

Main Sequence Runaway Project

Research Workshop on Evolved Stars

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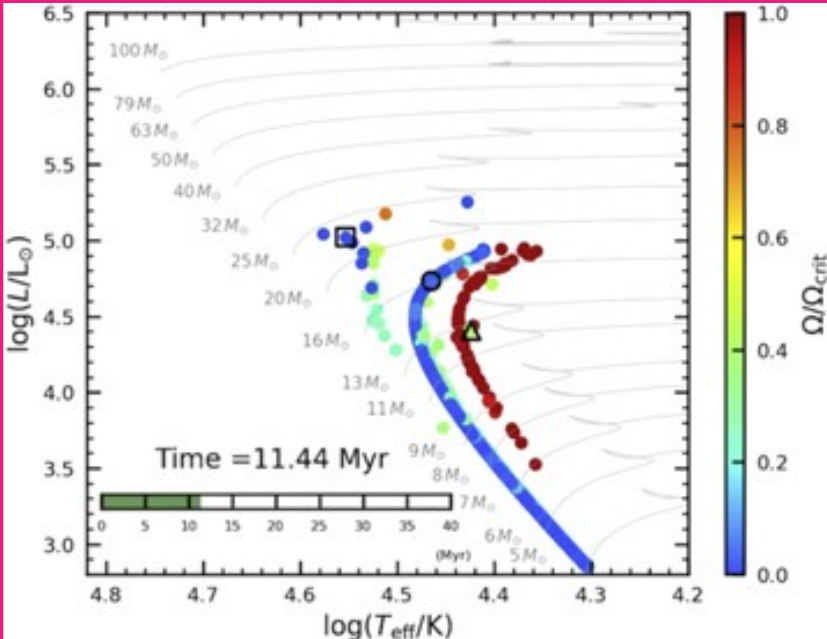
1. **Scientific background** What are we looking for?
2. **Observations** with the Perek telescope
3. **Reduction** Procedure to reduce observed data
4. **Analysis** Spectra fitting and Analysis
5. **Conclusions** What did we find?



Scientific background

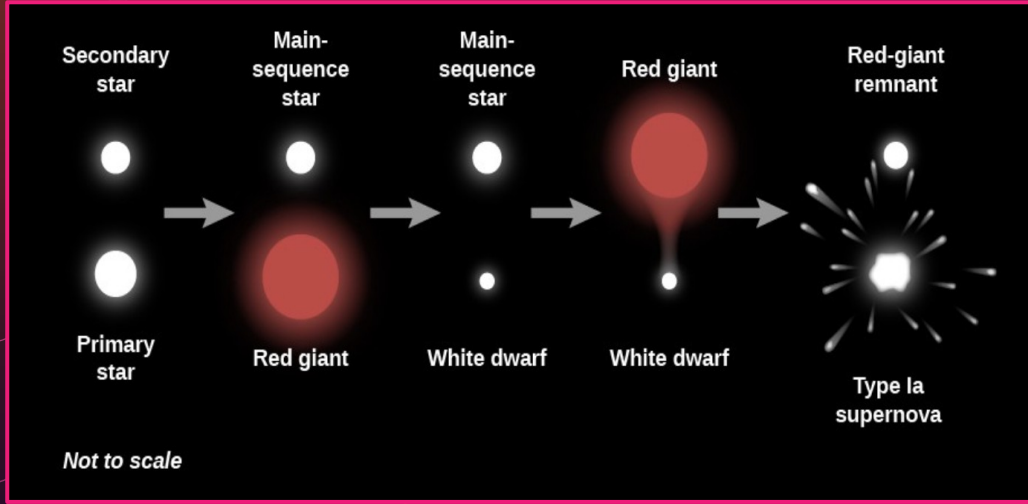
Binary evolution

- 60-80 % of stars are in multiple system



Credit: Wang et al. 2020

The supernova scenario



Credit: OpenStax CNX

What are we looking for?

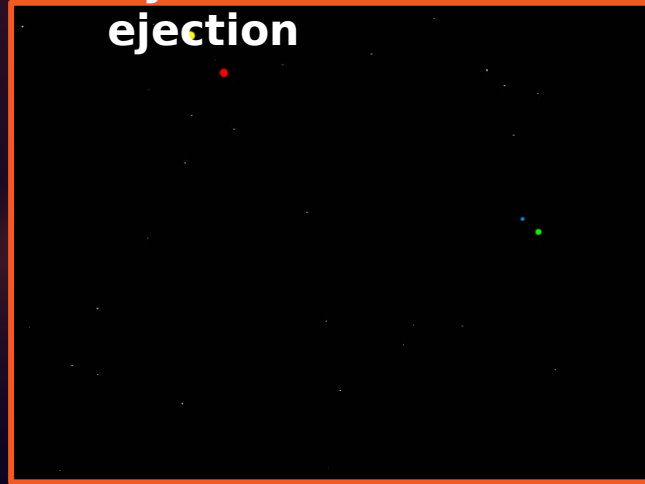
Runaway Stars = stars ejected from their cluster

- Characterised by their ejection velocities
- Velocity vectors point away from the disk

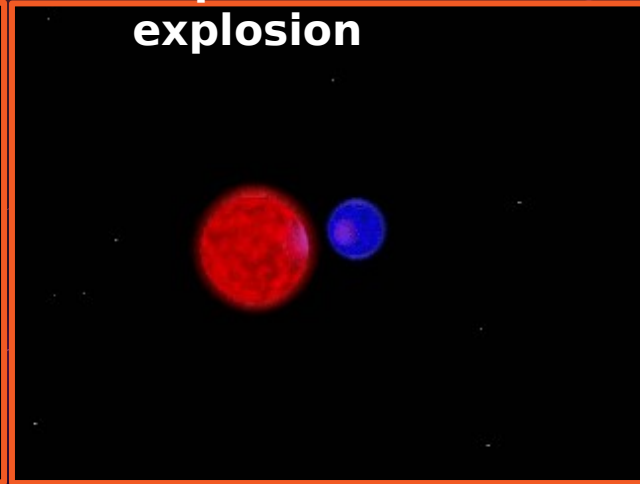
- $V_s > 30 \text{ km/s}$ (Runaways)
- $V_{esc} > V_s \gg 30 \text{ km/s}$ (Hyper-runaways)
- $V_s > V_{esc}$ (Hyper-velocity stars)

How are they generated?

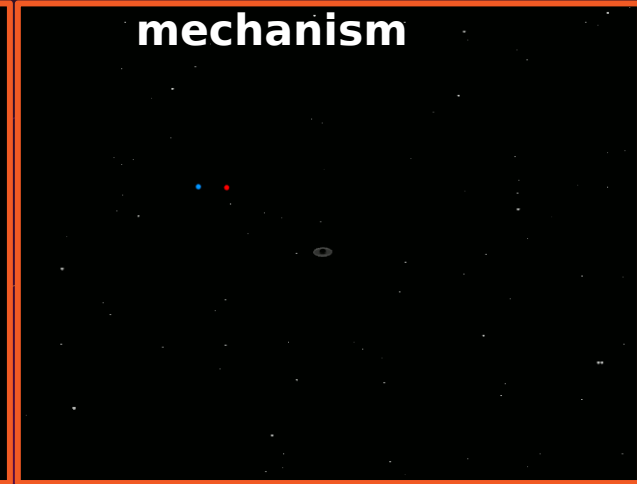
Dynamical ejection



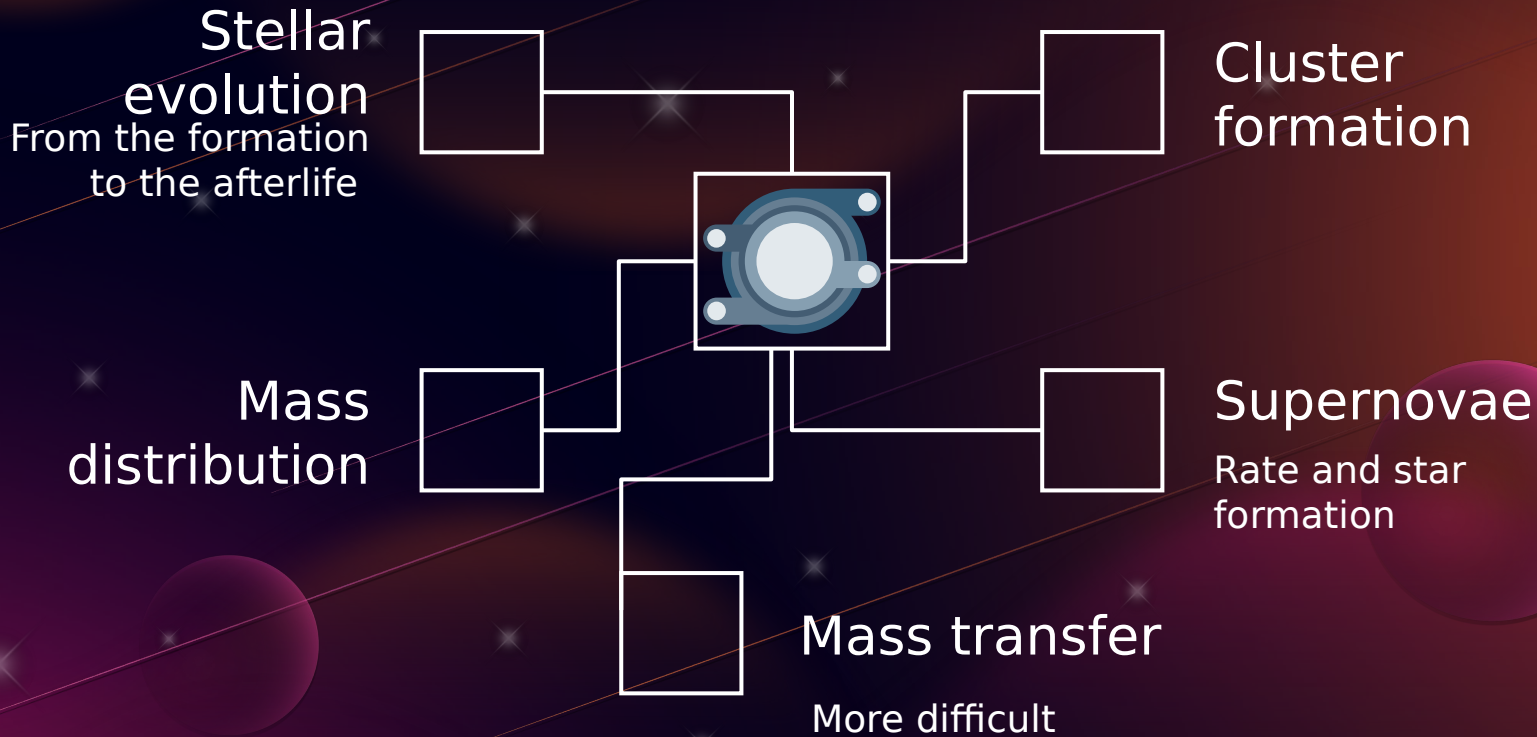
Supernova explosion



Hills mechanism



Why are we looking for them?



How are we studying them?

Study a cluster and study runaways from it

Study runaways and trace them back to their original cluster

How are we studying them?

**Study a cluster and
study runaways from it**

**Study runaways and trace
them back to their original
cluster**

The background is a dark, gradient space scene. It features several large, semi-transparent spheres in shades of purple, blue, and orange, resembling planets or moons. Scattered throughout are numerous small, bright white stars with four-pointed diffraction patterns. Two thin, parallel white lines run horizontally across the image, one near the top and one near the bottom, framing the central text.

Observations

Target Selection: Gaia DR3 and Simbad Crossmatch

- (Hot) Main Sequence B stars
(young stars)
- Relatively low magnitudes -
Fainter stars (9 - 12 mag)
- Tangential velocity sorting -
targets with higher v_{tan} given
priority (fast stars)
- Faintest stars observed at their
peak and/ during best seeing
(unknown stars)
- Further constraints on parallax,
 bp_{rp} , etc.

	designation	main_type	ra	dec	main_id
25	Gaia DR3 1297821542123473920	Star	249.39996	21.98763	TYC 1531-595-1
57	Gaia DR3 1877121680126046592	Star	339.63429	24.66997	TYC 2224-1842-1
60	Gaia DR3 2051435363079038976	Star	293.027	36.36118	TYC 2667-15-1
66	Gaia DR3 2109349118713707136	Star	274.38082	39.80271	TYC 3107-1105-1
67	Gaia DR3 4230376519786049024	Star	303.89078	-0.10058	TYC 5162-2358-1
33	Gaia DR3 1088668278463098880	Star	117.7477	64.3071	TYC 4121-1312-1
42	Gaia DR3 1942738816090384000	Star	350.01376	49.61111	TYC 3644-931-1
44	Gaia DR3 2046447089297417344	Star	292.35472	33.77783	TYC 2662-18-1
48	Gaia DR3 2234134067741889280	Star	298.58783	56.05935	TYC 3939-612-1
50	Gaia DR3 1621614384923908736	Star	240.06747	55.63778	TYC 3880-1204-1
64	Gaia DR3 1220093045066977408	Star	240.06663	25.73174	BD+26 2766
36	Gaia DR3 1702141998067604096	HotSubdwarf	223.6672	76.88794	BD+77 564
37	Gaia DR3 2072046778019185920	Star	297.5005	37.37644	HD 226054
40	Gaia DR3 1078362968292342272	HotSubdwarf	156.91343	73.69872	BD+74 435
32	Gaia DR3 125476717935463936	Star	49.05531	33.39643	HD 278483
63	Gaia DR3 1804623250649405440	Star	307.03016	14.55096	TYC 1099-367-1
65	Gaia DR3 2093534465017435776	Hsd_Candidate	283.13403	36.58004	LB 4237
71	Gaia DR3 1843479781115432704	Star	309.76539	24.77386	HD 340883
46	Gaia DR3 1134611822802497664	Star	176.78807	83.07573	BD+83 337
68	Gaia DR3 4536070477785678336	Star	278.68449	24.72221	HD 336540
59	Gaia DR3 1974040984426803968	Star	325.00327	45.04797	BD+44 3899

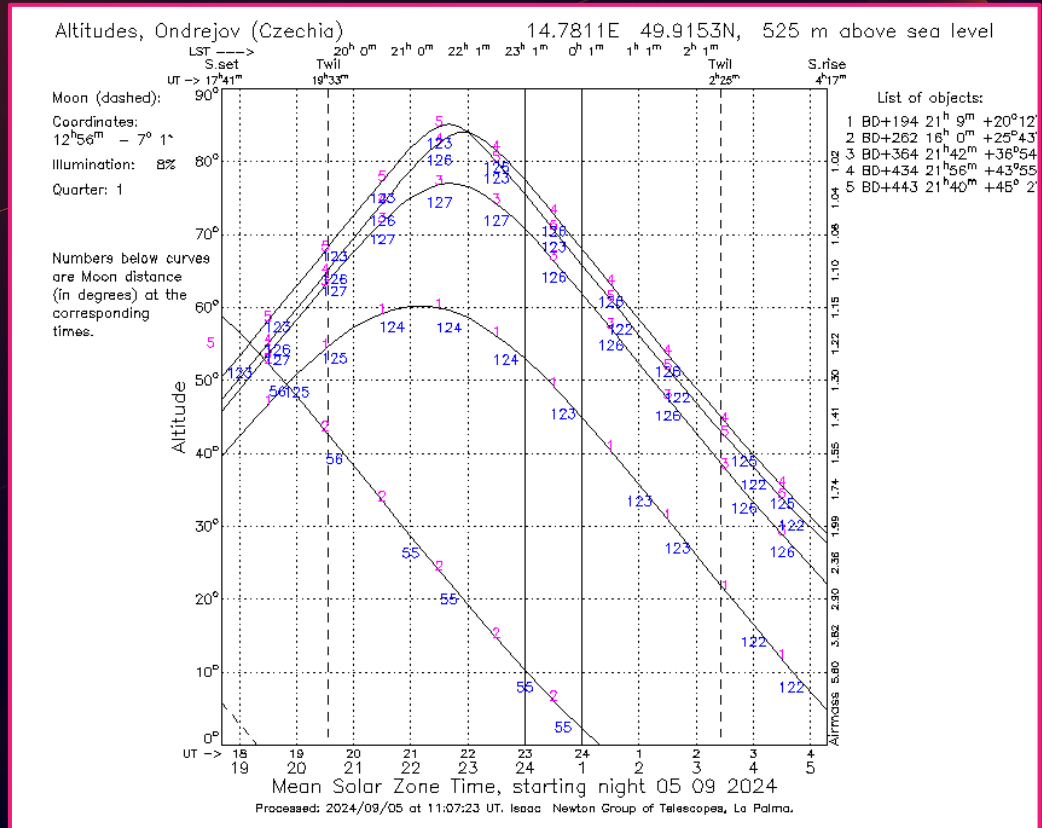
Sample Gaia DR3 data for selected sources
(Topcat)

Target Selection: Visibility Charts

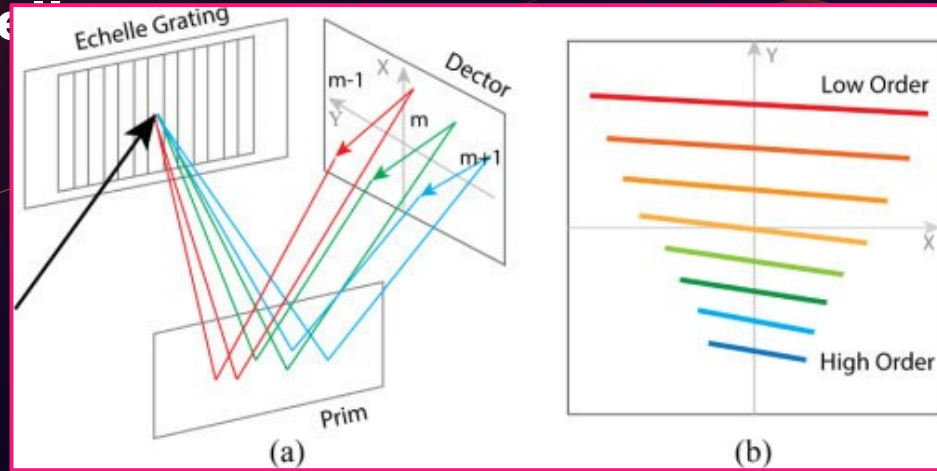
- Visibility checked using catserver.
- Target selection and order adjusted accordingly.
- ra and dec constraints based on location

45 spectra of 44 targets

<http://catserver.ing.iac.es/>



The Perek Telescope and the Echelle Spectrograph



Credit: Shen et al.
2018

Instrument	Wavelength coverage	Order length	Resolution power in H α region	Advantages
OES (Ondřejov Echelle Spectrograph)	3753-9195Å	70 Å (in UV) 145 Å (in IR)	32000	Resolution Spectral orders

The background is a dark, gradient space scene. It features several planets of different sizes and colors, including a large purple planet on the right, a medium-sized orange planet on the left, and a smaller purple planet in the bottom left. Numerous small, bright stars are scattered across the scene. Two thin, parallel white lines run horizontally across the image, one near the top and one near the bottom. The word "Reduction" is centered in the middle of the image in a white, sans-serif font.

Reduction

Reduction - Requirements and Procedure

- **Bias** = Camera readout noise
 - **Flat frames** = variations in pixels sensitivity
 - **Wavelength calibration** using Comp lamps
 - **Science Frames** = The observed spectra
- ❖ Bias correction (Zero correction)
 - ❖ Flat field correction and modelling
 - ❖ Wavelength calibration
 - ❖ Trimming of the object
 - ❖ Cosmic rays removal
 - ❖ JD and heliocentric correction
 - ❖ Normalization and Merging

IRAF display: Bias, Flats and Comparison Parameters

Image Reduction and Analysis Facility

PACKAGE = clpackage
TASK = oesred

input = e202409020034.fit Spectrum target to reduce(.fit)
(output = HD336540) Output filename
(idtarge= HD 336540) Target name on header
(napertu= 49) Number of apertures to be found

CALIBRATION PARAMETERS

(orgfile= no) do you want organize files?
(zerocom= no) Combine zero level images?
(trimcal= no) Trim flat and comp?
(iftrimc= yes) Use trim flat & comp?
(zerocor= no) Apply zero level correction to flat & comp?
(compcom= no) Combine comparison lamp images?
(flatcom= no) Combine flat field images?
(flatapa= yes) Extract flat apertures?
(compapa= no) Extract comparison apertures?
(iddatab= no) Use database folder for identification?

More

ESC-? for HELP

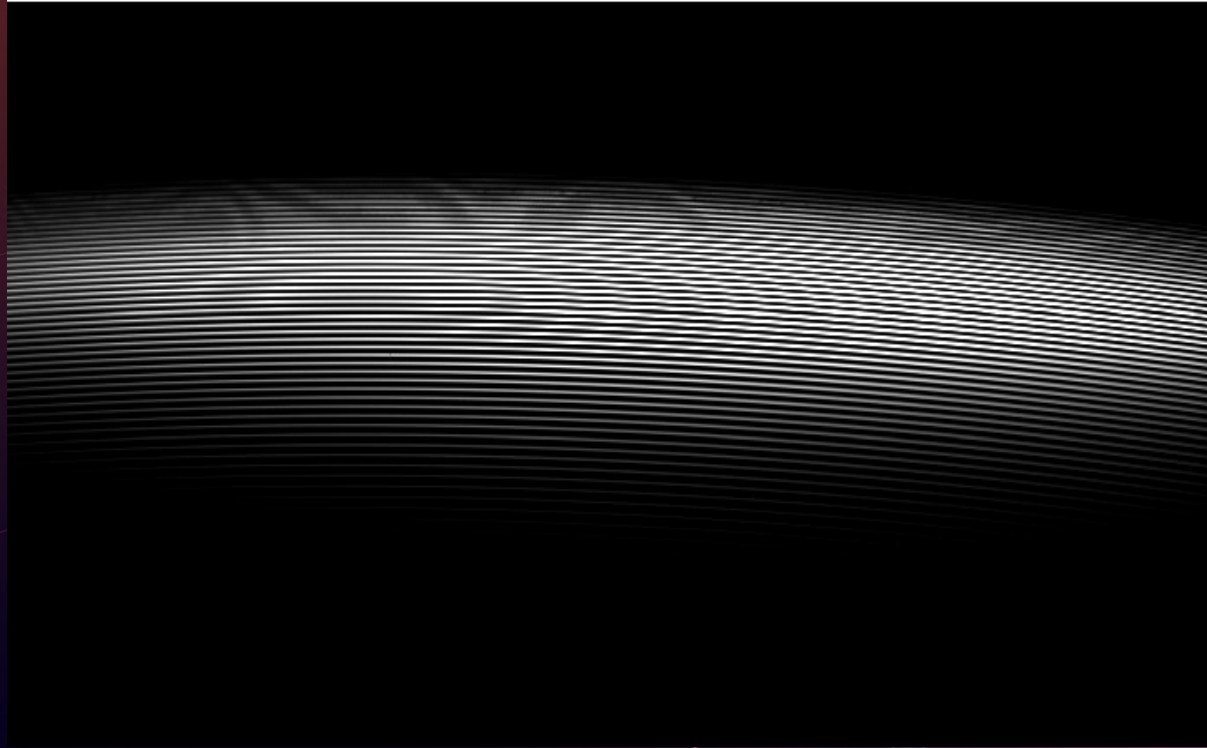
The Bias (Zero) Frame

- Shortest possible exposure
- Camera readout noise
- Bias correction
- ADC - charge to digital value
- Later applied to flat, calibration and science frames.

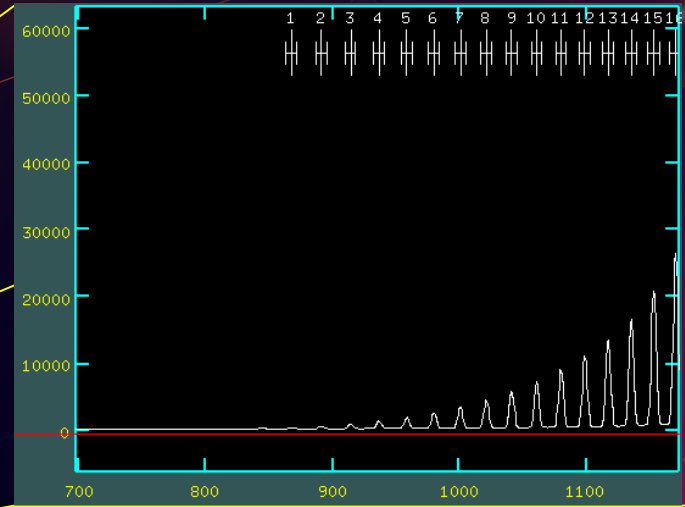
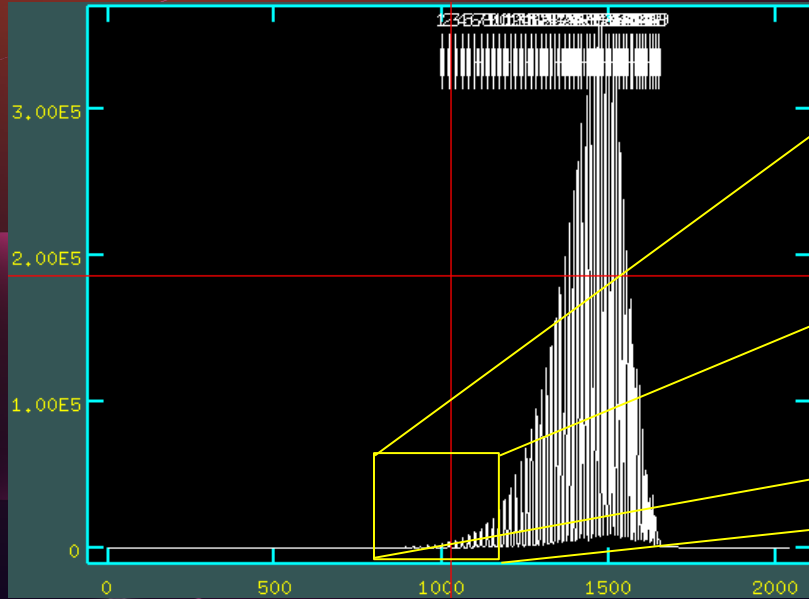


The Flat Frames

- Uniform (mostly) illuminated source
- Detector response to uniform light, including pixel-to-pixel variations
- Used for CCD sensitivity correction



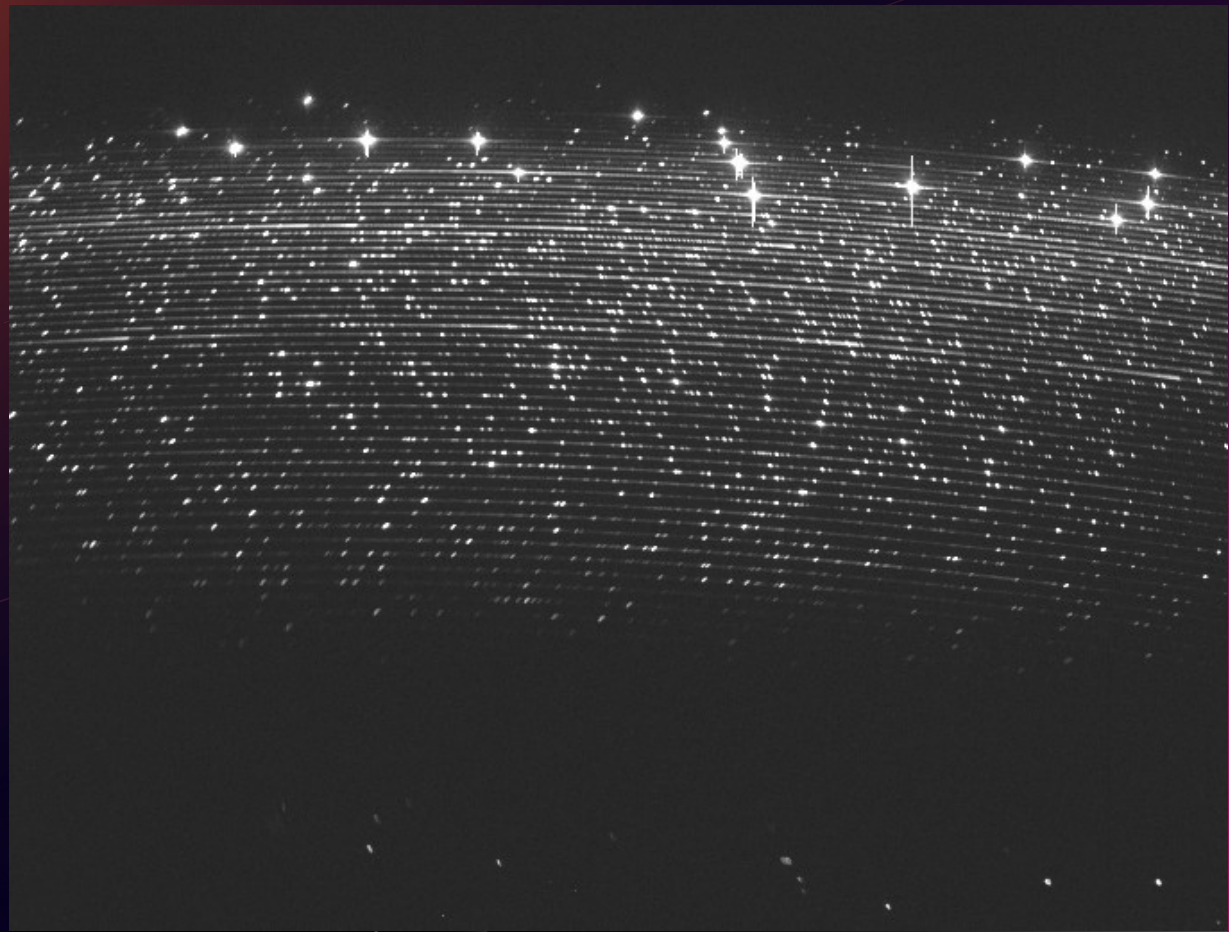
Modelling Flat Apertures



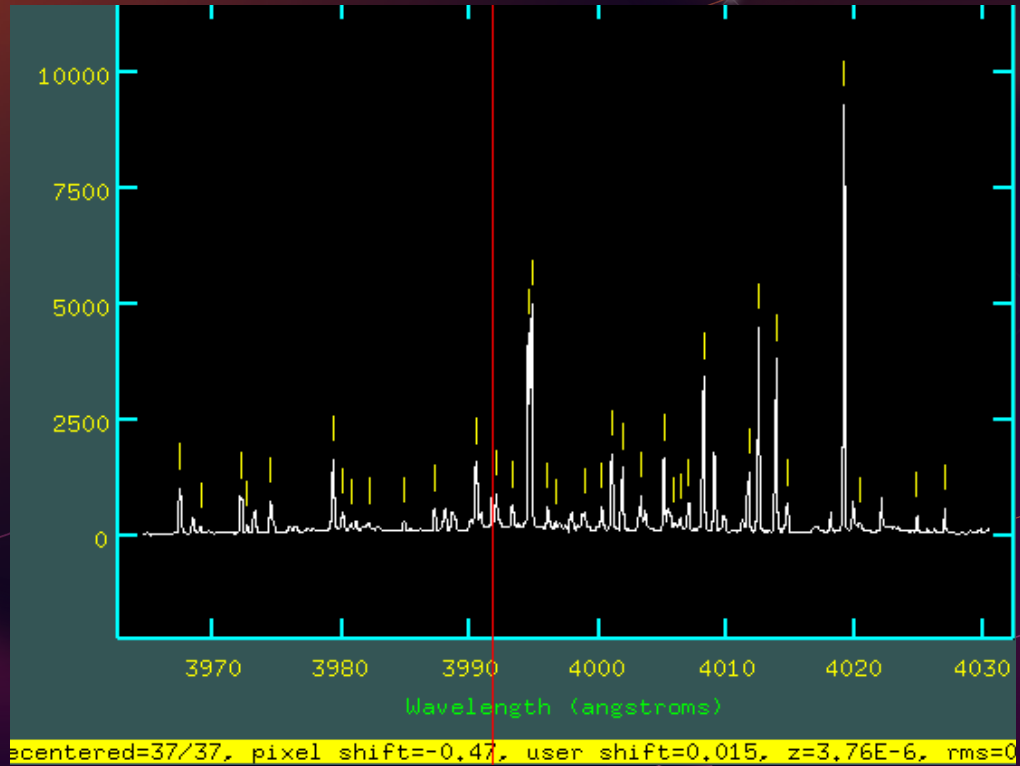
Selecting orders from bluer region

The Calibration Frame

- Iodine/ThAr Lamp
- To identify wavelengths in the spectrum.
- Used to compare with science frames
- Identification of wavelengths.



Wavelength Calibration



Object Parameters

IRAF

Image Reduction and Analysis Facility

PACKAGE = clpackage

TASK = oesred

More

(idfolde= idcomp_2307) folder name with identification database
(idencom= no) Identify features in spectrum for dispersion sol

OBJECT PARAMETERS

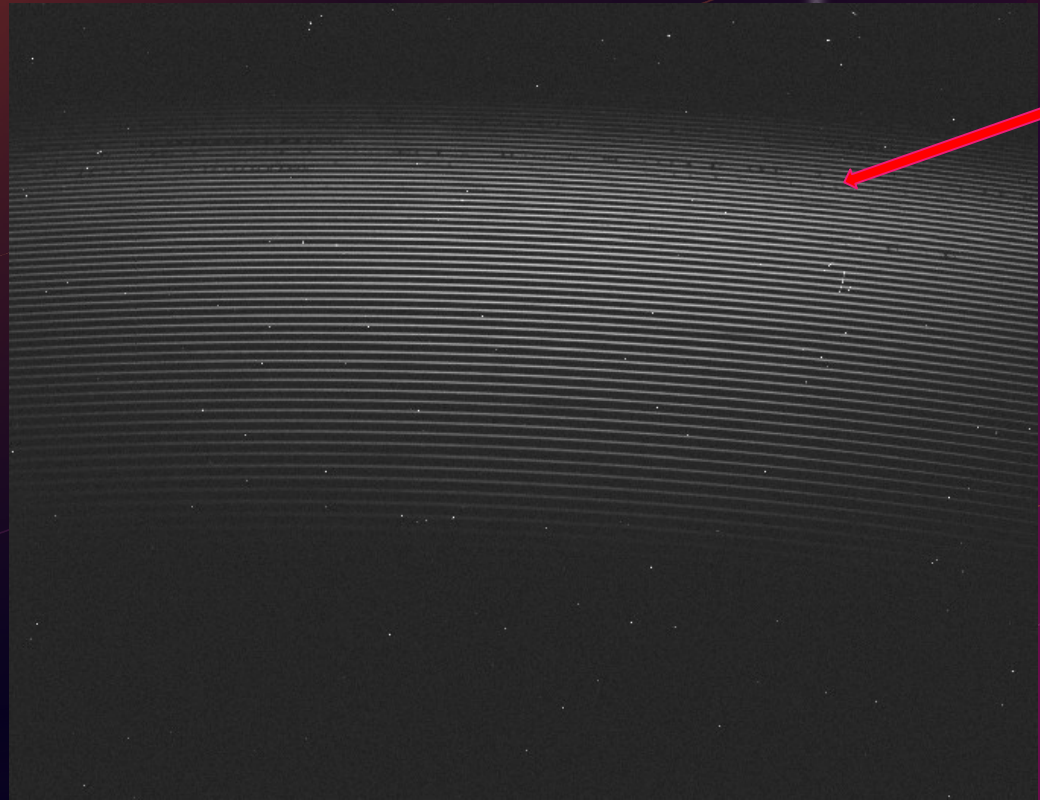
(trimob = no) Trim object?
(iftrimo= no) Use trim object?
(zerocor= yes) Apply zero level correction to object?
(crays = no) Remove cosmic rays?
(ifcrays= no) Use object with cosmic rays extraction?
(objecta= no) Extract object apertures?
(flatcor= no) Apply flat correction to object?
(helioco= no) calculate JD + RV-helio?
(idref = no) refer database identification to images?
(combine= no) combine NON-normalized spectra?
(rvcorr = no) Apply heliocentric correction to NON-normalized
(norm =) yes) normalize spectra?

More

ESC-? for HELP

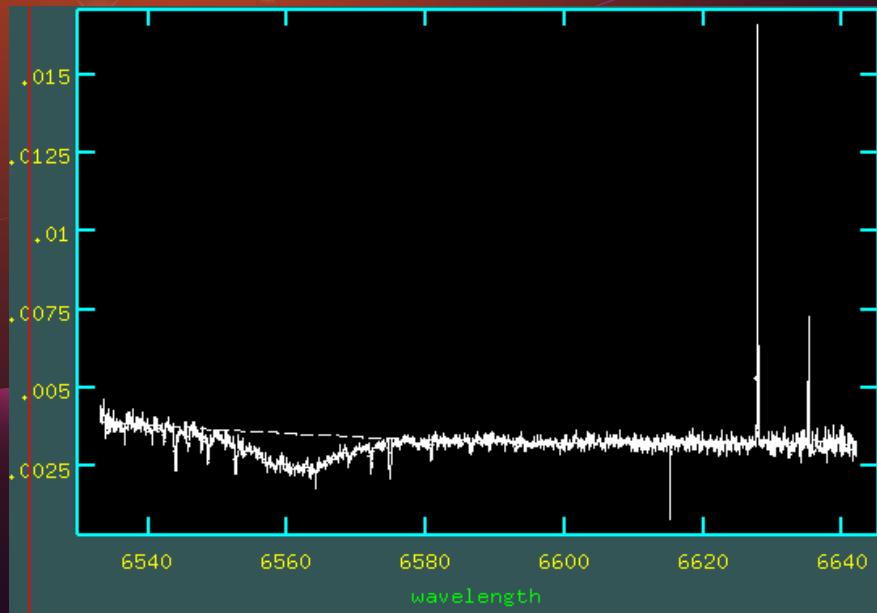
The Science Frame

- Raw spectrum of source
- Absorption lines can be seen
- B stars - presence of Balmer H lines and He lines



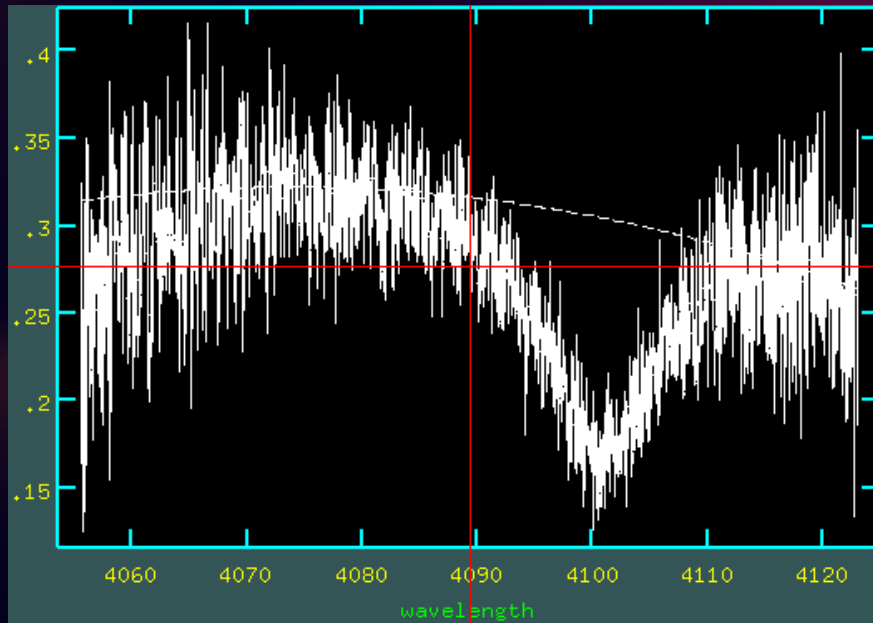
H-alpha

Normalisation of spectra



H-alpha and H-delta Balmer lines

● Merged after normalisation





Analysis

2 methods

```
graph TD; A[2 methods] --> B[Photometry]; A --> C[Spectroscopy]; B --> D[Spectral Energy Distribution fitting]; C --> E[Spectral line fitting];
```

Photometry

γ



Spectral Energy
Distribution fitting

Spectroscopy

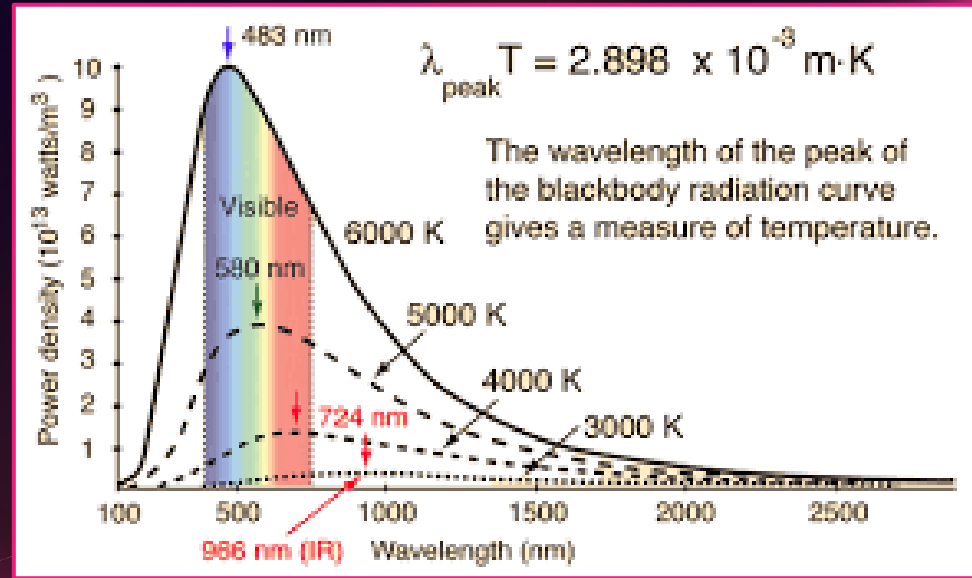


Spectral
line fitting

Spectral Energy Distribution (SED)

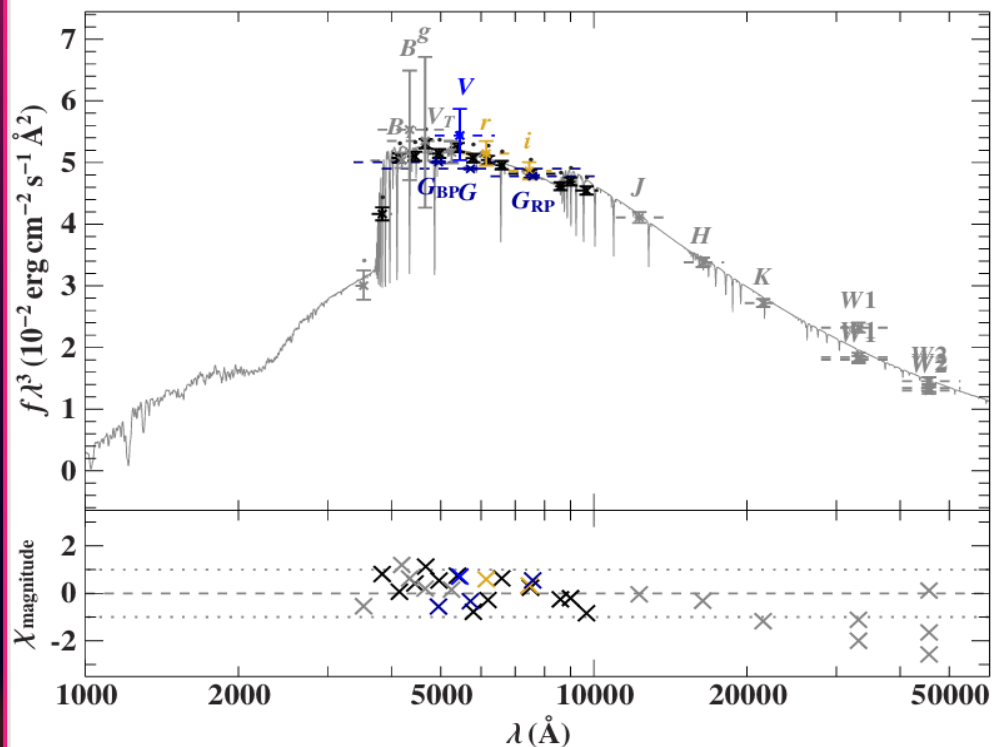
- SED = Energy flux density depending on the frequency (or wavelength)
- To study the physical properties:
 - Temperature
 - Composition
 - Luminosity

What is the relation between color(wavelength) and temperature?



Photometry results from GaiaDR3

HD226054



Object: HD226054	68% confidence interval
Color excess $E(B - V)$ from SFD (1998)	0.430 ± 0.029 mag
Color excess $E(B - V)$ from S&F (2011)	0.370 ± 0.025 mag
Color excess $E(B - V)$ from Stilism (Capitanio+ 2017)	0.166 ± 0.026 mag
Color excess $E(44 - 55)$	$0.088^{+0.014}_{-0.019}$ mag
Extinction parameter $R(55)$ (fixed)	3.02
Angular diameter $\log(\Theta)$ (rad)	$-10.025^{+0.018}_{-0.013}$
Parallax ϖ (<i>Gaia</i> , RUWE = 0.83, ZPO = -0.013 mas)	0.674 ± 0.026 mas
Distance d (<i>Gaia</i> , mode)	$(1.48 \pm 0.06) \times 10^3$ pc
Distance d (<i>Gaia</i> , median)	$(1.48 \pm 0.06) \times 10^3$ pc
Effective temperature T_{eff}	18000^{+1000}_{-1500} K
Surface gravity $\log(g)$ (cm s^{-2})	$4.2^{+0.4}_{-0.5}$
Microturbulence ξ (fixed)	0 km s^{-1}
Metallicity z (fixed)	0 dex
Helium abundance $\log(n(\text{He}))$ (fixed)	-1.05
Radius $R = \Theta/(2\varpi)$ (mode)	$3.09^{+0.17}_{-0.15} R_{\odot}$
(median)	$3.11^{+0.18}_{-0.16} R_{\odot}$
Mass $M = gR^2/G$ (mode)	$2.1^{+7.3}_{-1.6} M_{\odot}$
(median)	$6^{+9}_{-4} M_{\odot}$
Luminosity $L/L_{\odot} = (R/R_{\odot})^2(T_{\text{eff}}/T_{\text{eff},\odot})^4$ (mode)	930^{+220}_{-310}
(median)	910^{+270}_{-260}
Gravitational redshift $v_{\text{grav}} = GM/(Rc)$	$0.4^{+1.5}_{-0.4} \text{ km s}^{-1}$
Generic excess noise δ_{excess}	0.000 mag
Reduced χ^2 at the best fit	0.44

Fitting the spectra using SPAS

Star: /shared/spectroscopy/analysis28/analysis/DCN-LB4237_20240828.txt

$V_{rad} = 333$
 $T_{eff} = 0$
 $\log(g) = 0.00$
 $\log(\gamma) = +0.00$
 $V_{rot} = 0$
 $\zeta = 0$

V_{rad} 0
 T_{eff} 20000
 $\log(g)$ 3.5
 $\log(\gamma)$ -1.041
 V_{rot} 50
 ζ 0

Fit Err

Add Models: home/workshop/isis_grids/TLUSTY_BSTAR2006_norm_Z0.00_1

Check Models: _____

T_{eff} 00 21000 22000 23000 24000 25000 26000 27000 28000 29000 30000
 $\log(g)$ 3.0 3.25 3.5 3.75 4.0 4.25 4.5 4.75

Hd
 $\lambda_{X_0} = 4101.73$ R= 45000 V_{rad} Atmo

Hg
 $\lambda_{X_0} = 4340.46$ R= 45000 V_{rad} Atmo

Hb
 $\lambda_{X_0} = 4861.32$ R= 45000 V_{rad} Atmo

Ha
 $\lambda_{X_0} = 6562.80$ R= 45000 V_{rad} Atmo

He I 4922
 $\lambda_{X_0} = 4921.9313$ R= 45000 V_{rad} Atmo

He I 5016
 $\lambda_{X_0} = 5015.6783$ R= 45000 V_{rad} Atmo

FIT! ind. FIT!

Fitting the spectra using SPAS

Star: /shared/spectroscopy/analysis28/analysis/DCN-LB4237_20240828.txt

$V_{rad} = 75$
 $T_{eff} = 24632$
 $\log(g) = 4.05$
 $\log(y) = -1.04$
 $V_{rot} = 90$
 $zeta = 0$

V_{rad} 75
 T_{eff} 24638
 $\log(g)$ 4.0
 $\log(y)$ -1.041
 V_{rot} 90
 $zeta$ 0

Fit Err
Add Models: home/workshop/isis_grids/TLUSTY_BSTAR2006_norm_Z0.00_1
Check Models:

T_{eff} 00 21000 22000 23000 24000 25000 26000 27000 28000 29000 30000
 $\log(g)$ 3.0 3.25 3.5 3.75 4.0 4.25 4.5 4.75

He I 4472 $\lambda_{X_0} = 4471.4802$ R= 45000 V_{rad} Atmo

Hg $\lambda_{X_0} = 4340.46$ R= 45000 V_{rad} Atmo

Hb $\lambda_{X_0} = 4861.32$ R= 45000 V_{rad} Atmo

Ha $\lambda_{X_0} = 6562.80$ R= 45000 V_{rad} Atmo

He I 4922 $\lambda_{X_0} = 4921.9313$ R= 45000 V_{rad} Atmo

He I 5016 $\lambda_{X_0} = 5015.6783$ R= 45000 V_{rad} Atmo

FIT! ind. FIT!

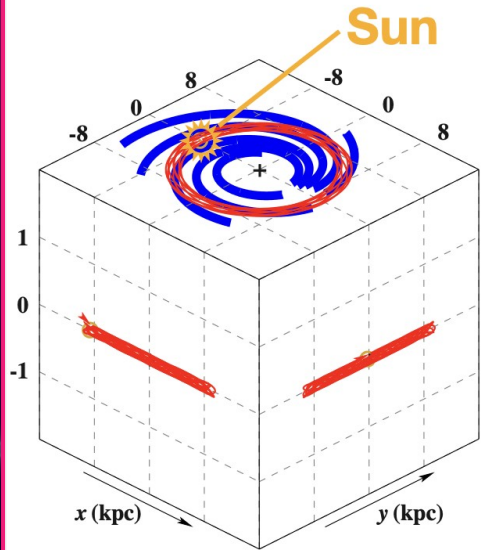
V_{rad}
 v_{rot}

Teff

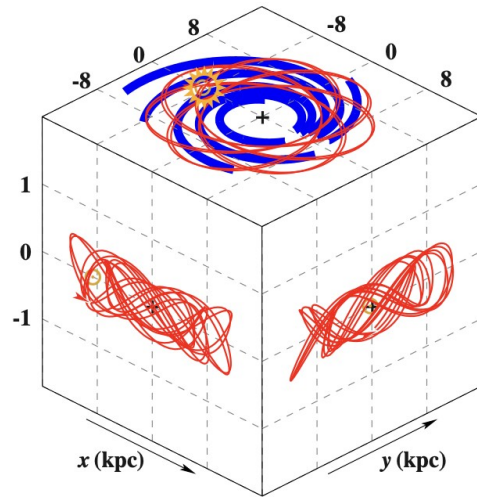
Log g

Log y

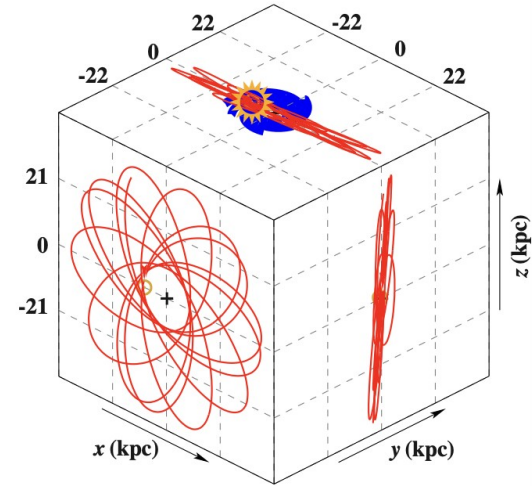
Orbit calculation using ISIS



BD+75 325
thin disk

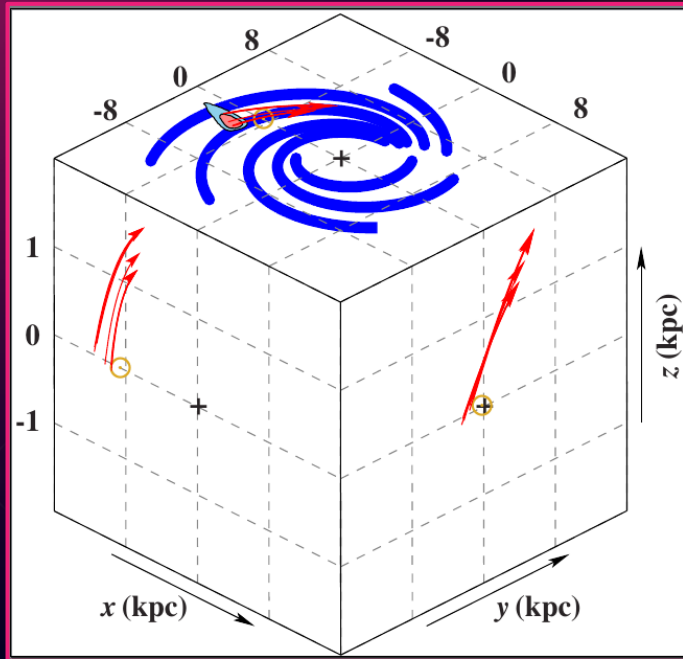


BD+37 442
thick disk

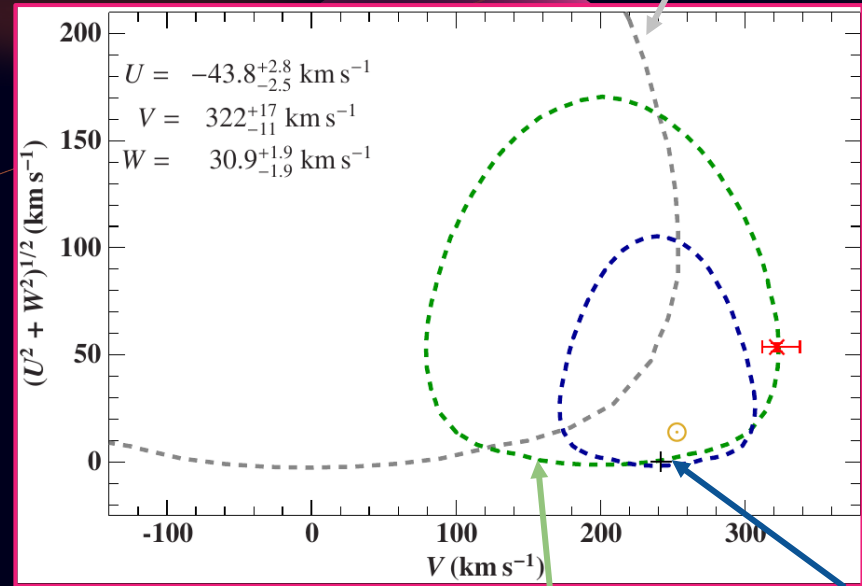


CBS 461
halo

The example of LB 4237



- Trajectory of the star in the galactic plane



Toomre diagram

Thin disk

Thick disk

Halo

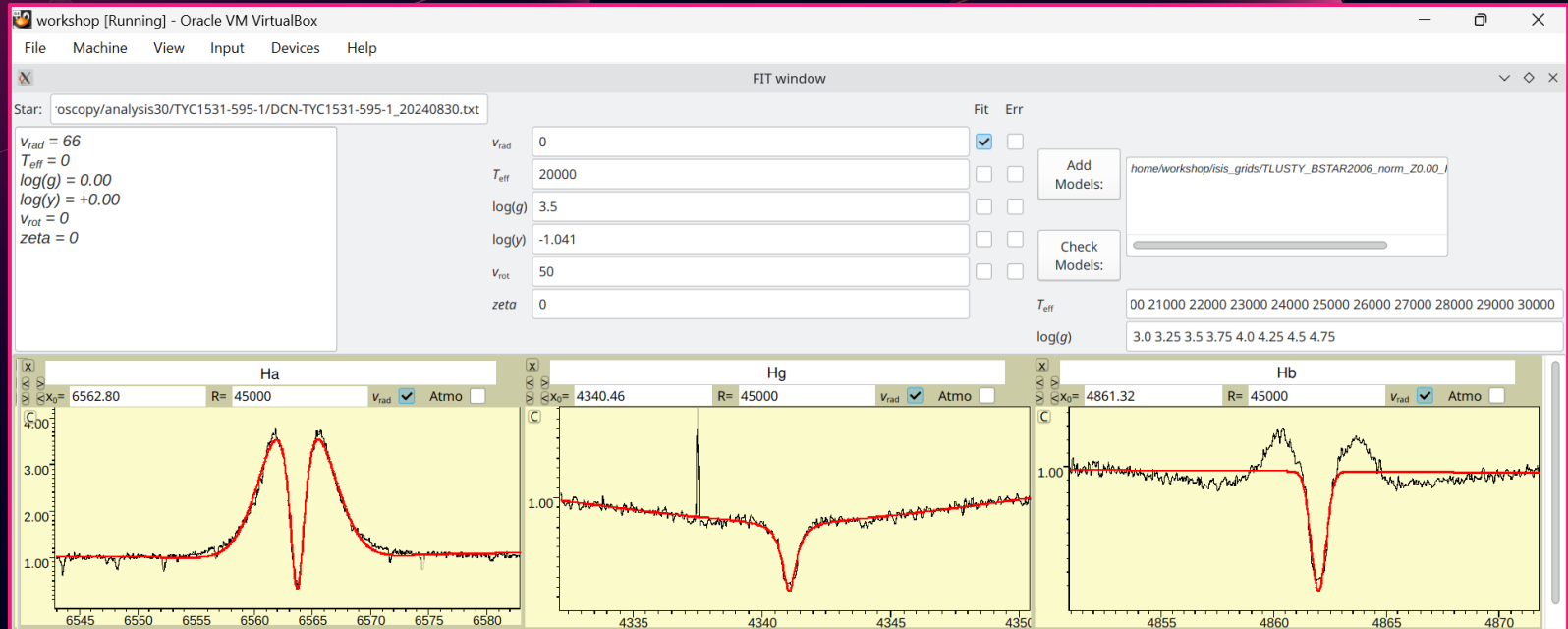
Kinematics results :

	x	y	z	r	u_x	u_y	u_z	u_{Grf}	$u_{\text{Grf}} - u_{\text{esc}}$	P_b	x_d	y_d	z_d	r_d	$u_{x,d}$	$u_{y,d}$	$u_{z,d}$	$u_{\text{Grf},d}$	u_{ej}	τ_{flight}	
	(kpc)				(km s^{-1})					(%)	(kpc)				(km s^{-1})					(Myr)	
Model I:																					
LB4237	-6.47	4.4	1.34	7.90	218	240	30.9	326	-294	100	-9.8	-2.0	0.0	10.1	68	266	71	286	140	24.4	
Stat.	+0.41	+1.0	+0.29	+0.30	+39	+14	+1.9	+17	+21	...	+0.6	+0.6	+0.1	+1.0	+35	+7	+5	+11	+21	+3.8	
	-0.30	-0.7	-0.20	-0.13	-26	-17	-1.9	-10	-11	...	-1.1	-0.5	-0.2	-0.6	-22	-6	-4	-8	-14	-2.9	

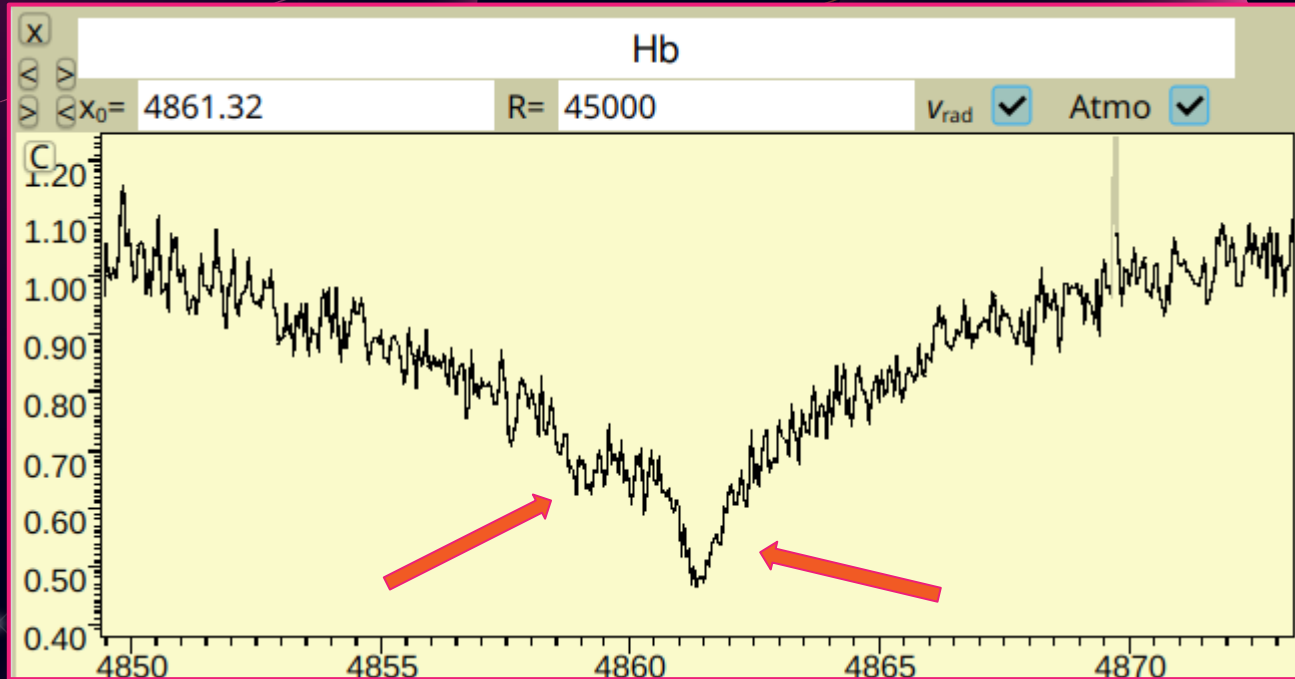
The background is a dark blue space scene. It features several glowing planets of different sizes and colors, including purple, pink, and orange. Numerous small, bright stars are scattered across the sky. Two thin, parallel white lines run horizontally across the image, one near the top and one near the bottom. The text 'Exceptional Cases' is centered in the middle of the image in a white, sans-serif font.

Exceptional Cases

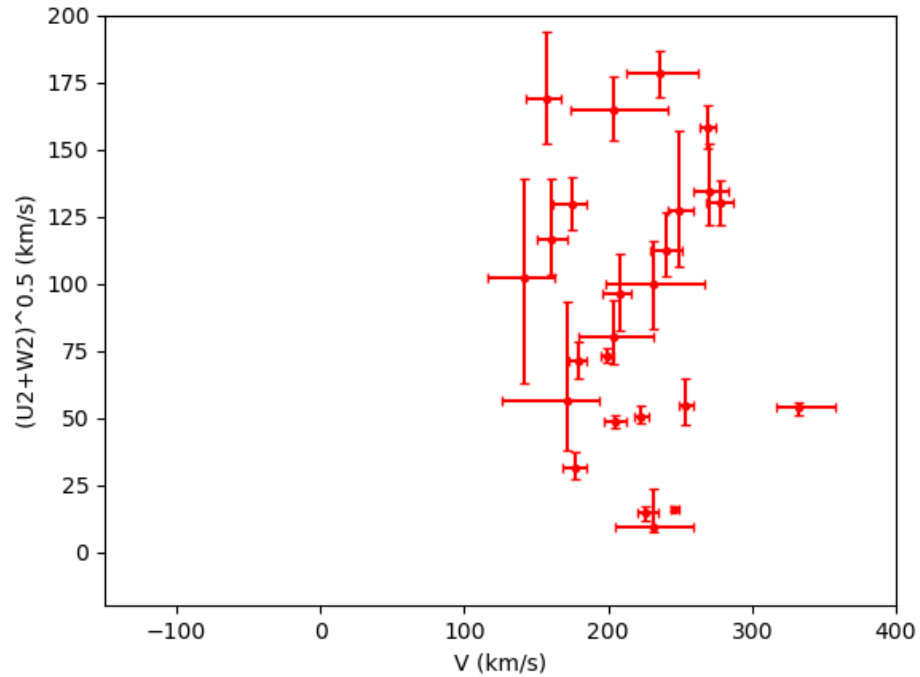
Star with Rotational Disc:



Binary system (TYC 3252-206-1):



Toomre Plot



Kinematics of Stars

Where do these runaway stars come from?

- Tracing back the stars to their possible open cluster(s)

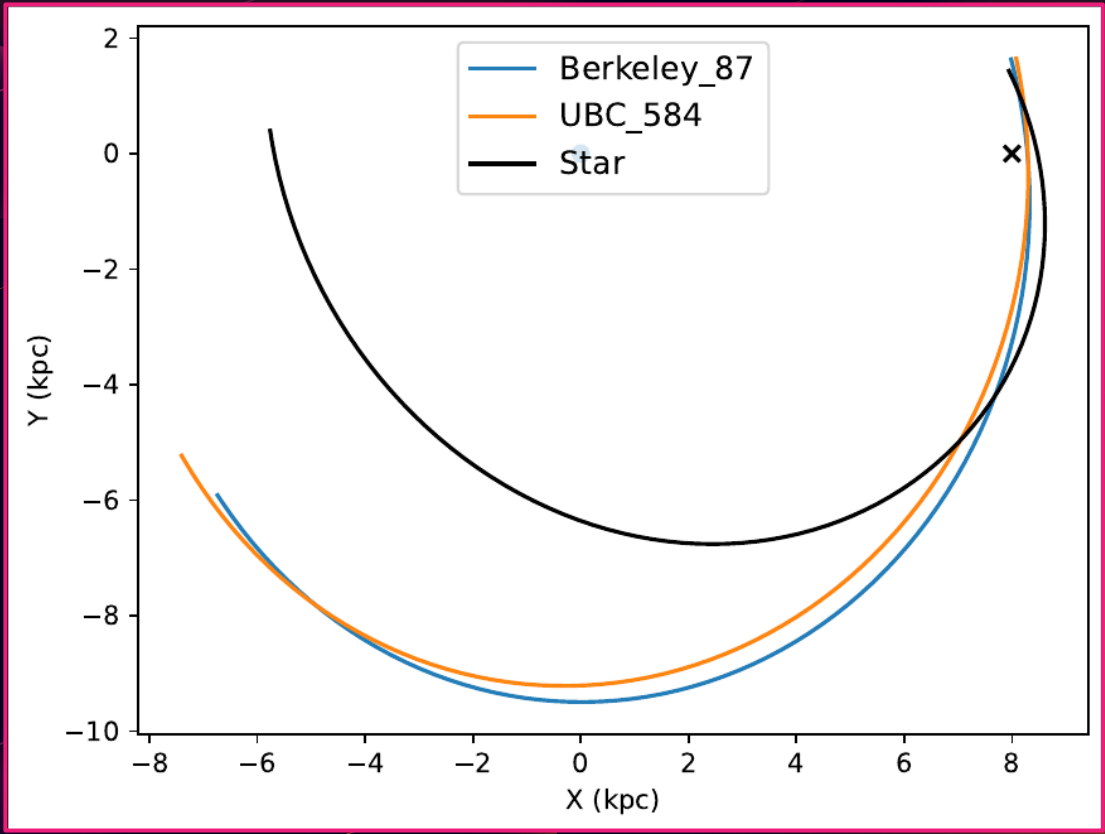
```
15
16
17 ra=5.7405
18 dec=39.6510417
19 rv= 7
20 name="TYC2787-1539-1"
21 #####
22
23 ts= np.linspace(0,-100.,100000)*units.Myr
24 orbits=[]
25 star_data= {
26     'parallax': [],
27     'pmra': [],
28     'pmdec': [],
29     'ra': [],
30     'dec': [],
31     'rv': []
```

	A	B	C	D	E	F
1	recno	Name	ID	AllNames	Type	CST
2	1	ADS_16795		1 ADS_16795	http://vizier	6.832199
3	2	AH03_J0748-26.9		2 AH03_J0748-26.9	http://vizier	11.58552
4	3	ASCC_5		3 ASCC_5,M	http://vizier	8.316422
5	4	ASCC_6		4 ASCC_6,M	http://vizier	19.25857
6	5	ASCC_9		5 ASCC_9,Th	http://vizier	17.56655
7	6	ASCC_11		6 ASCC_11,M	http://vizier	27.89349
8	7	ASCC_12		7 ASCC_12,M	http://vizier	19.41707
9	8	ASCC_13		8 ASCC_13,M	http://vizier	11.41564
10	9	ASCC_14		9 ASCC_14,M	http://vizier	3.353328
11	10	ASCC_18		10 ASCC_18,M	http://vizier	5.076724
12	11	ASCC_19		11 ASCC_19	http://vizier	9.307117
13	12	ASCC_20		12 ASCC_20,C	http://vizier	8.64395
14	13	ASCC_21		13 ASCC_21	http://vizier	11.05617
15	14	ASCC_23		14 ASCC_23,F	http://vizier	21.33467
16	15	ASCC_24		15 ASCC_24,F	http://vizier	5.833571
17	16	ASCC_27		16 ASCC_27,M	http://vizier	8.285251
18	17	ASCC_28		17 ASCC_28,M	http://vizier	3.510938
19	18	ASCC_29		18 ASCC_29,M	http://vizier	14.47895

Where do these runaway stars come from?

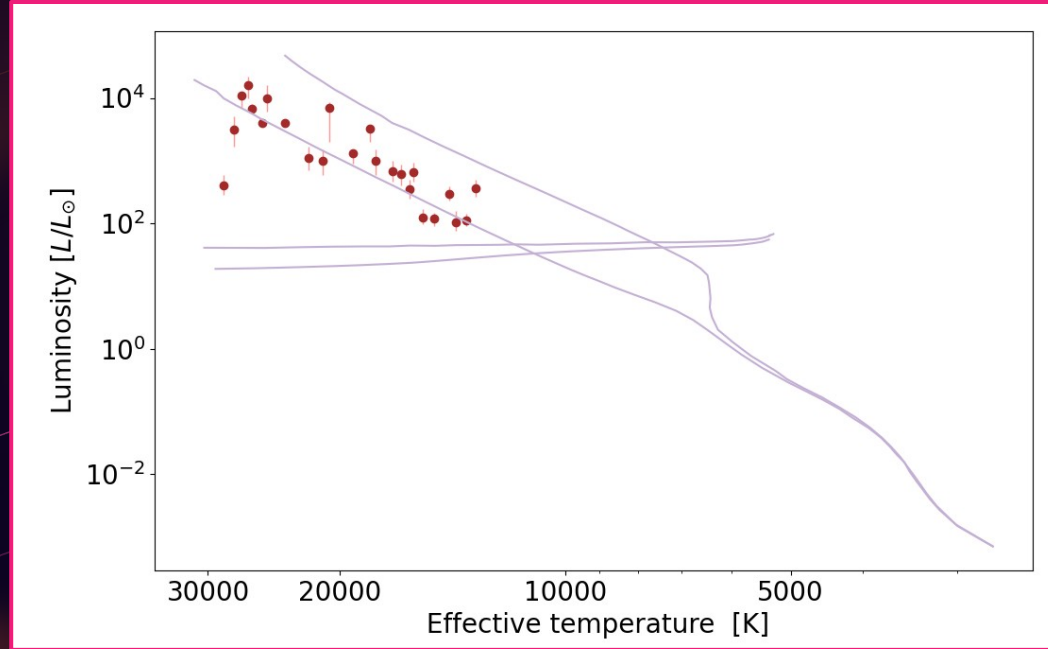
- Here: HD226054 → 2 possible clusters:

	ToF	Age
Berkeley_87:	-3.092 Myr	
	$2.89e+06$	
UBC_584:	-3.030 Myr	
	$4.97e+06$	

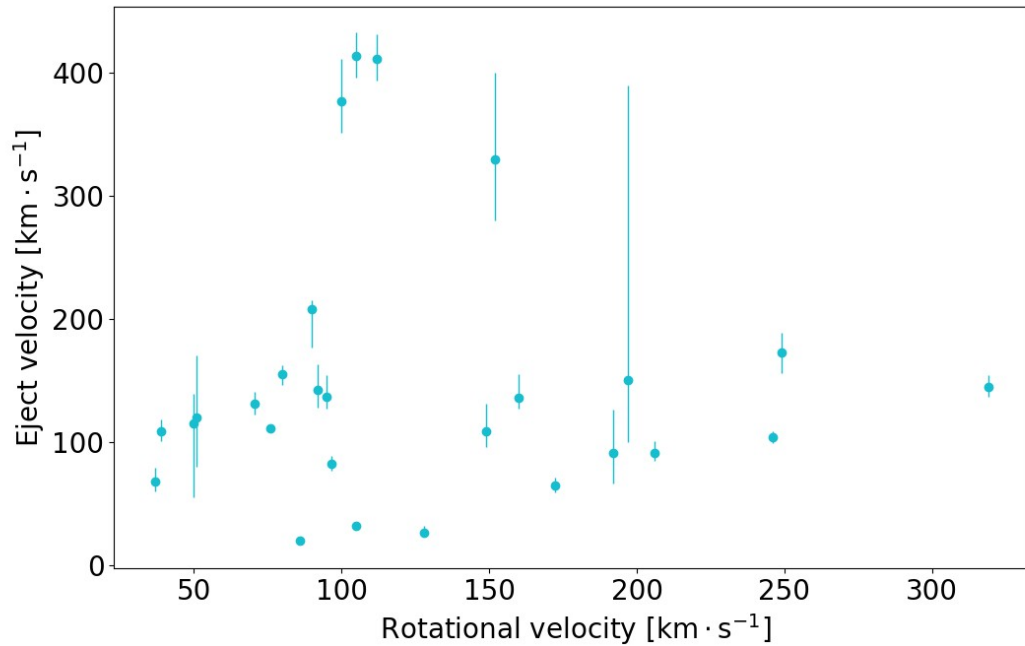


HR diagram

- Most on the MS
- Most T between 25000 K and 15000 K
- Most L between $100 L_{\odot}$ and 10000
- L_{\odot}
- None on the Horizontal Branch



Evolution of the ejection velocity depending on the rotational velocity

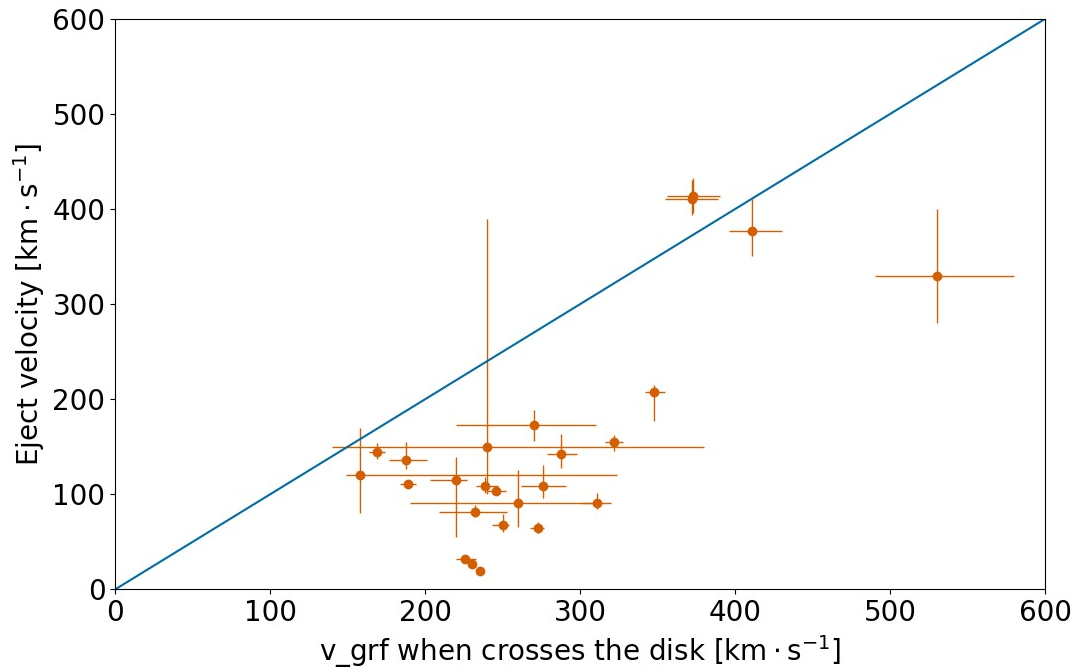


● Ejection velocity does not influence the rotational velocity for our sources

→ B-type stars

→ Not strongly bound systems

Evolution of the ejection velocity depending on v_{grf} from disk



- V_{grf} = the velocity in the ref frame of the galaxy with the galactic center as origin when it crosses the disk
- Star is in the galactic disk if $v_{\text{eject}} > v_{\text{grf}_d}$

The background is a dark space-themed gradient with several large, semi-transparent planets in shades of purple, blue, and orange. Numerous small, bright stars are scattered across the scene. Two thin white horizontal lines are positioned near the top and bottom of the image.

4. Conclusions

- ❖ Observed 45 stars in 4 nights
- ❖ Identified at least 10 runaway stars
- ❖ Determined the main parameters of the stars: T_{eff} , L , $\log g$, v_{ejc} , v_{rot} ...
- ❖ Identified at least 3 binaries and a disk around a star
- ❖ Found parent open cluster candidates for some stars
- ❖ Traced back the most probable trajectory of our star sample
- ❖ NO trend observed between the ejecting velocity and rotational velocity
- ❖ Our star's sample are still in the galactic disk → not ejected from the disk

Thank you for your
attention !