Trying to make sense of high resolution infrared spectra of cool stars

Hugh Jones

University of Hertfordshire

collaborators including

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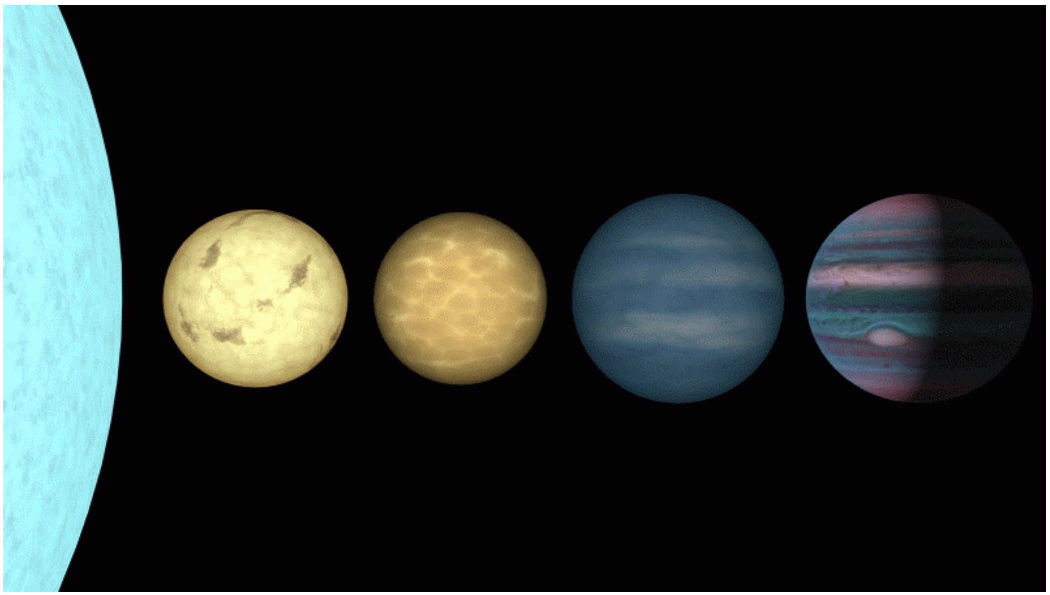
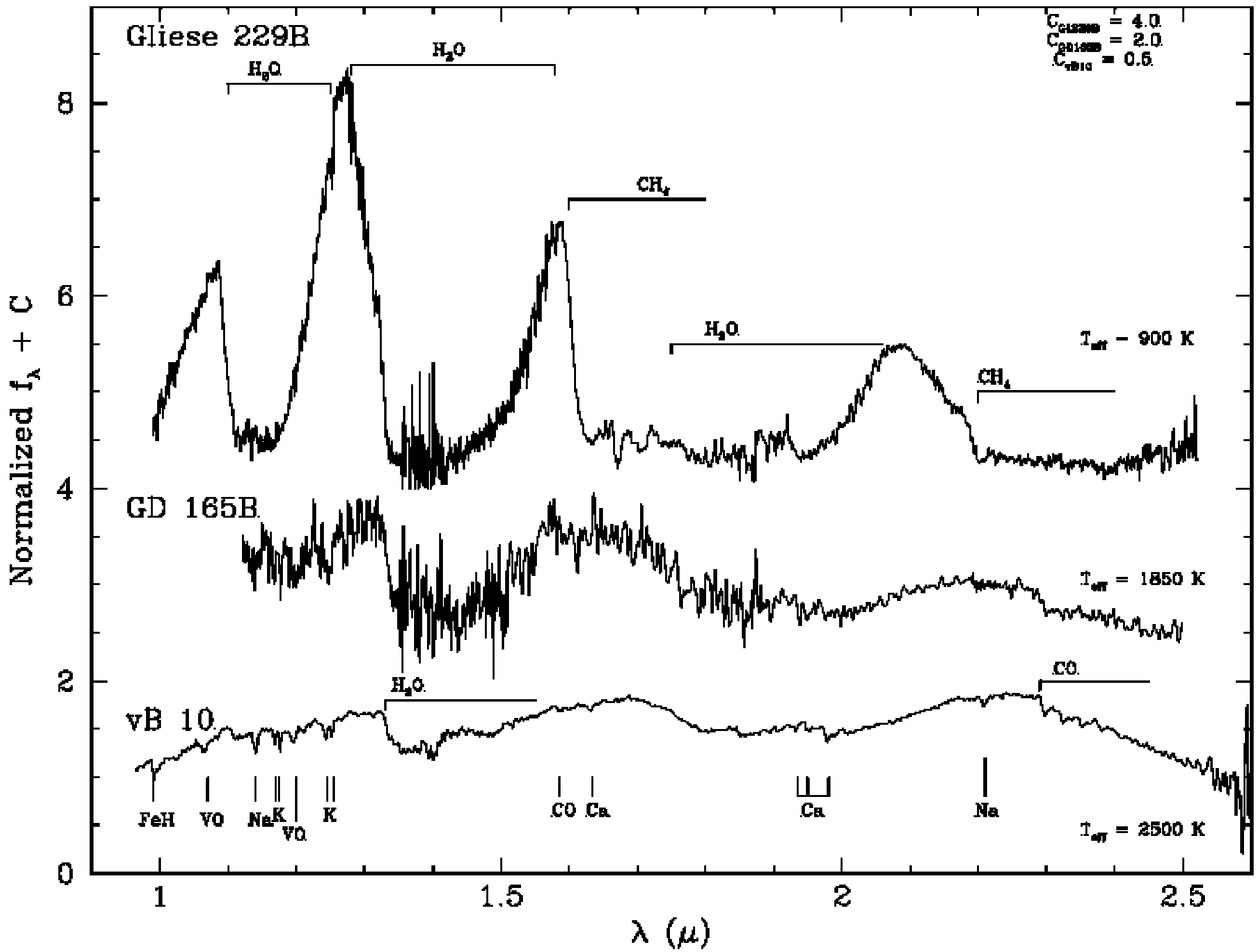


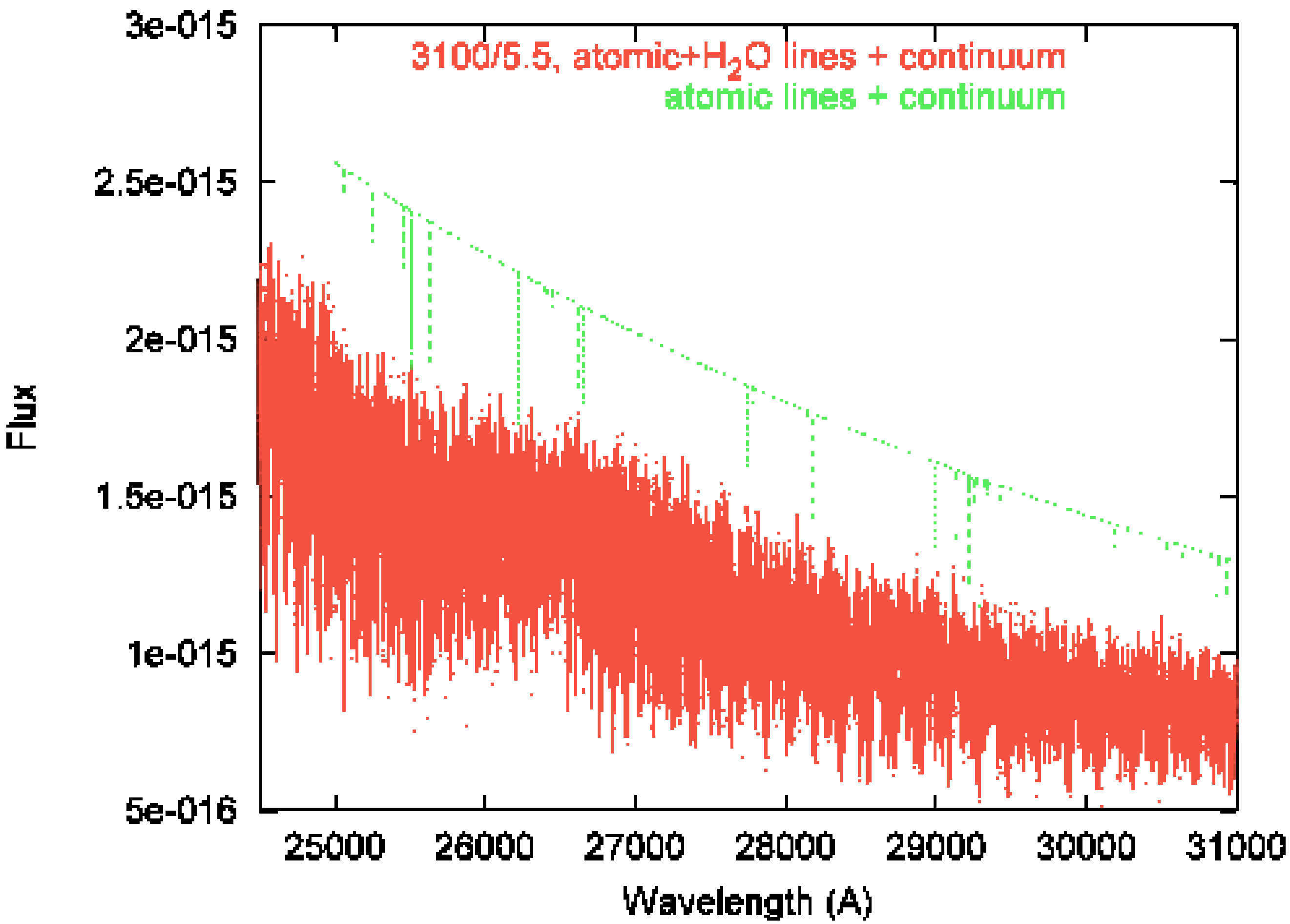
Robert Hurt

M to T dwarfs



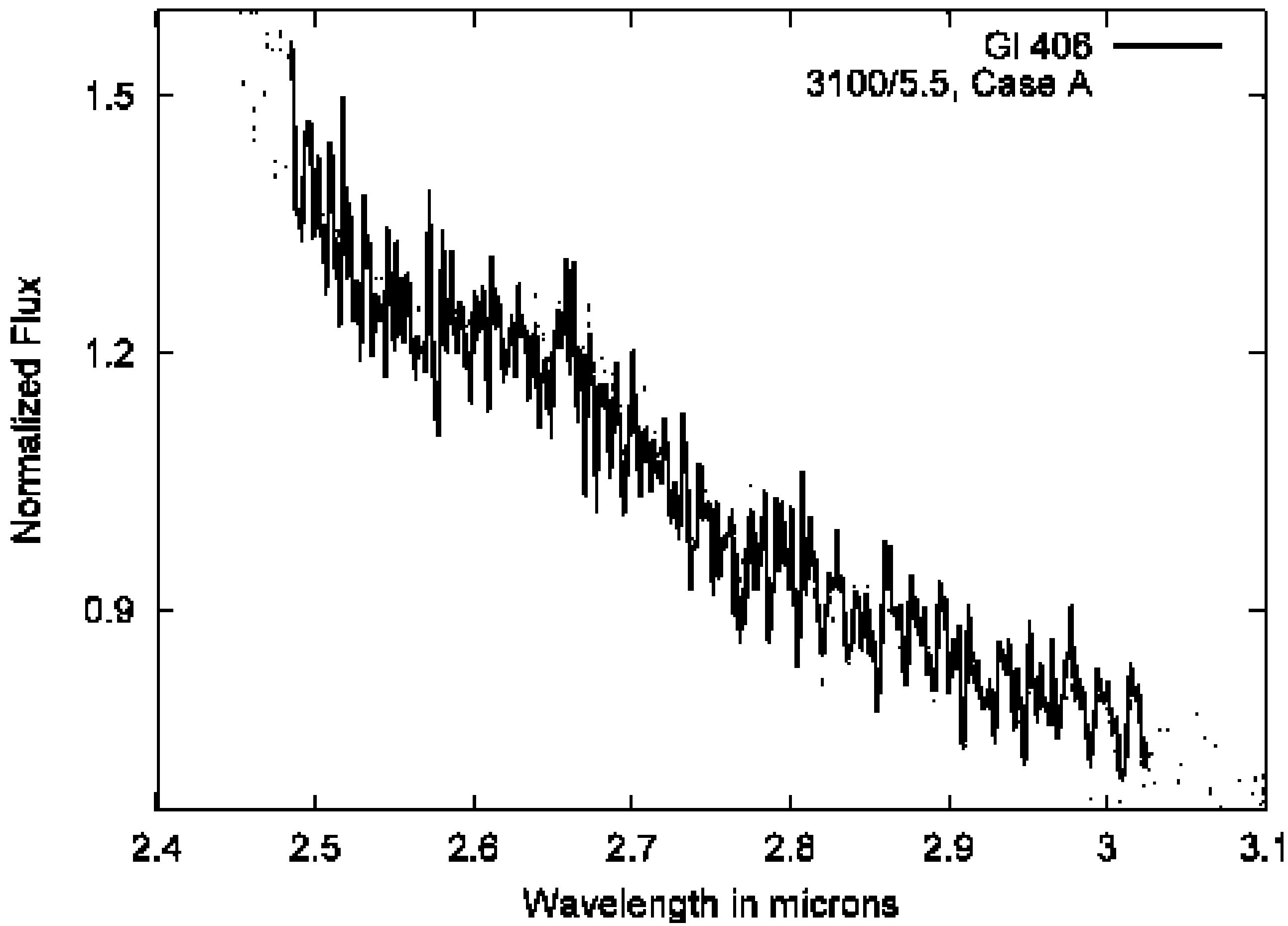
Oppenheimer et al. (1998)

Line lists are crucial (for sampling)



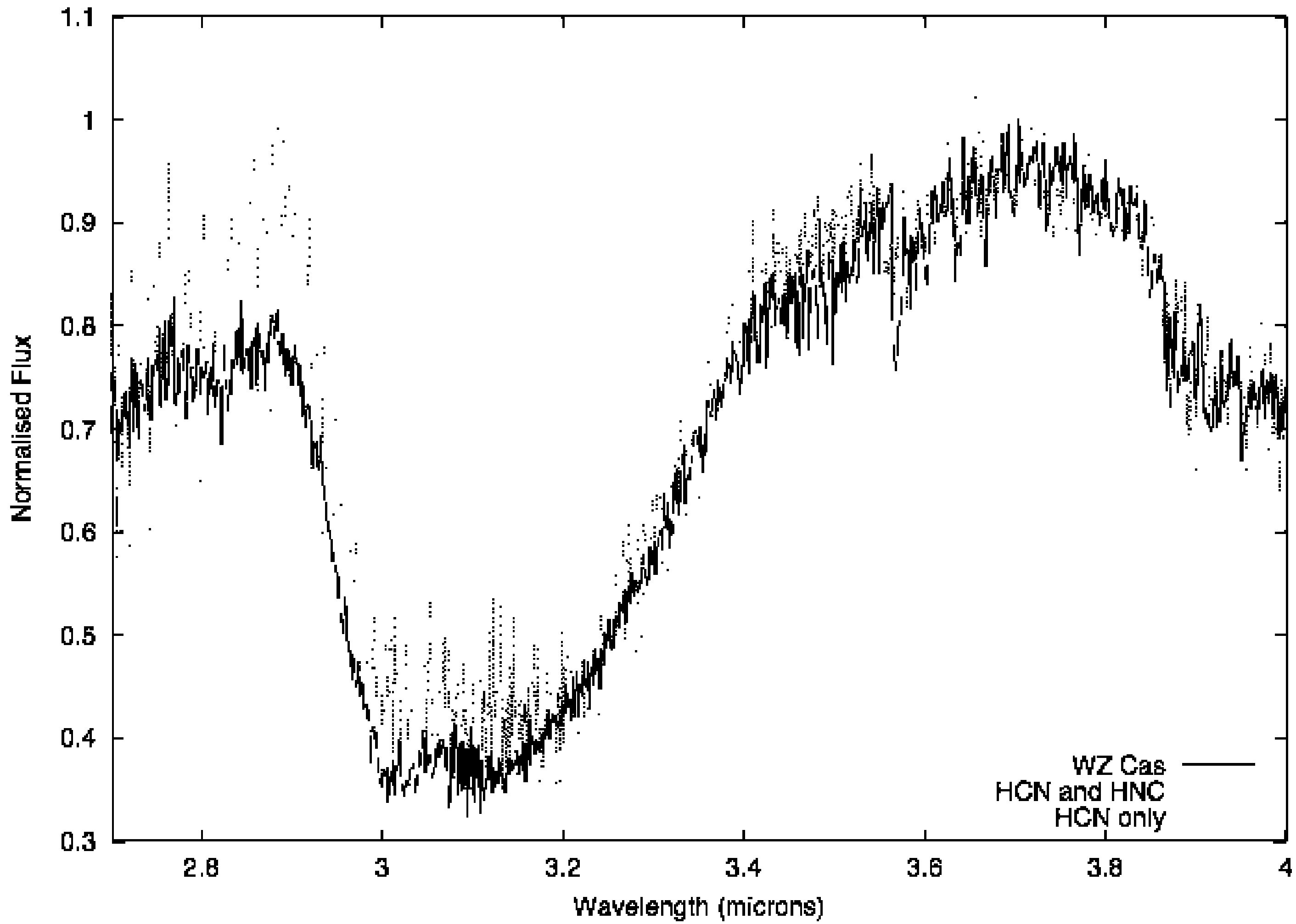
Jones, Pavlenko, Viti et al. 2002

Water vapour lists do a great job beyond 2 ⌠m



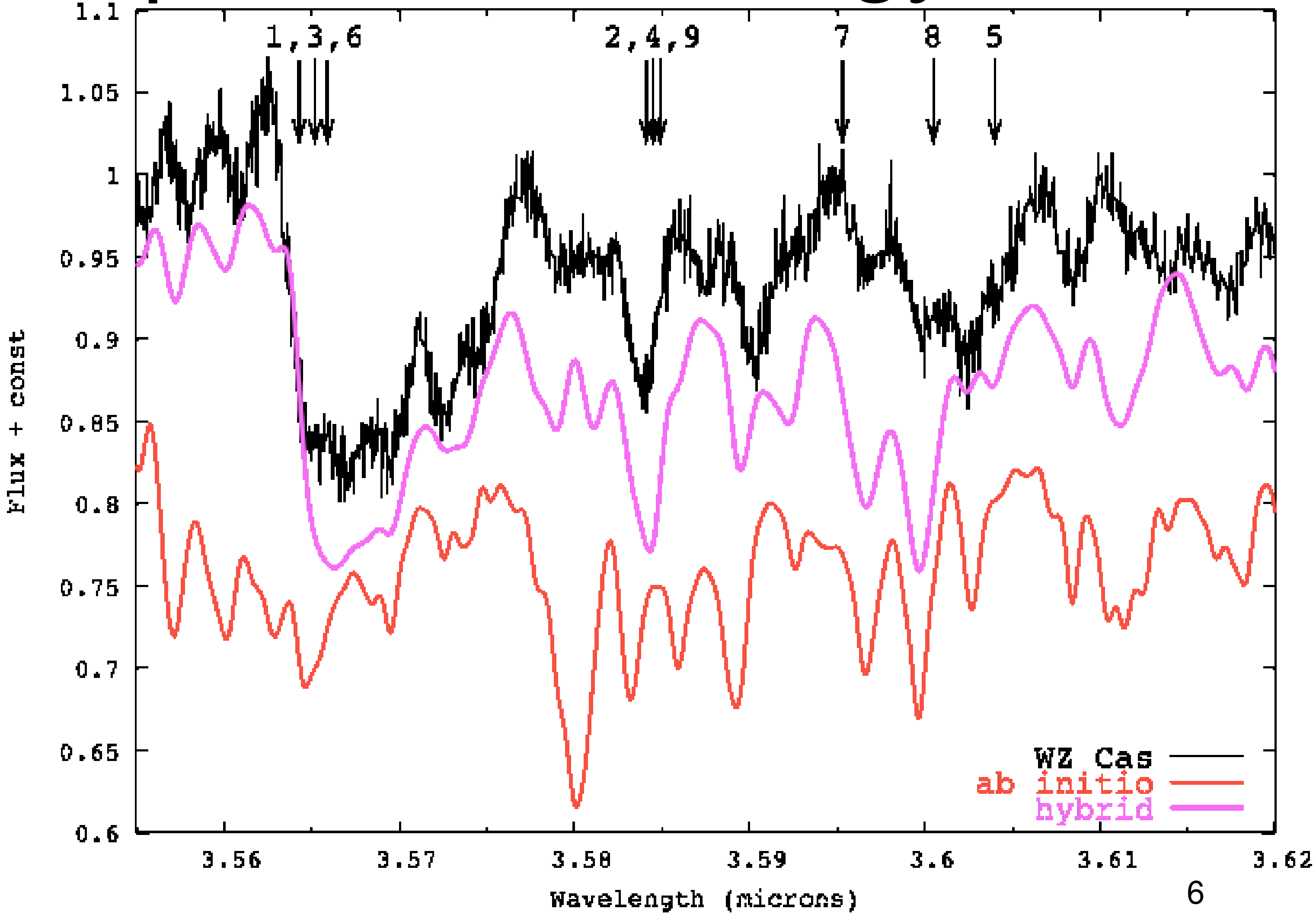
Jones, Pavlenko, Viti et al. 2002

HCN/HNC - start to model C-rich stars

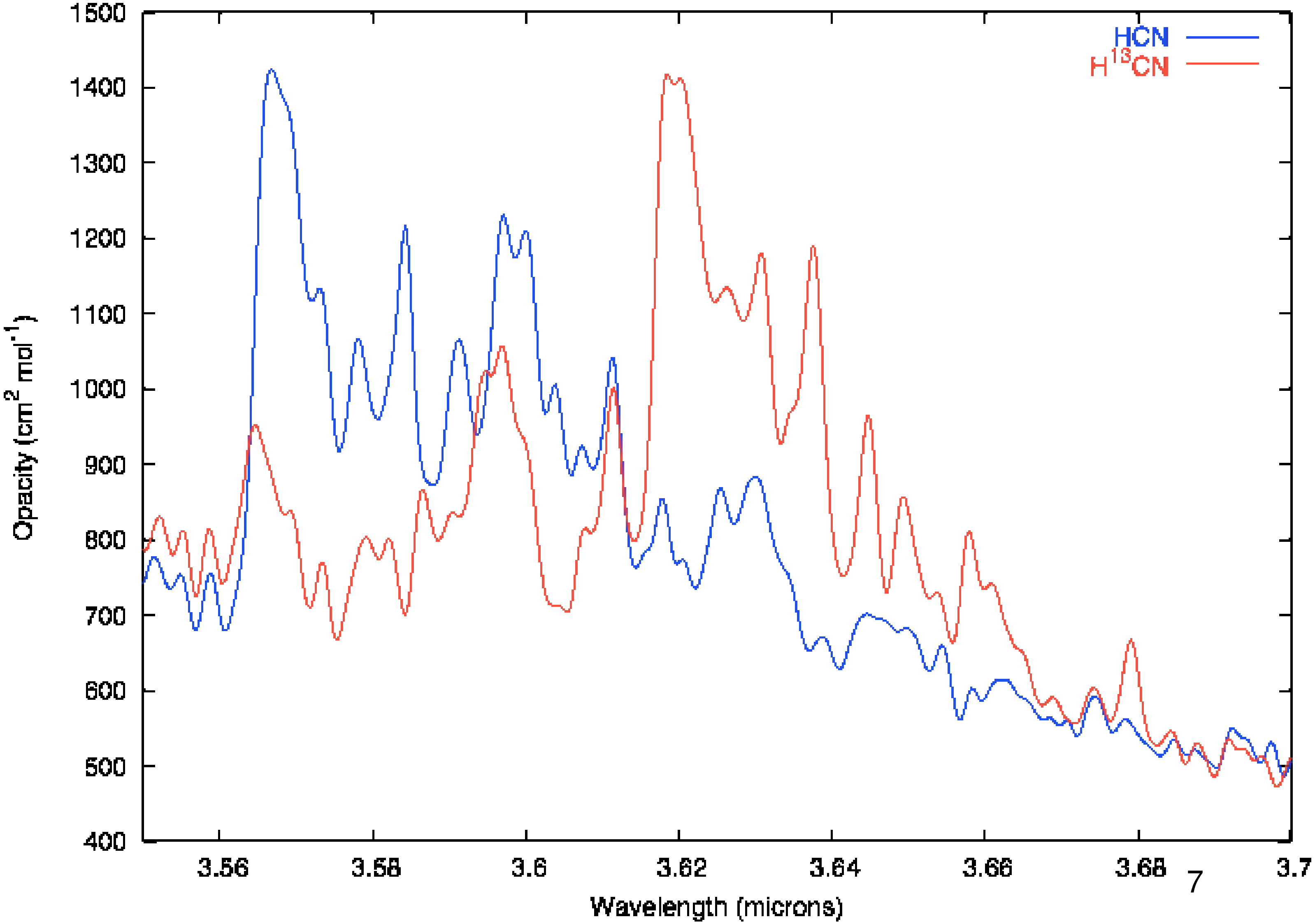


Harris, Pavlenko, Jones et al. (2003)

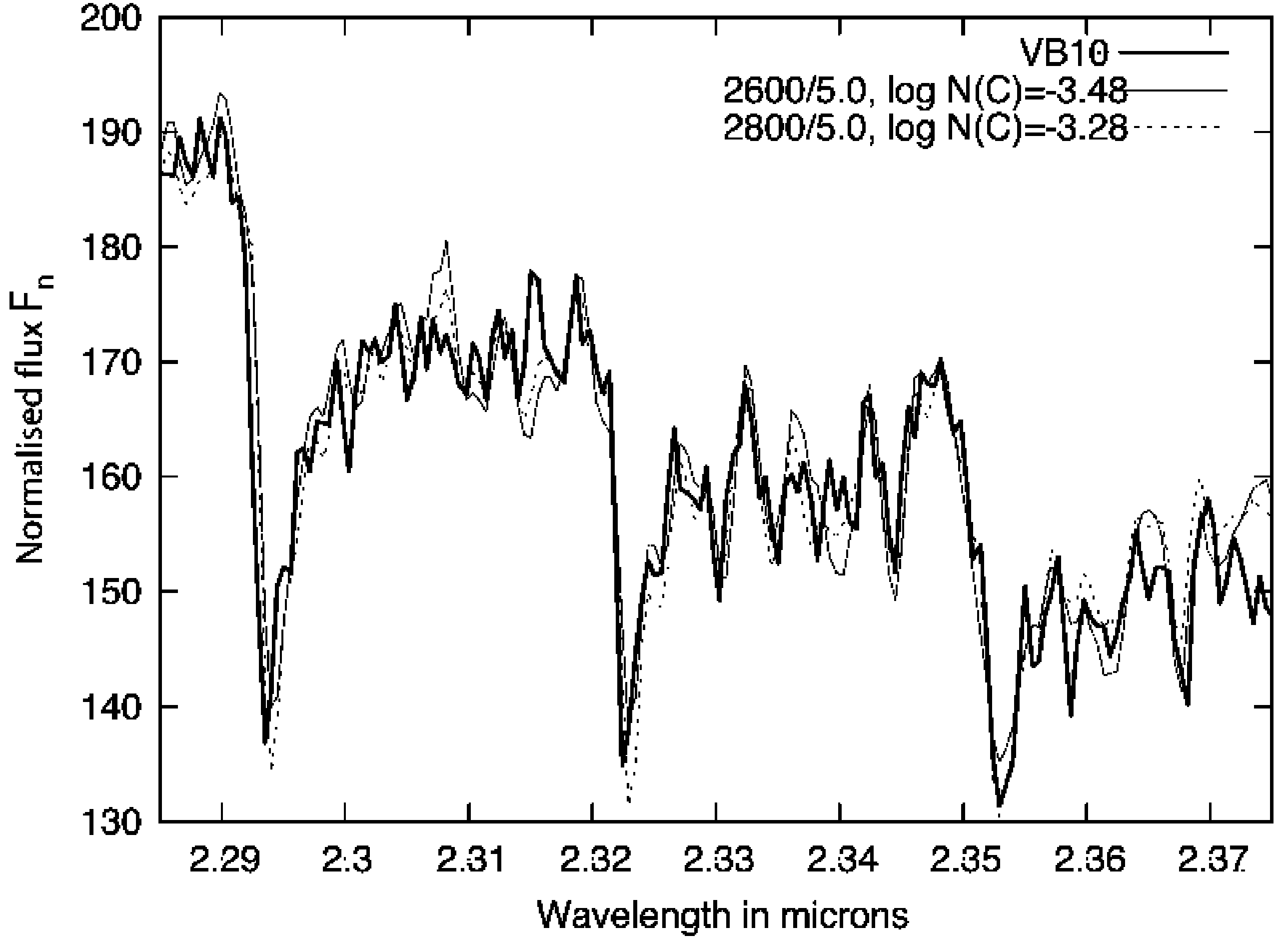
Improving fit to hot bands with experimental energy levels



Potential to measure $^{12}C/^{13}C$

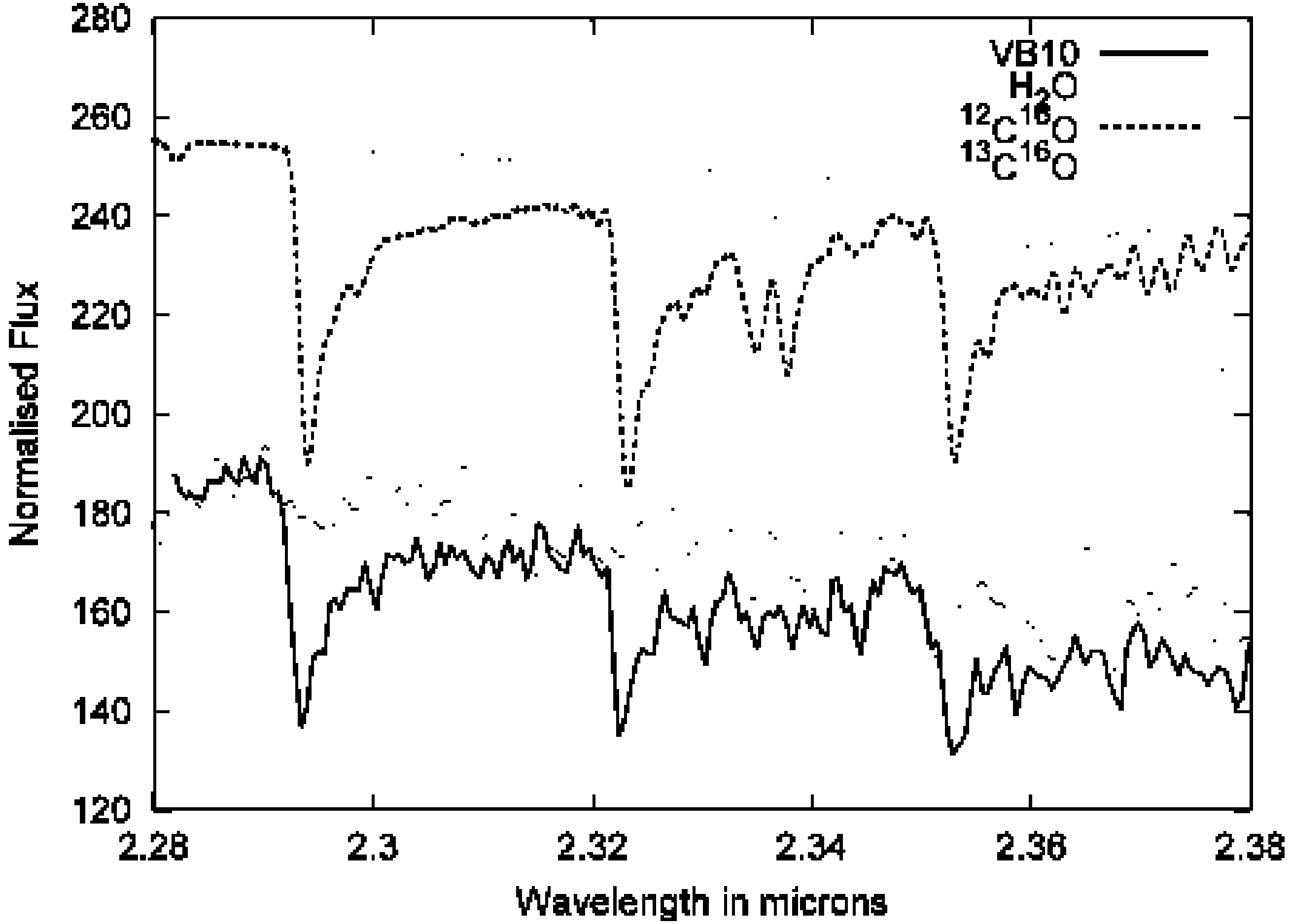


CO list excellent



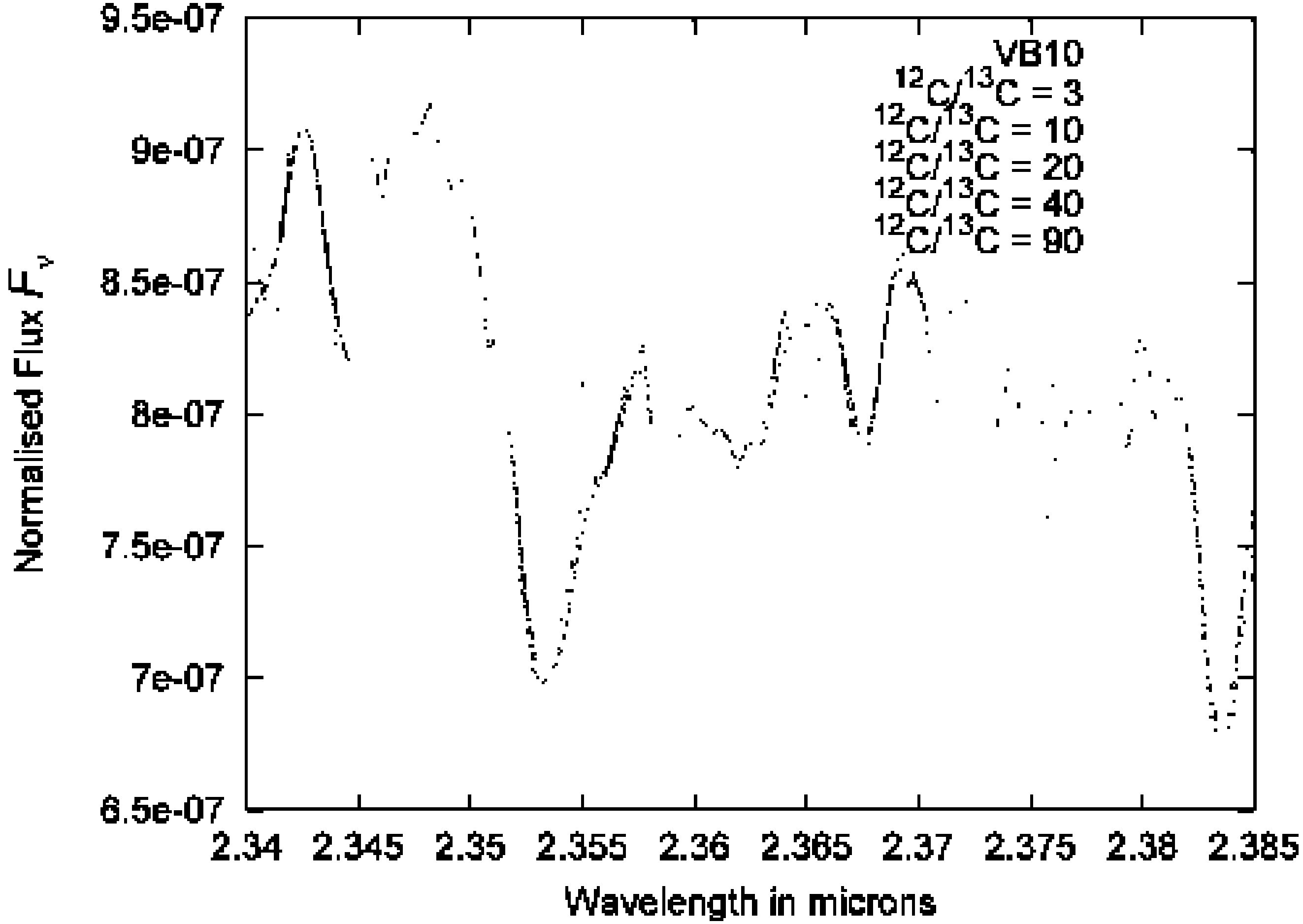
Pavlenko & Jones (2002)

CO list excellent - but need to be careful



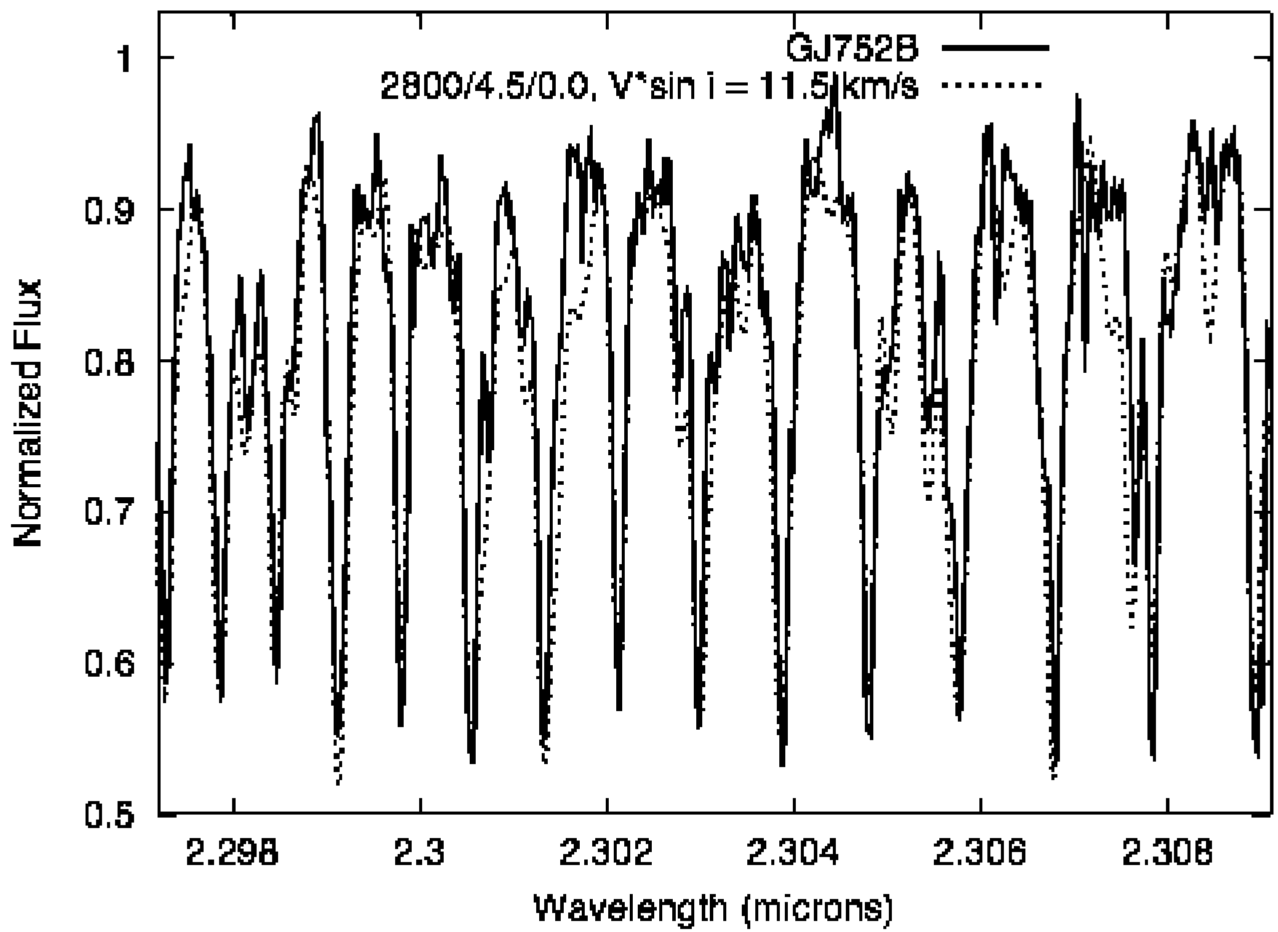
Pavlenko & Jones (2002)

$C^{12}O/C^{13}O$ determination



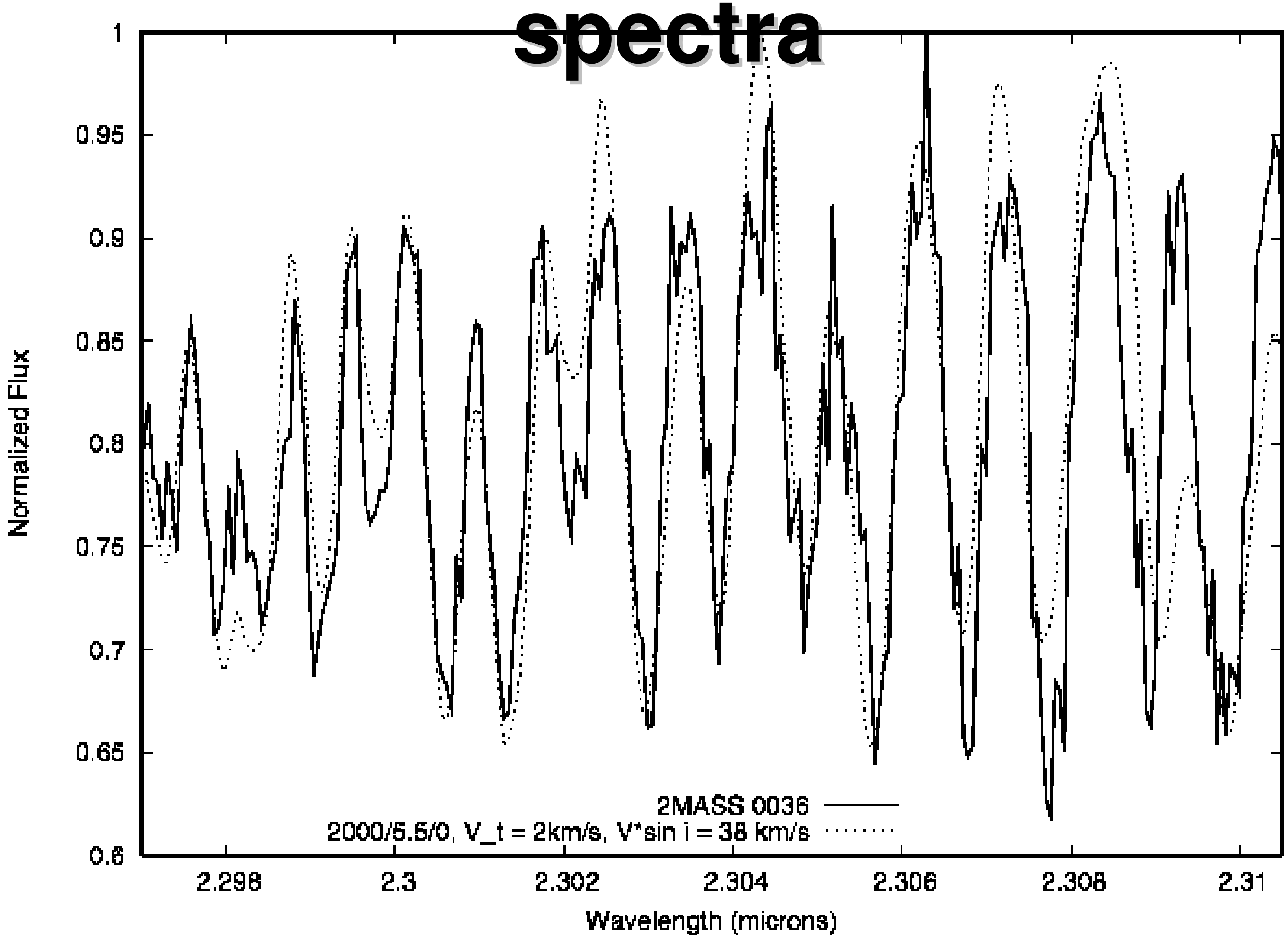
Pavlenko & Jones (2002)

Derive log g, V sin i, [M/H]



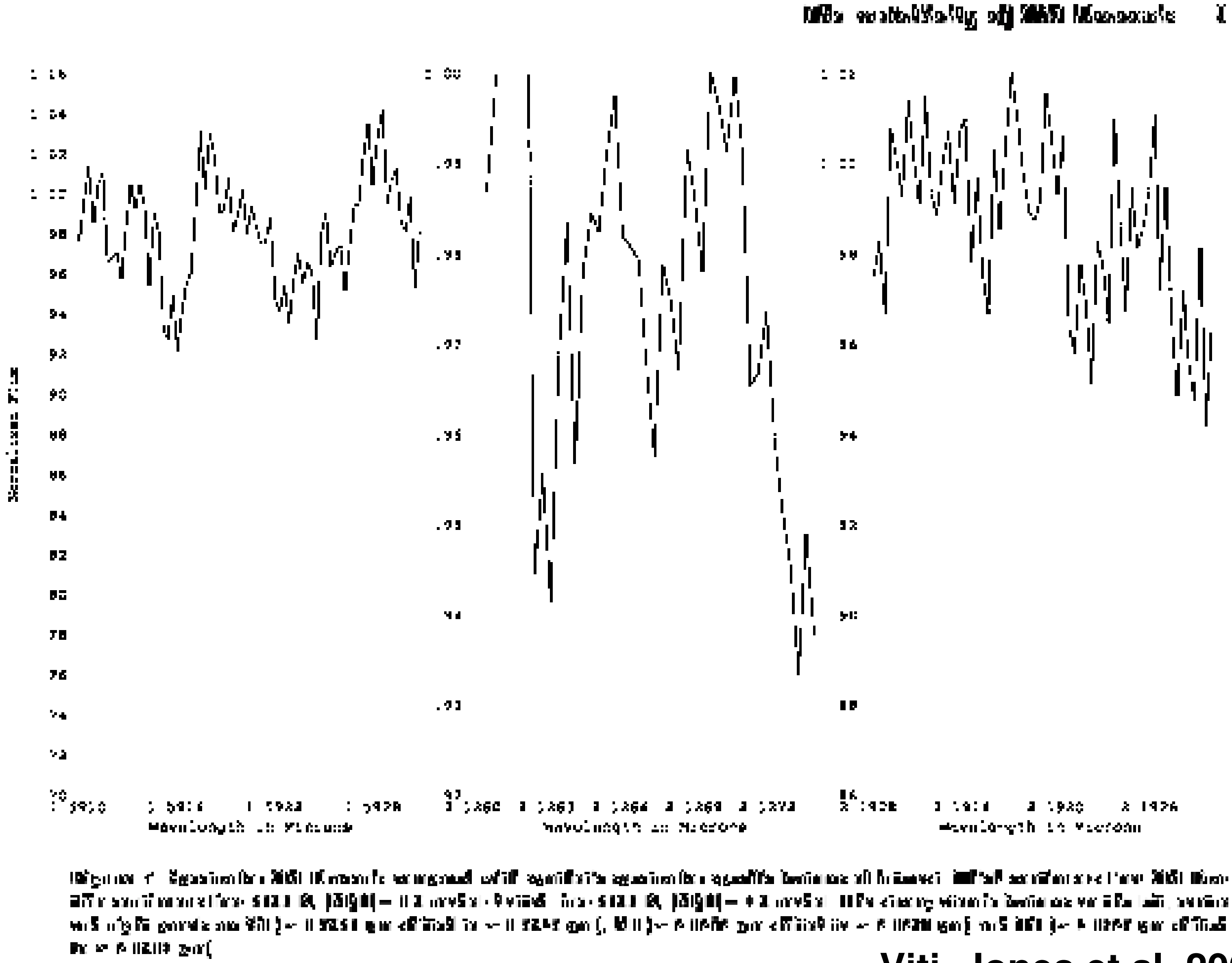
Jones, Pavlenko, Viti et al. 2005

Derive reliable parameters from similar pieces of high resolution spectra



Jones, Pavlenko, Viti et al. 2005

Poor fits to atomic lines in IR



Viti, Jones et al. 2002

PoSSO
(Physics of Sub-Stellar Objects)

intend to qualify for ‘EU’ network

University College London, University of Hertfordshire, Imperial College, University of Burgundy, Centre de Recherche Astronomique de Lyon, Instituto de Astrofisica de Canaries, Lund University, National Institute of Standards and Technology, National Solar Observatory, Hamburger Sternwarte, Niels Bohr Institute, Universitet van Amsterdam, Poznan University of Technology, Institut D’Astrophysique de Paris, Main Astronomical Observatory of Ukraine, University of California Los Angeles, Centre for Astrophysics

1) Identify 1.0-2.5 ⌠m features

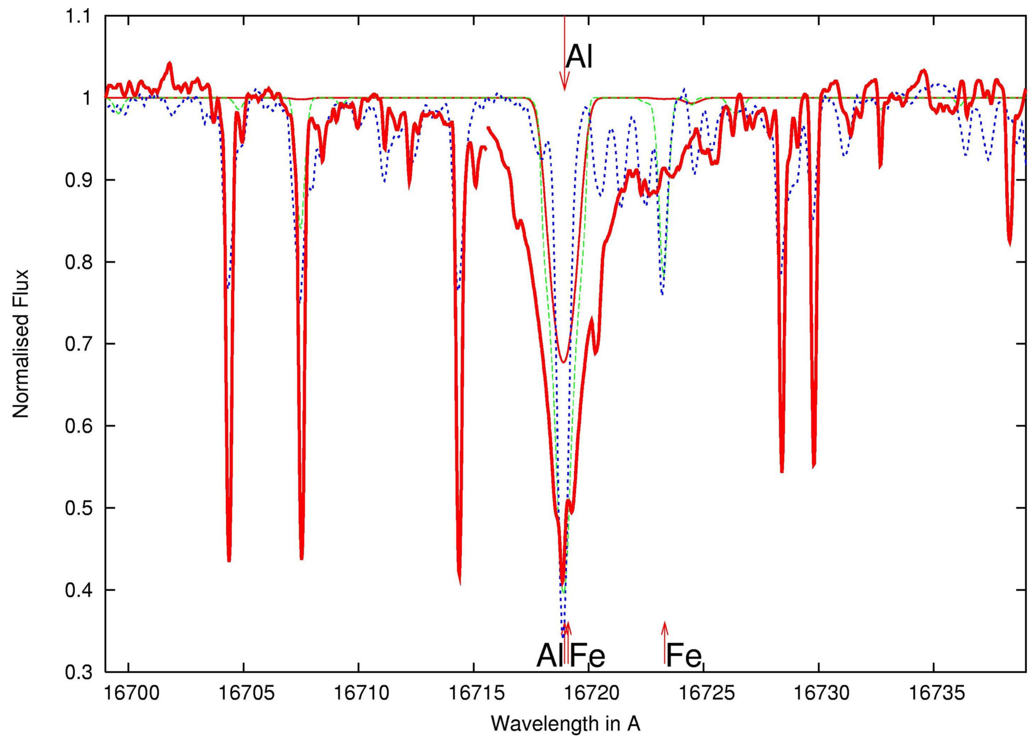
Spectral atlases from Hinkle, Wallace & Livingston

- Dark umbral sunspot (3300K)
- Arcuturus (4000K)

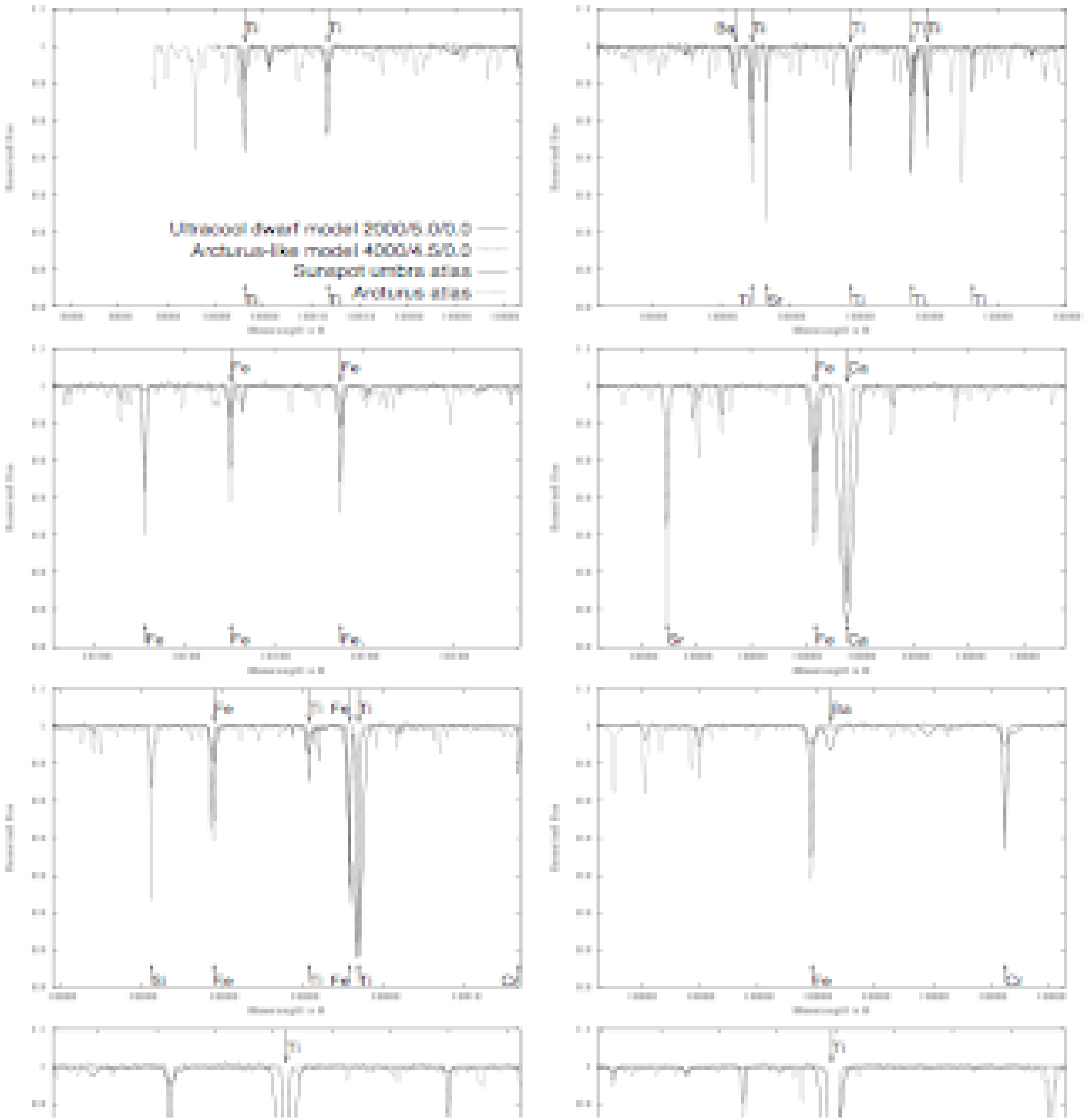
Synthetic spectra from Allard, Hauschildt & Pavlenko

- 2000 and 4000 K

Prioritised lines based on strength in sunspot umbral and synthetic spectra from 1-2.5 μm



Lyubchik, Jones, Pavlenko, Viti et al. 2004 www.astro.livjm.ac.uk/~hraj/spectratlas


Ultracool dwarf model 2000/5.0/0.0
Arcturus-like model 4000/4.5/0.0
Sunspot umbra atlas
Arcturus atlas
Ti
Fe
Ca
Ba
Si
Cr

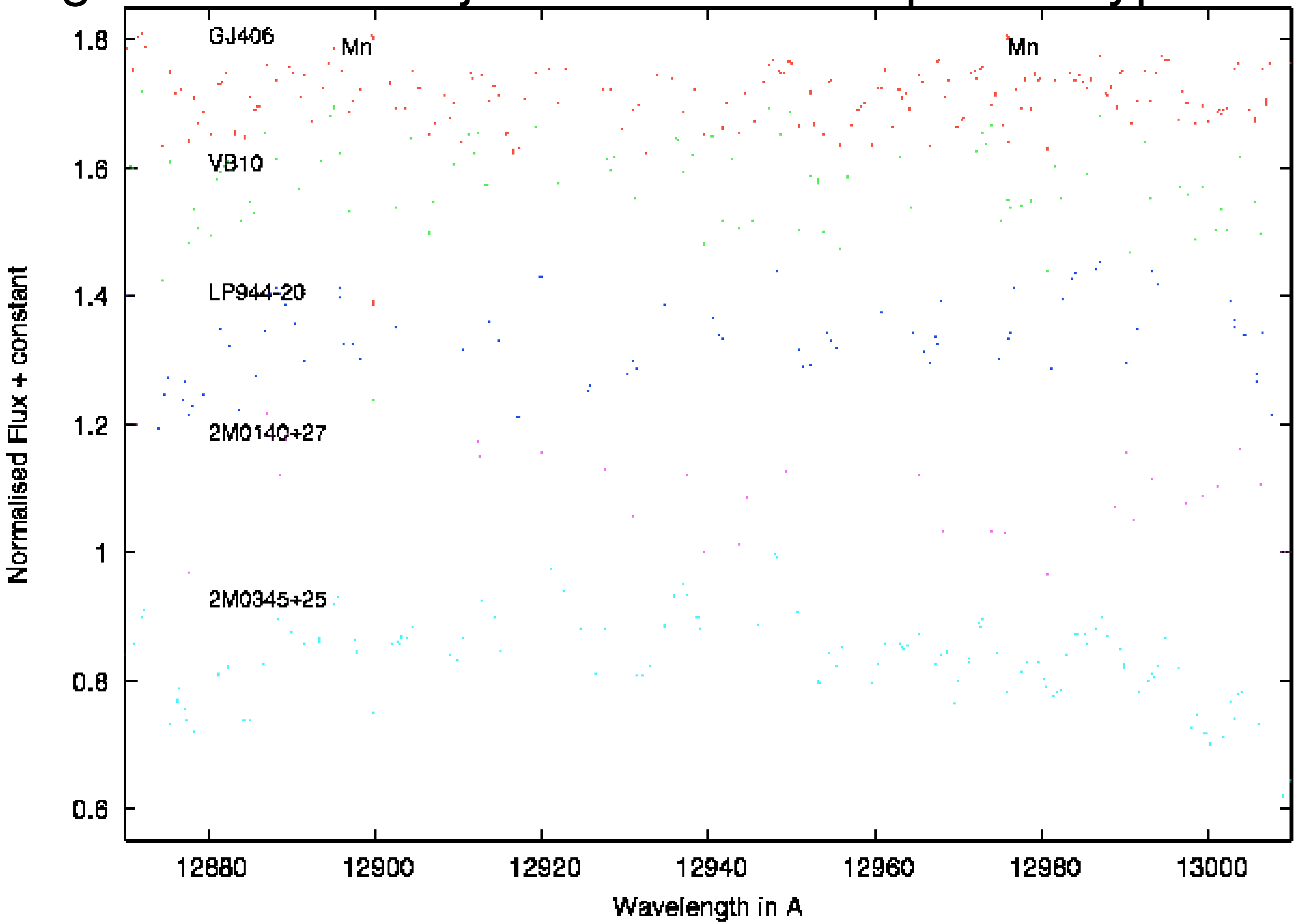
Pr	λ, Å	Atom	UCDS	ALS	ArAs	SeAs
1	11690.220	K I	0.913	0.483	0.40bl	~0.48
1	11769.639	K I	0.961	0.601	0.70	0.65
1	11772.838	K I	0.904	0.468	0.42	~0.55
3	11780.543	Ti I	0.522	0.736	0.75	0.82
3	11783.267	Fe I	0.485	0.453	0.40	0.67
3	11797.179	Ti I	0.779	0.757	0.75	0.82
2	11828.185	Mg I	0.705	0.430	0.21	0.50
1	11882.847	Fe I	0.277	0.353	0.29	0.55
1	11884.085	Fe I	0.364	0.398	0.33	0.57
2	11892.878	Ti I	0.731	0.606	0.57	0.70
2	11949.542	Ti I	0.700	0.571	0.55	0.72
	11955.955	Ca I	0.878	0.620	0.85	0.82
1	11973.050	Fe I	0.225	0.334	0.28	–
1	11973.848	Ti I	0.498	0.574	0.53	~0.50
1	12432.273	K I	0.080	0.582	0.67	0.65
2	12484.618	Ti I	0.793	0.661	0.98	0.98
1	12522.134	K I	0.022	0.528	0.57	0.60
3	12526.081	K I	0.429	0.989	0.97	0.99
2	12556.999	Fe I	0.790	0.606	0.62	0.80
	12600.277	Ti I	0.862	0.748	0.75	0.80
	12671.092	Ti I	0.864	0.746	0.75	0.83
2	12679.144	Na I	0.656	0.589	0.66	0.65
2	12679.224	Na I	0.658	0.604	0.66	0.65
	12738.383	Ti I	0.914	0.726	0.75	0.75
	12816.046	Ca I	0.857	0.615	0.79	0.76
2	12821.672	Ti I	0.628	0.519	0.45	0.67
	12823.868	Ca I	0.889	0.671	0.83	0.78
2	12831.442	Ti I	0.645	0.527	0.50	0.70
2	12847.033	Ti I	0.621	0.512	0.50	0.70
2	12879.769	Fe I	0.740	0.571	0.55	0.75
1	12899.764	Mn I	0.468	0.444	0.22	0.57
	12975.912	Mn I	0.851	0.587	0.46	0.75
	13011.895	Ti I	0.852	0.729	0.75	0.77
	13077.263	Ti I	0.896	0.798	0.70	0.80
1	13123.410	Al I	0.433	0.390	0.21	0.45
1	13150.753	Al I	0.500	0.415	0.25	0.52
	13233.279	*Rb I*	*0.442*	*1.000*	*1.00*	*0.88*
	13281.485	Mn I	0.902	0.632	0.55	0.82
2	13293.795	Mn I	0.619	0.497	0.33	0.72
1	13318.944	Mn I	0.547	0.465	0.27	0.67
	13271.782	*Lu I*	*0.385*	*0.718*	*1.00*	

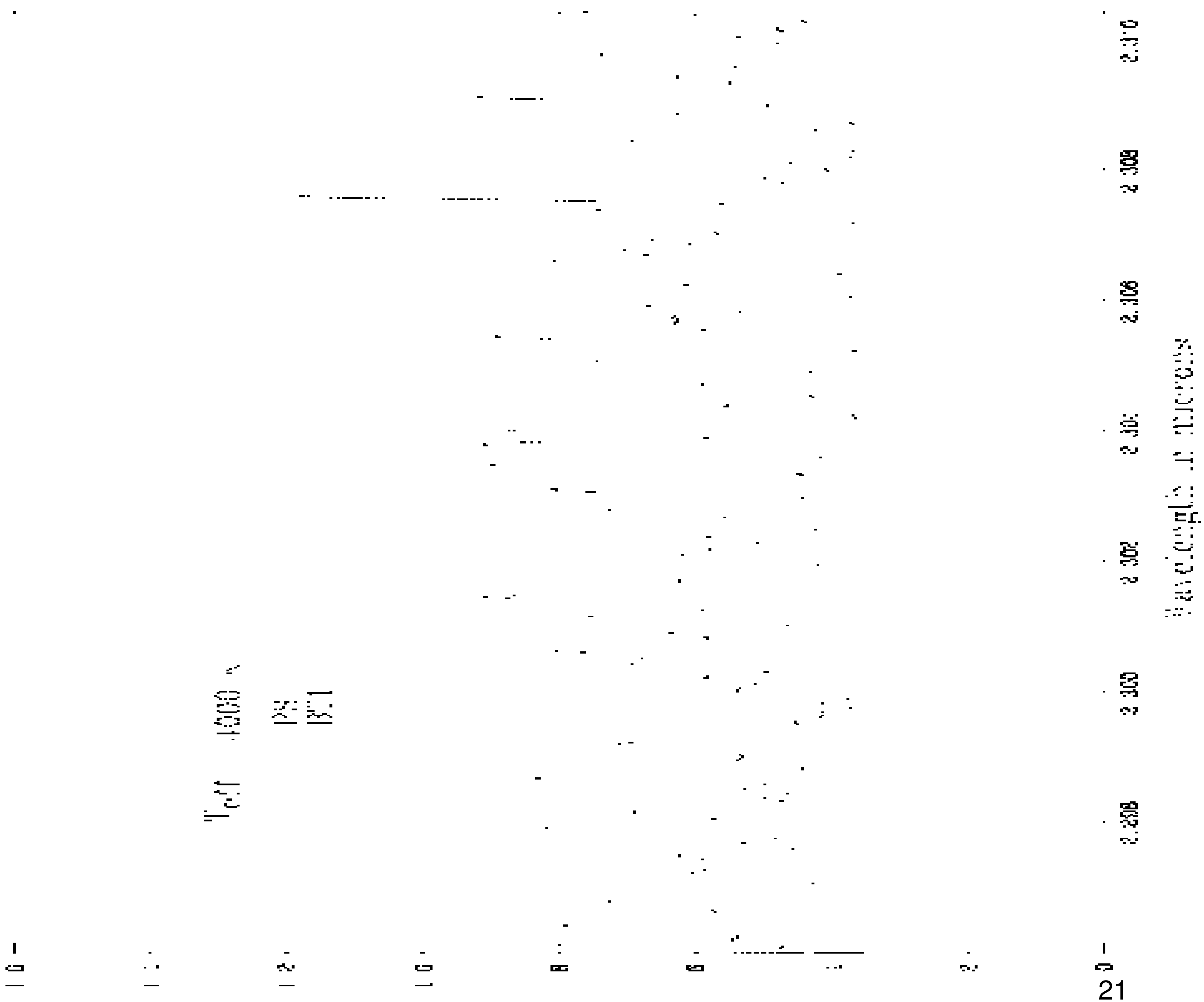
Pr	λ, Å	Atom	UCDS	ALS	ArAs	SeAs
	14423.053	V I	0.875	0.807	⊕	⊕
	14752.879	*Rb I*	*0.268*	*0.968*	⊕	⊕
2	14767.484	Na I	0.786	0.706	⊕	⊕
2	14779.732	Na I	0.706	0.615	0.99	0.57bl
	14999.917	*Ba I*	*0.435*	*0.952*	*1.00*	*0.85*
2	15024.992	Mg I	0.780	0.399	0.24	0.49
	15040.246	Mg I	0.815	0.412	0.24	0.55
	15057.099	Ca I	0.829	0.895	0.97	0.77
2	15077.291	Fe I	0.771	0.545	0.98	0.79
1	15163.067	K I	0.254	0.534	0.67	0.67
1	15163.067	K I	0.254	0.534	0.67	0.67
1	15168.376	K I	0.280	0.572	0.70	0.72
	15288.938	*Rb I*	*0.581*	*0.993*	*1.00*	*0.85*
	15289.966	*Rb I*	*0.288*	*0.949*	*1.00*	*0.90*
2	15334.847	Ti I	0.618	0.436	0.45	0.60
	15490.339	Fe I	0.858	0.642	0.64	1.00
2	15543.756	Ti I	0.628	0.451	0.47	0.65
	15602.842	Ti I	0.867	0.646	0.73	0.72
	15698.979	Ti I	0.855	0.699	0.70	0.75
2	15715.573	Ti I	0.629	0.446	0.50	0.67
	15836.788	Ti I	0.851	0.710	0.73	0.85
2	16136.823	Ca I	0.795	0.474	0.76	0.70
2	16150.763	Ca I	0.695	0.427	0.68	0.67
	16155.236	Ca I	0.829	0.496	0.80	0.80
2	16157.364	Ca I	0.674	0.416	0.67	0.62
2	16197.075	Ca I	0.635	0.398	0.55	0.56
	16204.087	Ca I	0.825	0.494	0.85	
2	16388.857	Na I	0.771	0.770	0.95	0.87
	16454.533	Si I	0.868	0.585	0.98	0.93
2	16718.957	Al I	0.678	0.398	0.55	0.45bl
2	16750.564	Al I	0.626	0.380	0.27	0.50
2	17108.662	Mg I	0.799	0.403	0.27	0.47
	17122.889	*Y I*	*0.581*	*0.489*	*0.99*	*0.96*
	17422.836	*Y I*	*0.537*	*0.431*	*1.00*	*0.90*
	17663.289	*Y I*	*0.524*	*0.425*	*0.95*	*0.98*
	17903.229	*Y I*	*0.488*	*0.558*	*1.00*	
	18049.897	*Y I*	*0.473*	*0.537*	*1.00*	
	18115.295	*Y I*	*0.458*	*0.533*	*1.00*	–
	18181.758	*Y I*	*0.450*	*0.539*	–	–
	18224.975	*Lu I*	*0.377*	*0.732*	*1.00*	
	18282.682	*Y I*	*0.583*	*0.411*	⊕	⊕

The shopping list

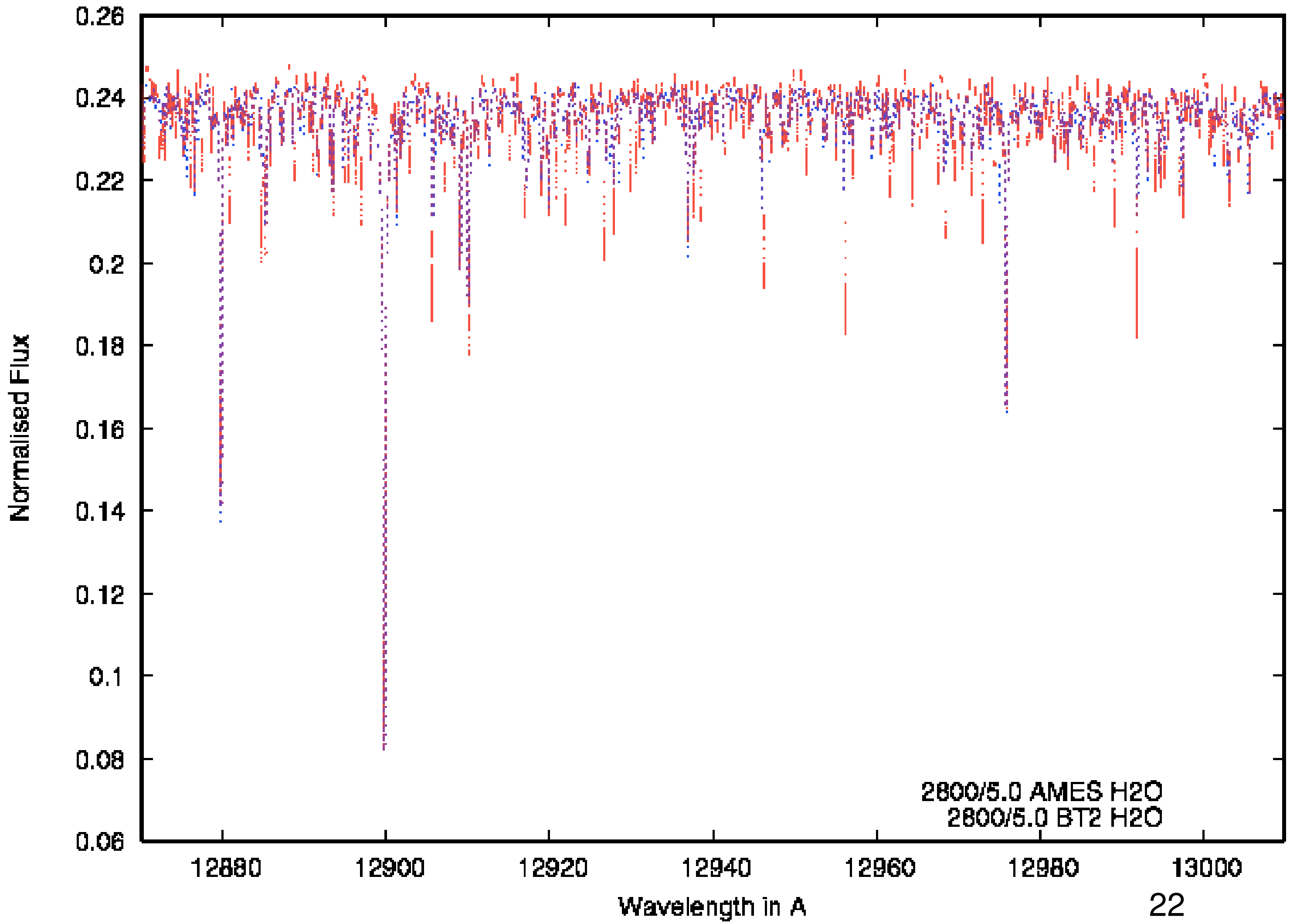
Metal-free	Oxygen-rich	Carbon-rich
HeH^+, H_3^+, **LiH**, H_2, H_2 CIA, **Molecular line broadening**	H_2,H_3^+,**H_2O**, TiO, CO, CH, OH, **VO, MgH, FeH, CaH, CaOH, AlH, CrH, SiH, TiH, AlO, MgO, NH_3, CH_4, dust (ZrO_2 , Mg_2SiO_4, $MgSiO_3$, Al_2O_3, $CaTiO_3$, Ti_2O_6, Ti_4O_7, Fe, Ni, Cu ...), NaI, FeI, MnI, ScI, FeI, NiI, TiI, MgI, AlI, CrI, KI, SiI, HeI, Line broadening - alkali & molecular**	H_2, CO, HCN, CN, CH, CS, **CH_4, C_3, C_2H_2, YO, ZrO, AlH, dust, Molecular line broadening**

‘.. presumably molecular features .. not noise .. consistent changes between objects of different spectral types’

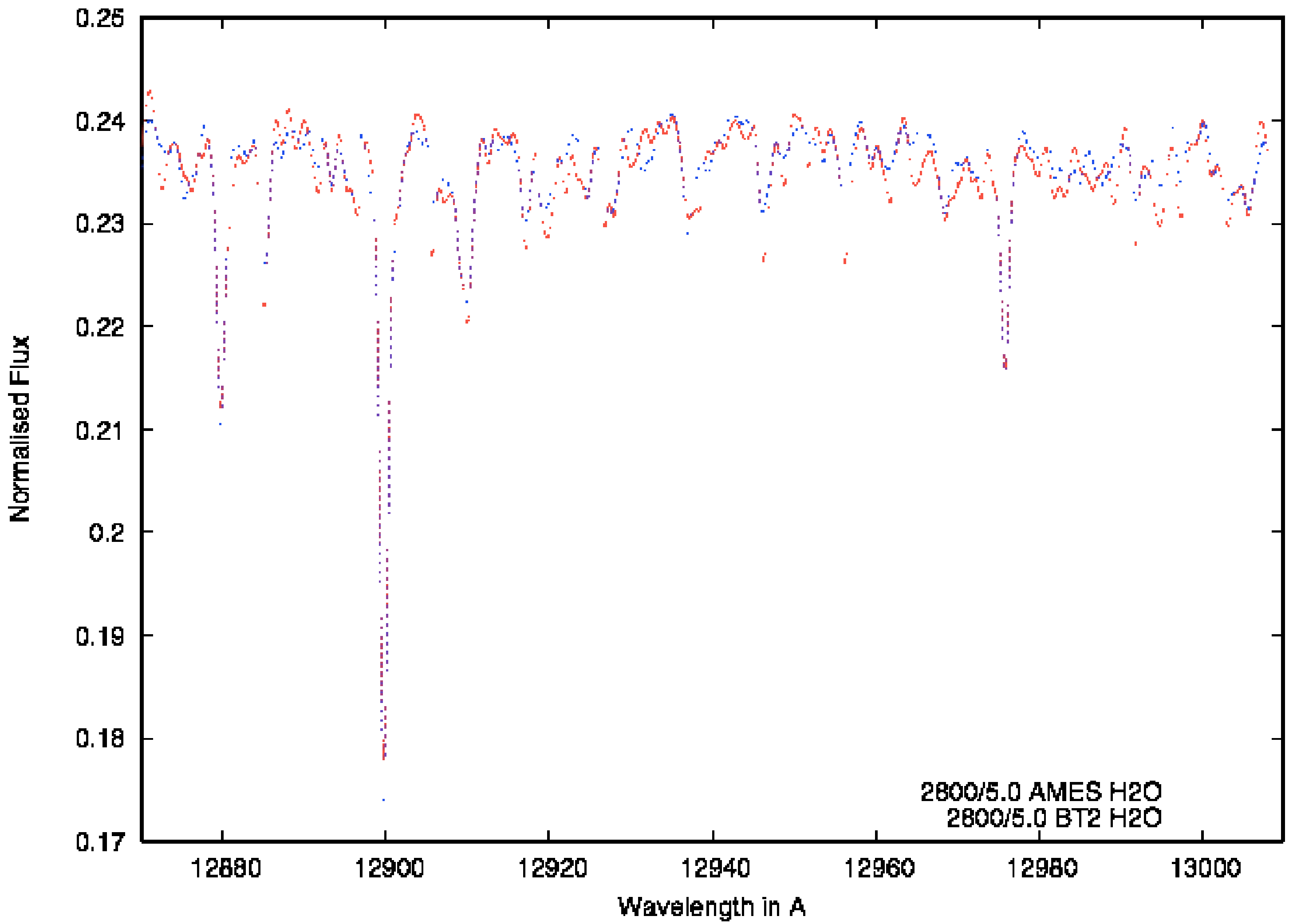




AMES/UCL water lists



Relatively minor differences



PoSSO Progress

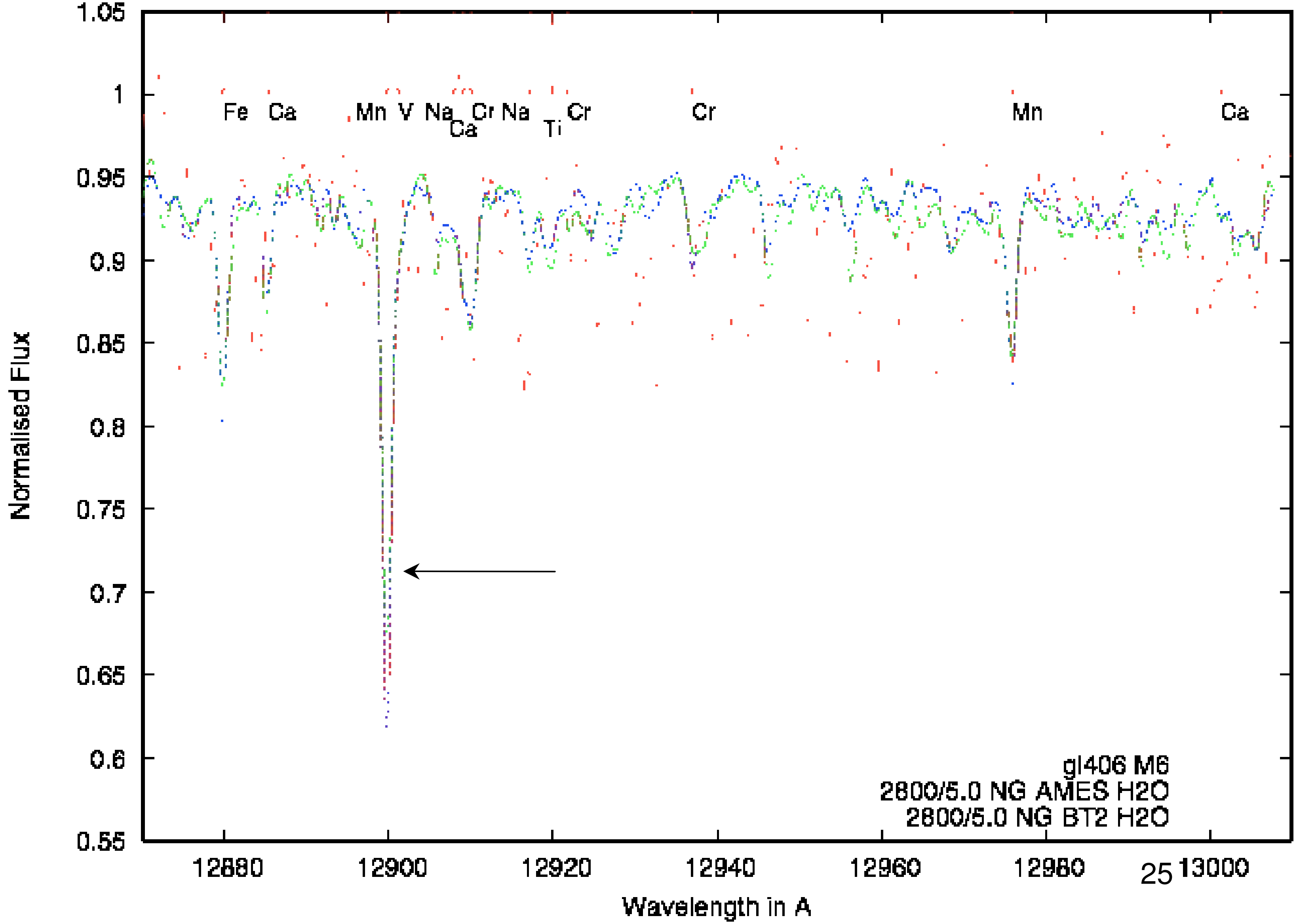
Atomic

- Measured - Mn & Ti
- Promising - Al & Cr
- Too hard - Na and K
- Near future - Sc, Fe, Y, Lu

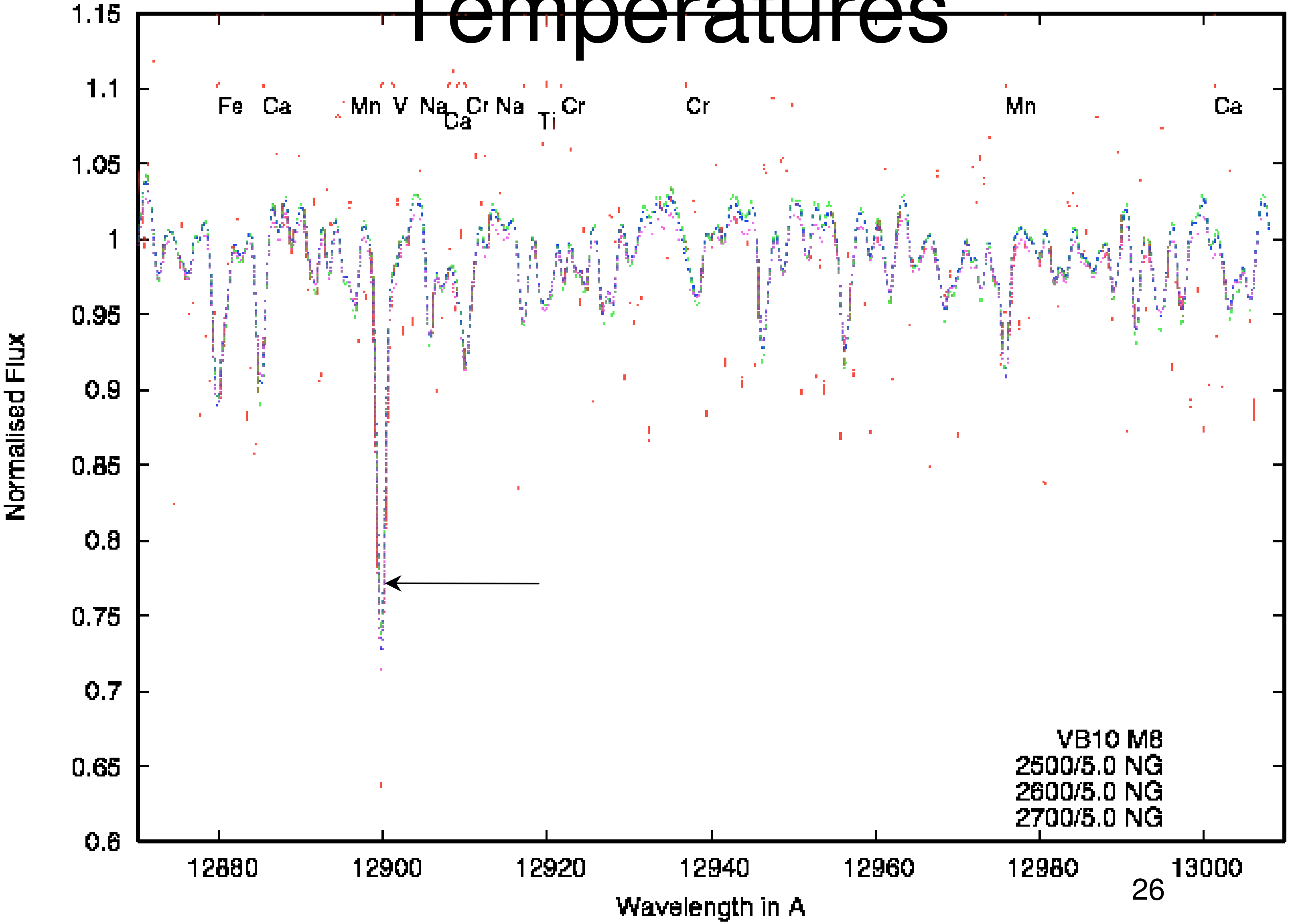
Molecular

- Computed - H_2O, HCN/HNC, H_3^+, TiO, VO,CaH
- Near future - NH_3

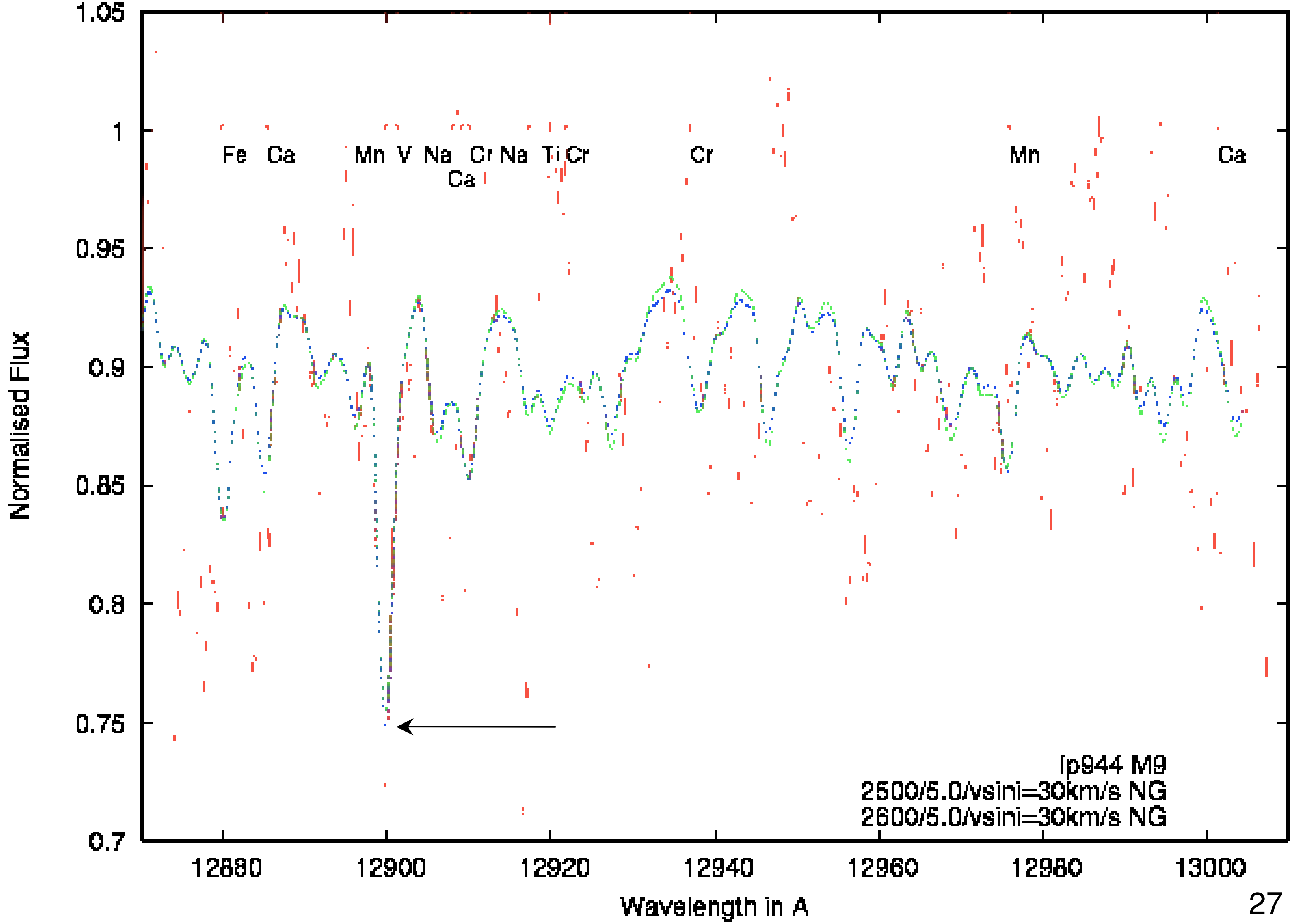
At least Mn ‘fits’

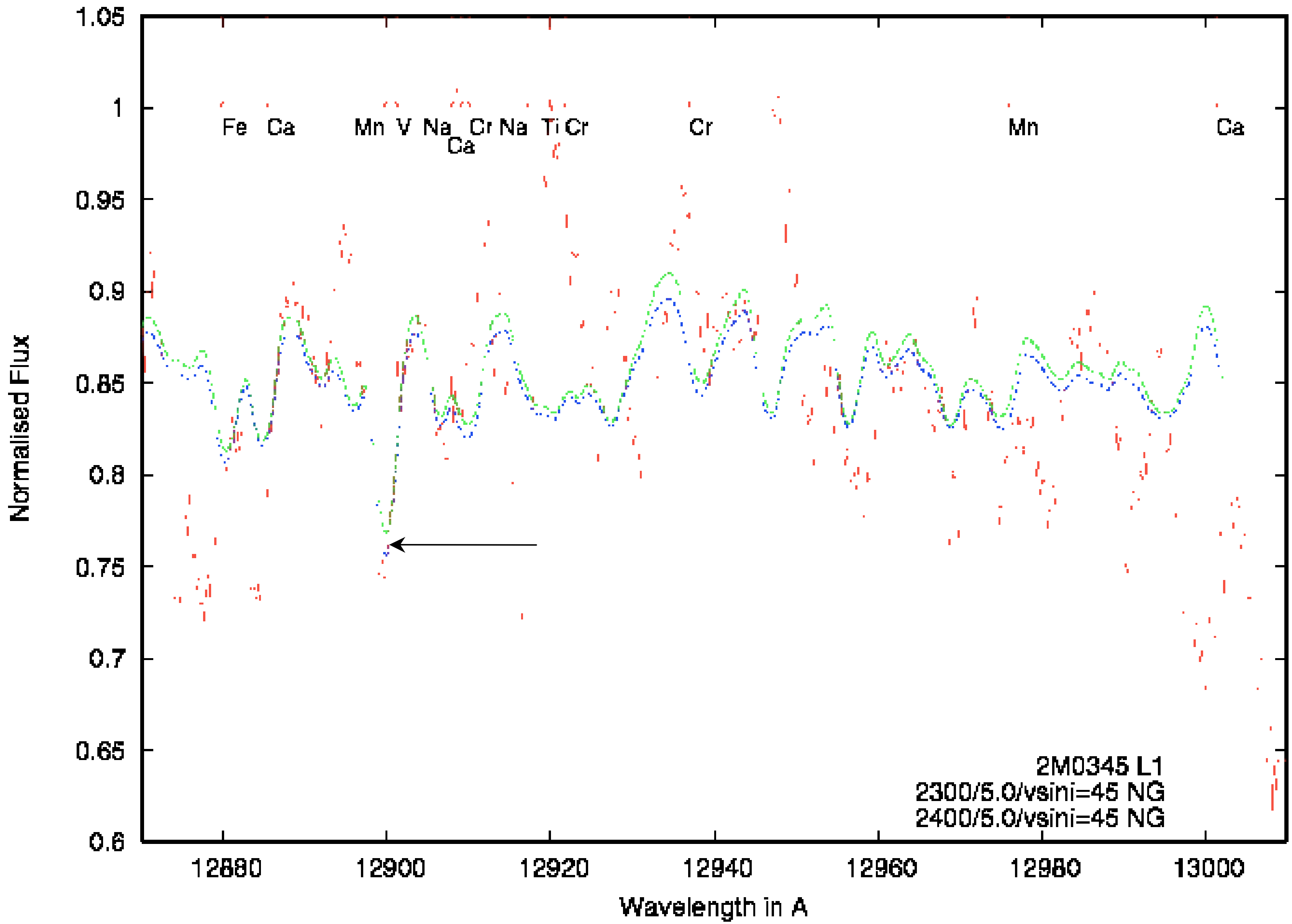


Worse towards lower Temperatures

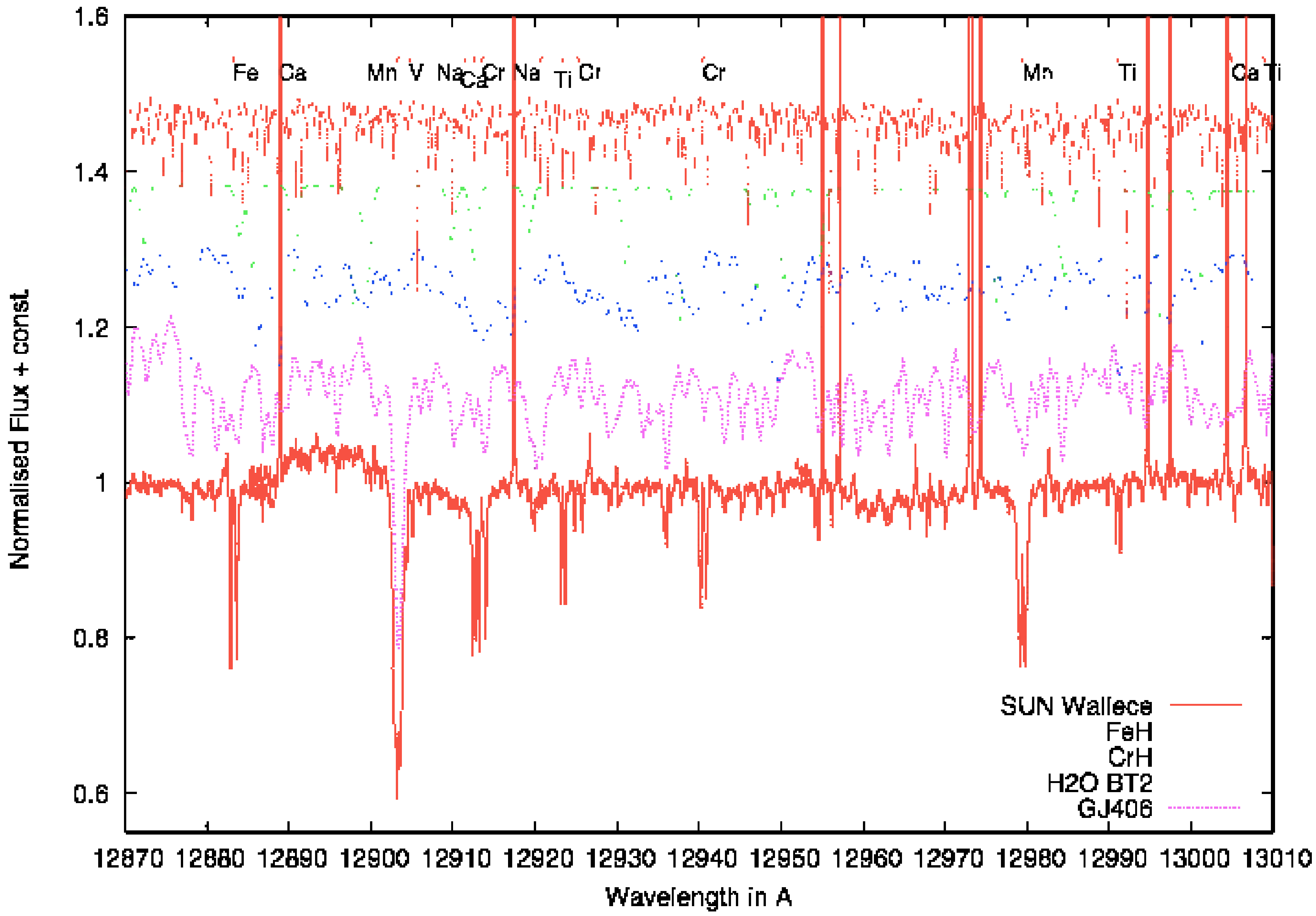


Rotation emphasizes problems



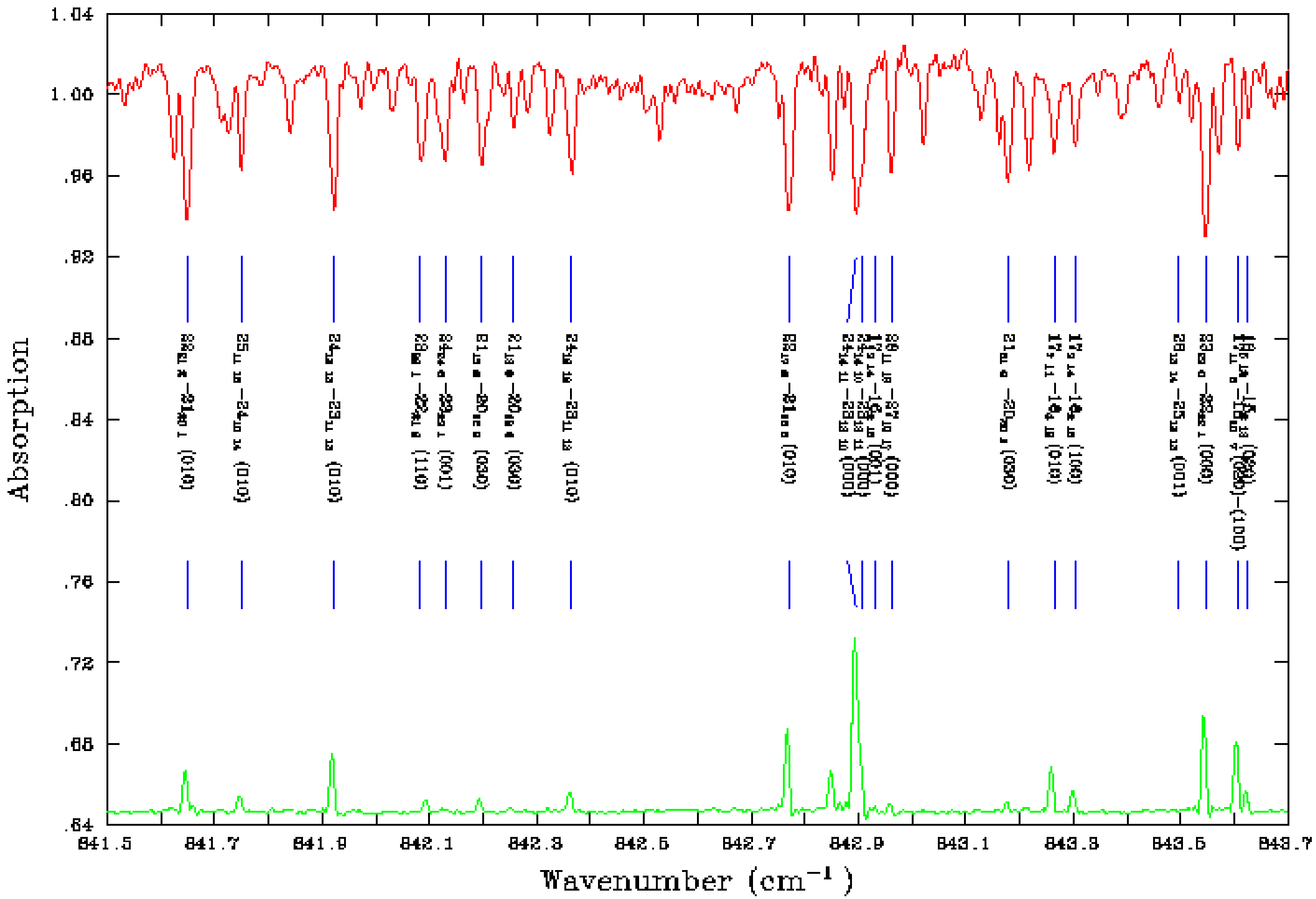


Fe
Ca
Mn
V
Na
Ca
Cr
Na
Ti
Cr
Cr
Mn
Ca
2M0345 L1
2300/5.0/vsini=45 NG
2400/5.0/vsini=45 NG
Normalised Flux
Wavelength in A
1.05
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
12880
12900
12920
12940
12960
12980
13000

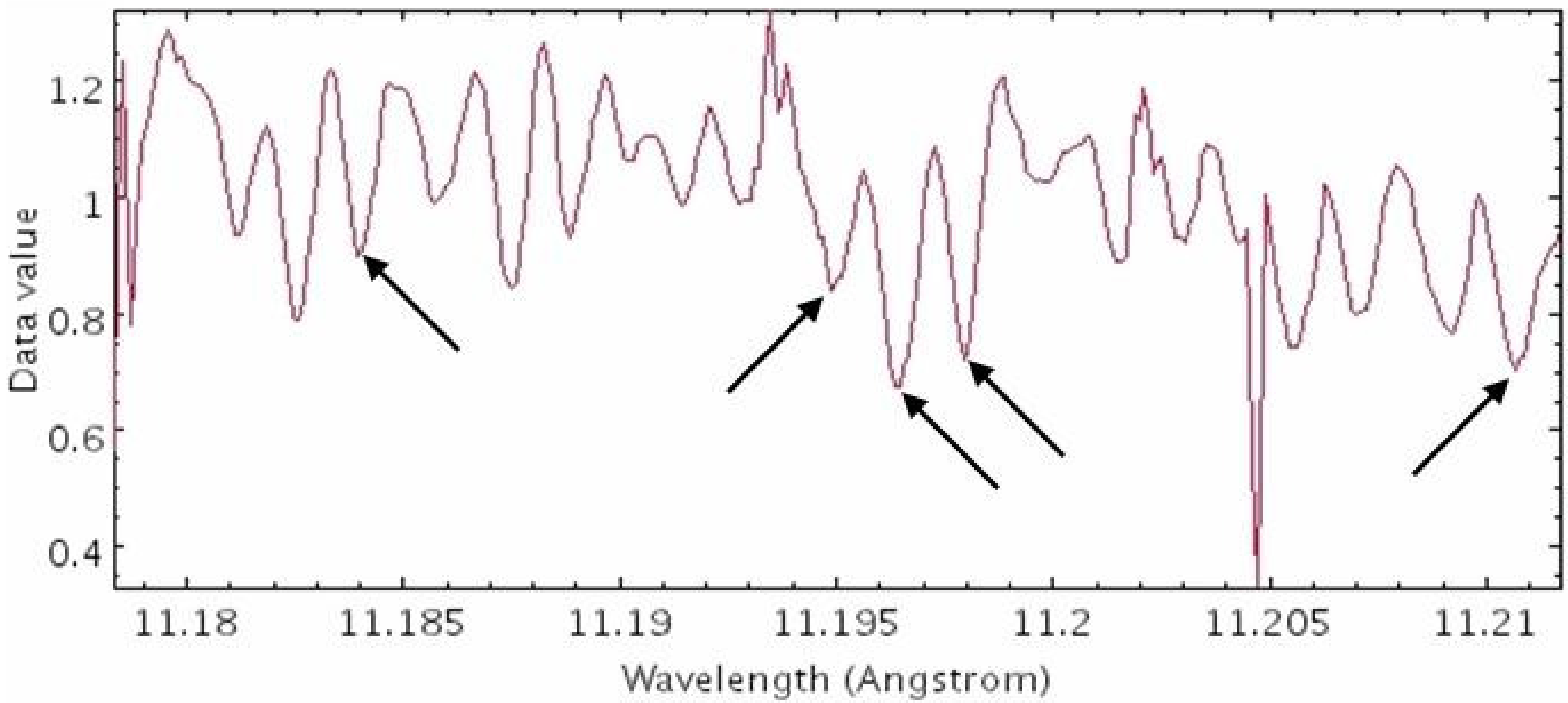

Fe
Ca
Mn
V
Na
Ca
Cr
Na
Ti
Cr
Cr
Mn
Ti
Ca
Ti
1.6
1.4
1.2
1
0.8
0.6
Normalised Flux + const
SUN Wallece
FeH
CrH
H2O BT2
GJ406
12870
12880
12890
12900
12910
12920
12930
12940
12950
12960
12970
12980
12990
13000
13010
Wavelength in A

Atom/molecule	Wavelength, A(vac)	GJ406	Solar Umbra
H_2O+FeH	12876.5	blended by FeH band	+
FeH+H_2O	12877		
FeH	12877–12878.5	+	-/+
FeH+H_2O(wing)	12881.2	+/-	+/-
H_2O	12882.5	+	-
Fe I	12883.312	??	+
H_2O+CrH+FeH	12883–12884	+	-
FeH+H_2O	12886.8	+	+/-
FeH	12888.0	-/+	-
Ca I	12888.835	?	-(H2O terr.)
FeH+H_2O	12888.9-12890.5	+	+/-
FeH	12892.5	+/-	lines/noise
FeH+H_2O	12894.5	+	+/–
FeH+H_2O	12895.9	+	+/–
??	12900.5	+	-
FeH+H_2O	12901.0	+	+
Mn I	12903.312	+	+
V I	12904.761	in Mn wing	-
H_2O	12906.		
FeH+H_2O(in wings)	12907.0	+	+
CrH+FeH+H_2O	12910.0	+/-	+/-
FeH+H_2O	12910.8		
Na I	12911.485	-	-
Ca I+FeH+CrH	12912.621	+	+
Cr I+FeH+H_2O	12913.610	+/-	+/-
FeH+H_2O	12917.0	+	?
CrH+FeH	12919.2	+	+
Na I+FeH	12920.811	+	-/+
Ti I+FeH	12923.453–12923.7	+	+
Cr I+FeH	12925.360–12925.5	+	+
H_2O	12927.5	+	+
FeH	12928.5–12930	+	-
FeH	12933.2	+	+/-
H_2O(?)	12934.0	+	+/-
H_2O+FeH(wing)	12936.2	+	+
Cr I+H_2O	12940.515	+	+
FeH	12943.3	+	+
FeH+H_2O	12945.2	+	+

Identify water lines in sunspots

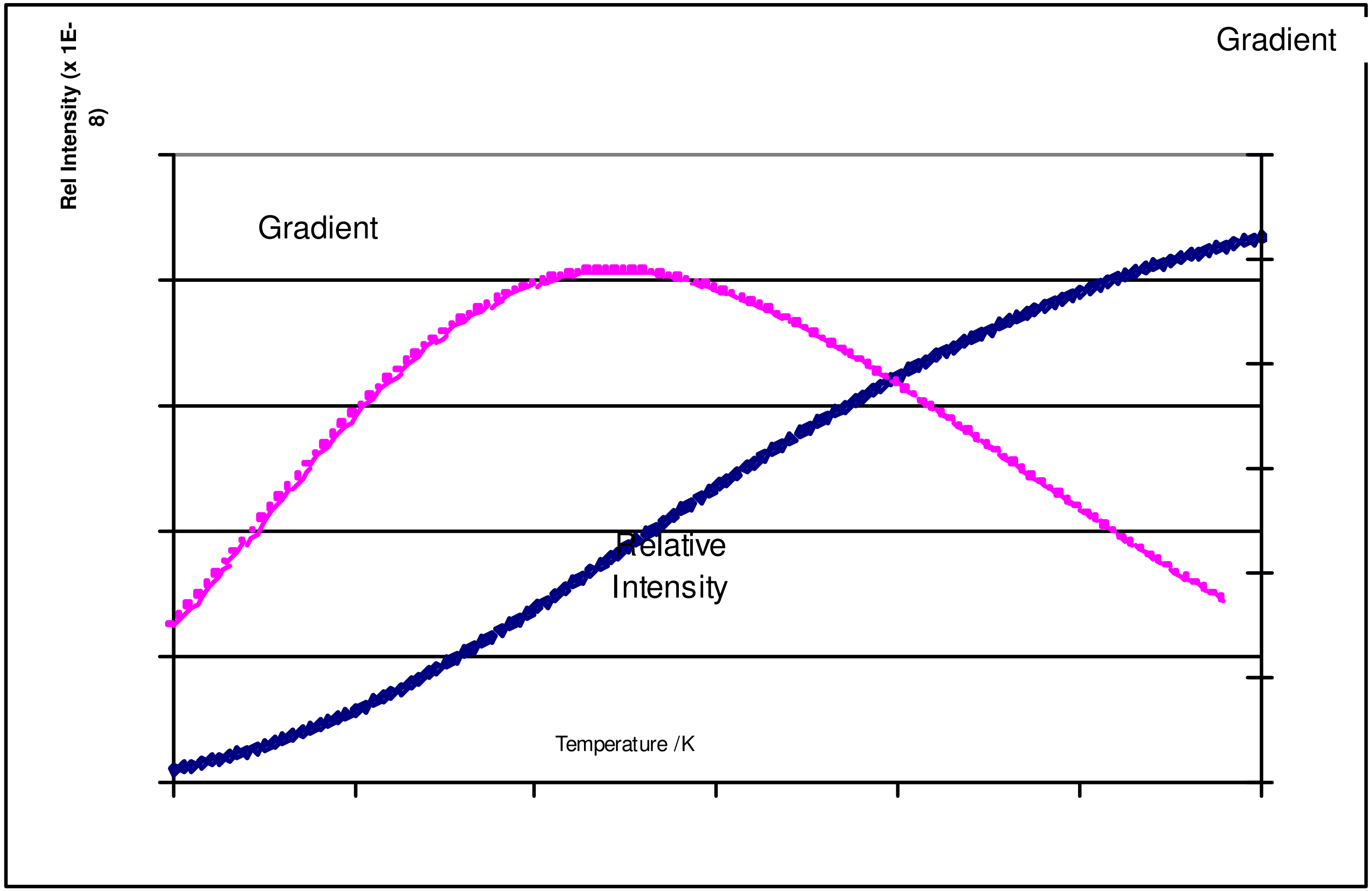


Identification of water lines



BS 337 Normalized

Sensitivity: Water Lines vs Temperature



Summary

Analyses relying on a certain molecules and atoms are promising, e.g., CO, HCN/HNC, H_2O, Mn

Multi-institute effort underway

Investment in observational tools has been made but important that we have necessary tools to interpret

Outstanding issues

Atomic data are generally very poor - necessary to measure (or empirically derive astrophysical oscillator strengths)

Many molecular line lists are incomplete

Uncertain dust species, grain sizes and composition

Temperature scales derived from different methodologies do not match

High-quality high-resolution spectra of benchmark objects can constrain many issues