Stark Broadening of Carbon and Oxygen Lines in Hot DQ White Dwarfs: Recent Results and Applications

Patrick Dufour

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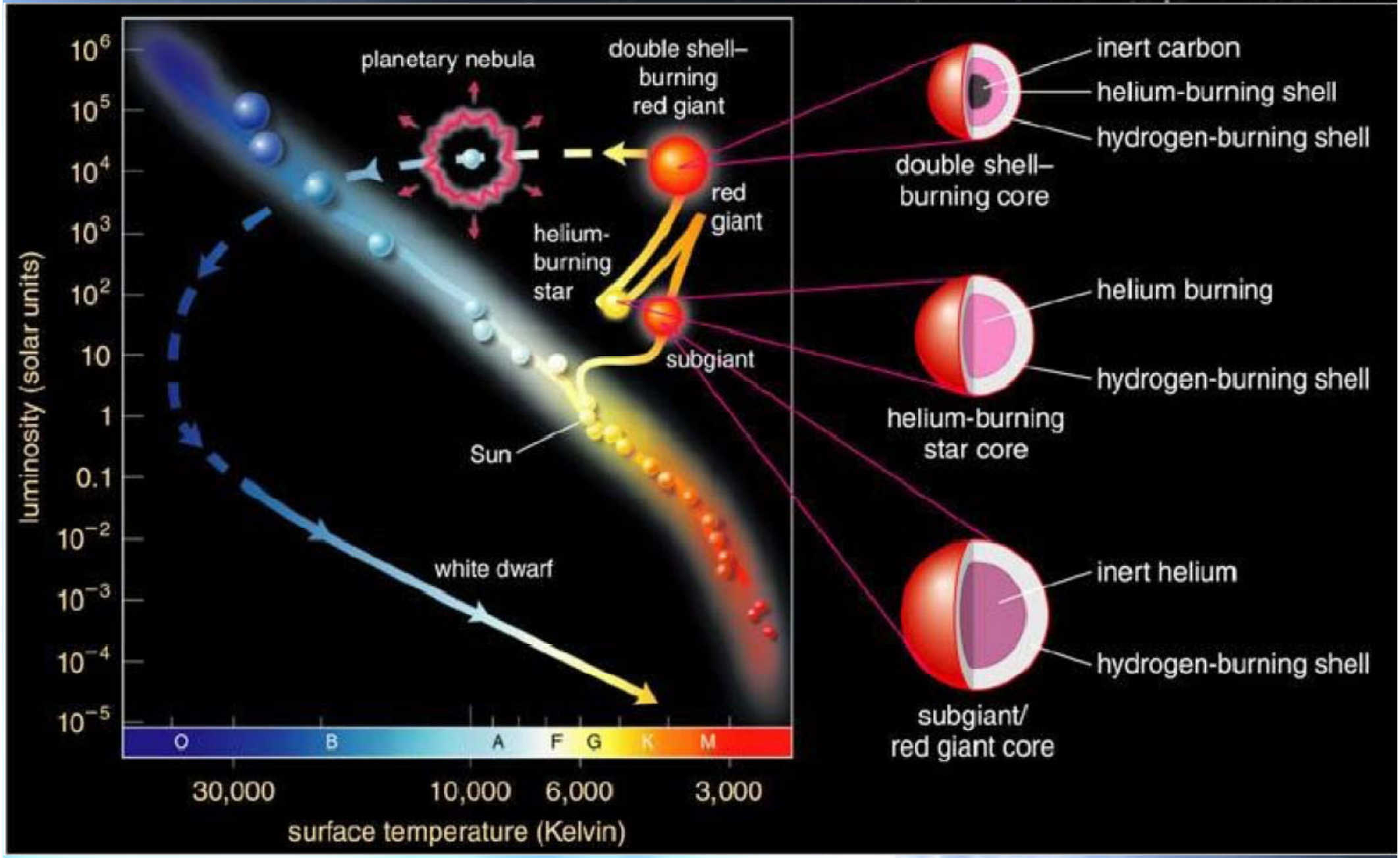
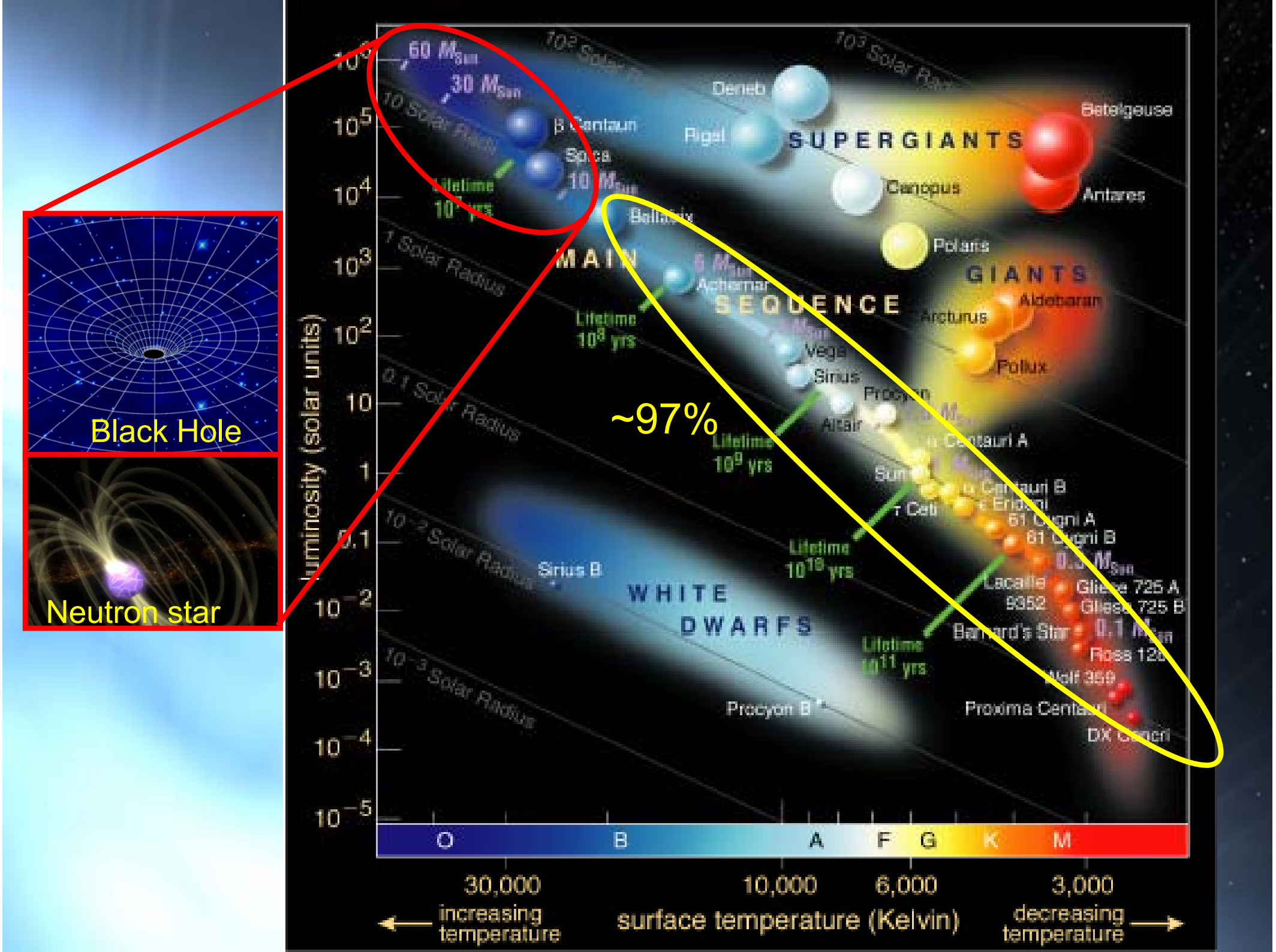
Université de Montréal

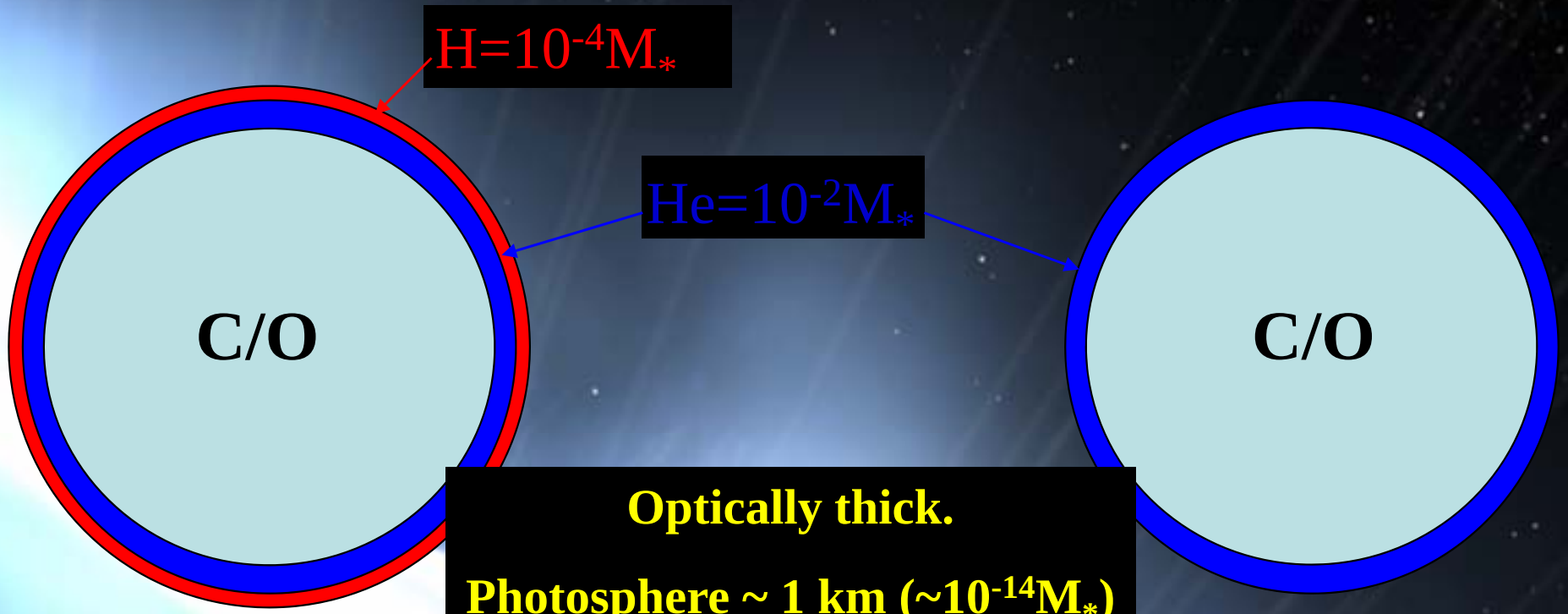
Outline

- A brief introduction: stellar evolution and white dwarf stars
- Carbon (and oxygen) in white dwarf stars
  - white dwarfs with traces of carbon
  - carbon dominated atmosphere white dwarfs
  - Future research directions
- Planets and abundance determinations
  - white dwarfs with traces of metals


planetary nebula
double shell–burning red giant
red giant
helium-burning star
subgiant
Sun
white dwarf
luminosity (solar units)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
O
B
A
F
G
K
M
30,000
10,000
6,000
3,000
surface temperature (Kelvin)
inert carbon
helium-burning shell
hydrogen-burning shell
double shell–burning core
helium burning
hydrogen-burning shell
helium-burning star core
inert helium
hydrogen-burning shell
subgiant/ red giant core

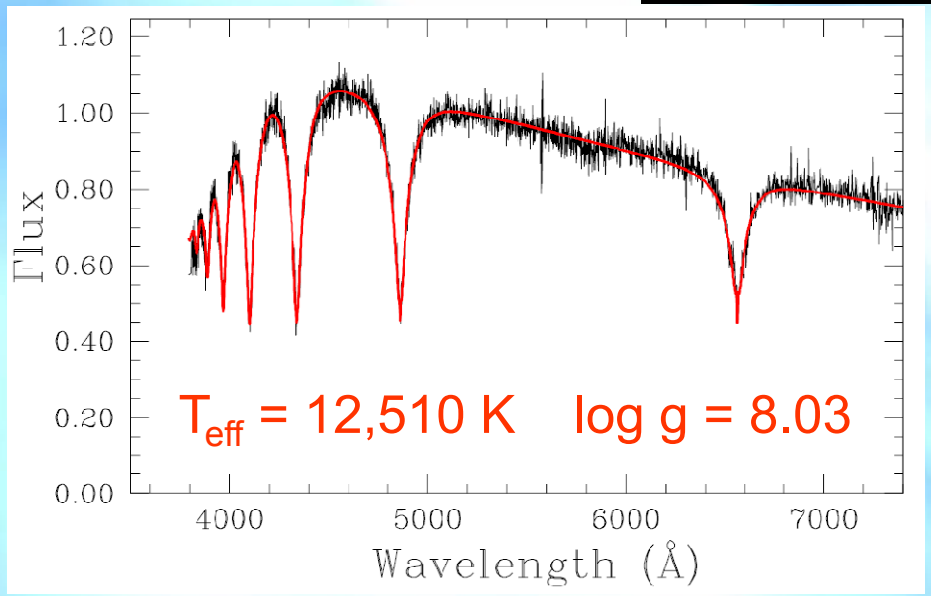

Black Hole
Neutron star
luminosity (solar units)
SUPERGIANTS
GIANTS
MAIN SEQUENCE
WHITE DWARFS
Deneb
Rigel
Betelgeuse
Canopus
Antares
Polaris
Aldebaran
Arcturus
Pollux
Achernar
Vega
Sirius
Procyon
Altair
Sun
τ Ceti
Sirius B
Procyon B
Lacaille 9352
Barnard's Star
Ross 128
Proxima Centauri
60 M
30 M
Lifetime 10^8 yrs
Lifetime 10^9 yrs
Lifetime 10^10 yrs
Lifetime 10^11 yrs
1 Solar Radius
0.1 Solar Radius
10^-2 Solar Radius
10^-3 Solar Radius
~97%
O
B
A
F
G
K
M
30,000
10,000
6,000
3,000
increasing temperature
surface temperature (Kelvin)
decreasing temperature

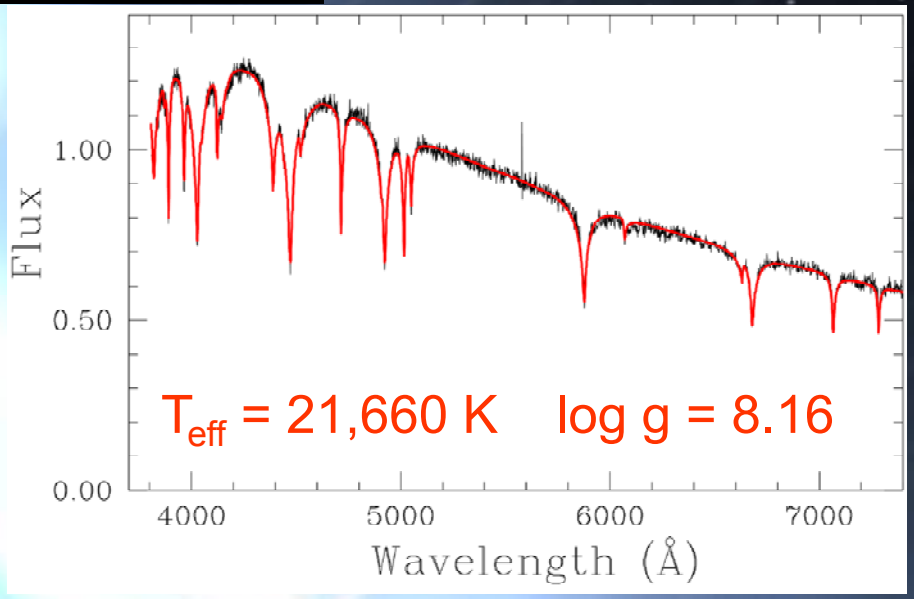
Standard Stellar Evolution Theory

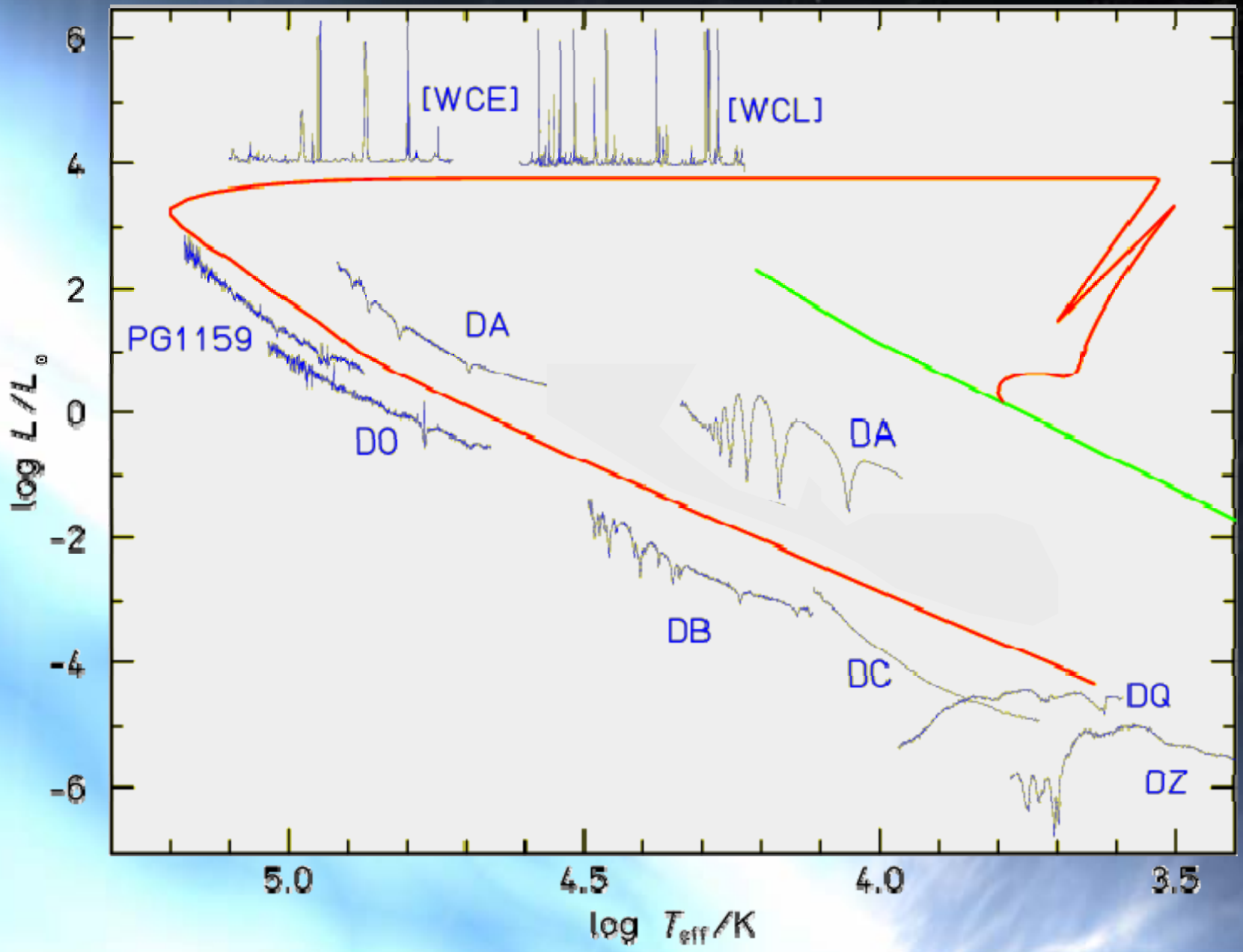


Optically thick.

Photosphere ~ 1 km (~$10^{-14}M_*$)







Rauch & Werner 1995

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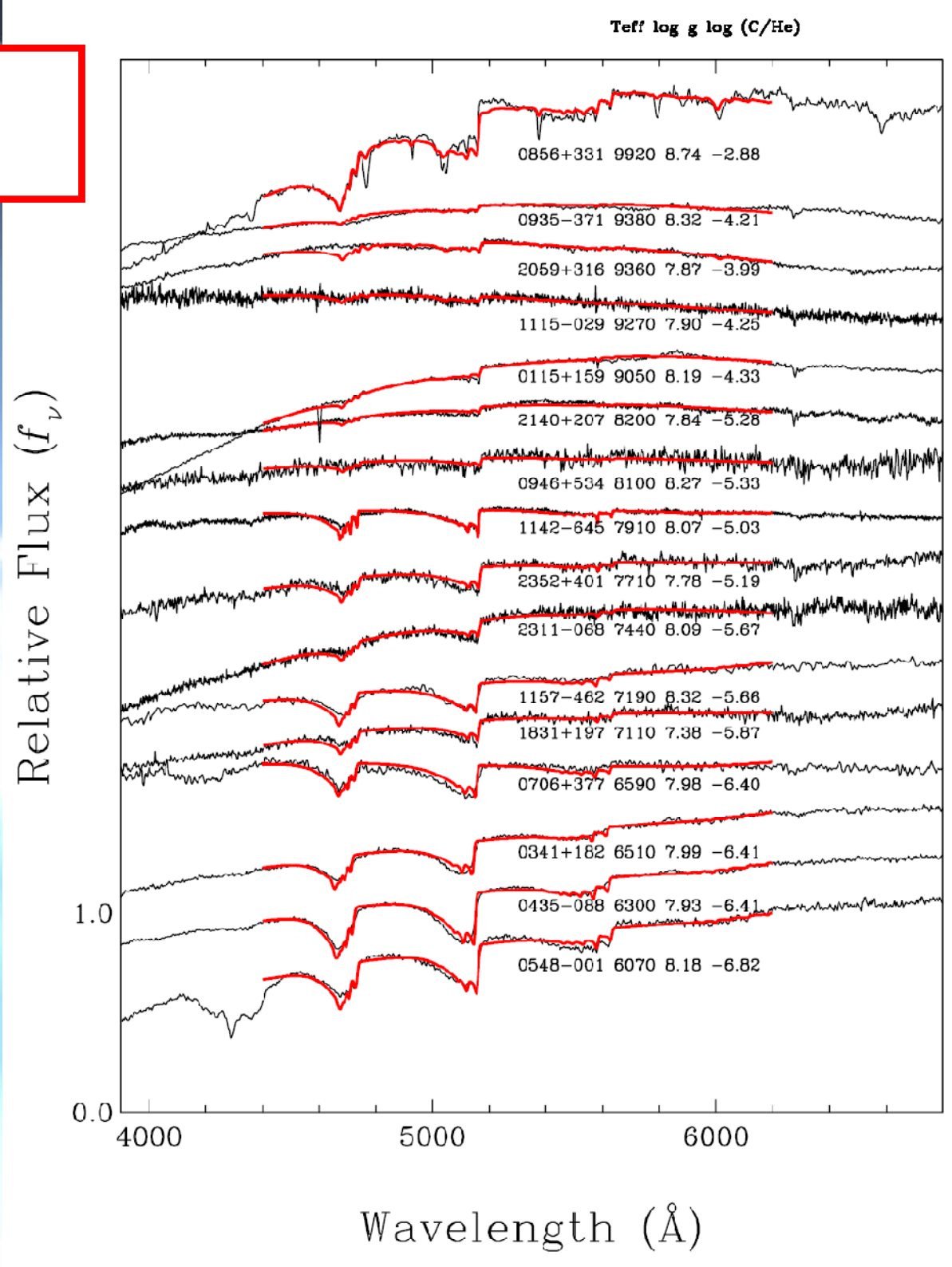
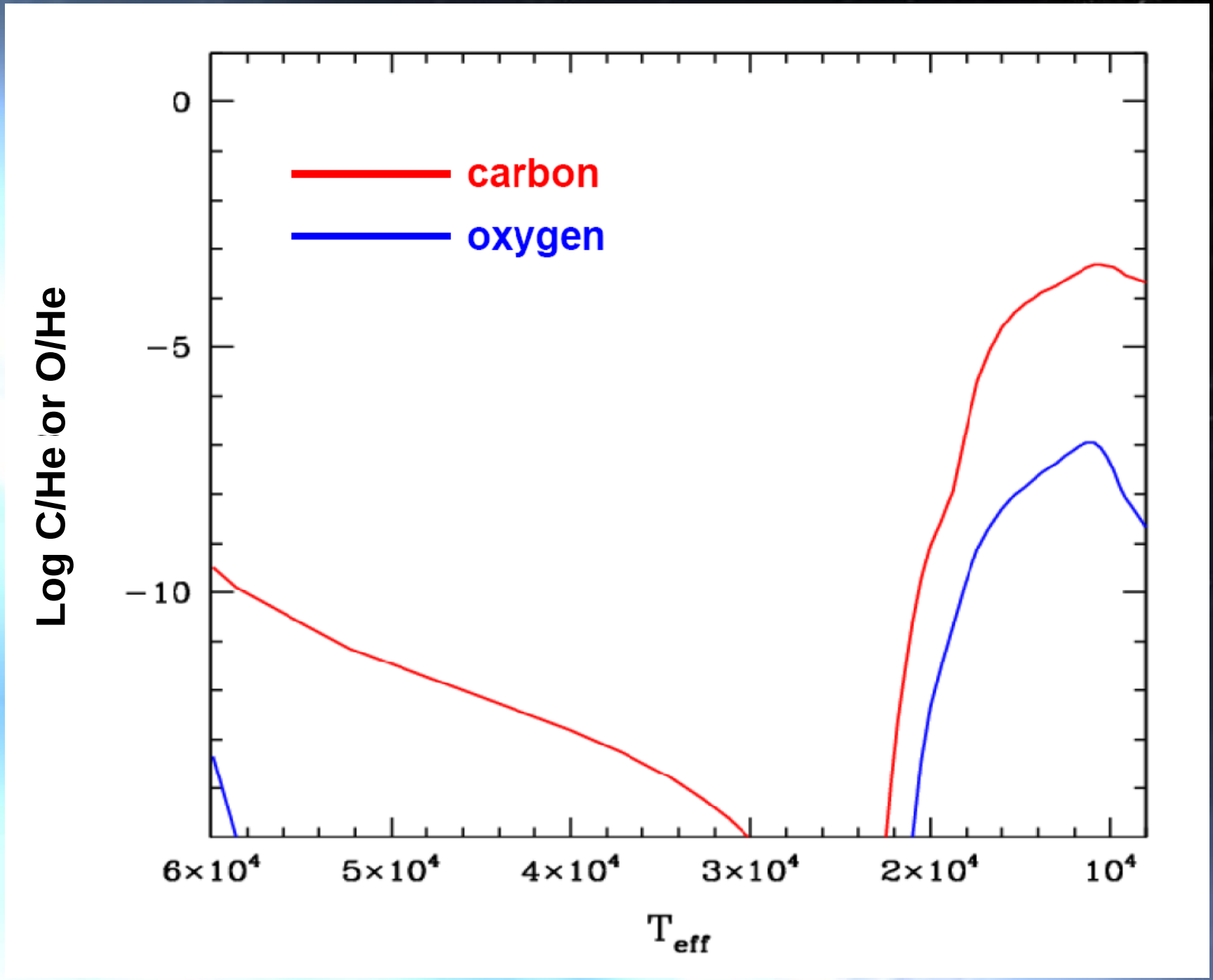
  - Future research directions
- Planets and abundance determinations
  - white dwarfs with traces of metals

Dufour et al., 2005

ApJ, 627, 404

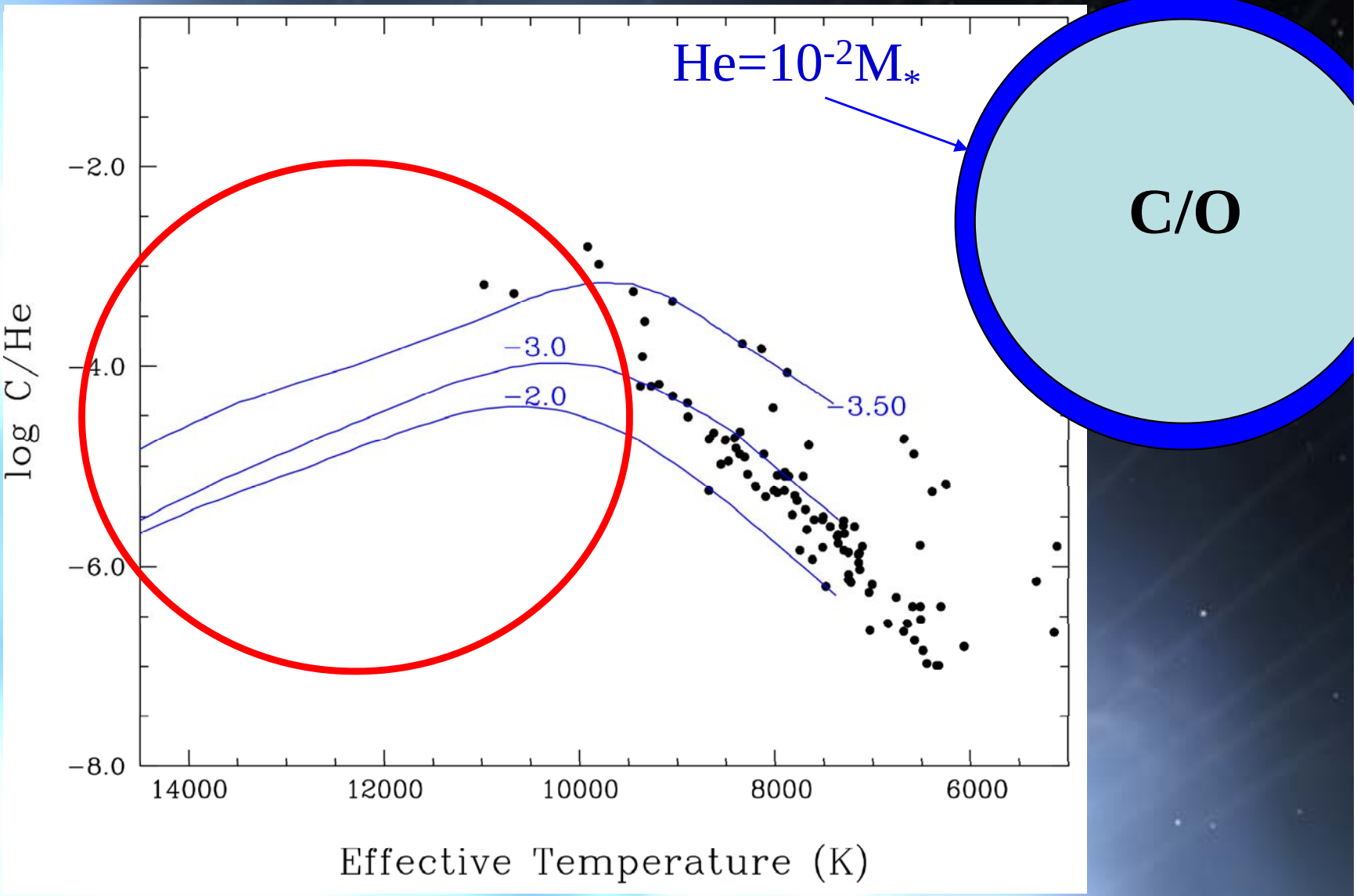


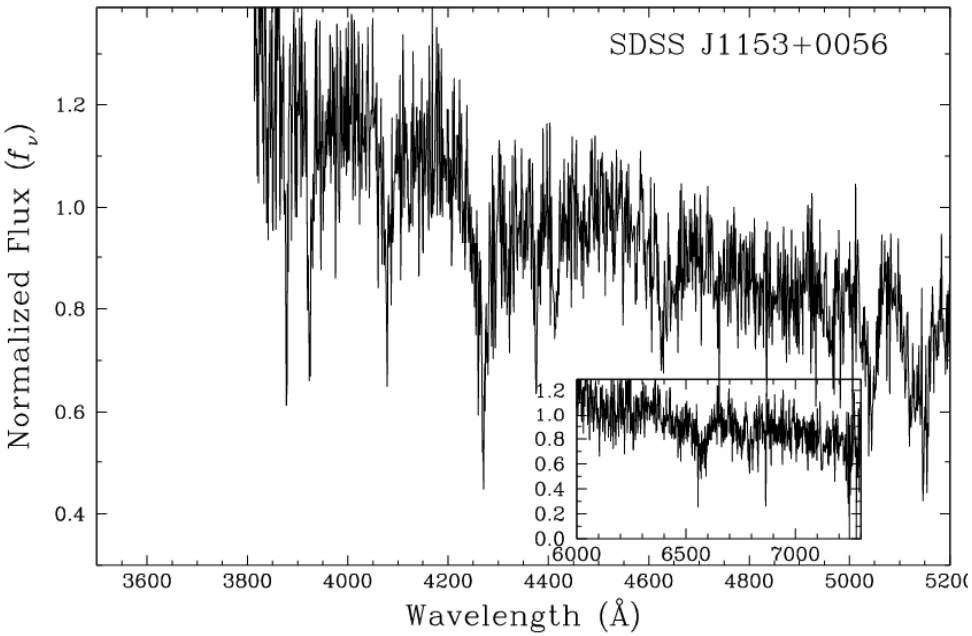

carbon
oxygen
Log C/He or O/He
0
−5
−10
6×10⁴
5×10⁴
4×10⁴
3×10⁴
2×10⁴
10⁴
T_eff

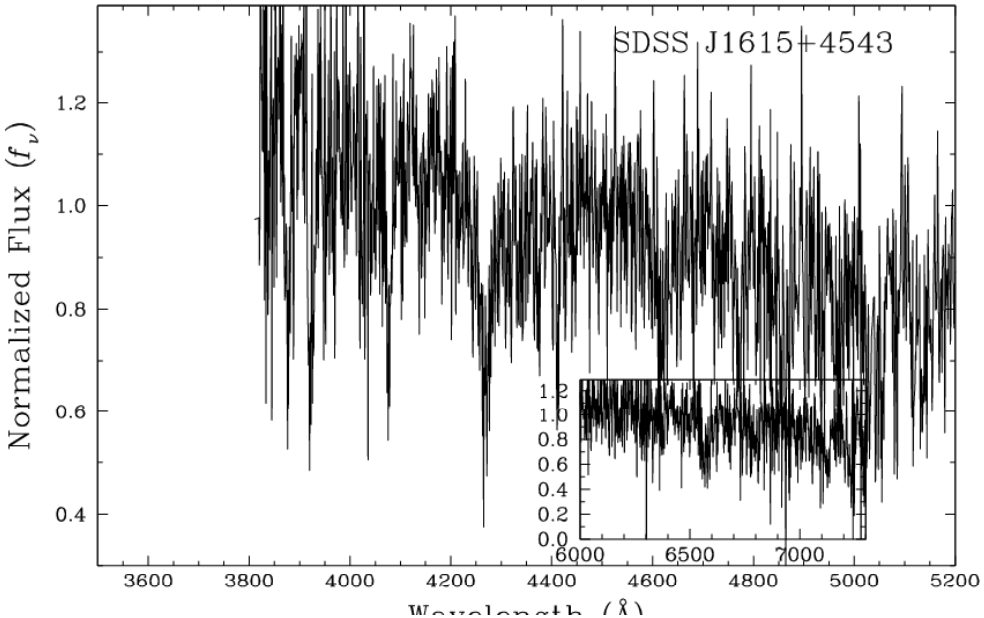
Stars with Unusual Compositions: Carbon and Oxygen in Cool White Dwarfs

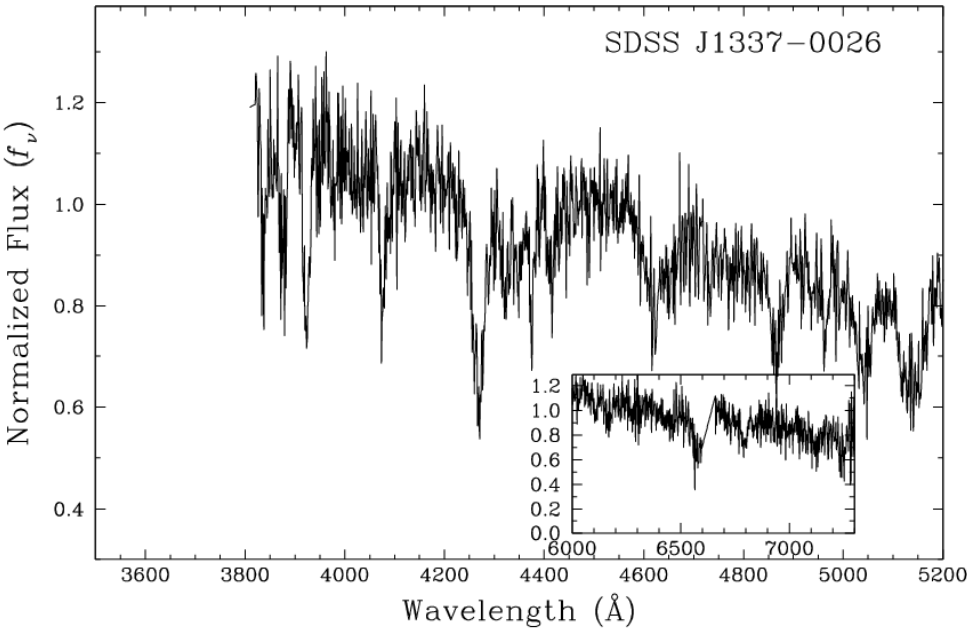
P. Dufour

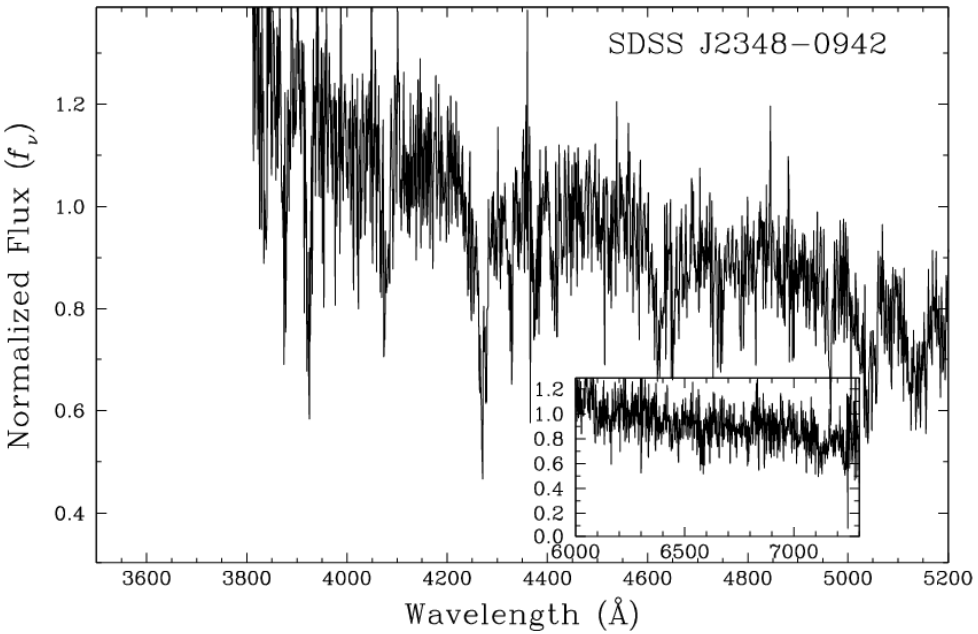
Review chapter to be published in "*White Dwarf Atmosphere and Circumstellar Environments*", D. W. Hoard (Ed.), Wiley-VCH, ISBN 978-3-527-41031-6

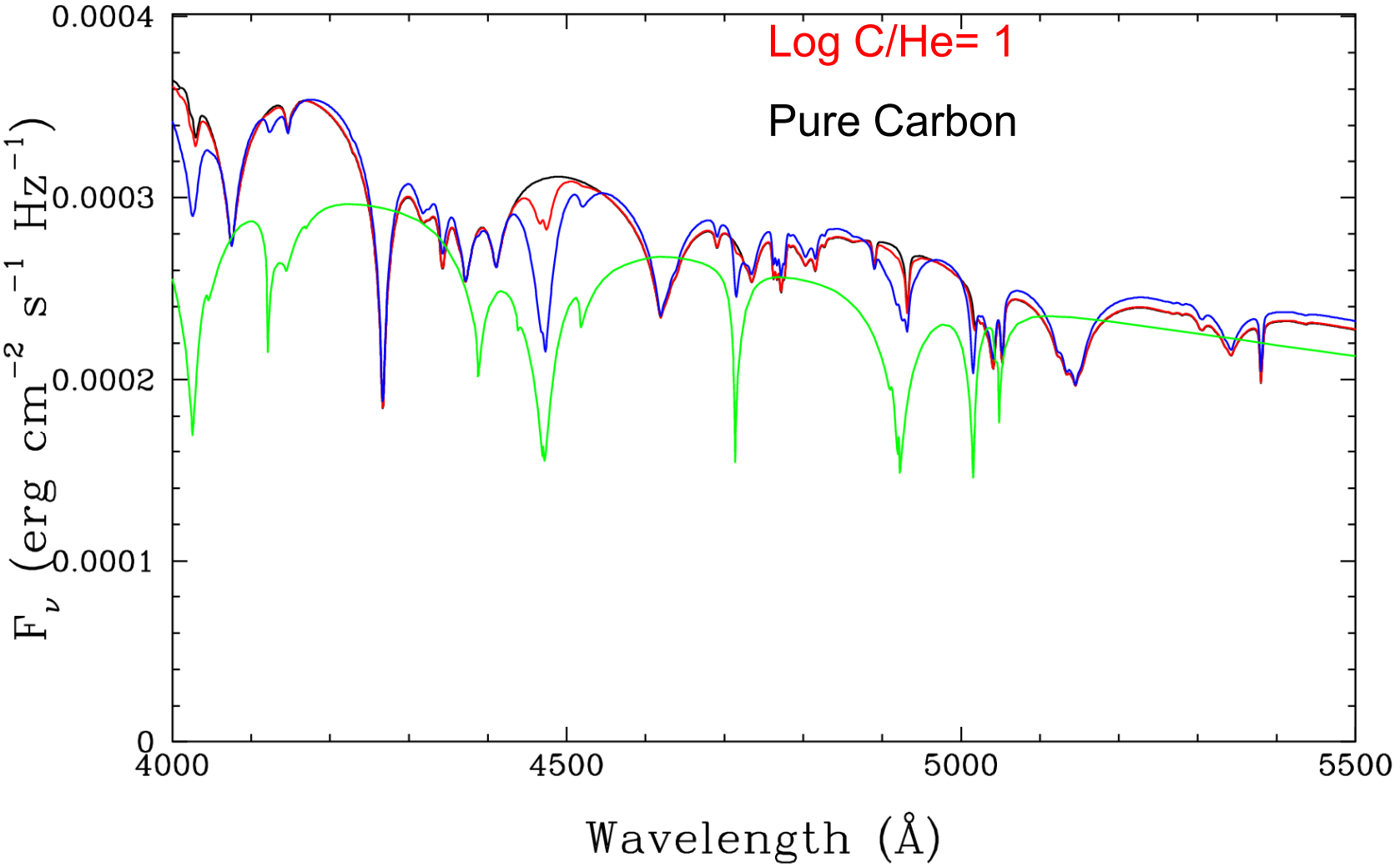


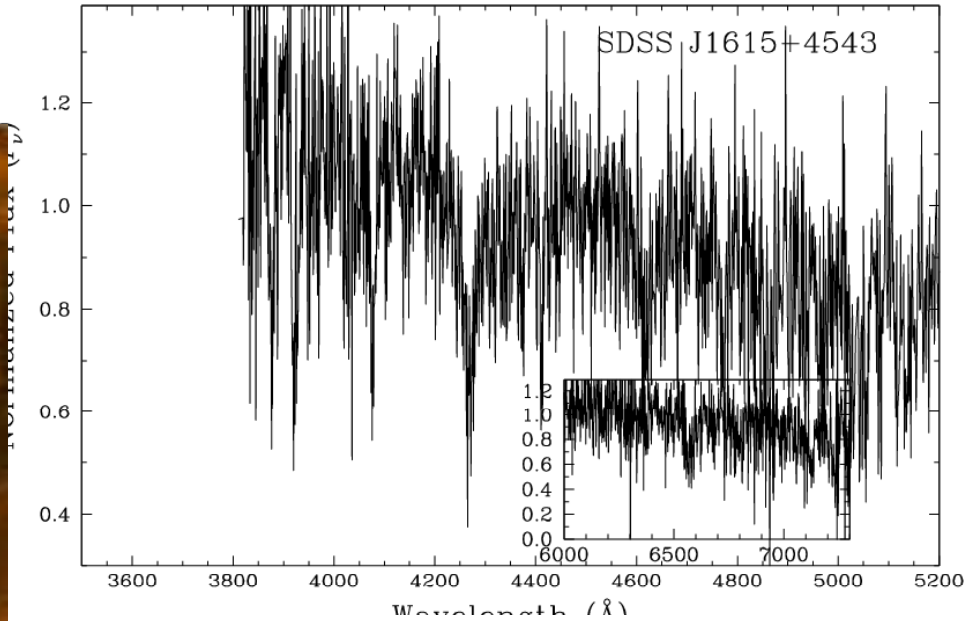

SDSS J1153+0056
Normalized Flux (f_ν)
Wavelength (Å)


SDSS J1615+4543
Normalized Flux (f_ν)

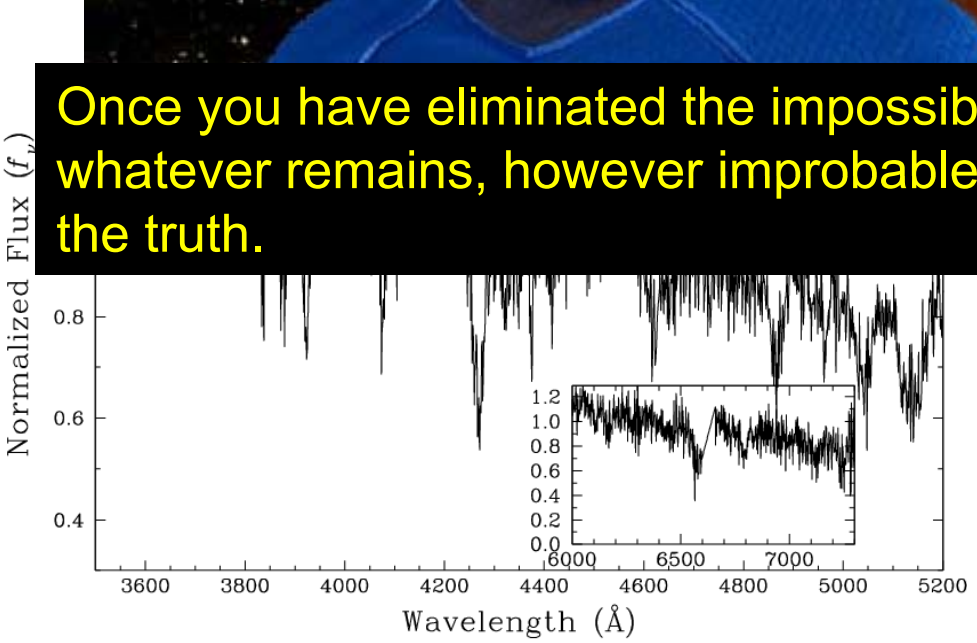

SDSS J1337−0026
Normalized Flux (f_ν)
Wavelength (Å)

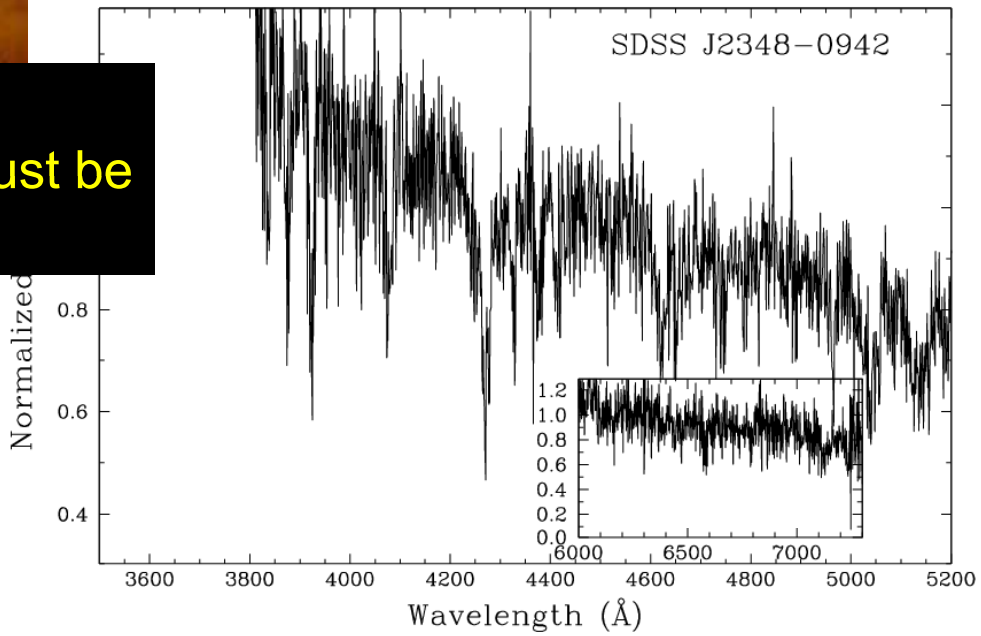

SDSS J2348−0942
Normalized Flux (f_ν)
Wavelength (Å)

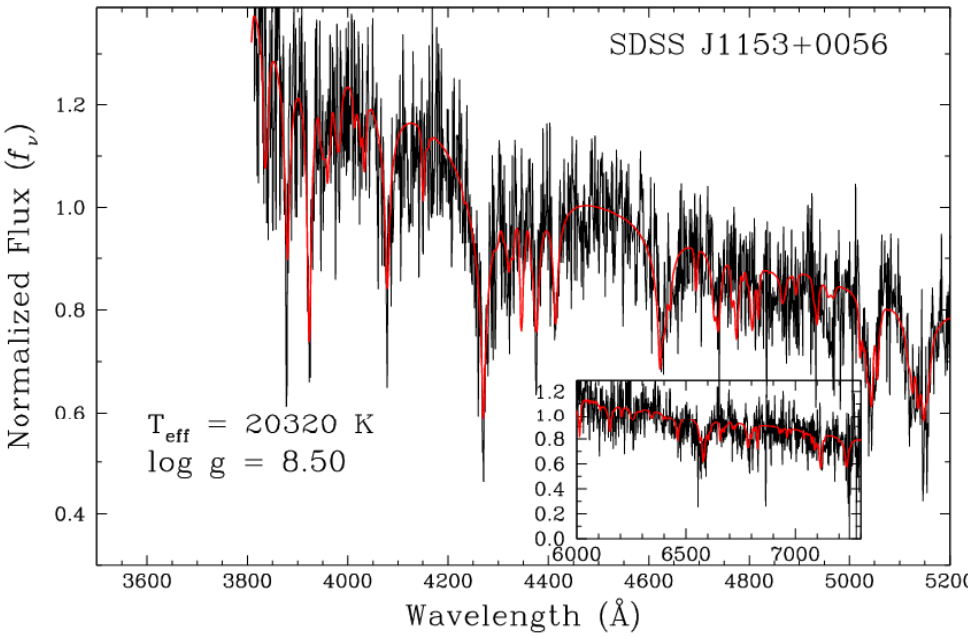

Pure Helium
Log C/He = 0
Log C/He= 1
Pure Carbon
0.0004
0.0003
0.0002
0.0001
0
4000
4500
5000
5500
F_ν (erg cm^{-2} s^{-1} Hz^{-1})
Wavelength (Å)

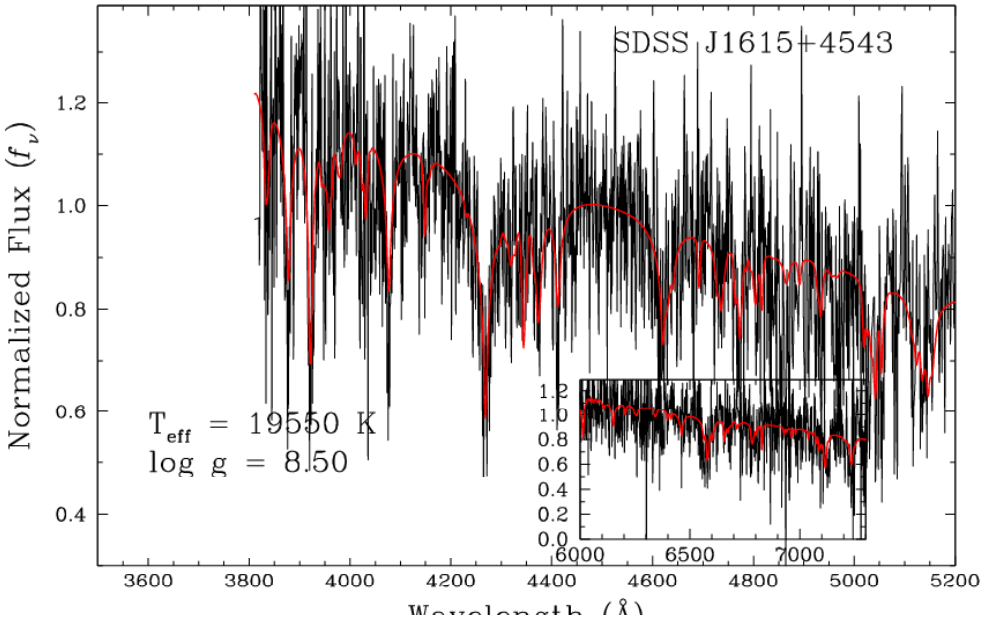


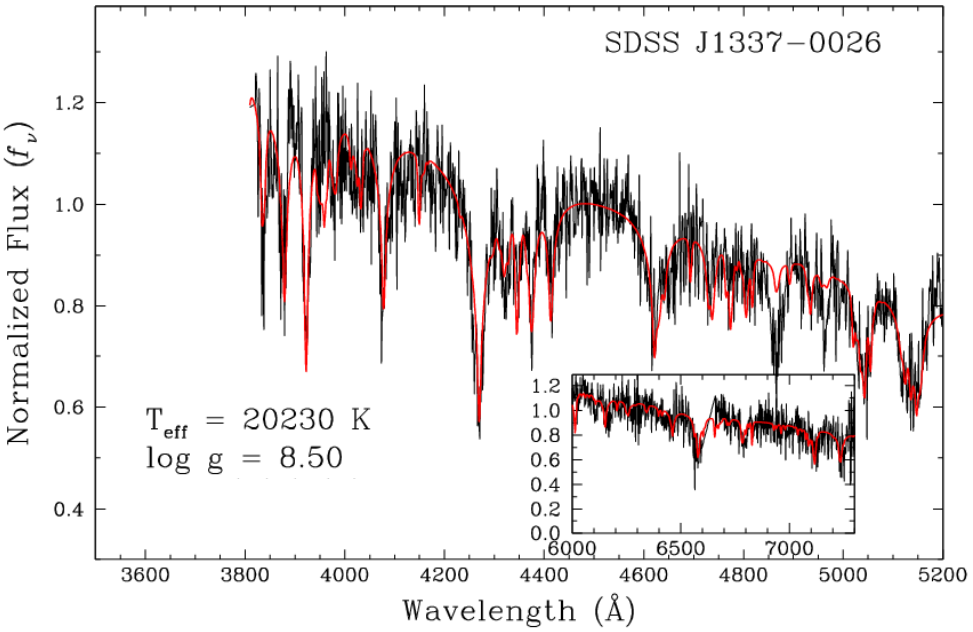
Once you have eliminated the impossible, whatever remains, however improbable, must be the truth.

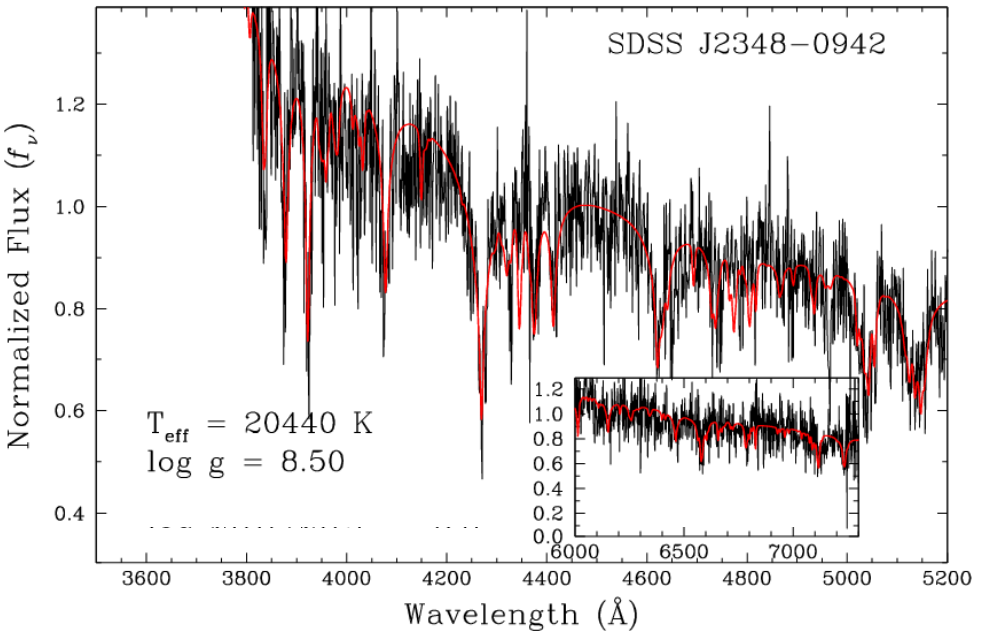


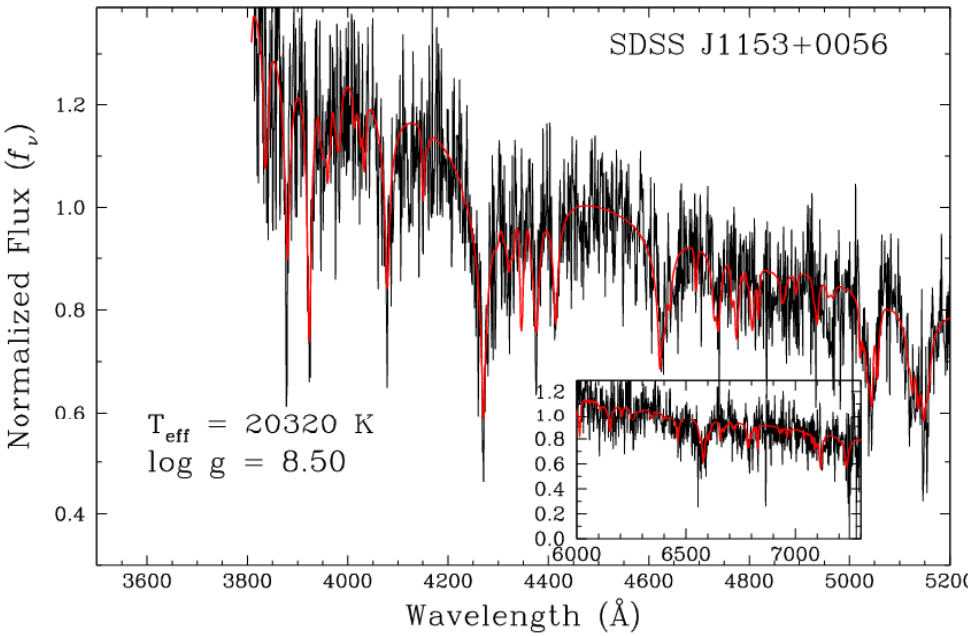


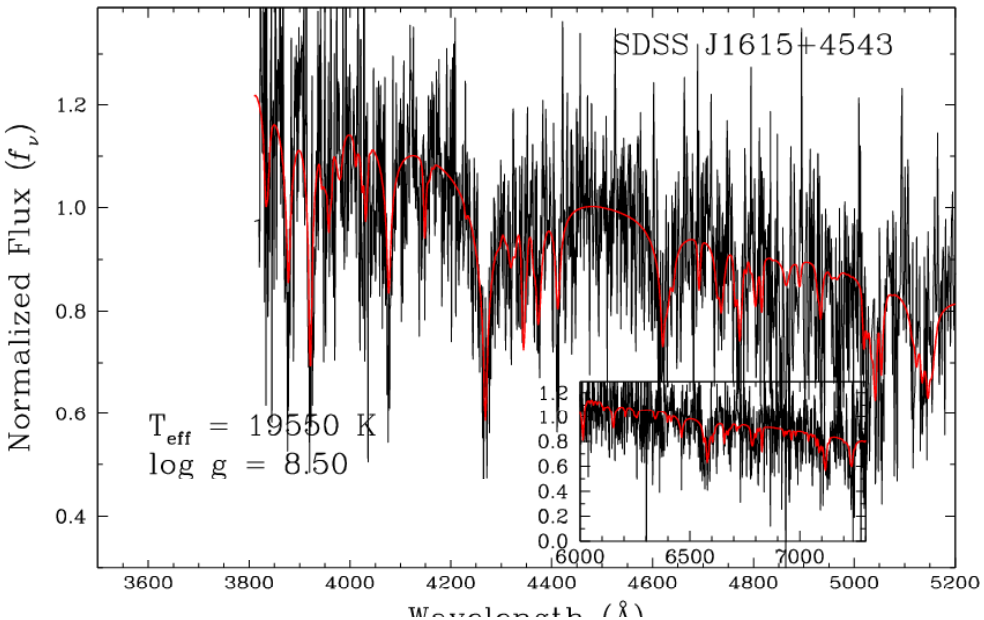

SDSS J1153+0056
T_{eff} = 20320 K
log g = 8.50
Normalized Flux (f_ν)
Wavelength (Å)

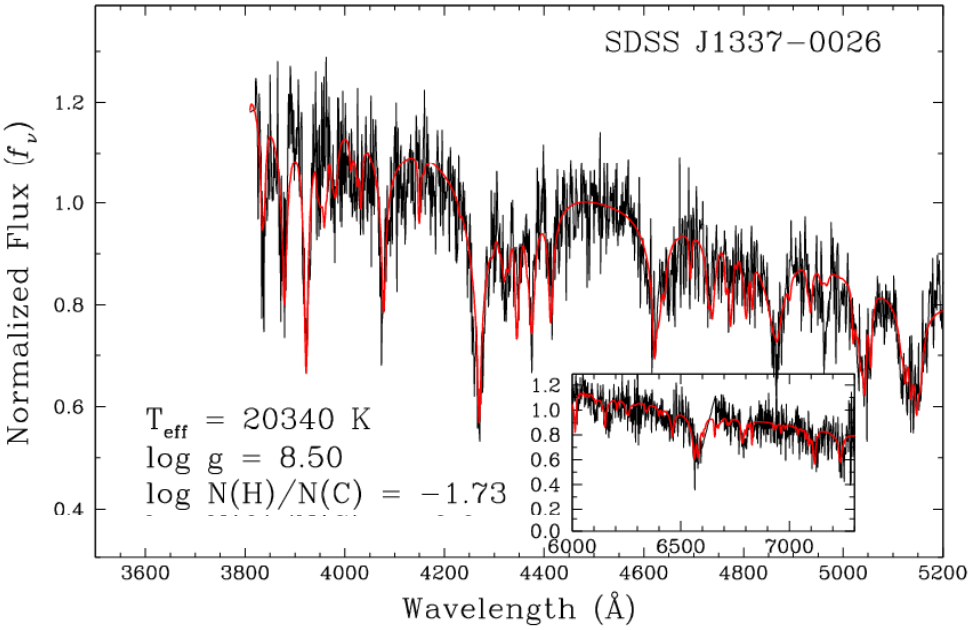

SDSS J1615+4543
T_{eff} = 19550 K
log g = 8.50
Normalized Flux (f_ν)

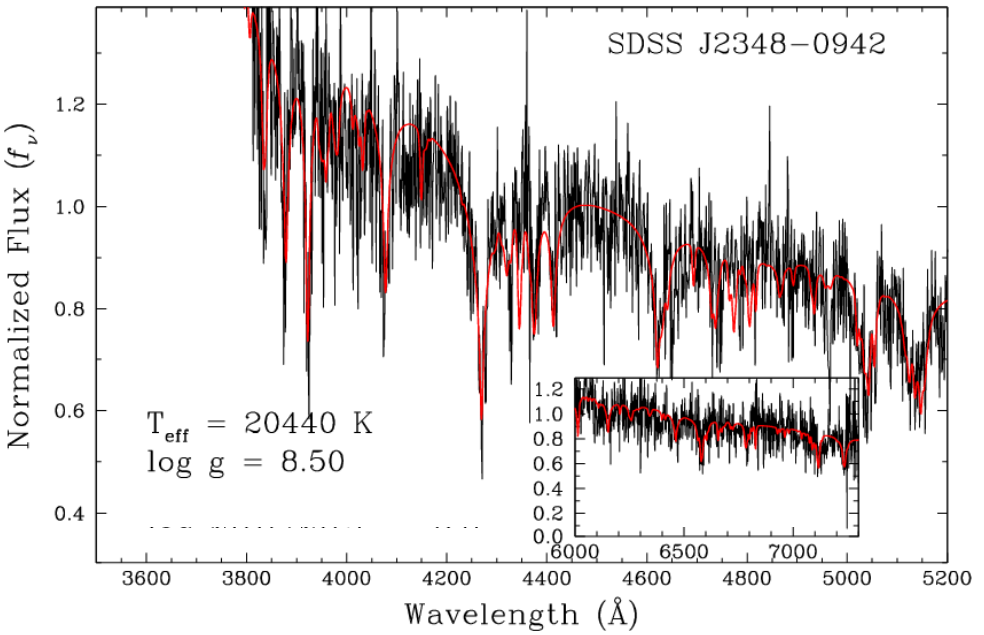

SDSS J1337−0026
T_{eff} = 20230 K
log g = 8.50
Normalized Flux (f_ν)
Wavelength (Å)


SDSS J2348−0942
T_{eff} = 20440 K
log g = 8.50
Normalized Flux (f_ν)
Wavelength (Å)


SDSS J1153+0056
T_eff = 20320 K
log g = 8.50
Normalized Flux (f_ν)
Wavelength (Å)


SDSS J1615+4543
T_eff = 19550 K
log g = 8.50
Normalized Flux (f_ν)


SDSS J1337−0026
T_eff = 20340 K
log g = 8.50
log N(H)/N(C) = −1.73
Normalized Flux (f_ν)
Wavelength (Å)


SDSS J2348−0942
T_eff = 20440 K
log g = 8.50
Normalized Flux (f_ν)
Wavelength (Å)

nature Vol 450|22 November 2007|doi:10.1038/nature06318

LETTERS

White dwarf stars with carbon atmospheres

P. Dufour[1], J. Liebert[1], G. Fontaine[2] & N. Behara[3]

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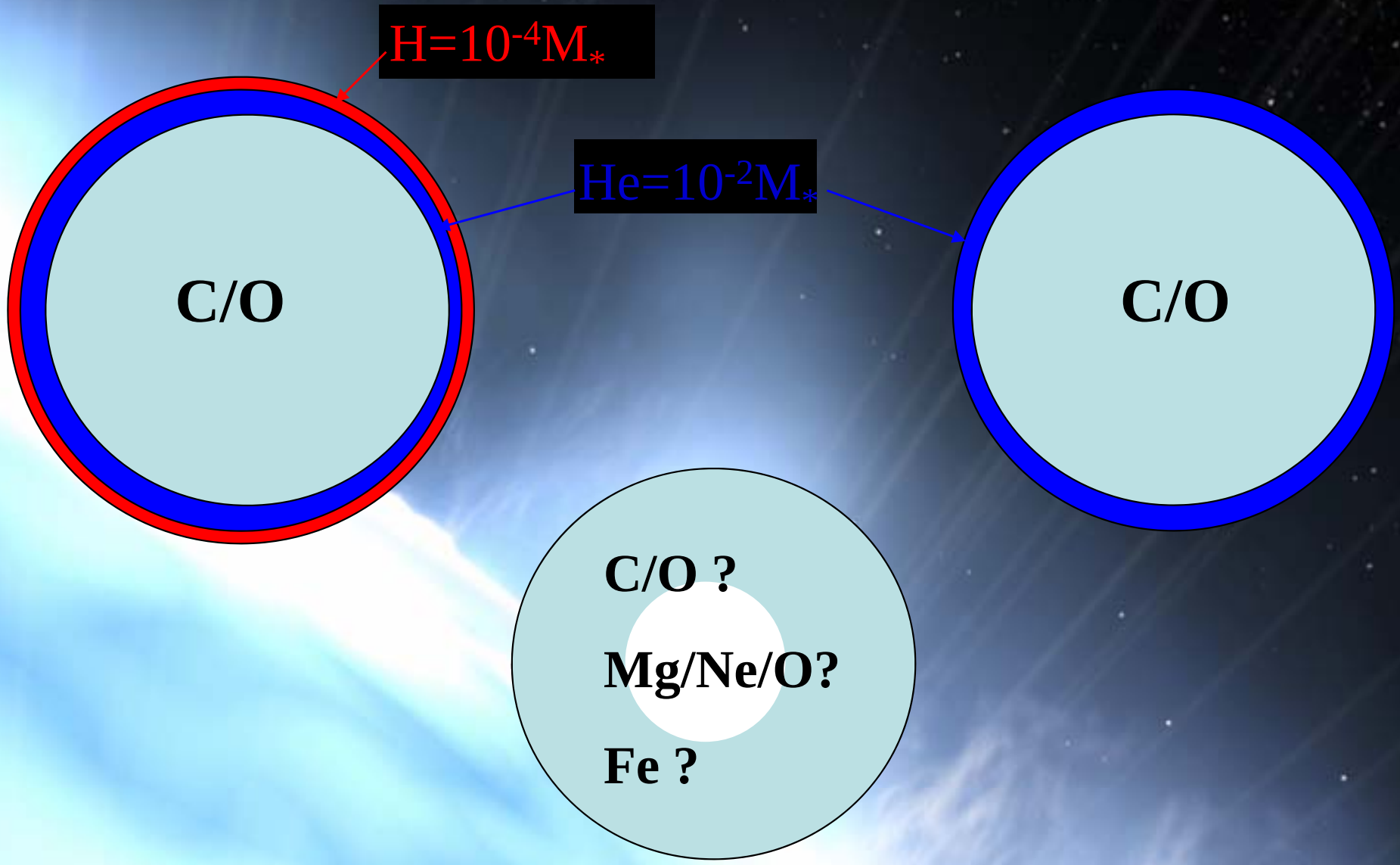
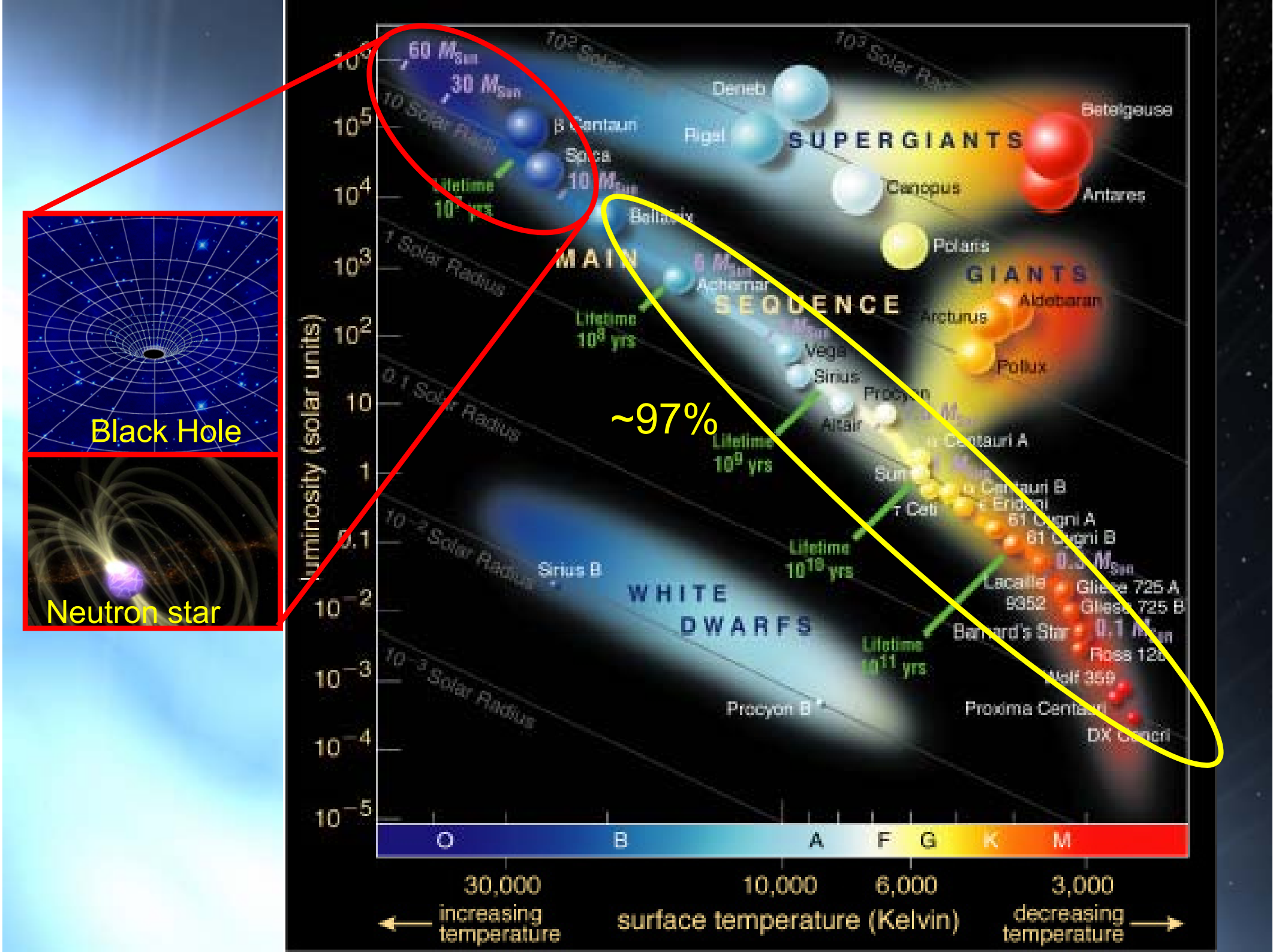
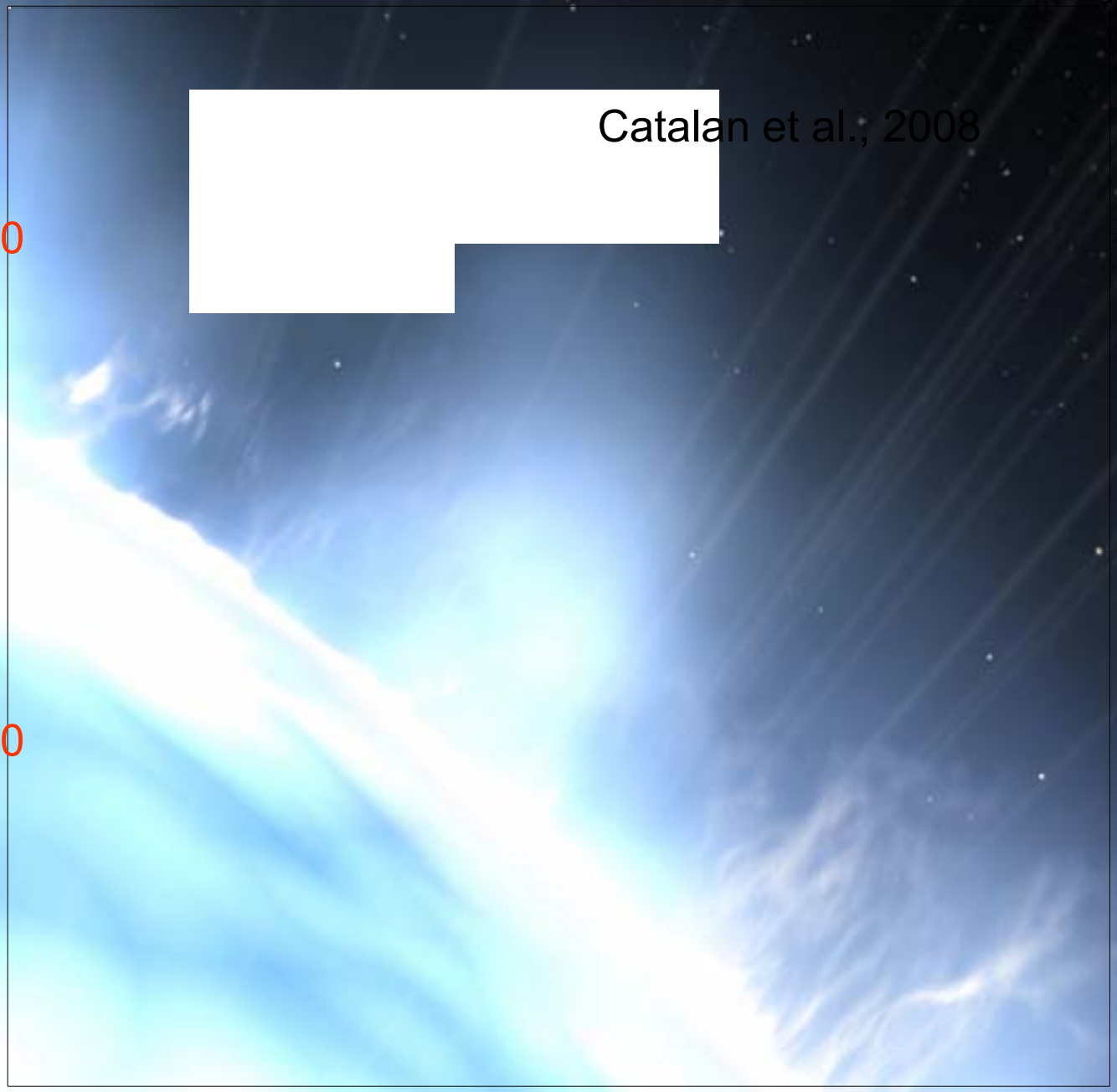
- A brief introduction: stellar evolution and white dwarf stars
- Carbon (and oxygen) in white dwarf stars
  - white dwarfs with traces of carbon
  - carbon dominated atmosphere white dwarfs
  - Future research directions
- Planets and abundance determinations
  - white dwarfs with traces of metals

Standard Stellar Evolution Theory




Black Hole
Neutron star
luminosity (solar units)
SUPERGIANTS
GIANTS
MAIN SEQUENCE
WHITE DWARFS
Deneb
Rigel
Betelgeuse
Canopus
Antares
Polaris
Aldebaran
Arcturus
Pollux
Achernar
Vega
Sirius
Procyon
Altair
Sun
τ Ceti
Sirius B
Procyon B
Lacaille 9352
Barnard's Star
Ross 128
Proxima Centauri
60 M
30 M
Lifetime 10^8 yrs
Lifetime 10^9 yrs
Lifetime 10^10 yrs
Lifetime 10^11 yrs
1 Solar Radius
0.1 Solar Radius
10^-2 Solar Radius
10^-3 Solar Radius
~97%
O
B
A
F
G
K
M
30,000
10,000
6,000
3,000
increasing temperature
surface temperature (Kelvin)
decreasing temperature

IFMR : Relationship between the progenitor's mass on MS and the final mass as a white dwarf

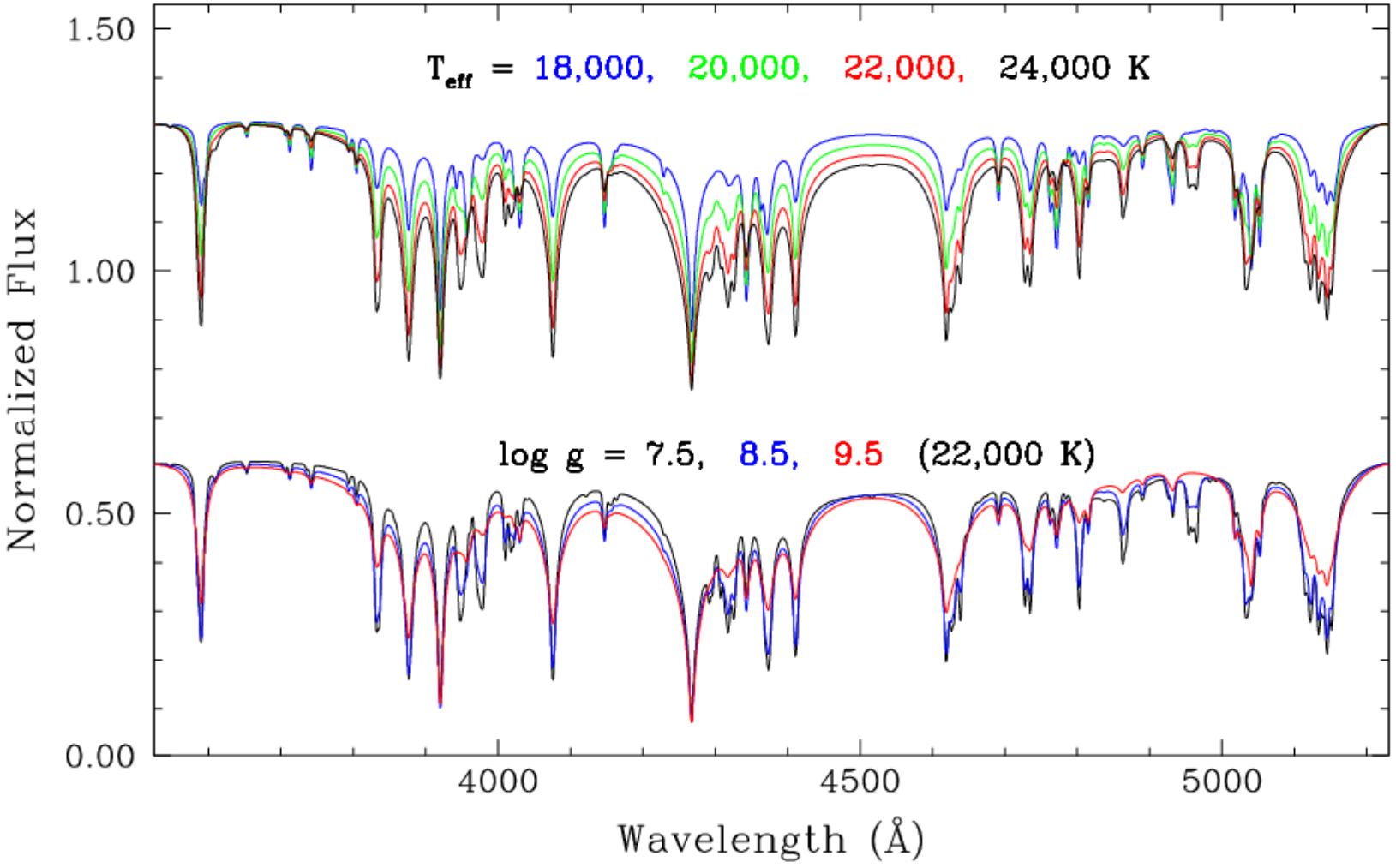


Model Atmosphere Grids

T_{eff} = 16,000 to 25,000 K in steps of 1,000 K

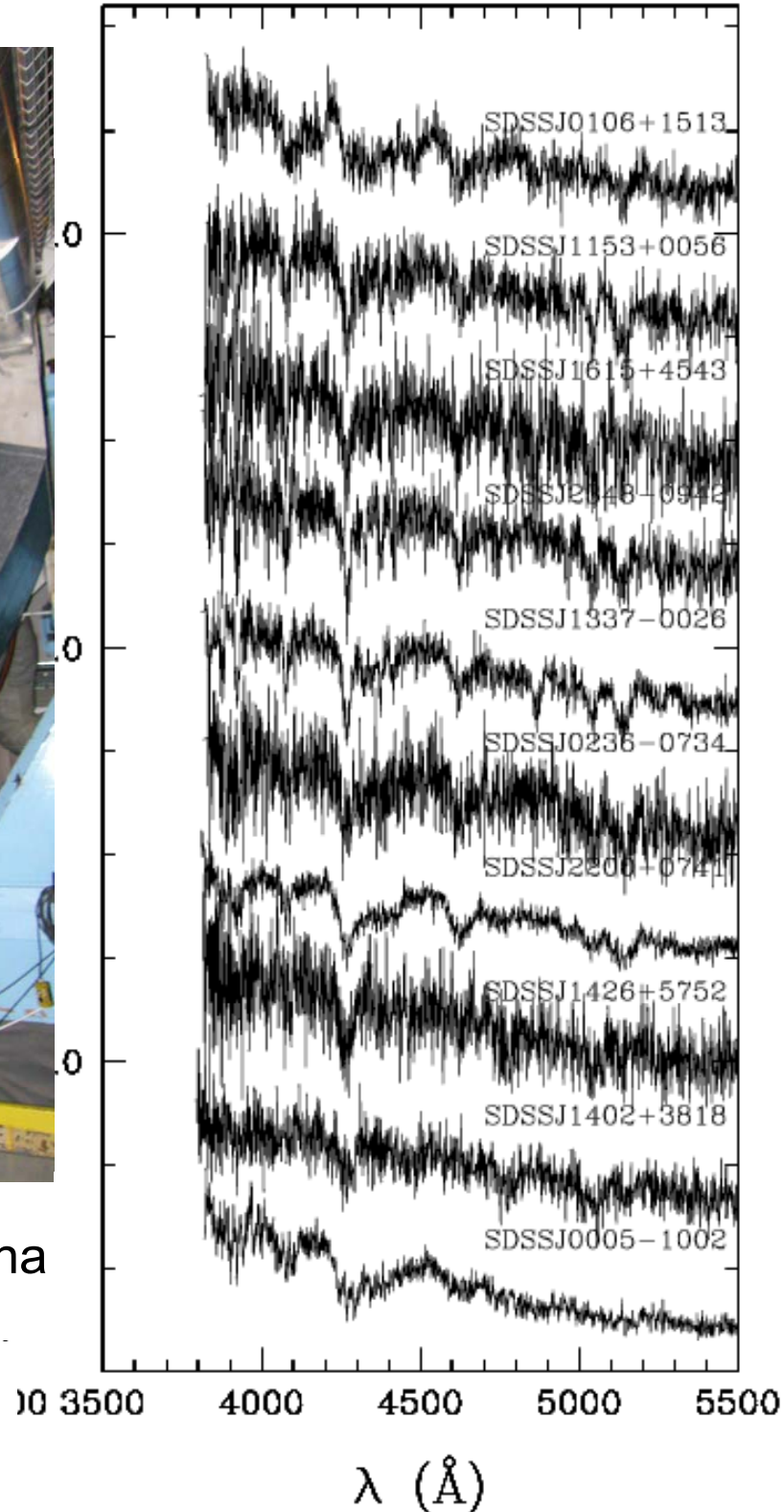
Log g = 7.5 to 10.0 in steps of 0.5

Several grids calculated for various H, He and O abundances (traces)

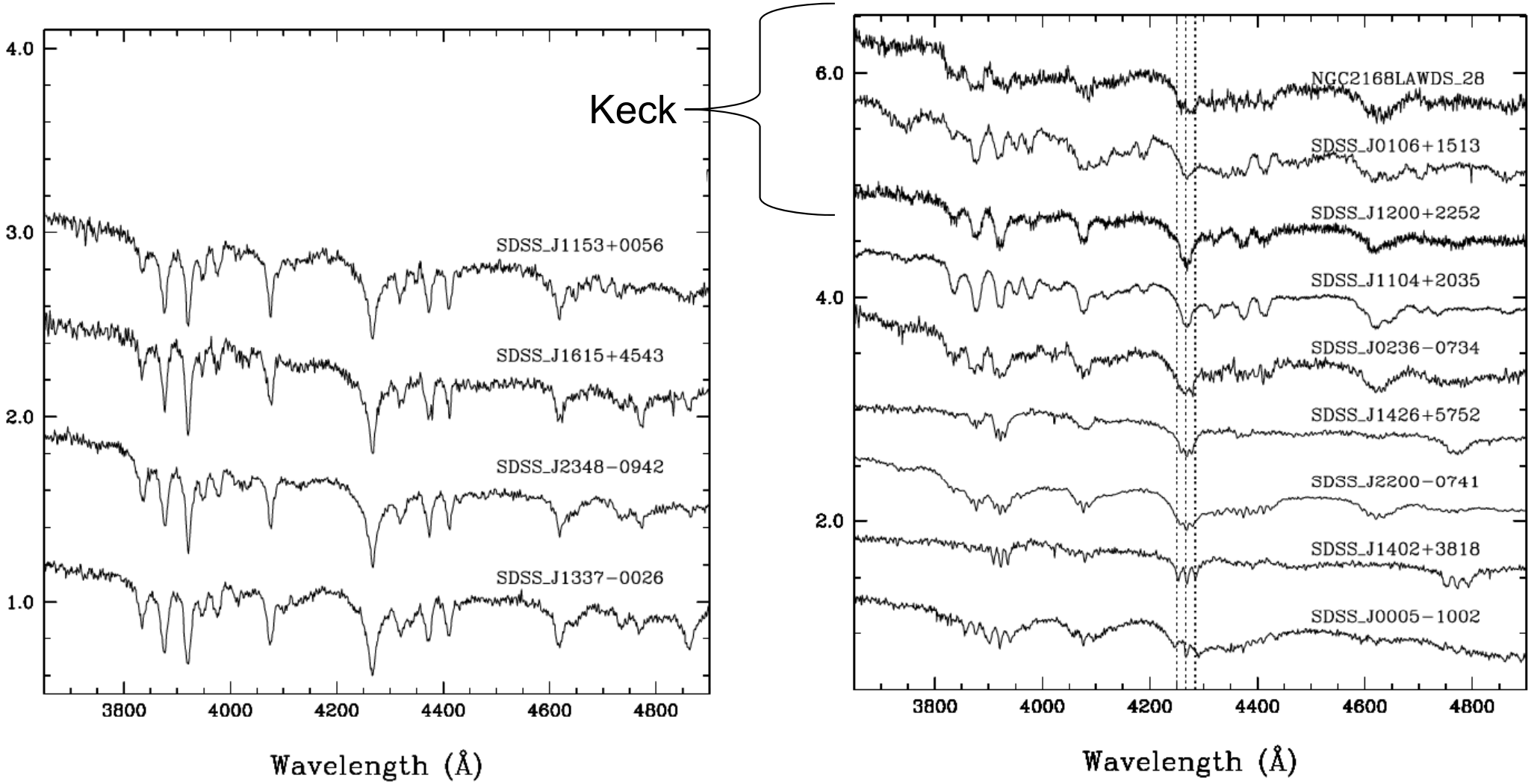


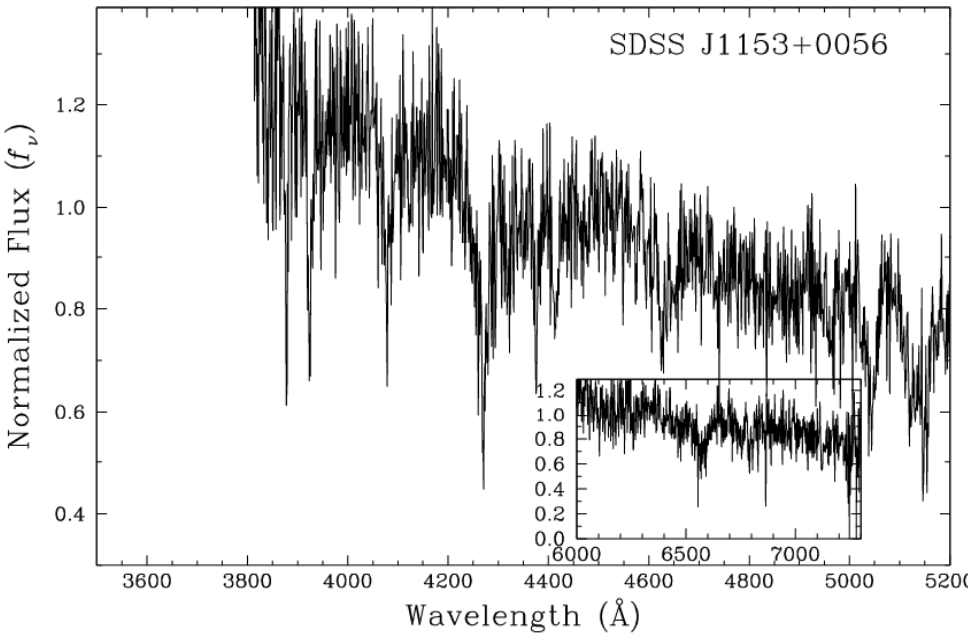
MMT (6.5 m), Mont Hopkins, Arizona

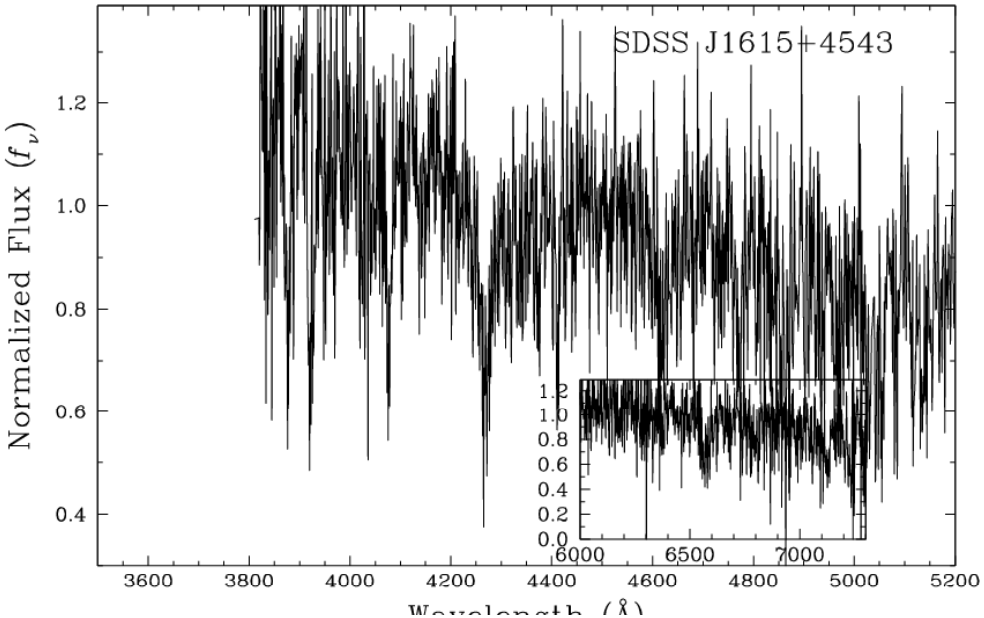
(10 nights)

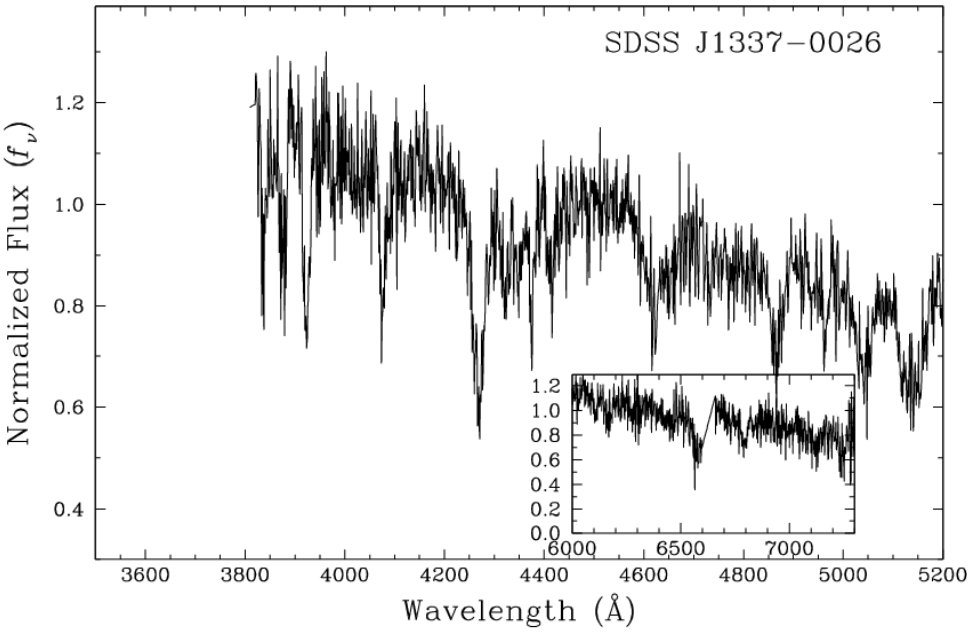


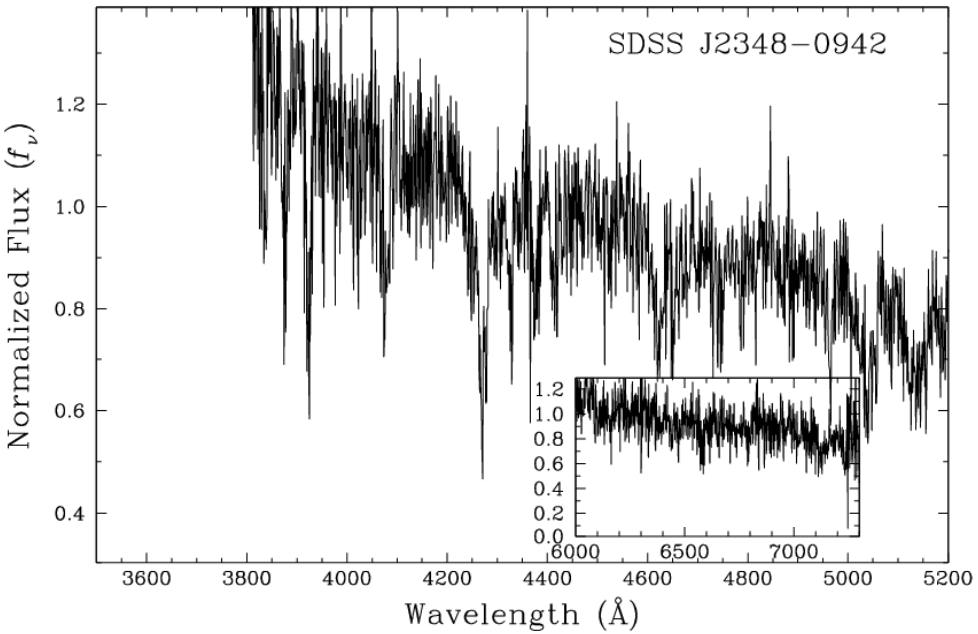
14 carbon atmosphere White Dwarfs known (out of ~30,000 catalogued WD)

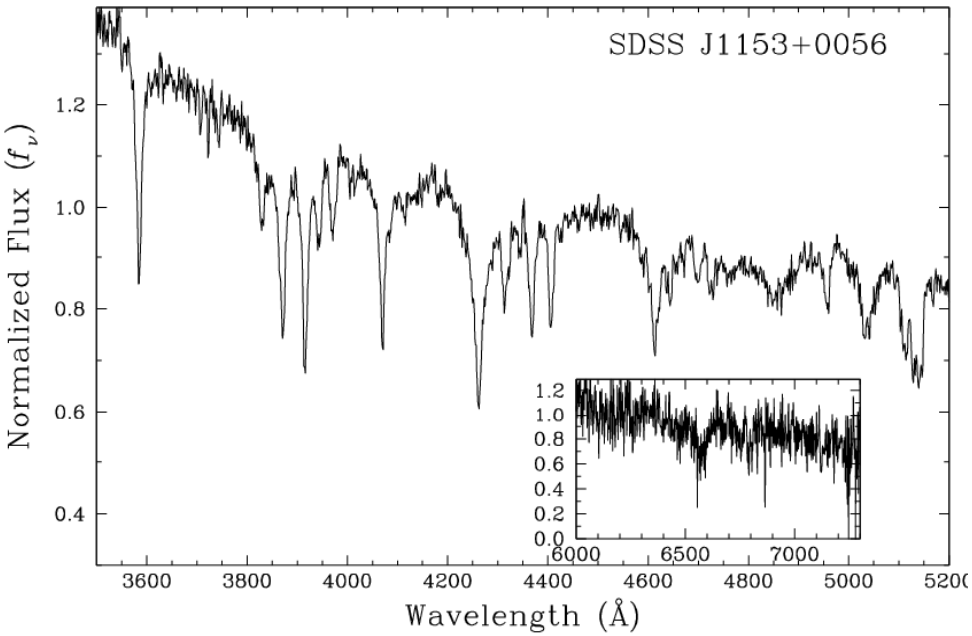


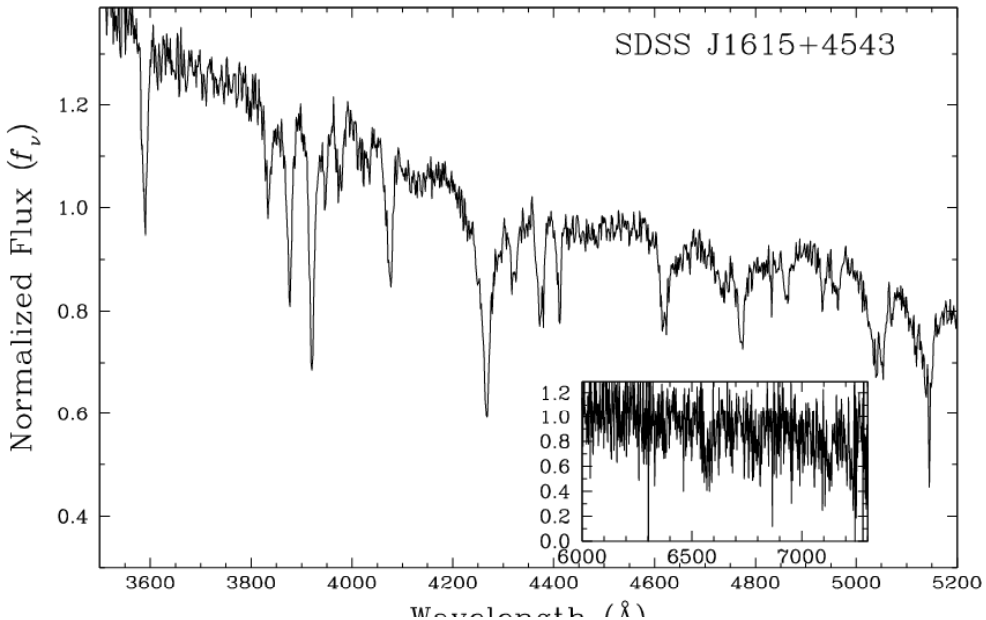

SDSS J1153+0056
Normalized Flux (f_ν)
Wavelength (Å)

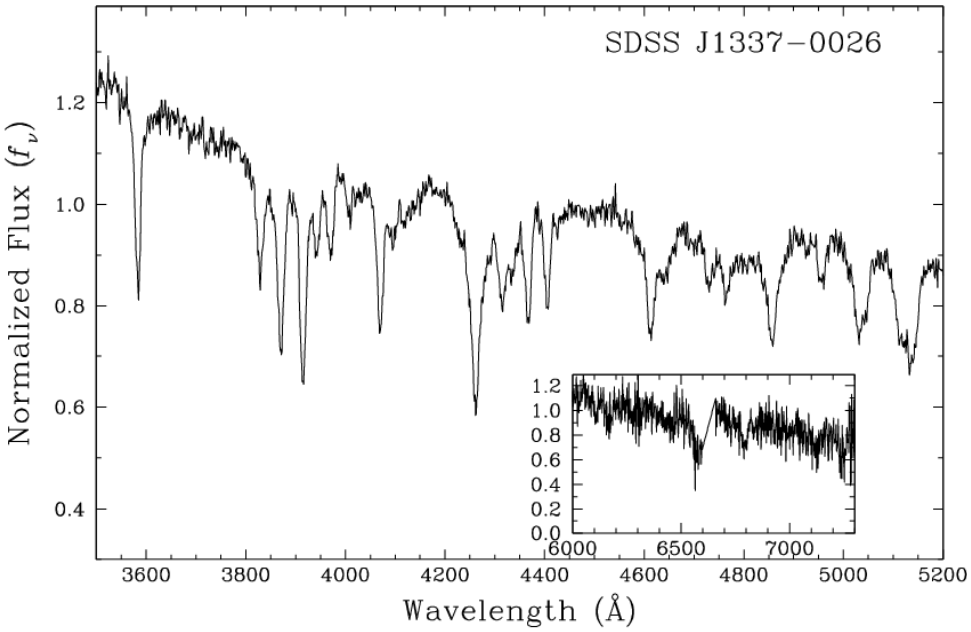

SDSS J1615+4543
Normalized Flux (f_ν)

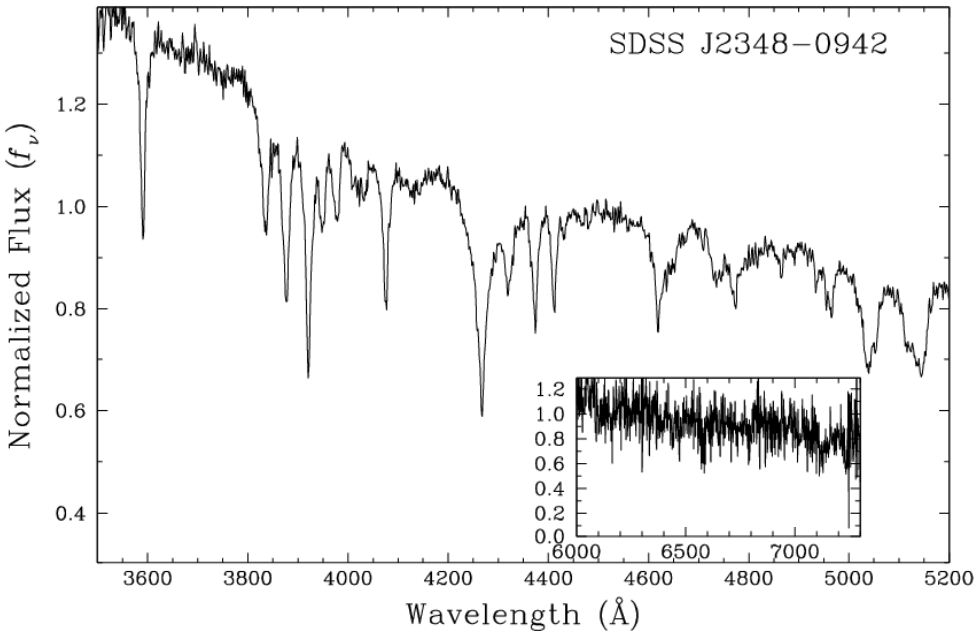

SDSS J1337−0026
Normalized Flux (f_ν)
Wavelength (Å)


SDSS J2348−0942
Normalized Flux (f_ν)
Wavelength (Å)


SDSS J1153+0056
Normalized Flux (f_ν)
Wavelength (Å)


SDSS J1615+4543
Normalized Flux (f_ν)


SDSS J1337−0026
Normalized Flux (f_ν)
Wavelength (Å)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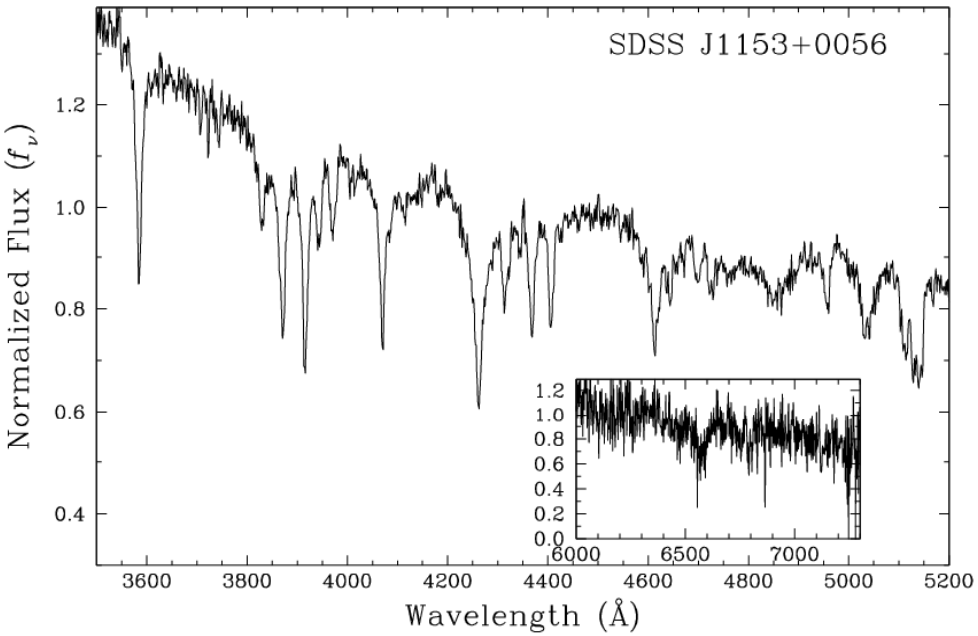
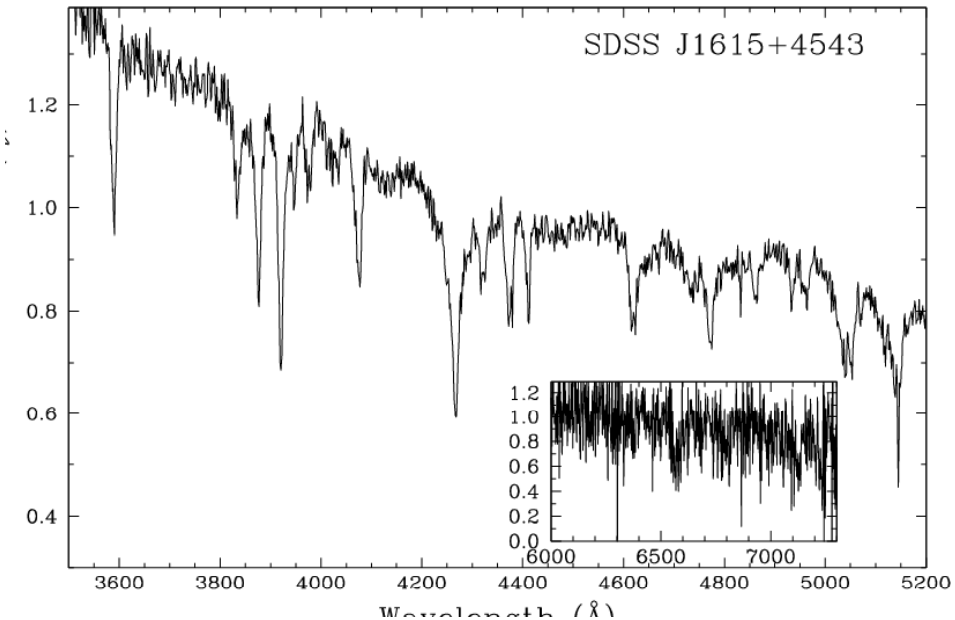
Normalized Flux (f_ν)
Wavelength (Å)


SDSS J1153+0056
Normalized Flux (f_ν)
Wavelength (Å)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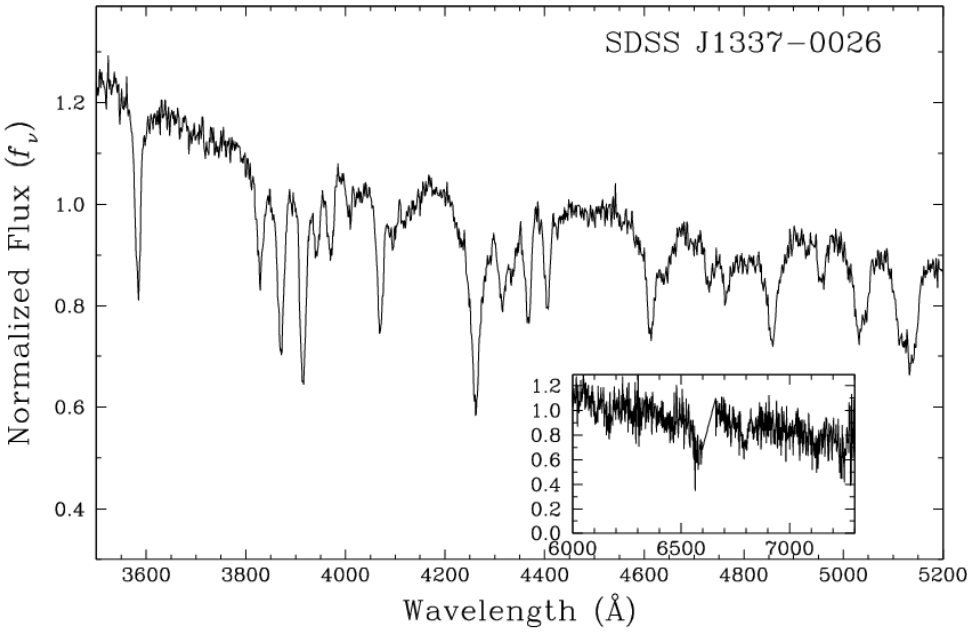
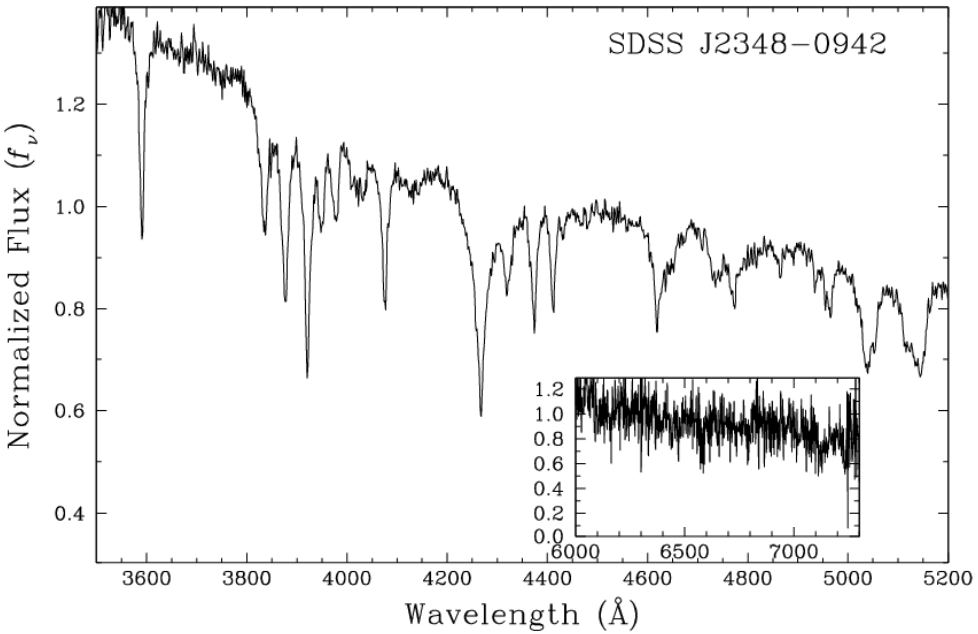
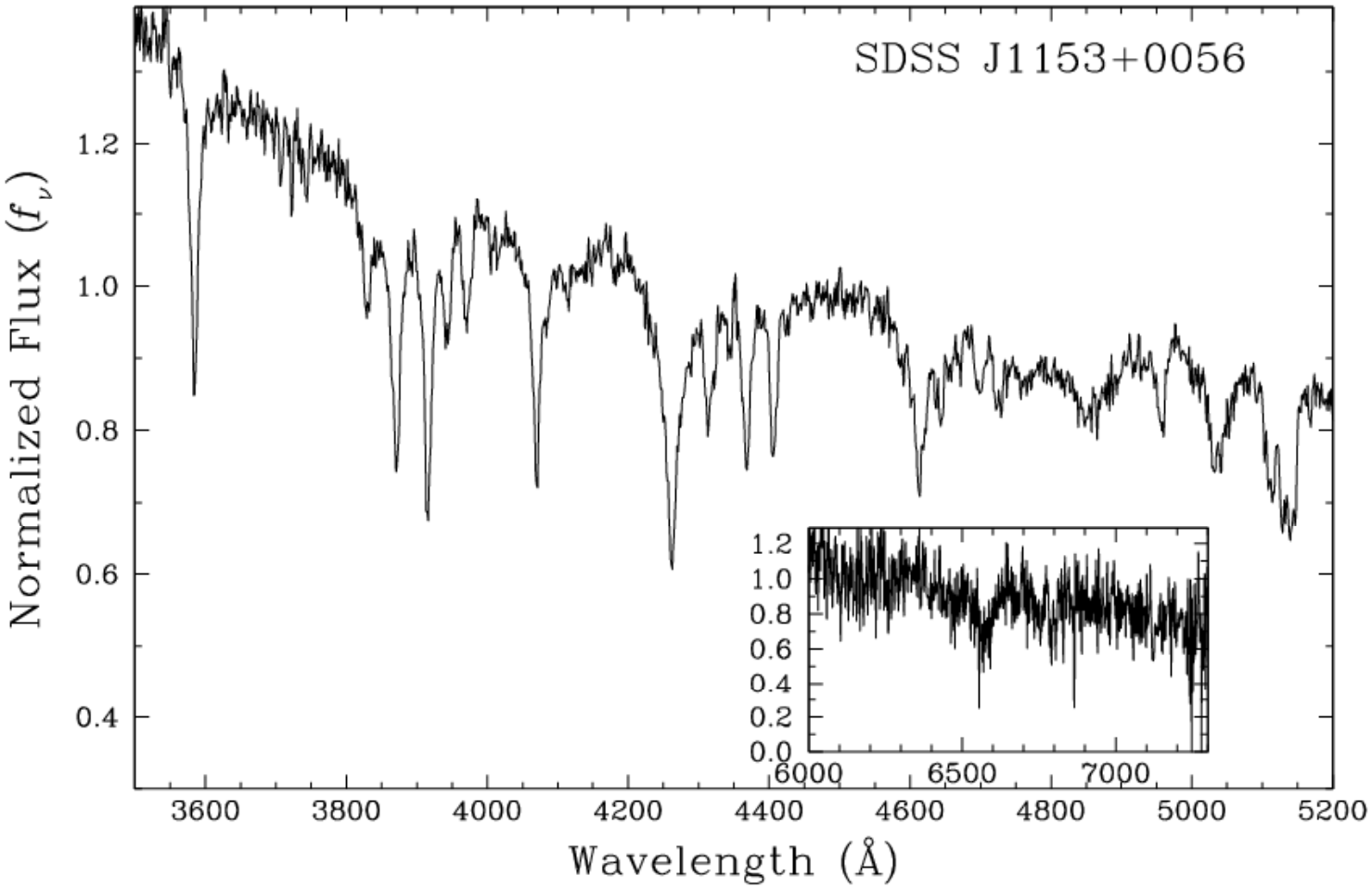
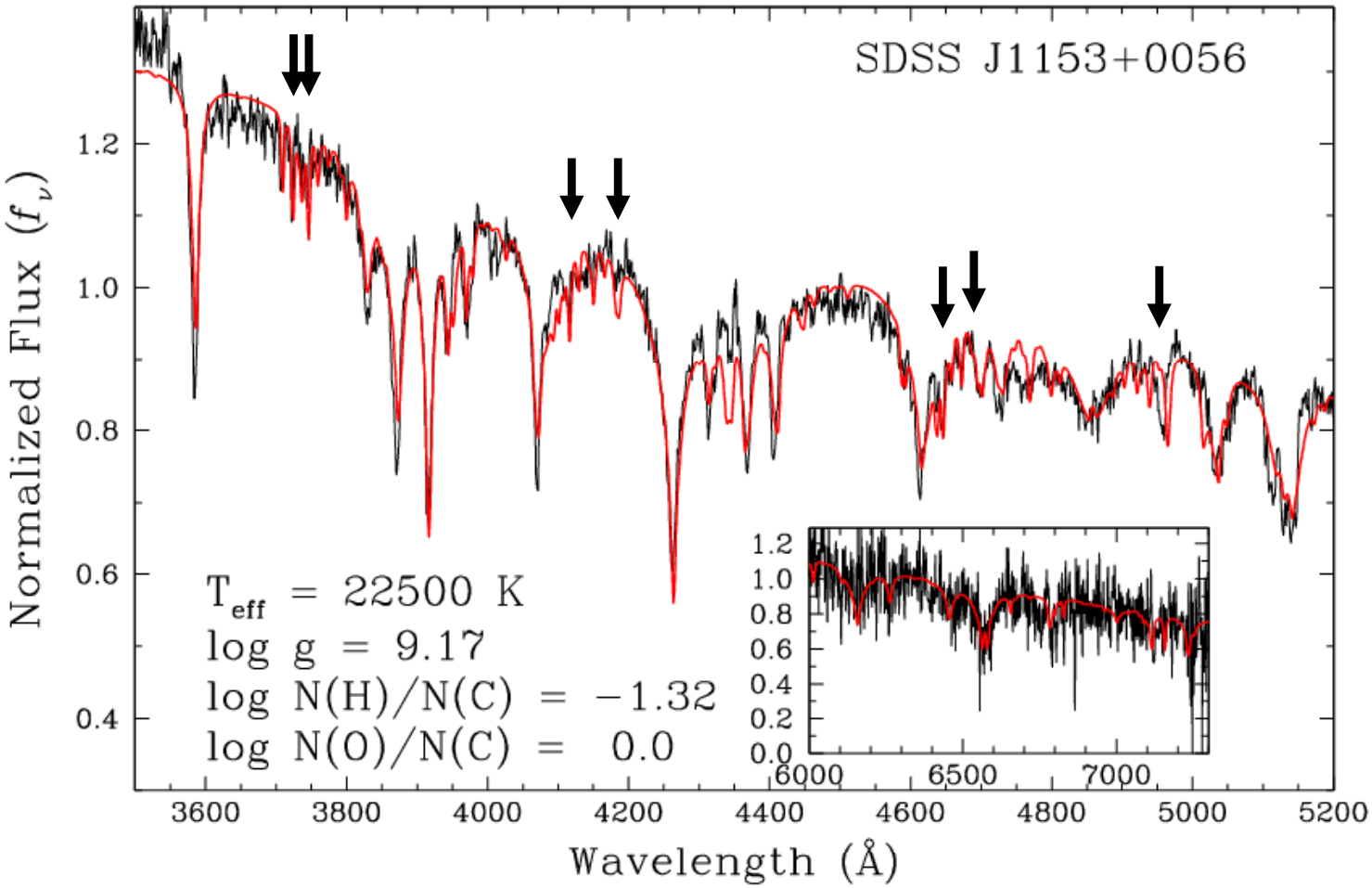

SDSS J1337−0026
Normalized Flux (f_ν)
Wavelength (Å)


SDSS J2348−0942
Normalized Flux (f_ν)
Wavelength (Å)


SDSS J1153+0056
Normalized Flux (f_ν)
Wavelength (Å)
0.4
0.6
0.8
1.0
1.2
3600
3800
4000
4200
4400
4600
4800
5000
5200
0.0
0.2
0.4
0.6
0.8
1.0
1.2
6000
6500
7000


SDSS J1153+0056
Normalized Flux (f_ν)
Wavelength (Å)
T_{eff} = 22500 K
log g = 9.17
log N(H)/N(C) = −1.32
log N(O)/N(C) = 0.0
0.4
0.6
0.8
1.0
1.2
3600
3800
4000
4200
4400
4600
4800
5000
5200
0.0
0.2
0.4
0.6
0.8
1.0
1.2
6000
6500
7000

Stark Damping Constant

In collaboration

Sylvie Sahal-Br

Milan S. Dimitri

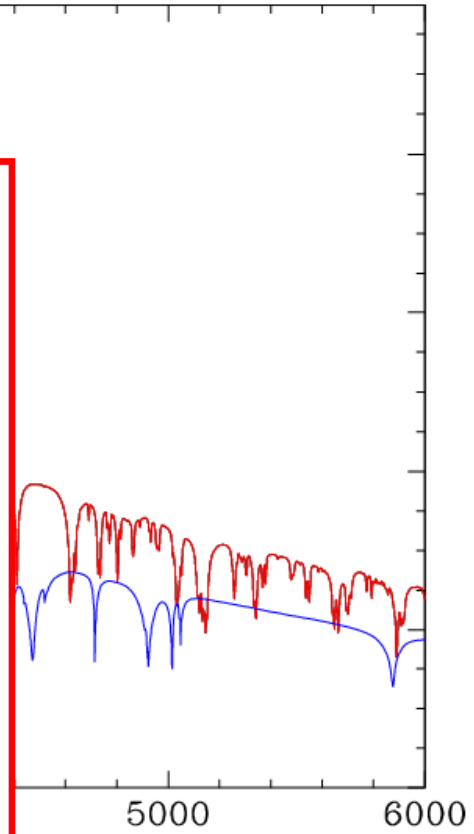
Nabil Ben Ness

Tunisie

$$\int H_\nu \, d\nu = \sigma \, T_{eff}^{4} / 4\pi$$

VALD data

4228.3262	6.00	-2.794			5.180	0.0	0.00	0.00	0.00
4238.7998	6.03	-1.449	484321.000	4.5	507906.000	2.5	0.00	0.00	0.00
4247.3110	6.02	-0.892	319720.344	1.0	343258.031	1.0	0.00	0.00	0.00
4252.1001	6.02	-1.310	340101.844	2.0	363613.000	1.0	0.00	0.00	0.00
4255.3818	6.02	-2.329	322003.688	2.0	345496.719	2.0	9.58	0.00	0.00
4255.4092	6.02	-1.598	322003.688	2.0	345496.562	1.0	9.59	0.00	0.00
4256.3730	6.02	-2.330	322009.594	3.0	345497.156	3.0	9.58	0.00	0.00
4256.4512	6.02	-1.427	322009.594	3.0	345496.719	2.0	9.59	0.00	0.00
4256.7500	6.02	-1.532	340127.531	1.0	363613.000	1.0	0.00	0.00	0.00
4257.8940	6.02	-1.267	322017.969	4.0	345497.156	3.0	9.59	0.00	0.00
4259.3501	6.02	-2.009	340141.844	0.0	363613.000	1.0	0.00	0.00	0.00
4267.0010	6.01	0.563	145549.266	1.5	168978.344	2.5	9.34	-4.76	0.00
4267.1831	6.01	0.716	145550.703	2.5	168978.766	3.5	9.34	-4.76	0.00
4267.2612	6.01	-0.584	145550.703	2.5	168978.344	2.5	9.34	-4.76	0.00
4269.0200	6.00	-2.542	61981.820	1.0	85399.812	2.0	0.00	-4.00	0.00
4281.9800	6.02	-1.765	347151.875	2.0	370499.000	1.0	0.00	0.00	0.00
4281.9800	6.02	-2.496	347151.875	2.0	370499.000	2.0	0.00	0.00	0.00
4282.2300	6.02	-1.594	347153.250	3.0	370499.000	2.0	0.00	0.00	0.00
4282.2300	6.02	-2.498	347153.250	3.0	370499.000	3.0	0.00	0.00	0.00
4282.6299	6.02	-1.434	347155.406	4.0	370499.000	3.0	0.00	0.00	0.00
4285.7031	6.01	-1.000	198425.438	1.5	221752.266	1.5	0.00	0.00	0.00



-Mahr

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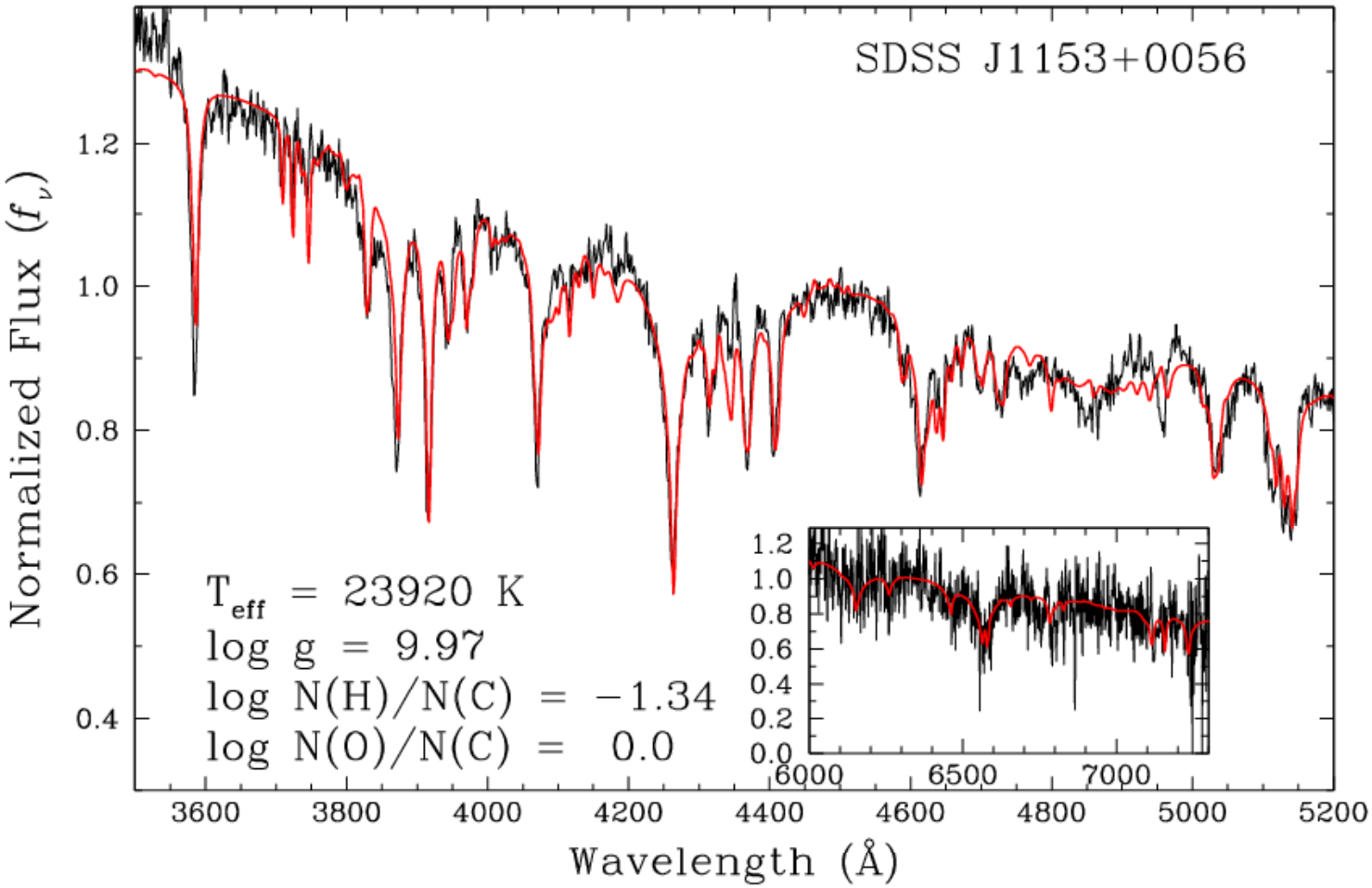

SDSS J1153+0056
Normalized Flux (f_ν)
Wavelength (Å)
T_{eff} = 23920 K
log g = 9.97
log N(H)/N(C) = −1.34
log N(O)/N(C) = 0.0
0.4
0.6
0.8
1.0
1.2
3600
3800
4000
4200
4400
4600
4800
5000
5200
0.0
0.2
0.4
0.6
0.8
1.0
1.2
6000
6500
7000

Log g max (Salpeter T=0)

(1961, ApJ, 134, 669)

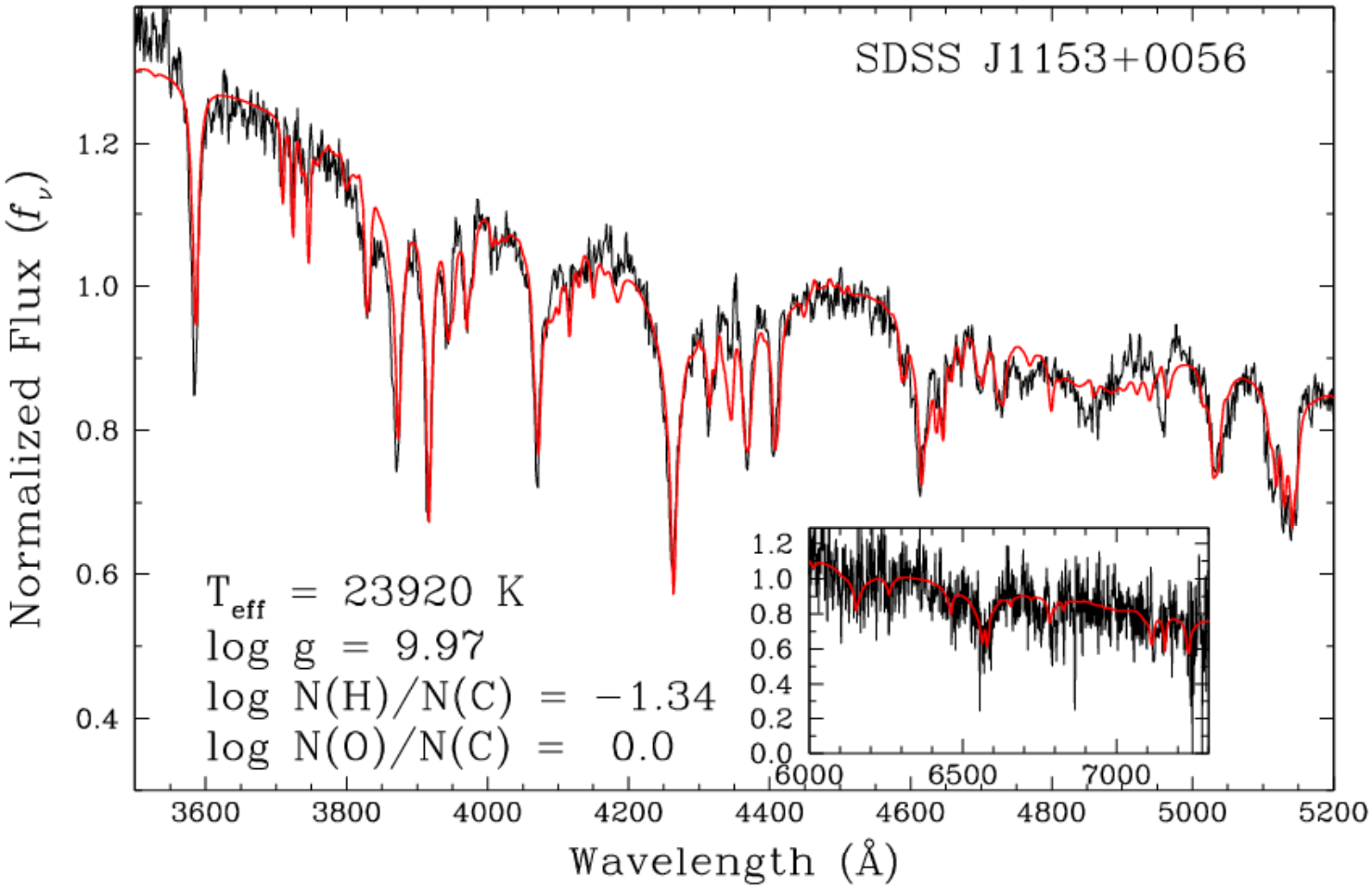
There is a maximum mass, corresponding to a maximal central density, above which hydrostatic equilibrium is no longer possible (fermion gas statistics → Chandrasekhar mass limit)

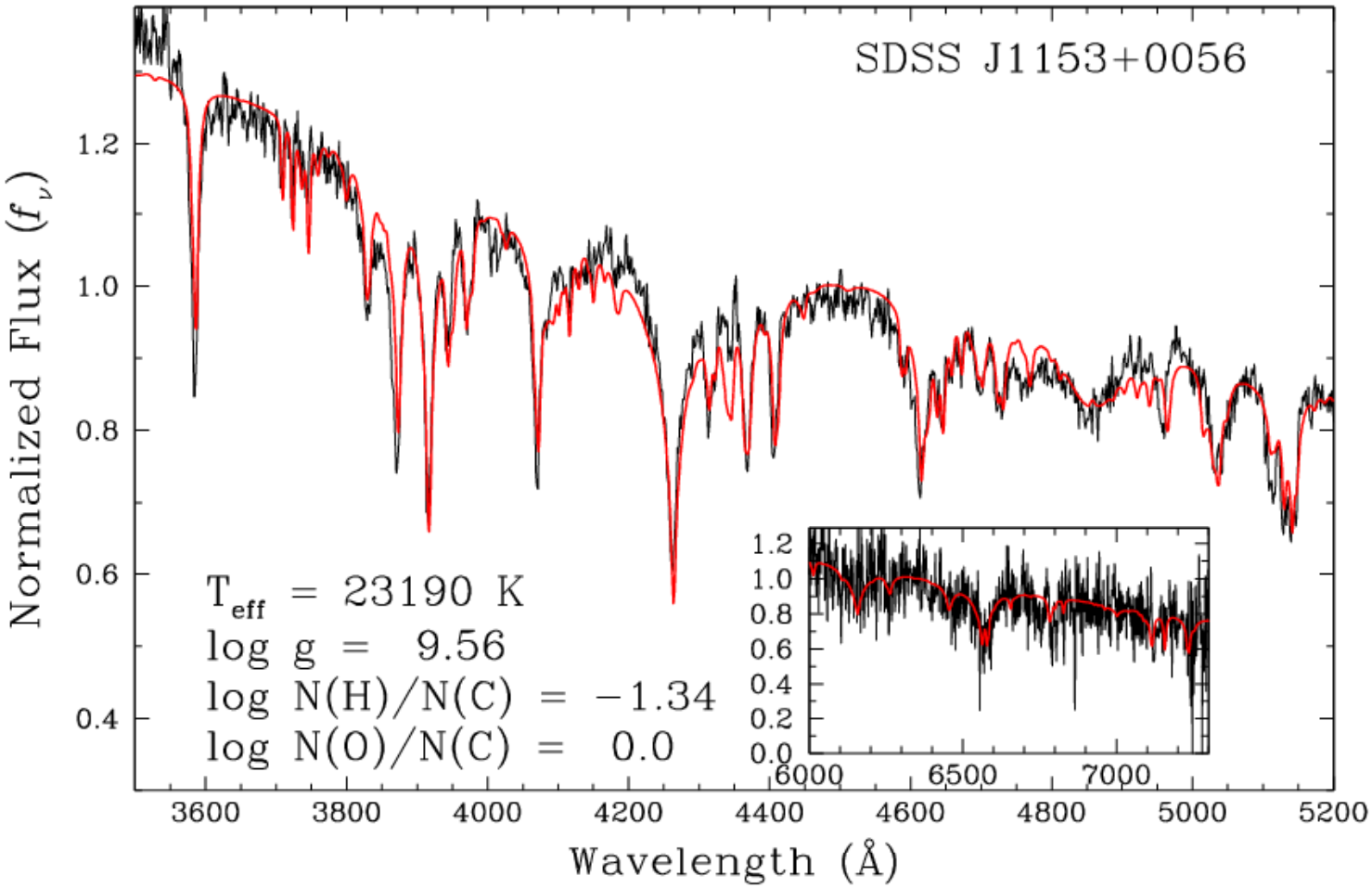
C^{12} → 9.91

Mg^{24} → 9.75

Fe^{56} → 9.49

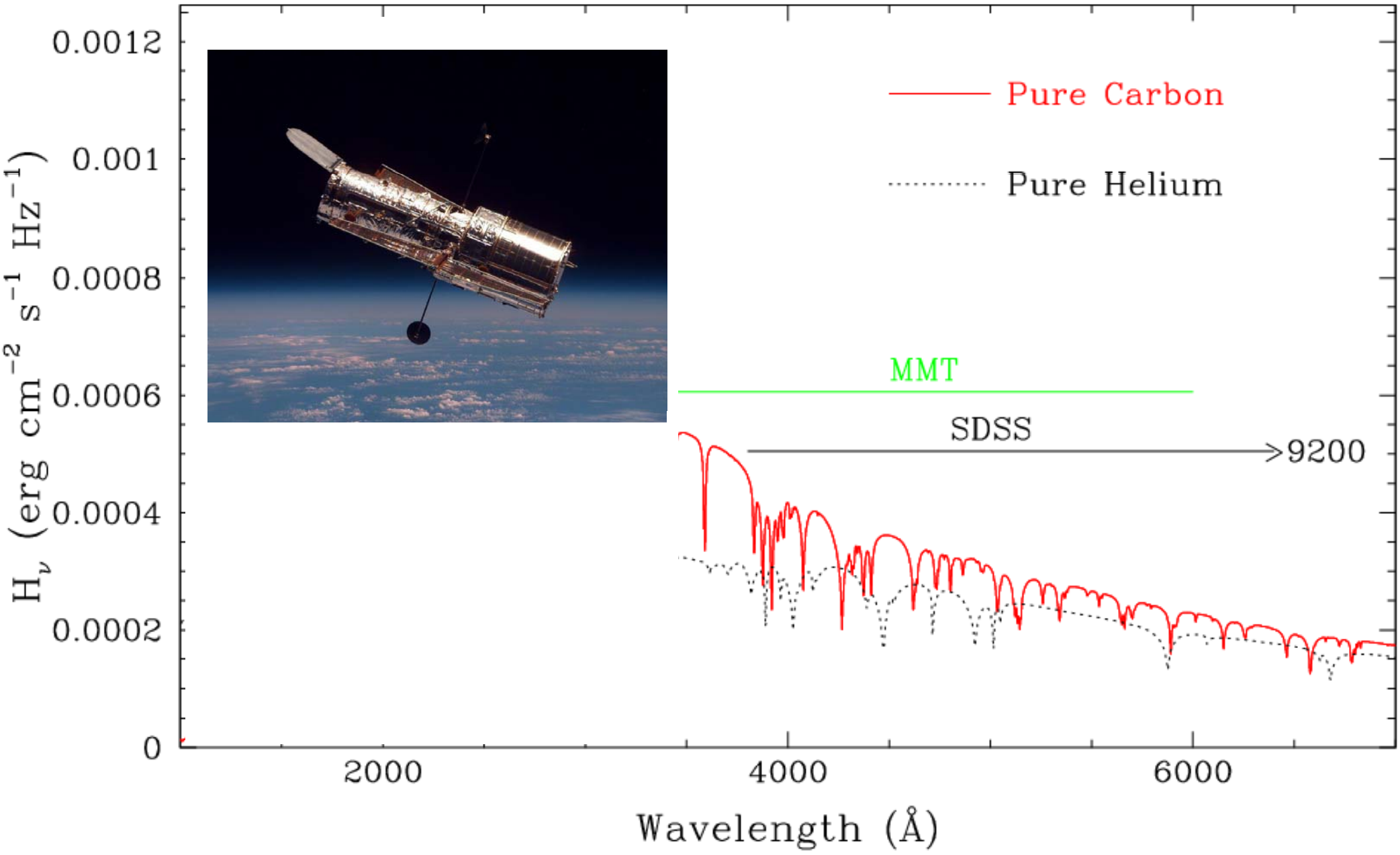
8th Serbian Conference on Spectral Line Shapes in Astrophysics

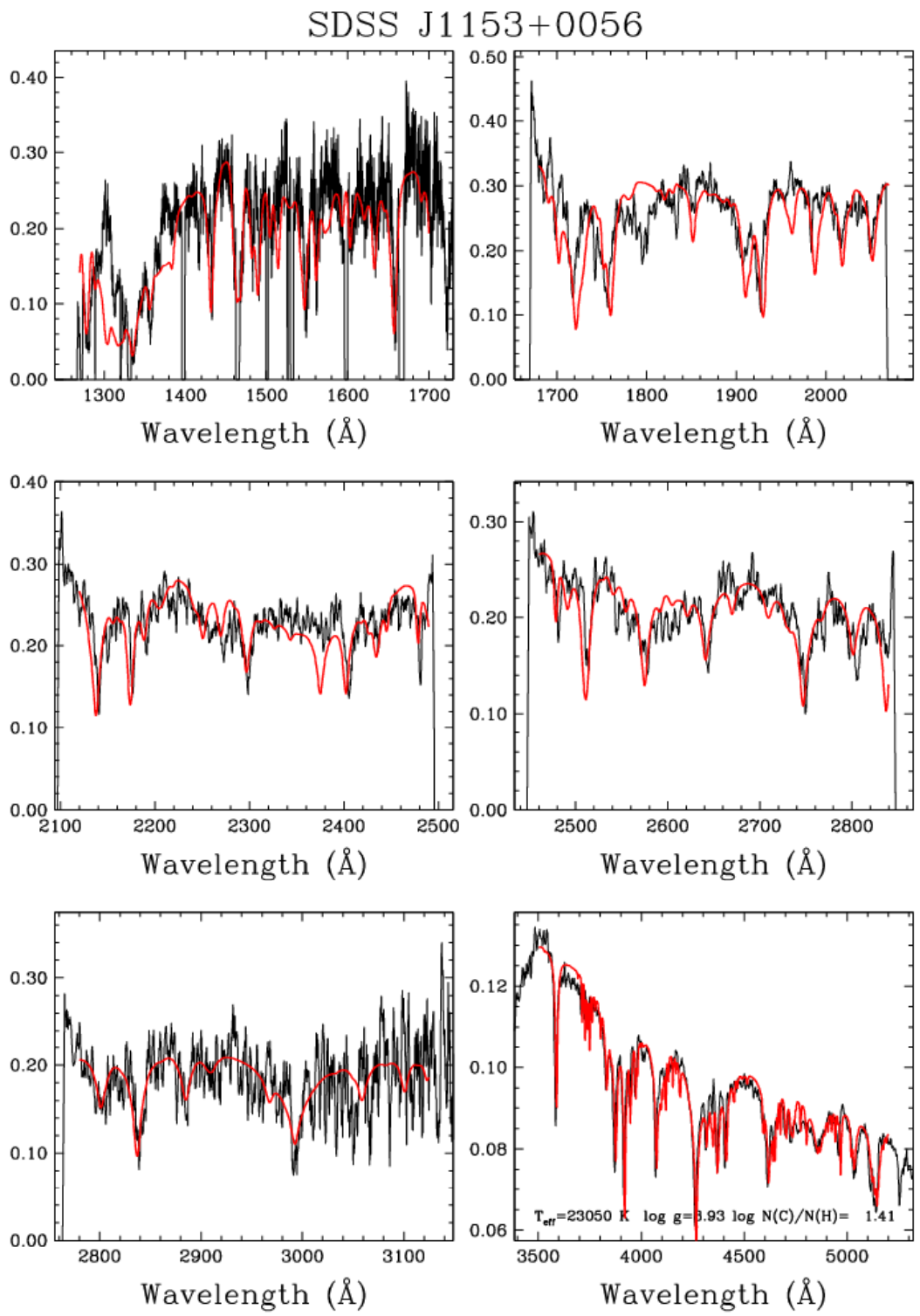

SDSS J1153+0056
Normalized Flux (f_ν)
Wavelength (Å)
T_{eff} = 23920 K
log g = 9.97
log N(H)/N(C) = −1.34
log N(O)/N(C) = 0.0
0.4
0.6
0.8
1.0
1.2
3600
3800
4000
4200
4400
4600
4800
5000
5200
0.0
0.2
0.4
0.6
0.8
1.0
1.2
6000
6500
7000

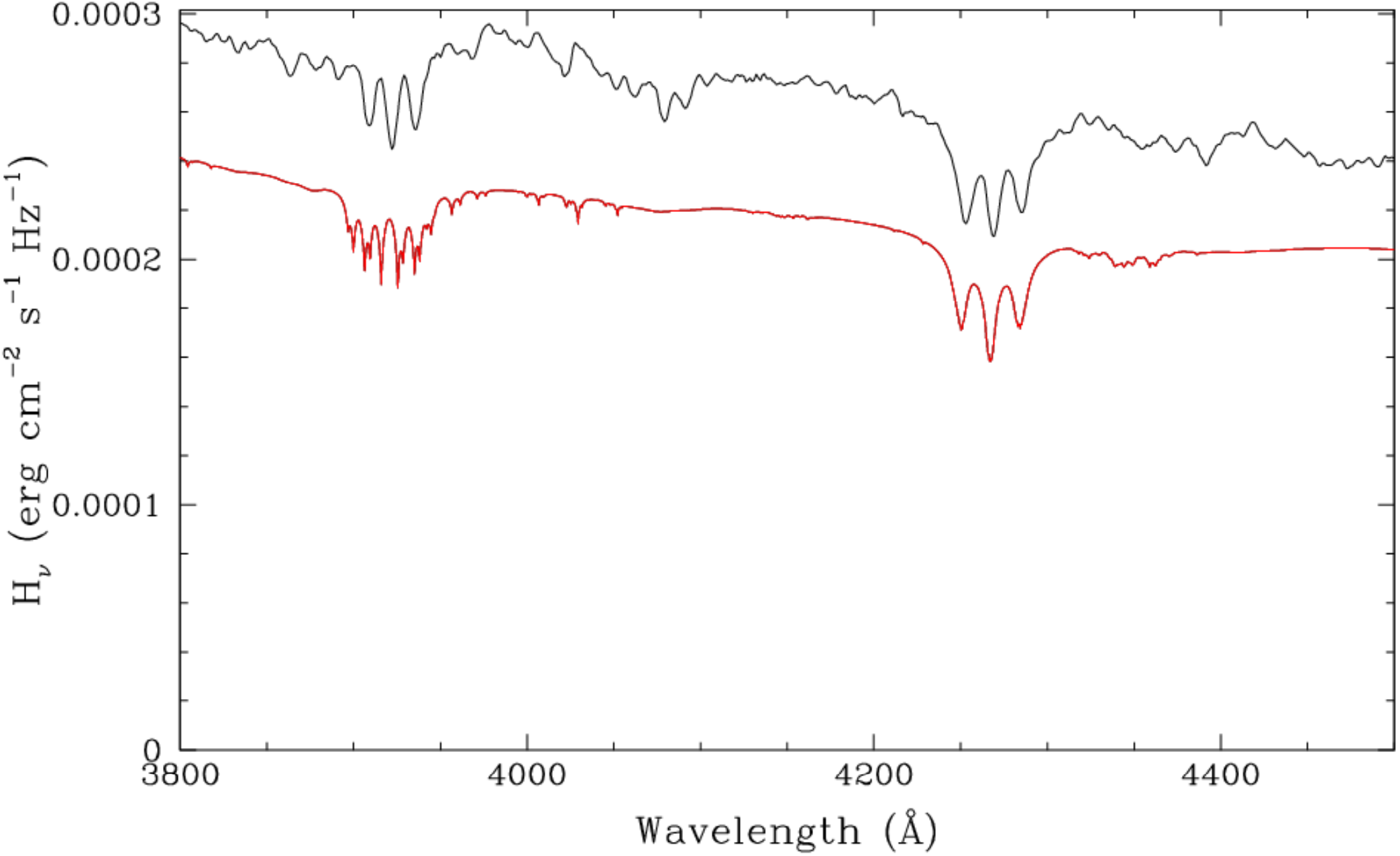

SDSS J1153+0056
Normalized Flux (f_ν)
Wavelength (Å)
T_{eff} = 23190 K
log g = 9.56
log N(H)/N(C) = −1.34
log N(O)/N(C) = 0.0
0.4
0.6
0.8
1.0
1.2
3600
3800
4000
4200
4400
4600
4800
5000
5200
0.0
0.2
0.4
0.6
0.8
1.0
1.2
6000
6500
7000

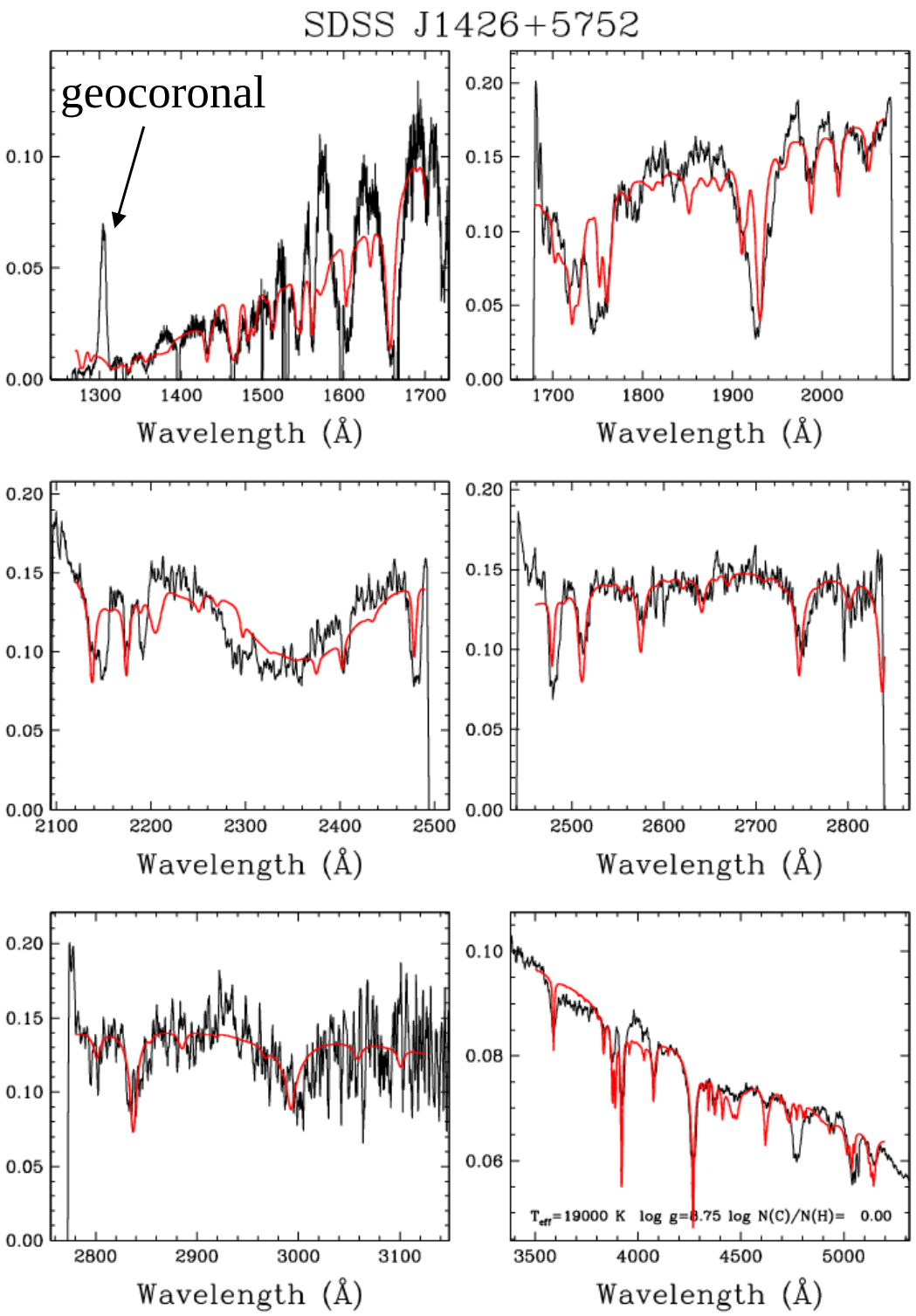
Outline

- A brief introduction: stellar evolution and white dwarf stars
- Carbon (and oxygen) in white dwarf stars
  - white dwarfs with traces of carbon
  - carbon dominated atmosphere white dwarfs
  - Future research directions
- Planets and abundance determinations
  - white dwarfs with traces of metals

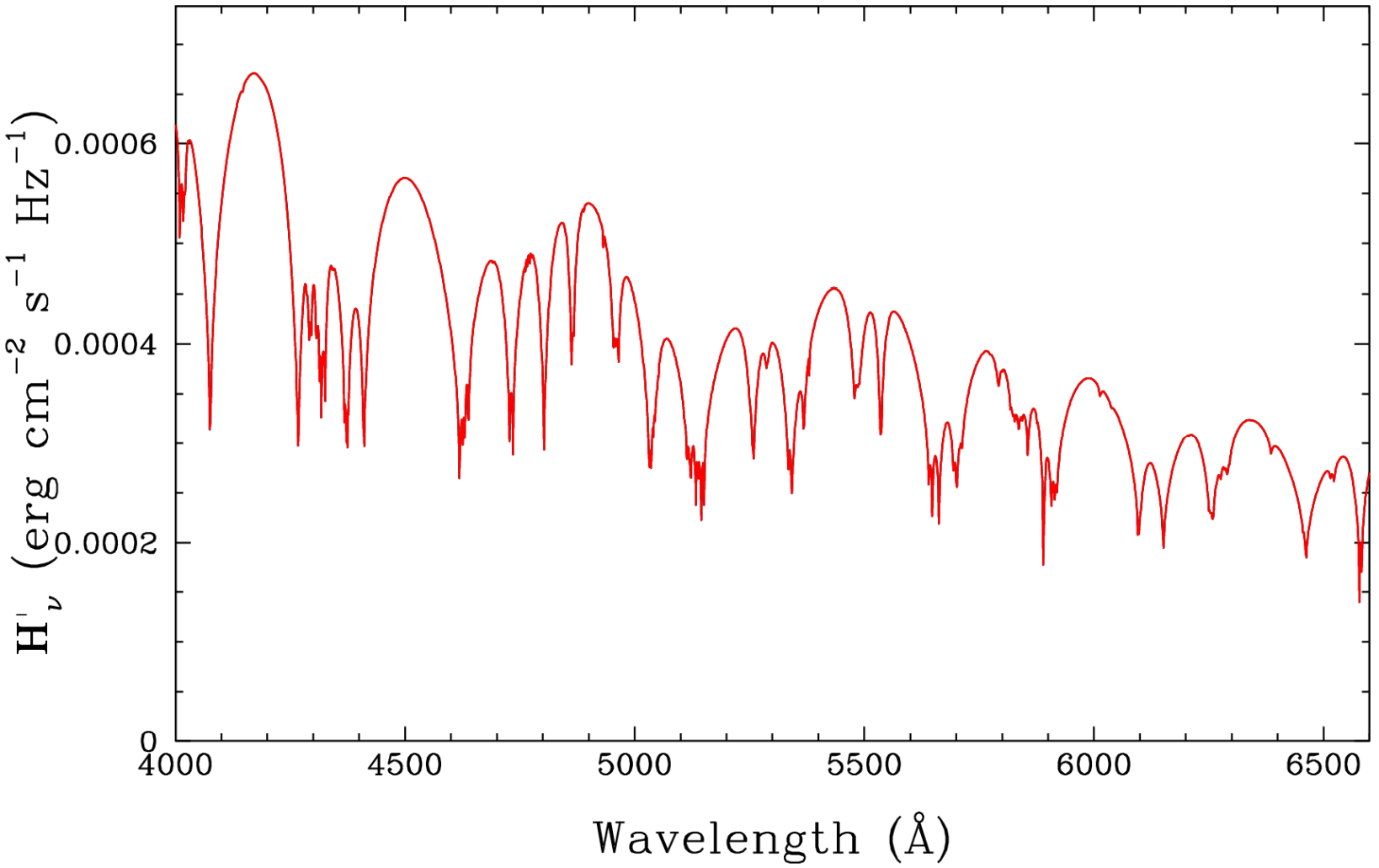

0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
H_ν (erg cm^{-2} s^{-1} Hz^{-1})
2000
4000
6000
Wavelength (Å)
Pure Carbon
Pure Helium
MMT
SDSS
9200


SDSS J1153+0056
Wavelength (Å)
Wavelength (Å)
Wavelength (Å)
Wavelength (Å)
Wavelength (Å)
Wavelength (Å)
T_eff=23050 K log g=3.93 log N(C)/N(H)= 1.41


0.0003
0.0002
0.0001
0
3800
4000
4200
4400
H_ν (erg cm^{-2} s^{-1} Hz^{-1})
Wavelength (Å)

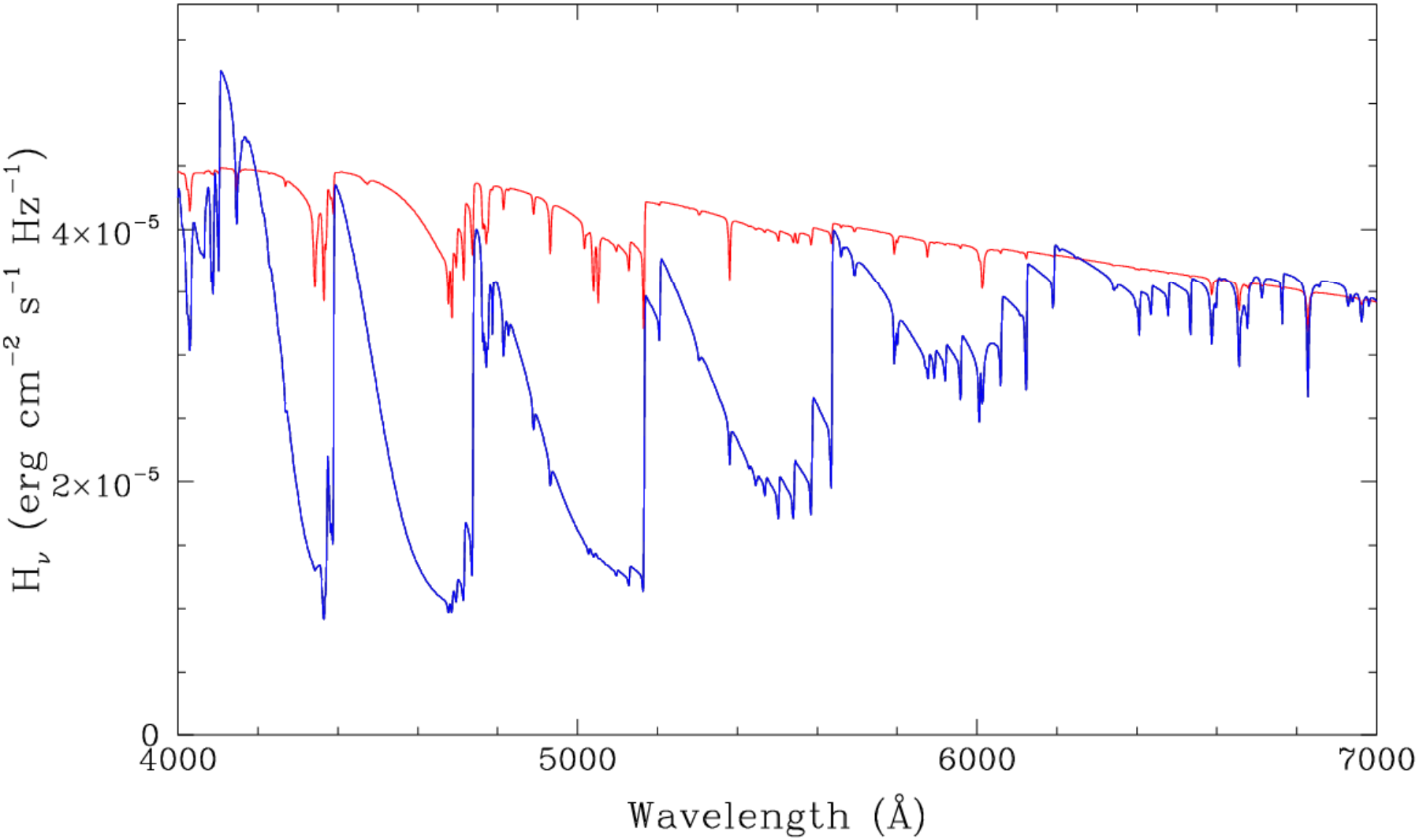

SDSS J1426+5752
geocoronal
Wavelength (Å)
Wavelength (Å)
Wavelength (Å)
Wavelength (Å)
Wavelength (Å)
Wavelength (Å)
T_eff=19000 K log g=3.75 log N(C)/N(H)= 0.00

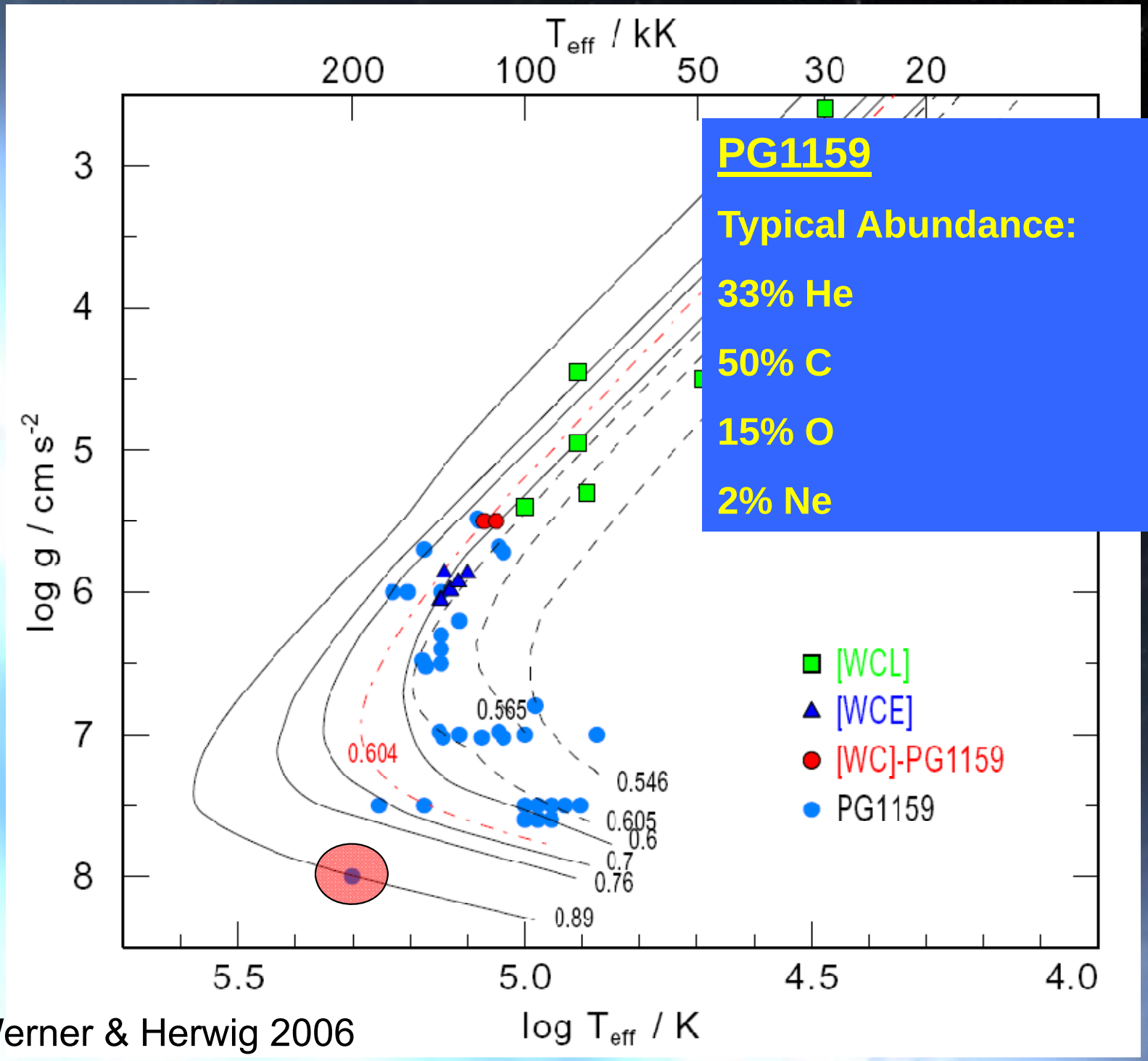
Pure Carbon, T_{eff} = 30,000 K



Pure Carbon, T_{eff} = 10,000 K

Log C/He = -3, T_{eff} = 10,000 K





PG1159

Typical Abundance:

33% He

50% C

15% O

2% Ne

Werner & Herwig 2006

H1504+65

- T_{eff} ~ 175,000 K – 200,000 K
- Log g = 8
- C ~ 48 %
- O ~ 48 %
- He < 1 %
- Combustion beyond carbon ?
- O/Ne/Mg core ?

Evolution

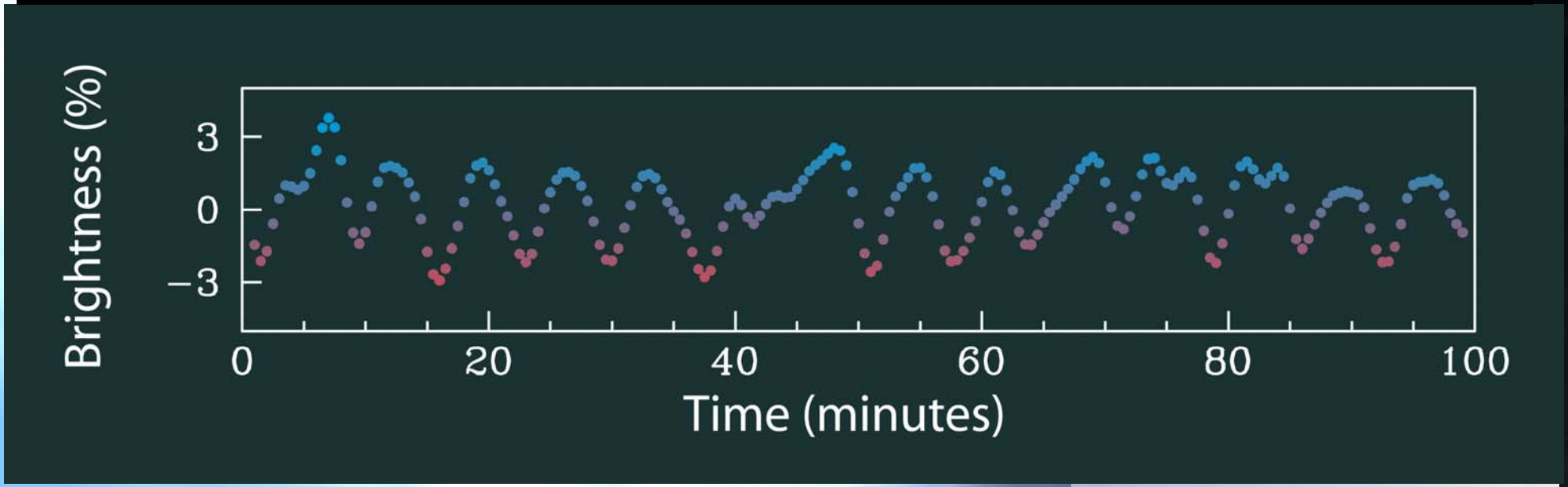

Hydrogen-rich
DA
150,000 K
DC
~4000 K
Helium-rich
H1504+65
DO
DB
?
Hot DQ
DQ (2nd sequence ?)

Pulsation ?

Pure Hydrogen → ZZ Ceti (12,000-13,000 K)

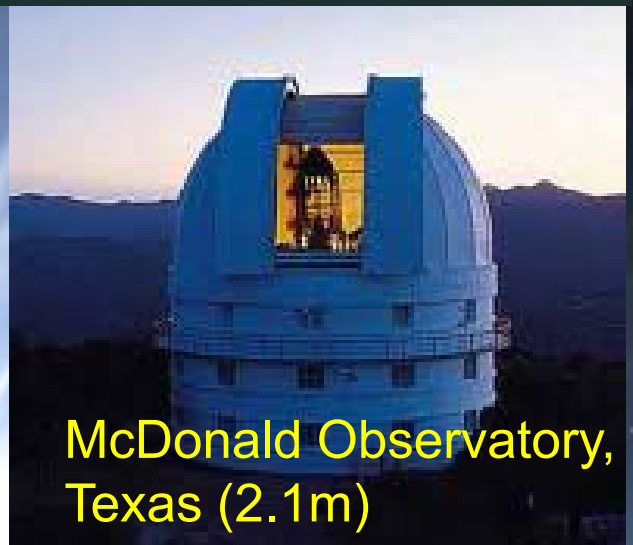
Pure Helium → V777 Her (22,000-25,000 K)

Carbone/Oxygen → ???



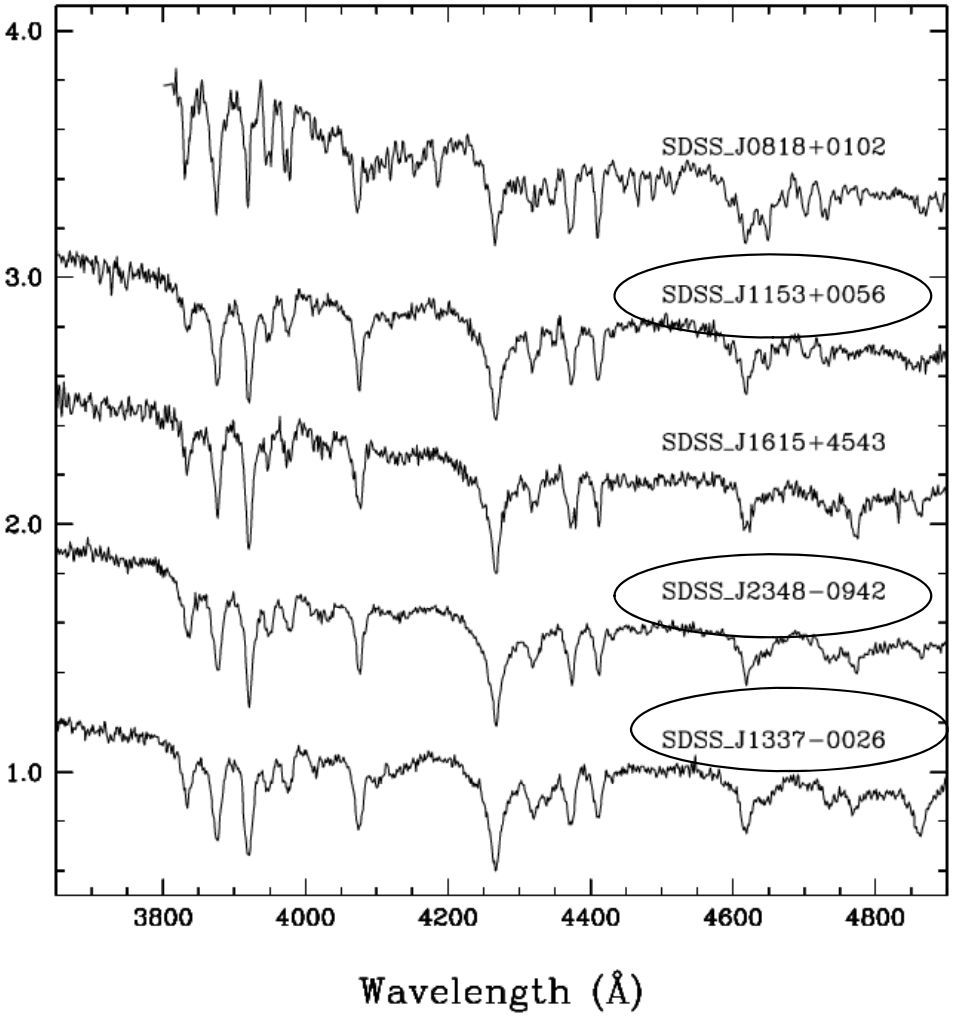
Discovery of a new pulsating star class!

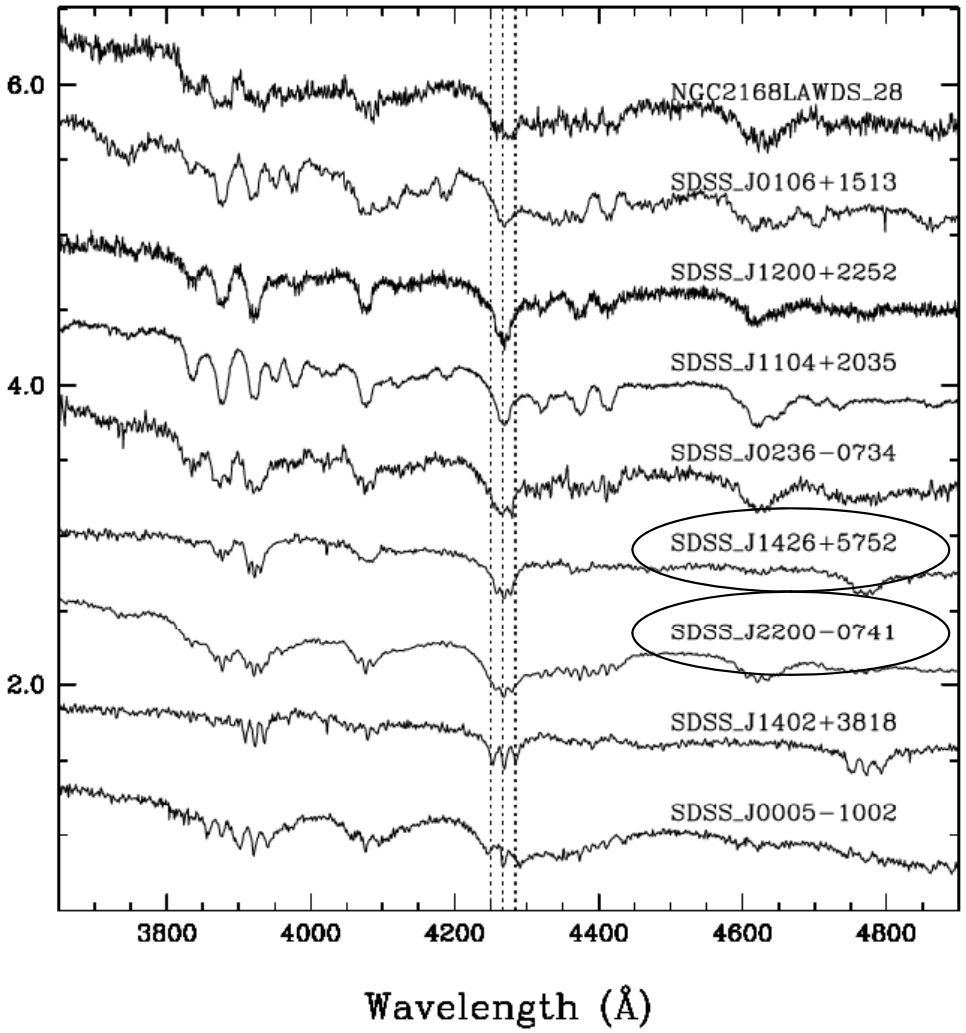
-Open a new window for asterosismological studies (information on the internal structure of the star)



McDonald Observatory, Texas (2.1m)

14 Hot DQ stars known/ 9 magnetic / 5 pulsating





FOLLOW-UP OBSERVATIONS OF THE SECOND AND THIRD KNOWN PULSATING HOT DQ WHITE DWARFS

P. Dufour[1,2], E. M. Green[1], G. Fontaine[2], P. Brassard[2], M. Francoeur[2], and M. Latour[2]
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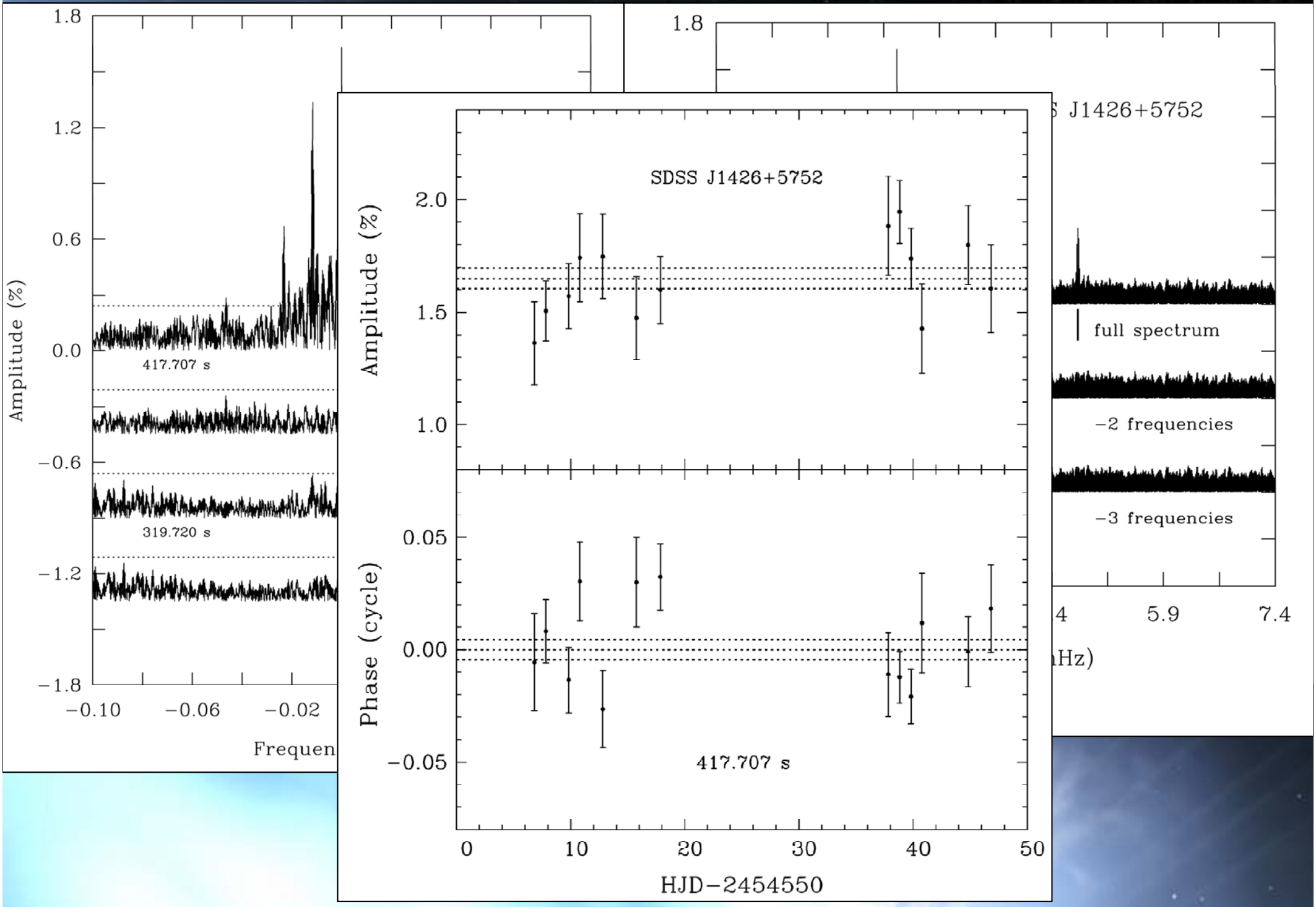
[2] Département de Physique, Université de Montréal, Montréal, QC H3C 3J7, Canada; fontaine@astro.umontreal.ca, brassard@astro.umontreal.ca, myriam@astro.umontreal.ca, marilyn@astro.umontreal.ca
Received 2009 April 8; accepted 2009 July 29; published 2009 August 26

FOLLOW-UP STUDIES OF THE PULSATING MAGNETIC WHITE DWARF SDSS J142625.71+575218.3

E. M. Green[1], P. Dufour[1,2], G. Fontaine[2], and P. Brassard[2]
[1] Steward Observatory, University of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721, USA; bgreen@as.arizona.edu
[2] Département de Physique, Université de Montréal, Montréal, QC H3C 3J7, Canada; dufourpa@astro.umontreal.ca, fontaine@astro.umontreal.ca, brassard@astro.umontreal.ca
Received 2009 March 24; accepted 2009 July 13; published 2009 August 24

Kuiper Telescope, Mont Bigelow, Arizona (1.6m)


1.8
1.2
0.6
0.0
−0.6
−1.2
−1.8
Amplitude (%)
417.707 s
319.720 s
−0.10
−0.06
−0.02
Frequen
1.8
J1426+5752
full spectrum
−2 frequencies
−3 frequencies
4
5.9
7.4
Hz)
SDSS J1426+5752
Amplitude (%)
2.0
1.5
1.0
Phase (cycle)
0.05
0.00
−0.05
417.707 s
0
10
20
30
40
50
HJD−2454550

Conclusions

-New type of stars with a Carbon/Oxygen surface (Dufour et al. 2007)

-formation and origin?

-High mass (progenitors ~7-10 M_{sun}) ?

-O/Ne/Mg core ?

-New generation of model atmosphere including state of the art Stark broadening

-HST (COS)

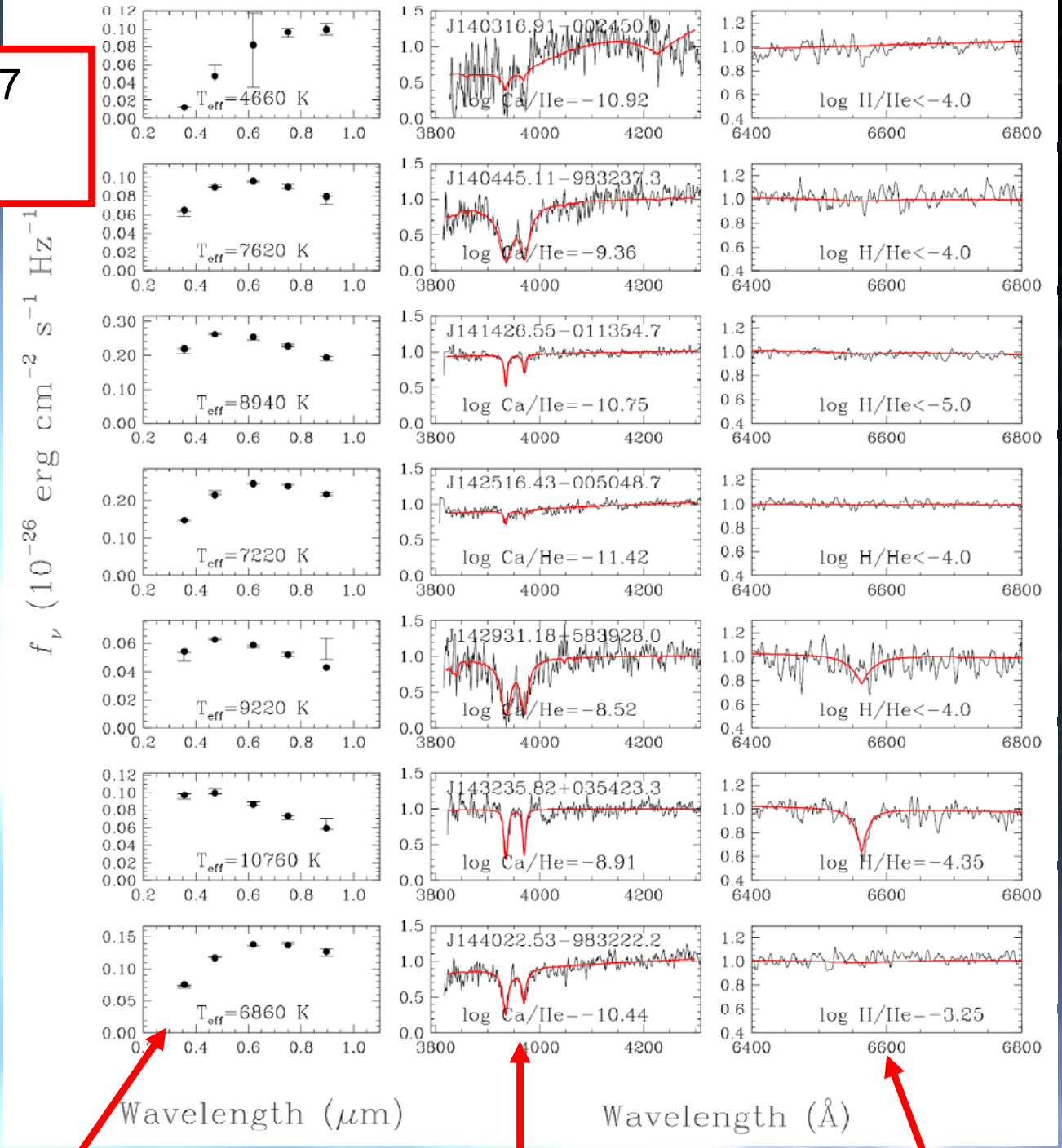
-Pulsations / magnétism

Outline

- A brief introduction: stellar evolution and white dwarf stars
- Carbon (and oxygen) in white dwarf stars
  - white dwarfs with traces of carbon
  - carbon dominated atmosphere white dwarfs
  - Future research directions
- Planets and abundance determinations
  - white dwarfs with traces of metals

Dufour et al., 2007

ApJ, 663, 1291



Photmetrie ugriz → Température

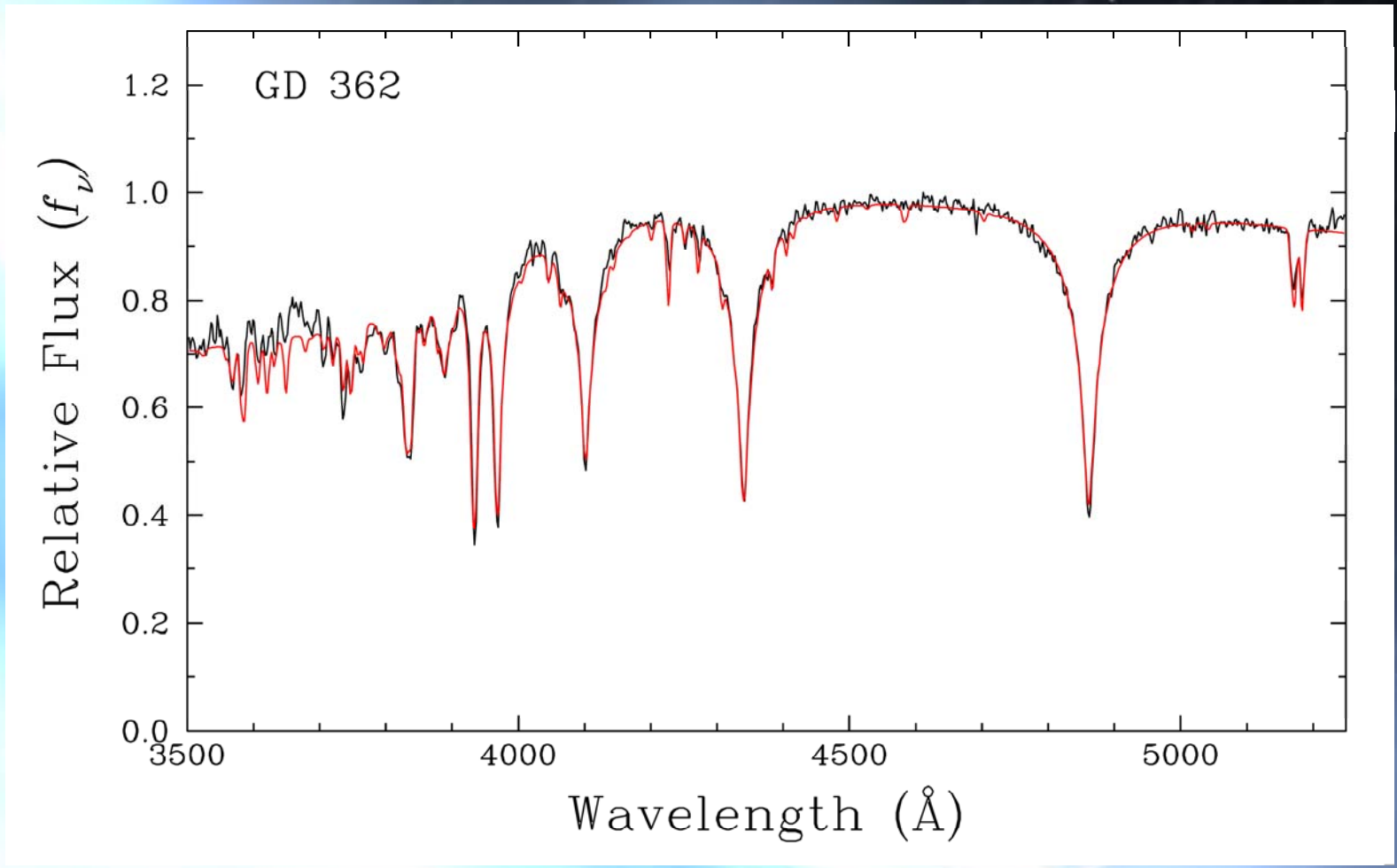
H & K (Calcium II)

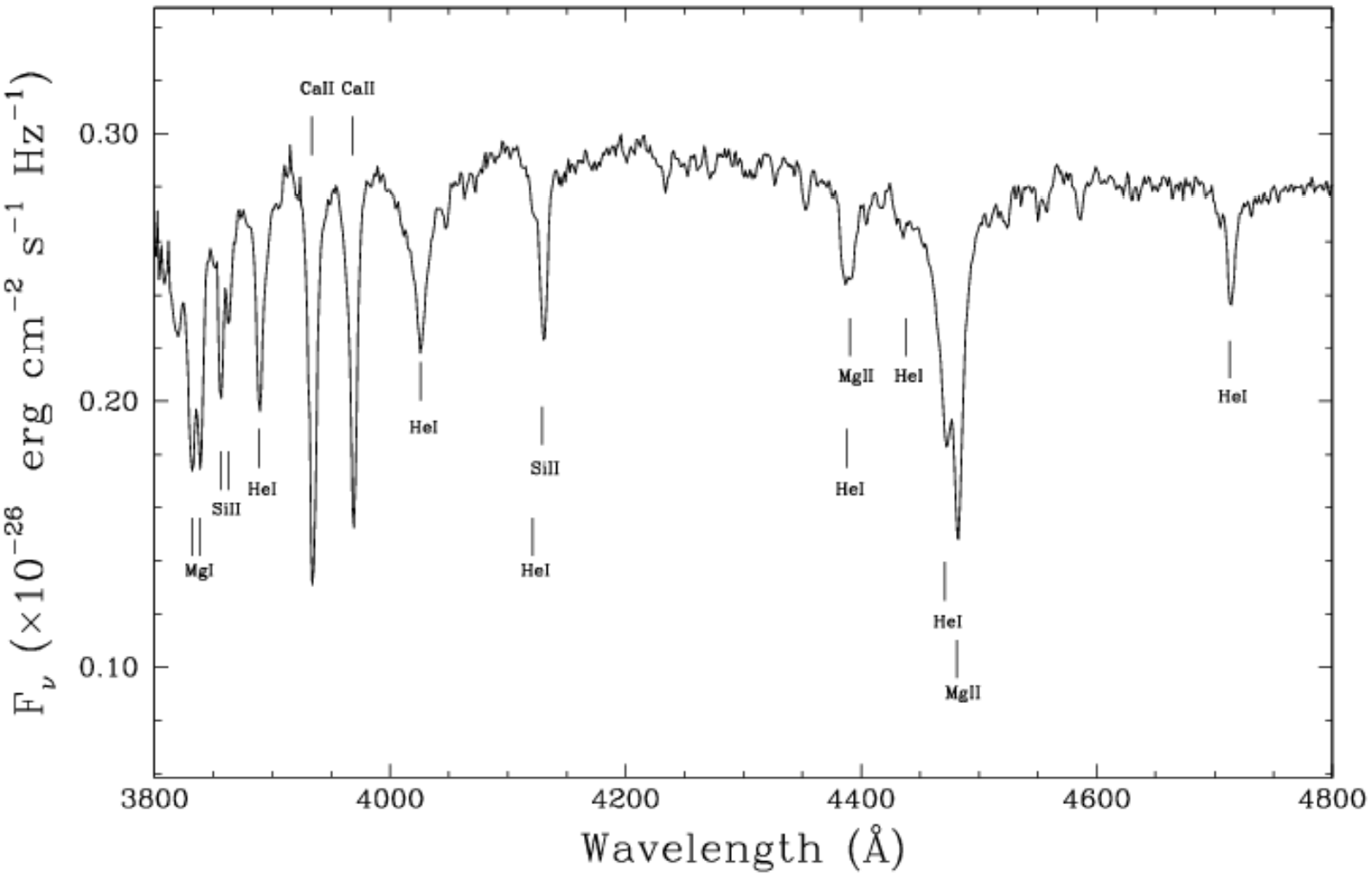
Hα: très sensible à la présence d'hydrogène

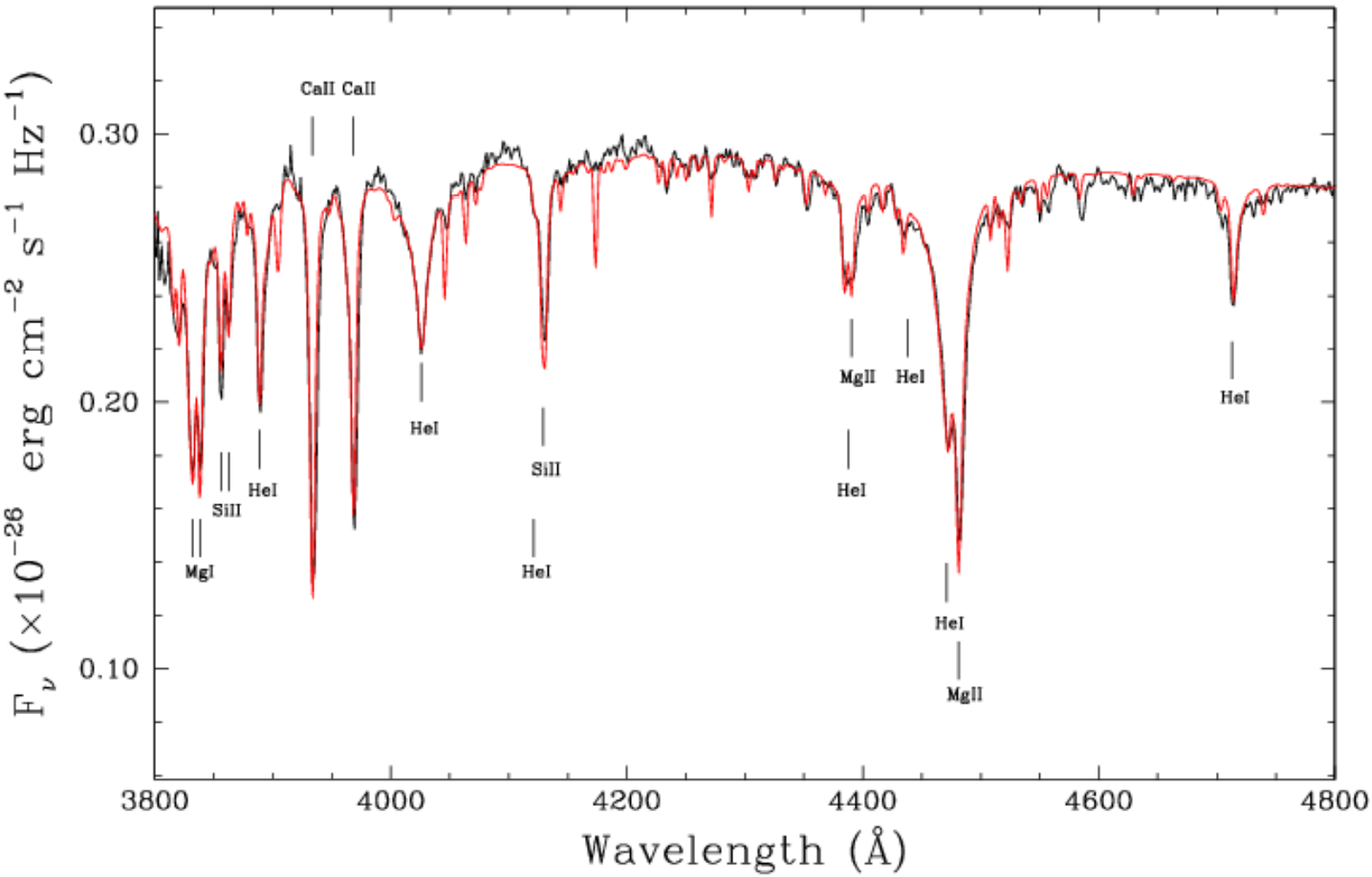
THE ASTROPHYSICAL JOURNAL, 617:L57–L60, 2004 December 10

DISCOVERY OF A COOL, MASSIVE, AND METAL-RICH DAZ WHITE DWARF

A. GIANNINAS, P. DUFOUR, AND P. BERGERON
Département de Physique, Université de Montréal, CP 6128, Succursale Centre-Ville, Montreal, PQ H3C 3J7, Canada;
gianninas@astro.umontreal.ca, dufourpa@astro.umontreal.ca, bergeron@astro.umontreal.ca
Received 2004 October 7; accepted 2004 October 28; published 2004 November 3

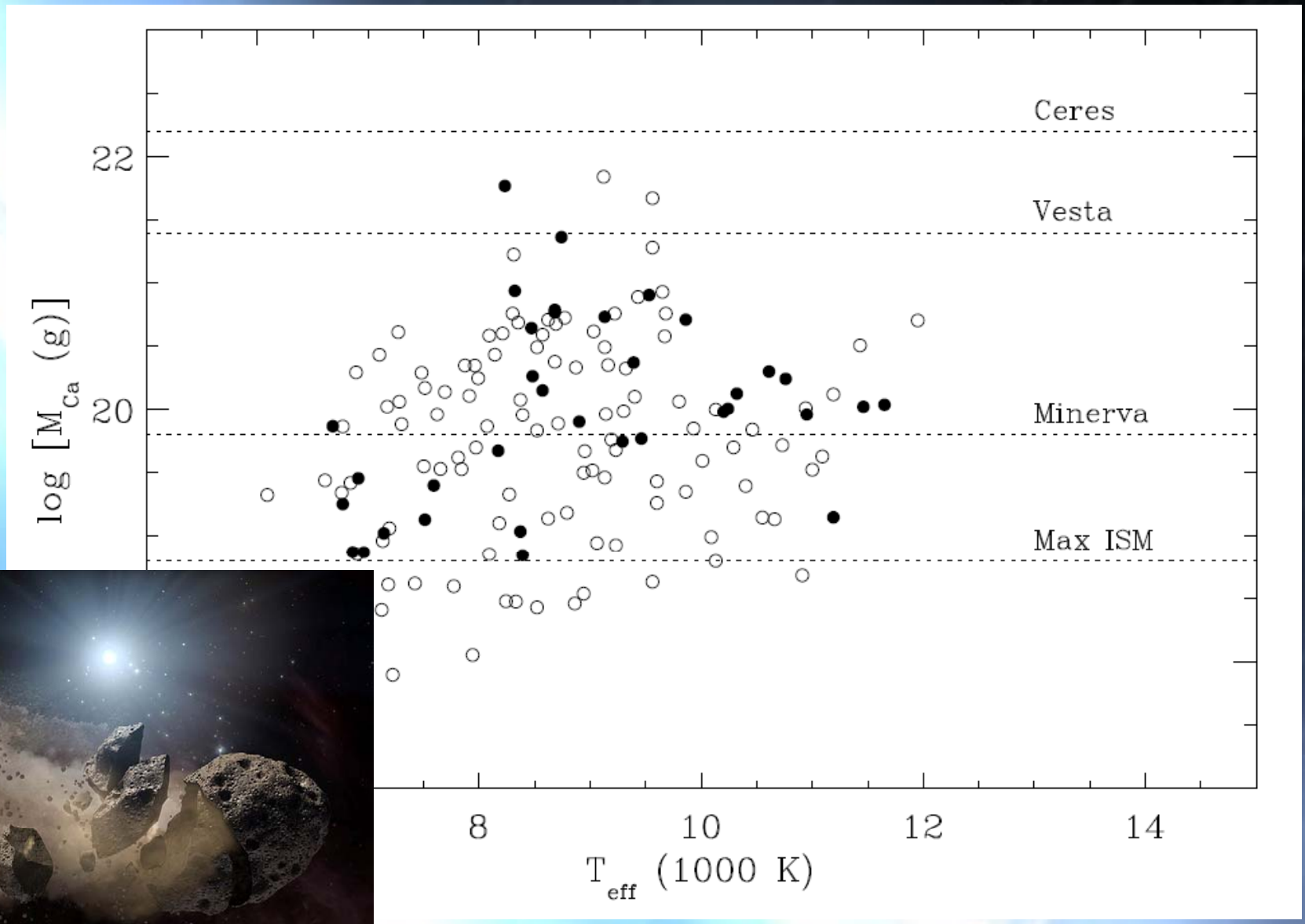


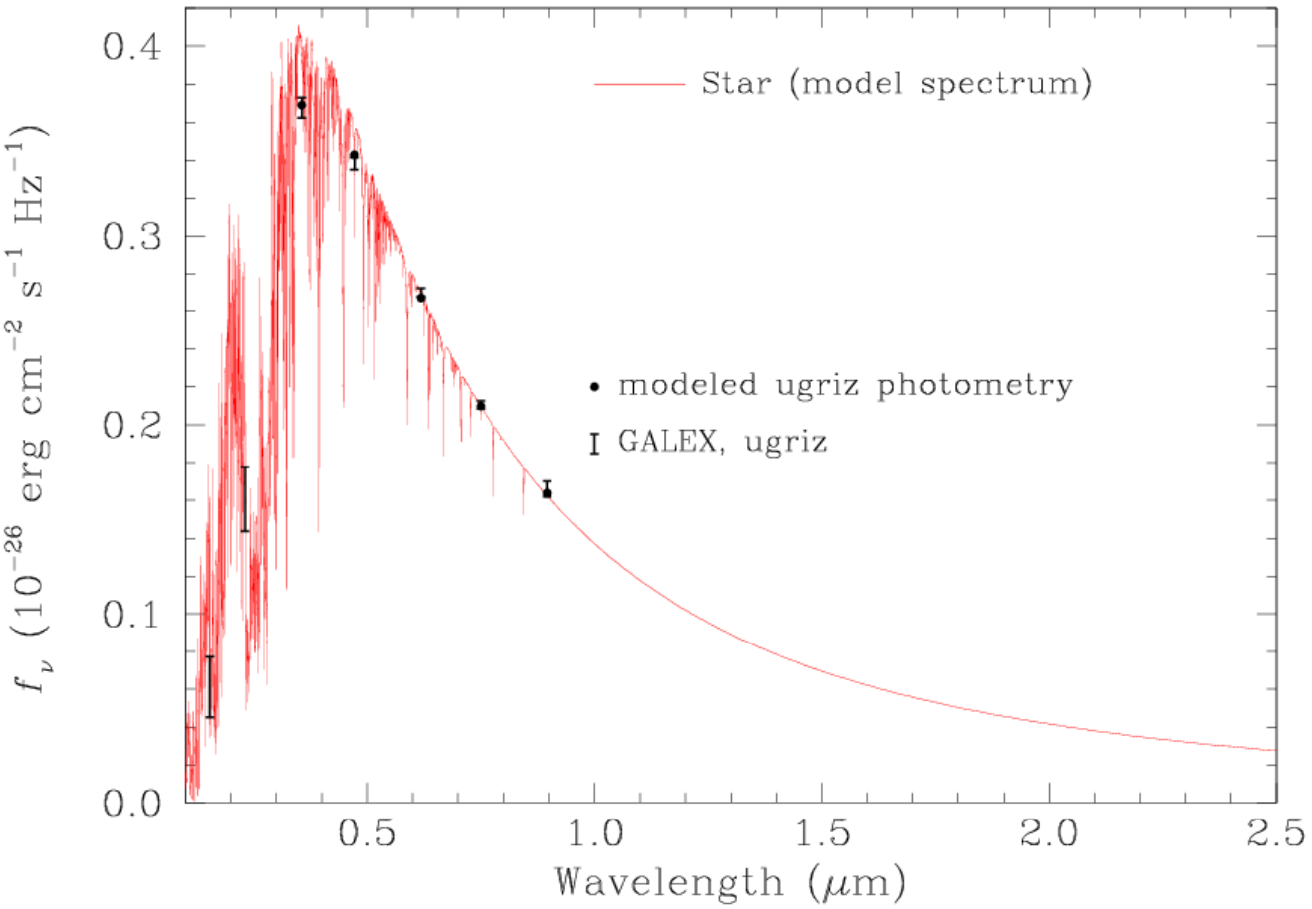

CaII CaII
HeI
SiII
HeI
MgII
HeI
HeI
MgI
SiII
HeI
HeI
MgII
0.30
0.20
0.10
3800
4000
4200
4400
4600
4800
Wavelength (Å)
F_ν ($\times 10^{-26}$ erg cm^{-2} s^{-1} Hz^{-1})

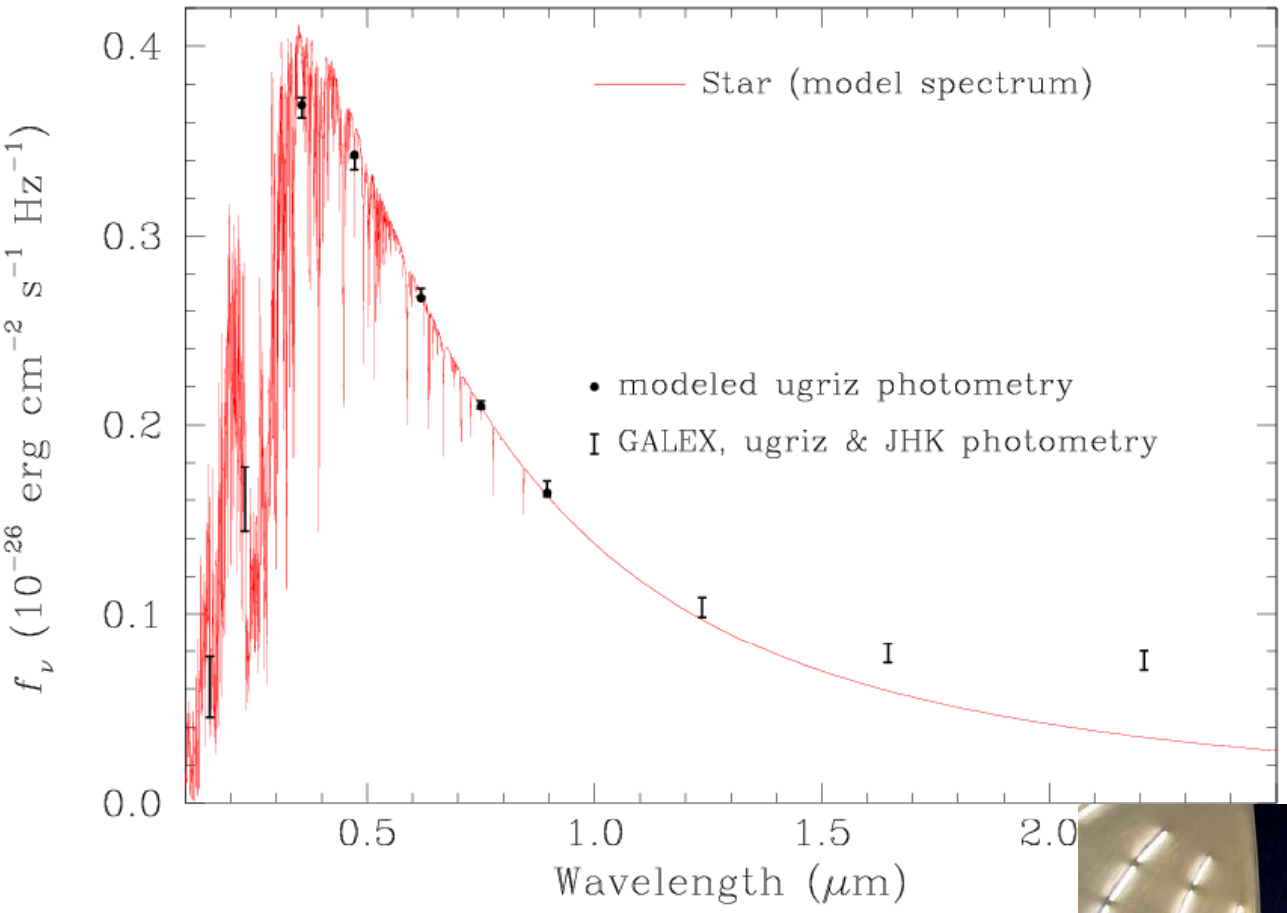

CaII CaII
HeI
SiII
HeI
MgI
SiII
HeI
HeI
MgII
HeI
HeI
HeI
MgII
HeI
0.30
0.20
0.10
3800
4000
4200
4400
4600
4800
F_ν ($\times 10^{-26}$ erg cm^{-2} s^{-1} Hz^{-1})
Wavelength (Å)

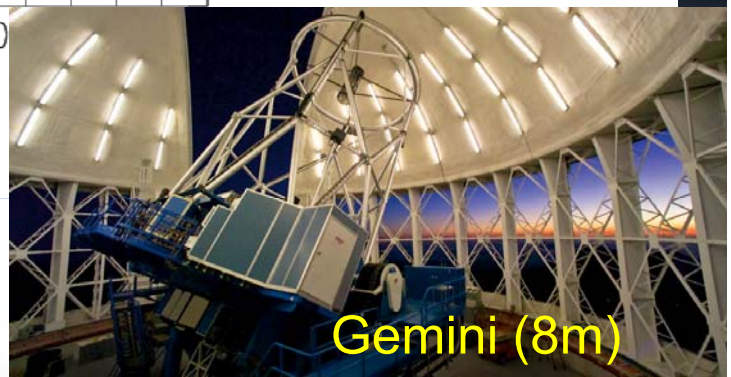
Statistical analysis of **142 DC** et **146 DZ**:

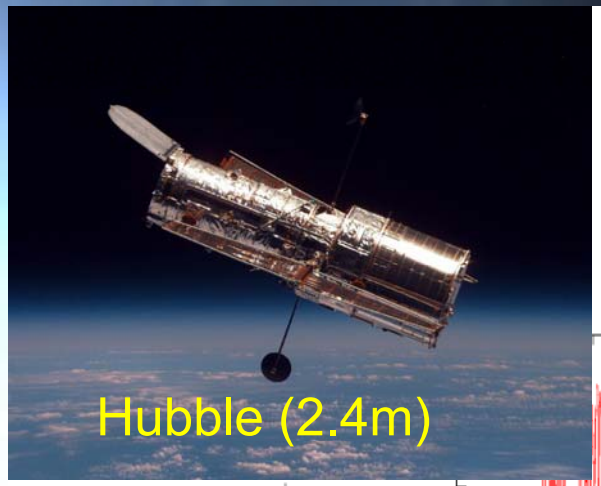
No correlation between the position of WD with and without metals vs Interstellar medium



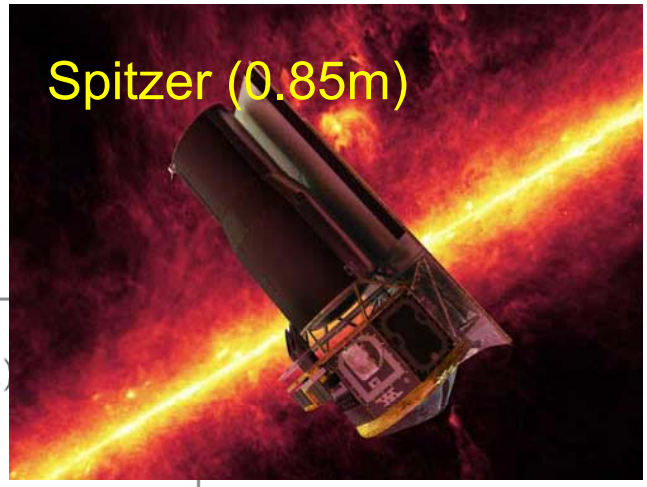

Star (model spectrum)
modeled ugriz photometry
GALEX, ugriz
f_ν (10^{-26} erg cm^{-2} s^{-1} Hz^{-1})
Wavelength (μm)
0.0
0.1
0.2
0.3
0.4
0.5
1.0
1.5
2.0
2.5

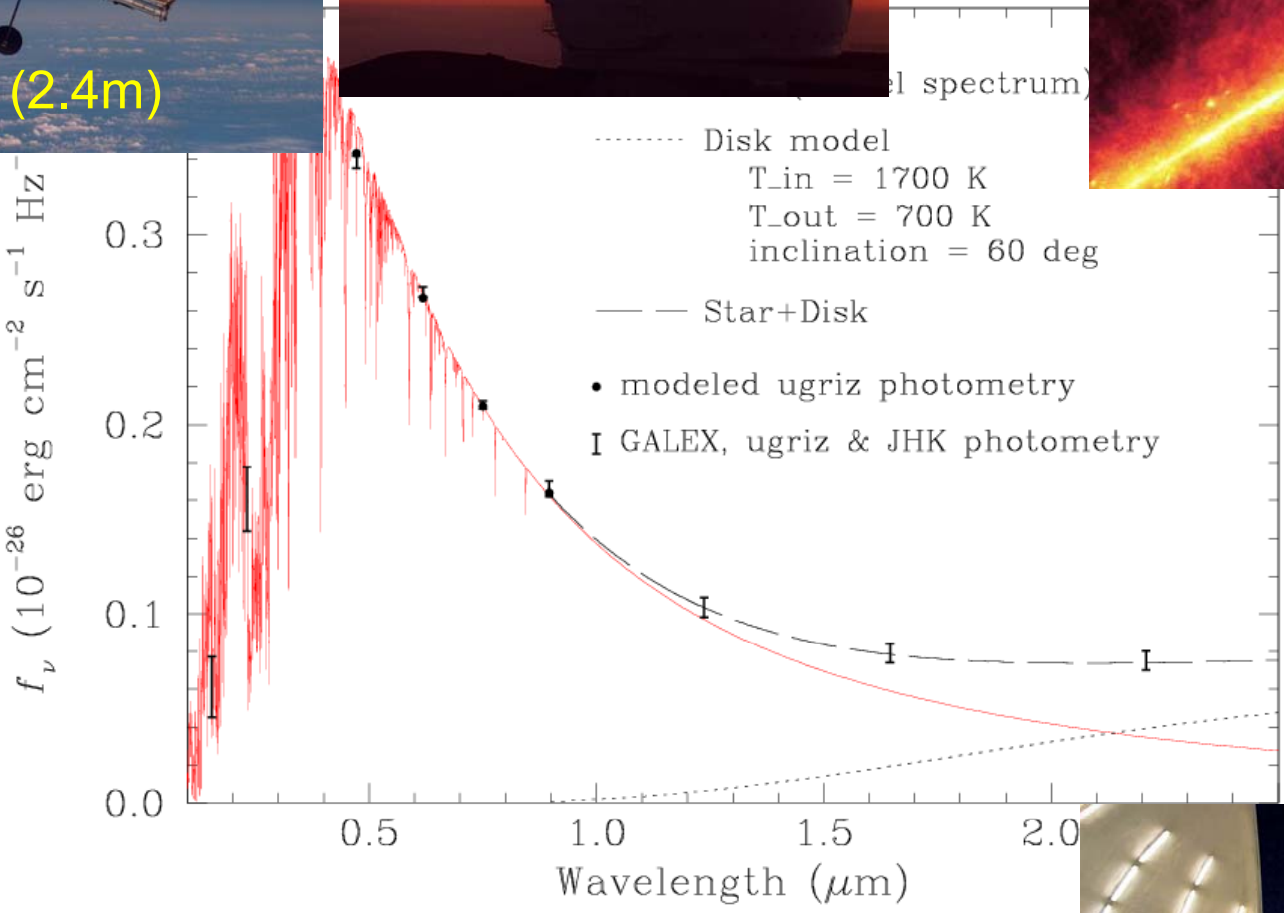

Star (model spectrum)
modeled ugriz photometry
GALEX, ugriz & JHK photometry
f_ν (10^{-26} erg cm^{-2} s^{-1} Hz^{-1})
Wavelength (μm)
0.0
0.1
0.2
0.3
0.4
0.5
1.0
1.5
2.0

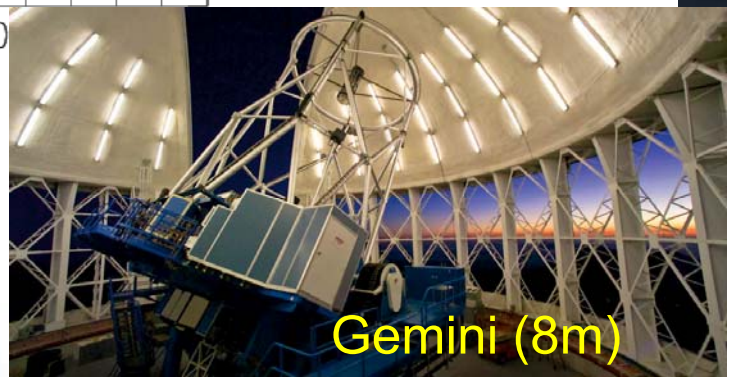

Gemini (8m)


Hubble (2.4m)


Keck (10m)


Spitzer (0.85m)


Disk model
T_in = 1700 K
T_out = 700 K
inclination = 60 deg
Star+Disk
modeled ugriz photometry
GALEX, ugriz & JHK photometry
f_ν (10^{-26} erg cm^{-2} s^{-1} Hz
0.0
0.1
0.2
0.3
0.5
1.0
1.5
2.0
Wavelength (μm)


Gemini (8m)

THE DISCOVERY OF THE MOST METAL-RICH WHITE DWARF: COMPOSITION OF A TIDALLY DISRUPTED EXTRASOLAR DWARF PLANET

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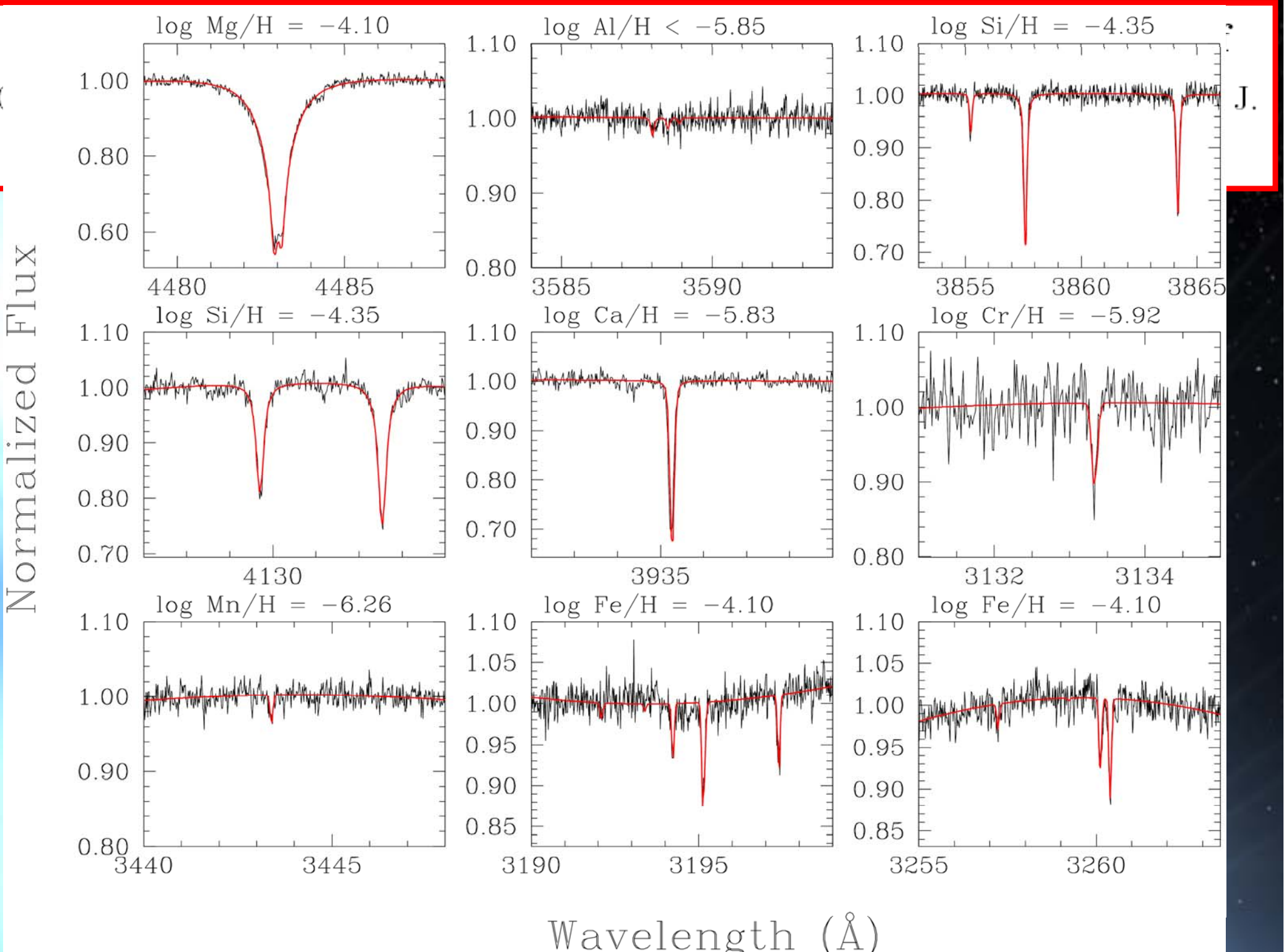
Table 1. Atmospheric and other parameters for SDSS J0738+1835

Parameter	Value
$T_{\rm eff}$ (K)	13600 ± 300
$\log g$	8.5 ± 0.2
$M/M_{\odot}$	0.907 ± 0.128
$R/R_{\odot}$	0.00886 ± 0.0015
$\log L/L_{\odot}$	−2.62 ± 0.14
D	136 pc ± 22
Age	595 Myr ± 219
log H/He	−5.7 ± 0.3
log O/He	−4.0 ± 0.2
log Mg/He	−4.7 ± 0.2
log Si/He	−4.9 ± 0.2
log Ca/He	−6.8 ± 0.3
log Fe/He	−5.1 ± 0.3
$\log(M_{\rm He}/M_{\star})$	−6.5 +0.8/−0.25

=0.966R_{Terre}

Total M > 4.3 x 10^{23} g


log Mg/H = −4.10
log Al/H < −5.85
log Si/H = −4.35
log Si/H = −4.35
log Ca/H = −5.83
log Cr/H = −5.92
log Mn/H = −6.26
log Fe/H = −4.10
log Fe/H = −4.10
Normalized Flux
Wavelength (Å)

Only a few white dwarfs with several metals known so far

The study of white dwarfs with extreme metal polution is the **ONLY** known technique (other than go there and dig!) to obtain the internal chemical compositions of extrasolar planetesimals/planets.

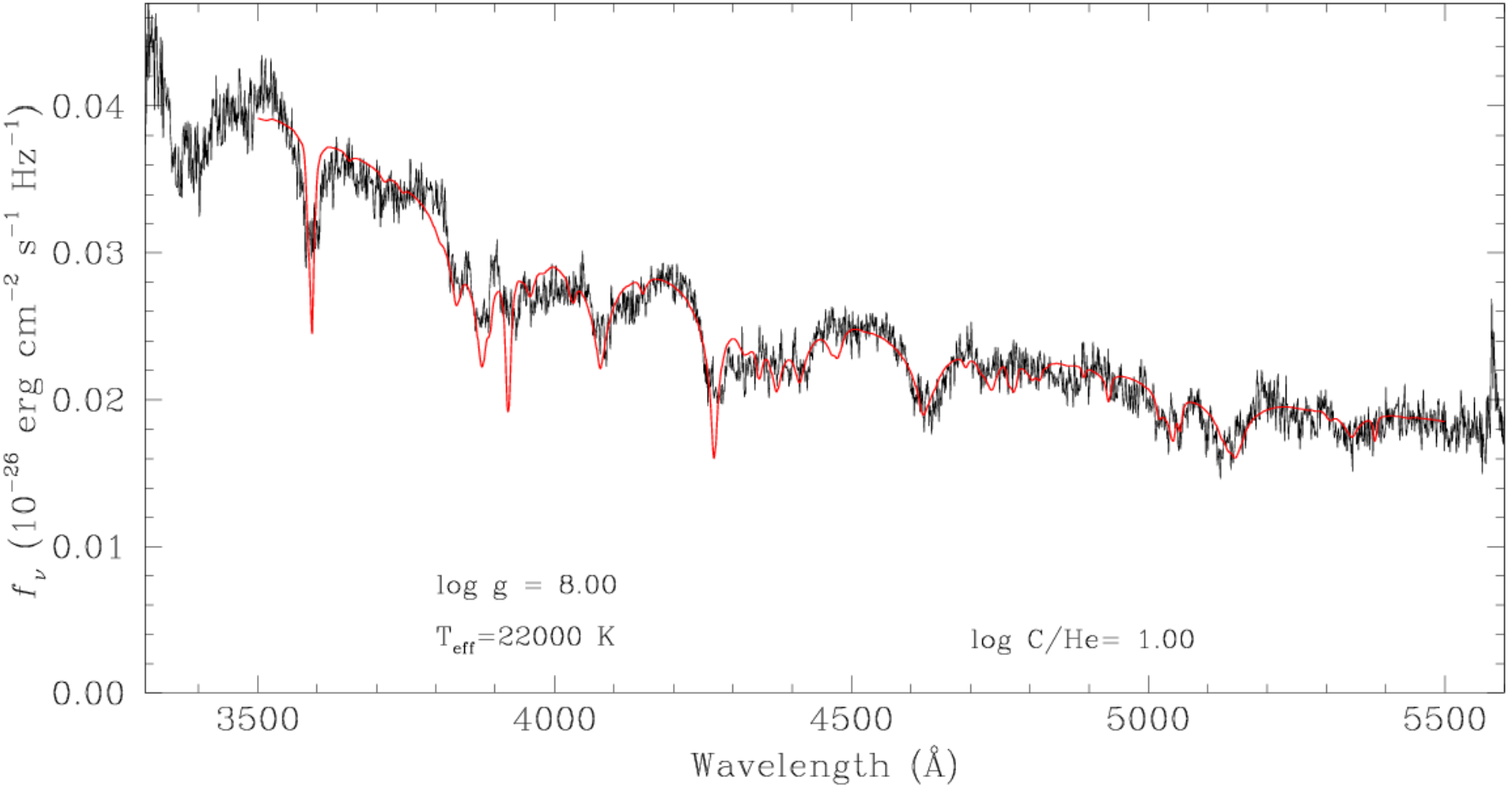

Thank You

Âge de l’amas (”Turnoff”) – Âge WD (M, Teff) = Temps de vie sur séq. princ.

↓

Masse du progéniteur

M35



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SDSS J142625.71+575218.3: THE FIRST PULSATING WHITE DWARF WITH A LARGE DETECTABLE MAGNETIC FIELD

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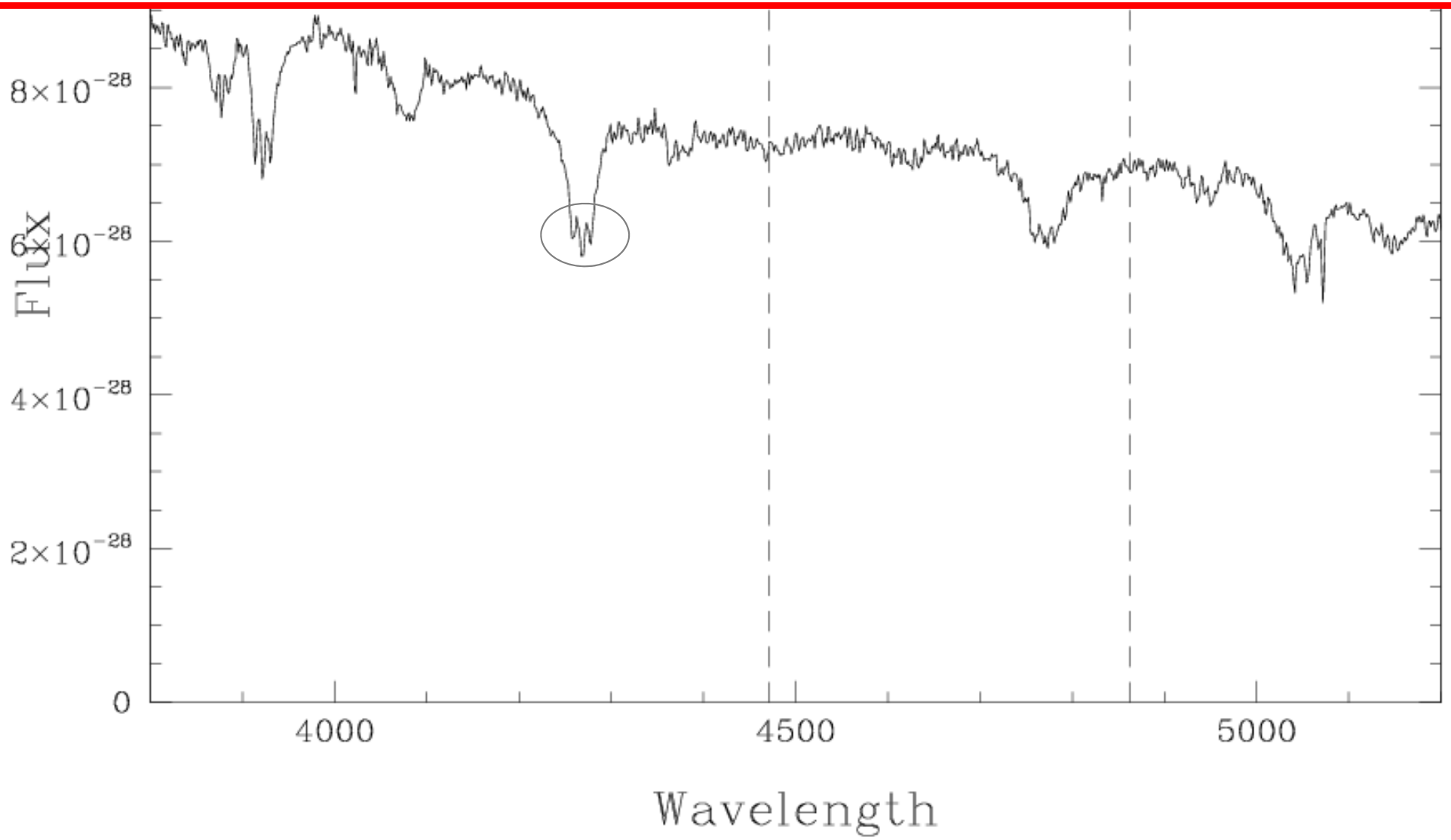
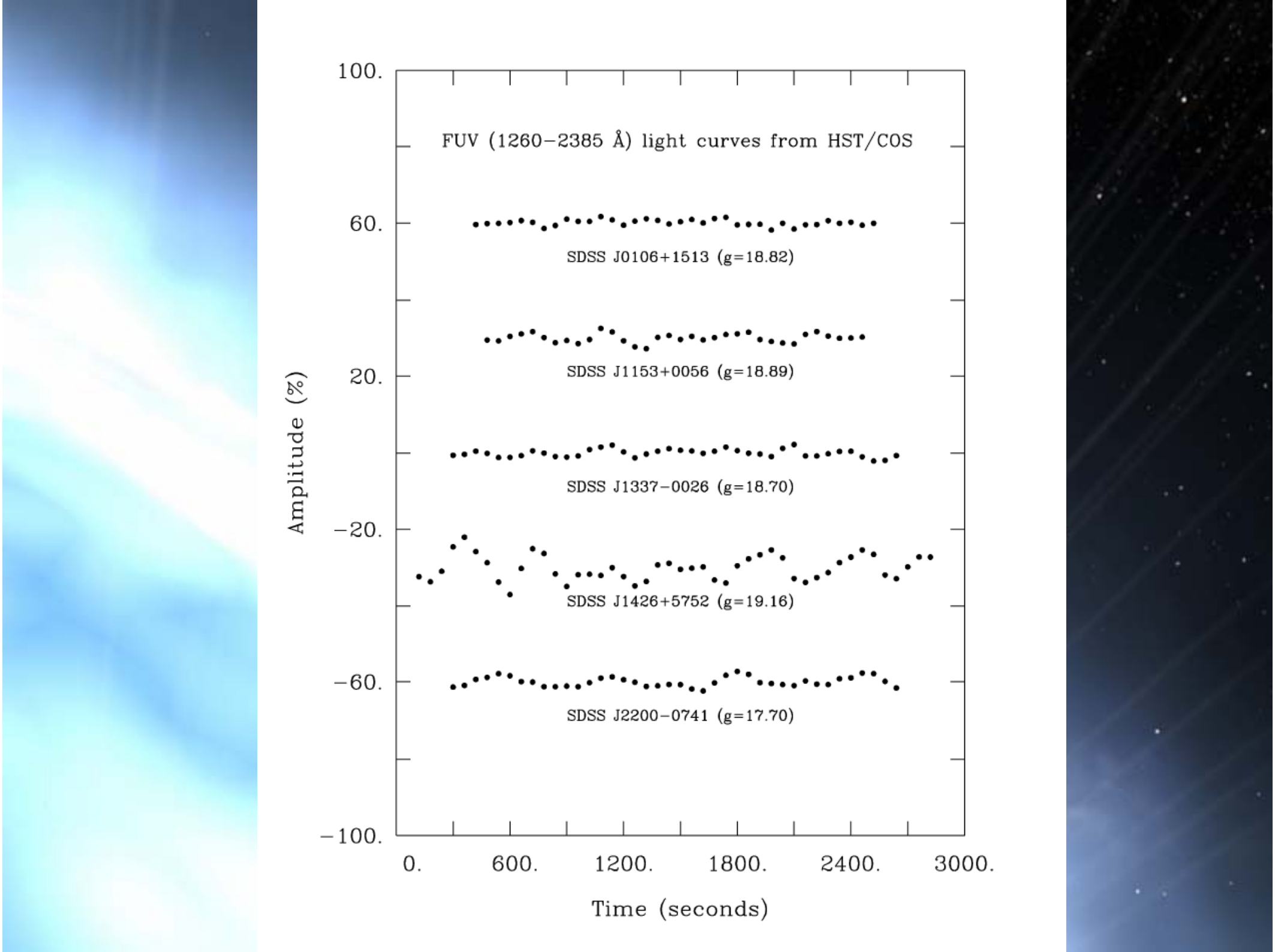
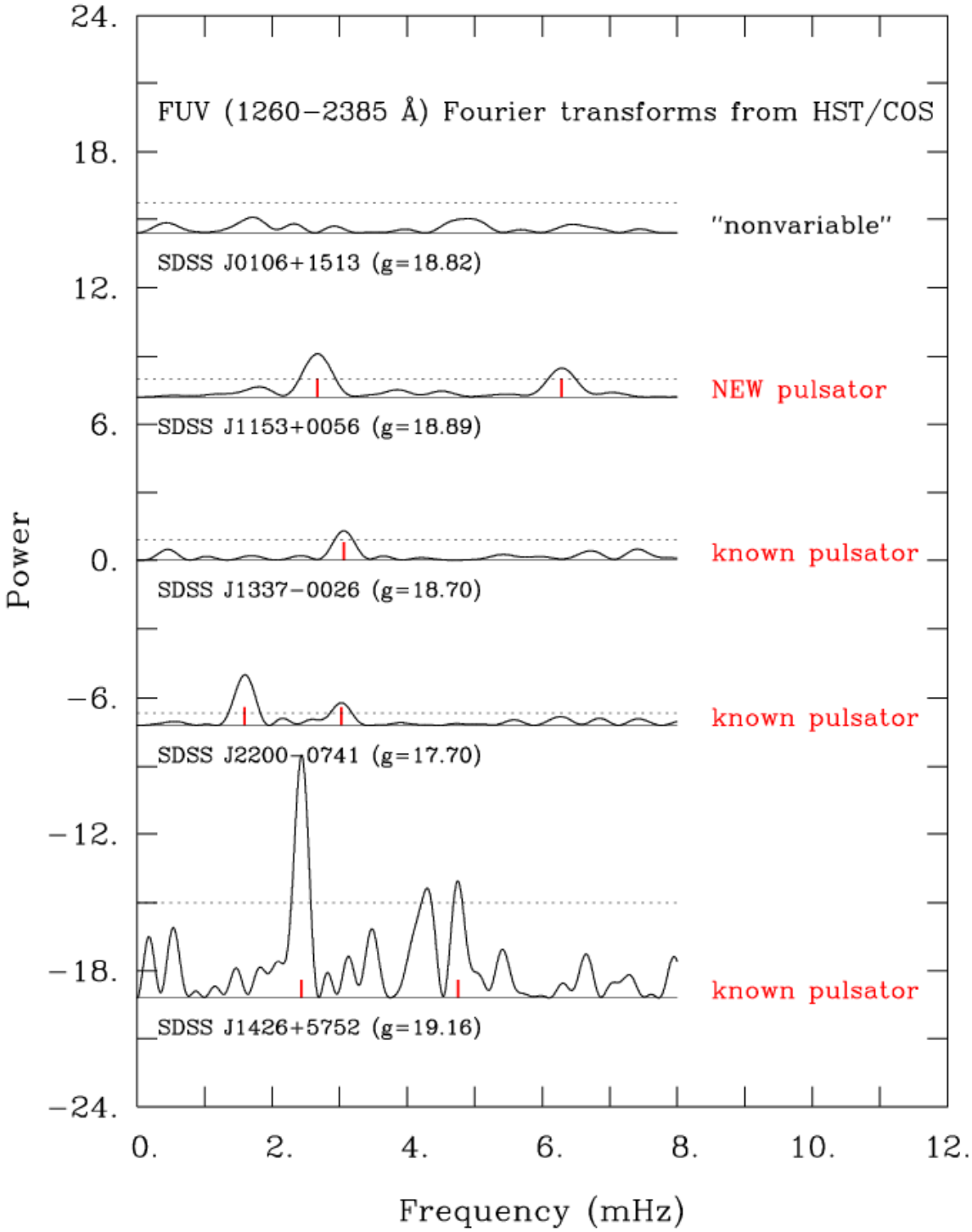
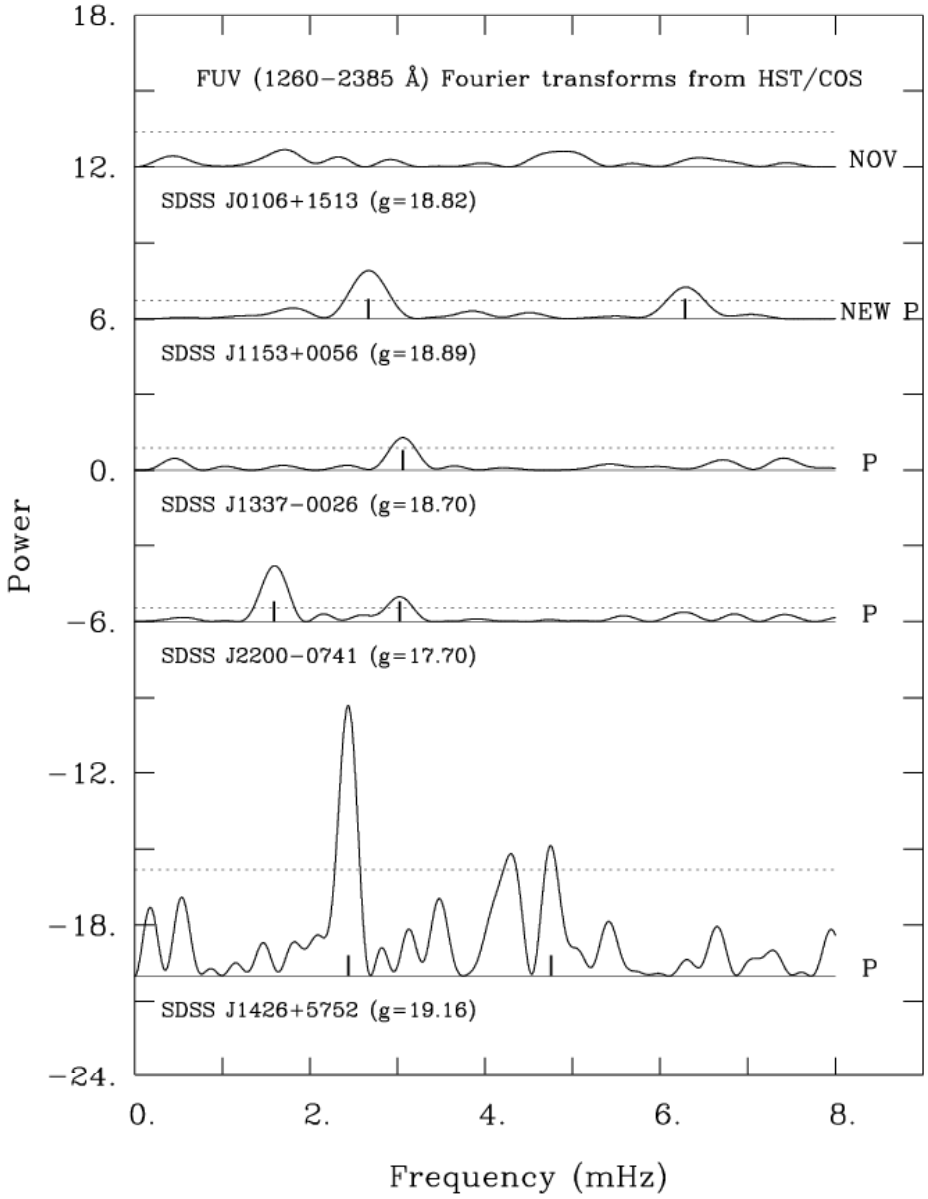



FUV (1260–2385 Å) light curves from HST/COS
SDSS J0106+1513 (g=18.82)
SDSS J1153+0056 (g=18.89)
SDSS J1337−0026 (g=18.70)
SDSS J1426+5752 (g=19.16)
SDSS J2200−0741 (g=17.70)
Amplitude (%)
100.
60.
20.
−20.
−60.
−100.
0.
600.
1200.
1800.
2400.
3000.
Time (seconds)


FUV (1260–2385 Å) Fourier transforms from HST/COS
"nonvariable"
SDSS J0106+1513 (g=18.82)
NEW pulsator
SDSS J1153+0056 (g=18.89)
known pulsator
SDSS J1337−0026 (g=18.70)
known pulsator
SDSS J2200−0741 (g=17.70)
known pulsator
SDSS J1426+5752 (g=19.16)
Power
Frequency (mHz)
24.
18.
12.
6.
0.
−6.
−12.
−18.
−24.
0.
2.
4.
6.
8.
10.
12.


FUV (1260–2385 Å) Fourier transforms from HST/COS
SDSS J0106+1513 (g=18.82)
NOV
SDSS J1153+0056 (g=18.89)
NEW P
SDSS J1337–0026 (g=18.70)
P
SDSS J2200–0741 (g=17.70)
P
SDSS J1426+5752 (g=19.16)
P
Power
18.
12.
6.
0.
−6.
−12.
−18.
−24.
0.
2.
4.
6.
8.
Frequency (mHz)

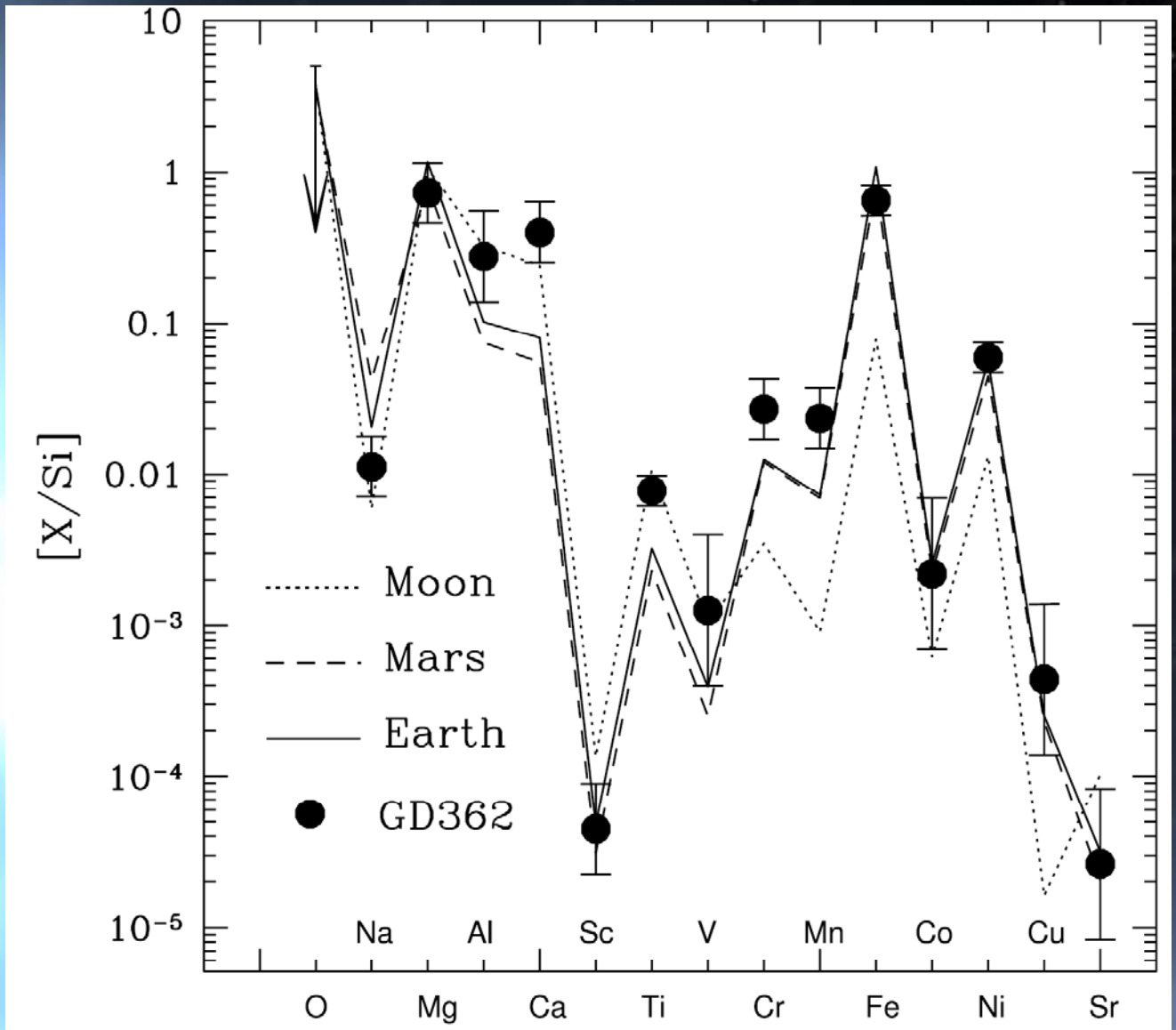


FIG. 3.—Elemental abundances by number relative to silicon. The GD 362 data are from Table 2, and those for Earth, Moon, and Mars are from Lodders & Fegley (1998).

On the formation of hot DQ white dwarfs

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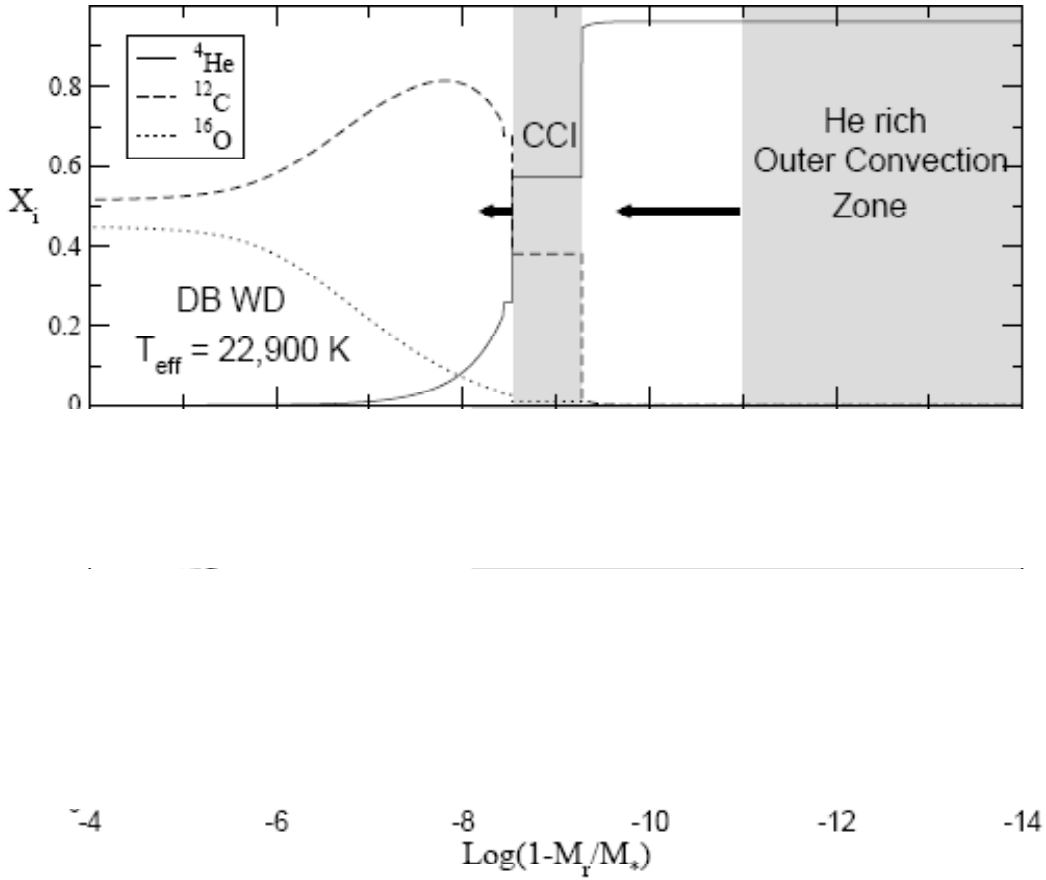

Fig. 1.— Abundance distribution of ^{4}He, ^{12}C, and ^{16}O as a function of the outer mass fraction at two selected effective temperatures for the 0.87 $M_\odot$ white dwarf with $M_{\rm He} = 10^{-8}\,M_{\rm WD}$. Gray areas denote convectively unstable zones. The inward-growing outer convection zone (upper panel) merges with the underlying convective C-rich intershell (CCI), leading to the formation of a white dwarf with a C atmosphere — a hot DQ — at about $T_{\rm eff} = 20,800$ K (bottom panel).