Spectroscopy of “Be” Stars Exhibiting Rapid Variability:

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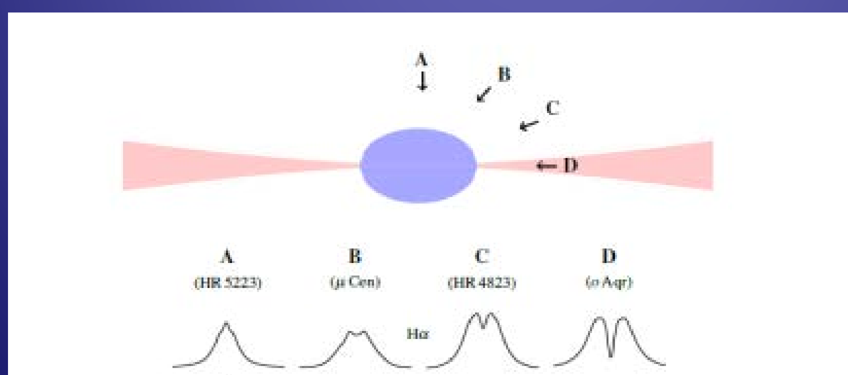
- Research objective: identify and document rapid variation in the line profile features of the H-alpha region in the spectra of selected Be stars.

- Be stars:
  - Spectral type ‘B’, non-Super Giant, stars with (Balmer) emission lines
  - Hypothesized circumstellar decretion disk
  - Very fast rotation (~ 300 km/s vsini) producing broad spectral lines
  - Emission profiles depend on line of sight:



Research team
(i.e., those contributing spectra)

- One American
- One Canadian
- One Brit
- Two Germans
- One Swede
- Two Spaniards
- One Italian
- One Netherlander

Selection of targets

- Names of Be stars exhibiting rapid variability were obtained from the astronomical literature
- Selection criteria:
  - Visible from the northern hemisphere (>dec -10°)
  - Altitude >30º Fall thru Spring
  - Brighter than 6th magnitude
  - not well studied for rapid variability

(rapid defined as ranging from minutes to a few days)

Preliminary list of targets

Name	Const	V mag	Spec Type	other Name	RA	DEC	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	# of spectra
bet Cep	CEP	3.22	B2IIIev	ALFIRK	21 28 39.60	70 33 38.57	Y	Y	Y	Y					8142
59 Cyg	CYG	4.74	B1.5Vnne	f1 Cyg	20 59 49.56	47 31 15.42	Y	Y	Y	Y					5289
omi And	AND	3.63	B6IIIpe		23 01 55.26	42 19 33.53	Y	Y	Y	Y	Y				4216
28 Cyg	CYG	4.93	B2.5Ve	b2 Cyg	20 09 25.62	36 50 22.64	Y	Y	Y	Y					3122
12 Vul	VUL	4.90	B2.5Ve		19 51 04.11	22 36 36.17	Y	Y	Y						2321
25 Cyg	CYG	5.10	B3IVe		19 59 55.20	37 02 34.39	Y	Y	Y	Y					1746
omi Cas	CAS	4.48	B5IIIe		00 44 43.52	48 17 03.71	Y	Y	Y	Y	Y	Y			600
60 Cyg	CYG	5.40	B1Ve		21 01 10.93	46 09 20.78	Y	Y	Y	Y					380
omi Aqr	AQR	4.70	B7IVe	31 Aqr Sadalmulk	22 03 18.84	-02 09 19.31	Y	Y	Y	Y					241
ome Ori	ORI	4.57	B2IIIe		05 39 11.15	04 07 17.28			Y	Y	Y	Y	Y	Y	3266
psi Per	PER	4.31	B5Ve		03 36 29.38	48 11 33.48			Y	Y	Y	Y	Y		2222
lam Eri	ERI	4.25	B2IVne	Kursi	05 09 08.78	-08 45 14.69				Y	Y	Y	Y		838
11 Cam	CAM	5.03	B2.5Ve		05 06 08.45	58 58 20.54			Y	Y	Y	Y	Y	Y	417
48 Per	PER	4.00	B3Ve	c Per	04 08 39.69	47 42 45.04				Y	Y	Y	Y		389

Acquisition of raw spectra

- Team member telescopes:
  - Mostly 8” to 14” SCTs ; one 20” Newtonian
- Spectrographs: StarEx, LowSpec, LHires III, UVEX
- Gratings: 1800 or 2400 L/mm
- High resolution required: R > 10,000
- Wavelength range: λλ6500 to 6700Å to encompass Hα (6562.8Å) and Helium I (6678Å)
- Typical exposure times range from 2 to 10 minutes, as required to achieve SNR of 40 to >100

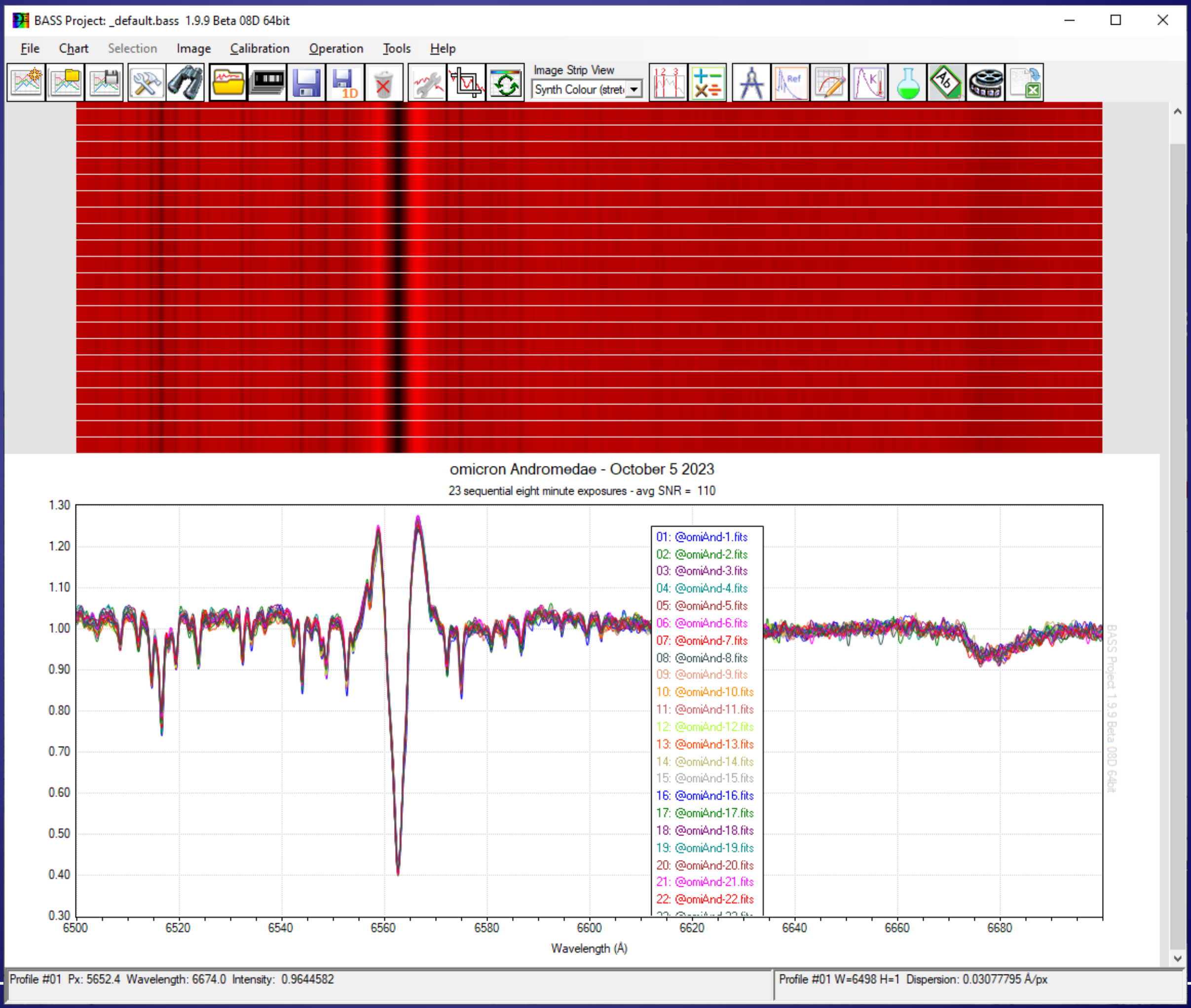
Processing of raw spectra
(my workflow; others may use alternative methods)

- SpecINTI used to process raw spectra into finished 1D profiles of EACH exposure separately (no stacking)
  - Masters (dark, bias, flat) used, but not obtained each night
  - Neon image obtained during each session
  - Output: 1D profiles of each exposure creating a time-series
- Profiles imported into BASS software for measurements
  - Continuum normalized and rectified (flattened) to 1.0
  - Standard deviation and SNR of the continuum measured
- Measurements transferred to spreadsheet for data storage and analysis

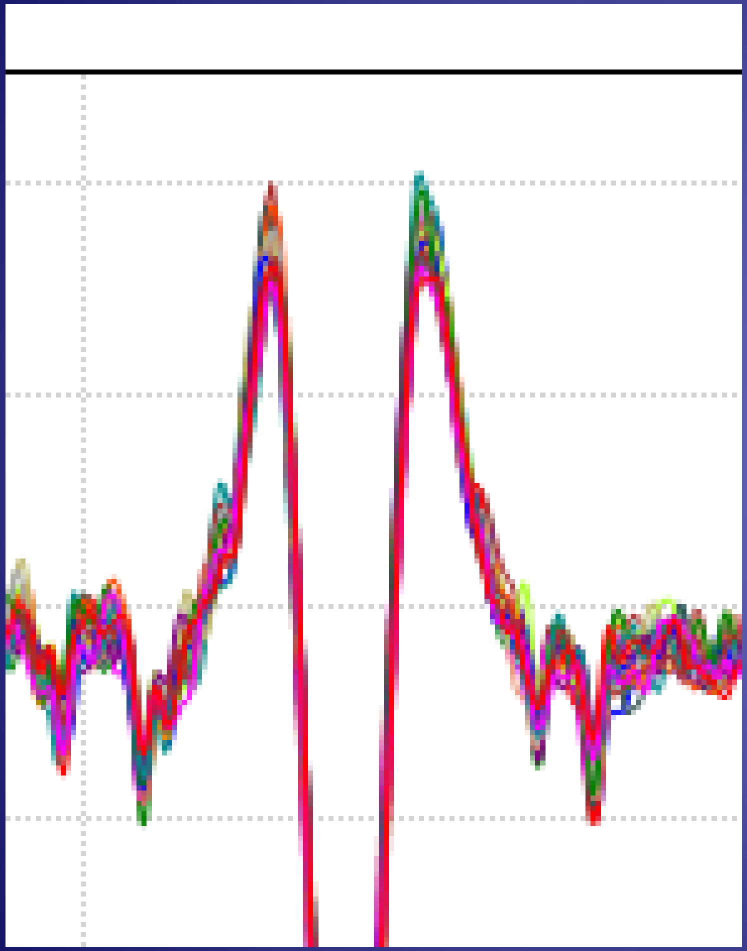
specinti_editor.exe - Shortcut

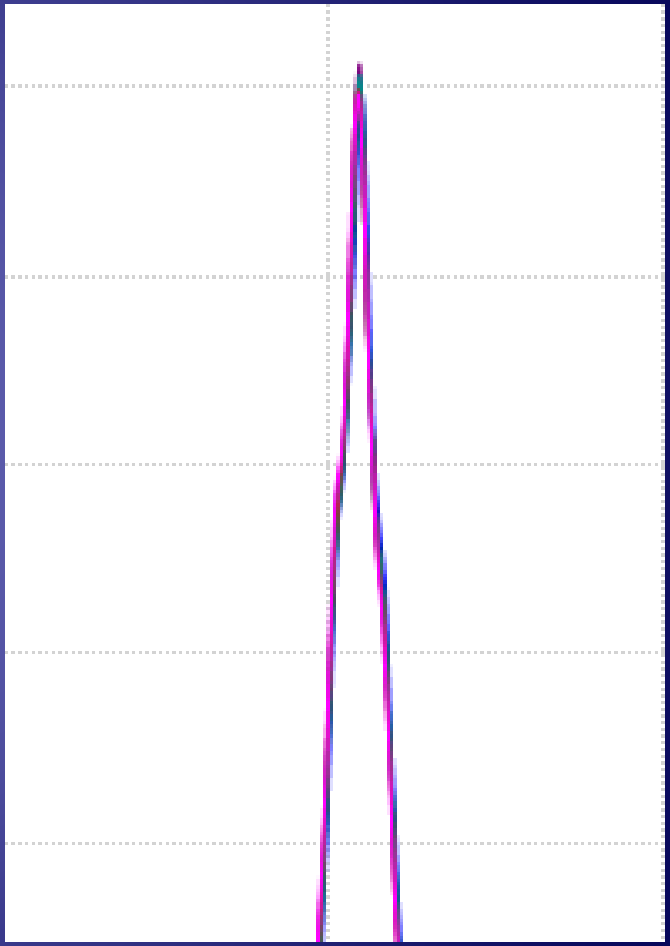
```
Observation file: E:/Spectroscopy/2024-01-10-48Per\obs-Jan10-48Per.yaml
****************************************************
Target: 48 Per
****************************************************
Offset: e:/spectroscopy/specINTI_master\__offset.fits
Dark: e:/spectroscopy/specINTI_master\__dark.fits
Flat_field: e:/spectroscopy/specINTI_master\__flat.fits
Target processing...
............
Dark coefficient = 0.800
Total exposure time = 5760.0 seconds
Target AltAz coordinates...
Elevation = 73.2 deg.
Azimut = 351.6 deg.
Computed mean Y = 477
Processing calibration...
............
Median filtering (optimal method)...
Gaussian filtering...
Tilt correction...
Computed tilt angle = -0.061
............
Slant correction...
Computed slant angle = -1.148
............
Smile correction...
............
Sky substraction (optimal method)...
Profile extraction (optimal method)...
Evaluate lines position...
Automatic search of calibration lines...
Number of calibration lines find = 5
Calibration function...
Calibration coefficients:
-5.688611541350073e-07, 0.06526594486123026, 6399.840352075182
O-C: [-0.009  0.011  0.003 -0.013  0.008]
Root Mean Square Error = 0.0091 A
Resampling...
FWHM = 8.16 pixels
Dispersion = 0.0614 A/pixel
Resolution power = 13104 @ 6571 A
Compute stacking...
Response correction...
Imposed spectral shift: 0.00 A
Multiply by Planck function...
Atmospheric transmission correction (corr_atmo parameter)...
AOD = 0.05
Angular elevation = 73.24 deg.
Normalize...
Cropping...
SIMPLE  = 'T       '
BITPIX  =                  -32
NAXIS1  =                 6440
```

The BASS software: fully capable on its own, but used here mostly for measuring line profile features: peak heights, absorption minimums, std dev, SNR

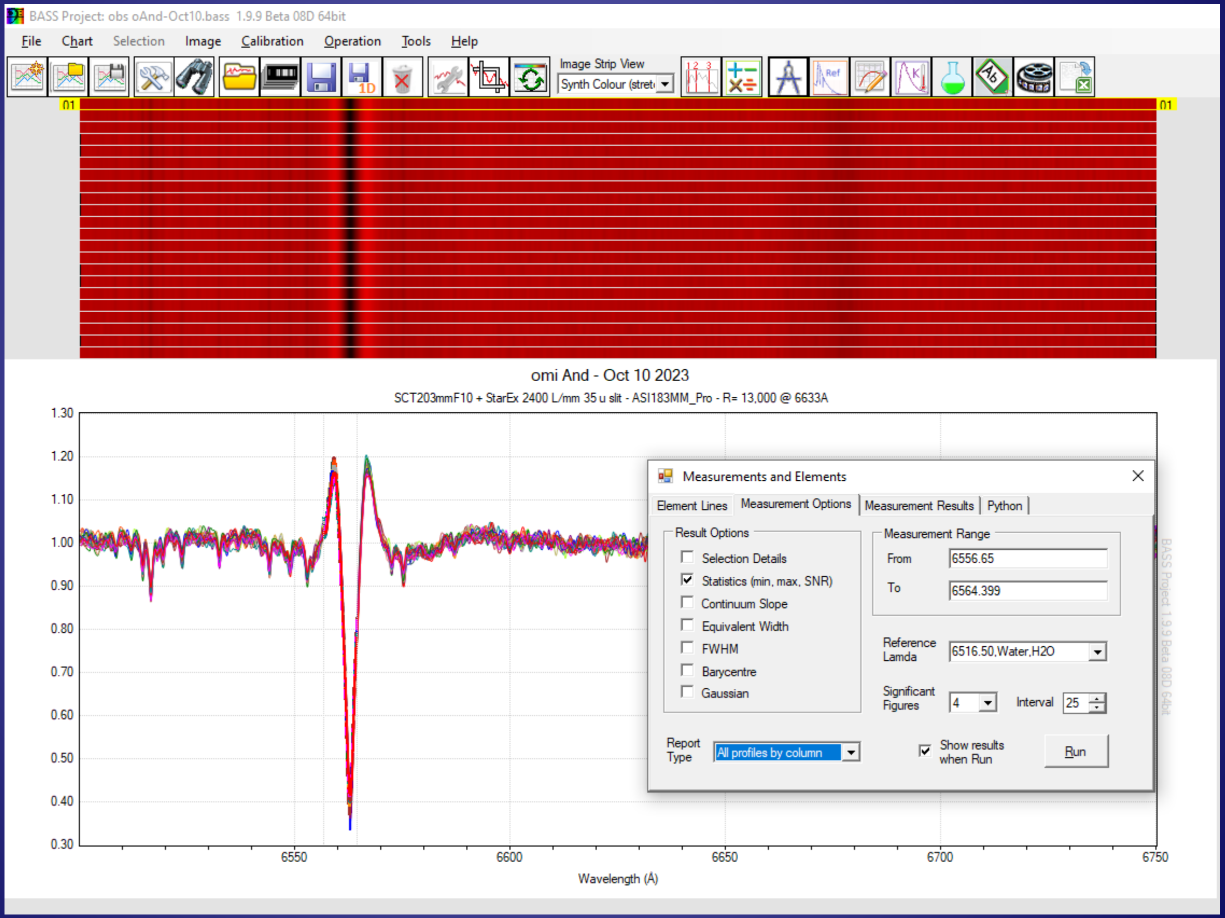


Zoomed in view of *omi And* showing variation in Ha peak compared to *11 Cam* showing no variation:





The BASS measure tool is used to quantify profile features of a group of spectral profiles simultaneously



Typical measurement results of a set of spectral profiles

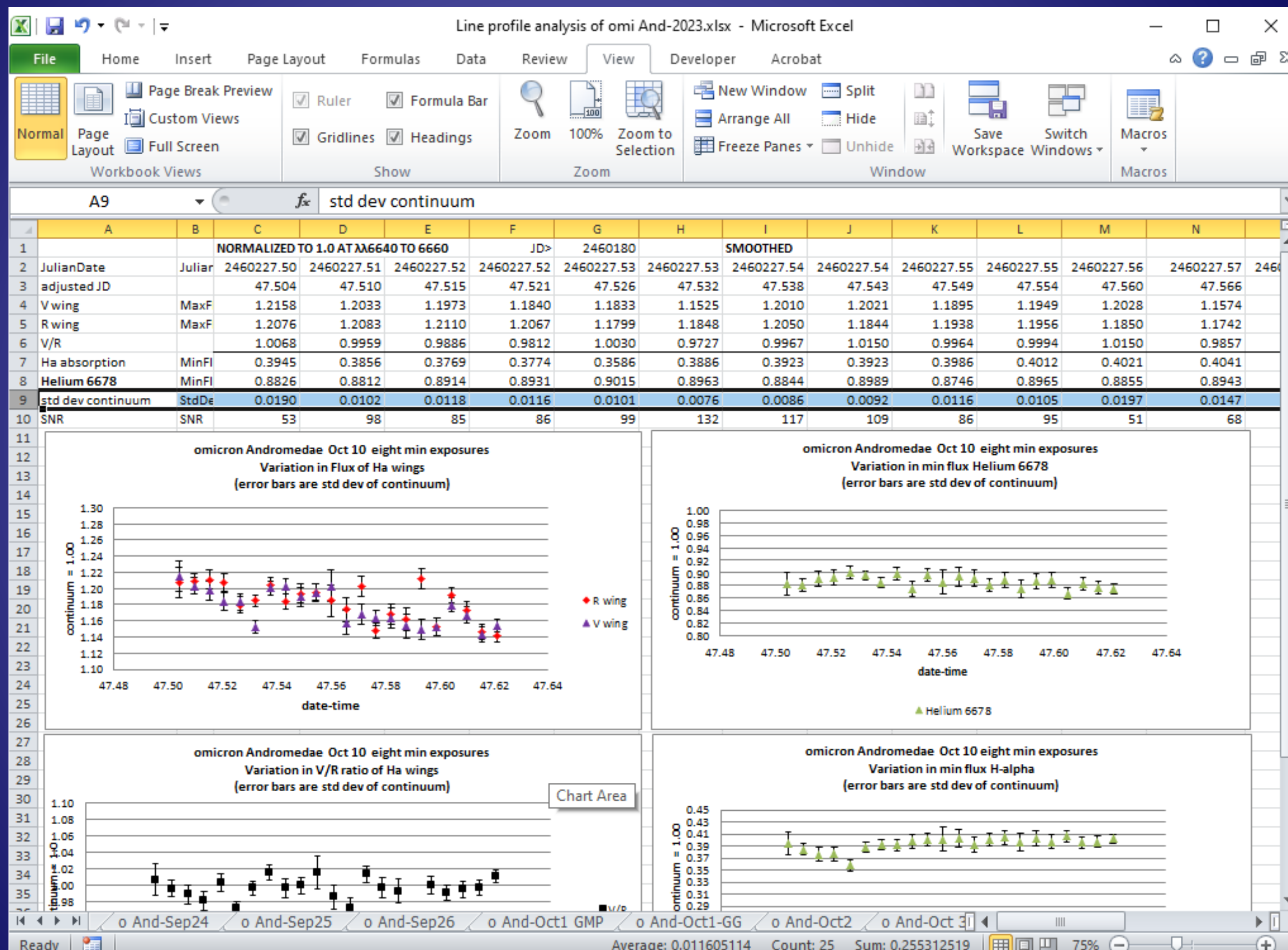
Measurements and Elements

Element Lines | Measurement Options | Measurement Results | Python

Sequence	01	02	03	04	05	06	07
Julian Date	2460227.50396991	2460227.50954861	2460227.51512731	2460227.52069444	2460227.52649306	2460227.53206018	24
Exp Time	480	480	480	480	480	480	48
Start Pixel	3242.843	3242.843	3243.091	3241.356	3241.232	3242.967	32
Start Lamda	6600	6600	6600	6600	6600	6600	66
Start Velocity							
Start Flux	1.00247979164124	0.978565394878387	0.987096607685089	0.987861335277557	1.00913977622986	1.00700891017914	1.0
End Pixel	3892.439	3892.439	3892.688	3890.953	3890.767	3892.501	38
End Lamda	6620	6620	6620	6620	6620	6620	66
End Velocity							
End Flux	0.998583614826202	0.985546350479126	1.00896334648132	0.984478652477264	1.01046407222748	0.991011500358582	0.9
Range Pixel	649.5967	649.5967	649.5969	649.5972	649.5349	649.5347	64
Range Lamda	20	20	20	20	20	20	20
Range Velocity							
Max Flux	1.02871990203857	1.02806794643402	1.02205812931061	1.02825057506561	1.03029263019562	1.02662324905396	1.0
Max Flux Pixel	3364.121	3494.929	3420.384	3280.634	3453.719	3497.015	33
Max Flux Lamda	6603.73413085938	6607.76123046875	6605.45837402344	6601.20910644531	6606.54296875	6607.822265625	66
Max Flux Velocity							
Min Flux	0.973210215568542	0.978620886802673	0.979101002216339	0.973565220832825	0.977776944637299	0.970684111118317	0.9
Min Flux Pixel	3867.252	3768.315	3722.118	3642.507	3758.377	3697.971	37
Min Flux Lamda	6619.22485351563	6616.17858886719	6614.74853515625	6612.35107421875	6615.92346191406	6614.01000976563	66
Min Flux Velocity							
Flux Range	0.0555096864700317	0.0494470596313477	0.0429571270942688	0.0546853542327881	0.0525156855583191	0.0559391379356384	0.0
Flux Average	1.00181320419678	1.00085080852875	1.00152106988265	1.00282451652345	1.00542203274008	1.00070597187898	1.0
Flux Average RMS	1.00189613874556	1.00091665405714	1.00157226925322	1.00289191508893	1.00548522910001	1.0007747222052	1.0
Std Deviation	0.0128909553653587	0.011480741974268	0.0101270488371212	0.0116267970763332	0.0112730660923939	0.0117304070967093	0.0
SNR	77.71442	87.17649	98.89565	86.25114	89.18798	85.30872	83
Area Profile							

Copy Results To Clipboard | Copy Row To Clipboard | Save R Value... | δλ

Line profile measurements are transferred to a spreadsheet

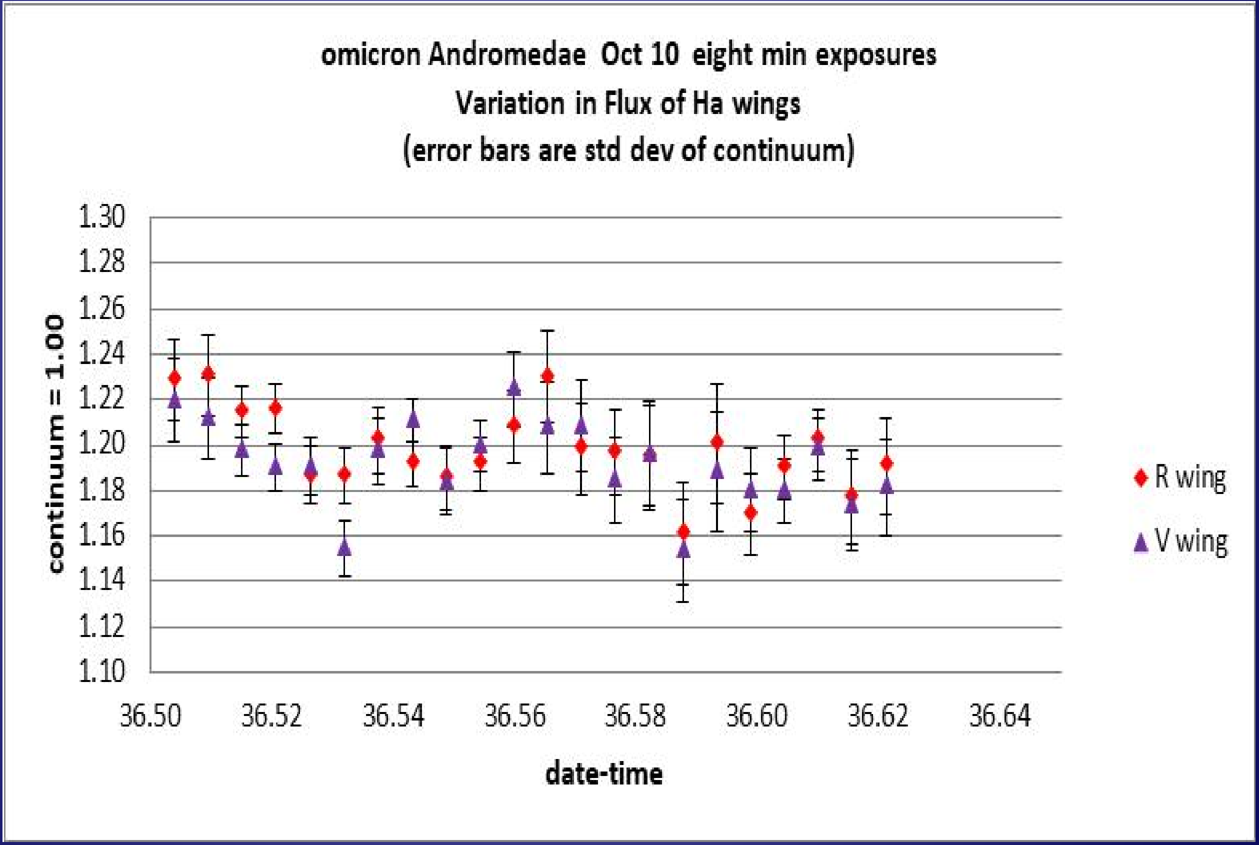


	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1			NORMALIZED TO 1.0 AT λλ6640 TO 6660			JD>	2460180		SMOOTHED					
2	JulianDate	Juliar	2460227.50	2460227.51	2460227.52	2460227.52	2460227.53	2460227.53	2460227.54	2460227.54	2460227.55	2460227.55	2460227.56	2460227.57
3	adjusted JD		47.504	47.510	47.515	47.521	47.526	47.532	47.538	47.543	47.549	47.554	47.560	47.566
4	V wing	MaxF	1.2158	1.2033	1.1973	1.1840	1.1833	1.1525	1.2010	1.2021	1.1895	1.1949	1.2028	1.1574
5	R wing	MaxF	1.2076	1.2083	1.2110	1.2067	1.1799	1.1848	1.2050	1.1844	1.1938	1.1956	1.1850	1.1742
6	V/R		1.0068	0.9959	0.9886	0.9812	1.0030	0.9727	0.9967	1.0150	0.9964	0.9994	1.0150	0.9857
7	Ha absorption	MinFl	0.3945	0.3856	0.3769	0.3774	0.3586	0.3886	0.3923	0.3923	0.3986	0.4012	0.4021	0.4041
8	**Helium 6678**	MinFl	0.8826	0.8812	0.8914	0.8931	0.9015	0.8963	0.8844	0.8989	0.8746	0.8965	0.8855	0.8943
9	std dev continuum	StdDe	0.0190	0.0102	0.0118	0.0116	0.0101	0.0076	0.0086	0.0092	0.0116	0.0105	0.0197	0.0147
10	SNR	SNR	53	98	85	86	99	132	117	109	86	95	51	68

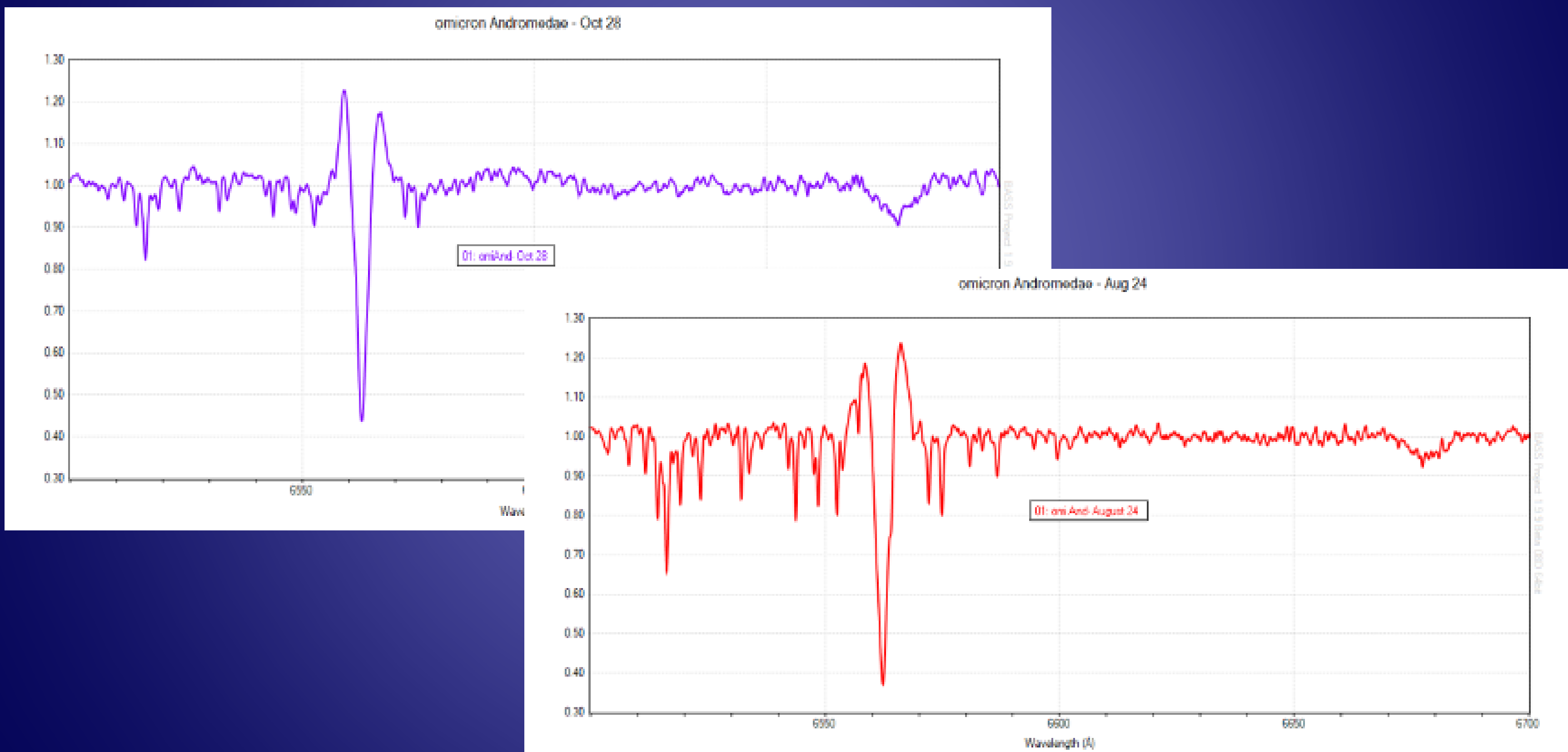
Various examples follow of data gathered so far:

Rapid Variation Hα wings during a 3 hr session

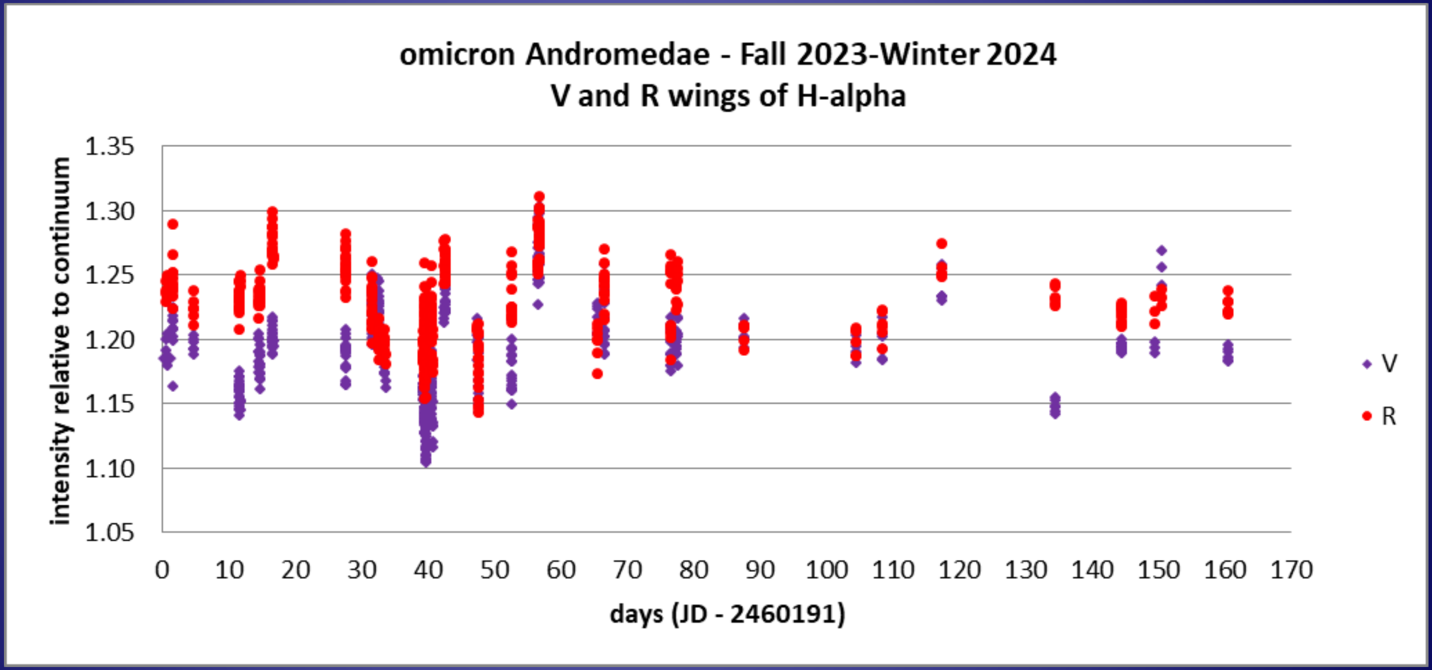
(sequential 8 minute exposures)



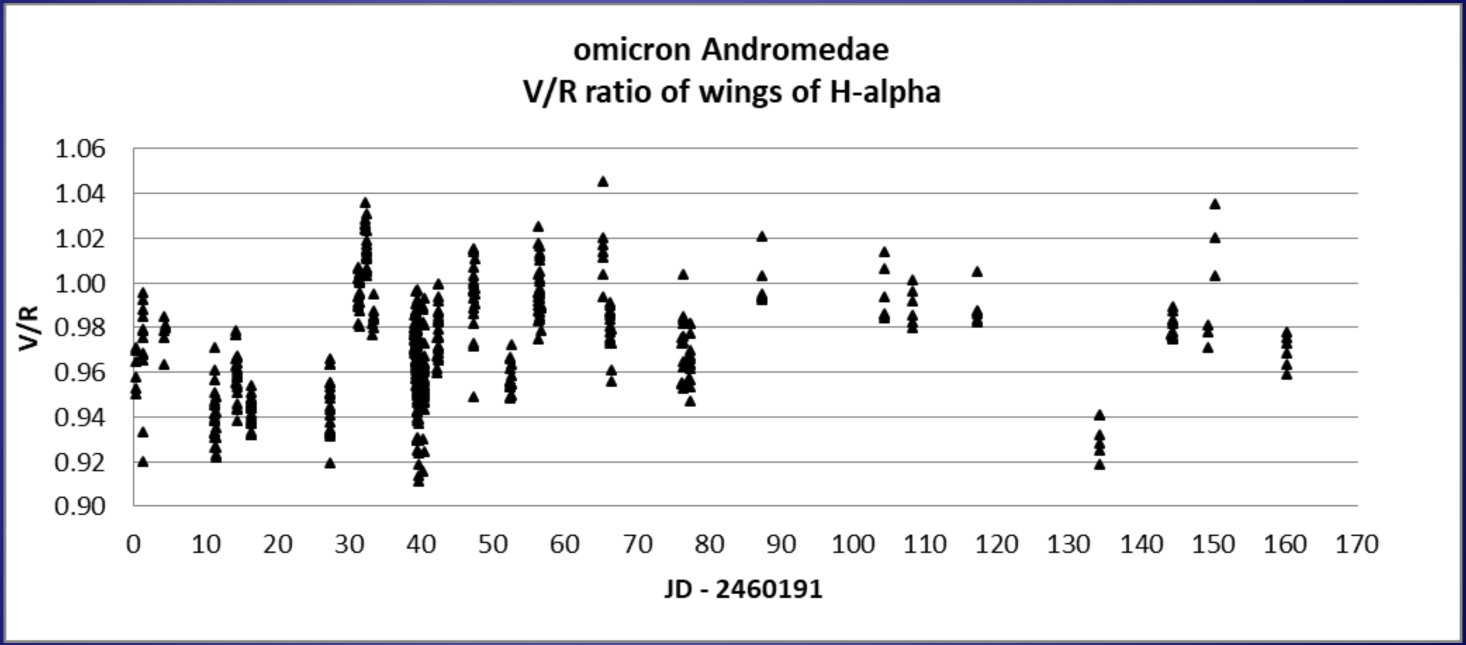
Variation in the relative intensity of the V wing compared to the R wing – two months



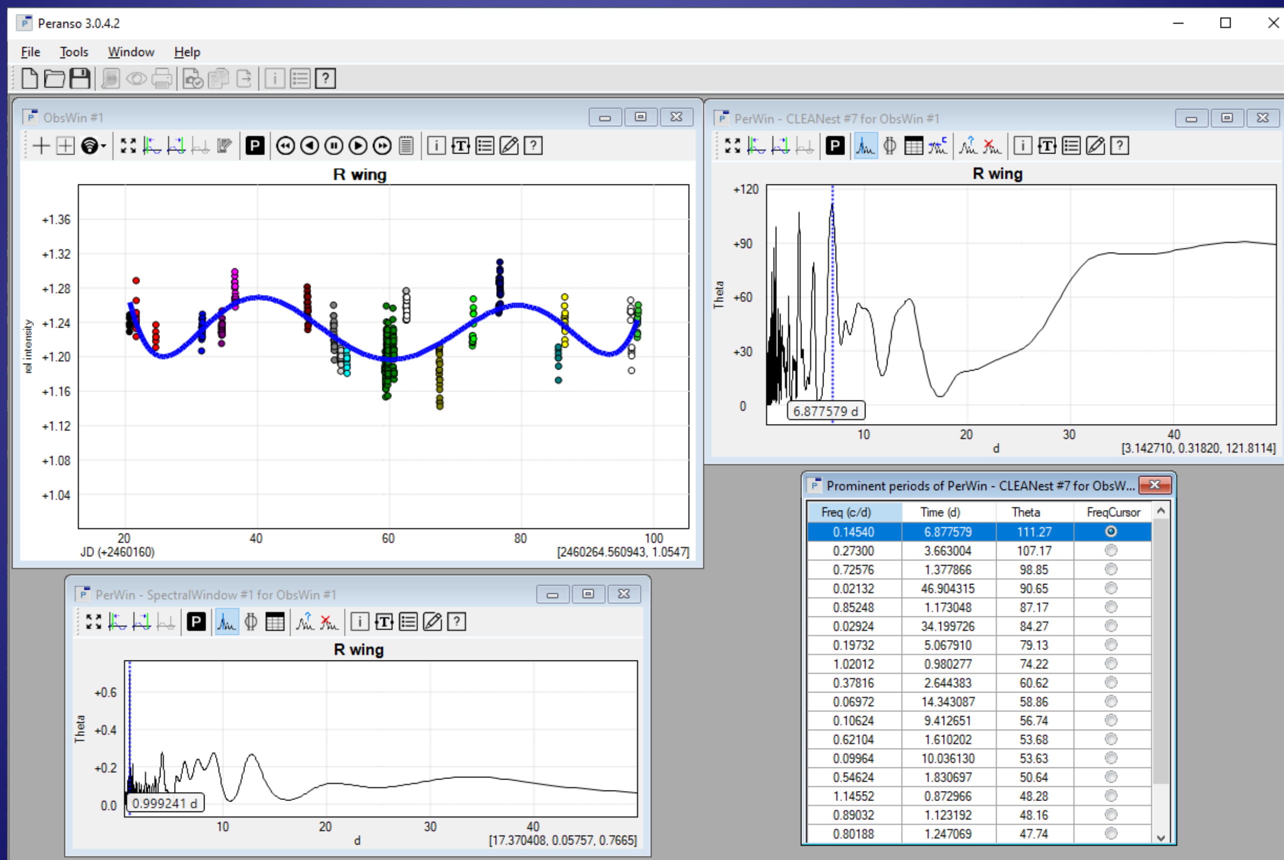
Longer term variation



Variation in V/R ratio of the Hα wings omicron Andromedae Fall, 2023



Line profile data will be analyzed for periodicity using Peranso software



Current status and preliminary conclusions

- It is too soon to draw conclusions, especially about the cause of the variation. (We may not be qualified to do anything other than speculate about causation.)

- We can say that amateurs with small telescopes, in some cases using DIY spectroscopes, can do legitimate science ... literally in their own backyards.

- More data will be collected, and additional Be stars will be targeted before we are through.

- Thanks for listening! Questions?