Isotopes in Stars

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What do we know:

Table 10. Nuclide abundances 4.56 Ga ago (normalized to N(Si) = 10^6 atoms)

Z		A	atom%	N	Z		A	atom%	N
1	H	1	99.9981	2.59E+10	20	Ca	46	0.004	2
1	H	2	0.00194						
			100						
2	He	3	0.0166						
2	He	4	99.9834						
			100						
3	Li	6	7.589						
3	Li	7	92.411						
			100						
4	Be	9	100						
5	B	10	19.820						
5	B	11	80.180						
			100						
6	C	12	98.889						
6	C	13	1.111						
			100						
7	N	14	99.634						
7	N	15	0.366						
			100						
8	O	16	99.763						
8	O	17	0.037						
8	O	18	0.200						
			100						
9	F	19	100						
10	Ne	20	92.9431						
10	Ne	21	0.2228						
10	Ne	22	6.8341						
			100						
11	Na	23	100						
12	Mg	24	78.992						
12	Mg	25	10.003						

IUPAC Recommended Isotopic Abundances

P. De Bievre and P.D.P. Taylor, *Int. J. Mass Spectrom. Ion Phys.* **123**, 149 (1993).

Isotope	Abundance
^{1}H	99.985 *1*
^{2}H	0.015 *1*
^{3}He	0.000137 *3*
^{4}He	99.999863 *3*
^{6}Li	7.5 *2*
^{7}Li	92.5 *2*
^{9}Be	100
^{10}B	19.9 *2*
^{11}B	80.1 *2*
^{12}C	98.90 *3*
^{13}C	1.10 *3*
^{14}N	99.634 *9*
^{15}N	0.366 *9*
^{16}O	99.762 *15*
^{17}O	0.038 *3*
^{18}O	0.200 *12*
^{19}F	100
^{20}Ne	90.48 *3*
^{21}Ne	0.27 *1*
^{22}Ne	9.25 *3*
^{23}Na	100

Isotope	Abundance
^{54}Fe	5.8 *1*
^{56}Fe	91.72 *30*
^{57}Fe	2.2 *1*
^{58}Fe	0.28 *1*
^{55}Mn	100
^{58}Ni	68.077 *9*
^{60}Ni	26.223 *8*
^{61}Ni	1.140 *1*
^{62}Ni	3.634 *2*
^{64}Ni	0.926 *1*
^{59}Co	100
^{63}Cu	69.17 *3*
^{65}Cu	30.83 *3*
^{64}Zn	48.6 *3*
^{66}Zn	27.9 *2*
^{67}Zn	4.1 *1*
^{68}Zn	18.8 *4*
^{70}Zn	0.6 *1*
^{69}Ga	60.108 *9*
^{71}Ga	39.892 *9*
^{70}Ge	21.23 *4*
^{72}Ge	27.66 *3*
^{73}Ge	7.73 *1*

Isotope	Abundance
^{96}Ru	5.52 *6*
^{98}Ru	1.88 *6*
^{99}Ru	12.7 *1*
^{100}Ru	12.6 *1*
^{101}Ru	17.0 *1*
^{102}Ru	31.6 *2*
^{104}Ru	18.7 *2*
^{102}Pd	1.02 *1*
^{104}Pd	11.14 *8*
^{105}Pd	22.33 *8*
^{106}Pd	27.33 *3*
^{108}Pd	26.46 *9*
^{110}Pd	11.72 *9*
^{103}Rh	100
^{106}Cd	1.25 *4*
^{108}Cd	0.89 *2*
^{110}Cd	12.49 *12*
^{111}Cd	12.80 *8*
^{112}Cd	24.13 *14*
^{113}Cd	12.22 *8*
^{114}Cd	28.73 *28*
^{116}Cd	7.49 *12*
^{107}Ag	51.839 *7*
^{109}Ag	48.161 *7*

Isotope	Abundance
^{136}Ce	0.19 *1*
^{138}Ce	0.25 *1*
^{140}Ce	88.48 *10*
^{142}Ce	11.08 *10*
^{138}La	0.0902 *2*
^{139}La	99.9098 *2*
^{141}Pr	100
^{142}Nd	27.13 *12*
^{143}Nd	12.18 *6*
^{144}Nd	23.80 *12*
^{145}Nd	8.30 *6*
^{146}Nd	17.19 *9*
^{148}Nd	5.76 *3*
^{150}Nd	5.64 *3*
^{144}Sm	3.1 *1*
^{147}Sm	15.0 *2*
^{148}Sm	11.3 *1*
^{149}Sm	13.8 *1*
^{150}Sm	7.4 *1*
^{152}Sm	26.7 *2*
^{154}Sm	22.7 *2*
^{151}Eu	47.8 *15*
^{153}Eu	52.2 *15*
^{152}Gd	0.20 *1*

Isotope	Abundan
^{180}W	0.13 *4*
^{182}W	26.3 *2*
^{183}W	14.3 *1*
^{184}W	30.67 *15*
^{186}W	28.6 *2*
^{184}Os	0.02 *1*
^{186}Os	1.58 *30*
^{187}Os	1.6 *3*
^{188}Os	13.3 *7*
^{189}Os	16.1 *8*
^{190}Os	26.4 *12*
^{192}Os	41.0 *8*
^{185}Re	37.40 *2*
^{187}Re	62.60 *2*
^{190}Pt	0.01 *1*
^{192}Pt	0.79 *6*
^{194}Pt	32.9 *6*
^{195}Pt	33.8 *6*
^{196}Pt	25.3 *6*
^{198}Pt	7.2 *2*
^{191}Ir	37.3 *5*
^{193}Ir	62.7 *5*
^{196}Hg	0.15 *1*
^{198}Hg	9.97 *8*

Isotopes:

Li(z=3) – 2 (11)

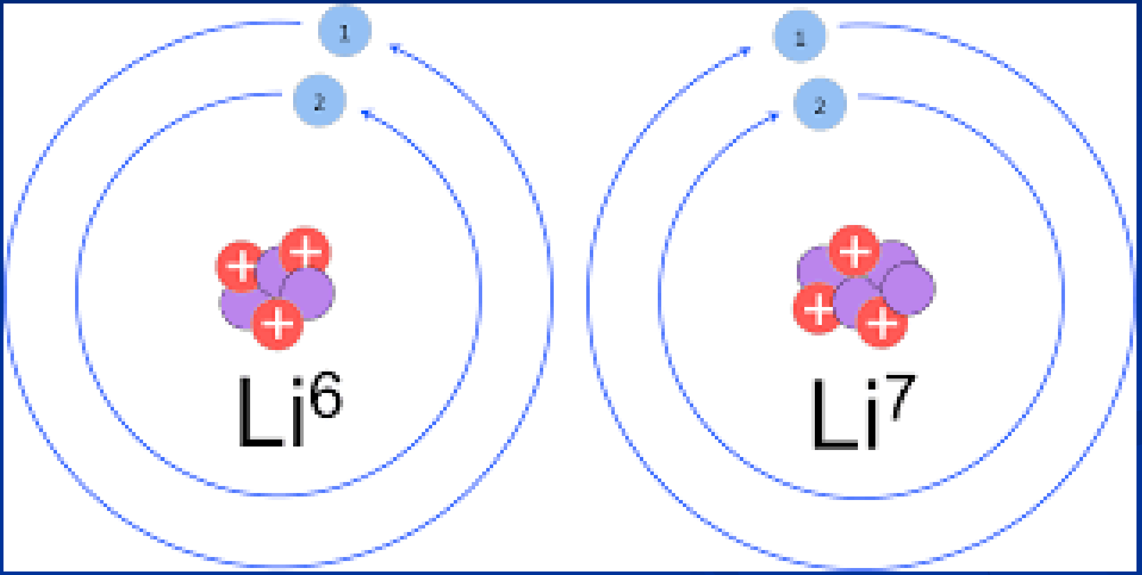
C(z=6) – 2 (13)

O(z=16) – 3 (13)

Si(z=14) – 3 (21)

Ti(z=22) – 5 (21)

Cs(z=55) – 1 (39)



Lithium-6 + Neutron → Tritium + Helium-4
Gain of 4.8 MeV Per Reaction

Lithium-7 + Neutron → Tritium + Helium-4 + Neutron
Loss of 2.5 MeV Per Reaction

Different origins:

6LI – spallation reaction

7Li – BB, stellar interiors

12C – triple alphaprocess

13C -nuclear fusion on late stages

– ^{46}Ti and ^{47}Ti are formed during explosive oxygen and silicon burning, respectively, in SN types II and Ia;

– ^{48}Ti is formed by explosive Si burning in type II SN;

– ^{49}Ti is formed by the explosive Si burning in type II SN;

– ^{50}Ti is formed in nuclear burning in type Ia SN.

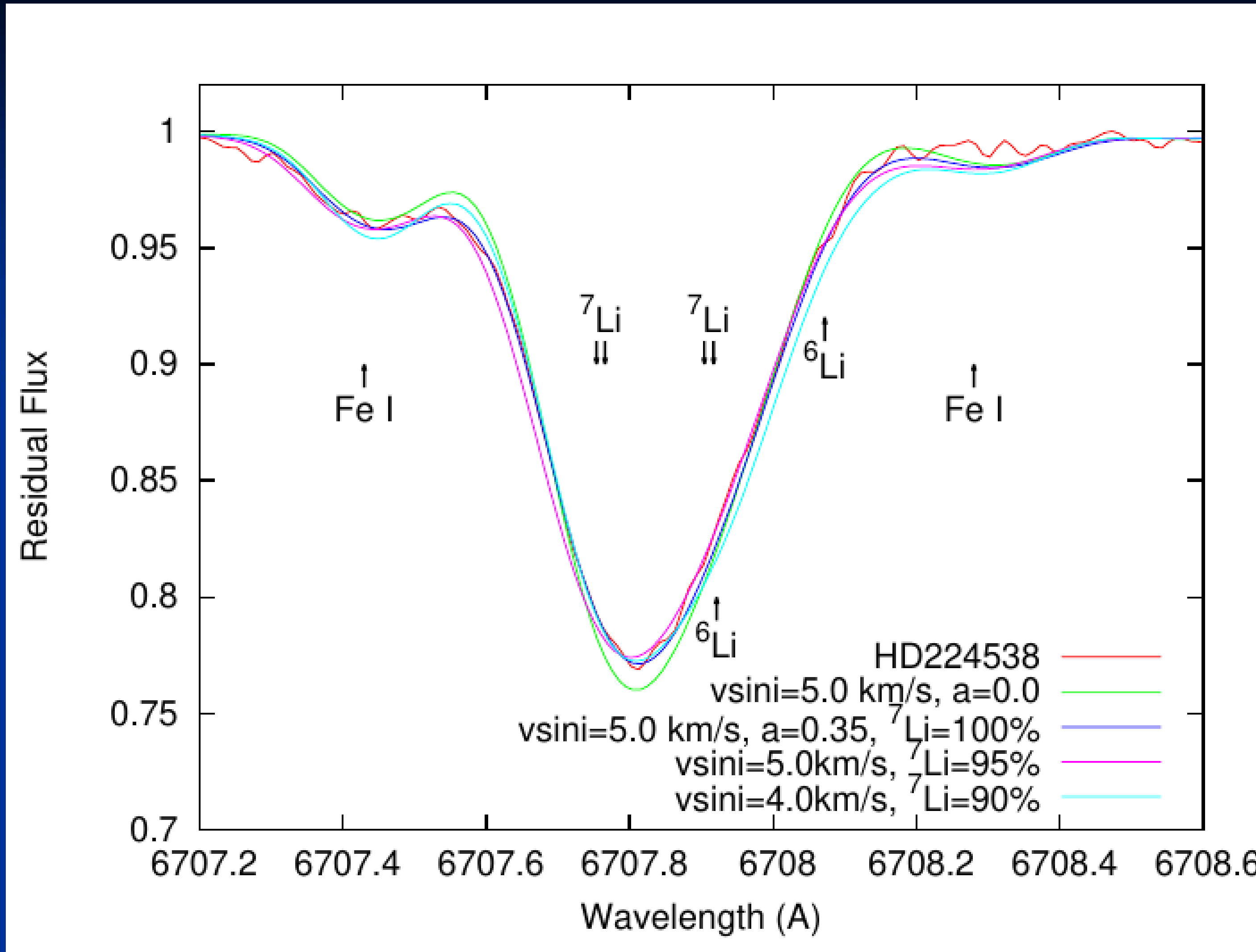
It is a very hard task to determine Ti isotopic ratios from the analysis of atomic lines because different isotopic lines have small isotopic shifts, see Kobayashi et al. (2019) and references therein. The broadening of spectral lines by macroturbulence in the stellar atmospheres as well as any notable rotation of stars almost prevents us from separating the atomic spectra of different isotopes (Tennyson 2019).

Atomic lines:

Very hard task:

Example of 6Li/7Li

6707.756	0.000	-0.428	7Li
6707.768	0.000	-0.206	7Li
6707.907	0.000	-0.808	7Li
6707.908	0.000	-1.507	7Li
6707.919	0.000	-0.808	7Li
6707.920	0.000	-0.808	7Li
6707.920	0.000	-0.479	6Li
6707.923	0.000	-0.178	6Li
6708.069	0.000	-0.831	6Li
6708.070	0.000	-1.734	6Li
6708.074	0.000	-0.734	6Li
6708.075	0.000	-0.831	6Li



A&A 611, A27 (2018)
DOI: 10.1051/0004-6361/201731547

Astronomy & Astrophysics

A detailed study of lithium in 107 CHEPS dwarf stars

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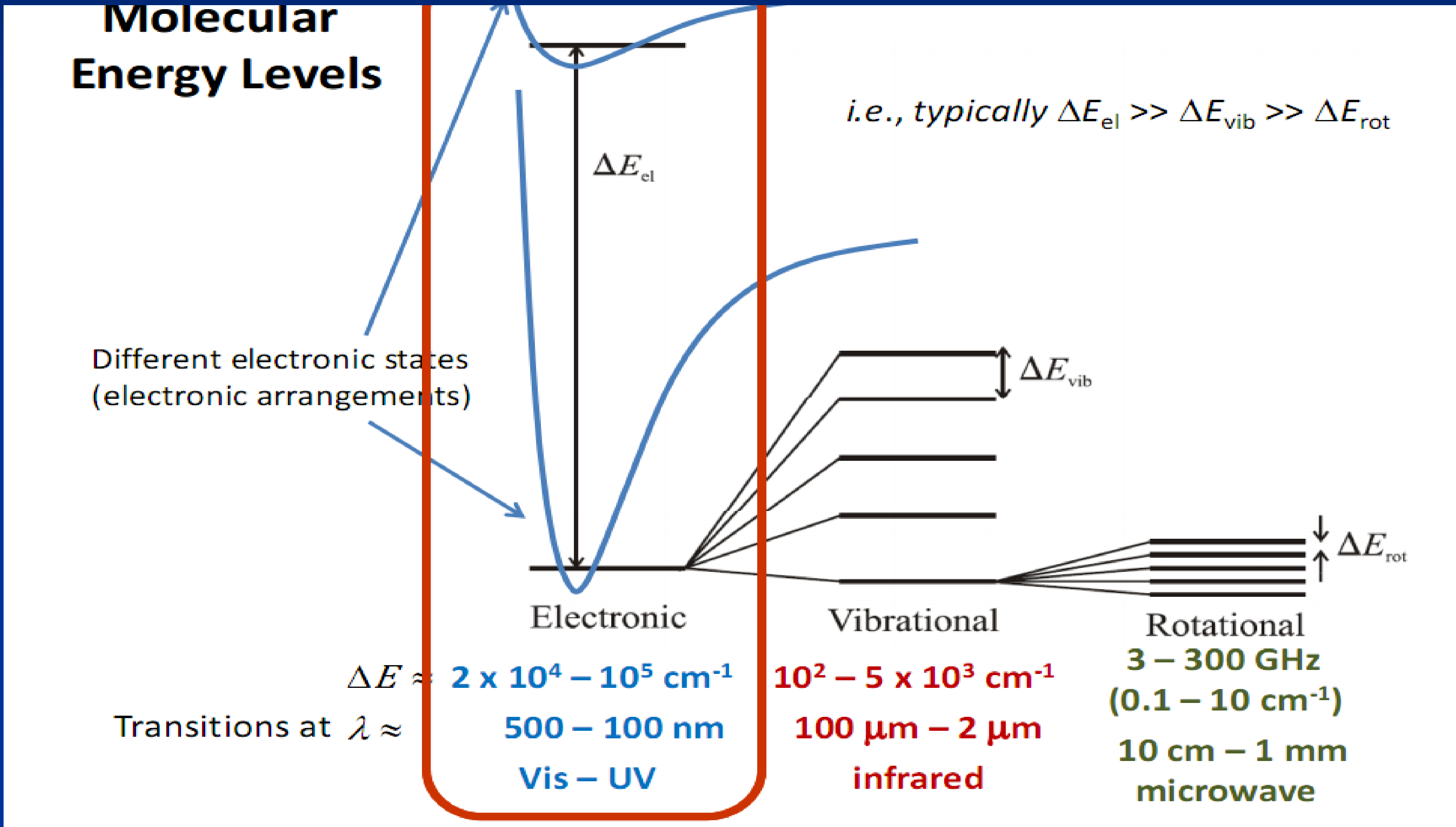
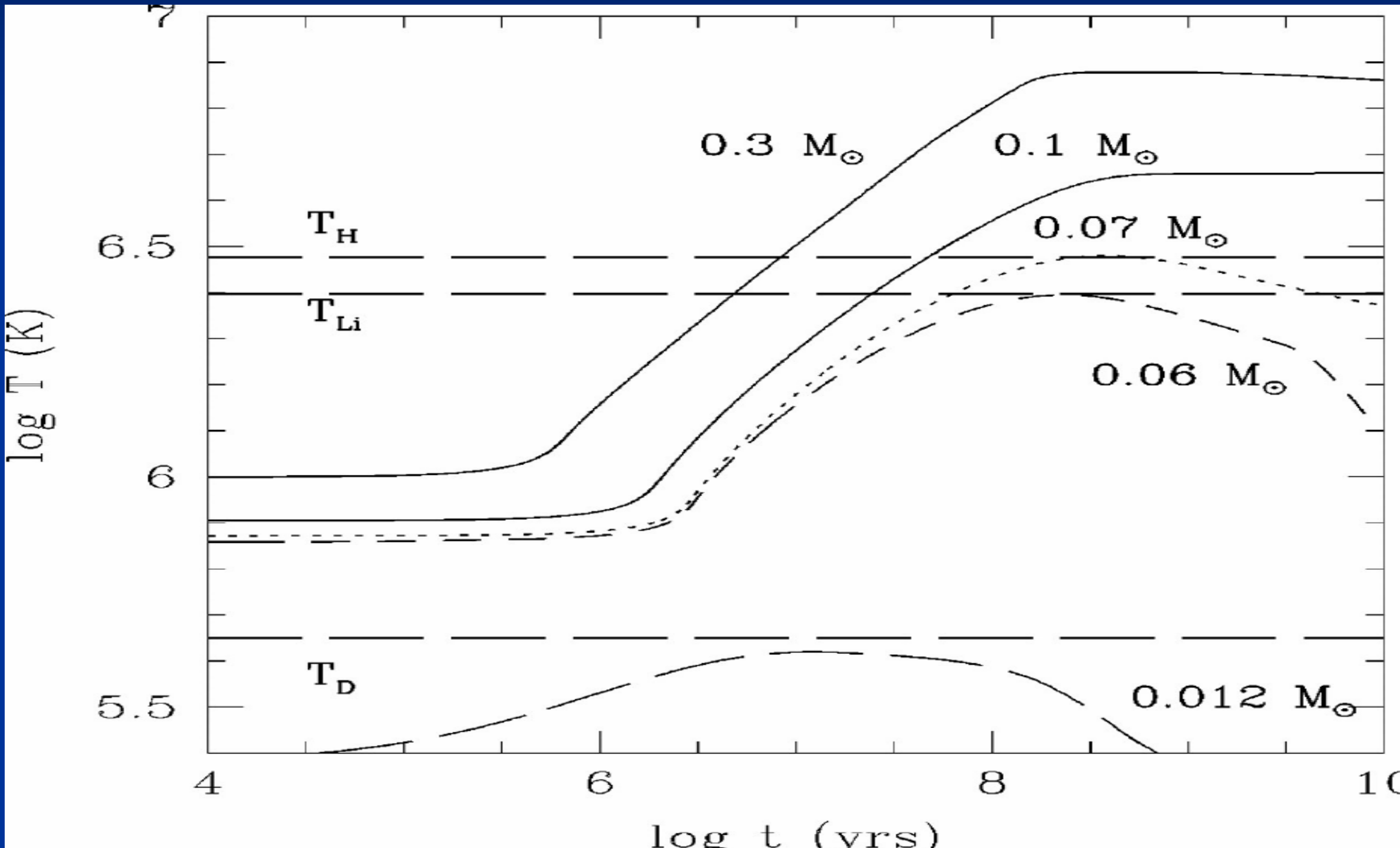
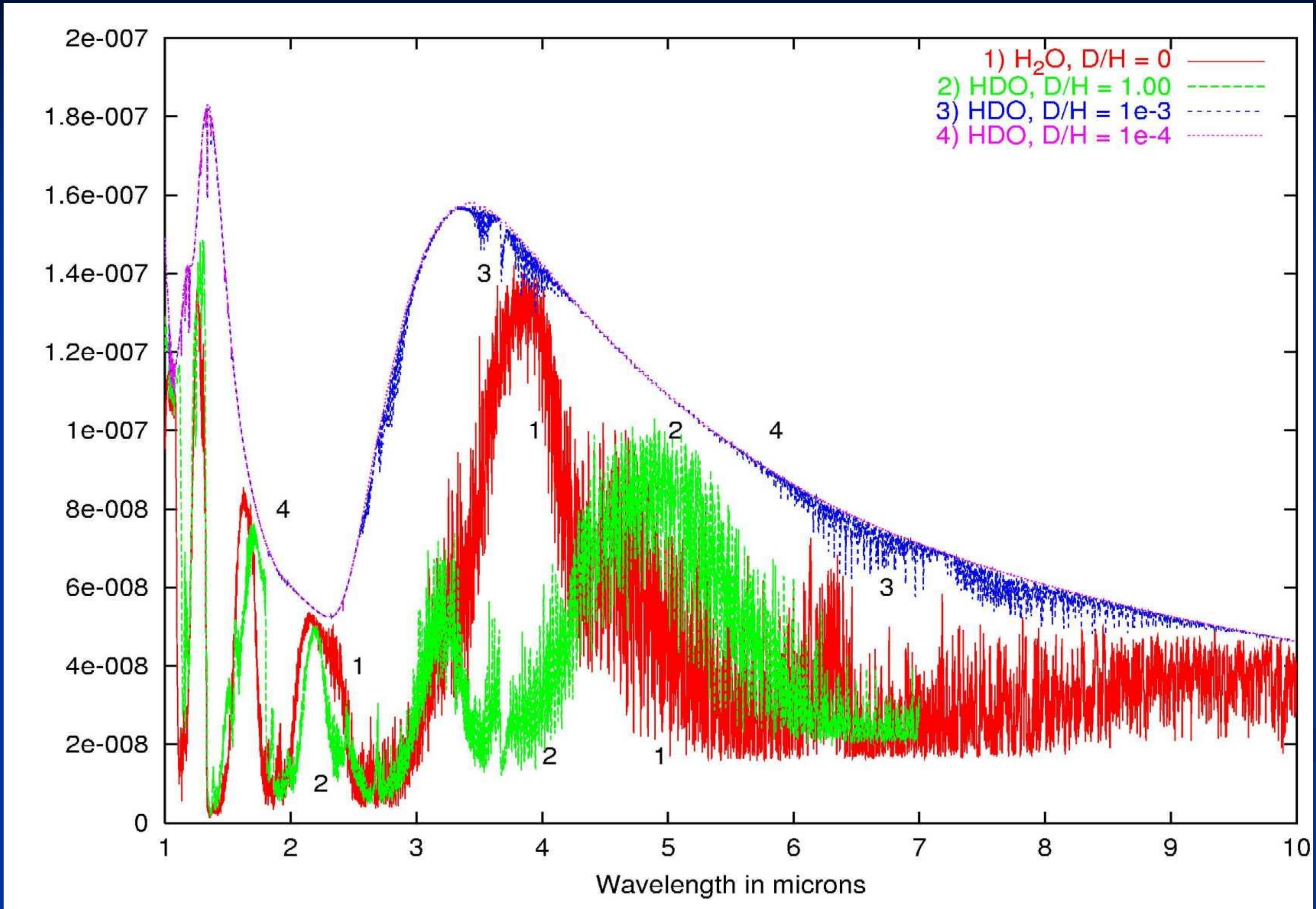
Molecular spectra



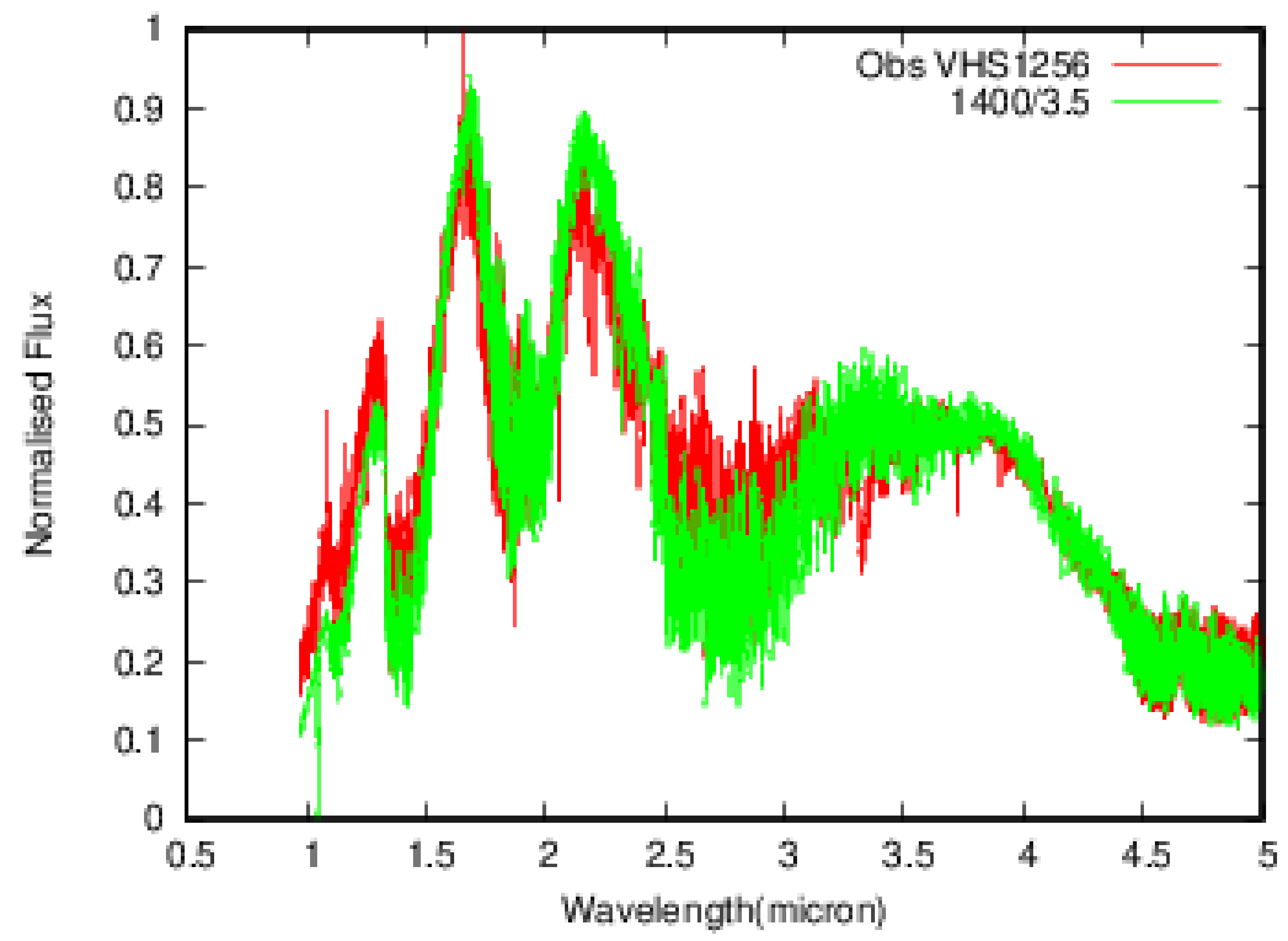
Deuterium test



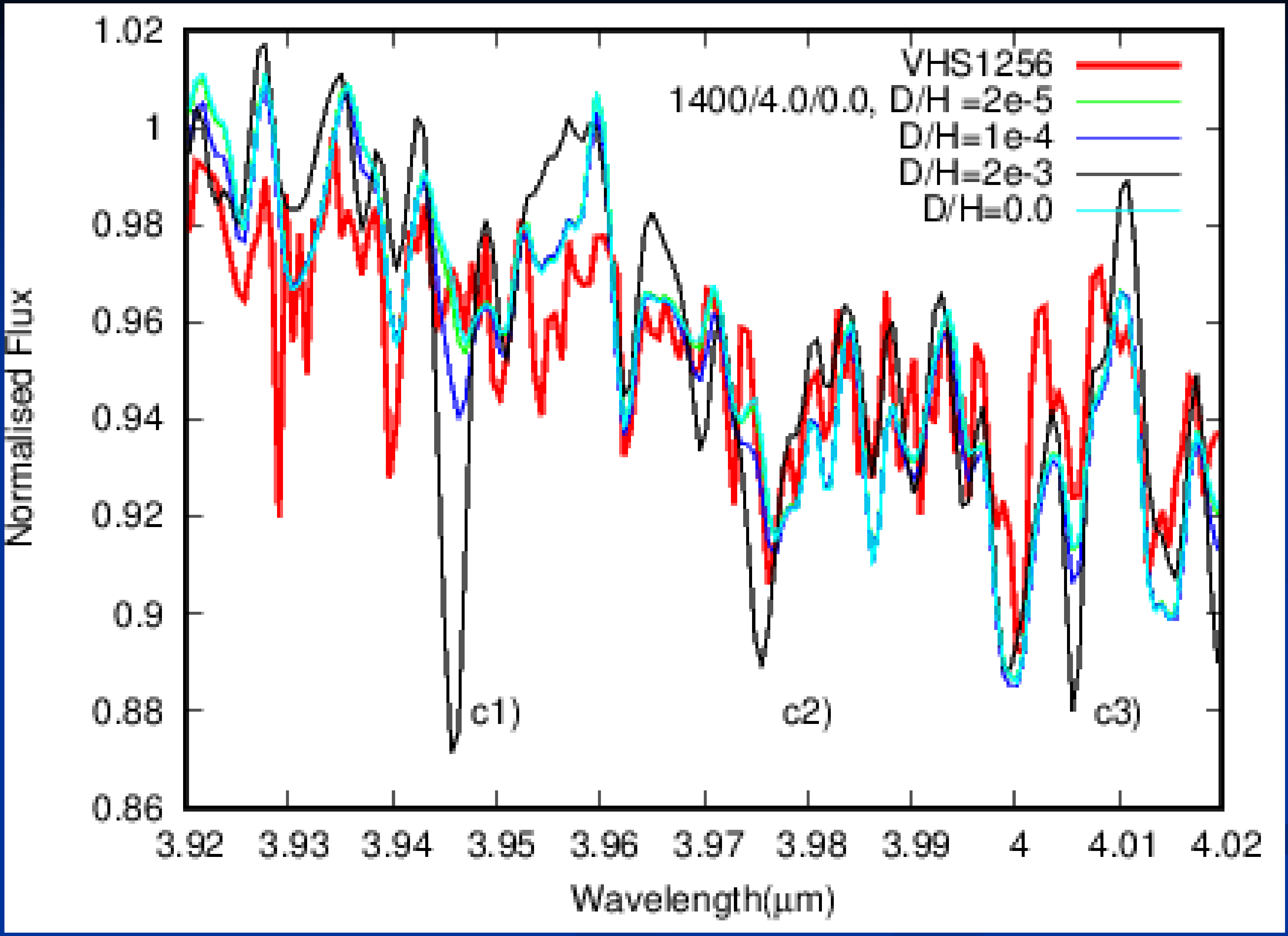
Central temperature vs. Age
(Chabrier & Baraffe 2000)



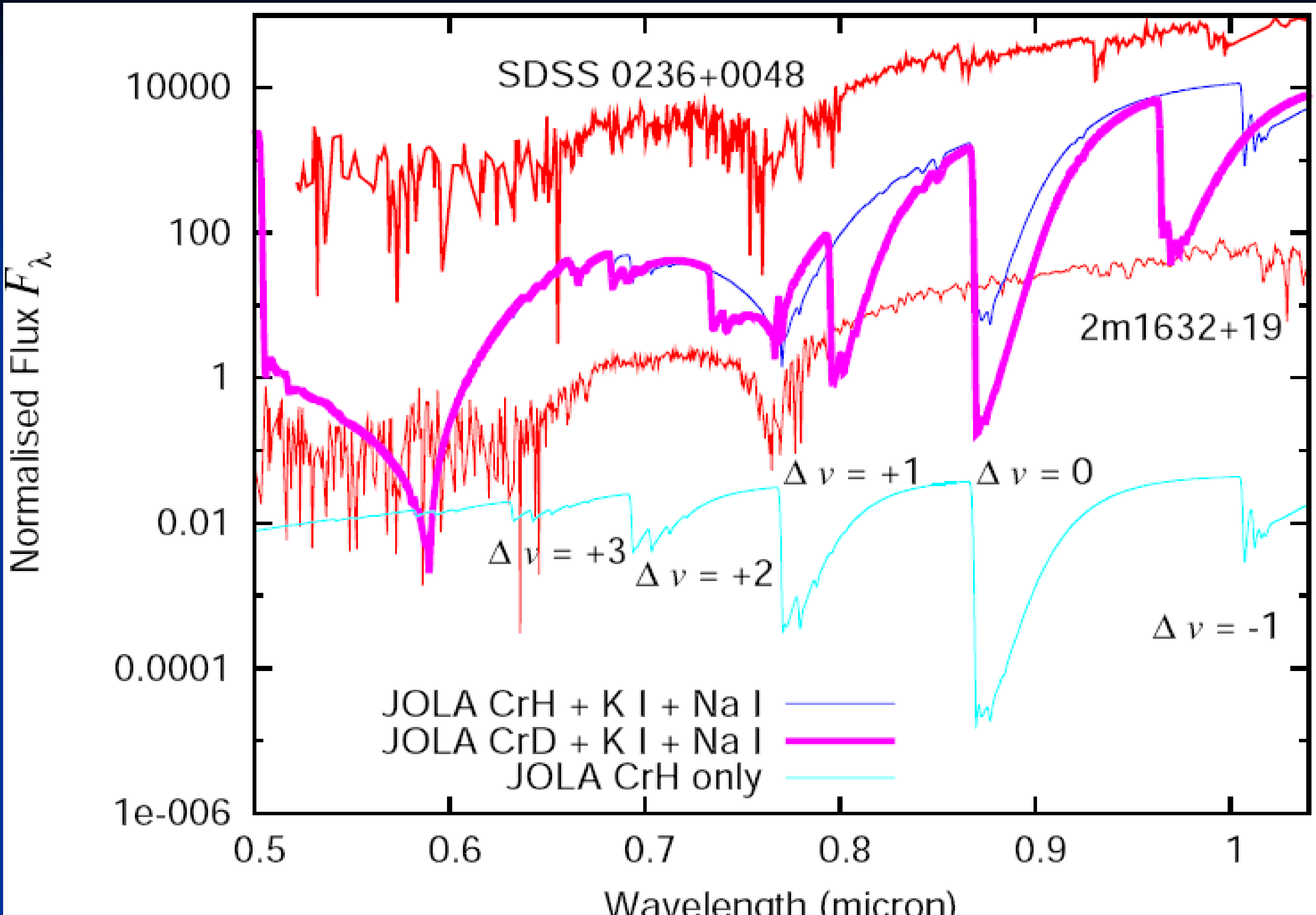
1) H2O, D/H = 0
2) HDO, D/H = 1.00
3) HDO, D/H = 1e-3
4) HDO, D/H = 1e-4
2e-007
1.8e-007
1.6e-007
1.4e-007
1.2e-007
1e-007
8e-008
6e-008
4e-008
2e-008
0
1
2
3
4
5
6
7
8
9
10
Wavelength in microns



Obs VHS1256
1400/3.5
Normalised Flux
Wavelength(micron)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

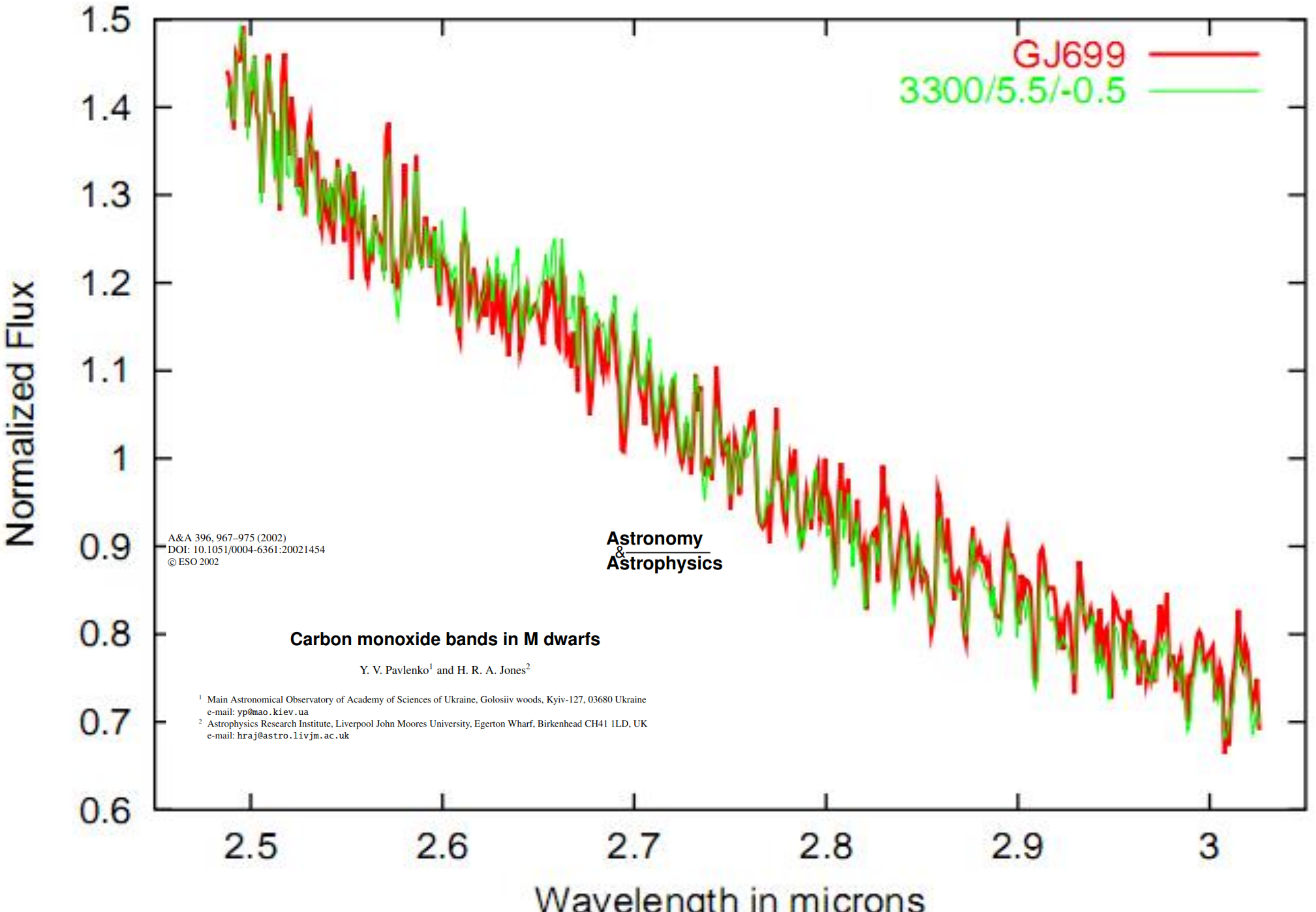


VHS1256
1400/4.0/0.0, D/H =2e-5
D/H=1e-4
D/H=2e-3
D/H=0.0
Normalised Flux
Wavelength(μm)
c1)
c2)
c3)
1.02
1
0.98
0.96
0.94
0.92
0.9
0.88
0.86
3.92
3.93
3.94
3.95
3.96
3.97
3.98
3.99
4
4.01
4.02


SDSS 0236+0048
2m1632+19
Δ ν = +1
Δ ν = 0
Δ ν = +3
Δ ν = +2
Δ ν = -1
JOLA CrH + K I + Na I
JOLA CrD + K I + Na I
JOLA CrH only
10000
100
1
0.01
0.0001
1e-006
0.5
0.6
0.7
0.8
0.9
1
Normalised Flux F_λ
Wavelength (micron)

Good molecular data are of crucial importance for us.

II. CO bands at 2.3 micron.



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Astronomy & Astrophysics

Carbon monoxide bands in M dwarfs

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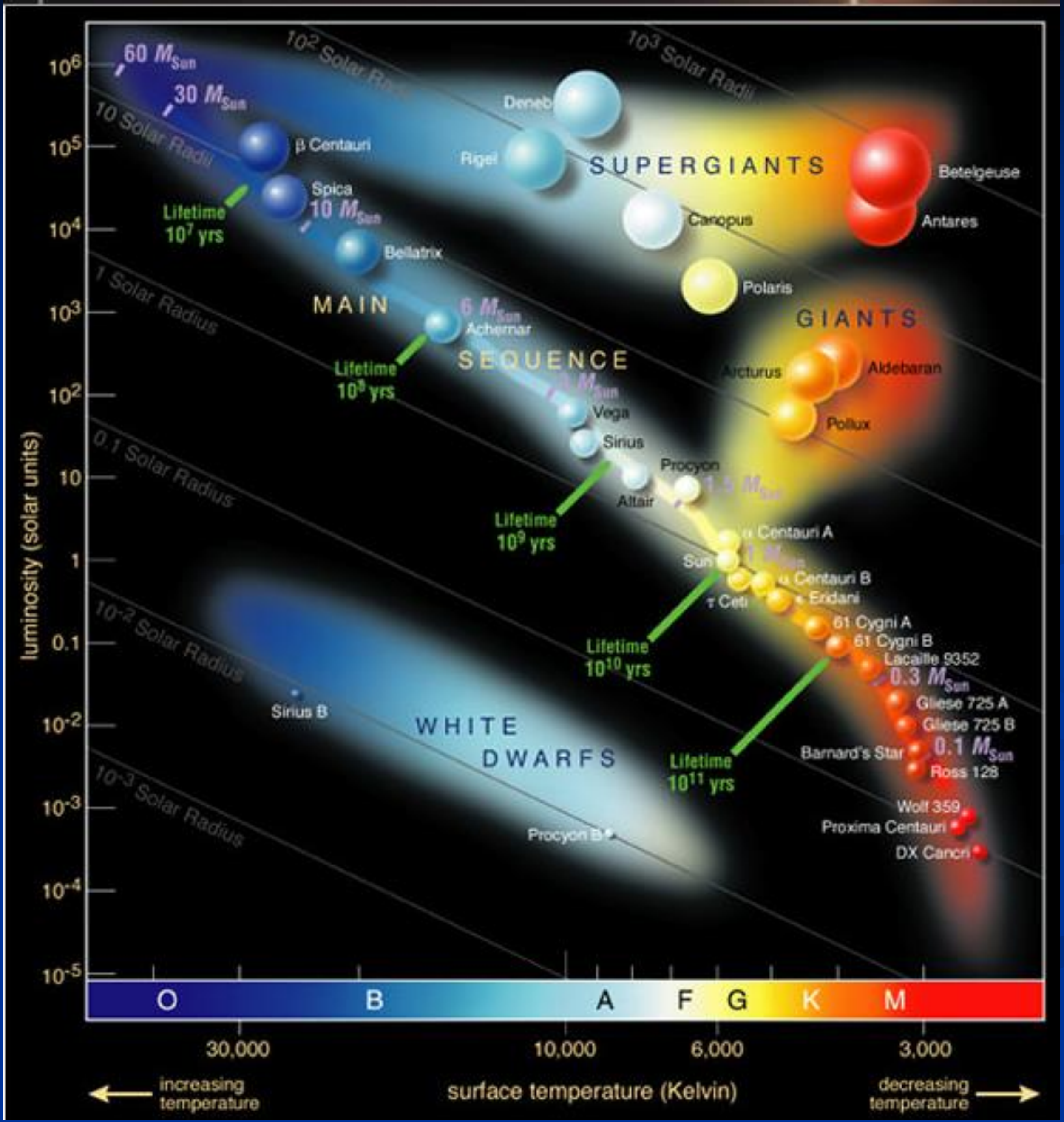
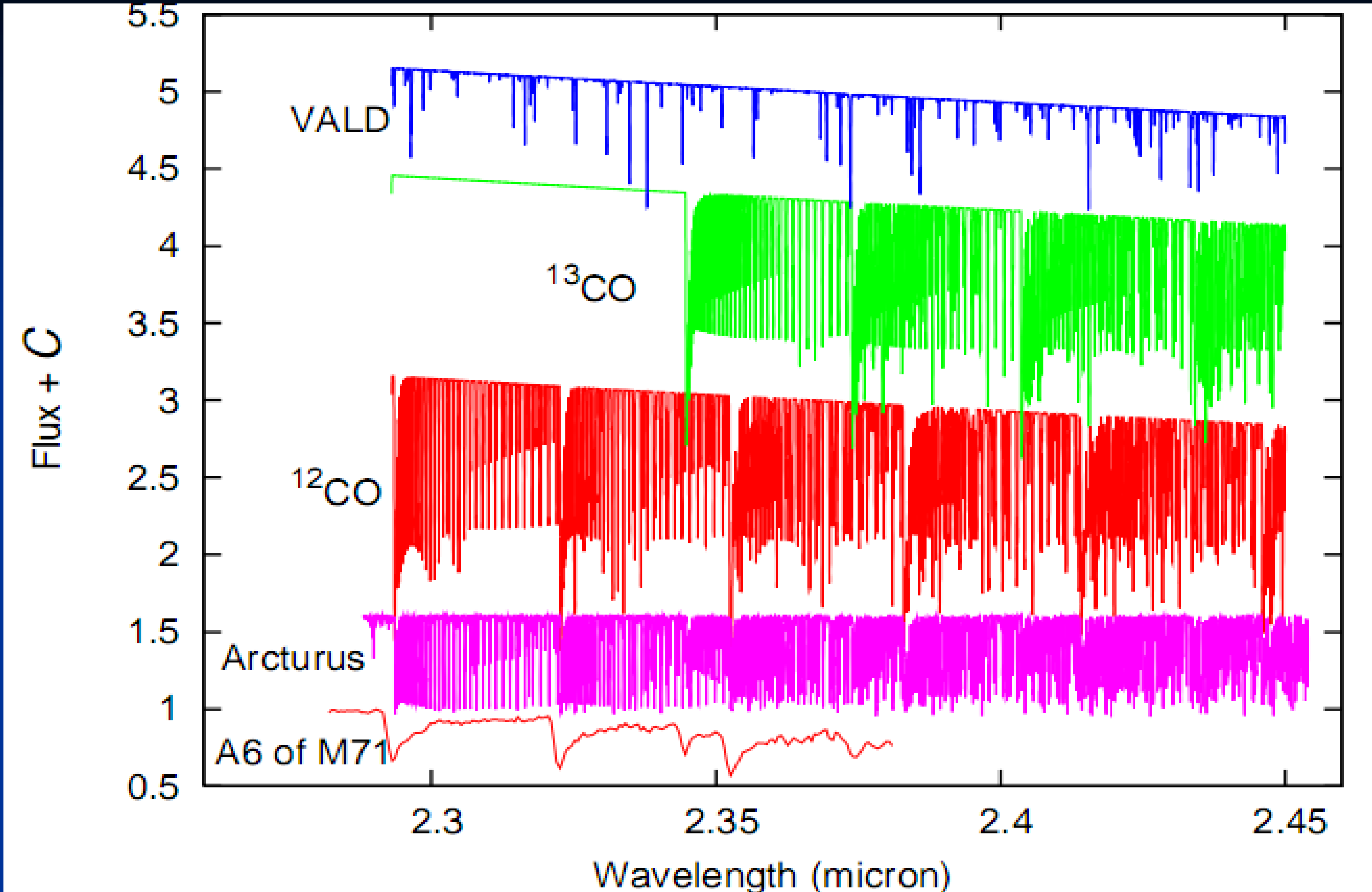
Arctur (K2 III)

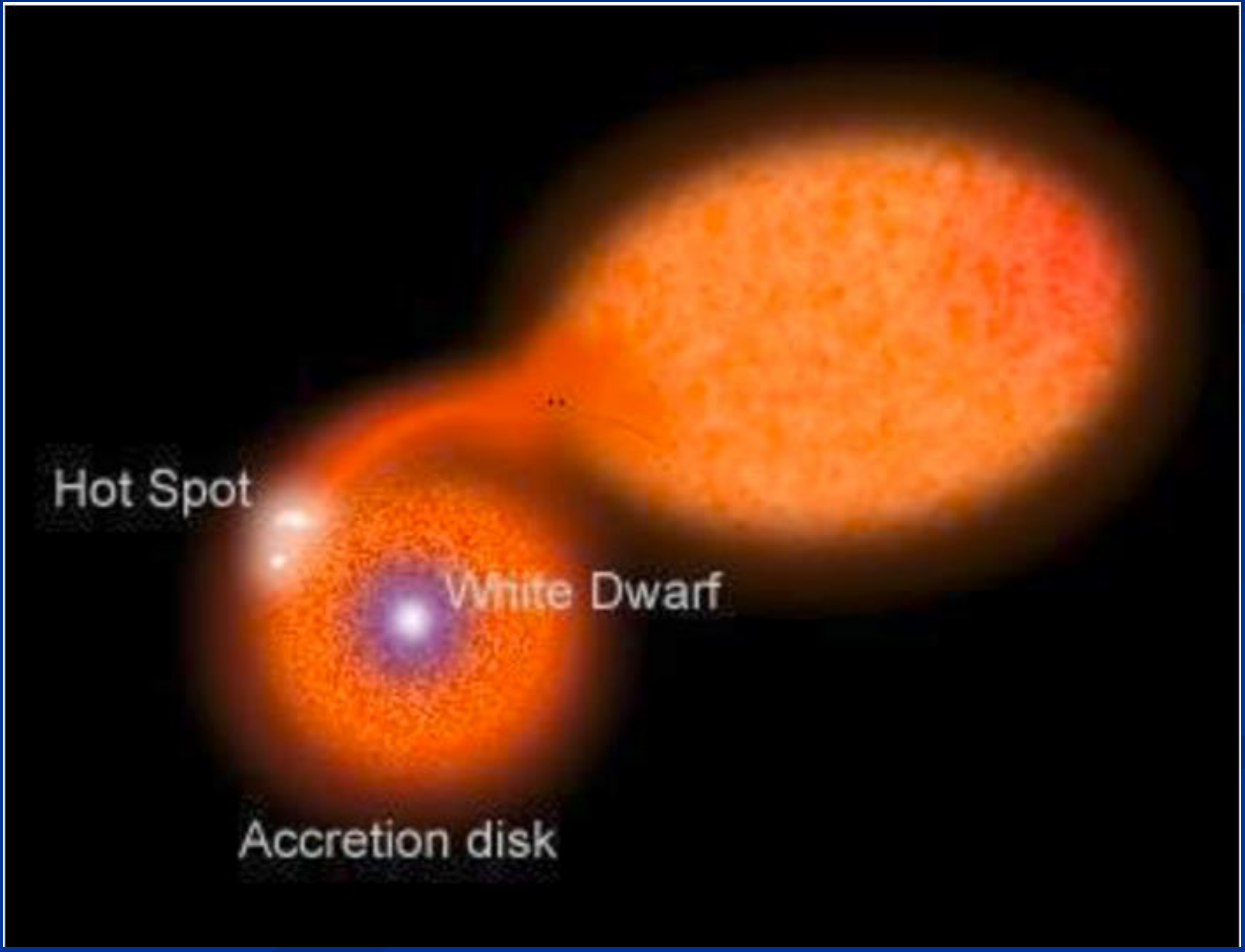


luminosity (solar units)
surface temperature (Kelvin)
increasing temperature
decreasing temperature
30,000
10,000
6,000
3,000
O
B
A
F
G
K
M
SUPERGIANTS
GIANTS
MAIN
SEQUENCE
WHITE
DWARFS
10 Solar Radii
10^2 Solar Radii
10^3 Solar Radii
1 Solar Radius
0.1 Solar Radius
10^{-2} Solar Radius
10^{-3} Solar Radius
60 M_{Sun}
30 M_{Sun}
10 M_{Sun}
6 M_{Sun}
1.5 M_{Sun}
1 M_{Sun}
0.3 M_{Sun}
0.1 M_{Sun}
Lifetime 10^7 yrs
Lifetime 10^8 yrs
Lifetime 10^9 yrs
Lifetime 10^{10} yrs
Lifetime 10^{11} yrs
Deneb
Rigel
Betelgeuse
Antares
Canopus
Polaris
Arcturus
Aldebaran
Pollux
β Centauri
Spica
Bellatrix
Achernar
Vega
Sirius
Procyon
Altair
α Centauri A
Sun
α Centauri B
τ Ceti
ε Eridani
61 Cygni A
61 Cygni B
Lacaille 9352
Gliese 725 A
Gliese 725 B
Barnard's Star
Ross 128
Wolf 359
Proxima Centauri
DX Cancri
Sirius B
Procyon B
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}



Pavlenko, Ya. V., 2008, The carbon abundance and 12C/13C isotopic ratio in the atmosphere of Arcturus from 2.3 µm CO bands, Astron. Rept, 52, 749-759.

III. 13C and 18O in T CrB



Pavlenko, Yakiv V.; Yurchenko, Sergei N.; Tennyson, Jonathan
Analysis of the first overtone bands of isotopologues of CO and SiO in stellar spectra. 2020, A&A, 633A, 52.

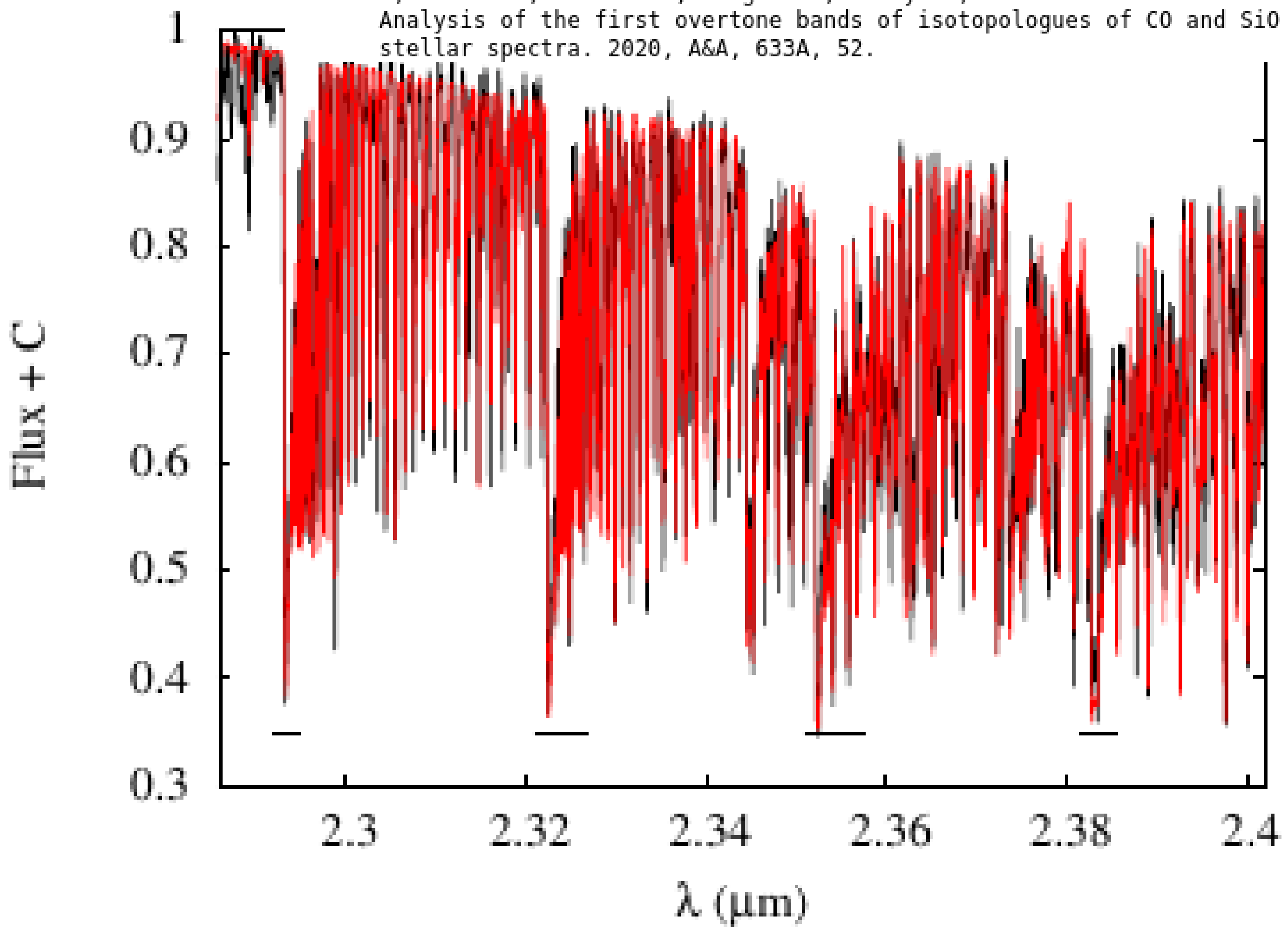


Figure 4. The fit to the first overtone CO bands; the wavelength ranges highlighted by the short lines were omitted from the analysis for reasons discussed in the text.

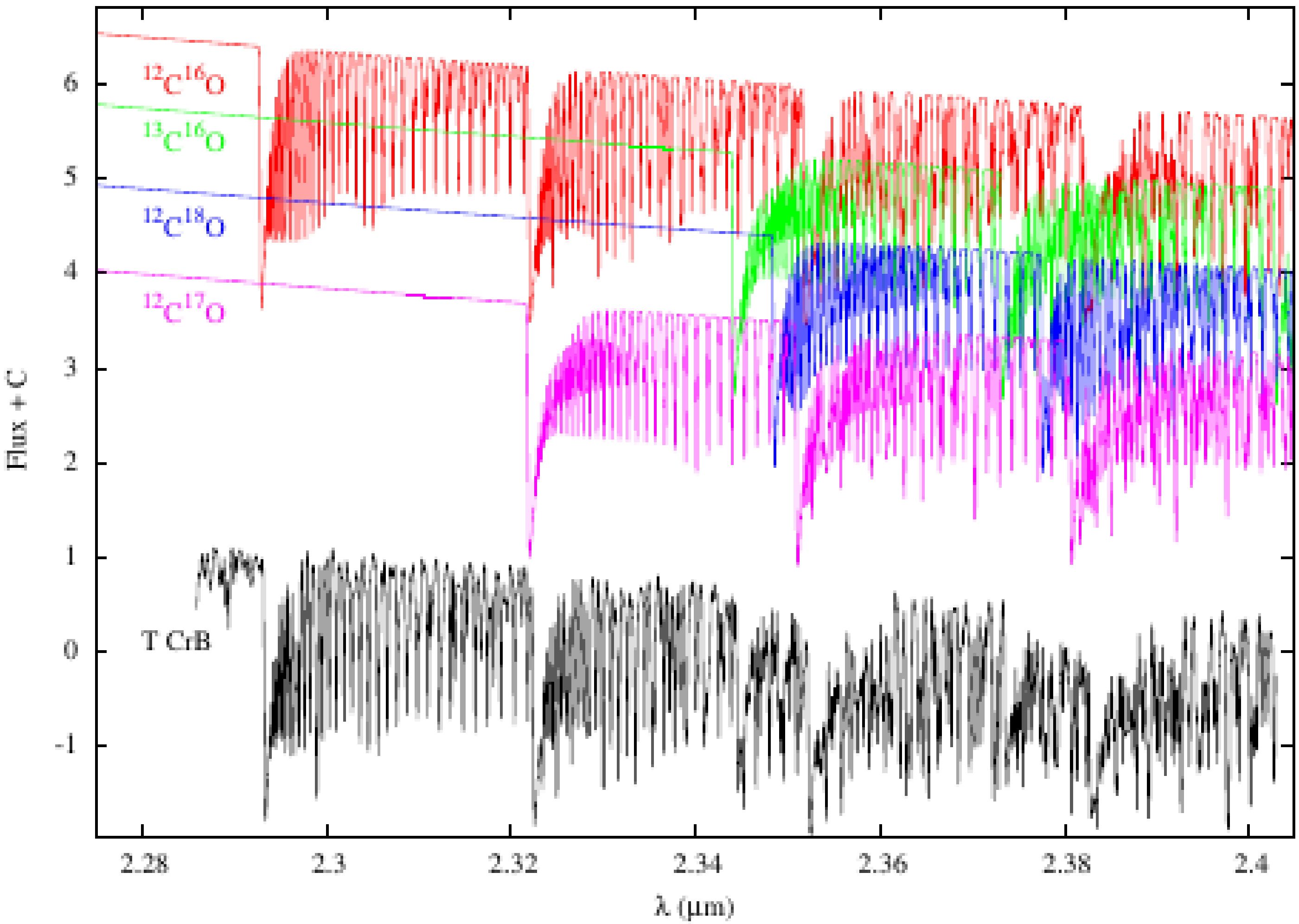
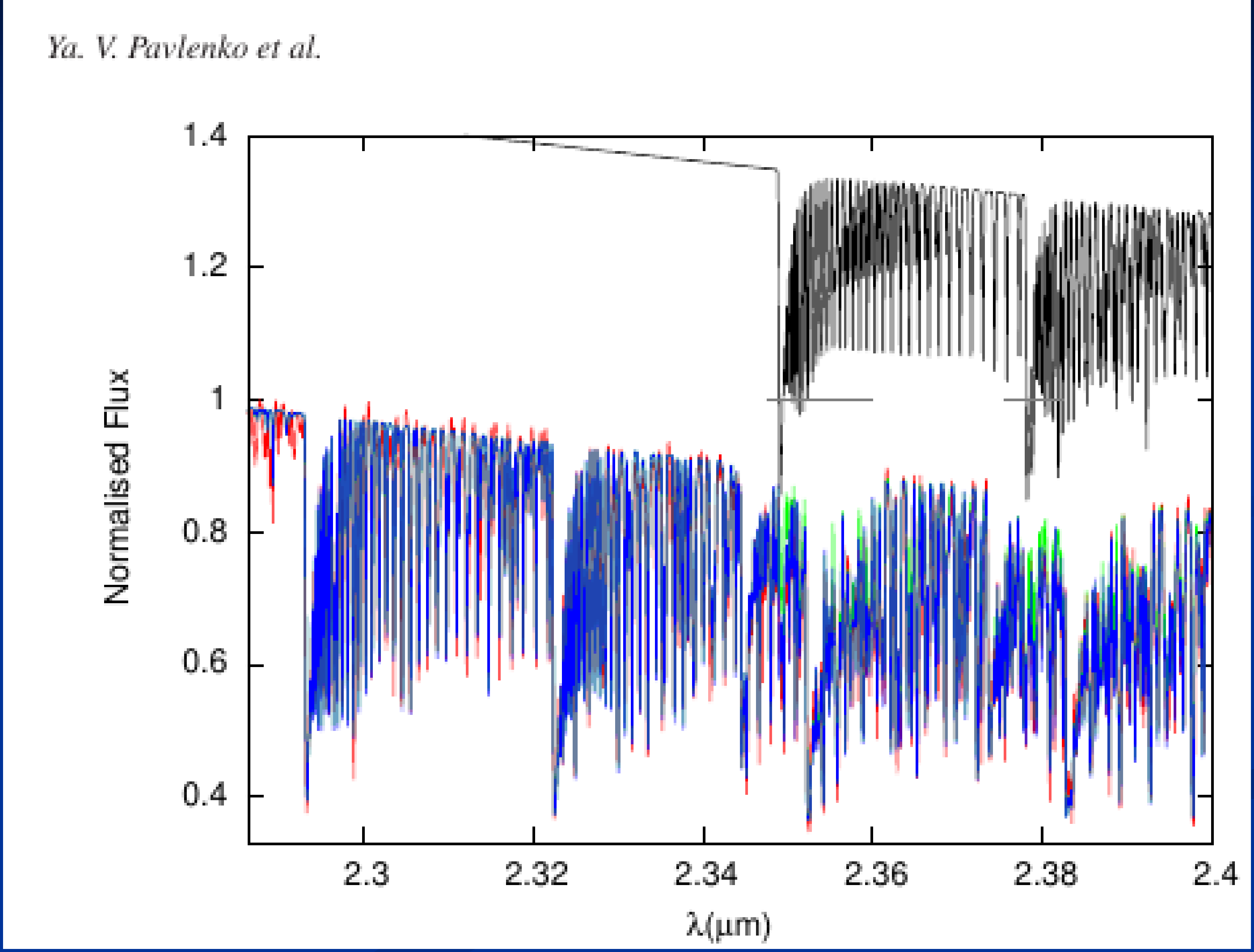


Figure 2. Identification of the isotopic bands of CO. $^{12}C^{16}O$: red; $^{13}C^{16}O$: green; $^{12}C^{18}O$: blue; $^{12}C^{17}O$: magenta. The T CrB spectrum is also shown (black). Note that the flux scale is arbitrary.


Ya. V. Pavlenko et al.
1.4
1.2
1
0.8
0.6
0.4
Normalised Flux
2.3
2.32
2.34
2.36
2.38
2.4
λ(μm)

SiO 1-st overtone bands

IV. Si isotopes

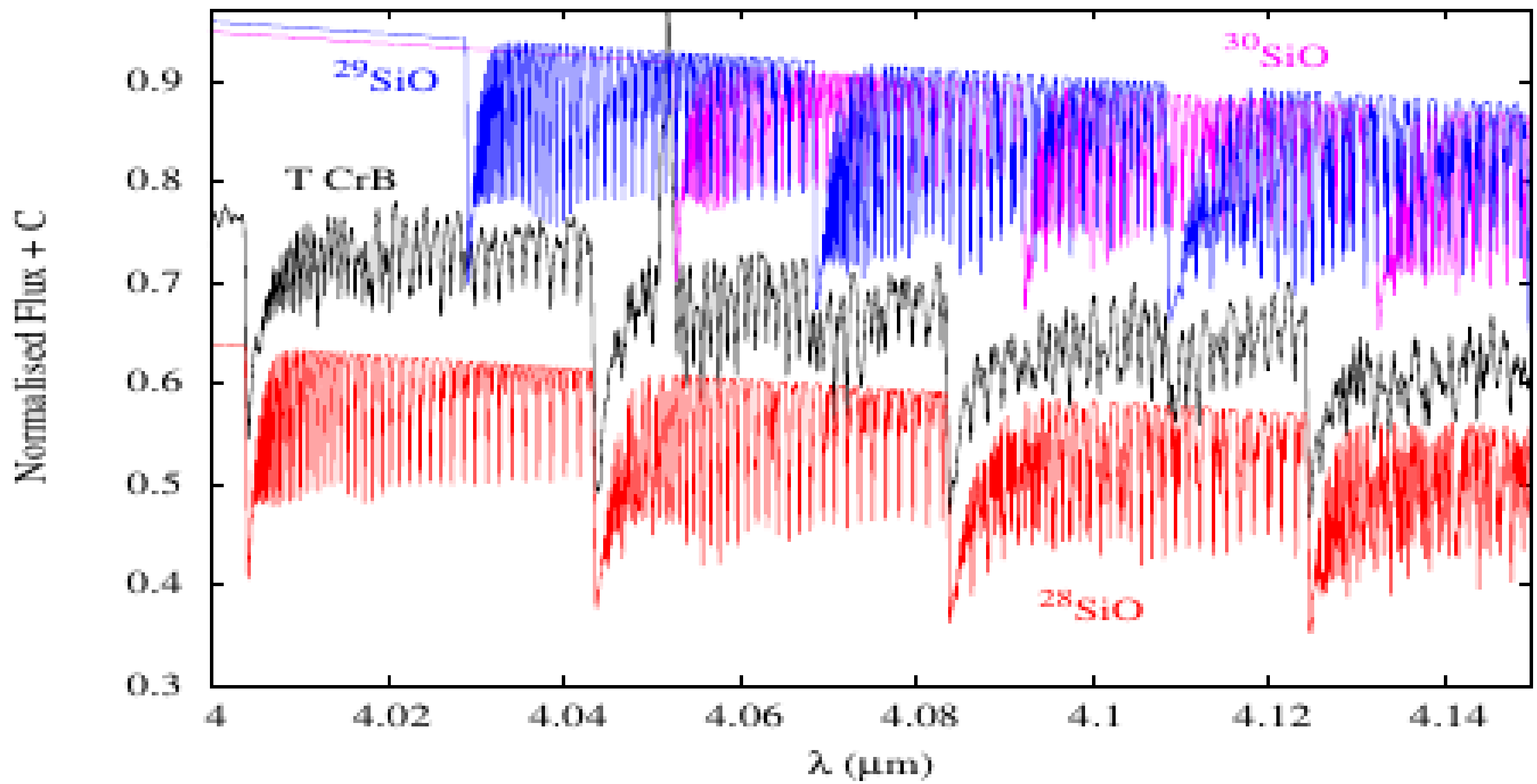


Figure 8. Identification of the SiO isotopologues in the region of the first overtone. T CrB (black curve): ^{28}SiO (red), ^{29}SiO (blue), ^{30}SiO (magenta).

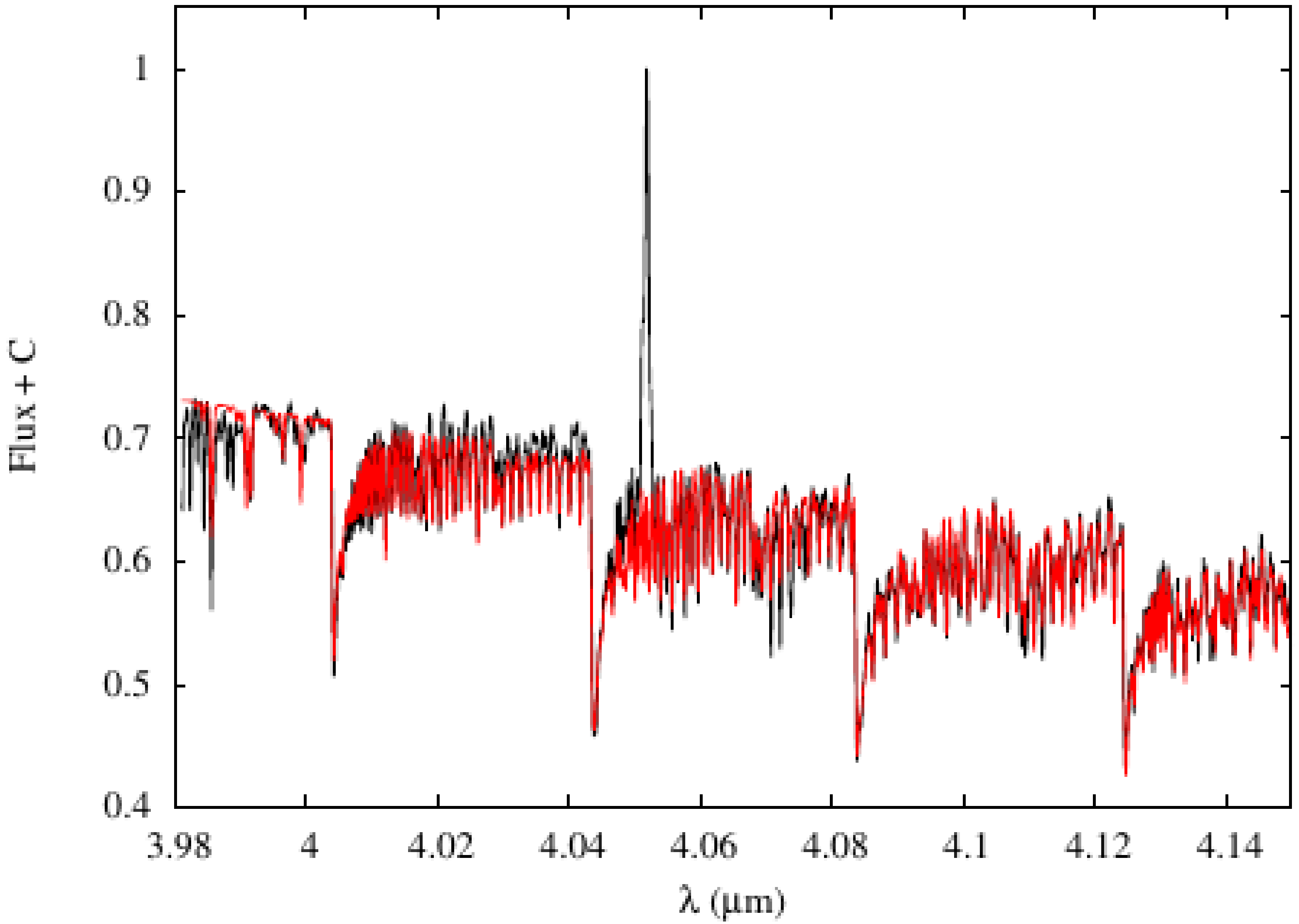


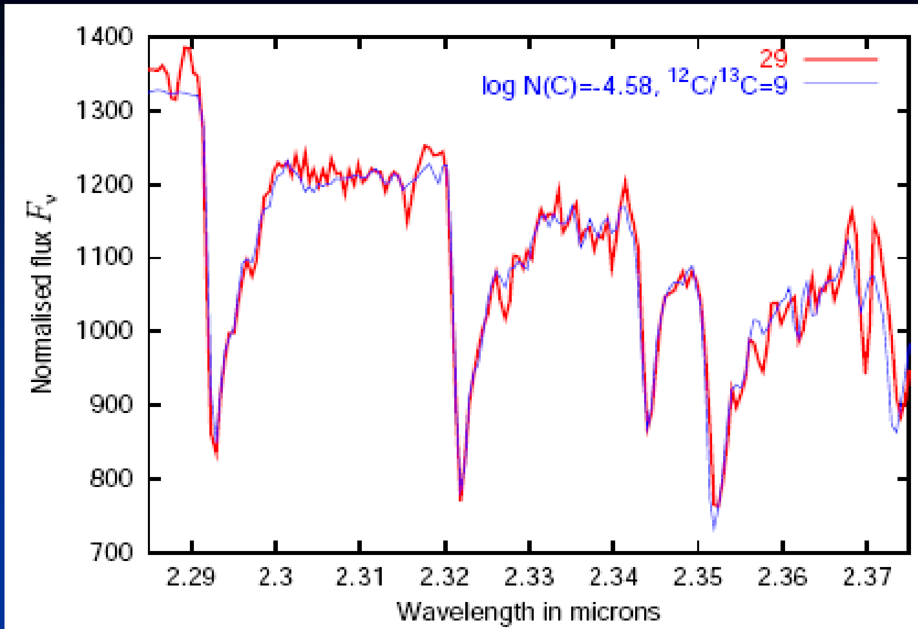
Figure 9. Fit (red) to the observed spectrum of T CrB (black) across the first overtone SiO bands; the emission feature is Br-α.

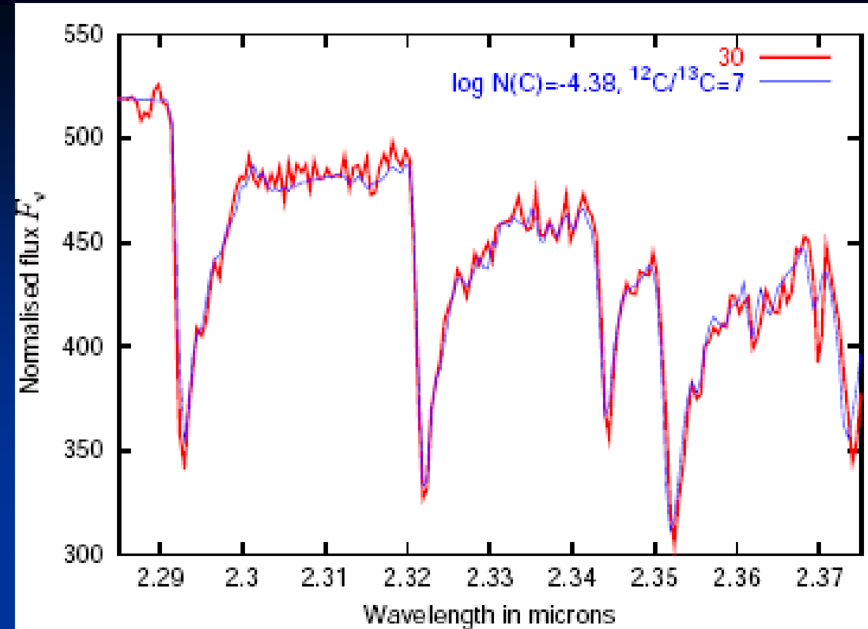
V.12C/13C in globular clusters

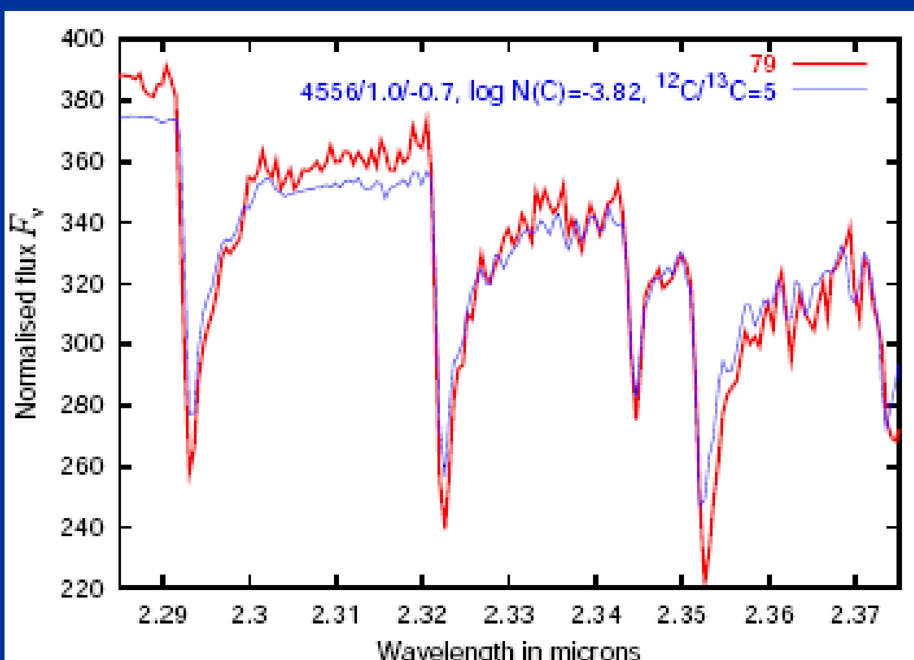
- M71: [Fe/H] = -0.7
- M5: [Fe/H] = -1.2
- M13: [Fe/H]= -1.4
- M3: [Fe/H] = -1.6

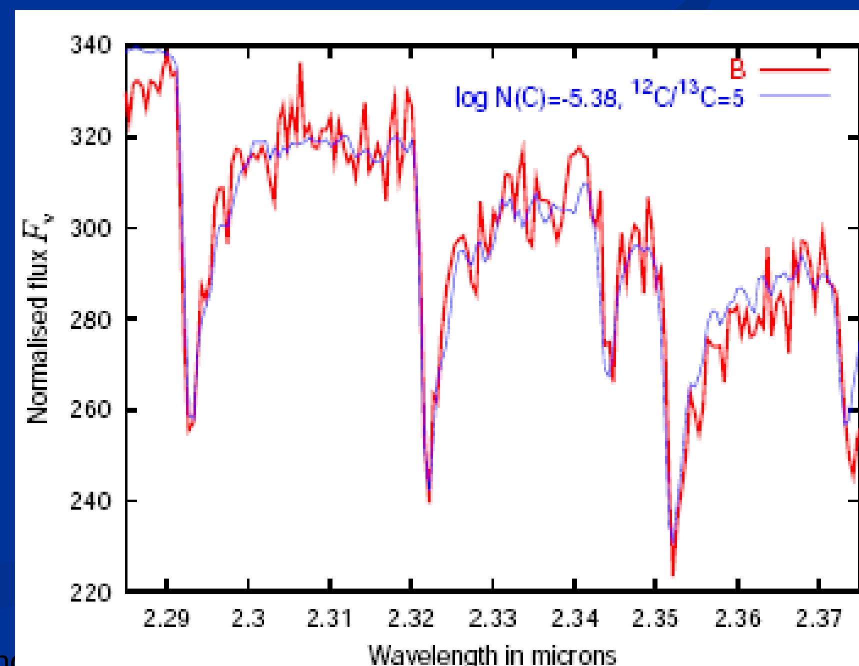
Table 2. Derived values for [C] and $^{12}C/^{13}C$ are given. Values of metallicity, temperature and gravity are taken from Alonso et al. (1999, 2000). Data was also taken of i61 in M5 and I-21 and IV-59 in M13, however, the S/N of the data is rather poor and so data for these objects is not included. Cluster non-members as determined by proper motions studies are given in italics.

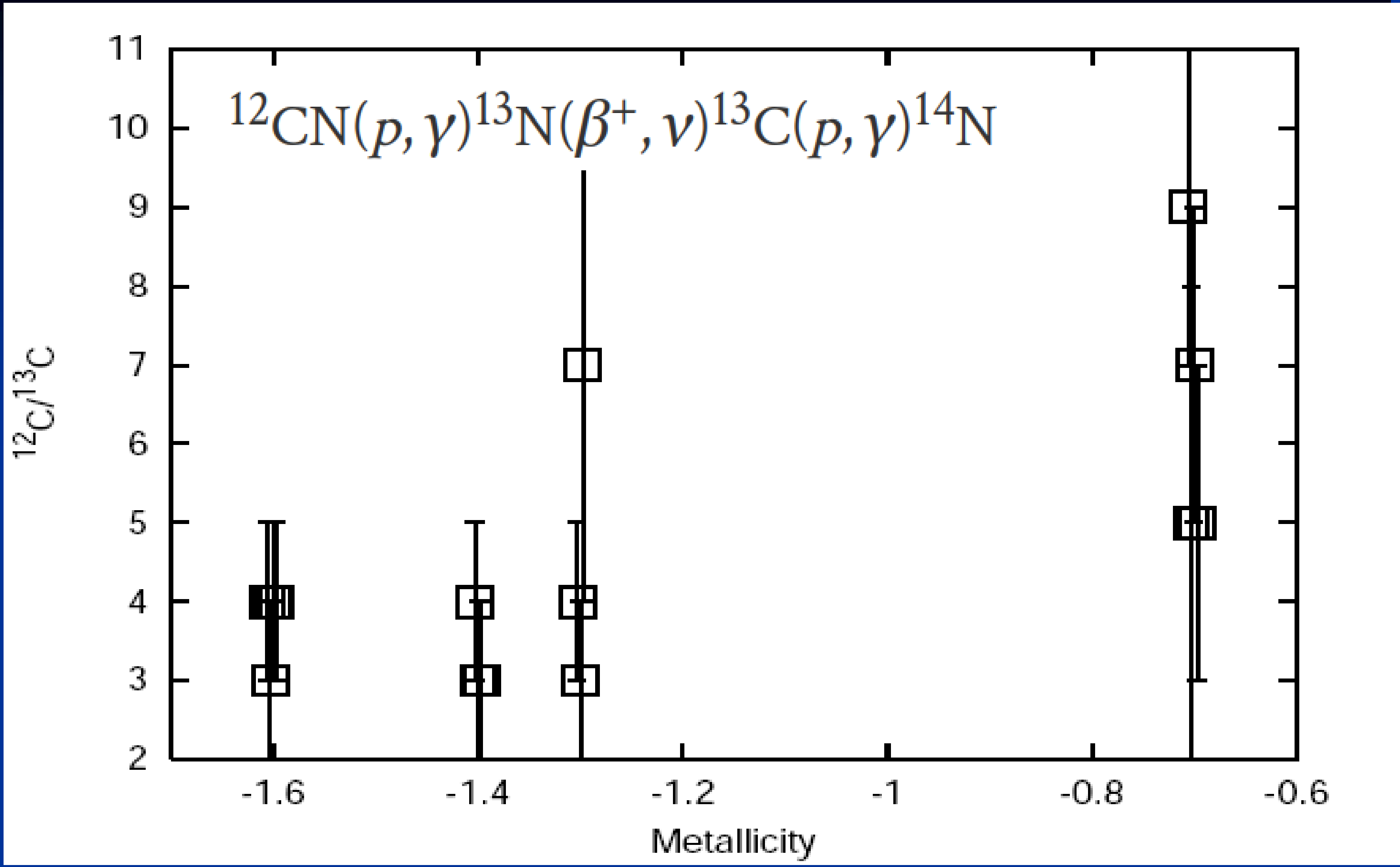
Cluster	[Fe/H]±0.1	Object	log $(L/L_{\odot})$	T_{eff}	log g	log N(C)	[C] ±0.1	$^{12}C/^{13}C$
M71 members	–0.71	21	2.33	4349±48	1.65	–4.38	-0.19	5±2
		30	2.84	3925±56	0.88	–4.38	-0.19	7±2
		B	3.08	3600±72	0.33	–5.38	-1.19	5±3
		29	3.19	3574±50	0.09	–4.58	-0.39	9±2
		C, noise	2.08	4856±60	2.51 –3.78	+0.41	95±10	
M71 non-member?		79?	1.80	4556±56	2.20	–3.98	+0.36	5±2
M71 non-members	–0.71	*N*, noise	*1.99*	*4840±60*	*2.12*	*–2.82*	*+1.37*	*3±1*
		A5	*1.86*	*4531±57*	*2.10*	*–4.18*	*+0.01*	*10±3*
		A7	*2.04*	*4411±53*	*1.92*	*–4.38*	*-0.19*	*20±5*
		A6	*2.70*	*3897±72*	*1.02*	*–4.18*	*-0.01*	*20±5*
M5	–1.3	IV-59	2.90	4243±45	1.0	-5.38	-0.6	7±3
		II-9	3.03	4230±48	0.9	-5.58	-0.8	3±1
		IV-81	3.23	3963±53	0.6	-5.58	-0.8	4±1
M13		I-24, noise	2.61	4374±57	1.10	-5.58	-0.5	5±5
	–1.4	II-76	2.87	4202±52	1.10	-5.58	-0.7	3±1
		III-73	2.99	4164±52	0.90	-5.58	-0.7	3±1
		III-56, noise	3.13	4013±41	0.70	-6.08	-1.0	7±2
		I-48, noise	3.21	3929±45	0.60	-6.68	-1.8	90±20
		II-67	3.28	3894±45	0.50	-6.38	-1.5	4±1
M3	–1.6	I-21	2.91	4124±52	1.0	-5.58	-0.5	4±1
		III-28	3.03	4092±43	0.8	-5.78	-0.7	4±1
		AA	3.12	3977±50	0.7	-5.78	-0.7	3±1
		II-46	3.12	3951±52	0.7	-5.58	-0.5	4±1
M3 non-member?		1397?	3.15	3916	2.5	-4.72	+1.3	5±1


29
log N(C)=-4.58, $^{12}C/^{13}C=9$
Normalised flux F_ν
1400
1300
1200
1100
1000
900
800
700
2.29
2.3
2.31
2.32
2.33
2.34
2.35
2.36
2.37
Wavelength in microns


30
log N(C)=-4.38, $^{12}C/^{13}C=7$
Normalised flux F_ν
550
500
450
400
350
300
2.29
2.3
2.31
2.32
2.33
2.34
2.35
2.36
2.37
Wavelength in microns

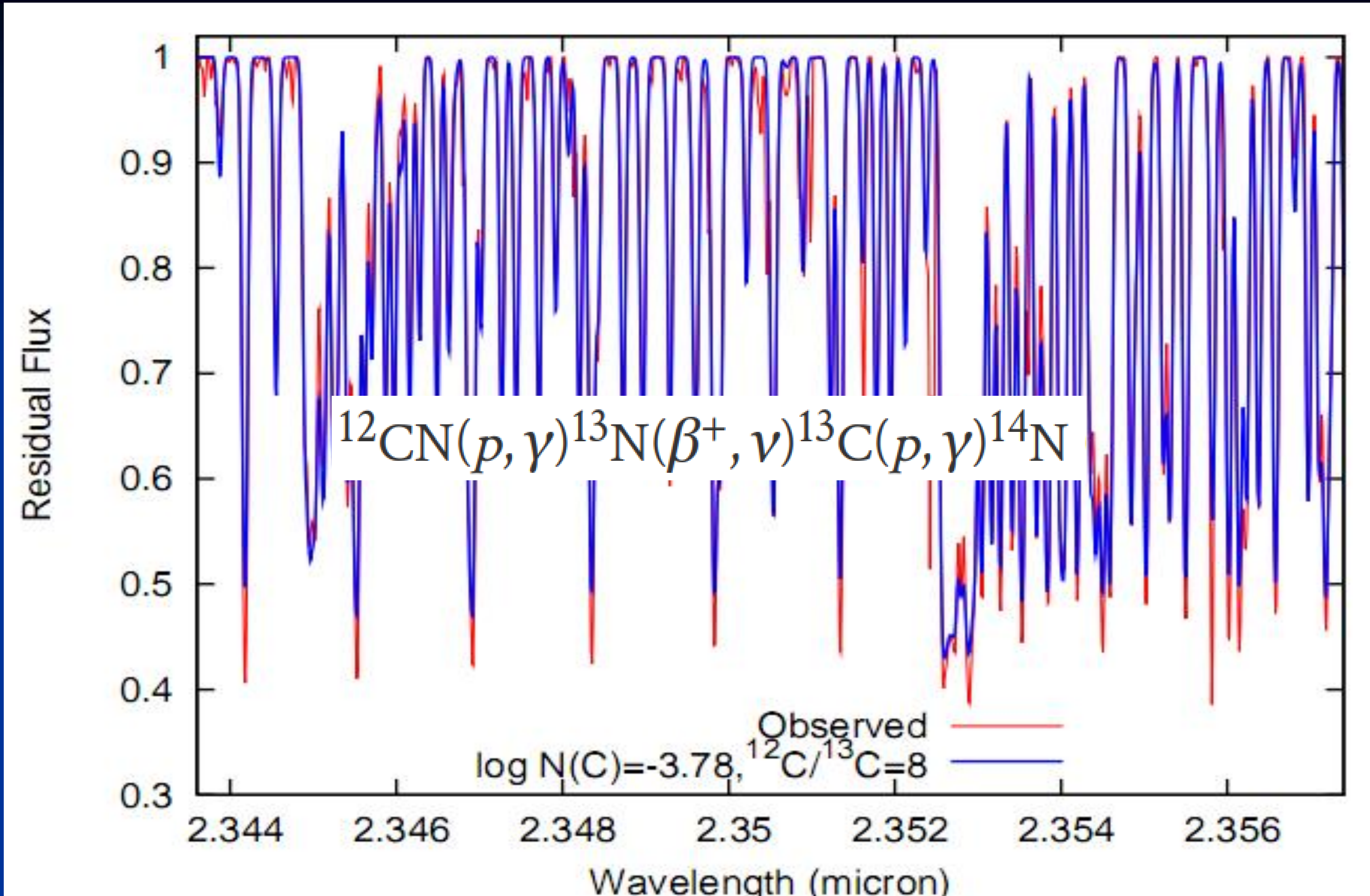

79
4556/1.0/-0.7, log N(C)=-3.82, $^{12}C/^{13}C=5$
Normalised flux F_ν
400
380
360
340
320
300
280
260
240
220
2.29
2.3
2.31
2.32
2.33
2.34
2.35
2.36
2.37
Wavelength in microns


B
log N(C)=-5.38, $^{12}C/^{13}C=5$
Normalised flux F_ν
340
320
300
280
260
240
220
2.29
2.3
2.31
2.32
2.33
2.34
2.35
2.36
2.37
Wavelength in microns



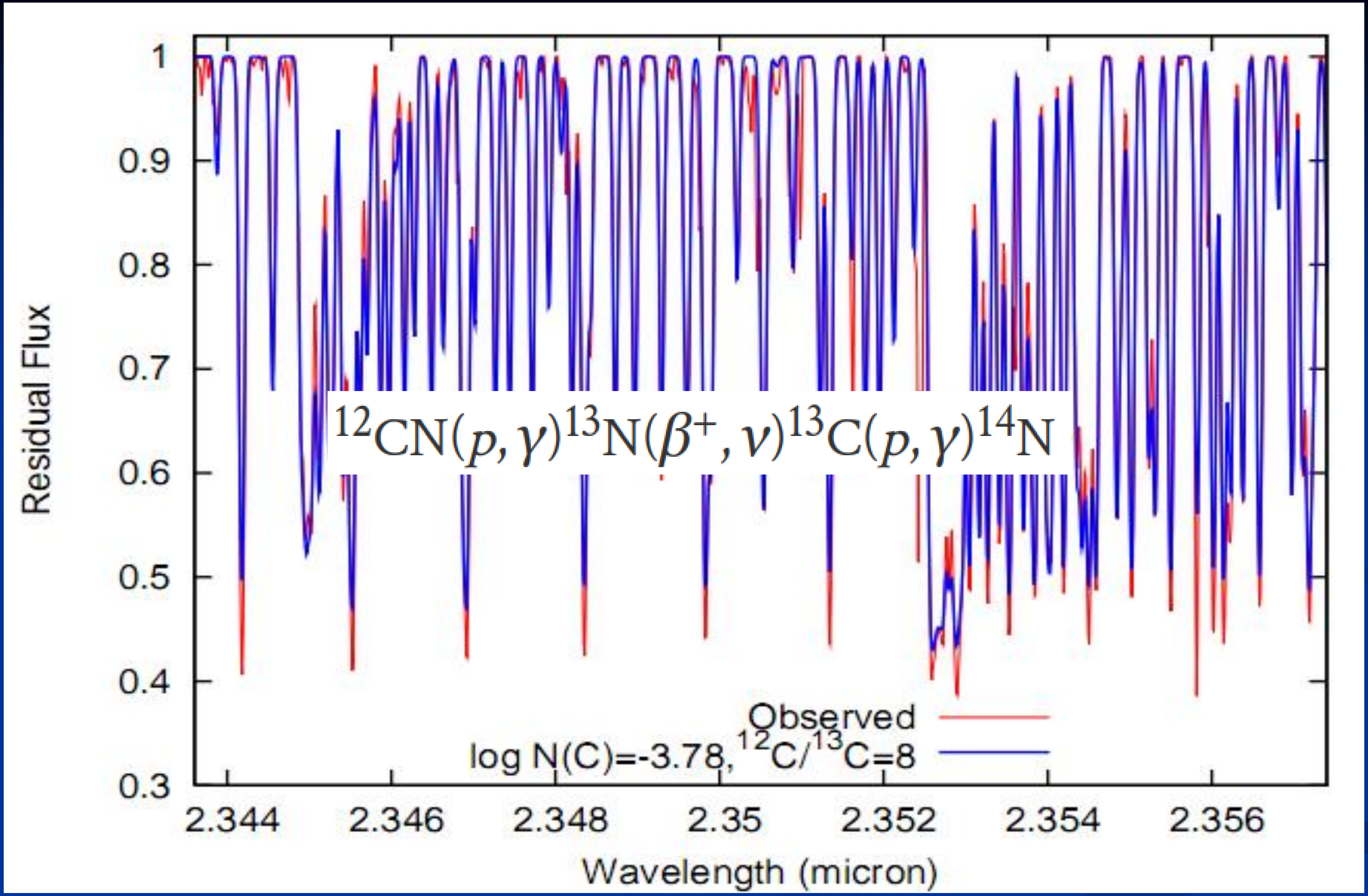
Isotopic ratios $^{12}C/^{13}C$ in giants of different clusters.

Two giants with $^{12}C/^{13}C > 90$ are not showed to simplify the plot.



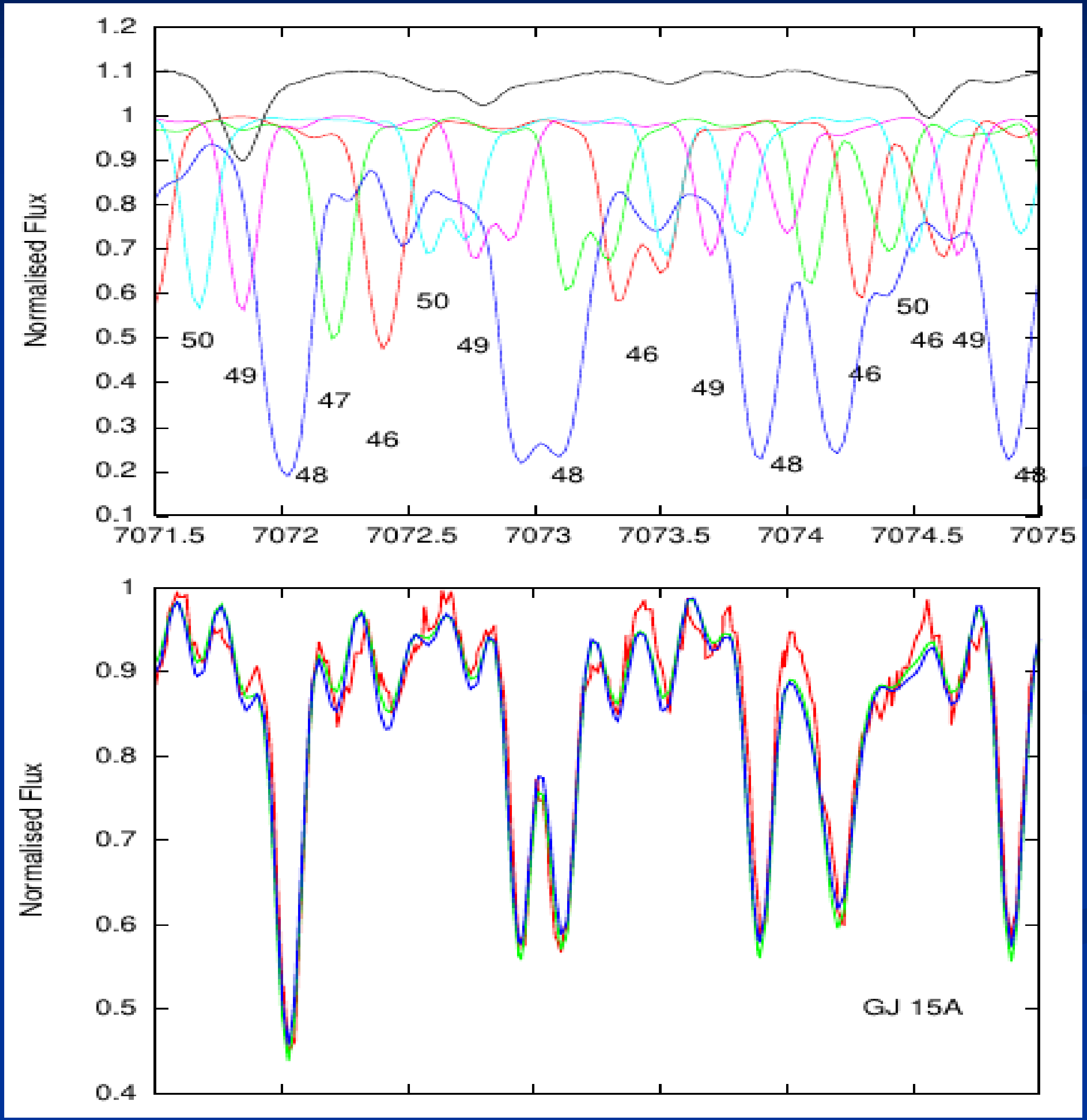
$$^{12}\mathrm{CN}(p,\gamma)^{13}\mathrm{N}(\beta^{+},\nu)^{13}\mathrm{C}(p,\gamma)^{14}\mathrm{N}$$

Pavlenko, Ya. V., 2008, The carbon abundance and 12C/13C isotopic ratio in the atmosphere of Arcturus from 2.3 µm CO bands, Astron. Rept, 52, 749-759.



Pavlenko, Ya. V., 2008, The carbon abundance and 12C/13C isotopic ratio in the atmosphere of Arcturus from 2.3 μm CO bands, Astron. Rept, 52, 749-759.

VI. Ti isotopogues



Ti isotopogues

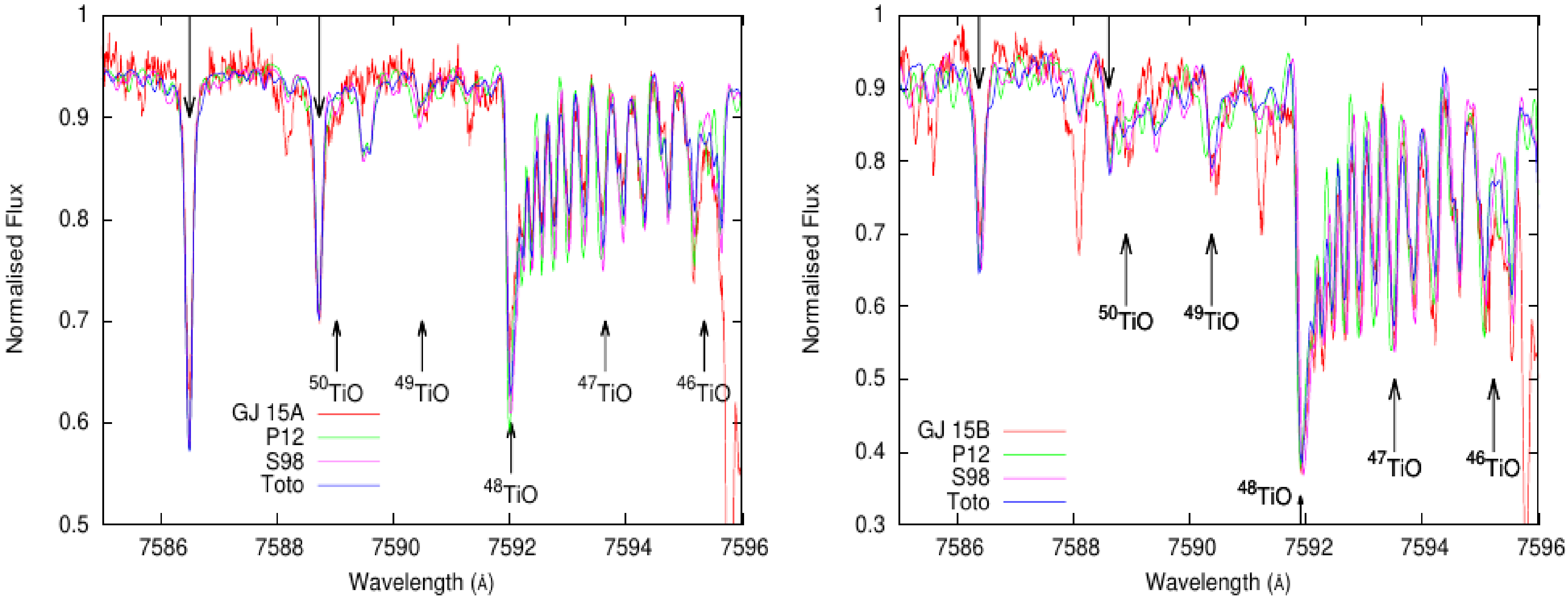


Fig. A.2. Comparison of fits to the observed TiO features in the x_2 spectral range in GJ 15A *(left panel)* and GJ 15B *(right panel)* using line lists of different authors. Here solar isotopic ratios of Ti were adopted.

Conclusions

We use the most accurate spectroscopic molecular inputs because modern observations provide the real challenge in the quality and quantity of the perfect observational data.

Astronomy often progresses amoeba-like: the advance in one pseudopod may not move the animal very far, but permits other parts to advance in their turn and can reveal portions of the organism that are in danger of being left behind.

V.Trimble, R.A.Bell, Q.Jl.R.astr.Soc.(1981),22, 361-379