Main Sequence Runaway Project

Research Workshop on Evolved Stars

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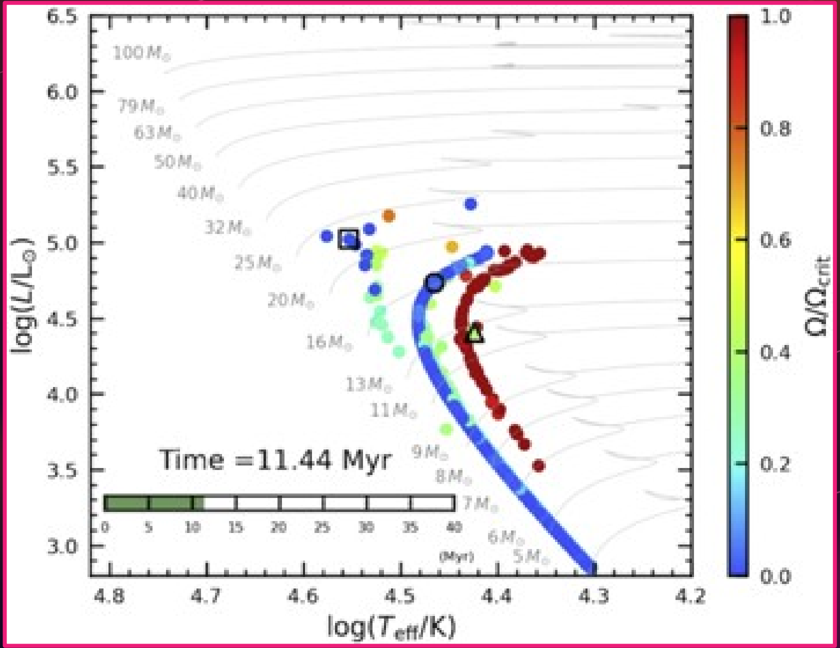
Scientific background

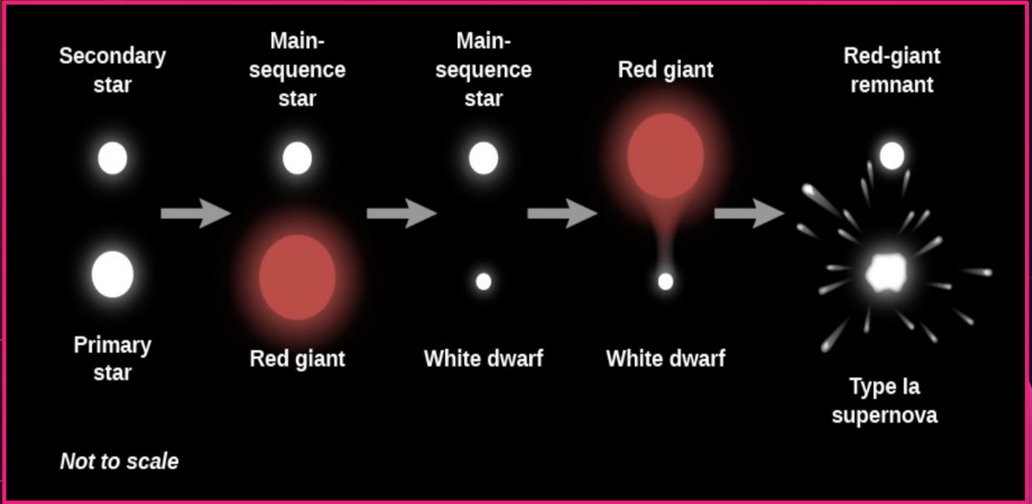
Binary evolution

- 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

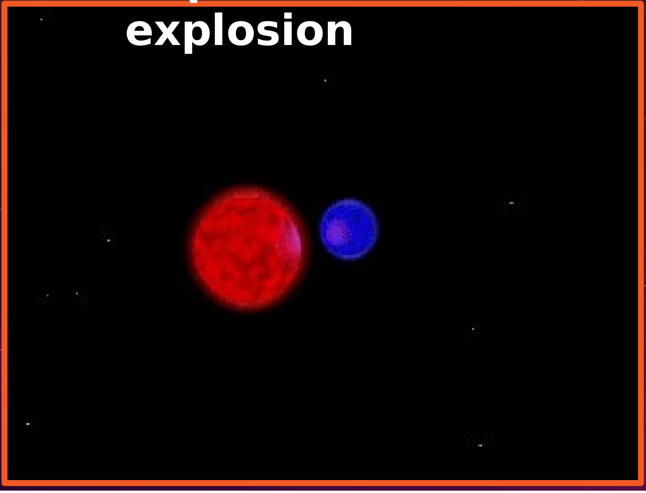
- Characterised by their ejection velocities
- Velocity vectors point away from the disk

- Vs > 30 km/s (Runaways)
- Vesc > Vs >> 30 km/s (Hyper-runaways)
- Vs > Vesc (Hyper-velocity stars)

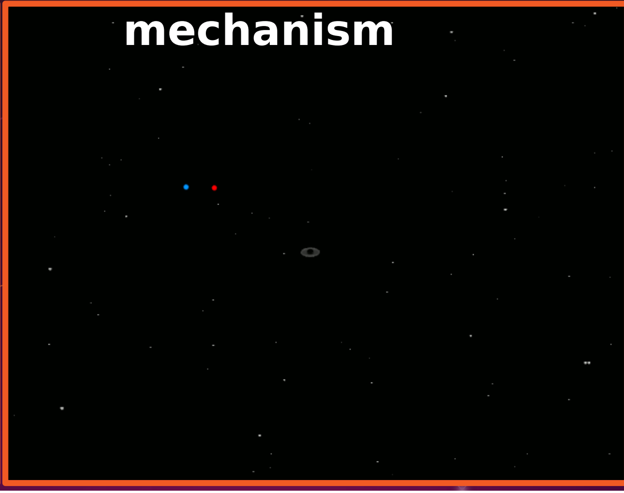
How are they generated?

Dynamical ejection

Supernova explosion

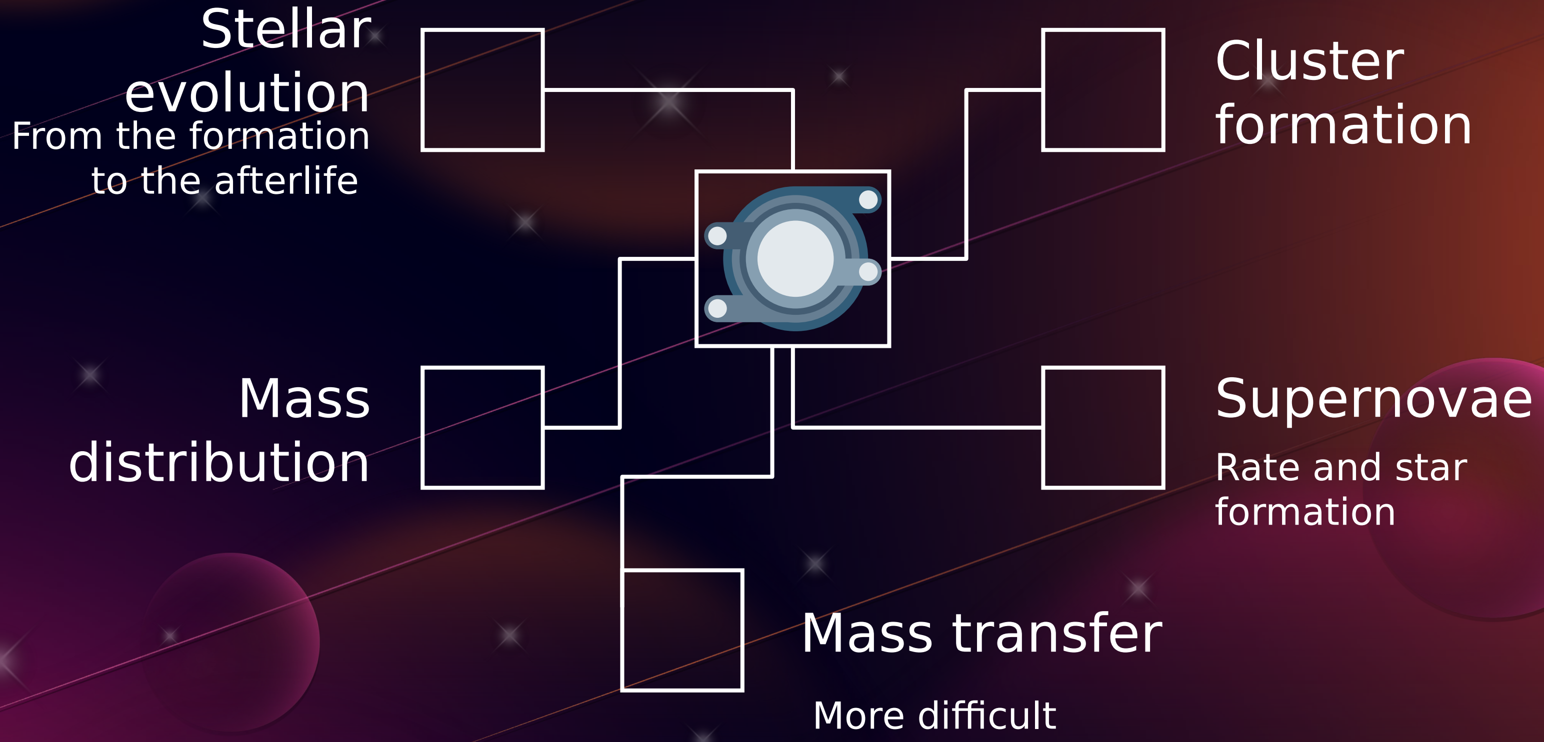


Hills mechanism



Credit: Andreas Irrgang

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

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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, rtc.

	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

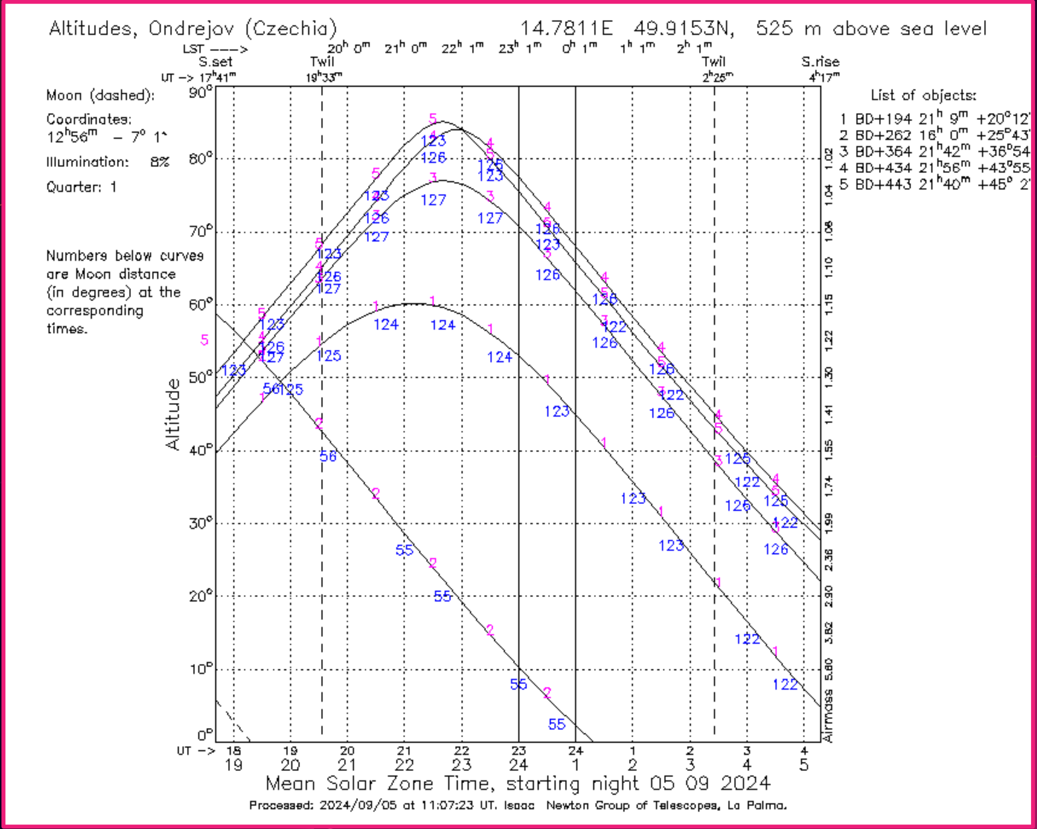
Sample Gaia DR3 data for selected sources (Topcat)

Target Selection: Visibility Charts

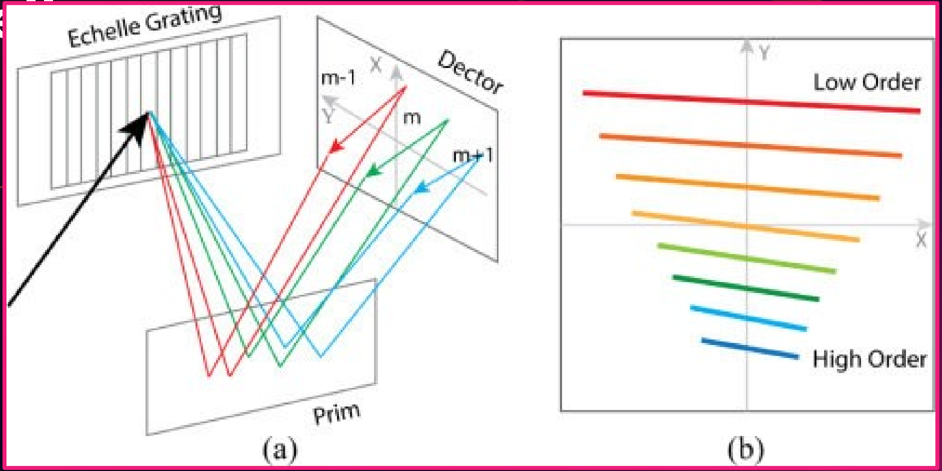
- Visibility checked using catserver.
- Target selection and order adjusted accordingly.
- ra and dec constraints based on location

45 spectra of 44 targets

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



The Perek Telescope and the Eche
spectrograph



Credit: Shen et al. 2018

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

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

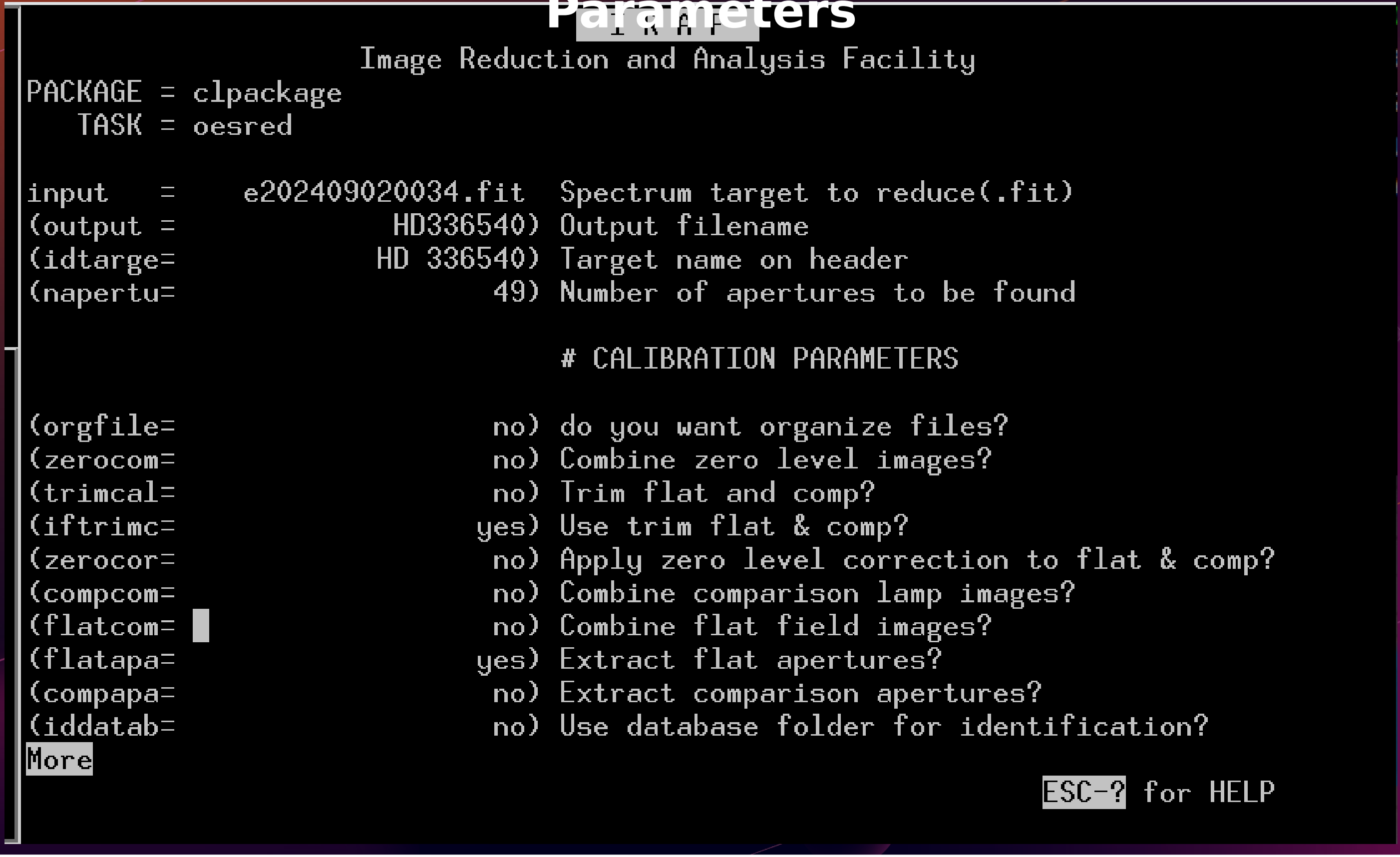
❖ Trimming of the object

❖ Cosmic rays removal

❖ JD and heliocentric correction

❖ Normalization and Merging

IRAF display: Bias, Flats and Comparison Parameters

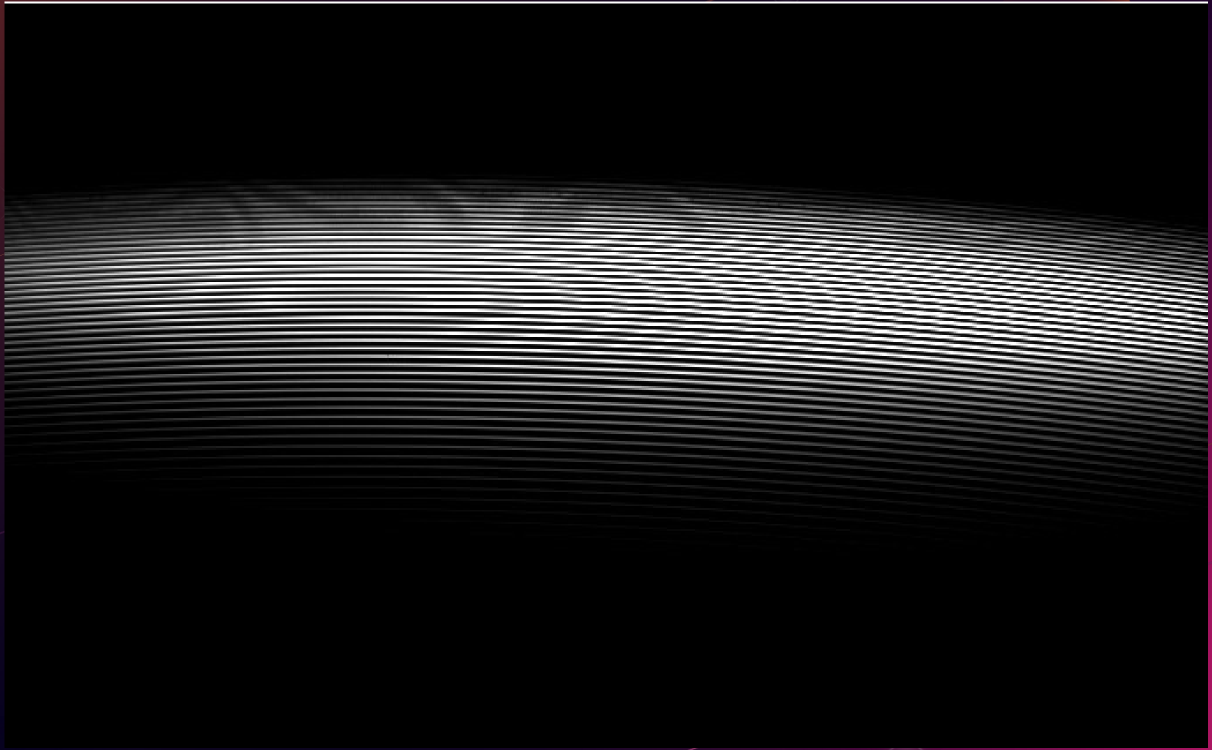


The Bias (Zero) Frame

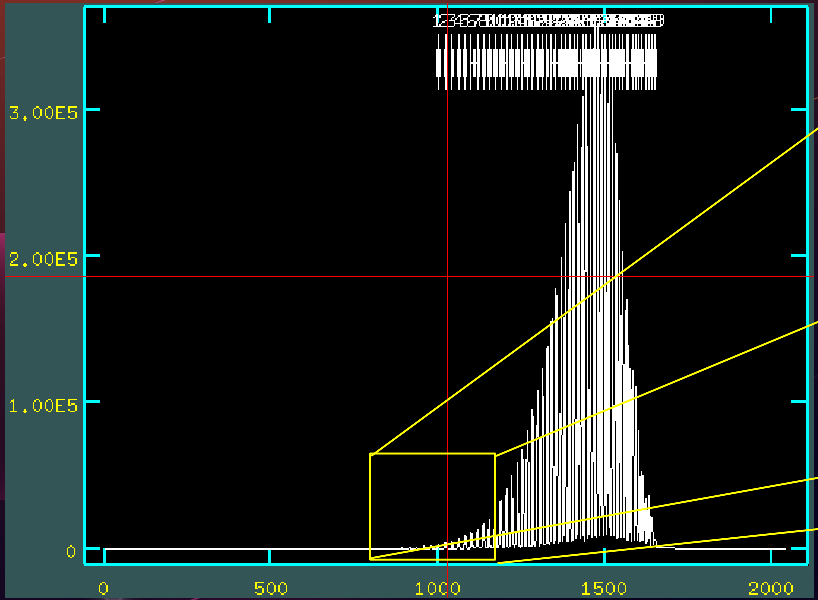
- Shortest possible exposure
- Camera readout noise
- Bias correction
- ADC - charge to digital value
- Later applied to flat, calibration and science frames.

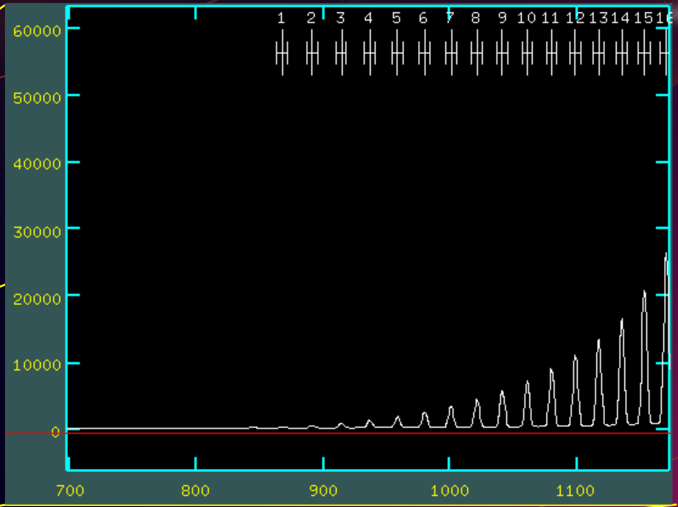
The Flat Frames

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



Modelling Flat Apertures

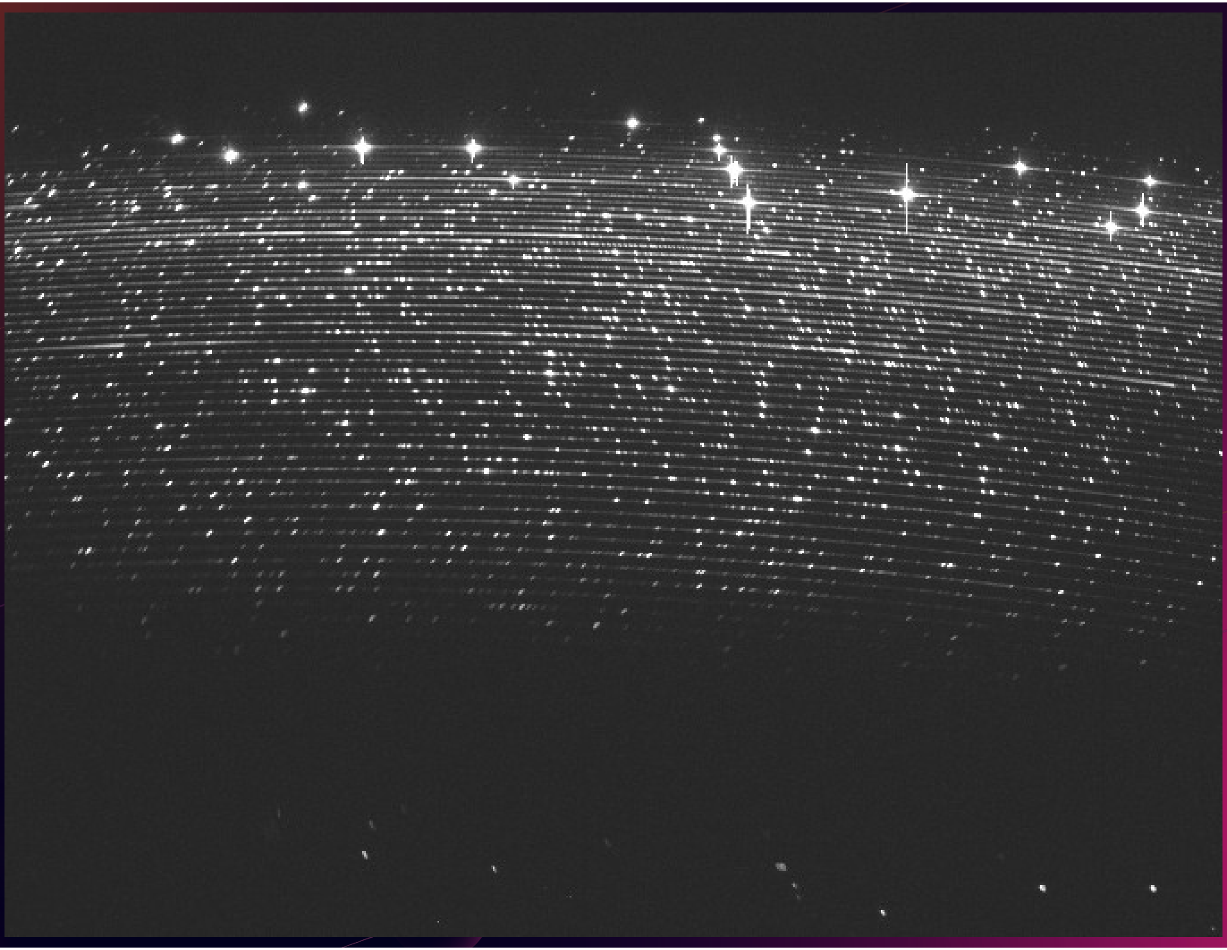




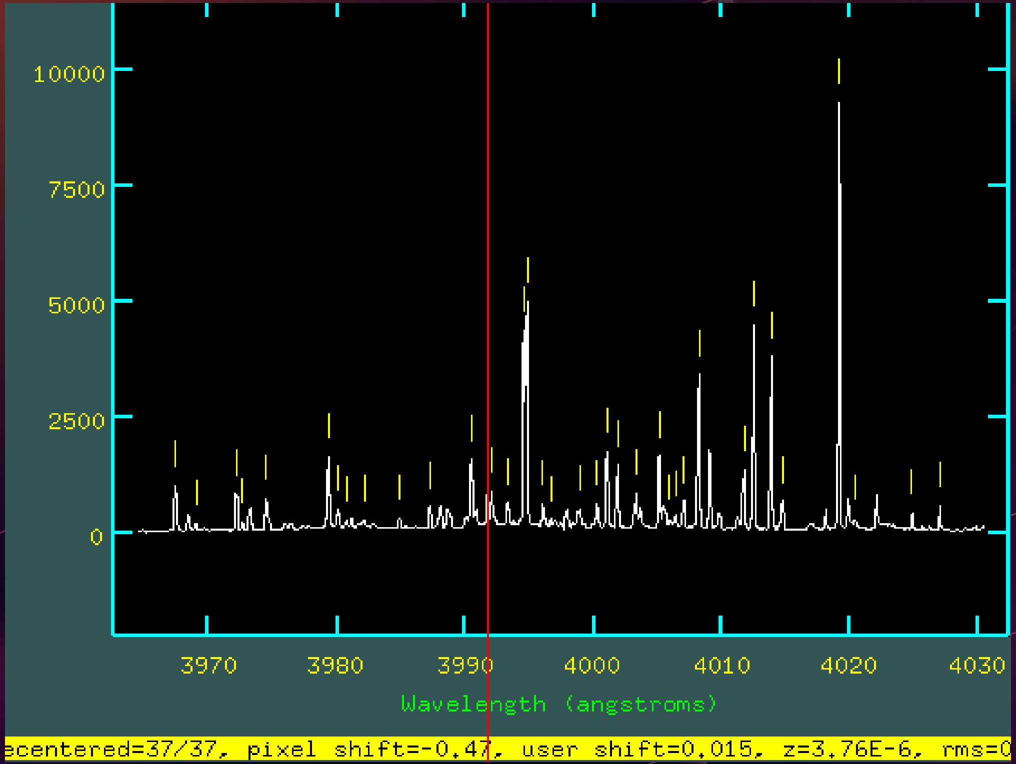
Selecting orders from bluer region

The Calibration Frame

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



Wavelength Calibration

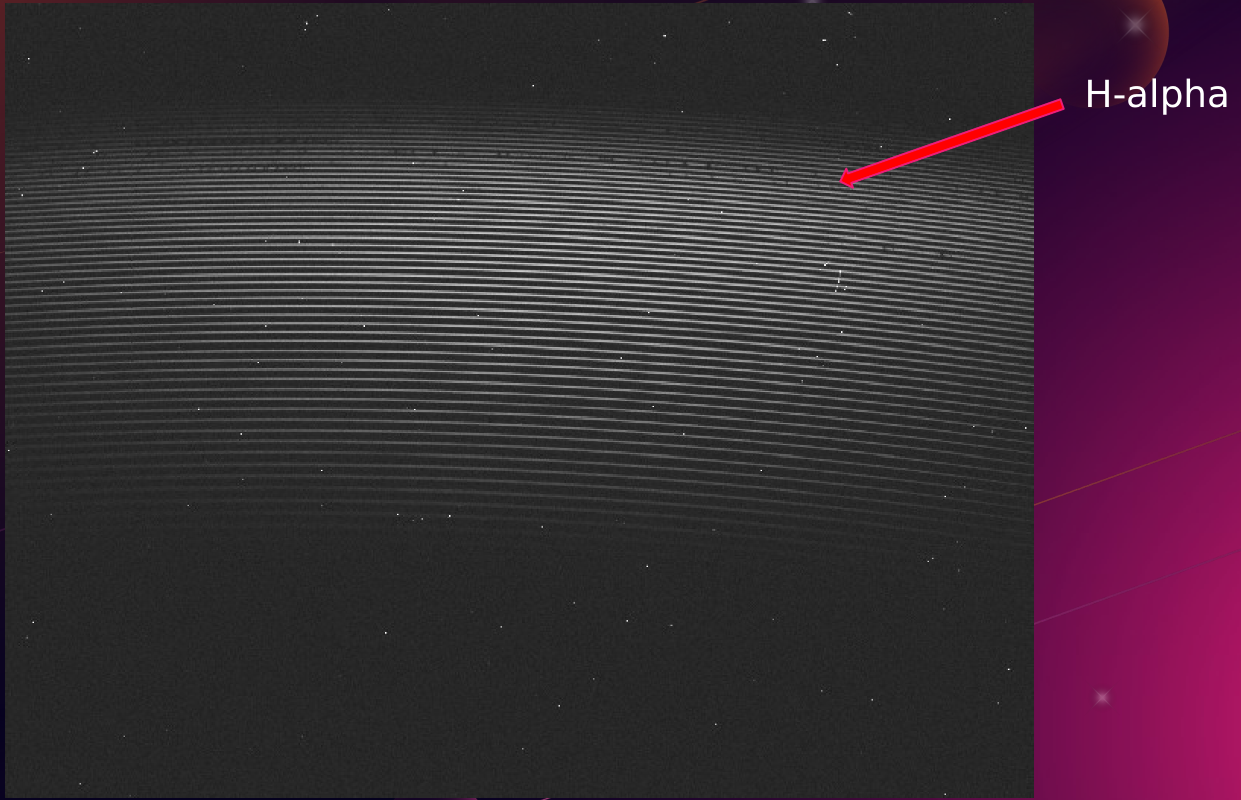


Object Parameters

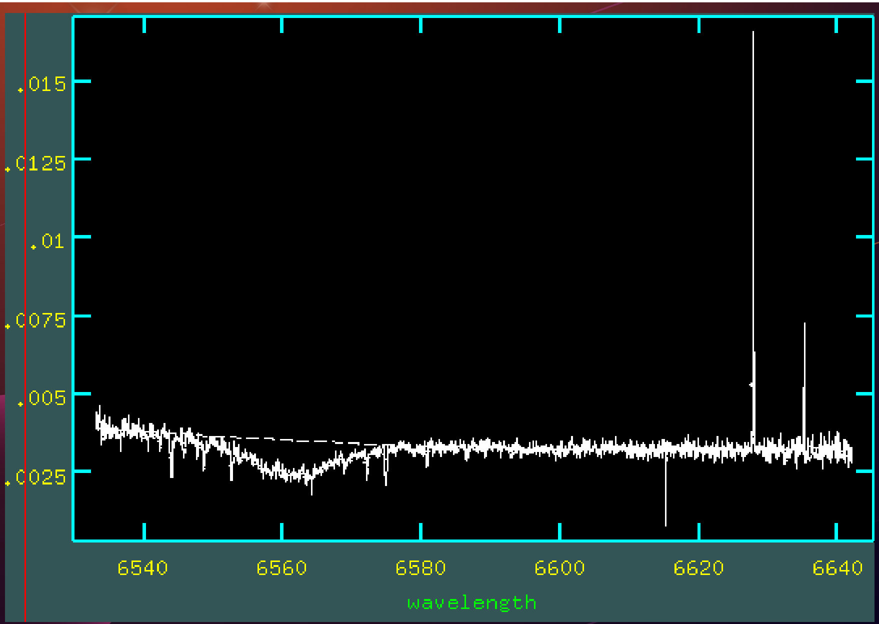
```
                              I R A F
                Image Reduction and Analysis Facility
PACKAGE = clpackage
   TASK = oesred
More
(idfolde=           idcomp_2307) folder name with identification database
(idencom=                    no) Identify features in spectrum for dispersion sol

                                 # 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
```

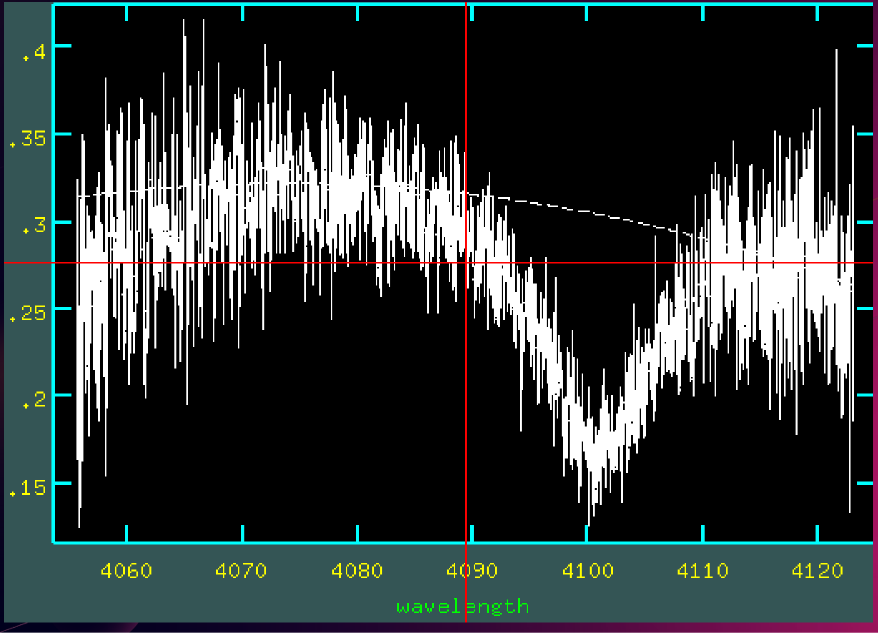
The Science Frame

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



Normalisation of spectra





H-alpha and H-delta Balmer lines

- Merged after normalisation

Analysis

2 methods

Photometry

Spectral Energy Distribution fitting

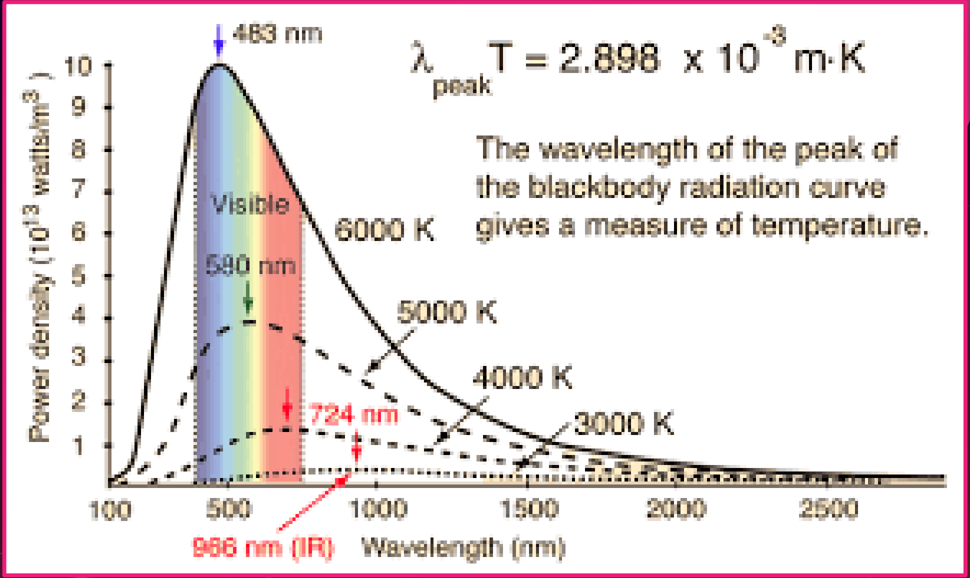
Spectroscopy

Spectral line fitting

Spectral Energy Distribution (SED)

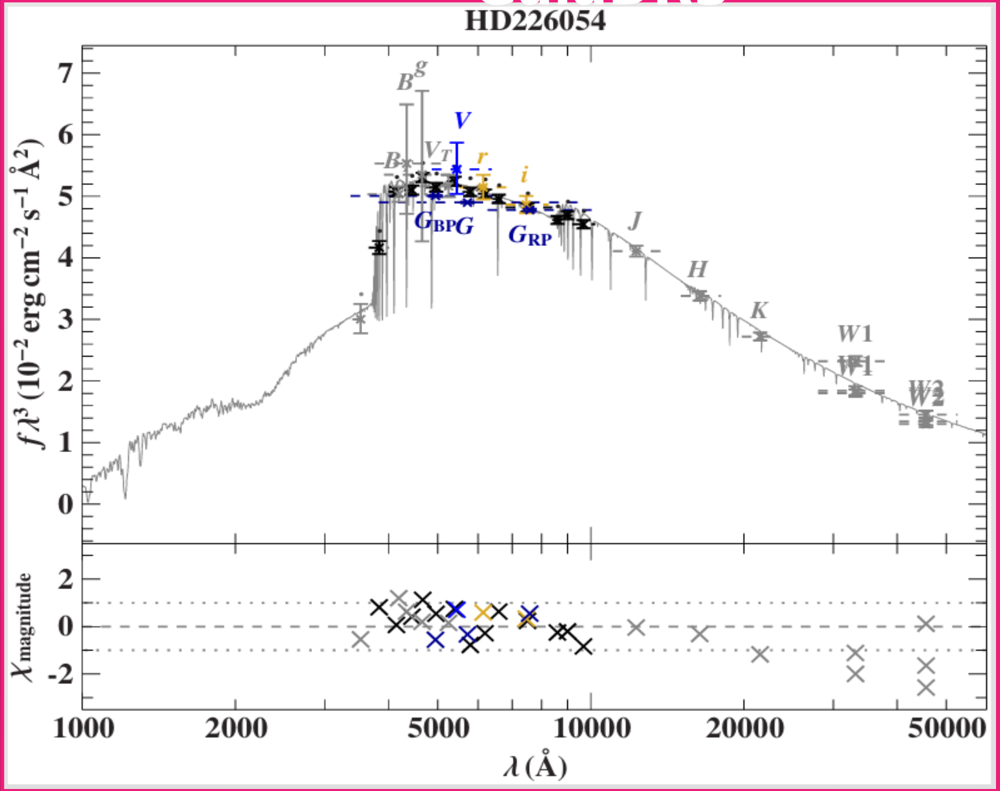
- SED = Energy flux density depending on the frequency (or wavelength)

- To study the physical properties:
  - Temperature
  - Composition
  - Luminosity



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

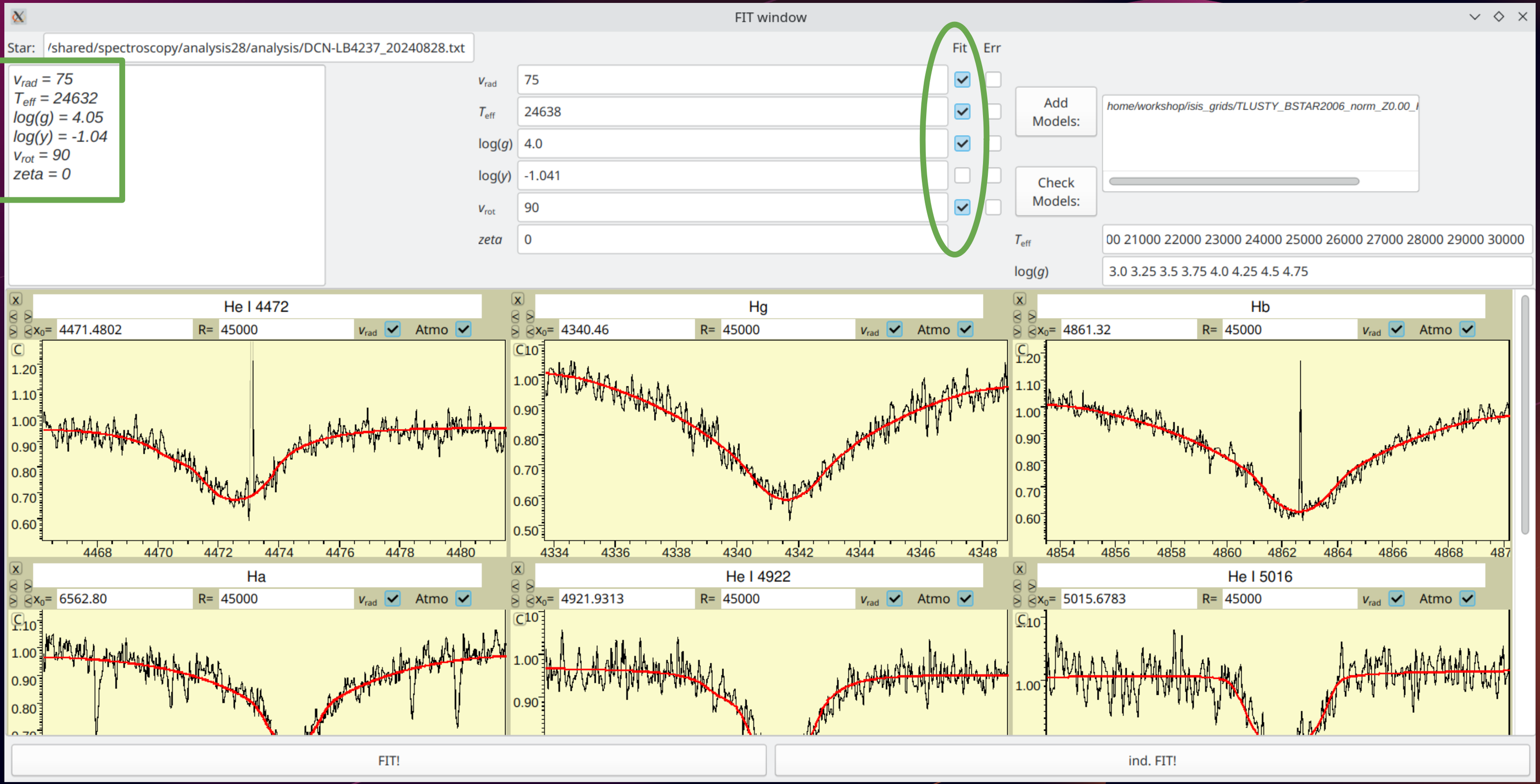
Photometry results from GaiaDR3



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 $\log(\Theta\,(\text{rad}))$	$-10.025^{+0.018}_{-0.013}$
Parallax ϖ (*Gaia*, RUWE = 0.83, ZPO = −0.013 mas)	0.674 ± 0.026 mas
Distance d (*Gaia*, mode)	$(1.48 \pm 0.06) \times 10^3$ pc
Distance d (*Gaia*, median)	$(1.48 \pm 0.06) \times 10^3$ pc
Effective temperature T_{eff}	18000^{+1000}_{-1500} K
Surface gravity $\log(g\,(\text{cm s}^{-2}))$	$4.2^{+0.4}_{-0.5}$
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 $v_{\text{grav}} = GM/(Rc)$	$0.4^{+1.5}_{-0.4}$ km s^{-1}
Generic excess noise δ_{excess}	0.000 mag
Reduced χ^2 at the best fit	0.44

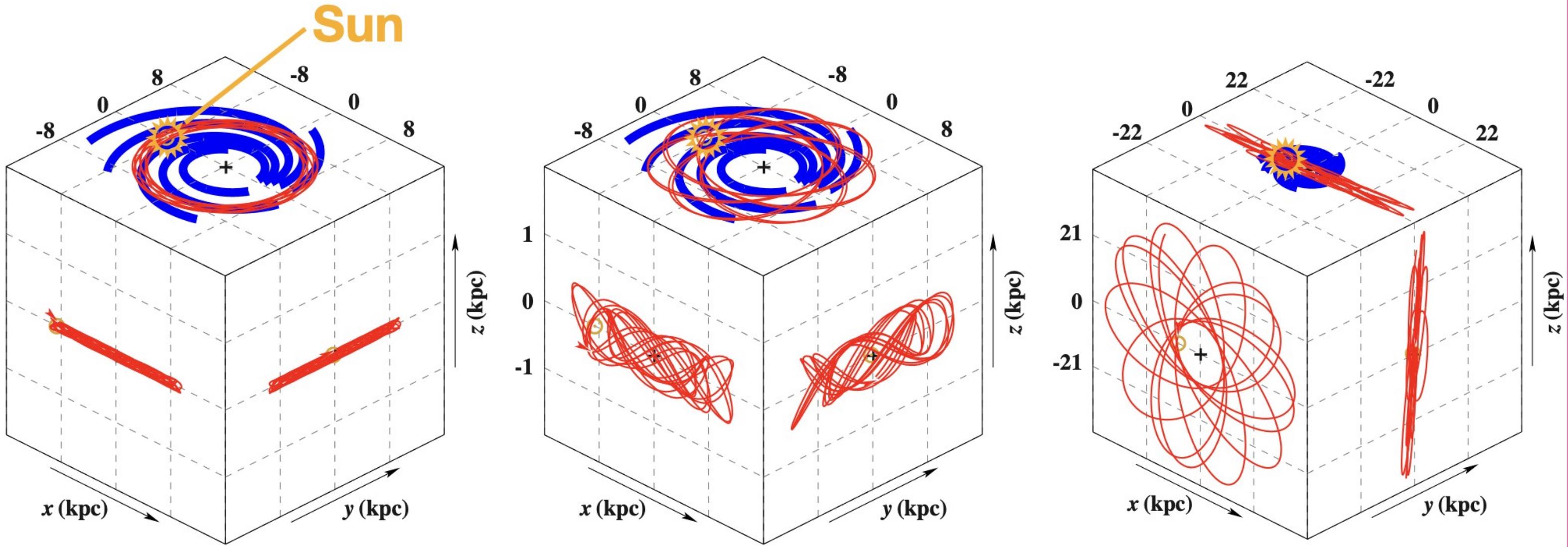
Fitting the spectra using SPAS

Fitting the spectra using SPAS



V_rad v_rot **Teff** **Log g** **Log y**

Orbit calculation using ISIS

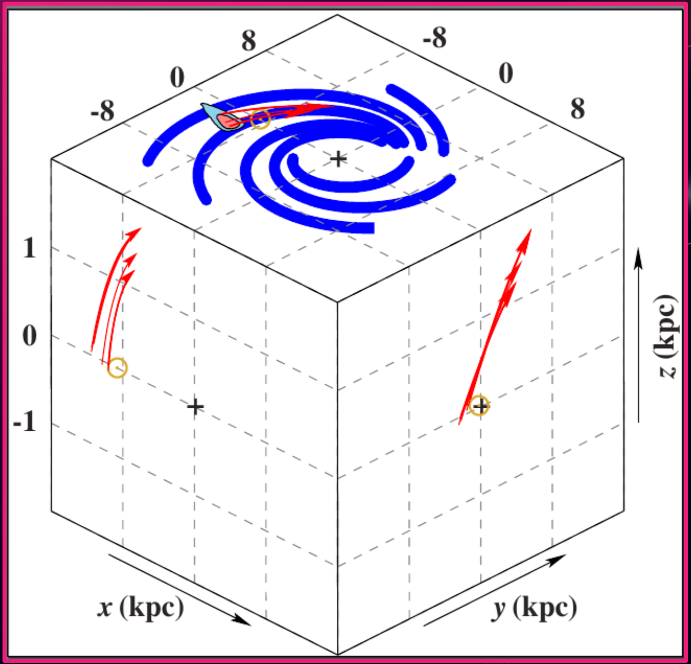


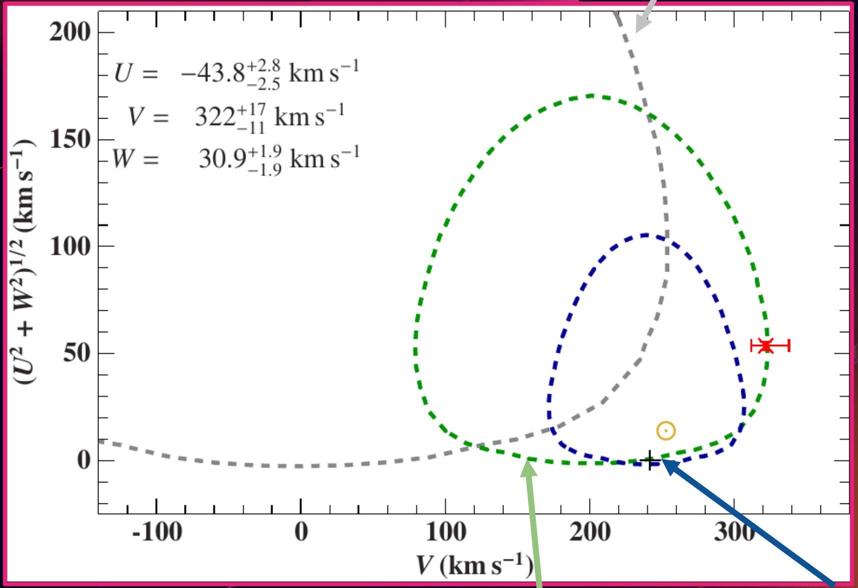
BD+75 325
thin disk

BD+37 442
thick disk

CBS 461
halo

The example of LB 4237





Toomre diagram

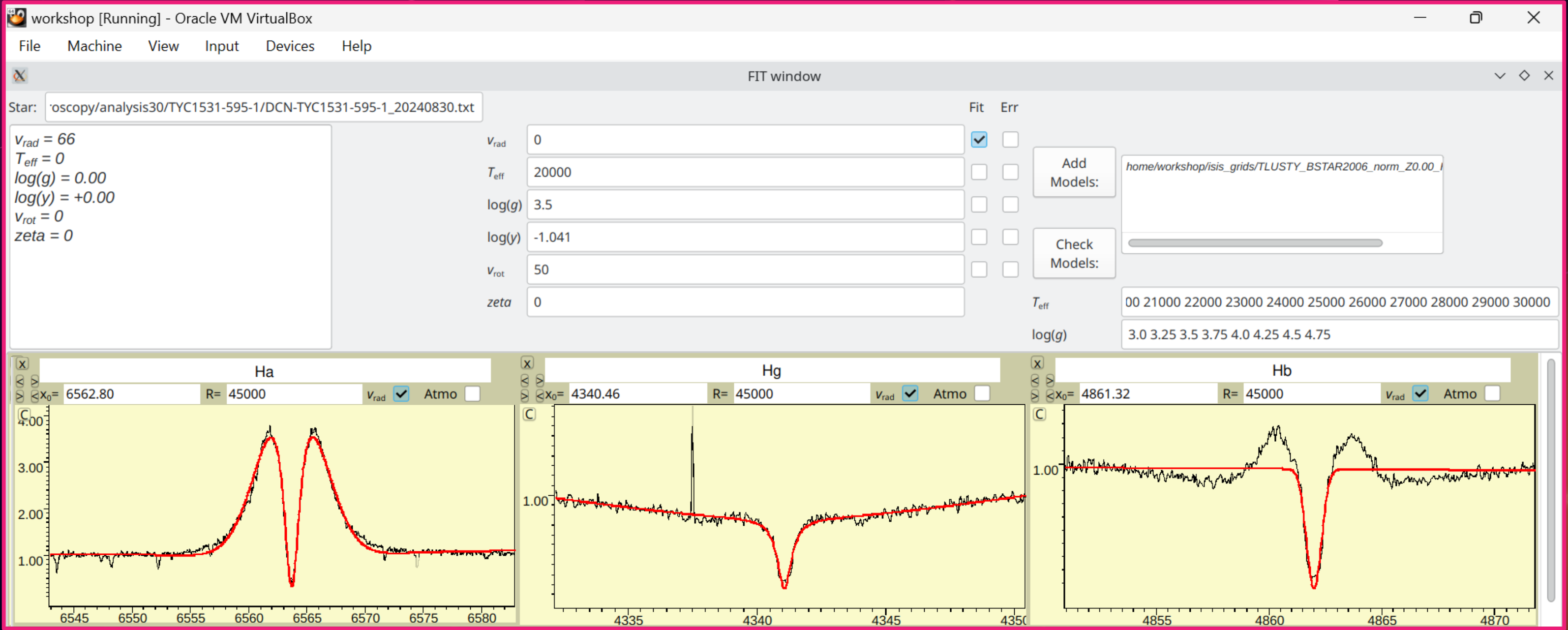
- Trajectory of the star in the galactic plane

Kinematics results :

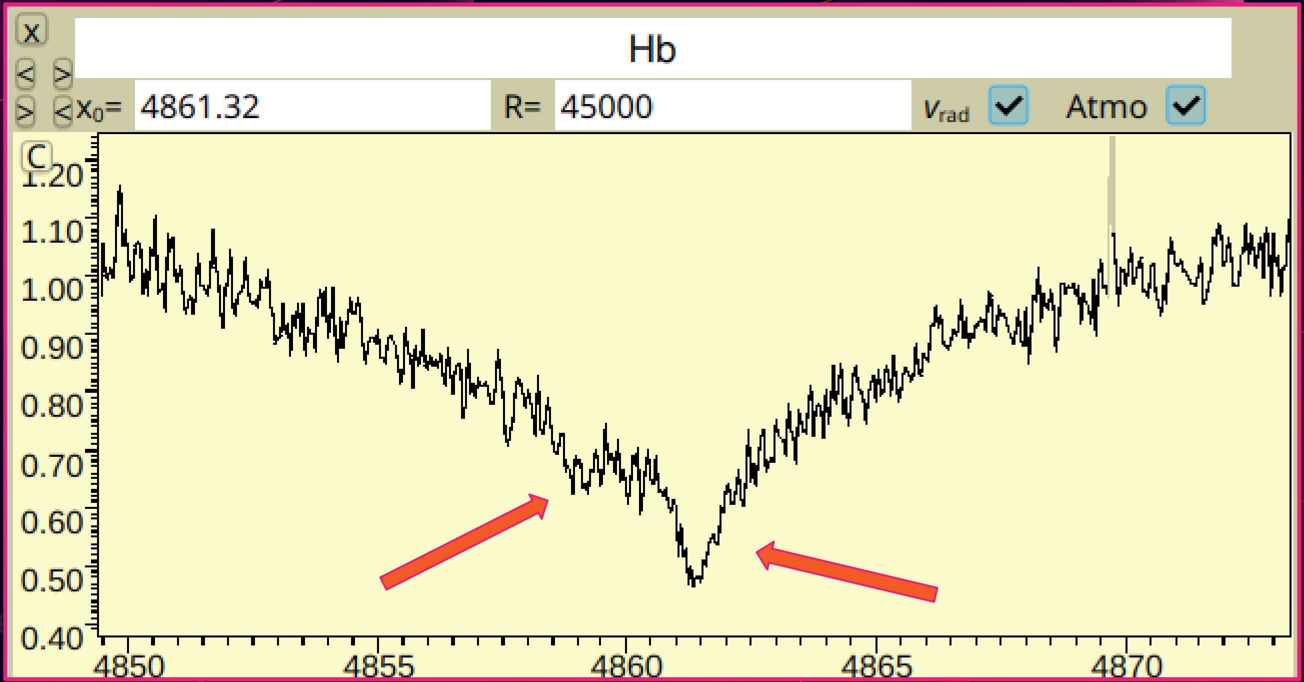
	x	y	z	r	v_x	v_y	v_z	v_{Grf}	$v_{Grf} - v_{esc}$	P_b	x_d	y_d	z_d	r_d	$v_{x,d}$	$v_{y,d}$	$v_{z,d}$	$v_{Grf,d}$	v_{ej}	τ_{flight}
	(kpc)				(km s^{-1})					(%)	(kpc)				(km s^{-1})					(Myr)
Model I:																				
LB4237	−6.47	4.4	1.34	7.90	218	240	30.9	326	−294	100	−9.8	−2.0	0.0	10.1	68	266	71	286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

Exceptional Cases

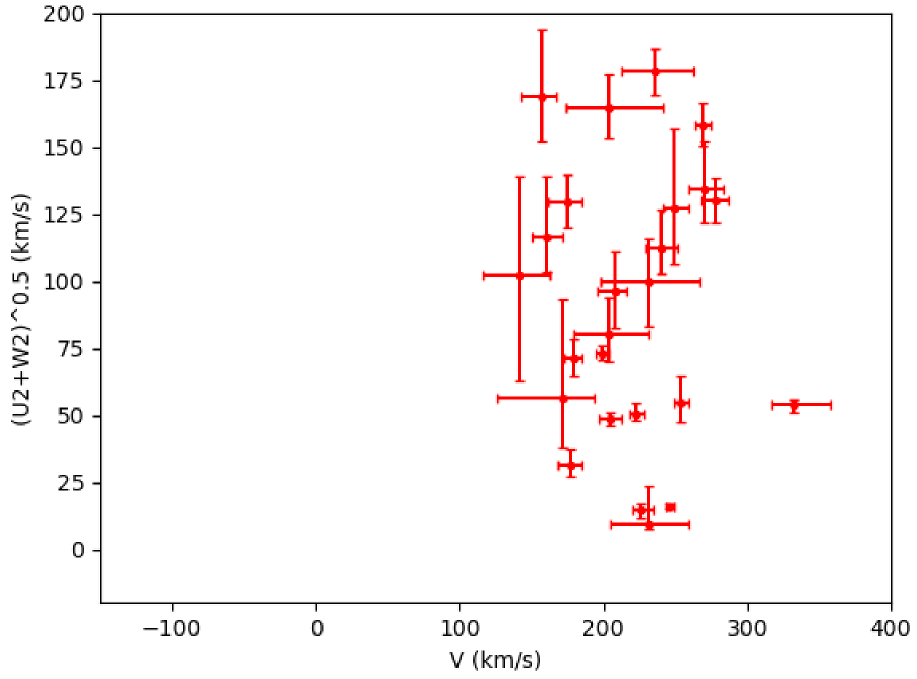
Star with Rotational Disc:



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)

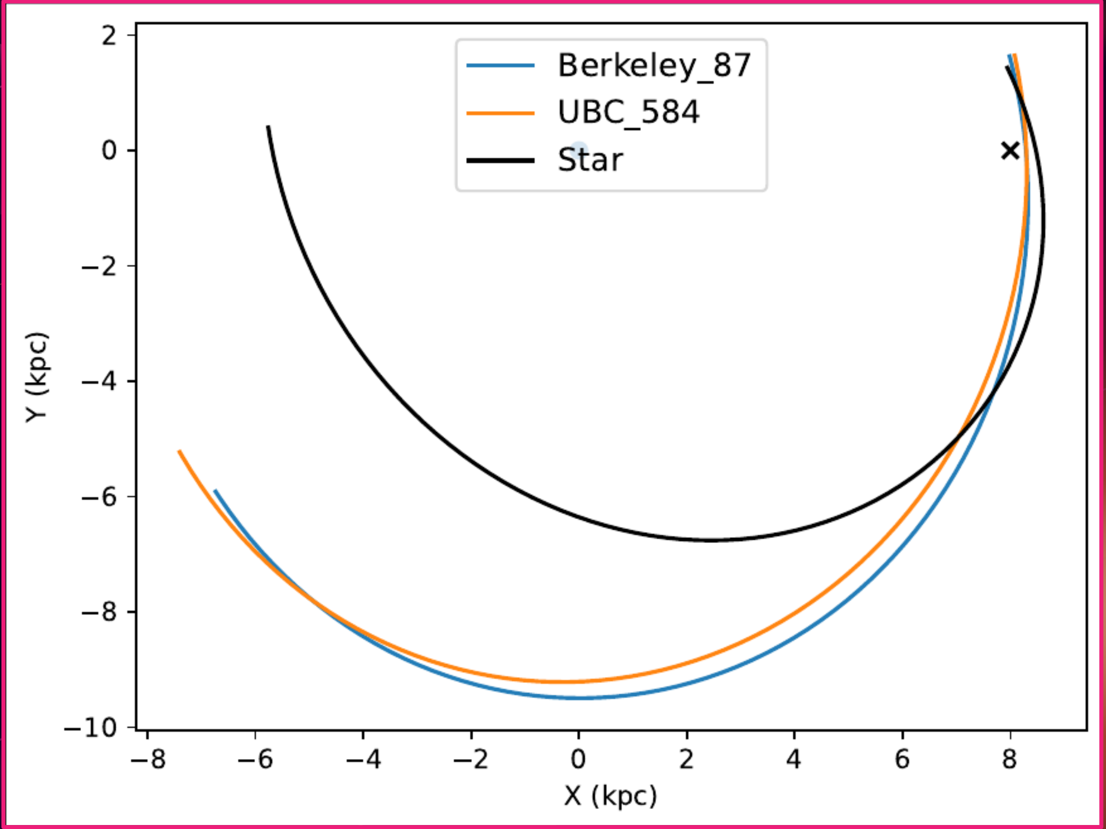
```python


ra=5.7405
dec=39.6510417
rv= 7
name="TYC2787-1539-1"
##############################################

ts= np.linspace(0,-100.,100000)*units.Myr
orbits=[]
star_data= {
    'parallax': [],
    'pmra': [],
    'pmdec': [],
    'ra': [],
    'dec': [],
    'rv': []
```

	A	B	C	D	E	F
1	recno	Name	ID	AllNames	Type	CST
2	1	ADS_16795	1	ADS_1679	http://vizie	6.832199
3	2	AH03_J0748-26.9	2	AH03_J074	http://vizie	11.58552
4	3	ASCC_5	3	ASCC_5,M	http://vizie	8.316422
5	4	ASCC_6	4	ASCC_6,M	http://vizie	19.25857
6	5	ASCC_9	5	ASCC_9,Th	http://vizie	17.56655
7	6	ASCC_11	6	ASCC_11,N	http://vizie	27.89349
8	7	ASCC_12	7	ASCC_12,N	http://vizie	19.41707
9	8	ASCC_13	8	ASCC_13,N	http://vizie	11.41564
10	9	ASCC_14	9	ASCC_14,N	http://vizie	3.353328
11	10	ASCC_18	10	ASCC_18,N	http://vizie	5.076724
12	11	ASCC_19	11	ASCC_19	http://vizie	9.307117
13	12	ASCC_20	12	ASCC_20,C	http://vizie	8.64395
14	13	ASCC_21	13	ASCC_21	http://vizie	11.05617
15	14	ASCC_23	14	ASCC_23,F	http://vizie	21.33467
16	15	ASCC_24	15	ASCC_24,A	http://vizie	5.833571
17	16	ASCC_27	16	ASCC_27,N	http://vizie	8.285251
18	17	ASCC_28	17	ASCC_28,N	http://vizie	3.510938
19	18	ASCC_29	18	ASCC_29,N	http://vizie	14.47895

Where do these runaway stars come from?

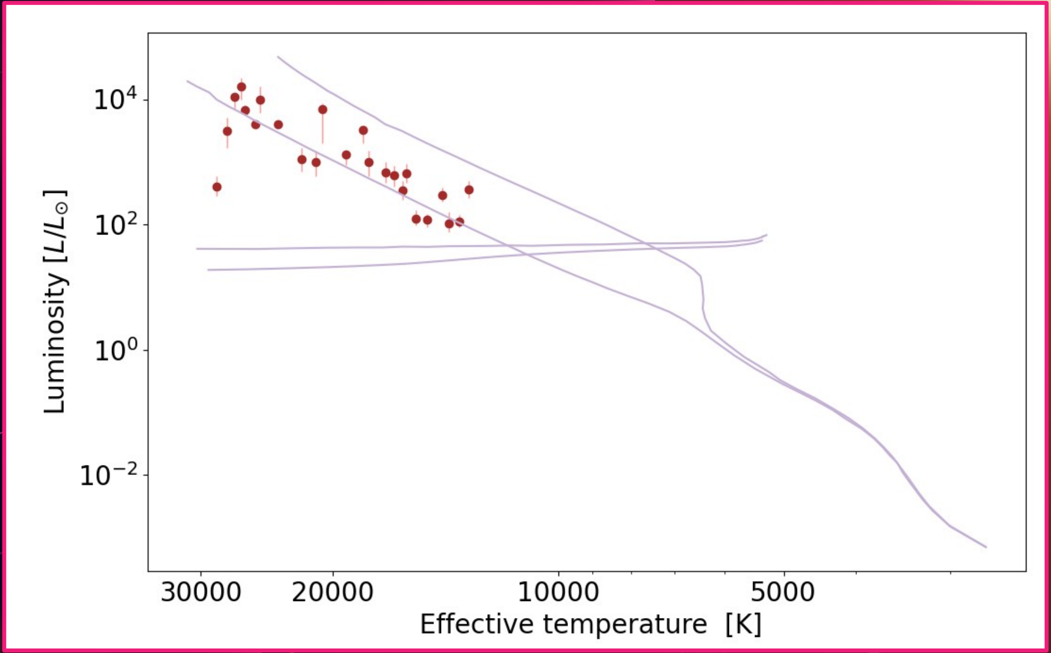
– Here: HD226054 → 2 possible clusters:

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

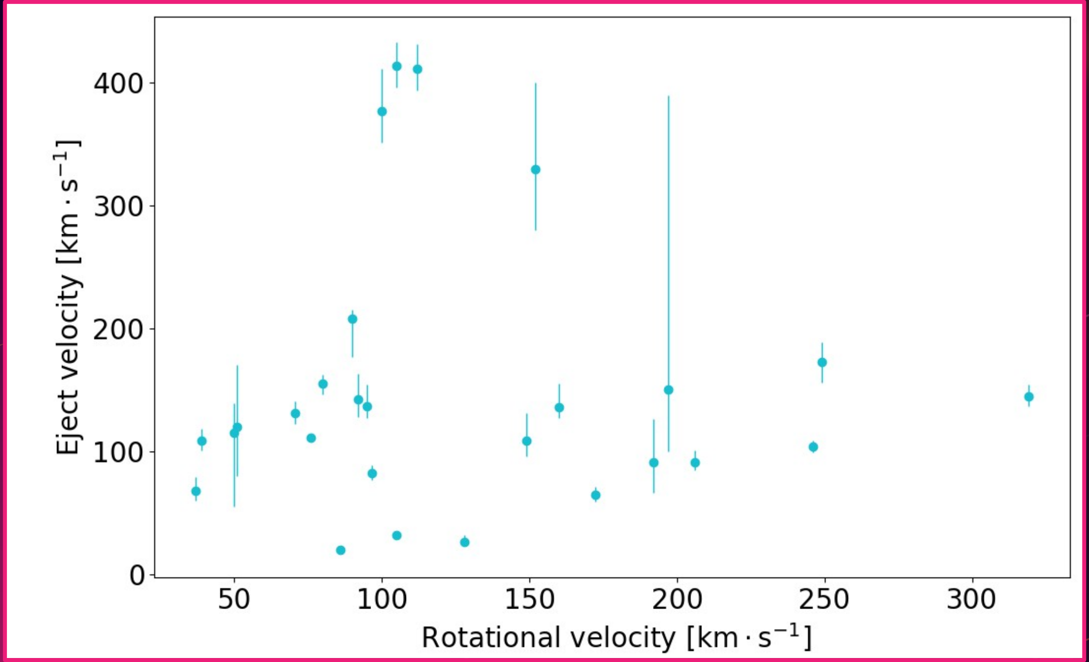


HR diagram

- Most on the MS
- Most T between 25000 K and 15000 K
- Most L between 100 L⊙ and 10000 L⊙
- None on the Horizontal Branch



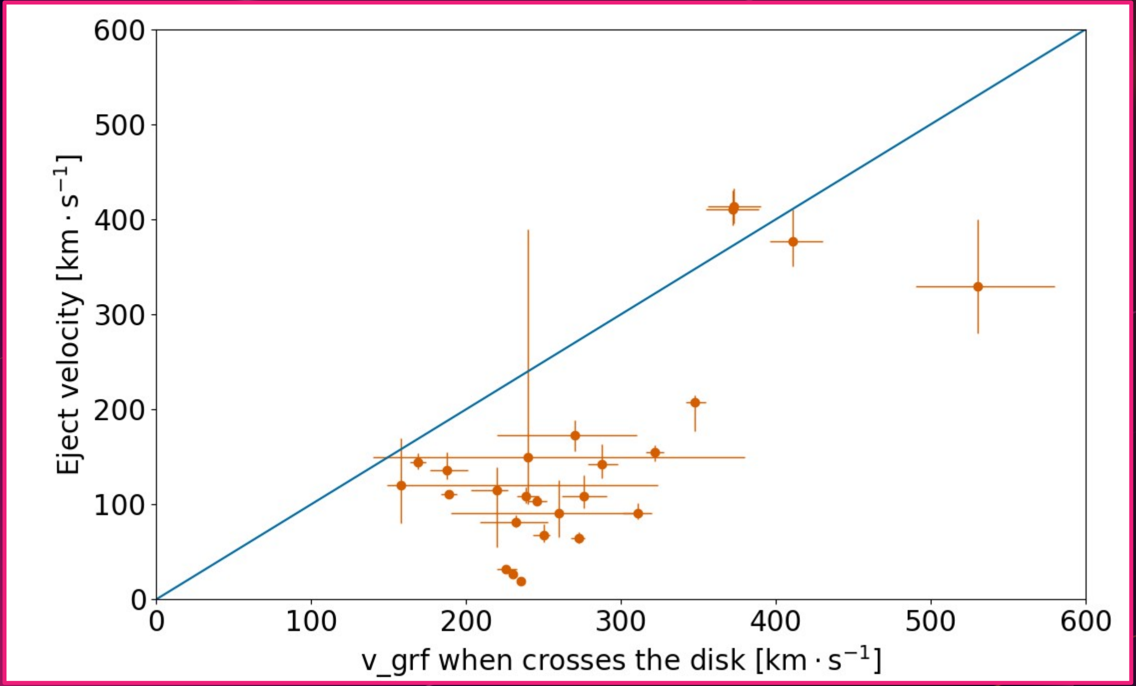
Evolution of the ejection velocity depending on the rotational velocity



- Ejection velocity does not influences 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_eject > v_grf_d

4. Conclusions

- Observed 45 stars in 4 nights
- Identified at least 10 runaway stars
- Determined the main parameters of the stars: Teff, 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 !