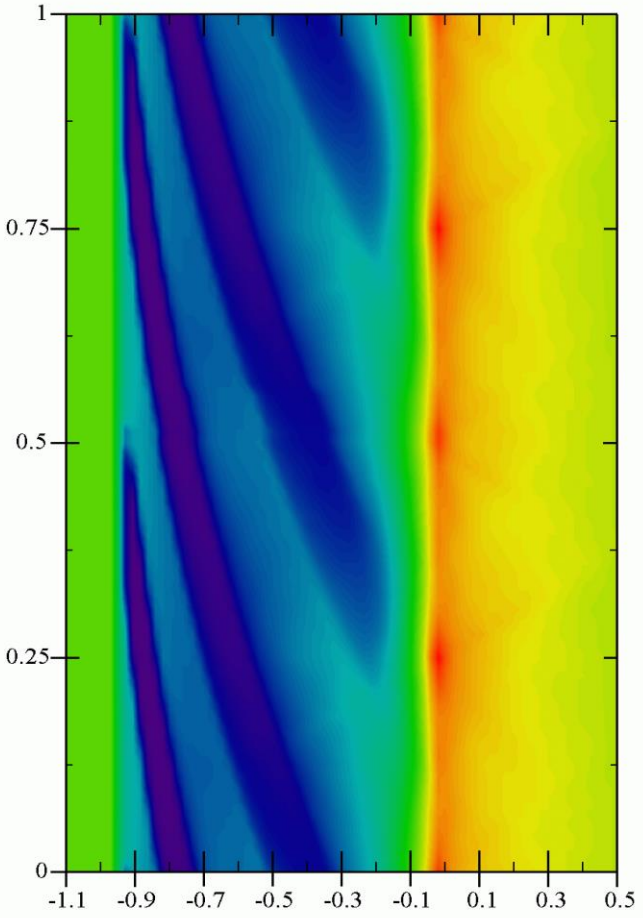


Roterende gasgolven zijn het gevolg van 2 heldere vlekken aan de evenaar die 5 maal trager draaien dan het oppervlak:

$P_{rot} = 4{,}12$ d $P_{spot} = 20{,}6$ d

Dynamisch spectrum van de Si IV lijn berekend met Wind3D





$\Delta\lambda / \lambda * c / v_\infty$

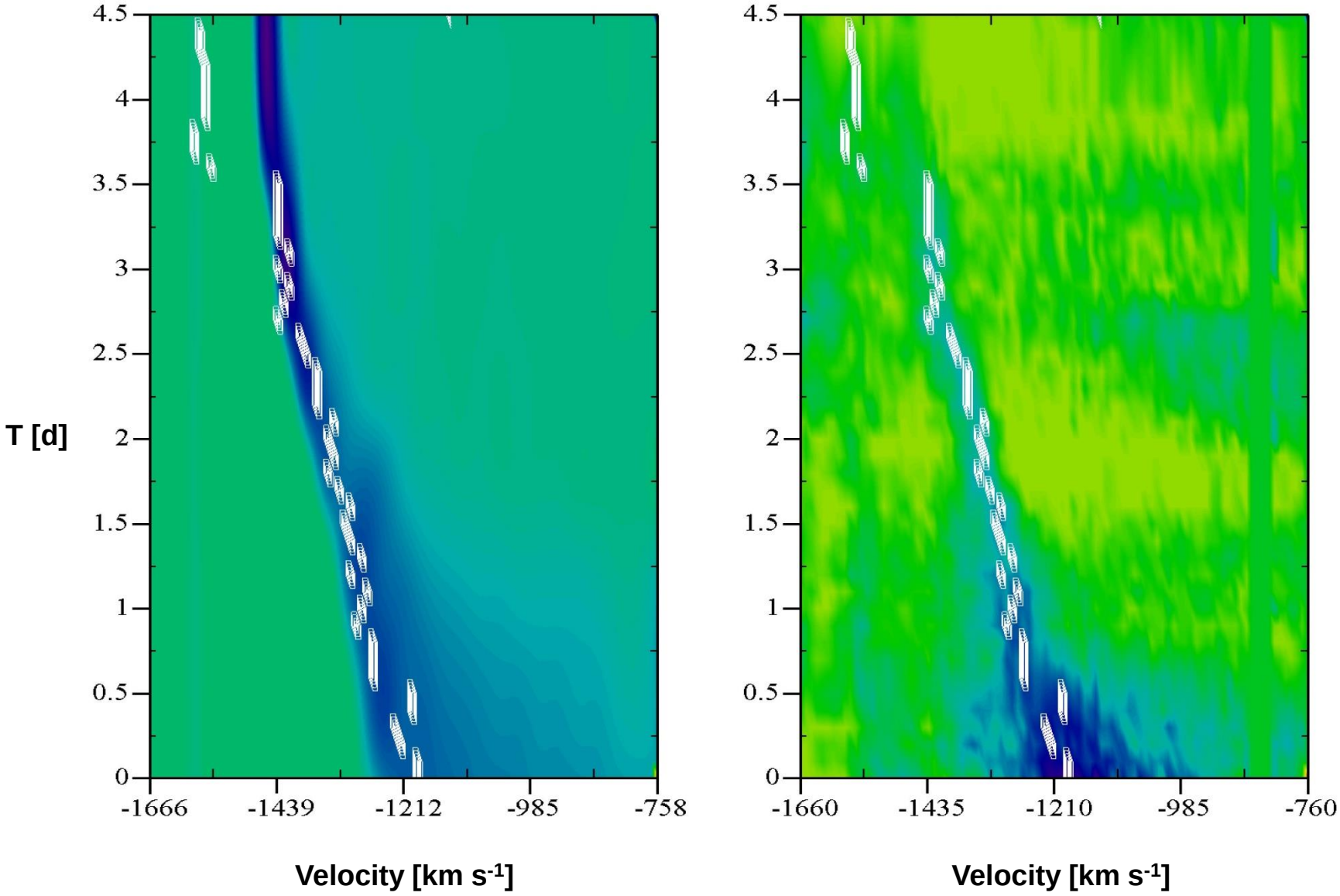
- **Nauwe componenten versmallen omdat de spreiding van geprojecteerde snelheden in de gasgolven afneemt verder boven het steroppervlak.**

2-spot model beste fit: $V_{spot} = V_{rot} / 5$

$A_{spot} = 0{,}2 \quad \Phi_{spot} = 20^o$

$A_{spot} = 0{,}08 \quad \Phi_{spot} = 30^o$

J Puppis IUE waarnemingen

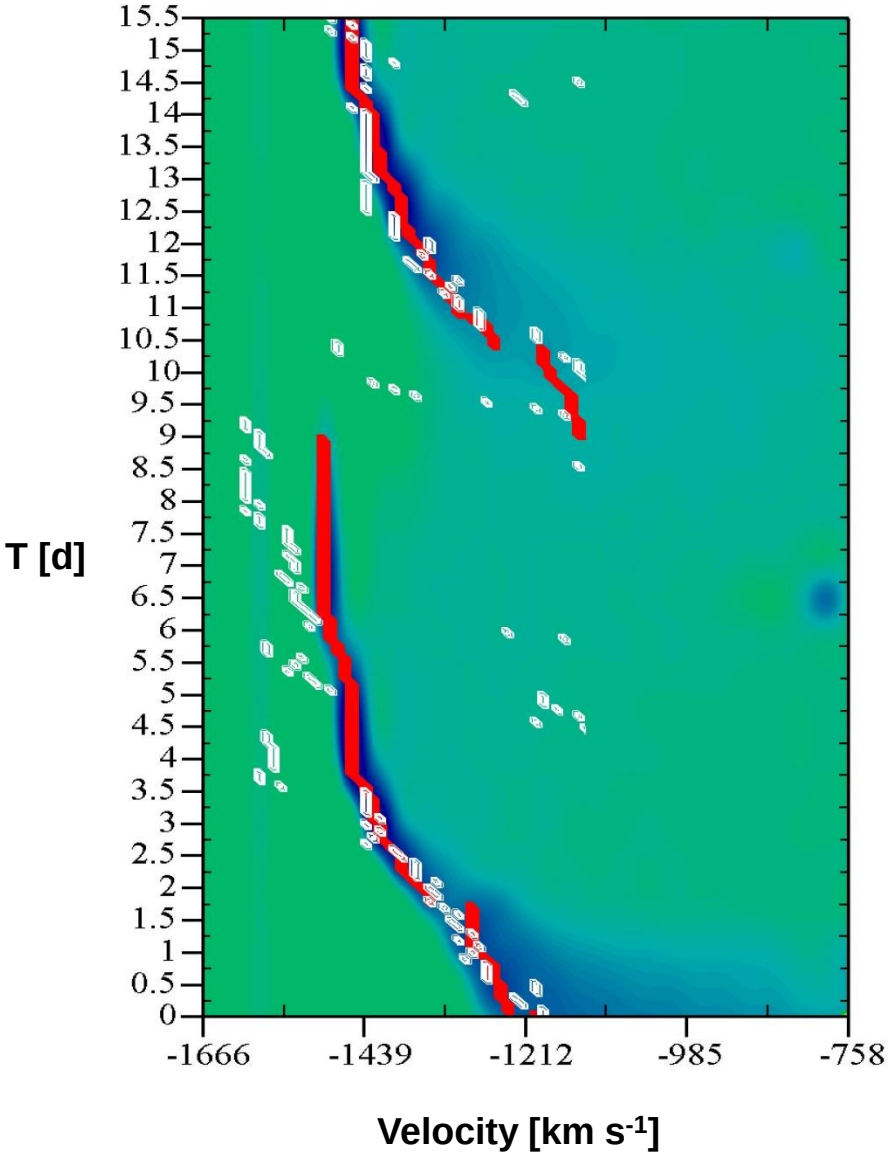


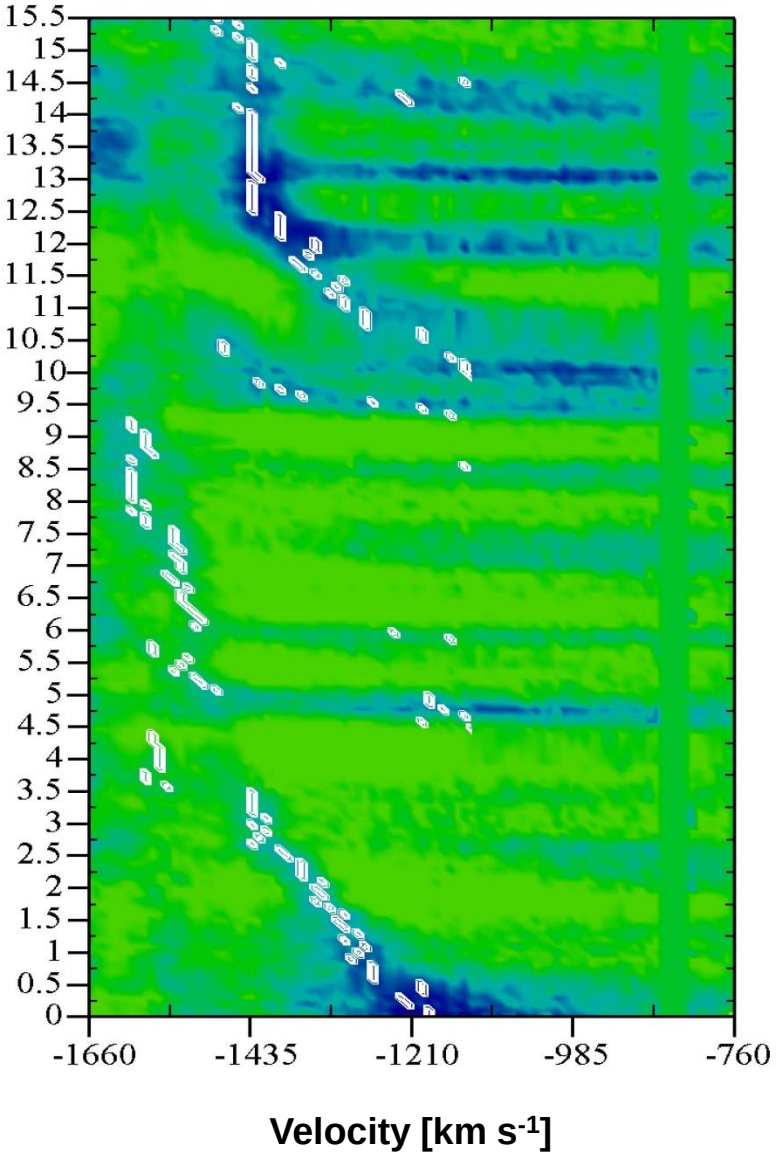
2-spot model beste fit: $V_{spot} = V_{rot} / 5$

$A_{spot} = 0{,}2 \quad \Phi_{spot} = 20^o$

$A_{spot} = 0{,}08 \quad \Phi_{spot} = 30^o$

J Puppis IUE waarnemingen





Tweepolige Hα nevel van LBV MWC 314

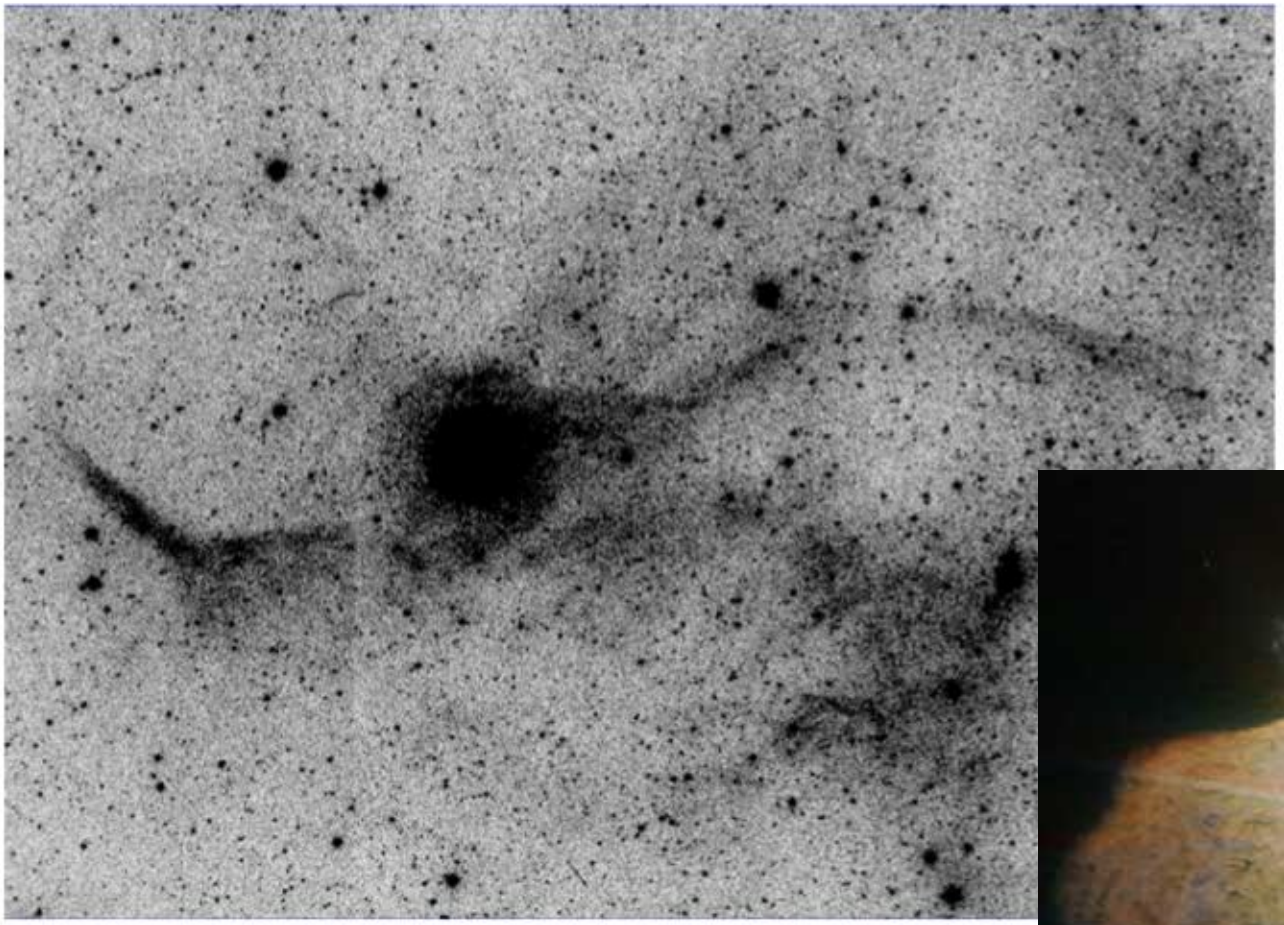
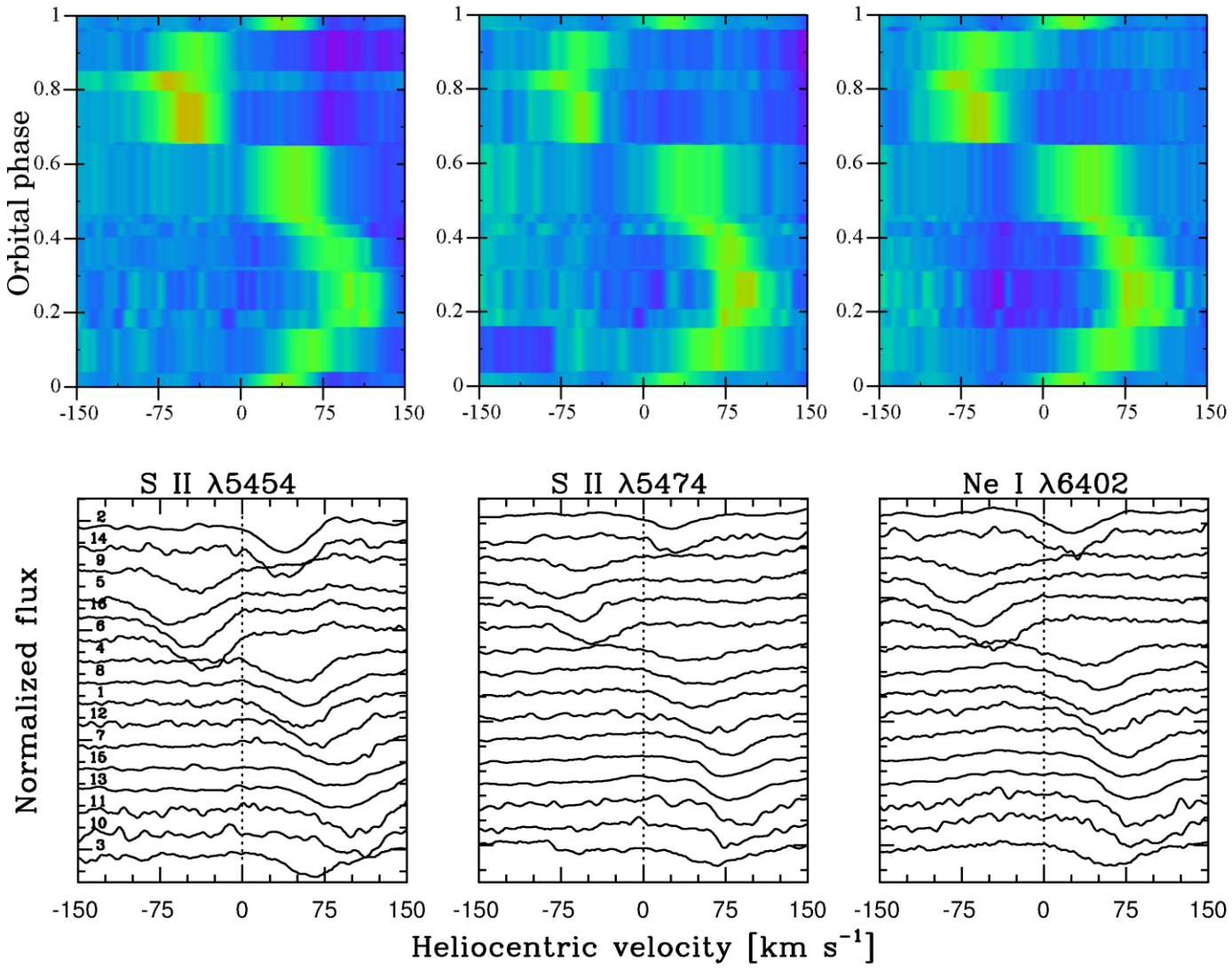


Fig. 1. Narrow band Hα image of the environments of MWC 314 showing the large east-west bipolar feature 12′.5 vertically. For all figures, north is up and east to the left.

LBV η Carinae
dubbelster P_{orb}= 5,5 jr

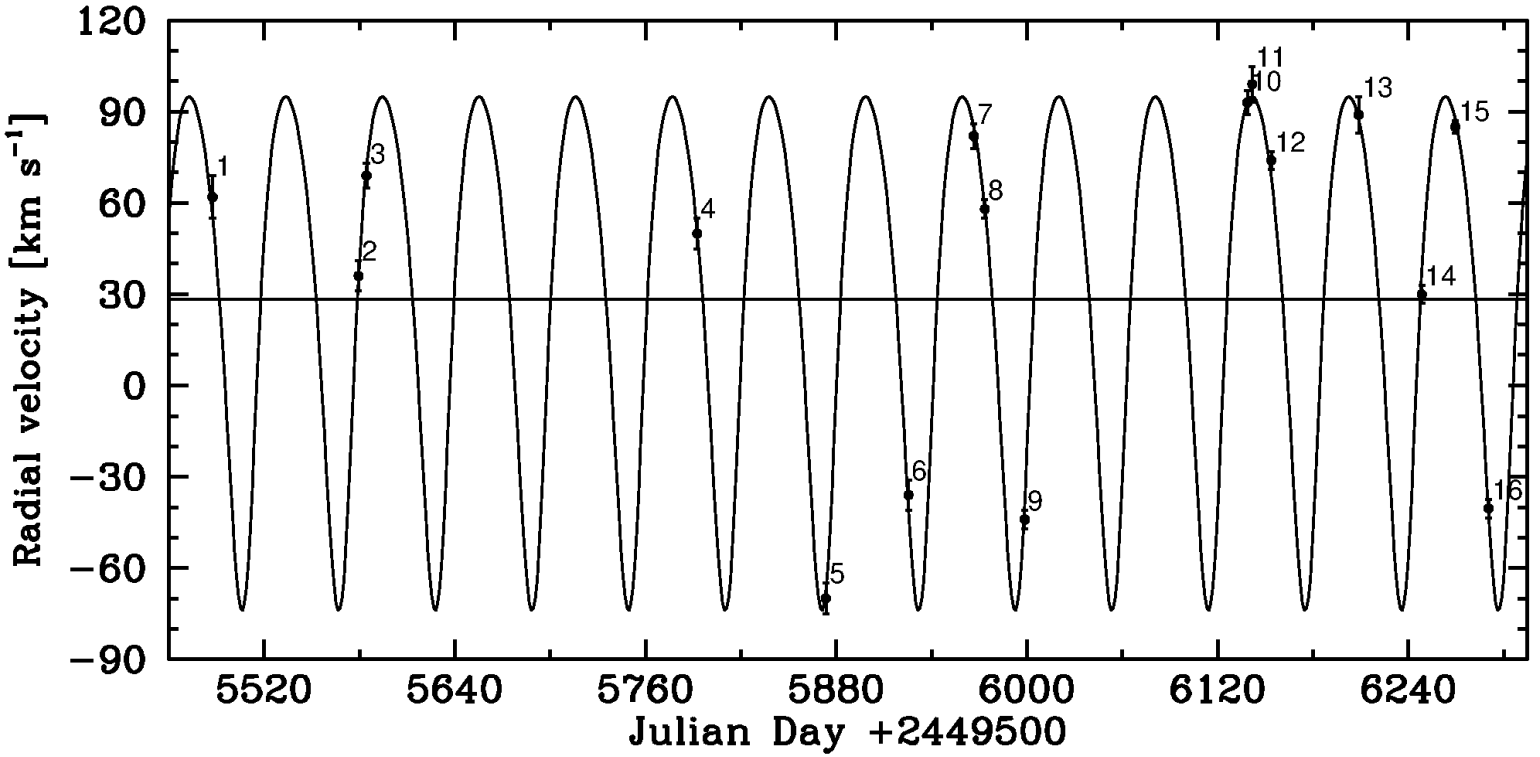
Fotosferische absorptielijnen met orbitale fase



- **S-golf waargenomen in absorptielijnen met amplitude van ~160 km/s.**
- **Dopplerverschuivingen tgv orbitale beweging van zware primaire ster.**

Monitoring van radiële snelheid in 2009-2011

- **16 Mercator-HERMES & ESO-FEROS spectra sep 2009 – aug 2011**



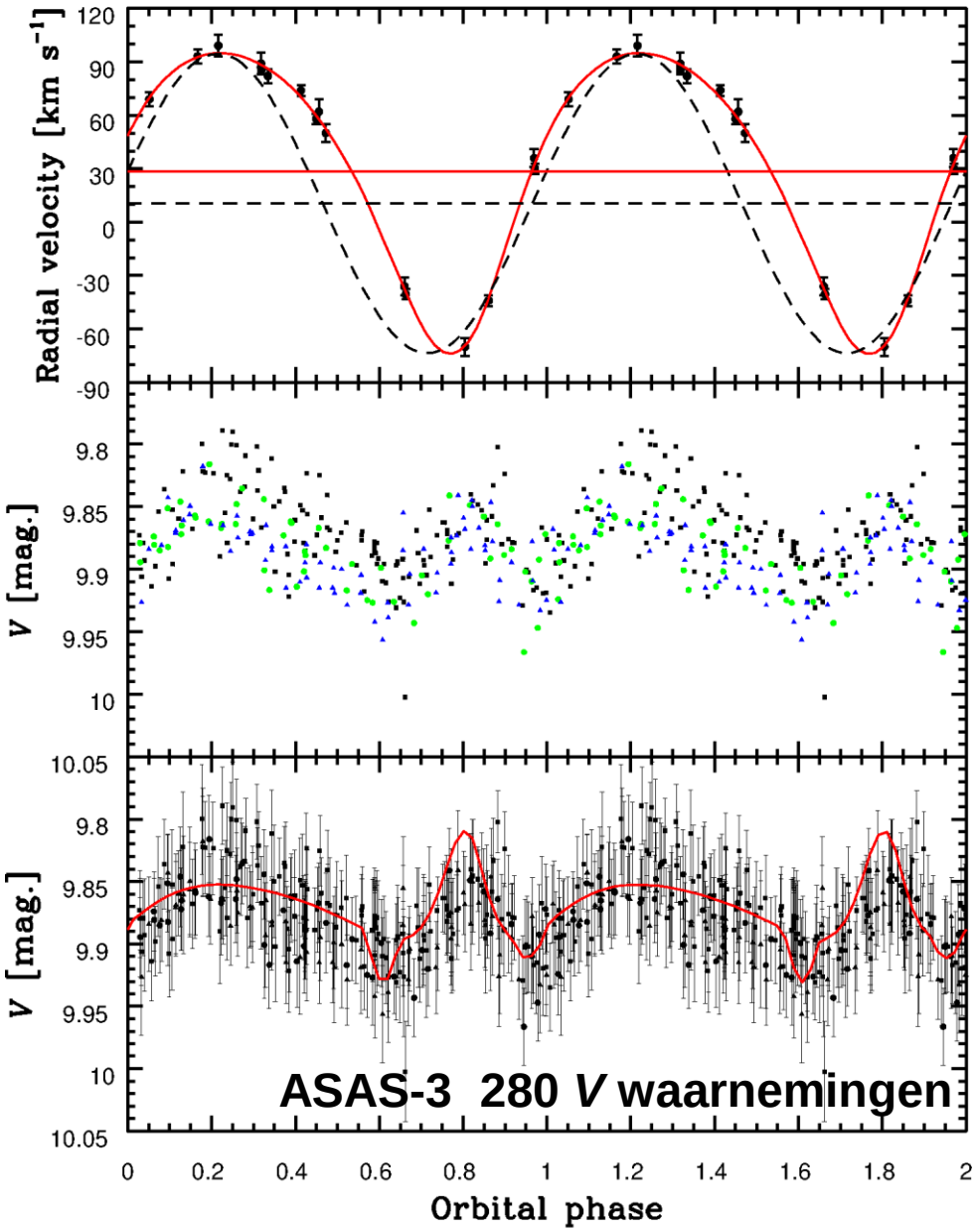
Baanelementen: P_{orb} = 60.799 d

$e = 0.235 \pm 0.003$

$i = 72.8° \pm 13.05$

$a = 262.5 \pm 19\ R_\odot$

Beste fits op radiële snelheid- en *V*-krommen



PHOEBE code
<u>gecombineerde best fit</u>
op radiële snelheid en *V*

MWC 314 is een zware dubbelster met een LBV ster die haar Roche volume vult.

***V*-kromme met partiële eclipsen voor $i = 72° \pm 13°$**

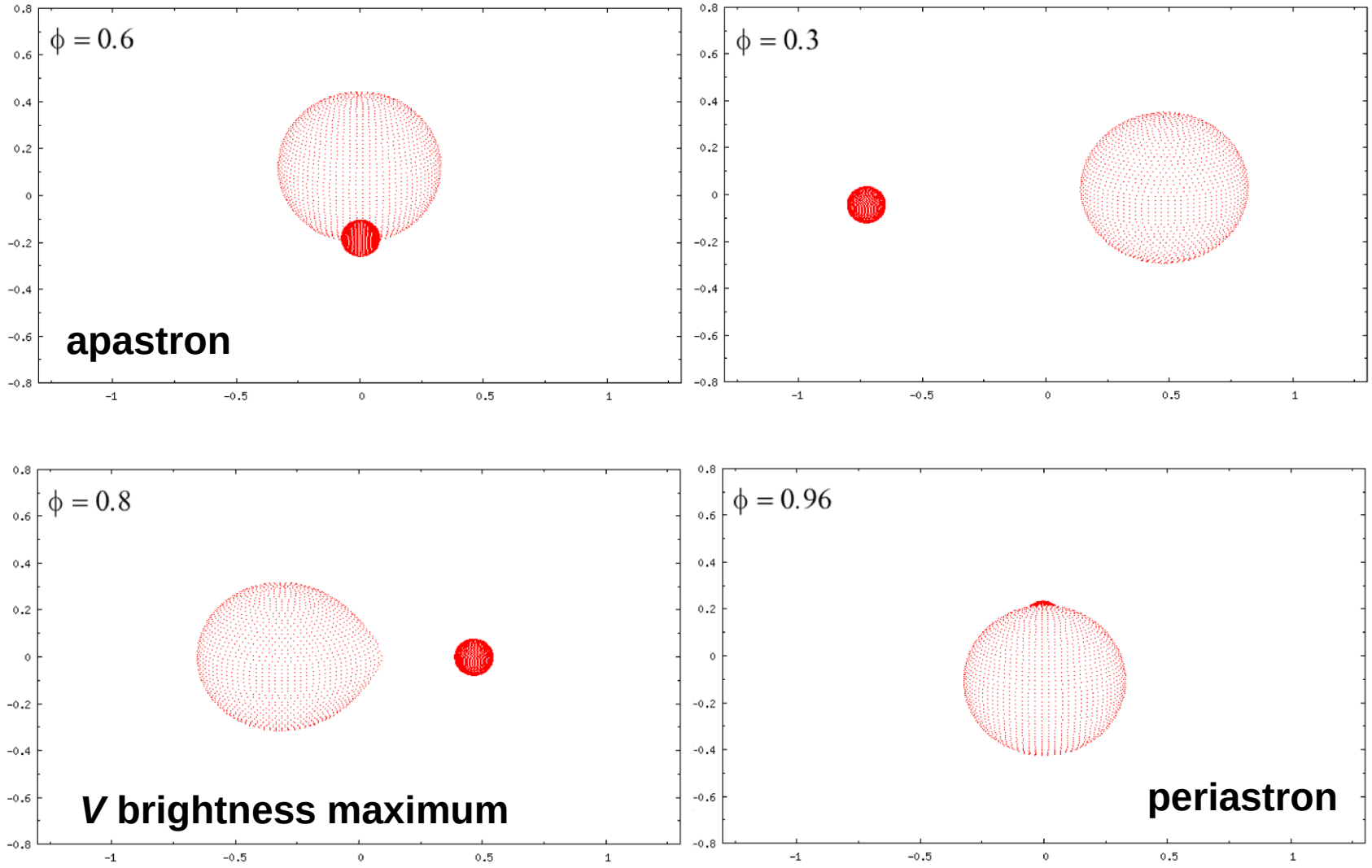
<u>Primaire ster:</u>

$M_1 = 39{,}6 \pm 4{,}3\ M_\odot$
$R_1 = 86{,}8\ R_\odot$

<u>Secundaire ster:</u>

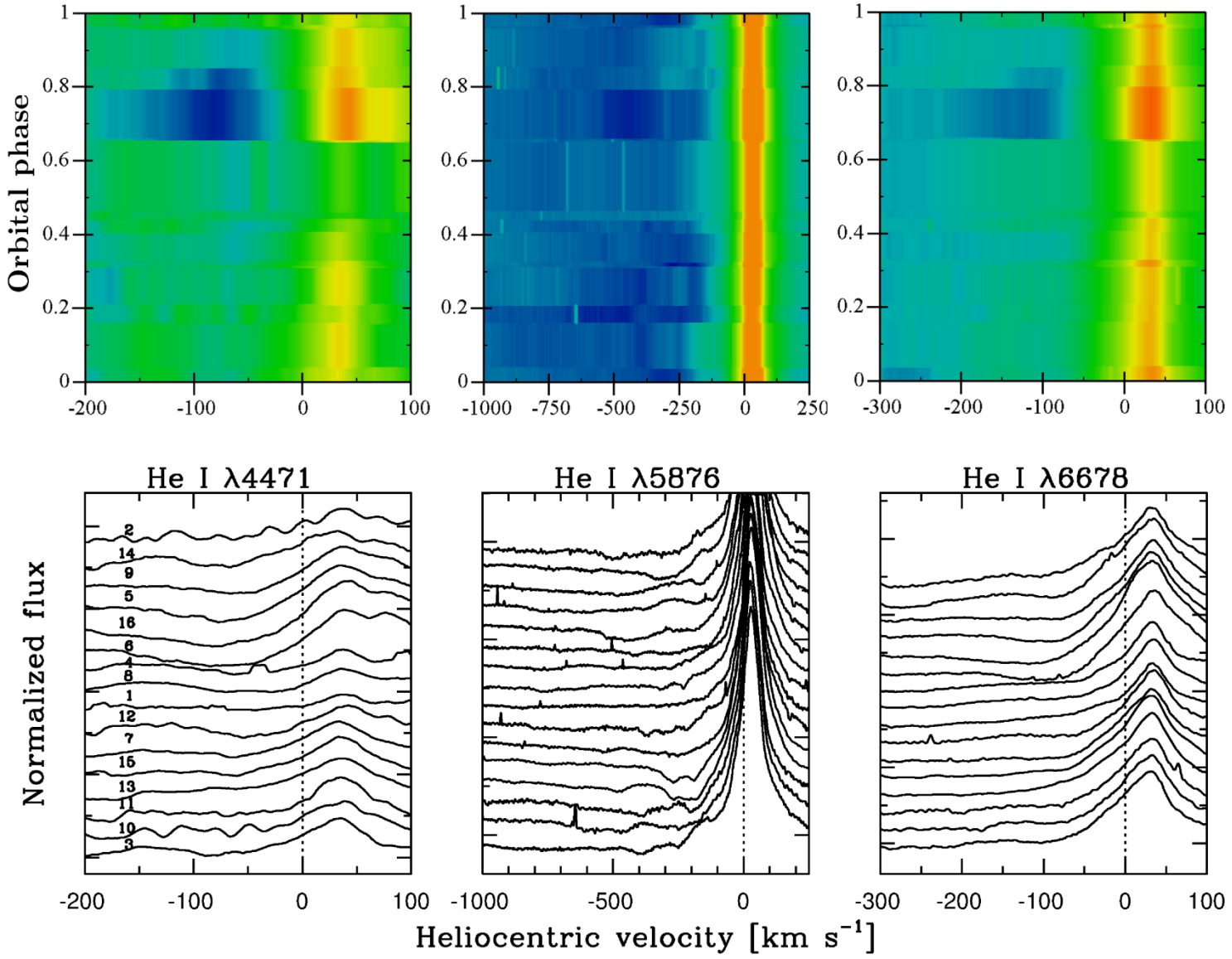
$M_2 = 26{,}3 \pm 2{,}5\ M_\odot$
$R_2 = 20{,}4\ R_\odot$

Primaire LBV ster vult haar Roche volume



- **Helderheidsmaximum in kwadratuur met grootste vervorming van primaire ster.**
- **Roche overvulling door LBV hoofdster voedt circumbinaire schijf in MWC 314?**

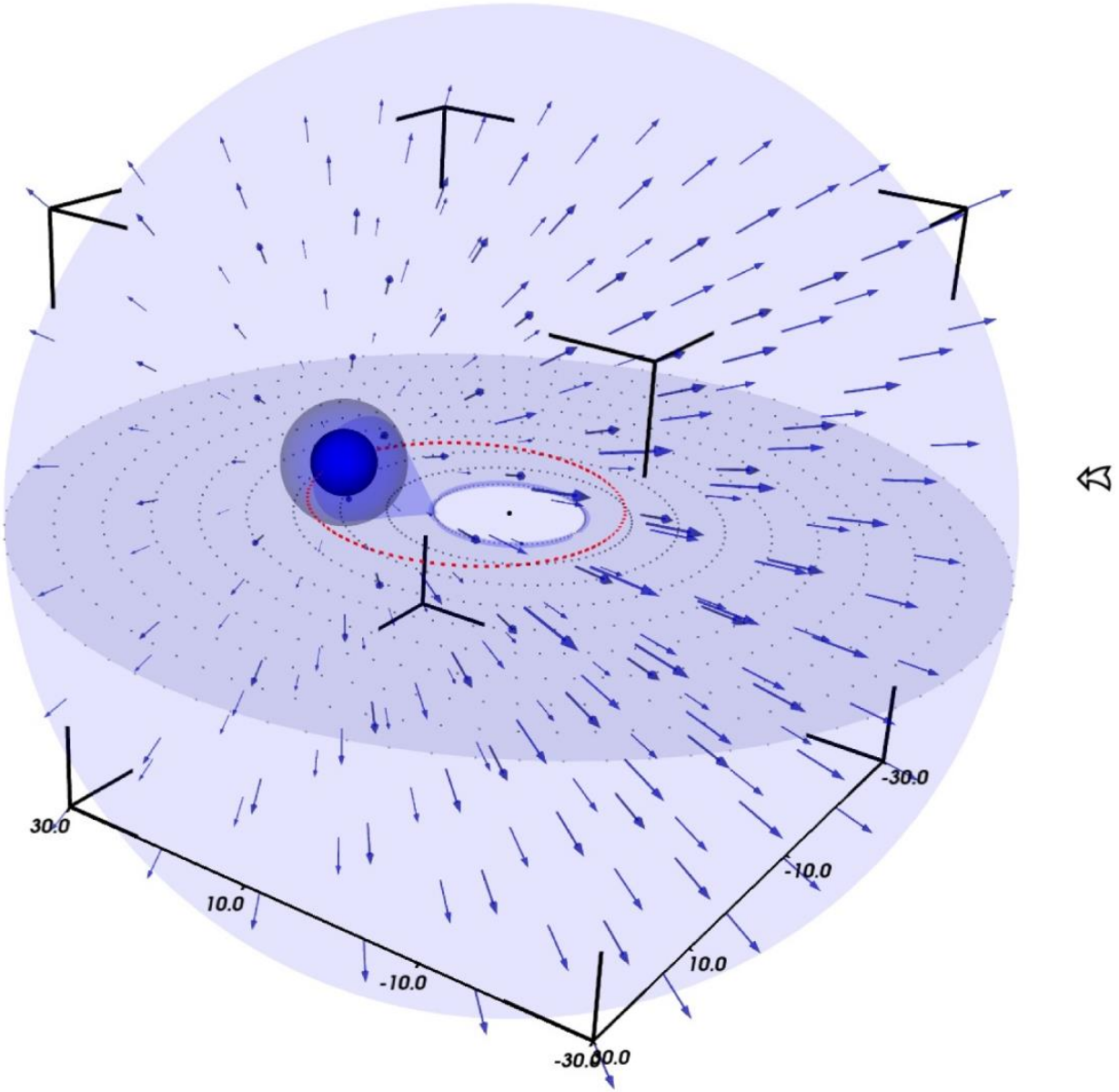
Orbitale veranderingen van P Cyg-type He I lijnen



- **Alle He I lijnen vertonen sterke orbitale modulatie van absorptie in wind.**
- **Max. windabsorptie ϕ= 0,65–0,85 bij max. blauwverschuiving van LBV.**

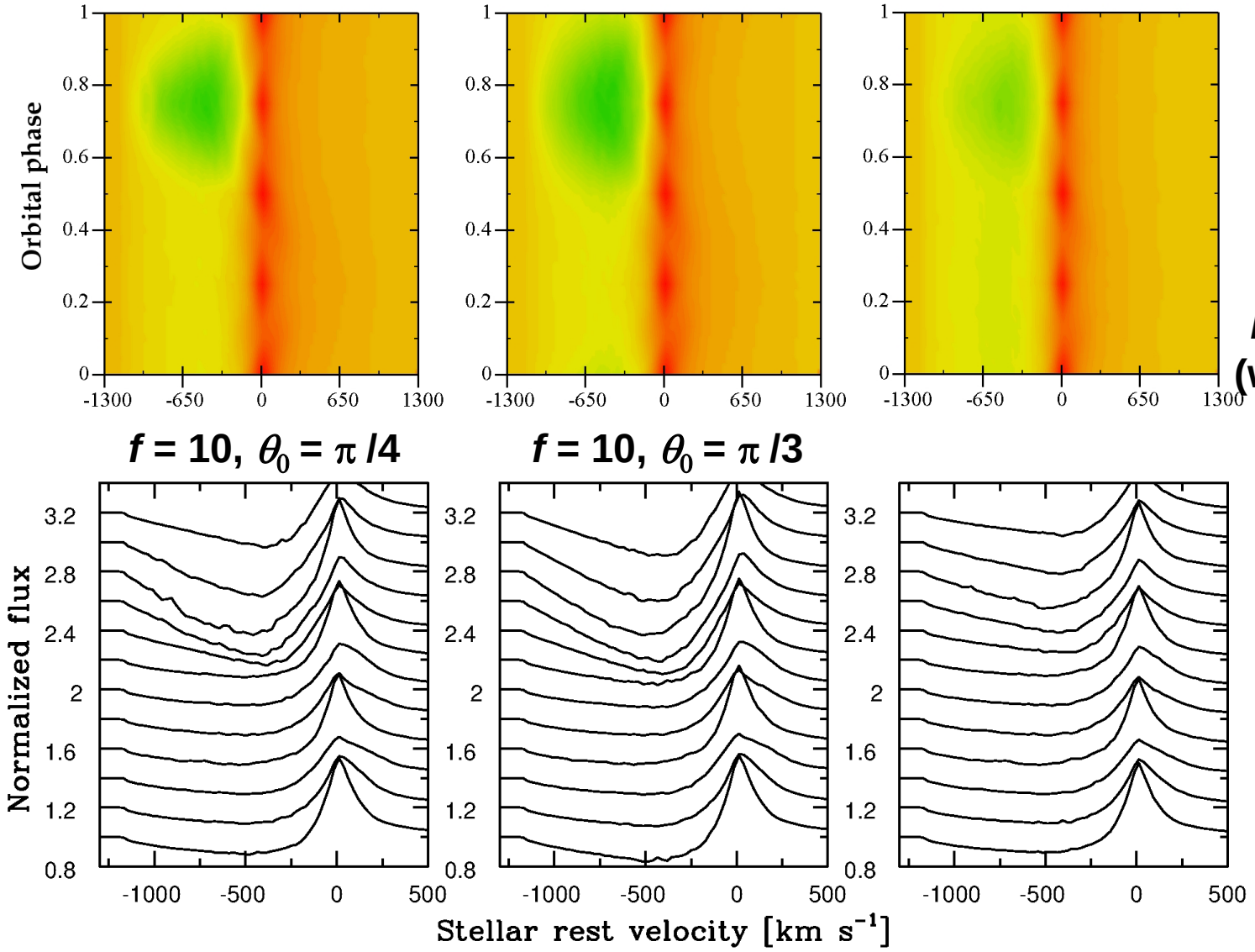
Asymmetrisch 3-D wind model van MWC 314

LBV in apoastron



- **β-wet wind model is asymmetrisch omheen gemeenschappelijk zwaartepunt maar wordt meer symmetrisch op grotere afstanden.**

Beste fit op orbitale veranderingen van He I lijn met Wind3D



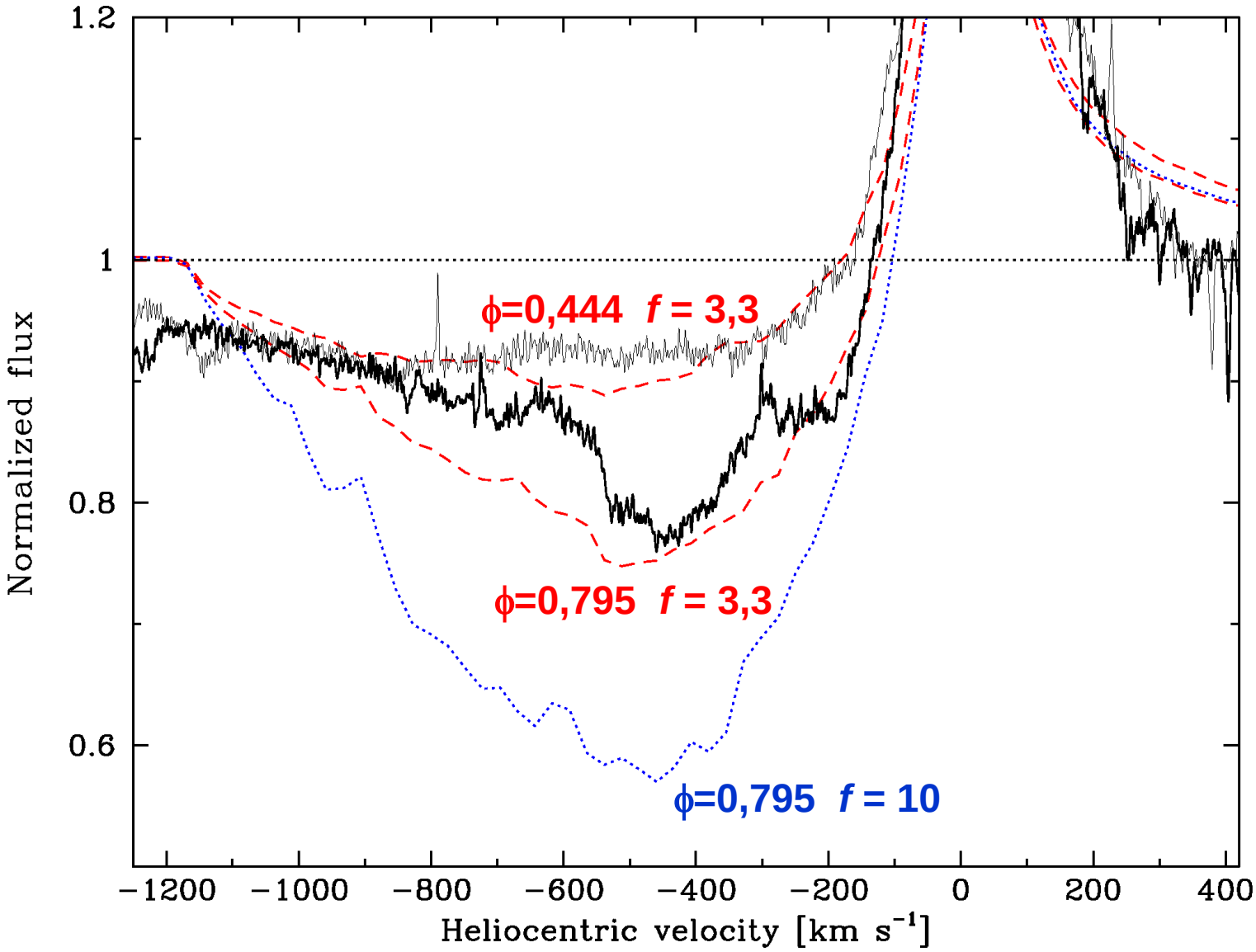
Best fit:
f = 3,3

Openings-hoek θ_0 = π /4

K_1 = 84,5 km/s (waargen. Vrad)

- **3-D wind model produceert sterkere absorptie bij ϕ = 0,65 – 0,8.**
- **Beste fit met Wind3D op absorptiegedeelte van P Cygni –type He I lijn.**

Wind3D beste fit op orbitale variaties in He I λ5876



- **3-D beste fit met Wind3D voor model met verhoogde wind dichtheid van factor *f* = 3,3.**

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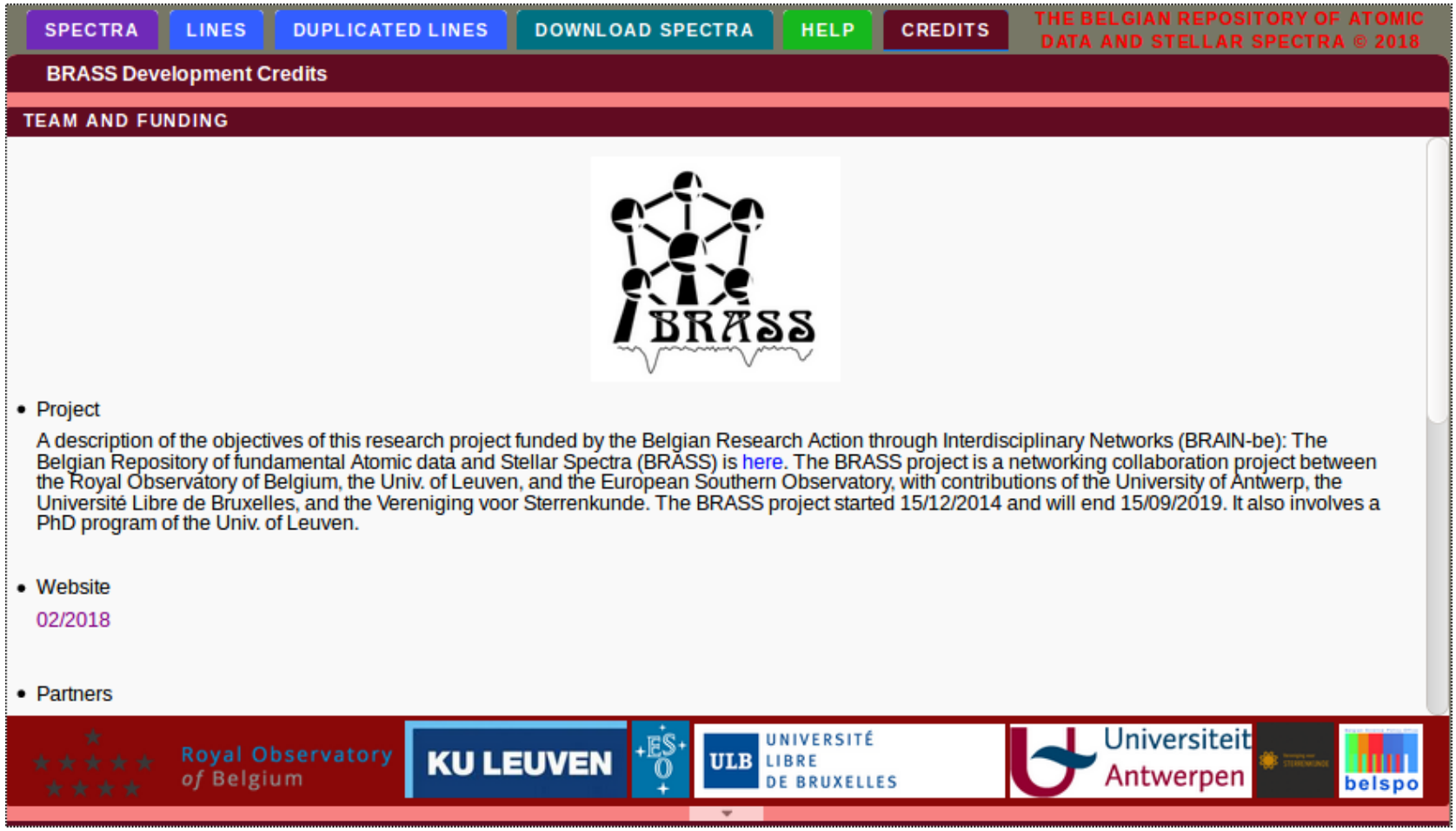

brass.sdf.org

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BRASS Spectra and Data Display

BENCHMARK STARS

K-stars
- HERMES Arcturus
- HERMES Eps Eri

G-stars
- HERMES 70 Oph
- HERMES 70 Vir
- KPNO-FTS Sun
- HERMES 51 Peg

F-stars
- HERMES 10 Tau
- HERMES Beta Com
- HERMES Procyon

A-stars
- HERMES 68 Tau

REFERENCE STARS

A-stars
HERMES Astar TBC

B-stars
VLT-UVES Bstar TBC

WAVELENGTH REGIONS

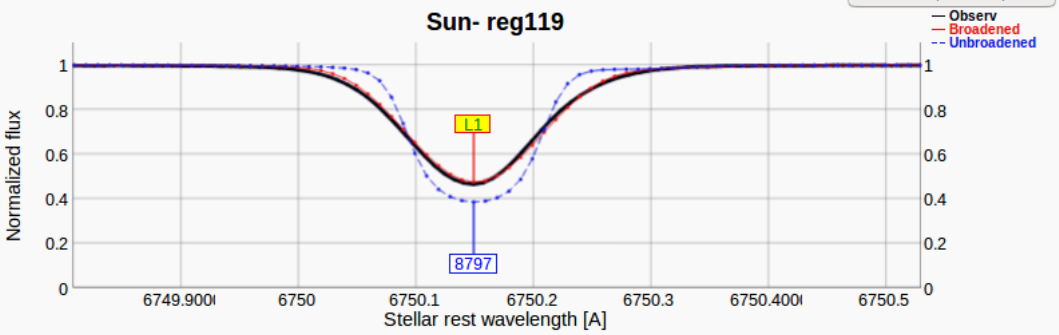
- 113 6560-6590 A
- 114 6590-6620 A
- 115 6620-6650 A
- 116 6650-6680 A
- 117 6680-6710 A
- 118 6710-6740 A
- 119 6740-6770 A
- 120 6770-6800 A

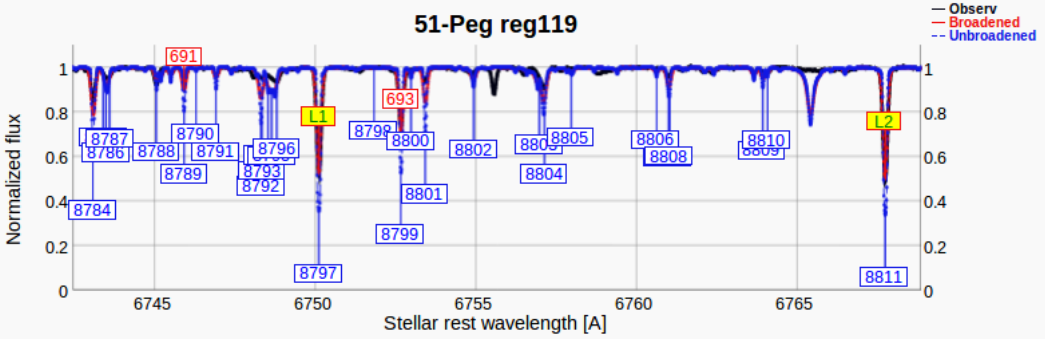
LOADED WAVELENGTH REGIONS

REGION #1 | REGION #2 | REGION #3 | REGION #4 | ATOMIC DATA QUALITY | GAUSS LINE FIT

Load Region #1 | Set wavelength zoom | Locked | Unlocked | Refresh

Shift top labels | Up | Down | send to top Gauss pane





Shift bottom labels | Up | Down | send to bottom Gauss pane

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ATOMIC DATA SPECTRUM 1

Save my list to file: brasslines1.html

Clear lines list | Clear graded list | Clear my list

Sun-
8797 Fe 1 6750.15
loggf= -2.720
Ref= SpectroWeb
Elow= 2.4241 eV
Rad= 6.690
Stark= -6.130
Lande= 1.500
Cal depth= 0.642

Sun-
692 Fe 1 6750.15
loggf= -2.617963
Ref= BRASS 2018
Elow= 2.424 eV
Cal depth= 0.5300
% blending= 0.110
View data quality

Sun-
L1 Fe 1 6750.15
loggf= -2.617963
Ref= BRASS 2018
Elow= 2.424 eV
Cal depth= 0.5300
% blending= 0.110
View data quality

Sun-
692 Fe 1 6750.15
loggf= -2.617963
Ref= BRASS 2018
Elow= 2.424 eV
Cal depth= 0.5300
% blending= 0.110
View data quality

Sun-
L2 Ni 1 6767.77
loggf= -2.14
Ref= BRASS 2018
Elow= 1.826 eV
Cal depth= 0.5633
% blending= 0.079
View data quality

Sun-
694 Ni 1 6767.77
loggf= -2.14
Ref= BRASS 2018
Elow= 1.826 eV
Cal depth= 0.5633
% blending= 0.079
View data quality

Sun-
694 Ni 1 6767.77
loggf= -2.14
Ref= BRASS 2018
Elow= 1.826 eV
Cal depth= 0.5633
% blending= 0.079
View data quality

ATOMIC DATA SPECTRUM 2

Save my list to file: brasslines2.html

Clear lines list | Clear graded list | Clear my list

51-Peg
8811 Ni 1 6767.77
loggf= -2.170
Ref= SpectroWeb
Elow= 1.8260 eV
Rad= 8.013
Stark= -6.145
Lande= 1.430
Cal depth= 0.644

51-Peg
692 Fe 1 6750.15
loggf= -2.617963
Ref= BRASS 2018
Elow= 2.424 eV
Cal depth= 0.4721
% blending= 0.110
View data quality

51-Peg
L1 Fe 1 6750.15
loggf= -2.617963
Ref= BRASS 2018
Elow= 2.424 eV
Cal depth= 0.4721
% blending= 0.110
View data quality

51-Peg
692 Fe 1 6750.15
loggf= -2.617963
Ref= BRASS 2018
Elow= 2.424 eV
Cal depth= 0.4721
% blending= 0.110
View data quality

51-Peg
L2 Ni 1 6767.77
loggf= -2.14
Ref= BRASS 2018
Elow= 1.826 eV
Cal depth= 0.5014
% blending= 0.079
View data quality

Display | Toggle Custom Theme

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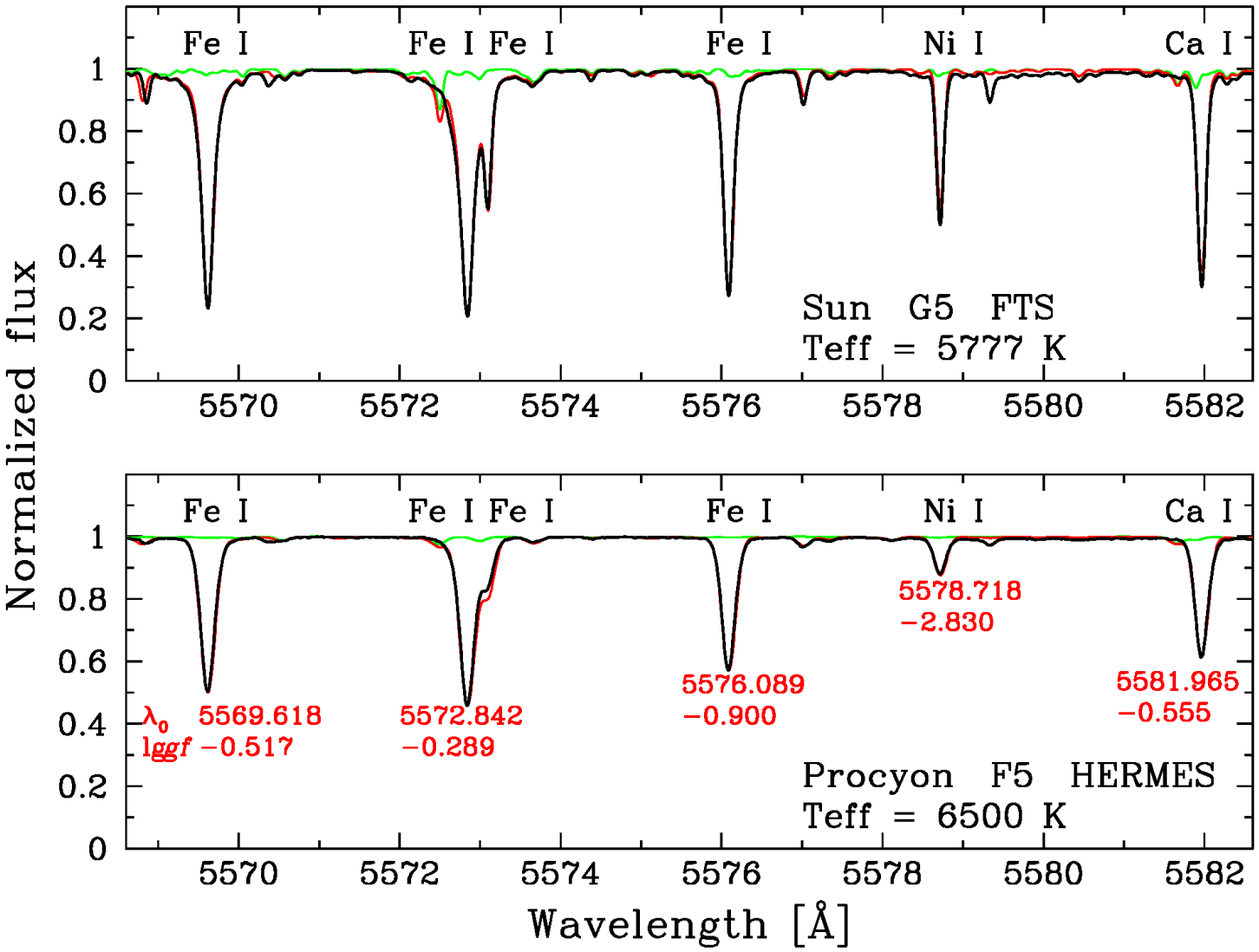

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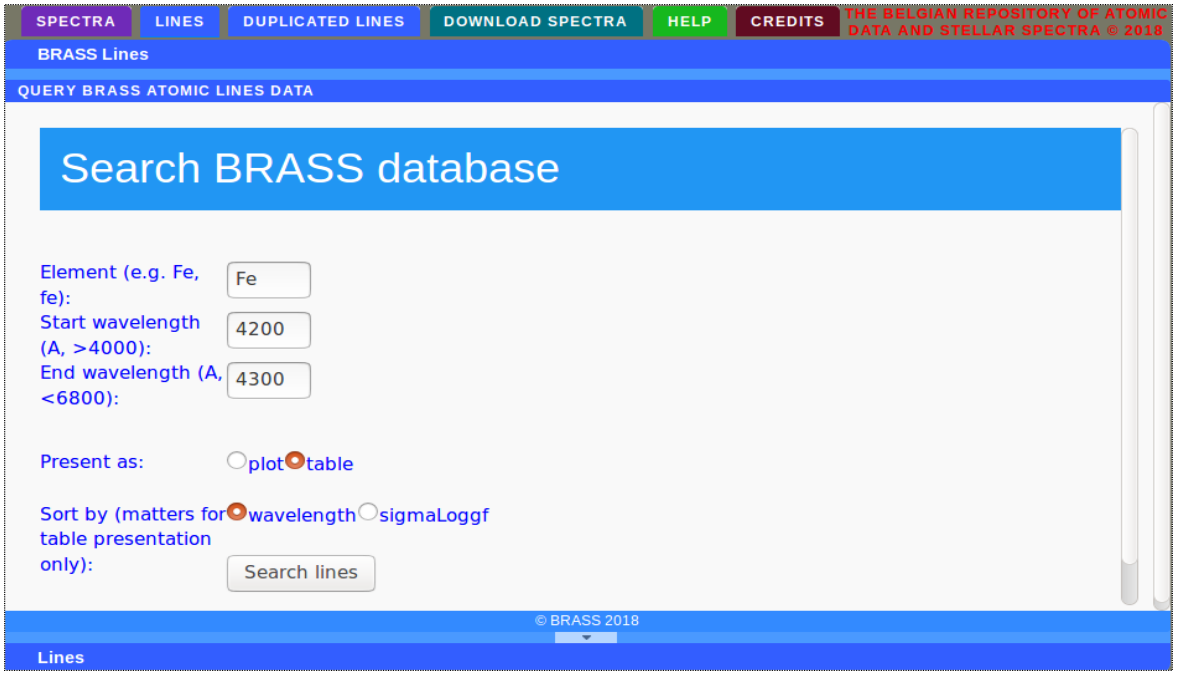

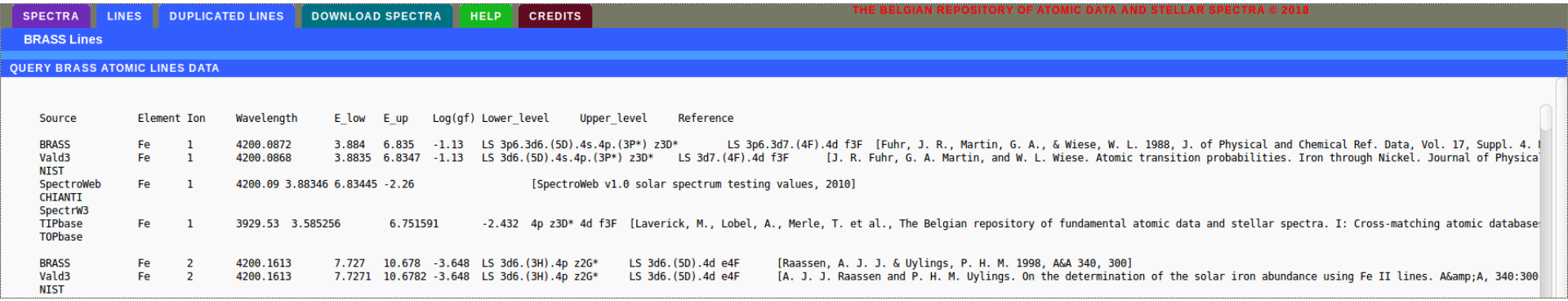

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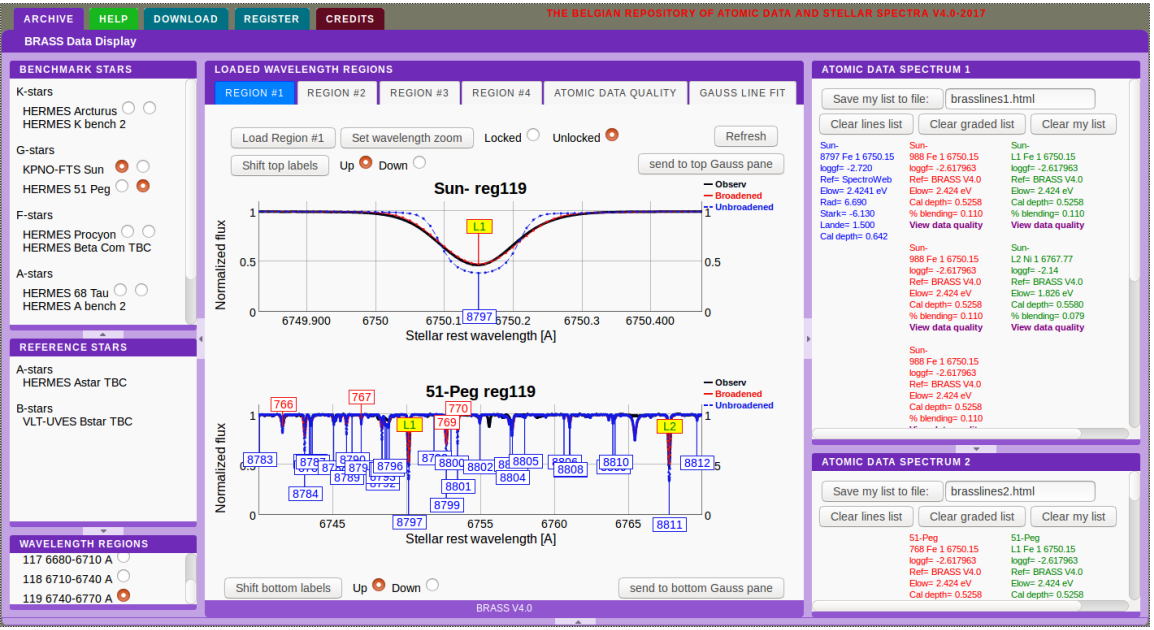
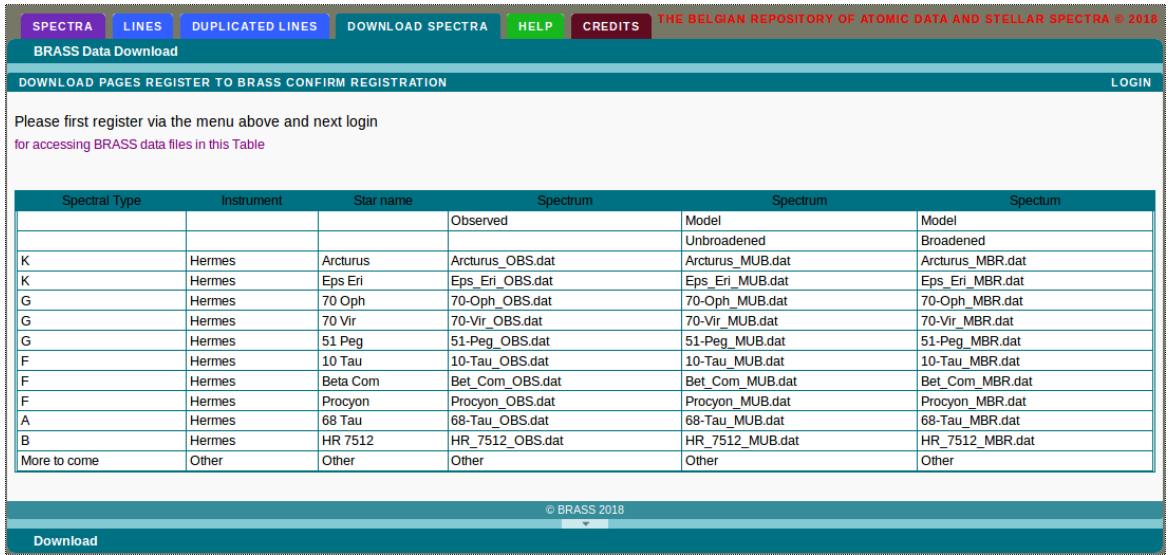


- **Interactief onderzoek van lijn-identificaties en atomaire gegevens.**

- **BRASS benchmark spectra reeds gedeeltelijk online beschikbaar.**



Spectral Type	Instrument	Star name	Spectrum	Spectrum	Spectum
			Observed	Model	Model
				Unbroadened	Broadened
K	Hermes	Arcturus	Arcturus_OBS.dat	Arcturus_MUB.dat	Arcturus_MBR.dat
K	Hermes	Eps Eri	Eps_Eri_OBS.dat	Eps_Eri_MUB.dat	Eps_Eri_MBR.dat
G	Hermes	70 Oph	70-Oph_OBS.dat	70-Oph_MUB.dat	70-Oph_MBR.dat
G	Hermes	70 Vir	70-Vir_OBS.dat	70-Vir_MUB.dat	70-Vir_MBR.dat
G	Hermes	51 Peg	51-Peg_OBS.dat	51-Peg_MUB.dat	51-Peg_MBR.dat
F	Hermes	10 Tau	10-Tau_OBS.dat	10-Tau_MUB.dat	10-Tau_MBR.dat
F	Hermes	Beta Com	Bet_Com_OBS.dat	Bet_Com_MUB.dat	Bet_Com_MBR.dat
F	Hermes	Procyon	Procyon_OBS.dat	Procyon_MUB.dat	Procyon_MBR.dat
A	Hermes	68 Tau	68-Tau_OBS.dat	68-Tau_MUB.dat	68-Tau_MBR.dat
B	Hermes	HR 7512	HR_7512_OBS.dat	HR_7512_MUB.dat	HR_7512_MBR.dat
More to come	Other	Other	Other	Other	Other

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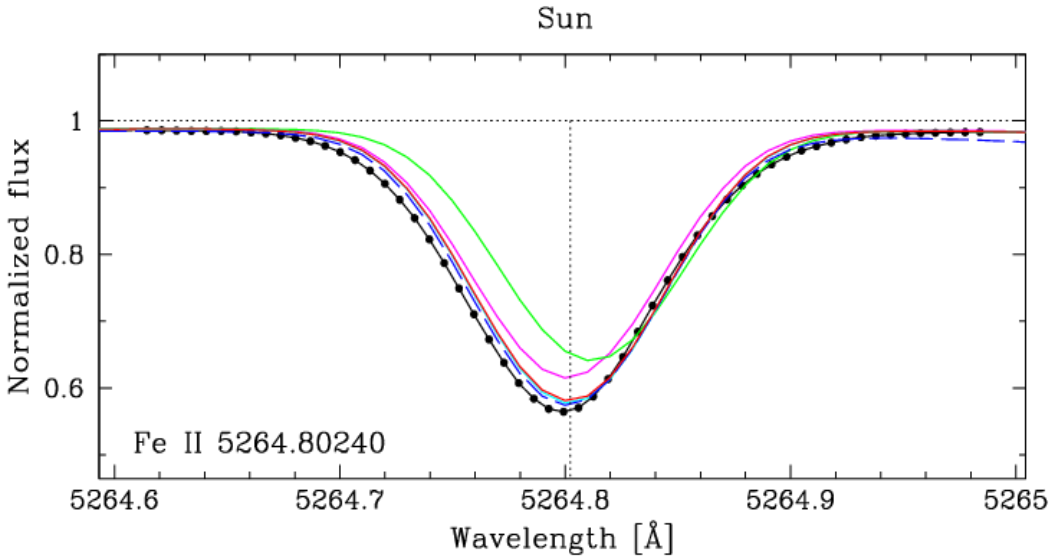
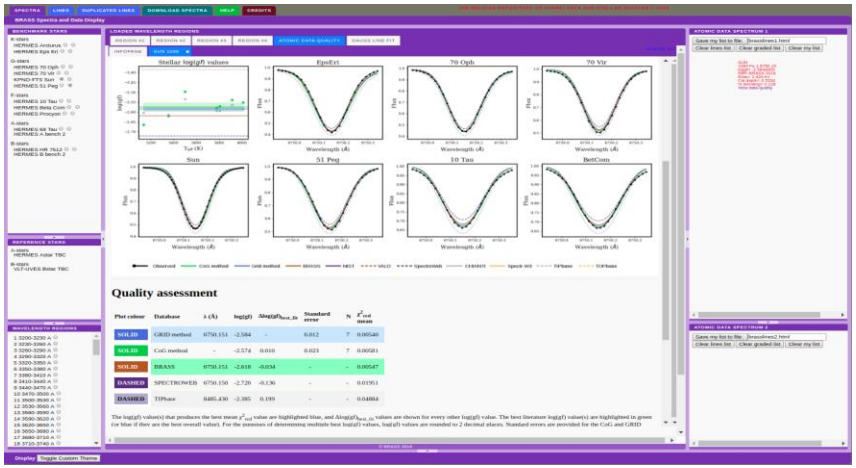


Source	λ [Å]	log(gf)	Δlog(gf)	χ²(λcorr)	W_{eq} [mÅ]	Nor. depth
Observed	5264.79877				48.2	0.4314
G-benchmarks	*5264.80133*	*-3.115*		0.0075	46.4	0.42718
BRASS	5264.80240	-3.13	0.015	0.0127	45.0	0.42132
NIST	5264.8026	-3.23	0.115	0.0286	40.7	0.38659
SpectroWeb	5264.812	-3.303	0.188	0.0405	37.8	0.36060
VALD	5264.8024	-3.12	0.005	0.0115	45.4	0.42459

- **Kwantitatieve beoordeling van de kwaliteit van diverse bronnen van atomaire data.**

- **Gedetailleerde fits op elke lijn in verschillende benchmark spectra.**



Belgian Repository of fundamental Atomic data and Stellar Spectra

SPECTRA | LINES | DUPLICATED LINES | DOWNLOAD SPECTRA | HELP | CREDITS

THE BELGIAN REPOSITORY OF ATOMIC DATA AND STELLAR SPECTRA © 2018

BRASS Spectra and Data Display

BENCHMARK STARS

K-stars
- HERMES Arcturus
- HERMES Eps Eri

G-stars
- HERMES 70 Oph
- HERMES 70 Vir
- KPNO-FTS Sun
- HERMES 51 Peg

F-stars
- HERMES 10 Tau
- HERMES Beta Com
- HERMES Procyon

A-stars

REFERENCE STARS

A-stars
HERMES Astar TBC

B-stars
VLT-UVES Bstar TBC

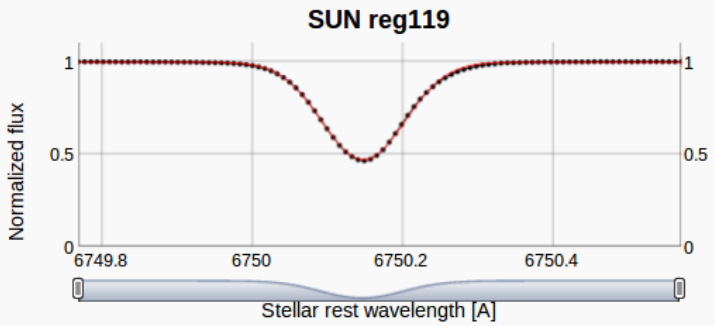
WAVELENGTH REGIONS

- 114 6590-6620 A
- 115 6620-6650 A
- 116 6650-6680 A
- 117 6680-6710 A
- 118 6710-6740 A
- 119 6740-6770 A
- 120 6770-6800 A

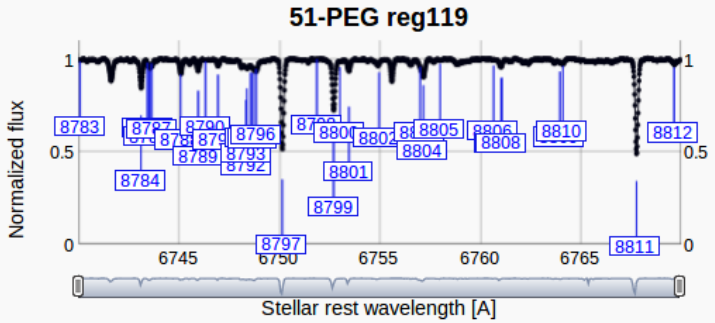
LOADED WAVELENGTH REGIONS

REGION #1 | REGION #2 | REGION #3 | REGION #4 | ATOMIC DATA QUALITY | GAUSS LINE FIT

run top Gauss fit | Reset zoom | Shift top labels | Up / Down | Add top fit to my list | Refresh



SUN reg119
Single Gauss best fit parms.
Line wavel. = 6750.1484 A
Bkgr. flux level = 0.9943
Gauss sigma = 55.17 mA
Norm. line depth = 0.5316
Eqv. width = 73.51 mA
Eqv. width error = 0.79 mA
Used fit points = 98
Fit quality = 0.99613



run bottom Gauss fit | Reset zoom | Shift bottom labels | Up / Down | Add bottom fit to my list

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ATOMIC DATA SPECTRUM 1

Save my list to file: brasslines1.html

Clear lines list | Clear graded list | Clear my list

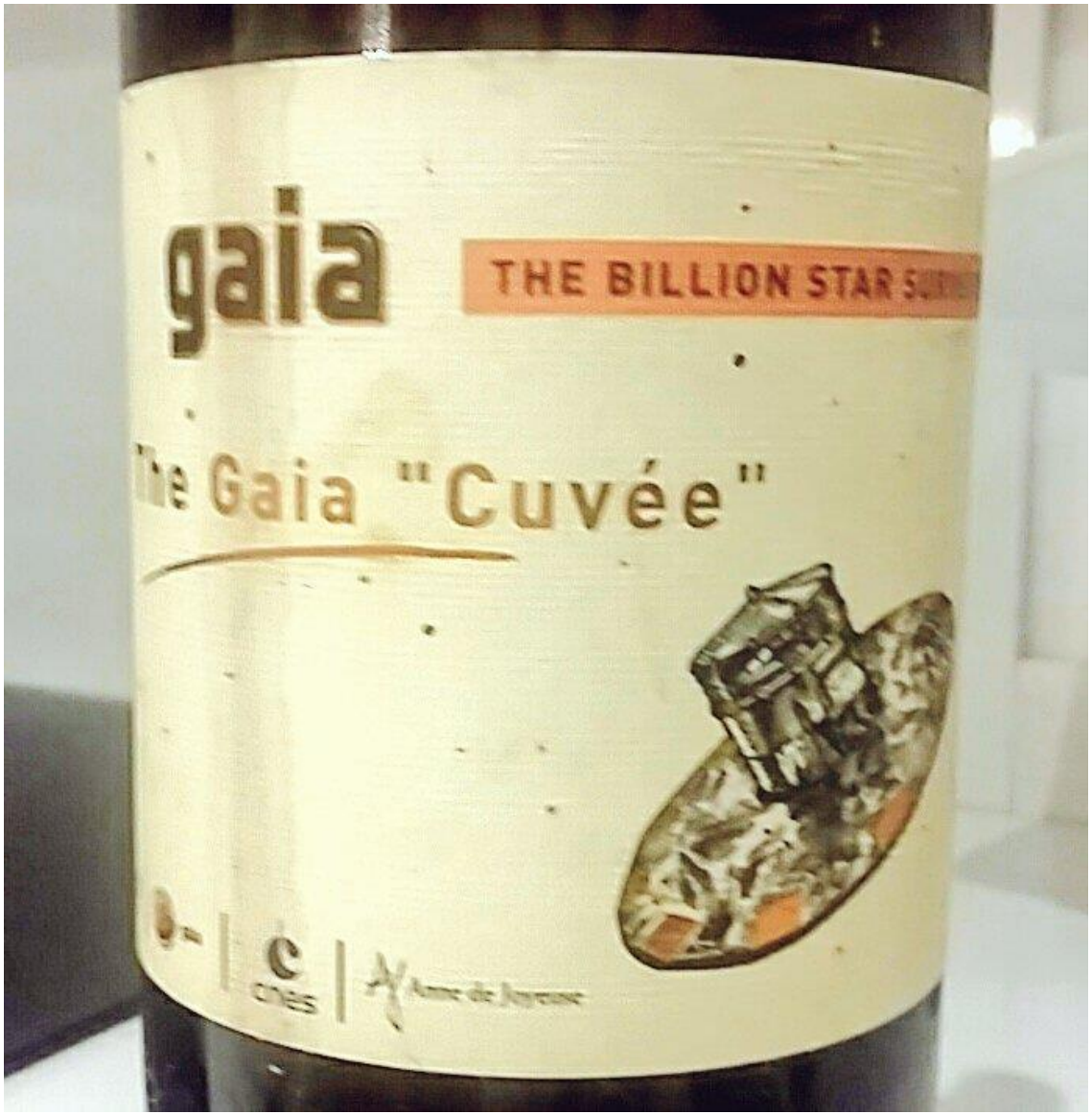
SUN reg119
8797 Fe 1 6750.15
loggf= -2.720
Ref= SpectroWeb
Elow= 2.4241 eV
Rad= 6.690
Stark= -6.130
Lande= 1.500
Cal depth= 0.642

SUN reg119
Single Gauss best fit parms.
Line wavel = 6750.1484 A
Bkgr. flux level = 0.9943
Gauss sigma = 55.17 mA
Norm. line depth = 0.5316
Eqv. width = 73.51 mA
Eqv. width error = 0.79 mA
Used fit poits = 98
Fit quality = 0.99613

ATOMIC DATA SPECTRUM 2

Save my list to file: brasslines2.html

Clear lines list | Clear graded list | Clear my list

Display | Toggle Custom Theme

Dank voor de uitnodiging