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

Patrick Dufour

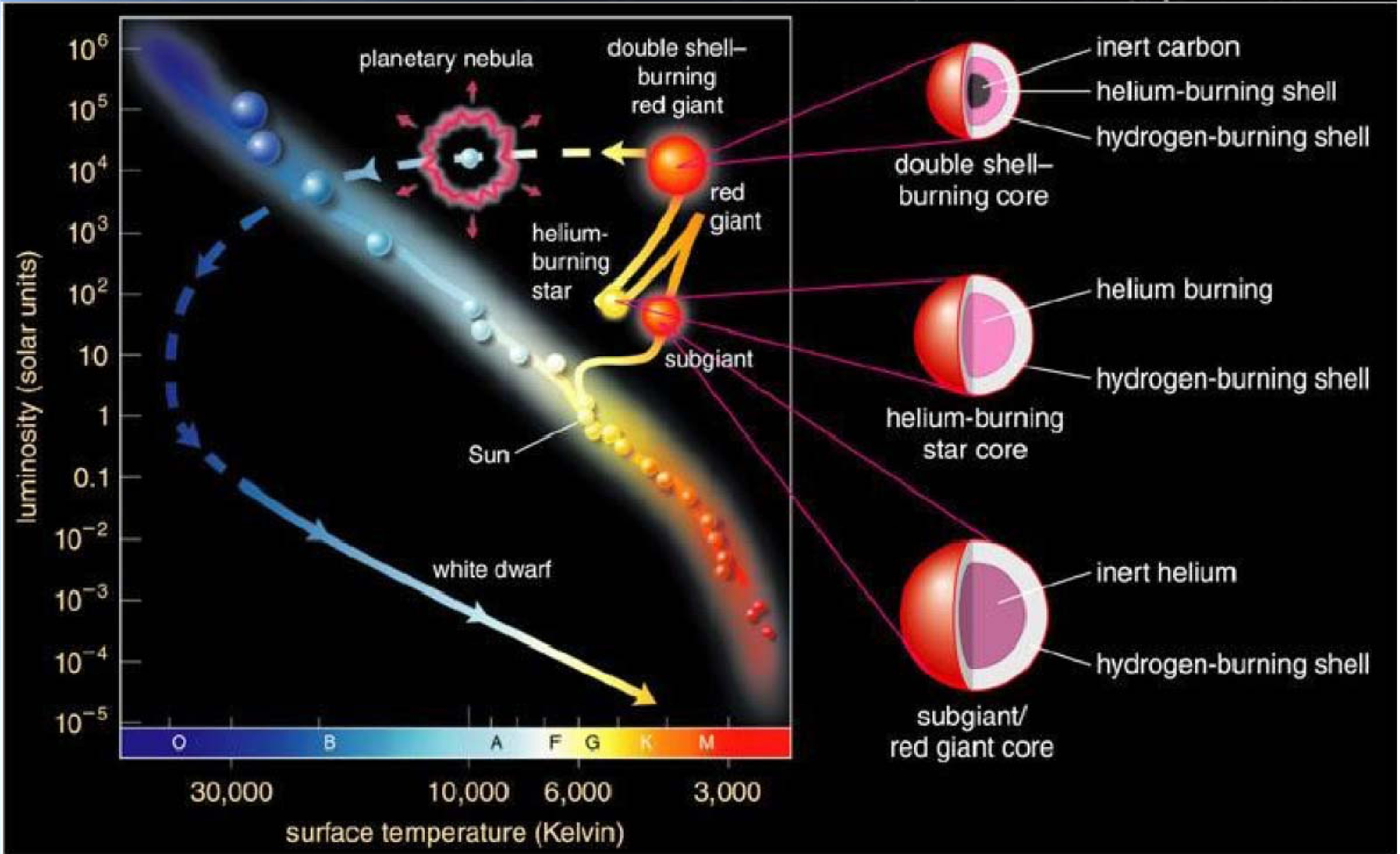
Département de physique

Centre de Recherche en Astrophysique du Québec

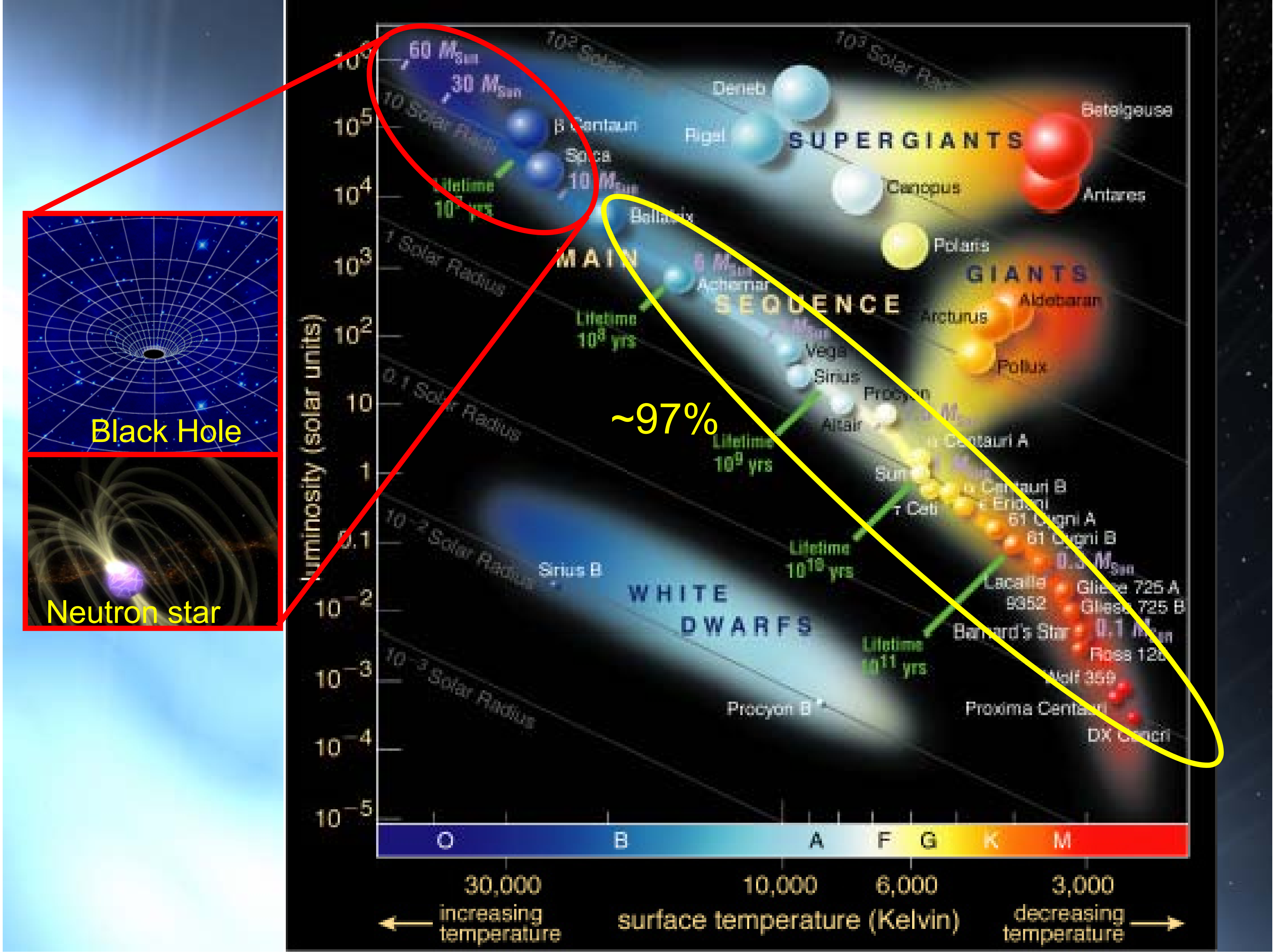
Université de Montréal

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

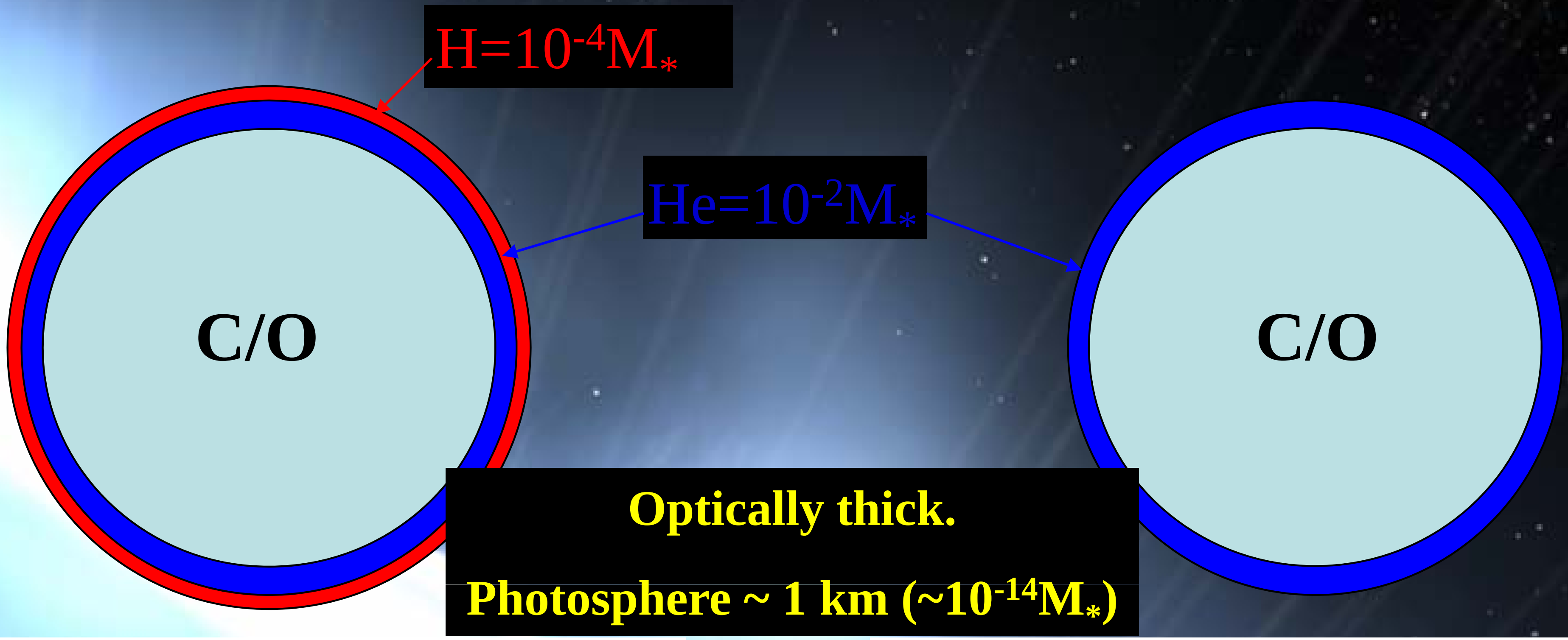


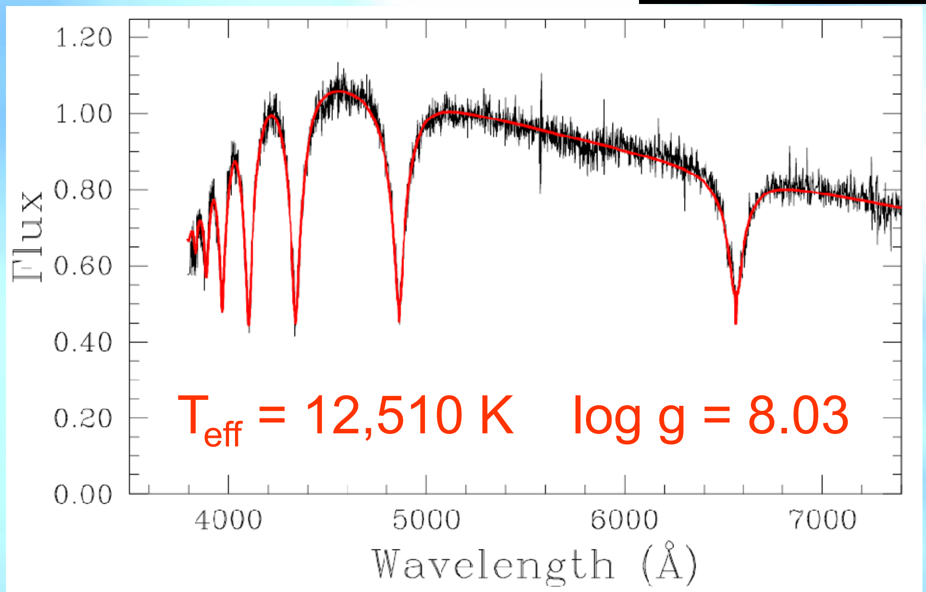
luminosity (solar units)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^-2
10^-3
10^-4
10^-5
planetary nebula
double shell–burning red giant
red giant
helium-burning star
subgiant
Sun
white dwarf
O
B
A
F
G
K
M
30,000
10,000
6,000
3,000
surface temperature (Kelvin)
inert carbon
helium-burning shell
hydrogen-burning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

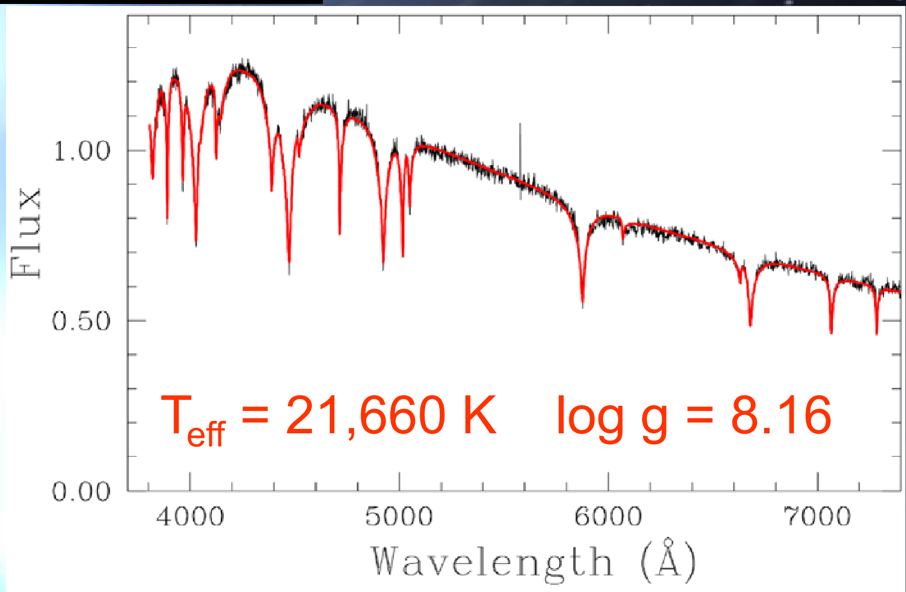


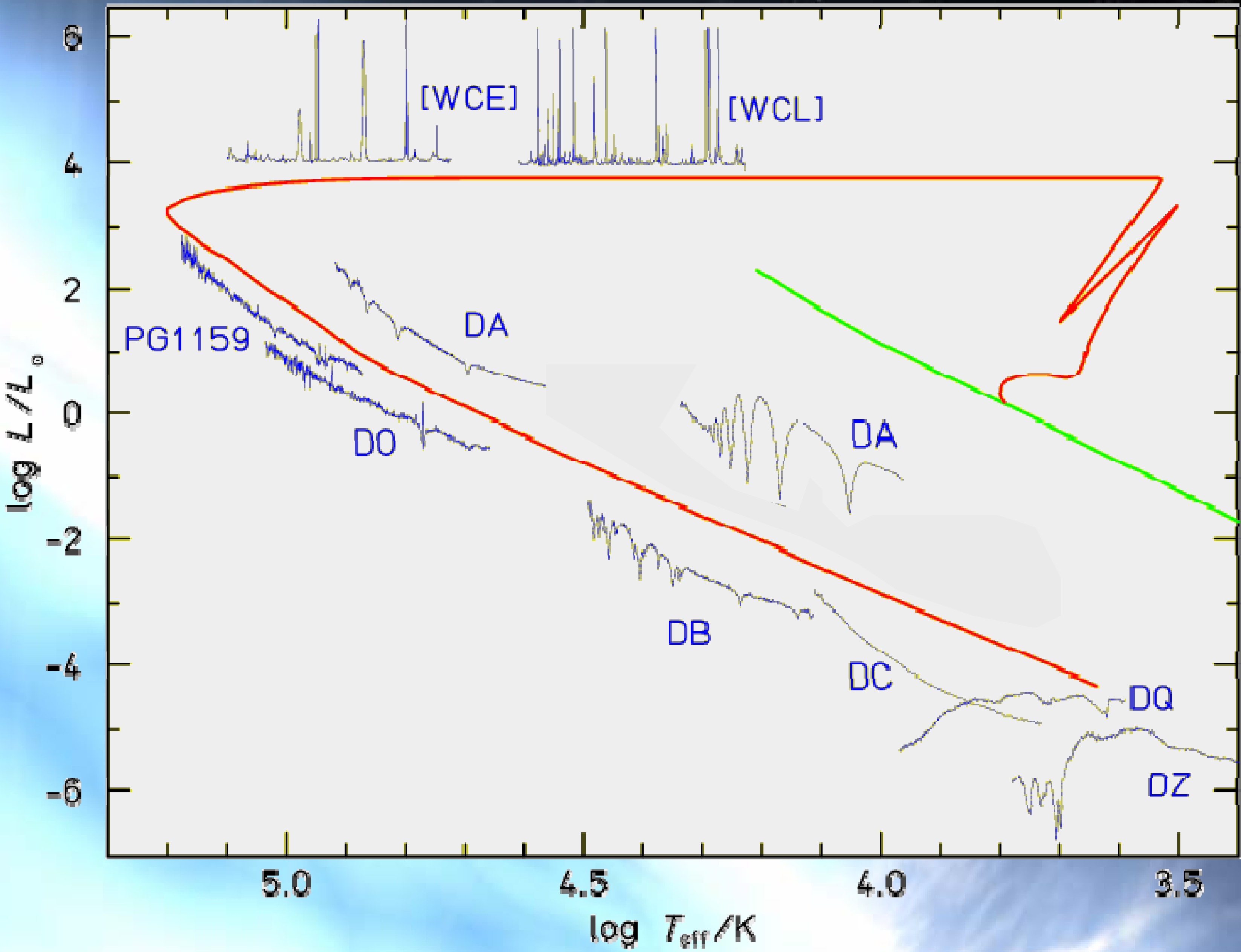
Black Hole
Neutron star
~97%
60 M_{Sun}
30 M_{Sun}
10 M_{Sun}
β Centauri
Spica
Bellatrix
Achernar
Vega
Sirius
Procyon
Altair
α Centauri A
Sun
α Centauri B
τ Ceti
ε Eridani
61 Cygni A
61 Cygni B
0.3 M_{Sun}
Lacaille 9352
Gliese 725 A
Gliese 725 B
Barnard's Star
0.1 M_{Sun}
Ross 128
Wolf 359
Proxima Centauri
DX Cancri
Deneb
Rigel
SUPERGIANTS
Betelgeuse
Antares
Canopus
Polaris
GIANTS
Aldebaran
Arcturus
Pollux
MAIN
SEQUENCE
WHITE
DWARFS
Sirius B
Procyon B
10^2 Solar Radii
10^3 Solar Radii
10 Solar Radii
1 Solar Radius
0.1 Solar Radius
10^{-2} Solar Radius
10^{-3} Solar Radius
Lifetime 10^7 yrs
Lifetime 10^8 yrs
Lifetime 10^9 yrs
Lifetime 10^{10} yrs
Lifetime 10^{11} yrs
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
increasing temperature
surface temperature (Kelvin)
decreasing temperature

Standard Stellar Evolution Theory









Rauch & Werner 1995

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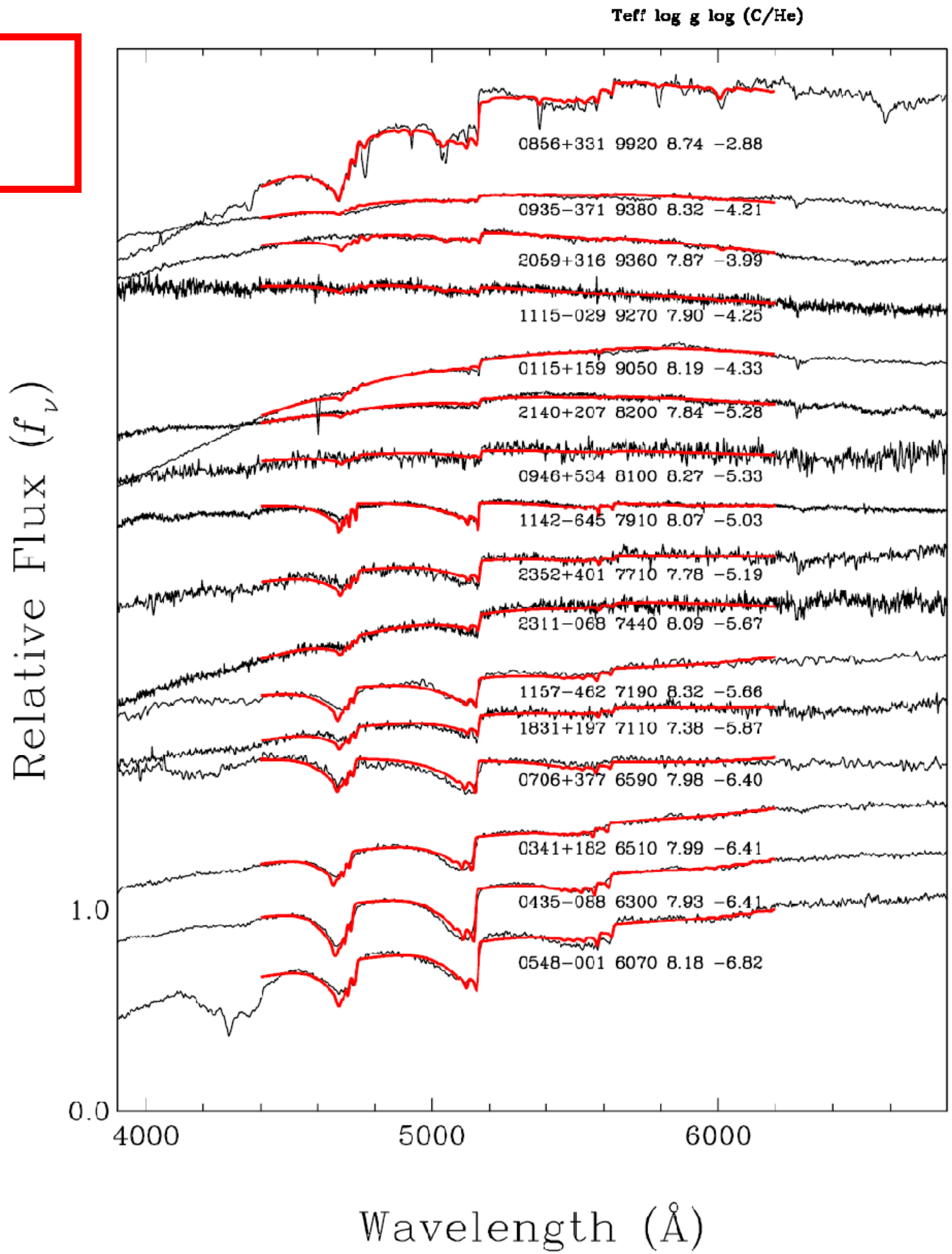
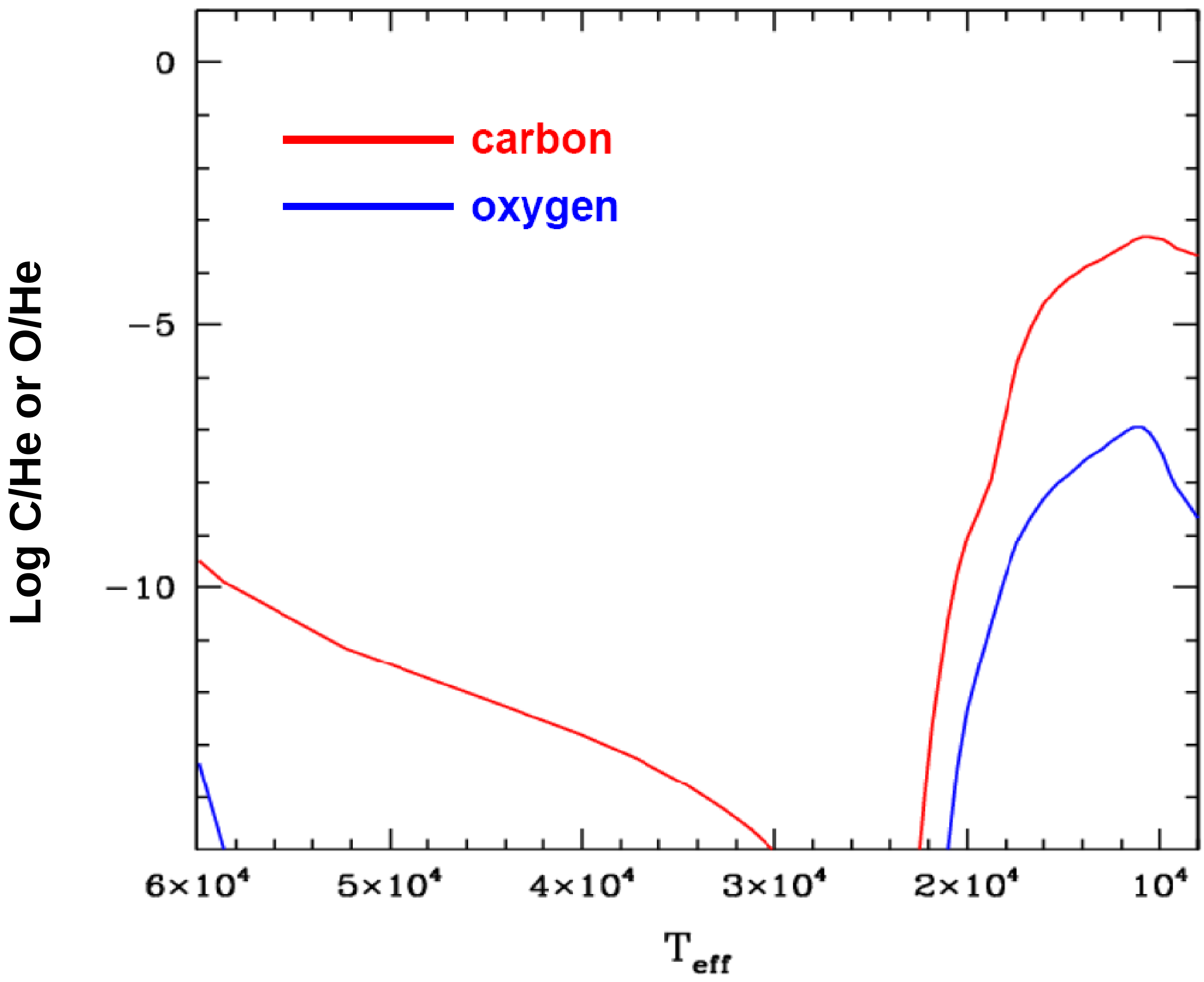
- Planets and abundance determinations
  - white dwarfs with traces of metals

Dufour et al., 2005

ApJ, 627, 404



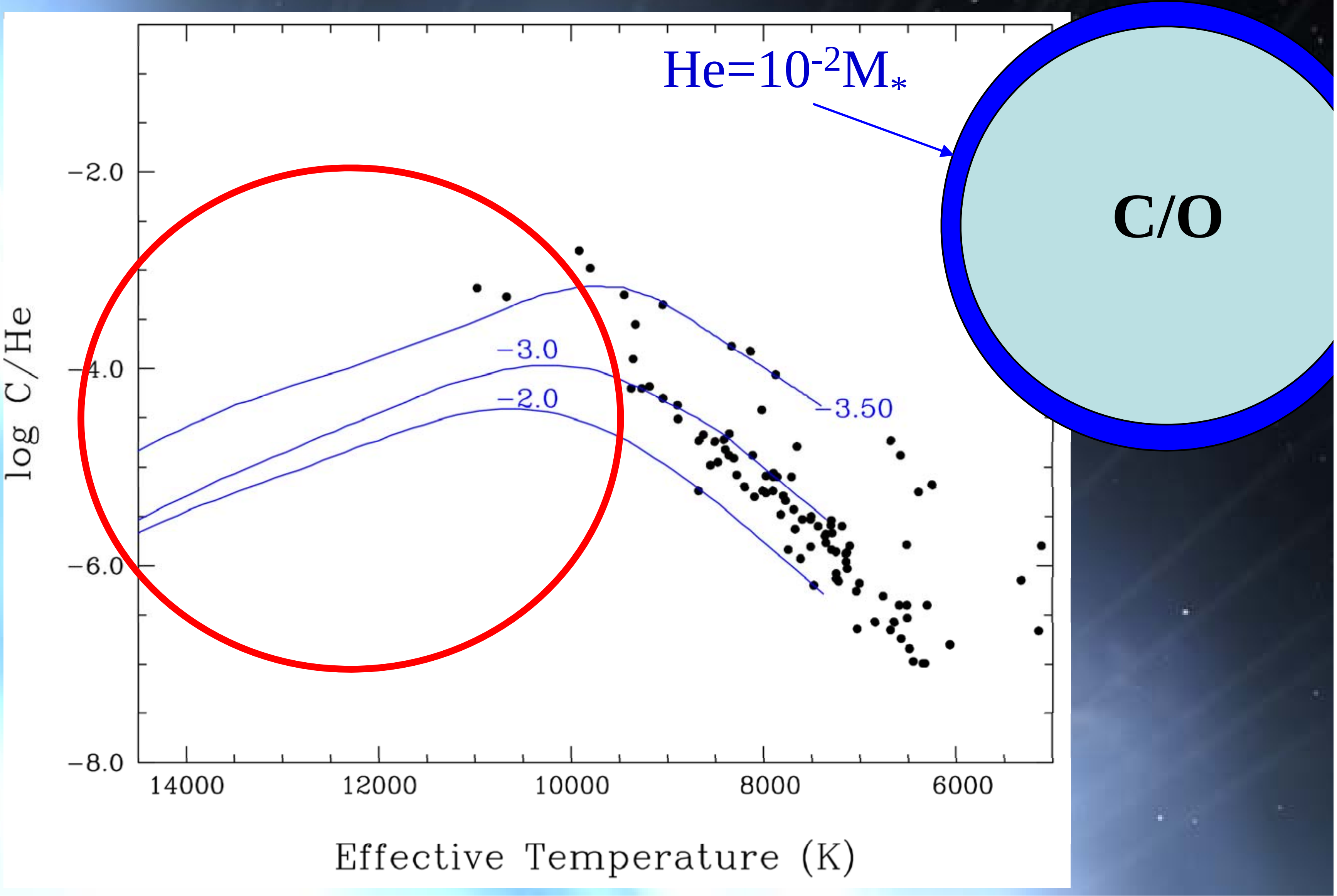


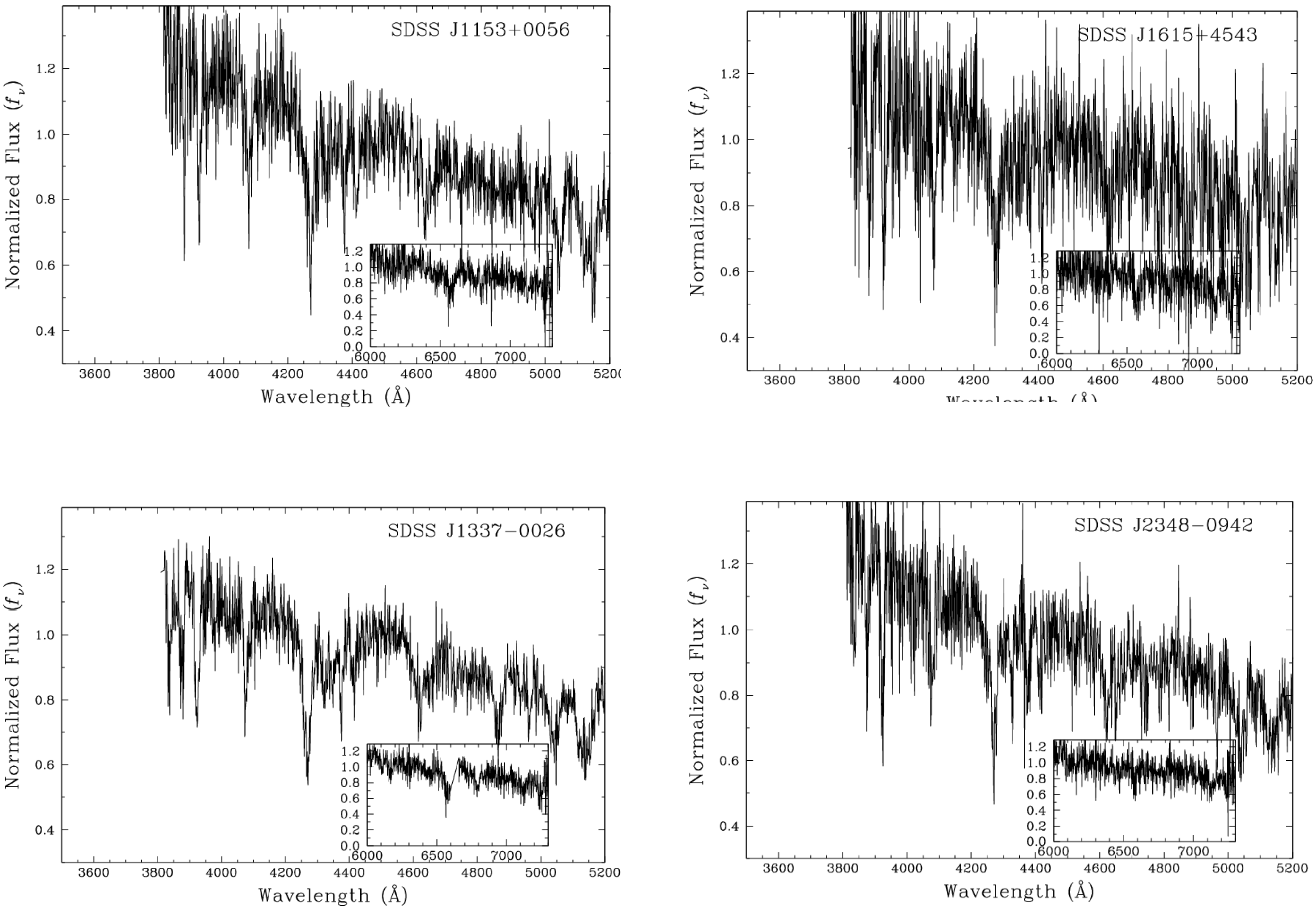
carbon
oxygen
Log C/He or O/He
0
−5
−10
6×10⁴
5×10⁴
4×10⁴
3×10⁴
2×10⁴
10⁴
T_eff

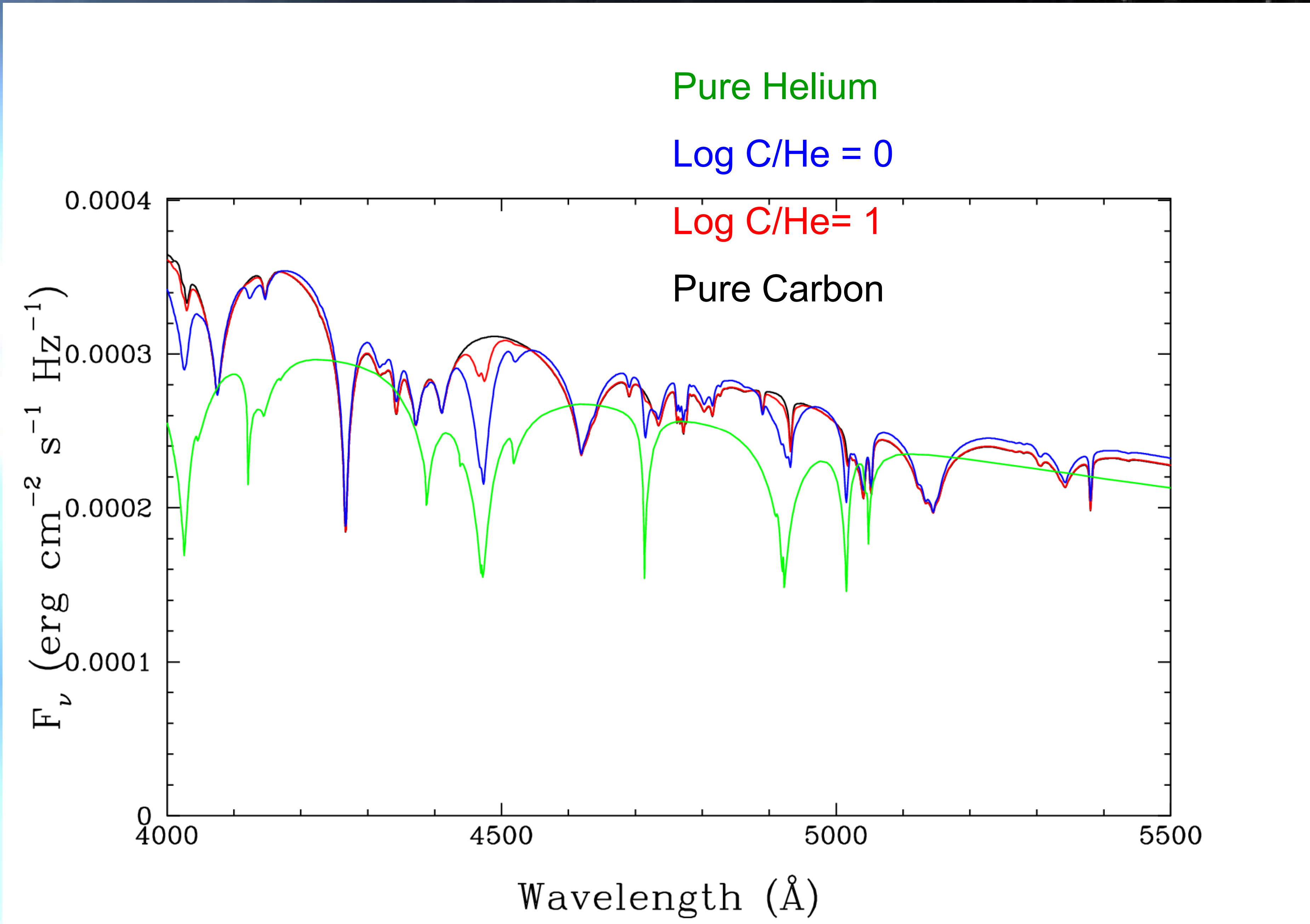
Stars with Unusual Compositions: Carbon and Oxygen in Cool White Dwarfs

P. Dufour

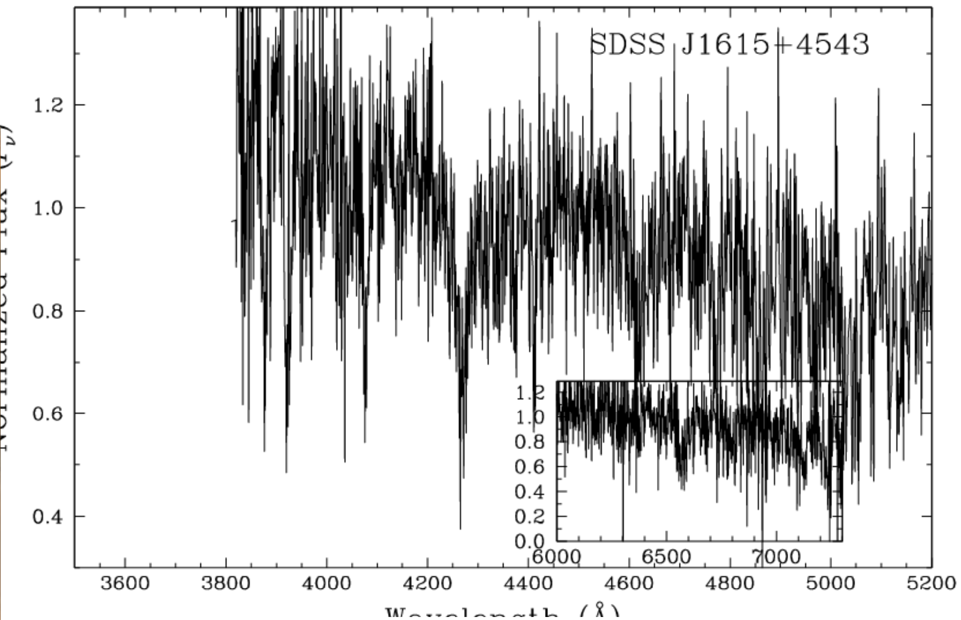
Review chapter to be published in "*White Dwarf Atmosphere and Circumstellar Environments*", D. W. Hoard (Ed.), Wiley-VCH, ISBN 978-3-527-41031-6



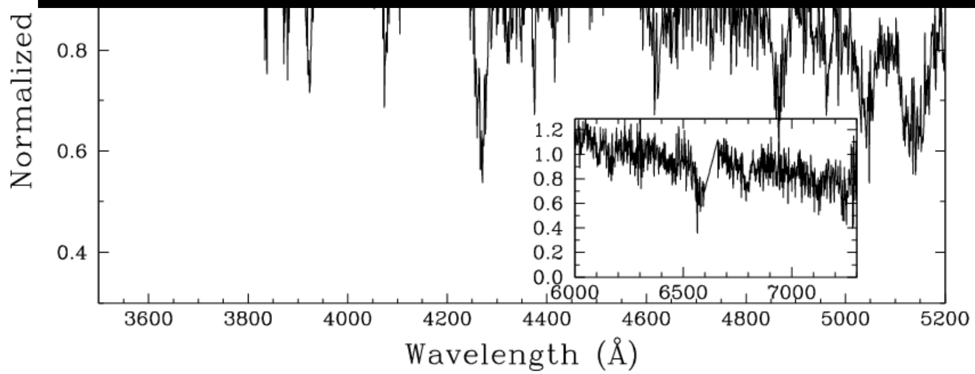

SDSS J1153+0056
SDSS J1615+4543
SDSS J1337−0026
SDSS J2348−0942
Normalized Flux (f_ν)
Wavelength (Å)
3600
3800
4000
4200
4400
4600
4800
5000
5200
0.4
0.6
0.8
1.0
1.2
6000
6500
7000
0.0
0.2

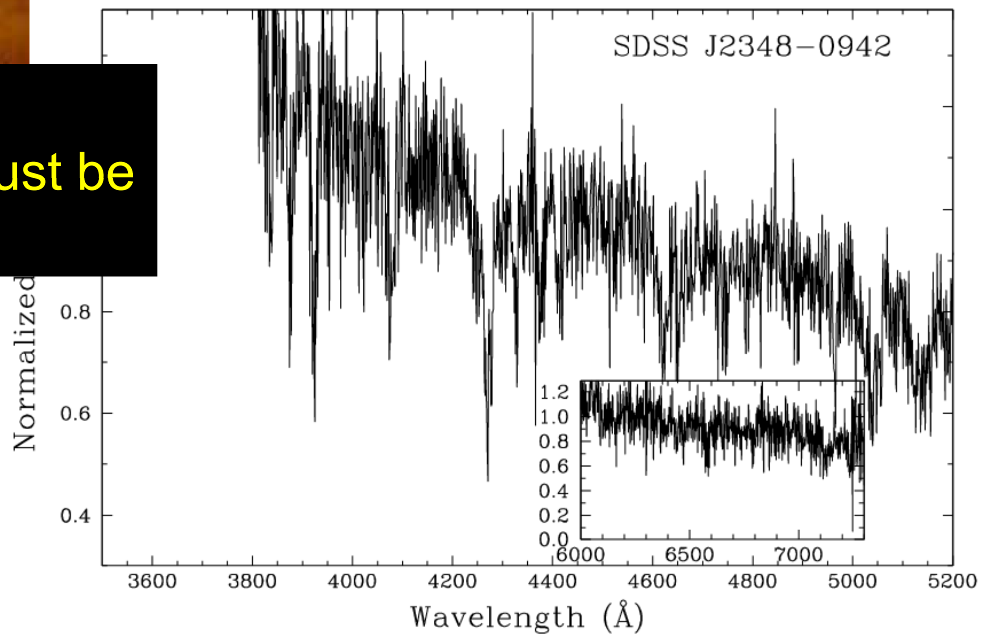


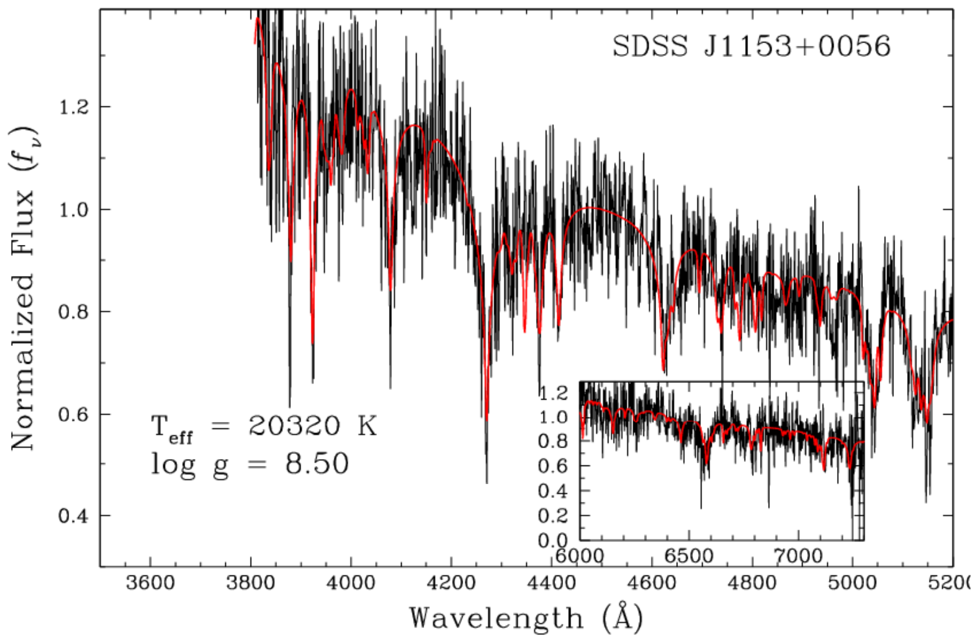
Pure Helium
Log C/He = 0
Log C/He= 1
Pure Carbon
0.0004
0.0003
0.0002
0.0001
0
4000
4500
5000
5500
Wavelength (Å)
F$_\nu$ (erg cm^{-2} s^{-1} Hz^{-1})

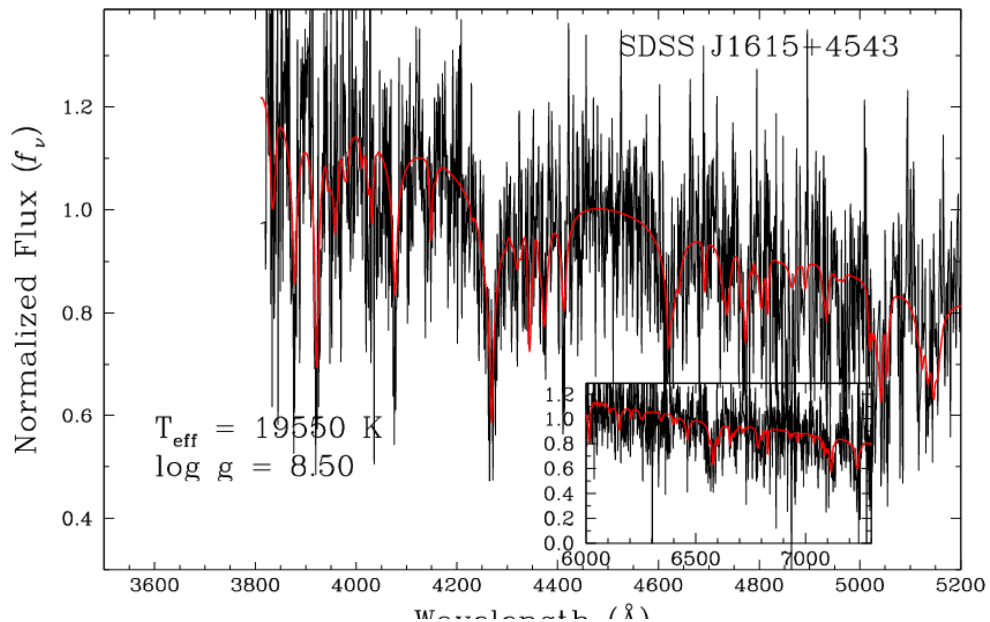


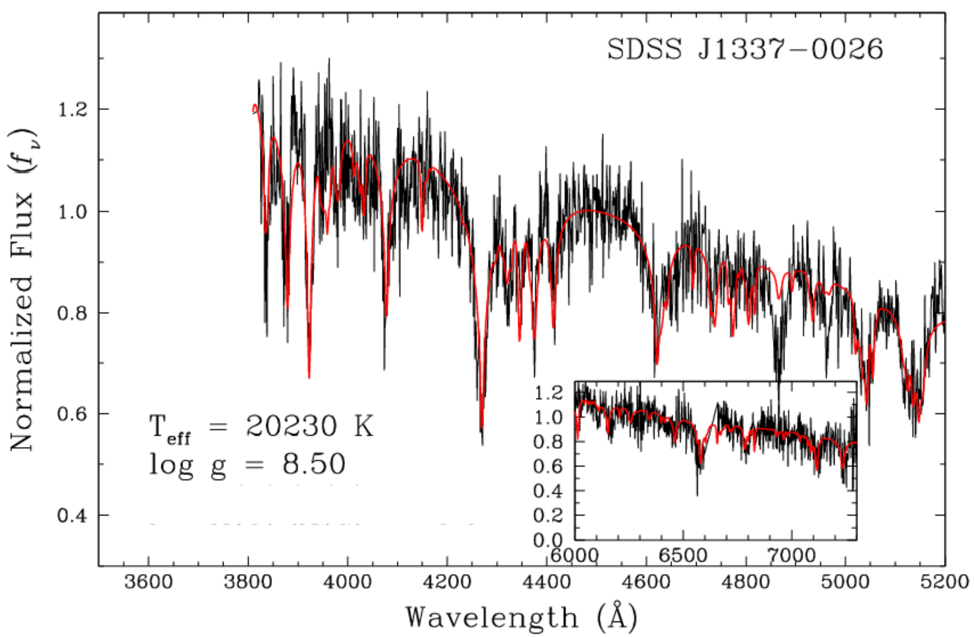
Once you have eliminated the impossible, whatever remains, however improbable, must be the truth.

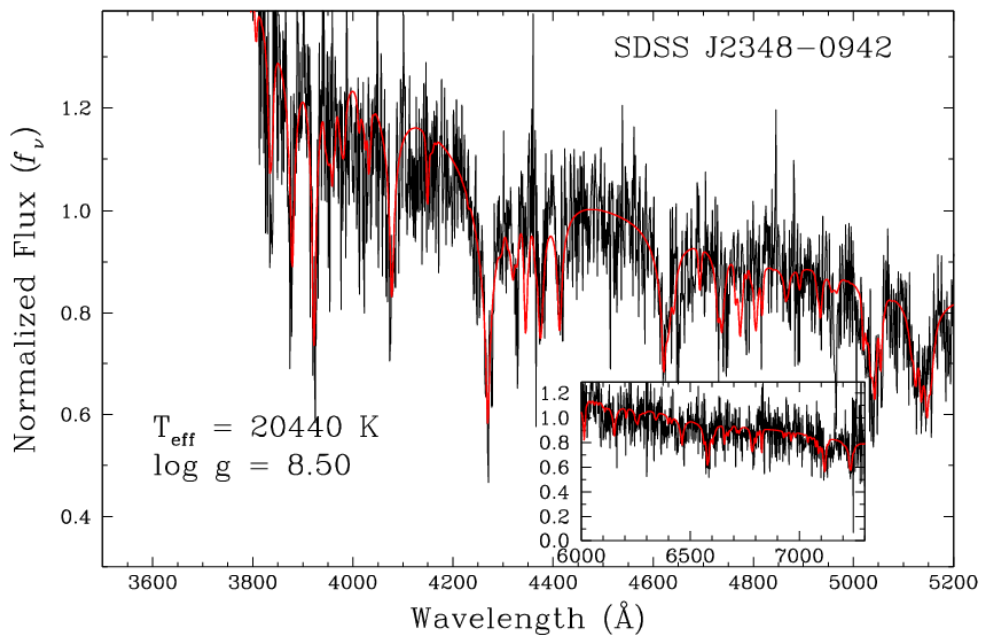


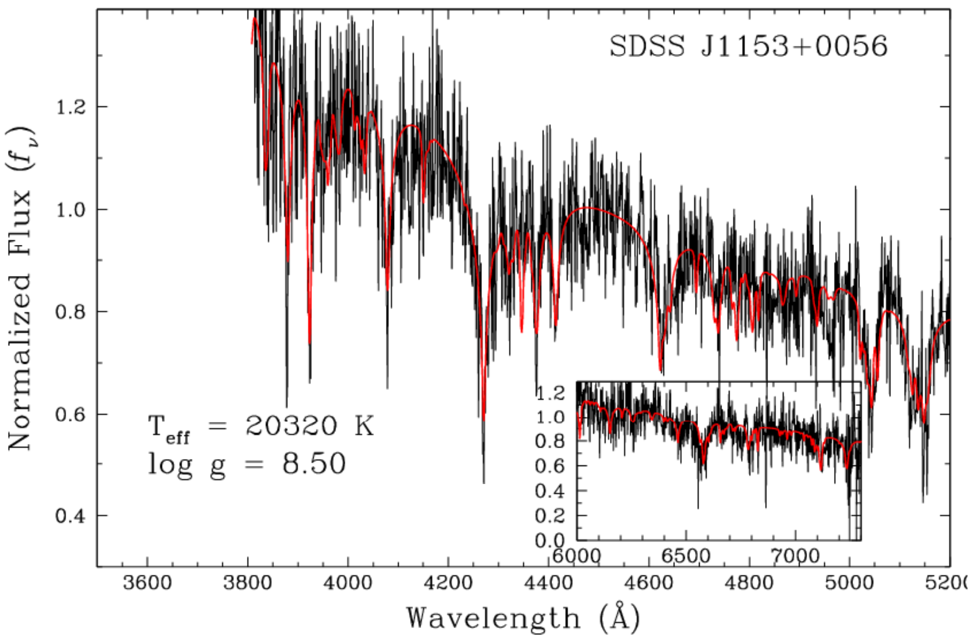


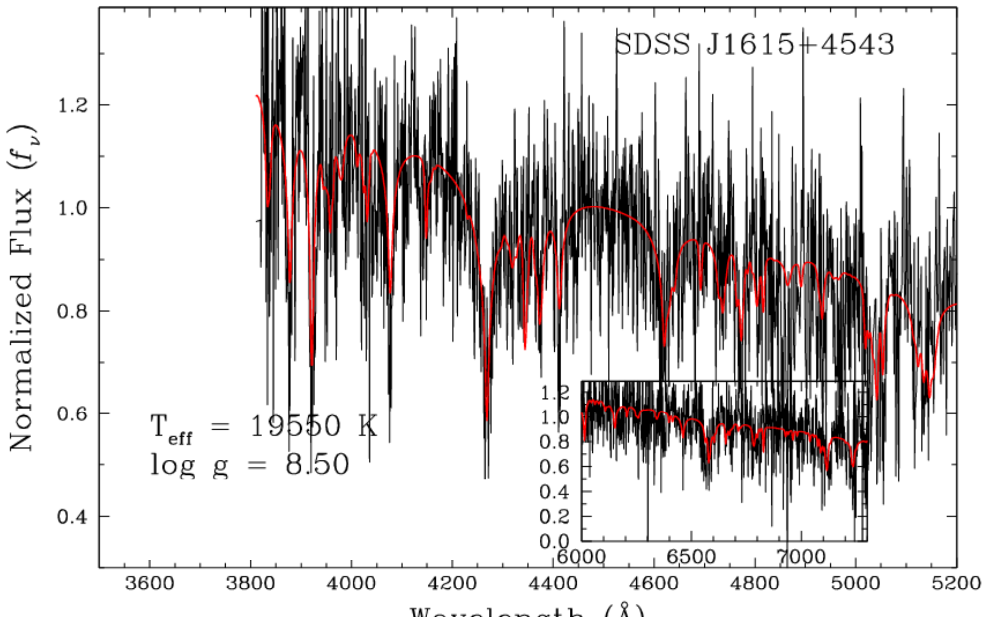

SDSS J1153+0056
Teff = 20320 K
log g = 8.50
Normalized Flux (fν)
Wavelength (Å)

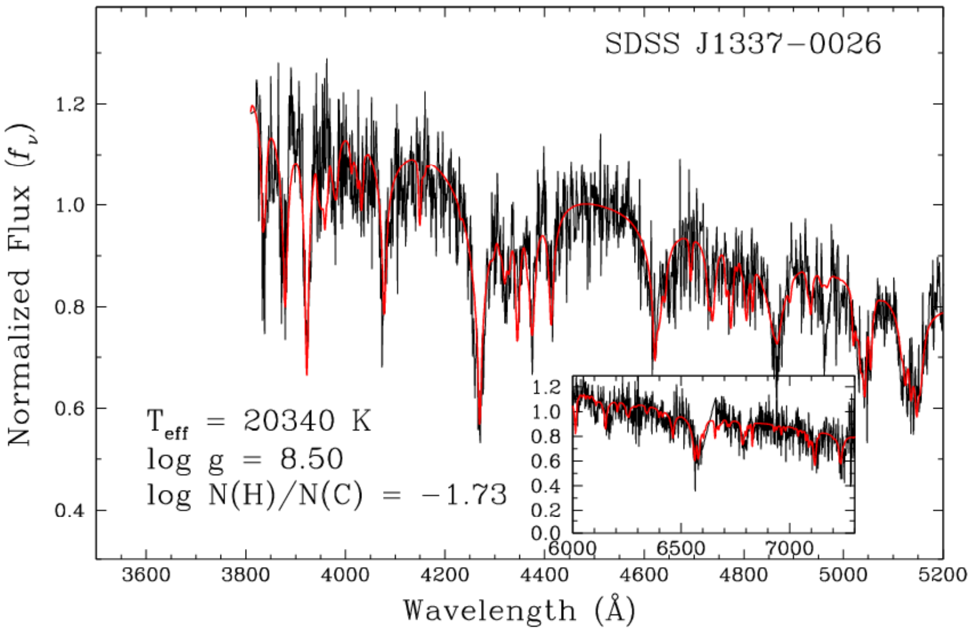

SDSS J1615+4543
Teff = 19550 K
log g = 8.50
Normalized Flux (fν)

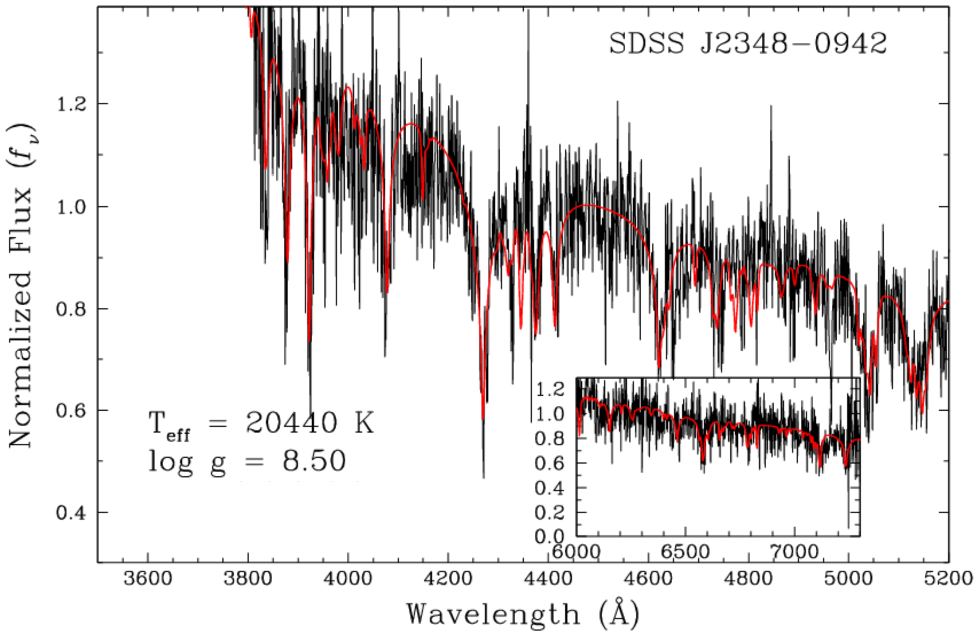

SDSS J1337−0026
Teff = 20230 K
log g = 8.50
Normalized Flux (fν)
Wavelength (Å)


SDSS J2348−0942
Teff = 20440 K
log g = 8.50
Normalized Flux (fν)
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)

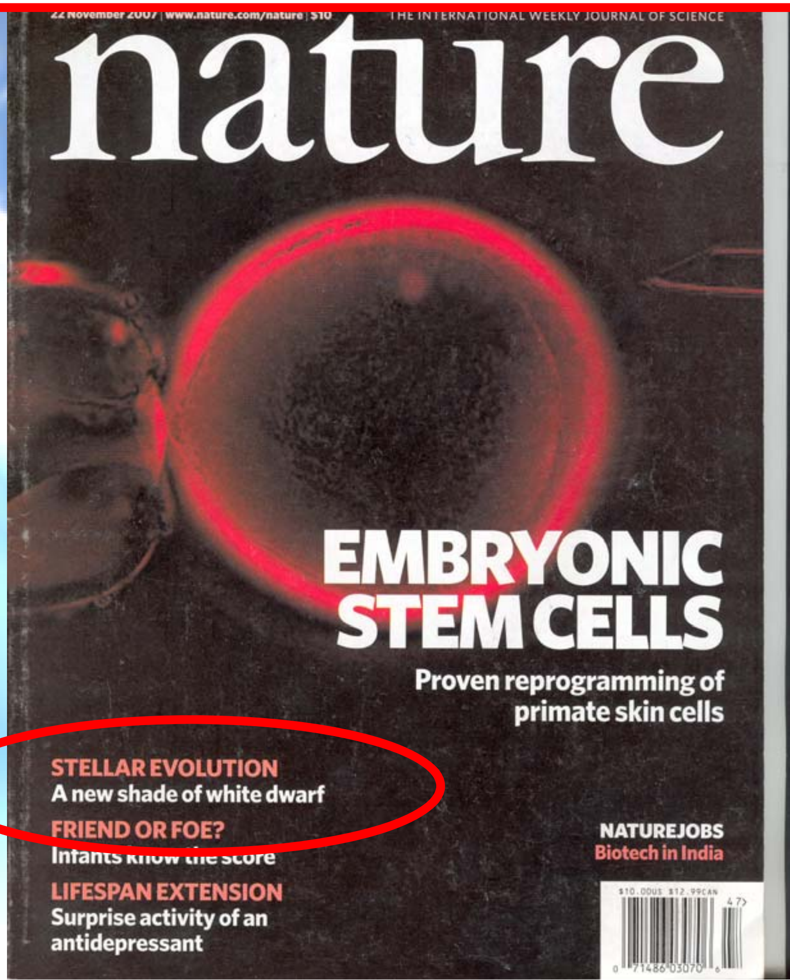
nature

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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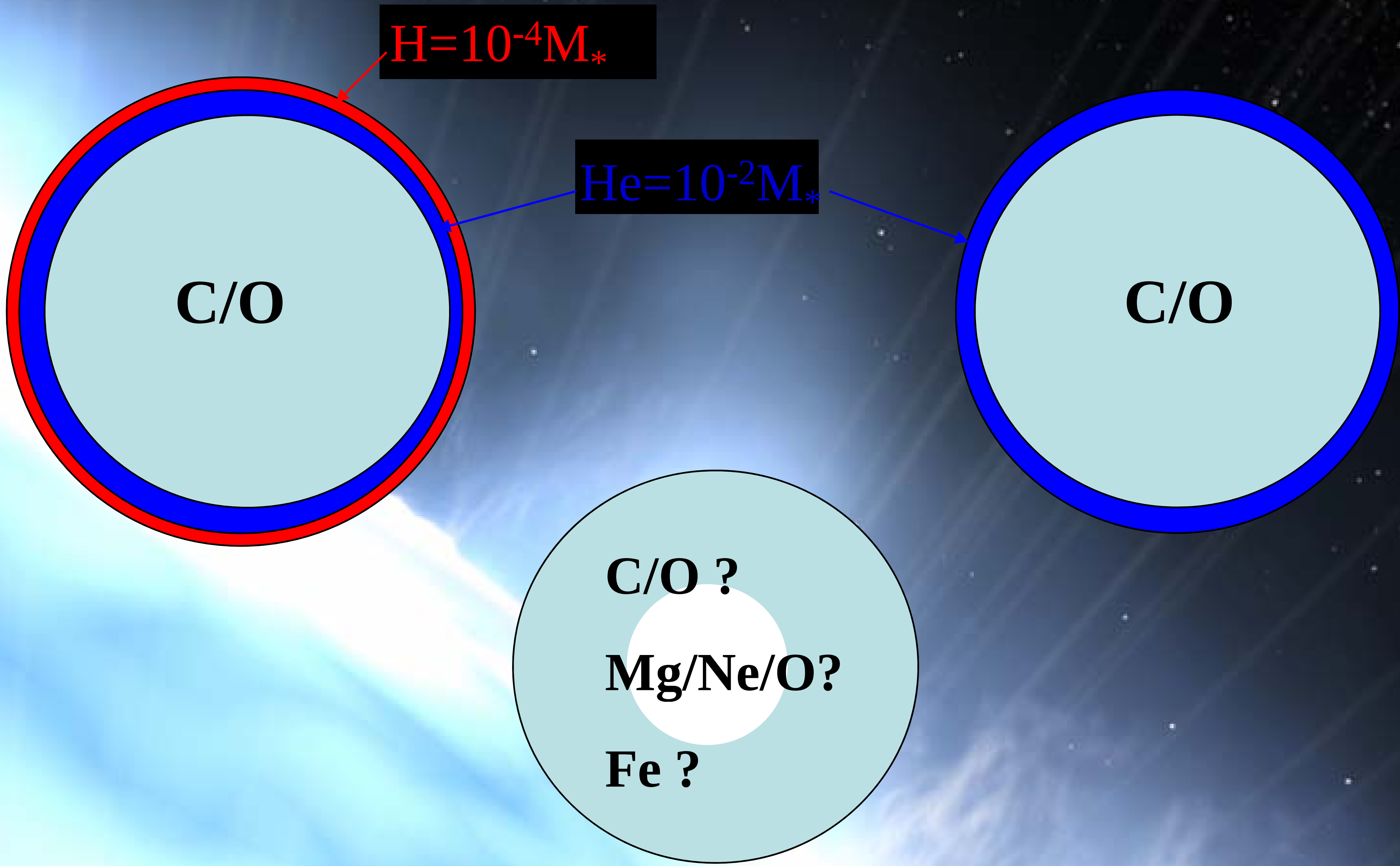
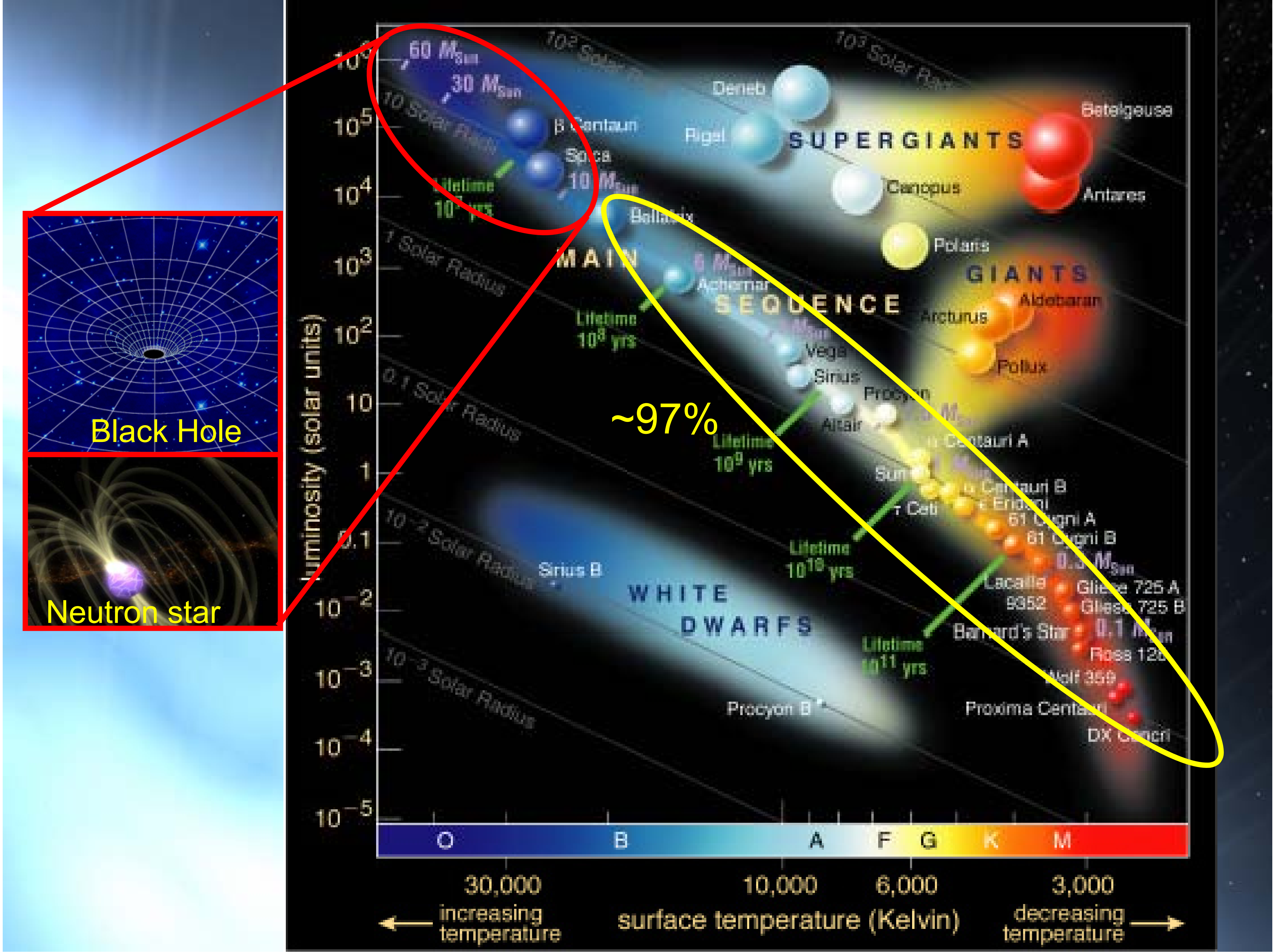
Standard Stellar Evolution Theory




Black Hole
Neutron star
~97%
SUPERGIANTS
GIANTS
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SEQUENCE
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DWARFS
Deneb
Rigel
Betelgeuse
Antares
Canopus
Polaris
Aldebaran
Arcturus
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
60 M_{Sun}
30 M_{Sun}
10 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
10^2 Solar Radii
10^3 Solar Radii
10 Solar Radii
1 Solar Radius
0.1 Solar Radius
10^{-2} Solar Radius
10^{-3} Solar Radius
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
increasing temperature
surface temperature (Kelvin)
decreasing temperature

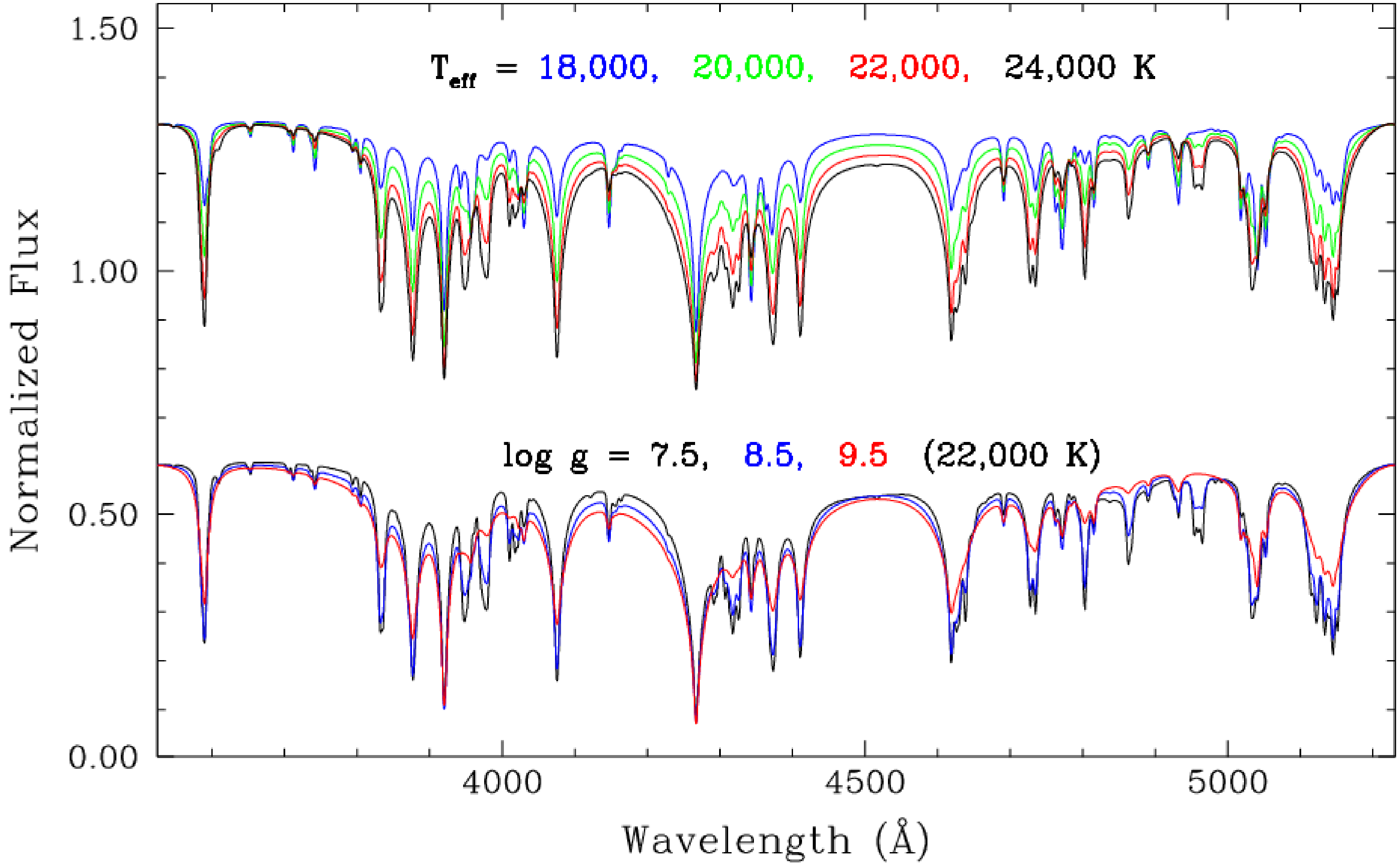
IFMR : Relationship between the progenitor’s mass on MS and the final mass as a white dwarf

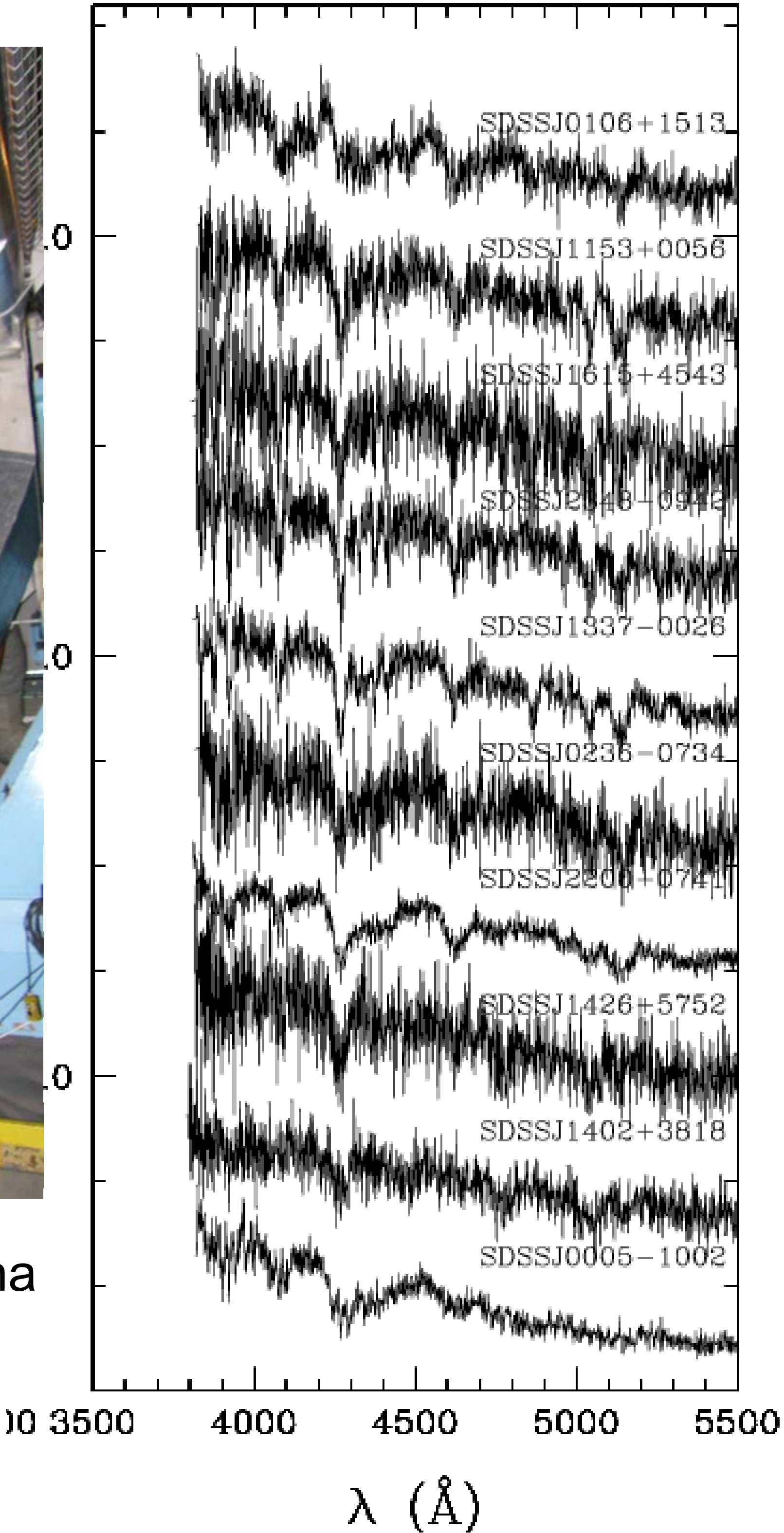
Model Atmosphere Grids

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)

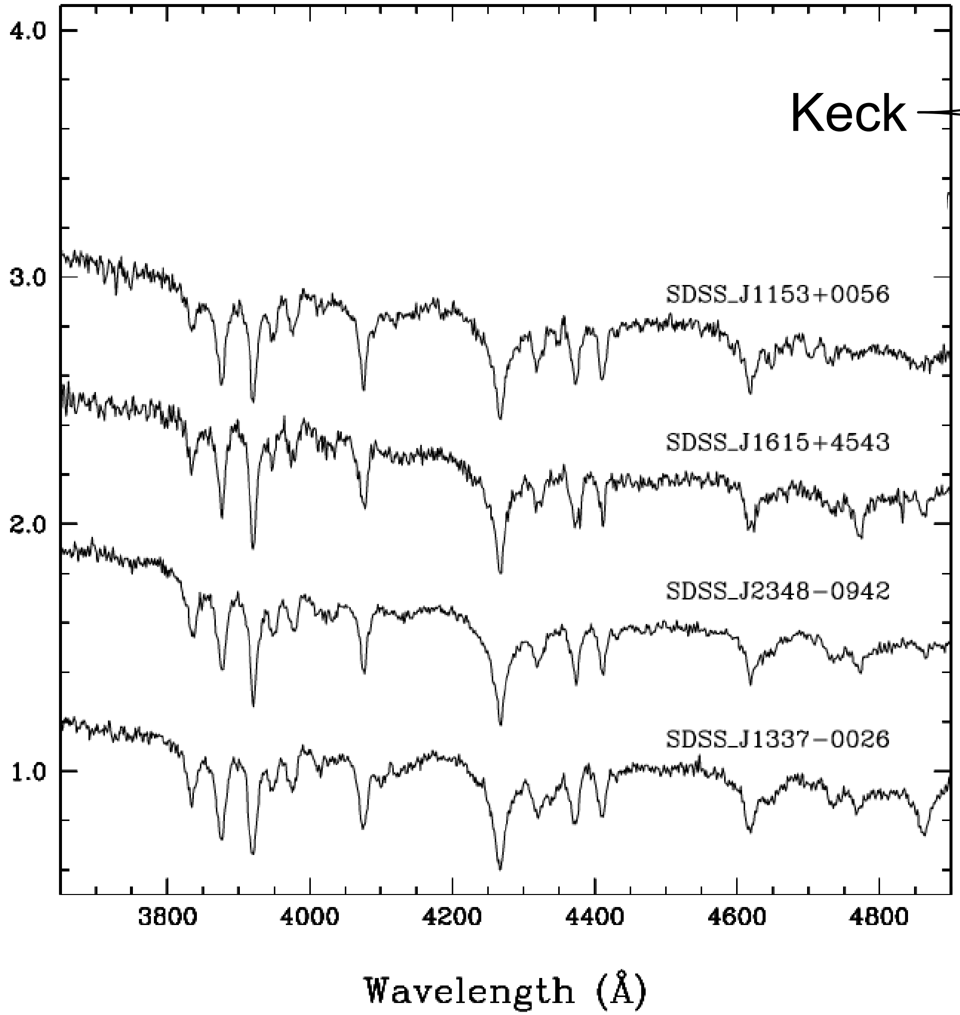


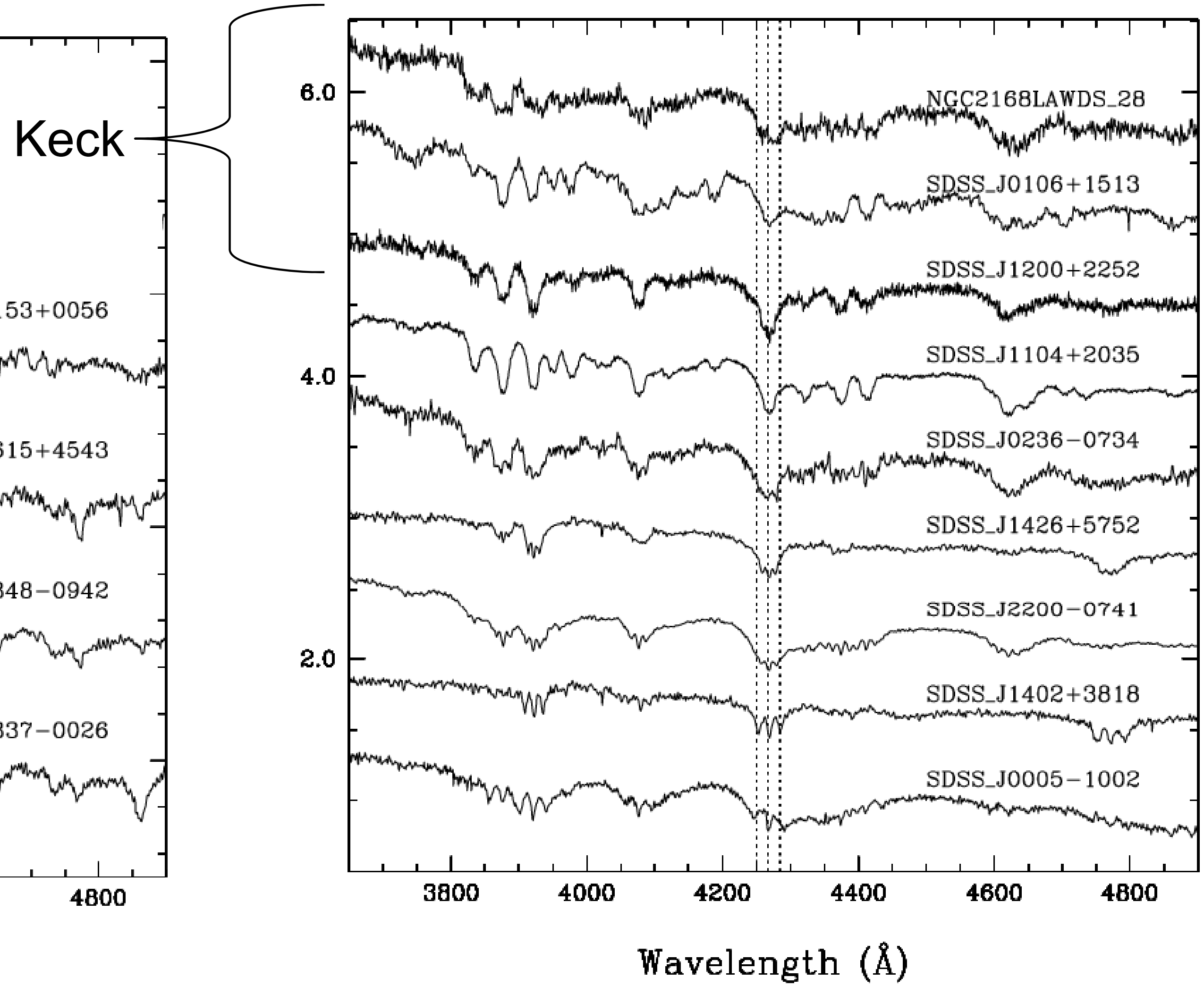


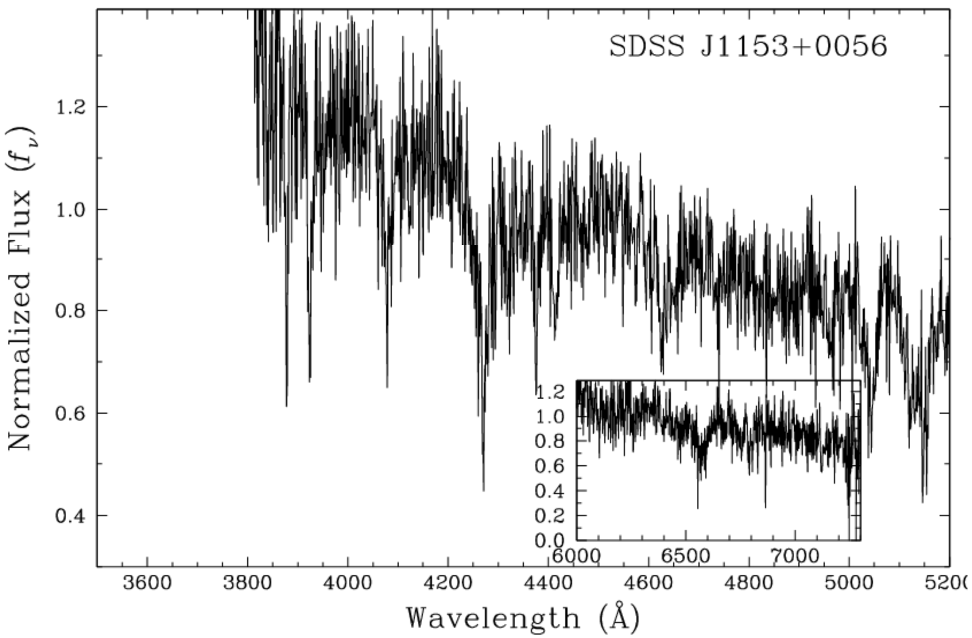
MMT (6.5 m), Mont Hopkins, Arizona

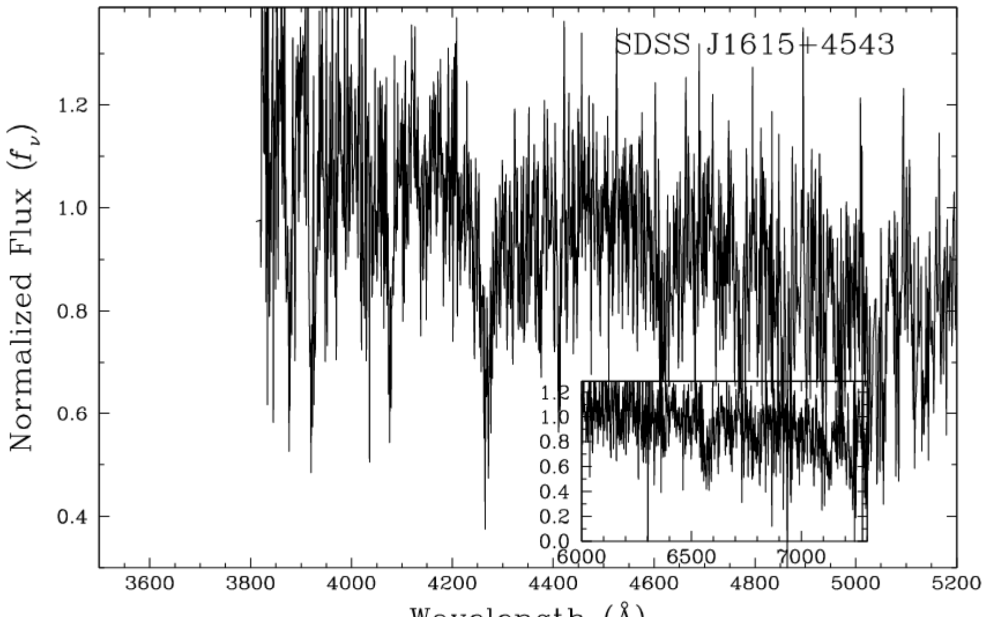
(10 nights)

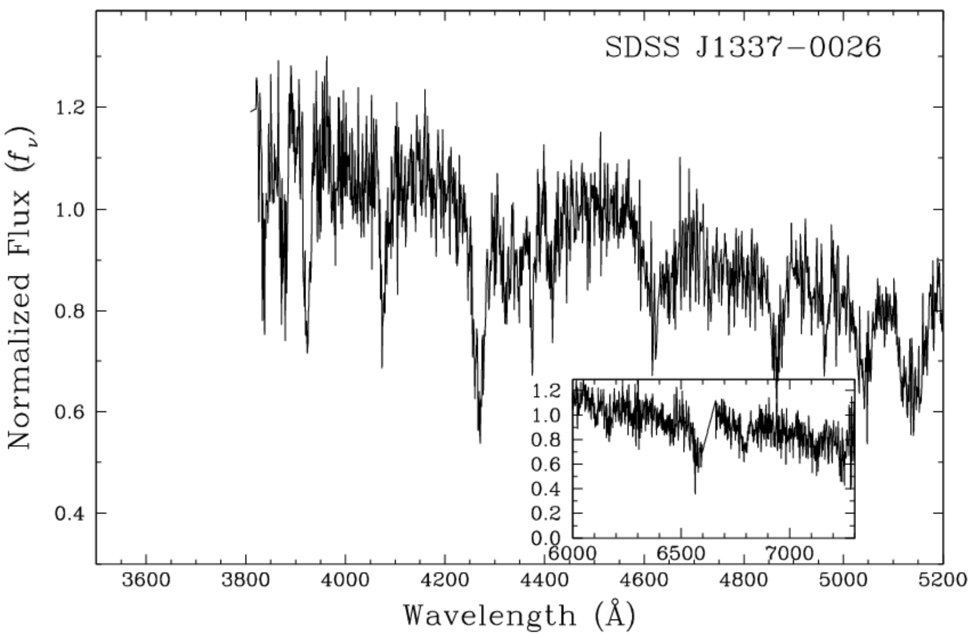
14 carbon atmosphere White Dwarfs known (out of ~30,000 catalogued WD)

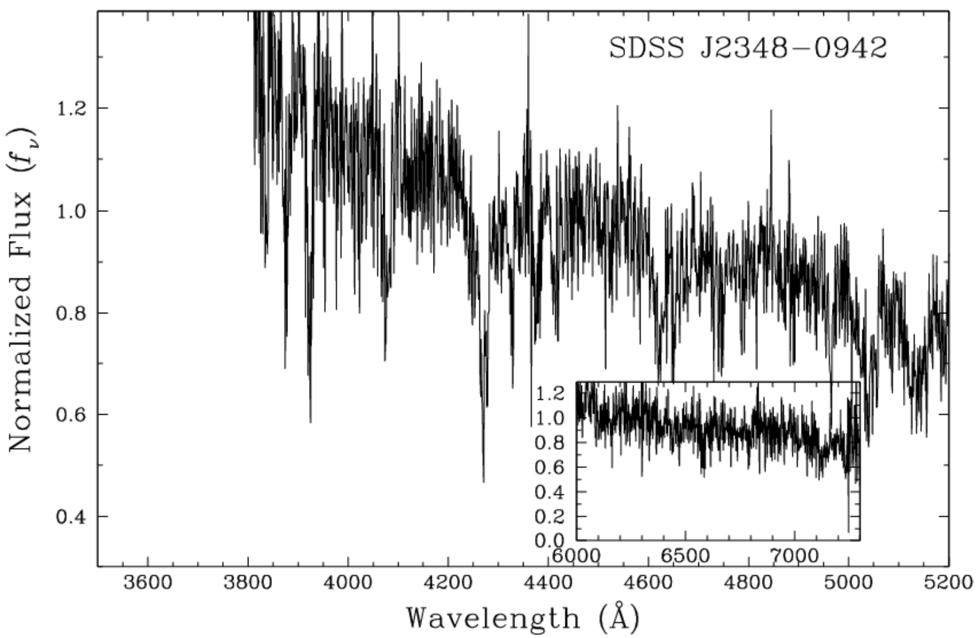





SDSS J1153+0056
Normalized Flux (f_ν)
Wavelength (Å)


SDSS J1615+4543
Normalized Flux (f_ν)


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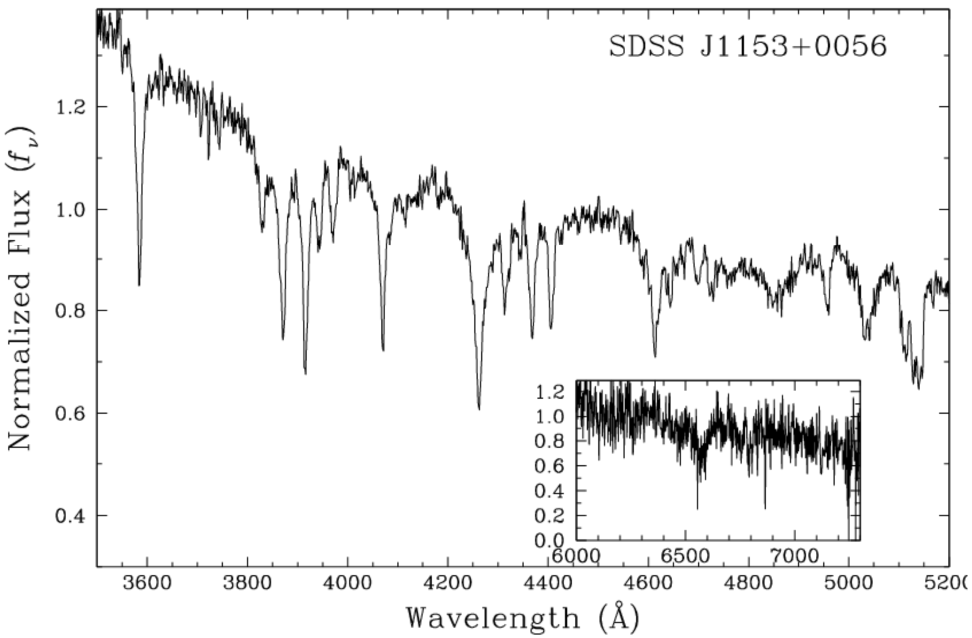
Normalized Flux (f_ν)
Wavelength (Å)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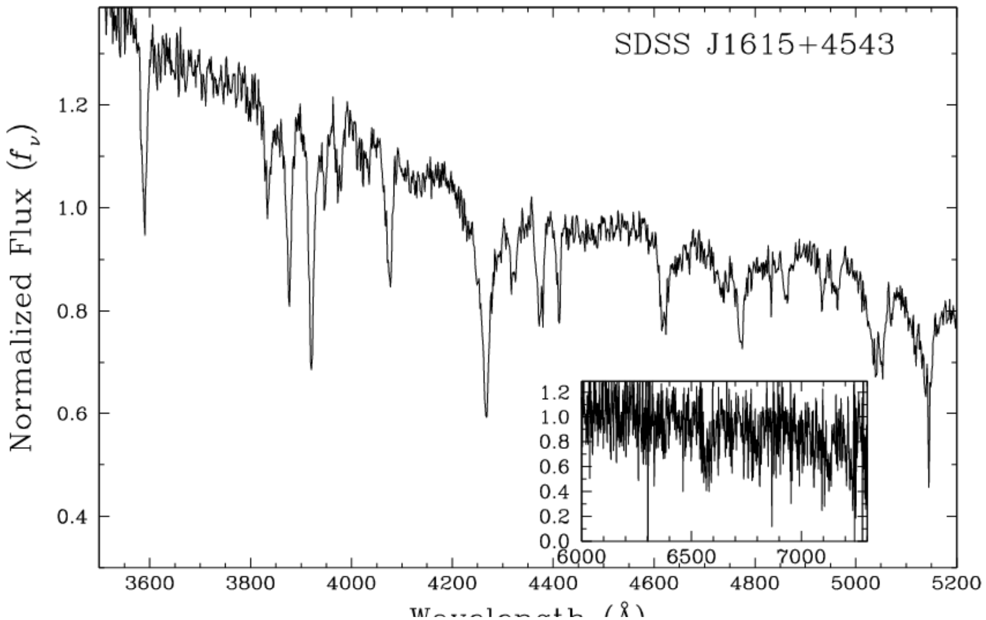
Normalized Flux (f_ν)
Wavelength (Å)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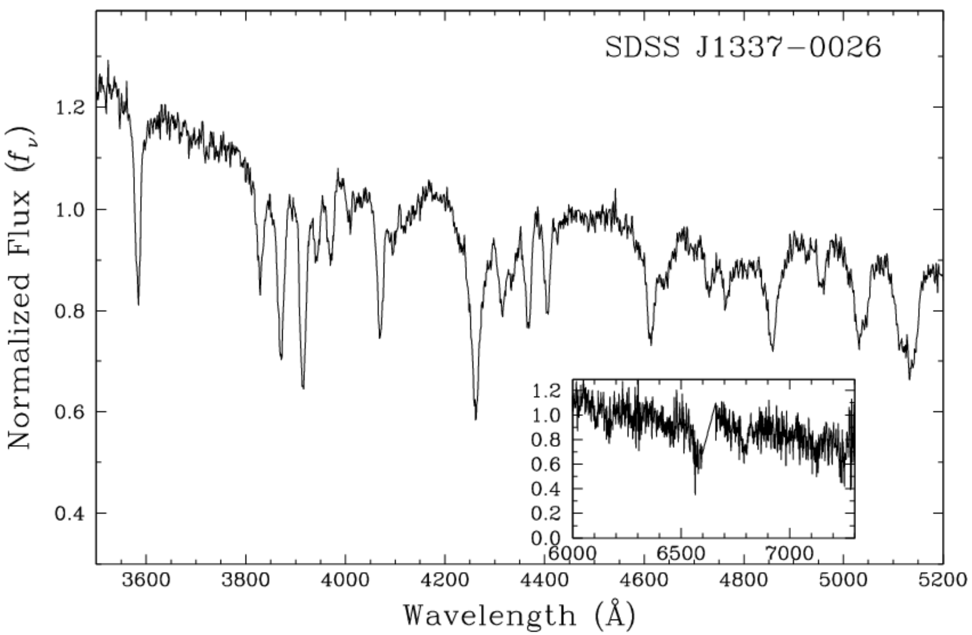
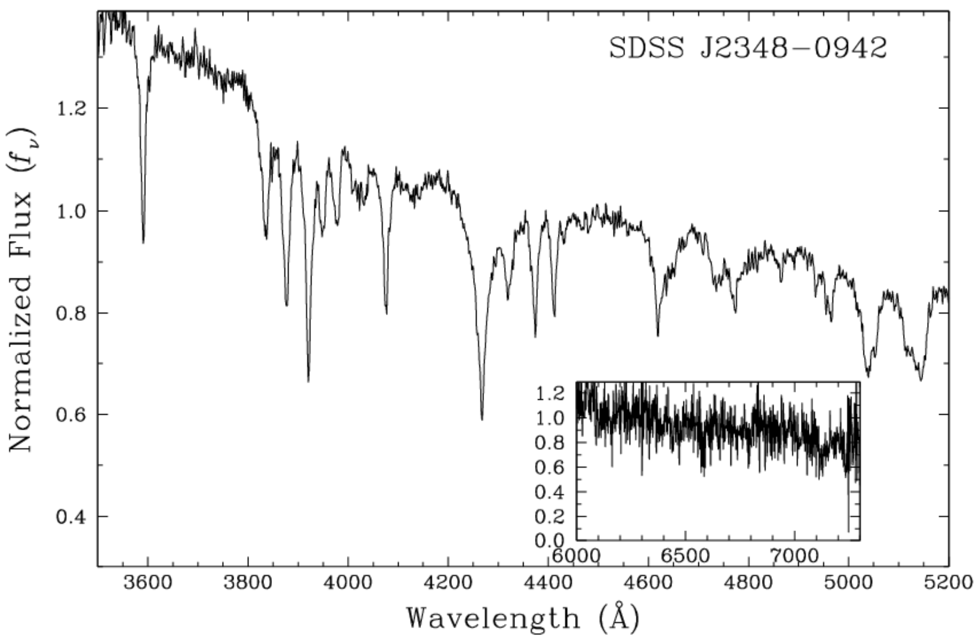
Normalized Flux (f_ν)


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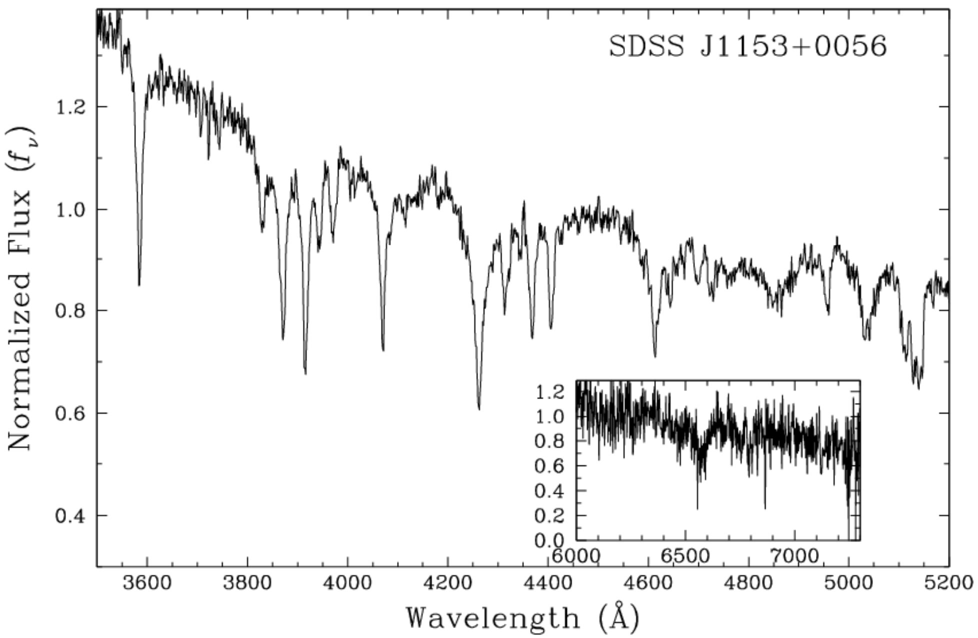
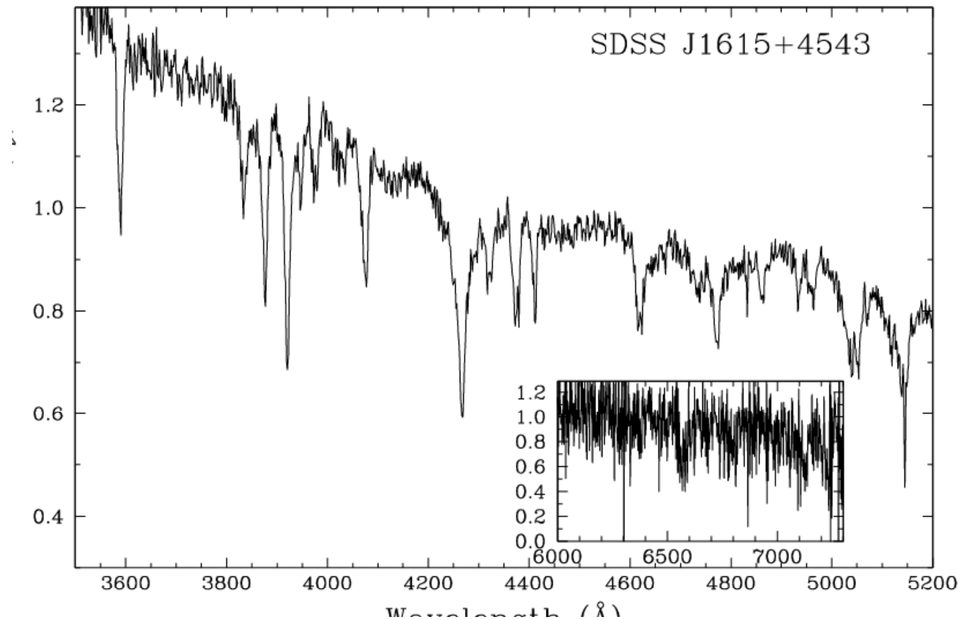
Normalized Flux (f_ν)
Wavelength (Å)


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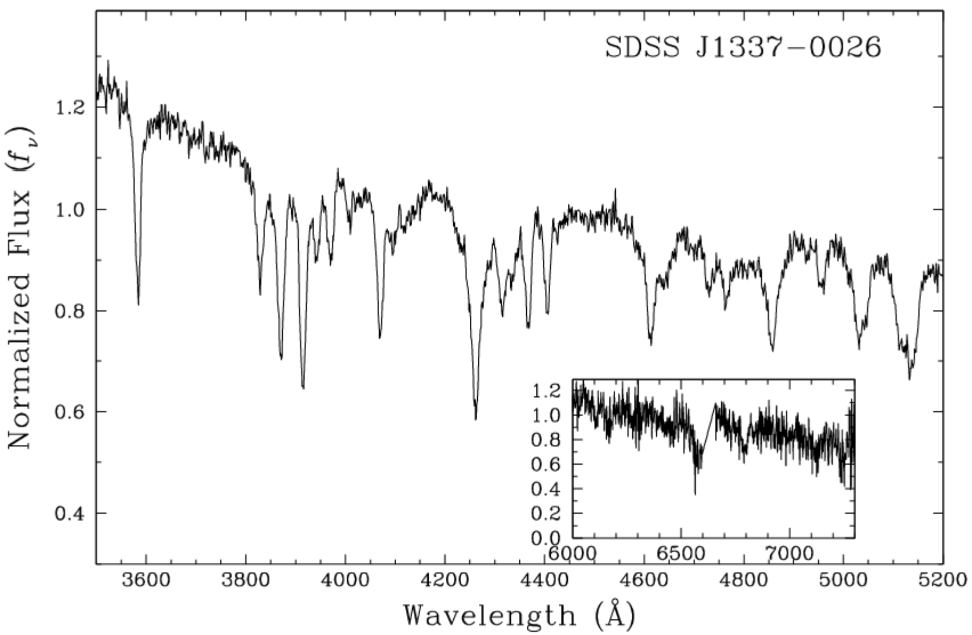
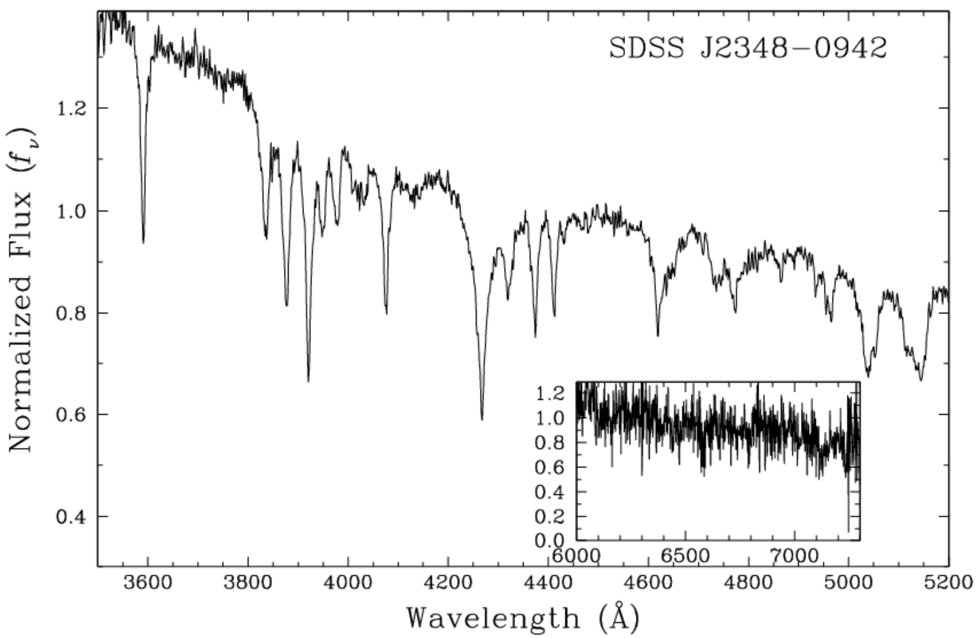

SDSS J1337−0026
Normalized Flux (f_ν)
Wavelength (Å)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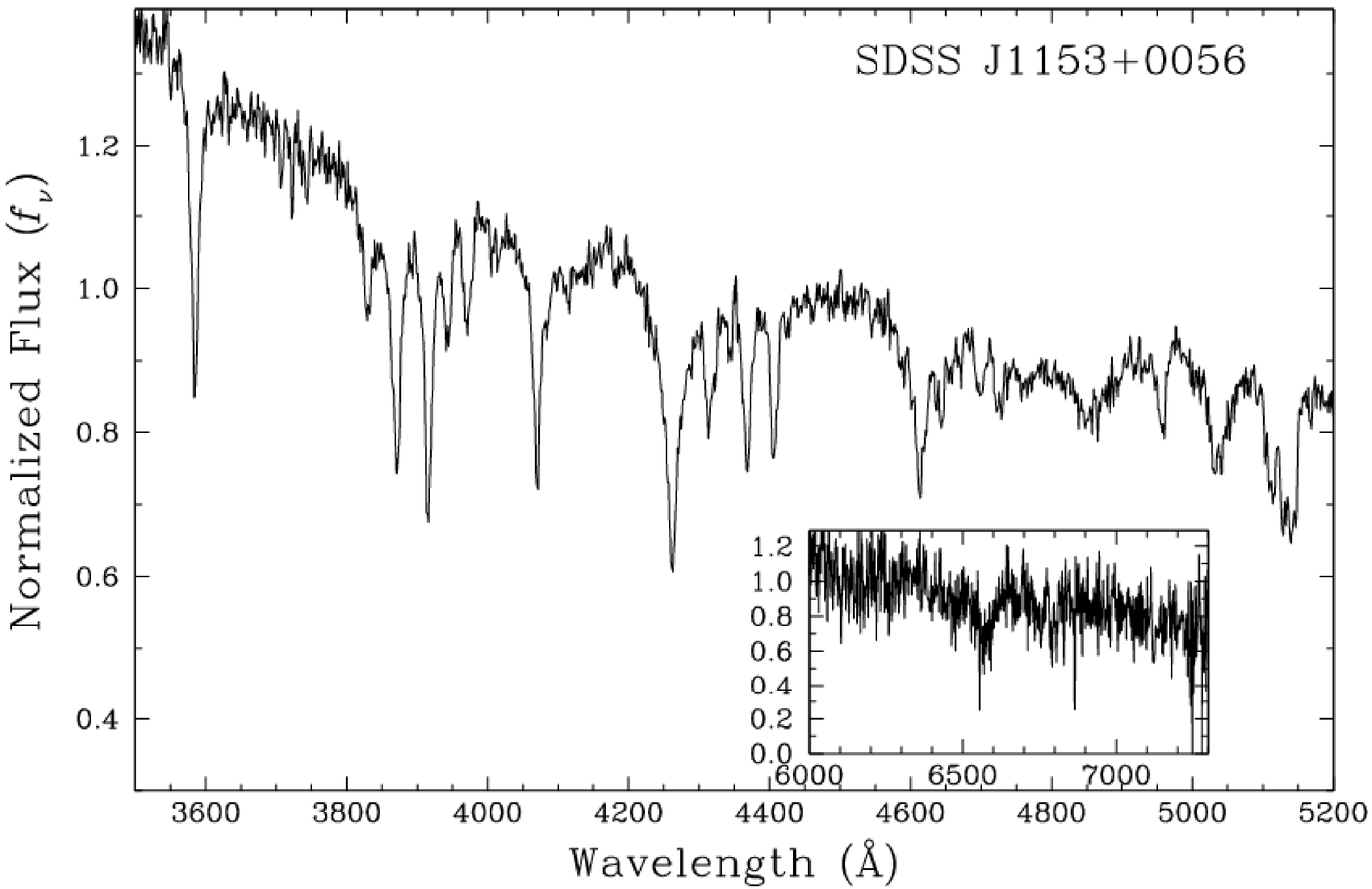
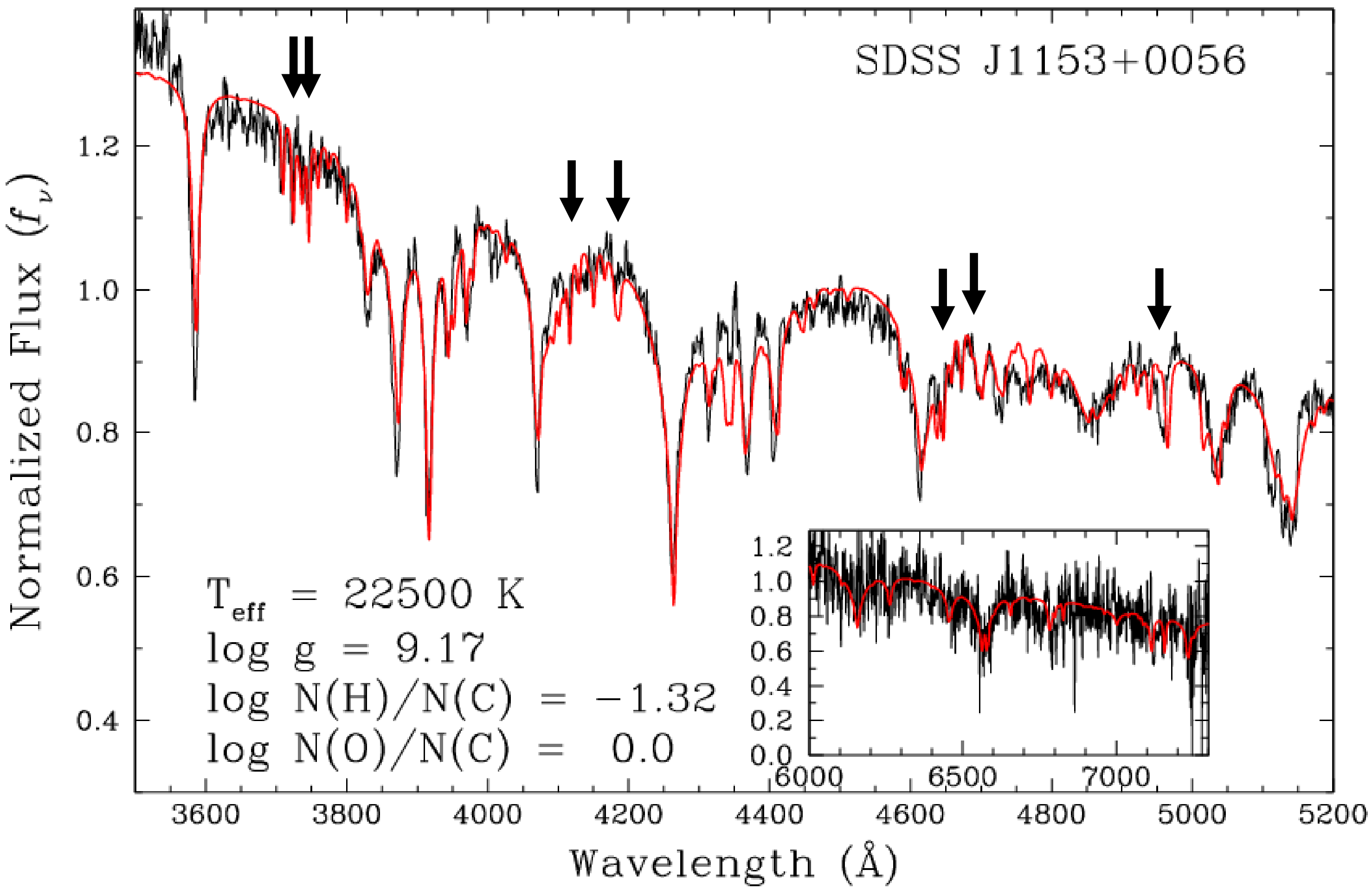
Normalized Flux (f_ν)
Wavelength (Å)


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
1.2
1.0
0.8
0.6
0.4
3600
3800
4000
4200
4400
4600
4800
5000
5200
0.0
0.2
6000
6500
7000

Stark Damping Constant

In collaboration wit

Sylvie Sahal-Br

Milan S. Dimitri

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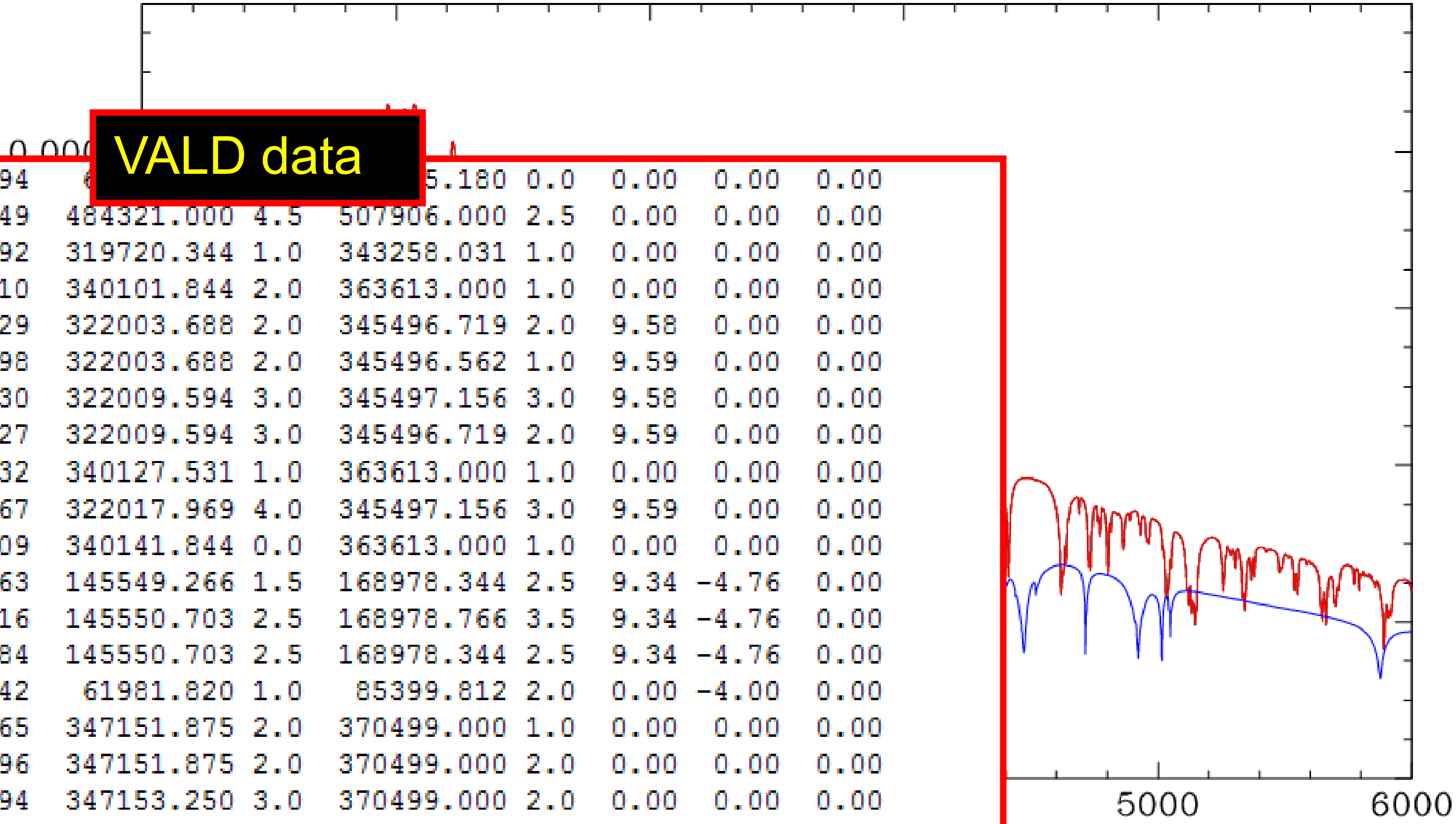
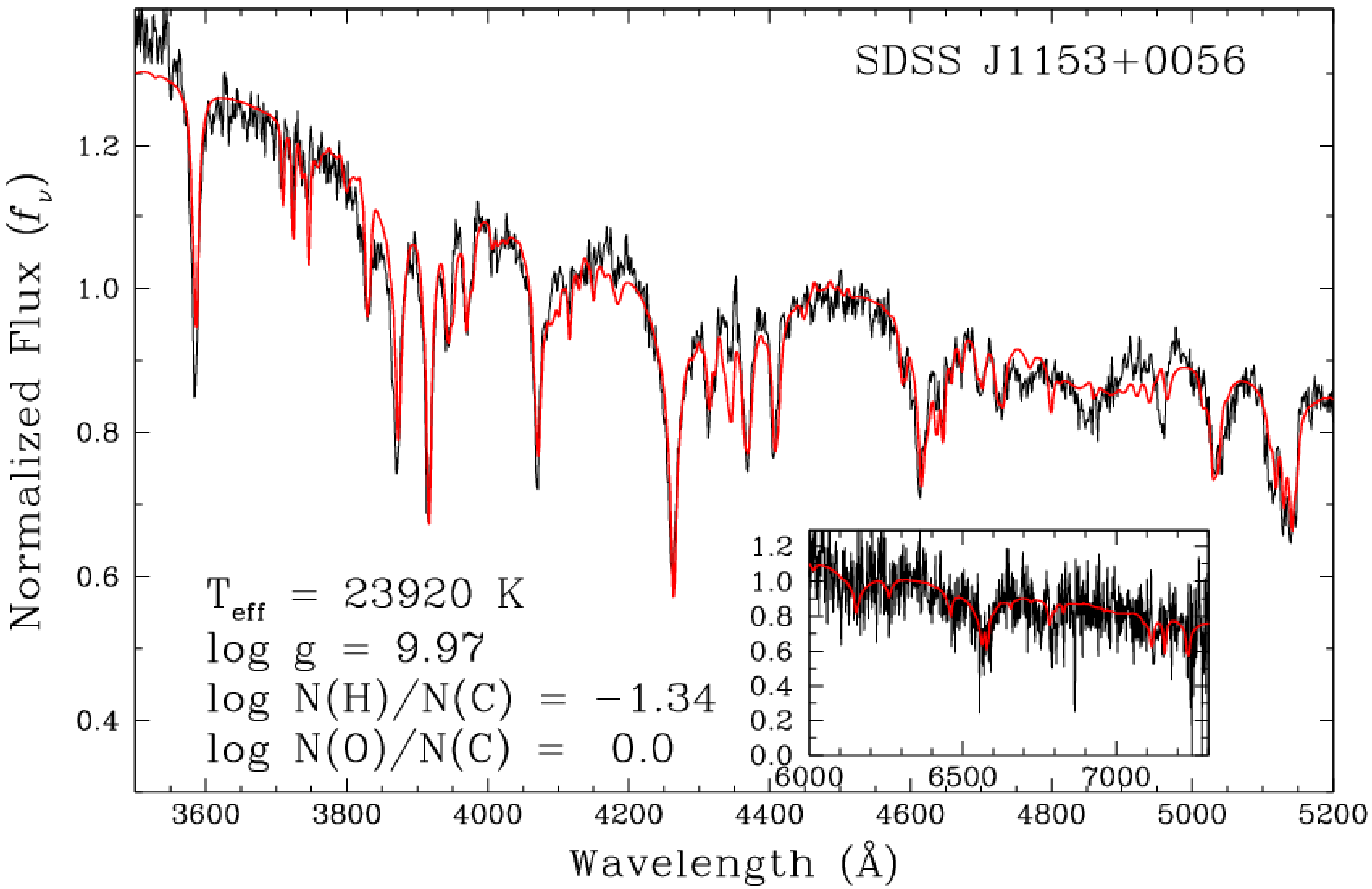
$$\int H_\nu \, d\nu = \sigma T_{eff}^4 / 4\pi$$



VALD data

4228.3262	6.00	-2.794	6		…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


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
1.2
1.0
0.8
0.6
0.4
3600
3800
4000
4200
4400
4600
4800
5000
5200
6000
6500
7000

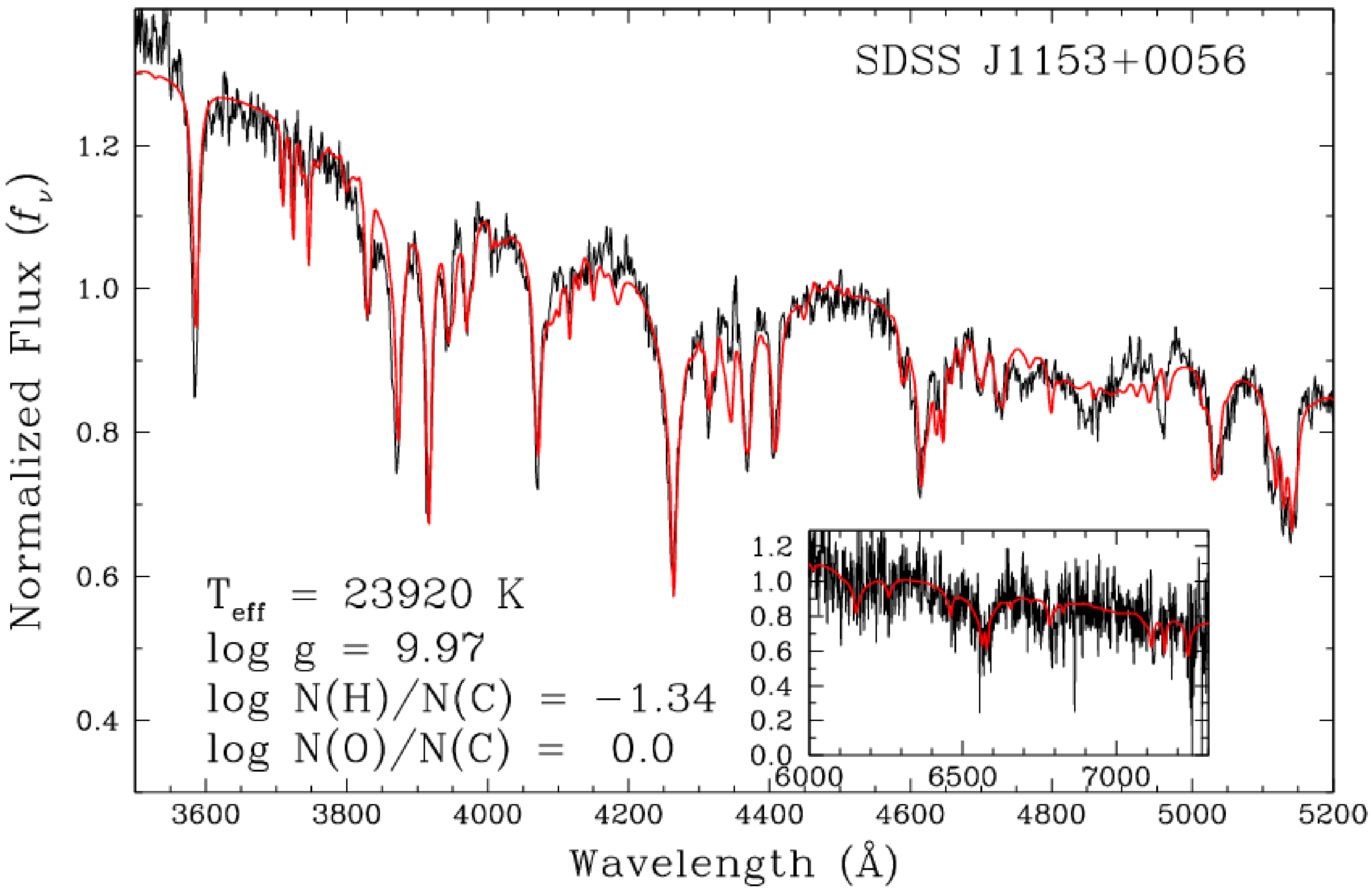
Log g max (Salpeter T=0)

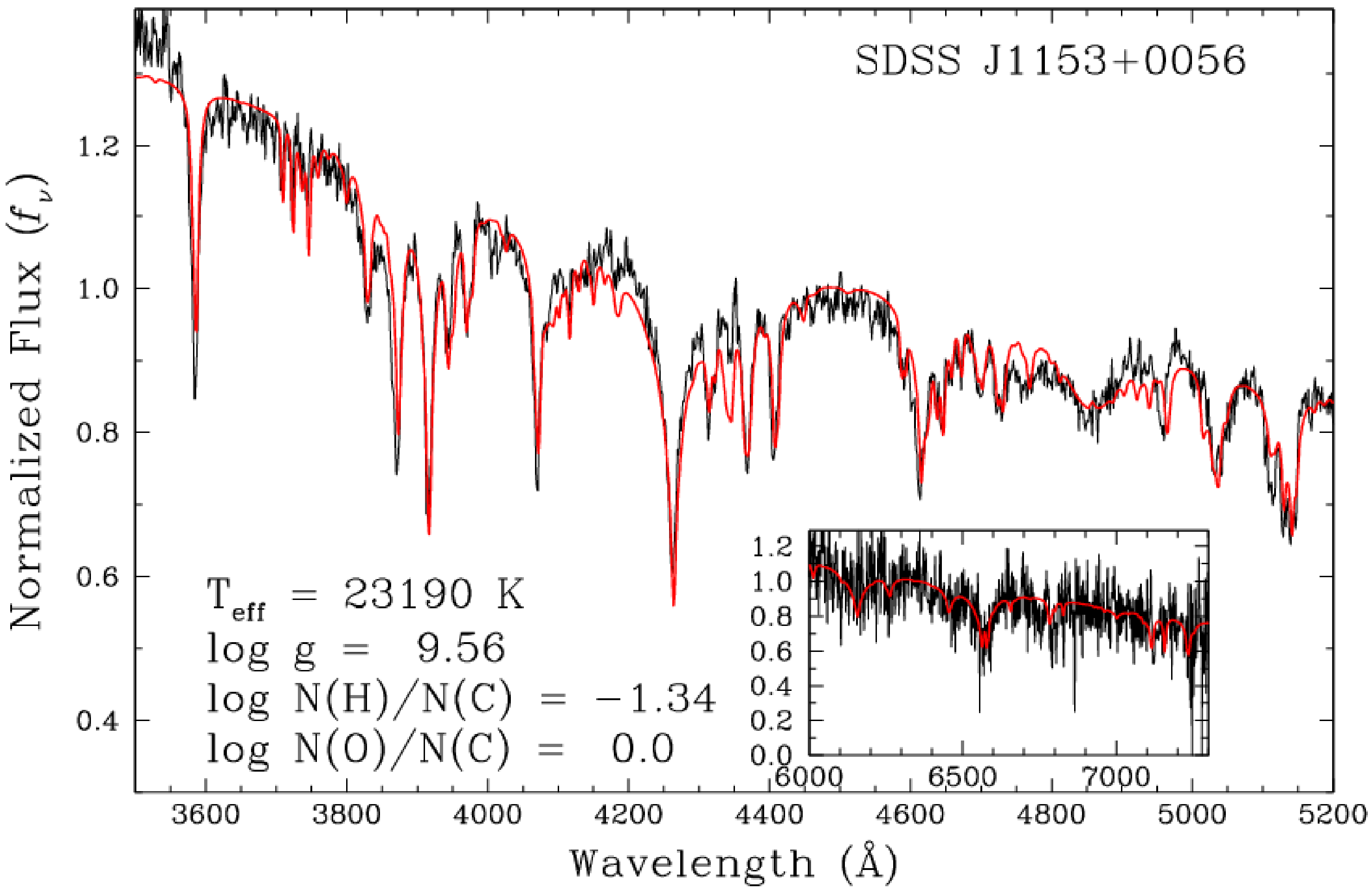
(1961, ApJ, 134, 669)

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

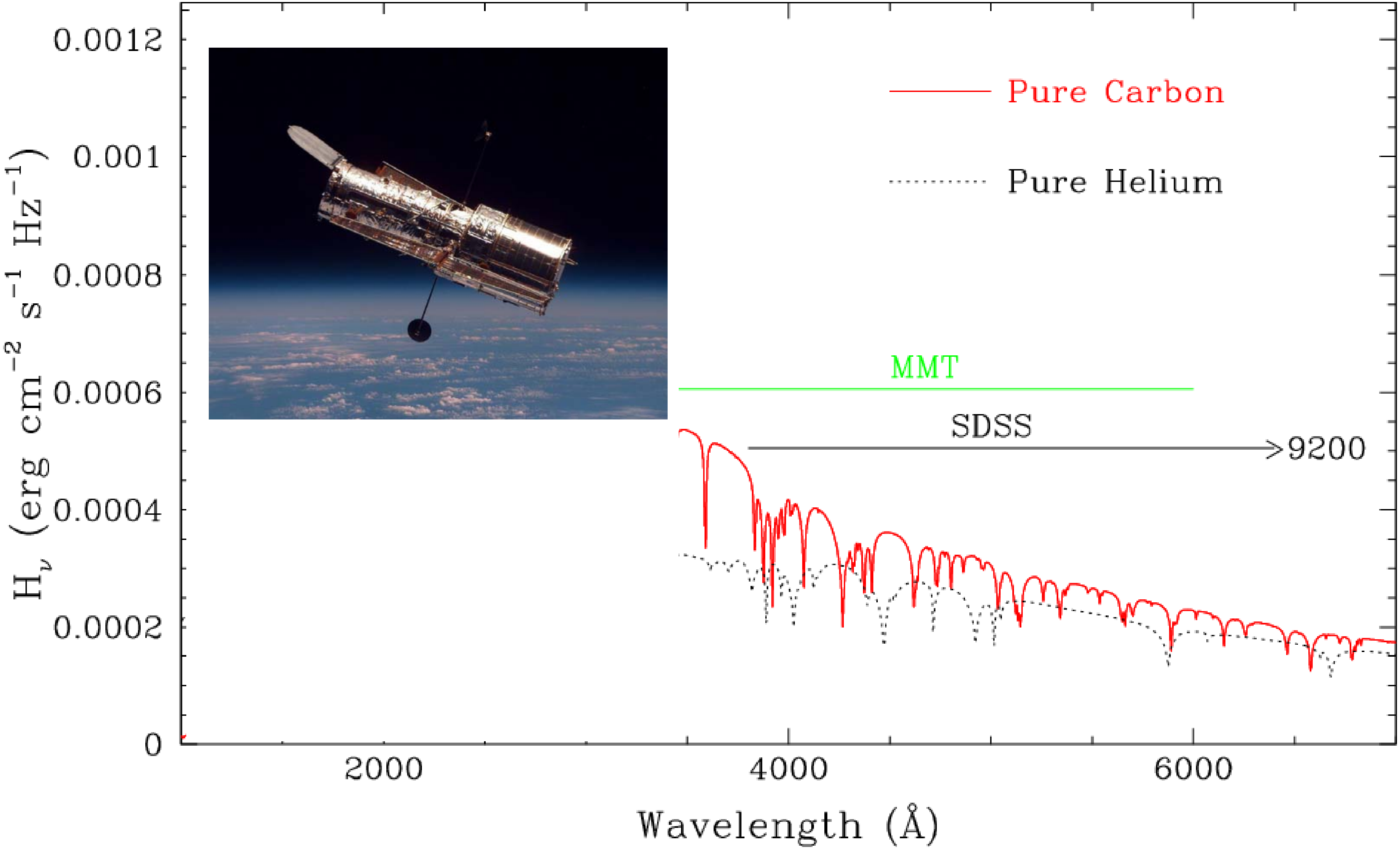

SDSS J1153+0056
Normalized Flux (f_ν)
Wavelength (Å)
T_{eff} = 23920 K
log g = 9.97
log N(H)/N(C) = −1.34
log N(O)/N(C) = 0.0



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

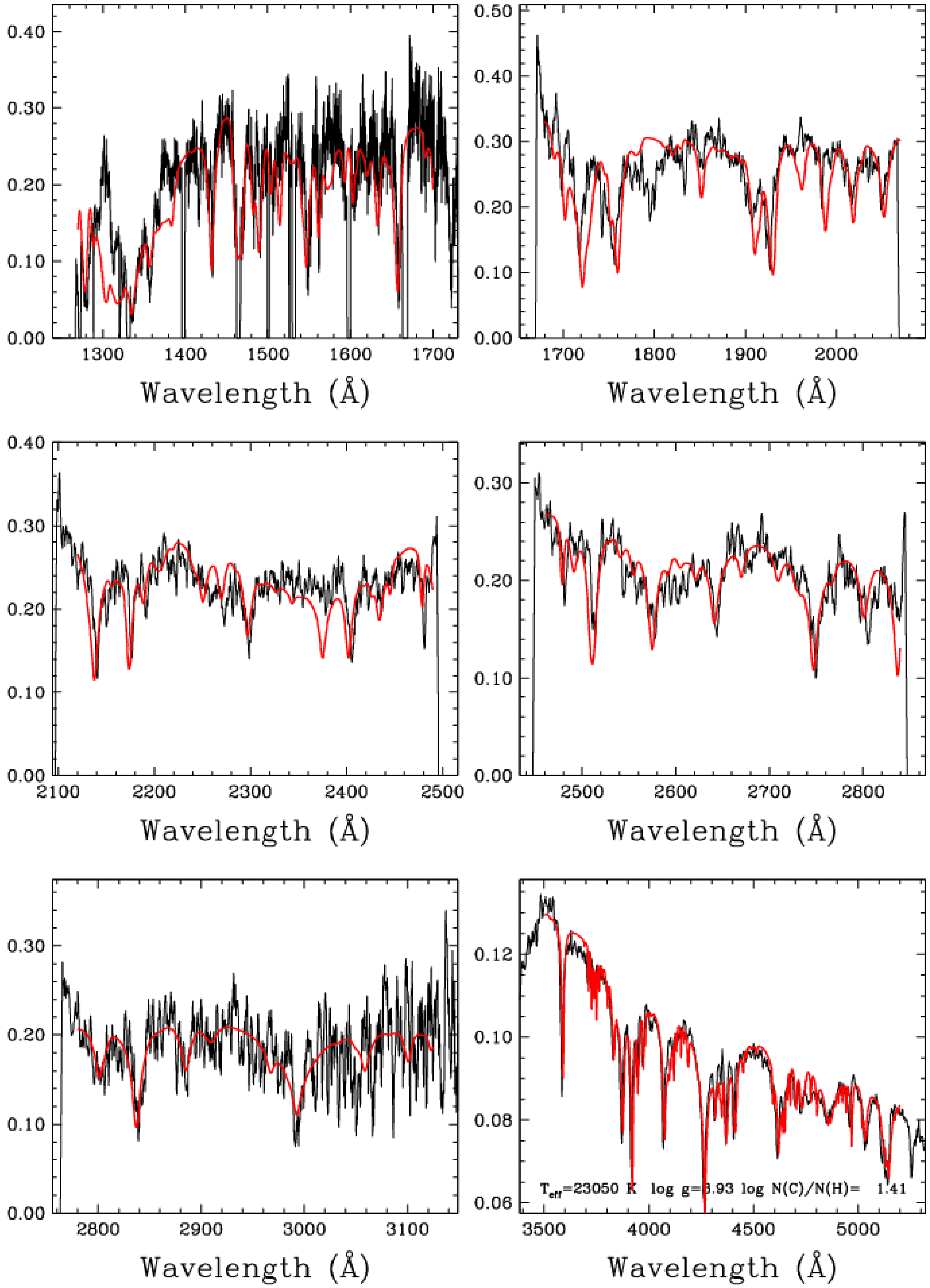
Outline

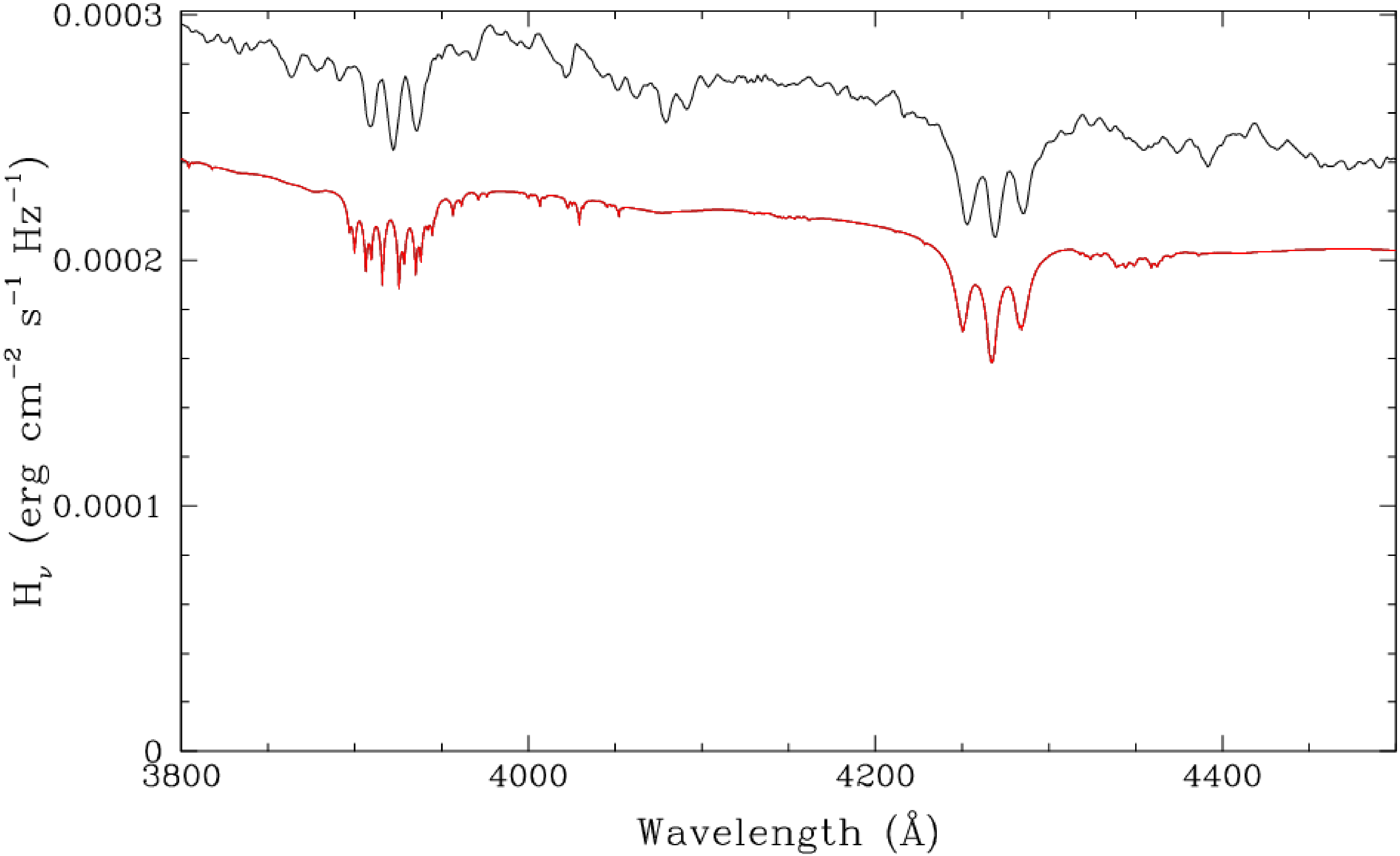
- A brief introduction: stellar evolution and white dwarf stars
- Carbon (and oxygen) in white dwarf stars
  - white dwarfs with traces of carbon
  - carbon dominated atmosphere white dwarfs
  - Future research directions
- Planets and abundance determinations
  - white dwarfs with traces of metals



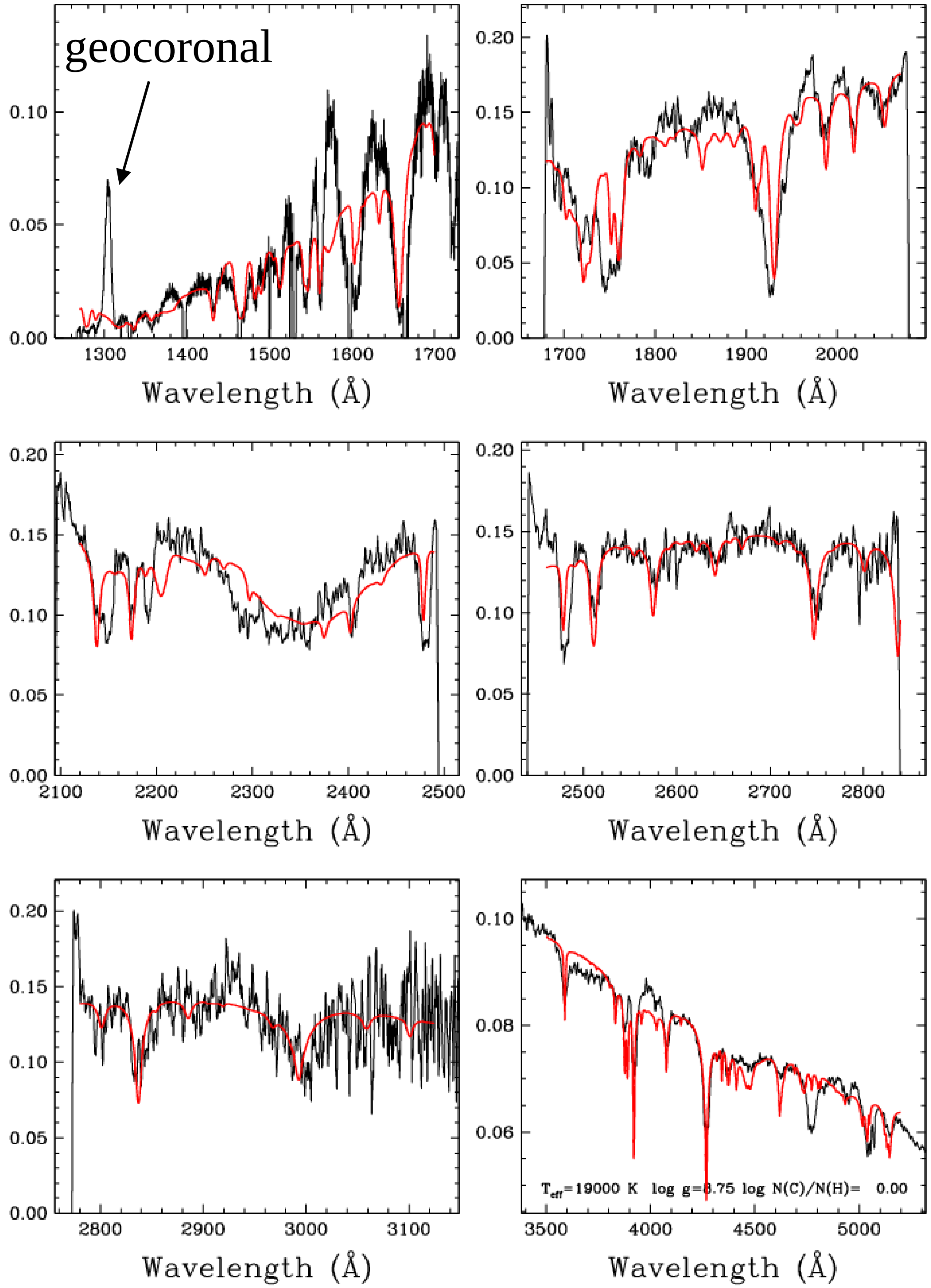
Pure Carbon
Pure Helium
MMT
SDSS
>9200
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
2000
4000
6000
Wavelength (Å)
H_ν (erg cm^{-2} s^{-1} Hz^{-1})

SDSS J1153+0056

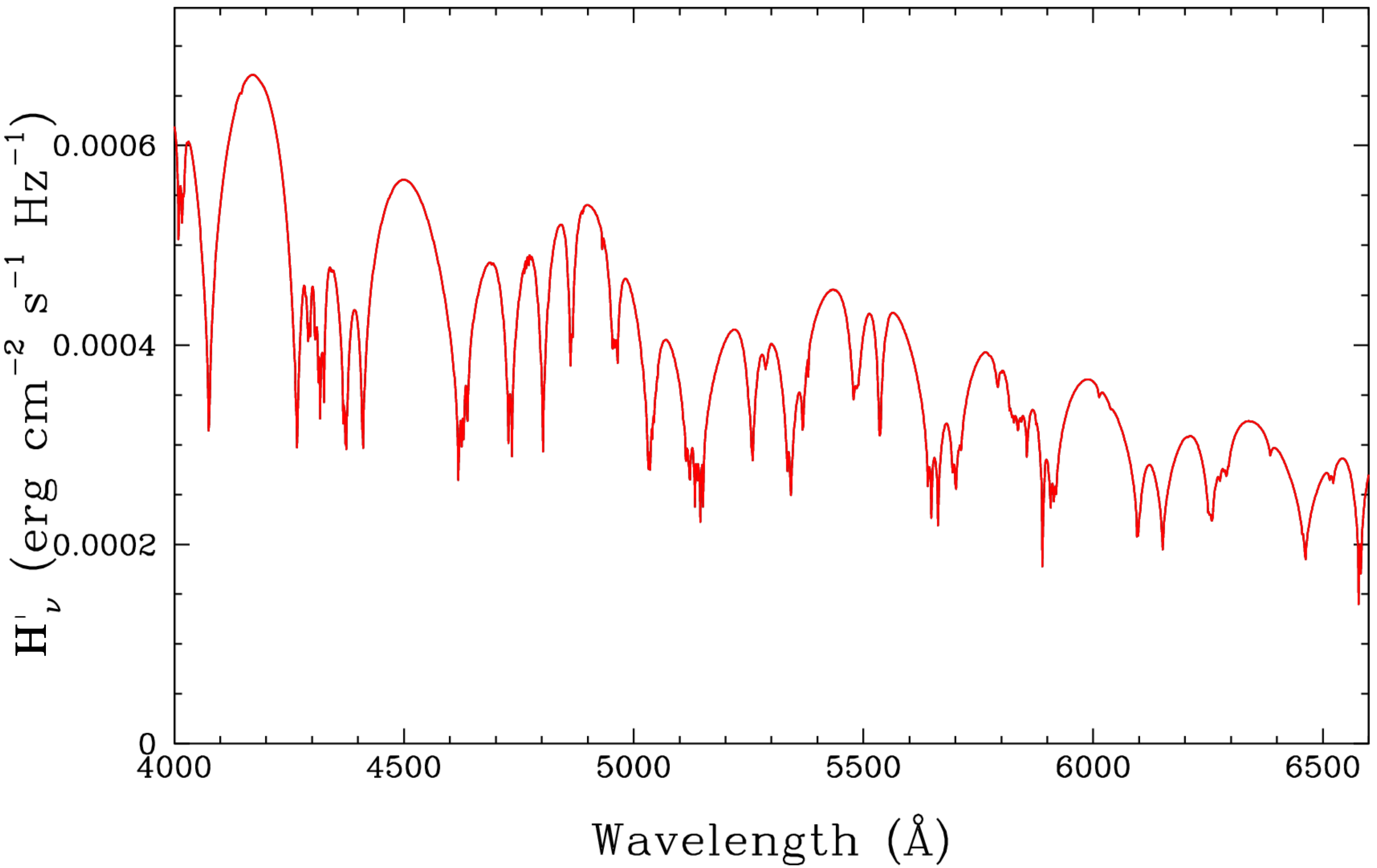



0.0003
0.0002
0.0001
0
3800
4000
4200
4400
H_ν (erg cm^{-2} s^{-1} Hz^{-1})
Wavelength (Å)

SDSS J1426+5752

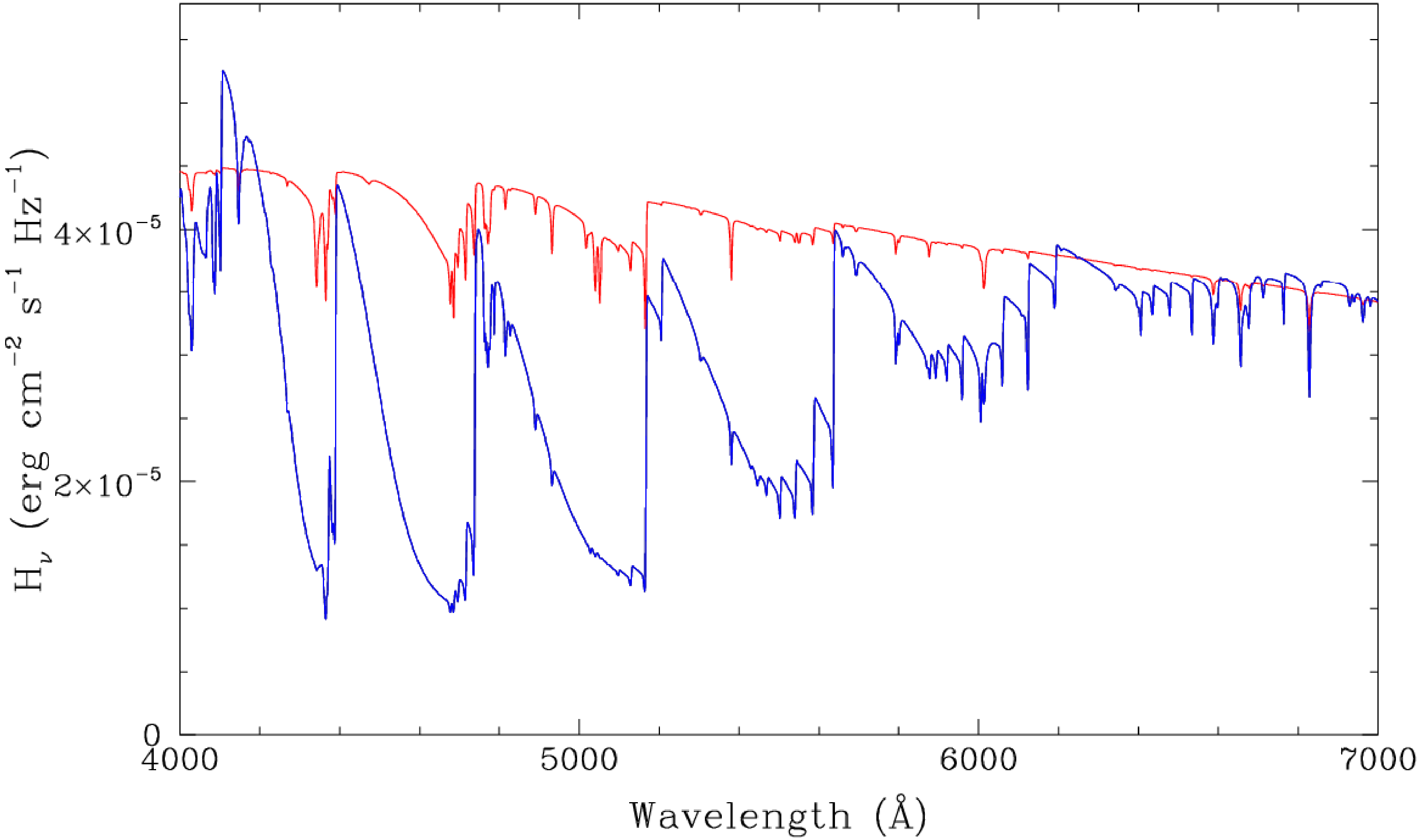


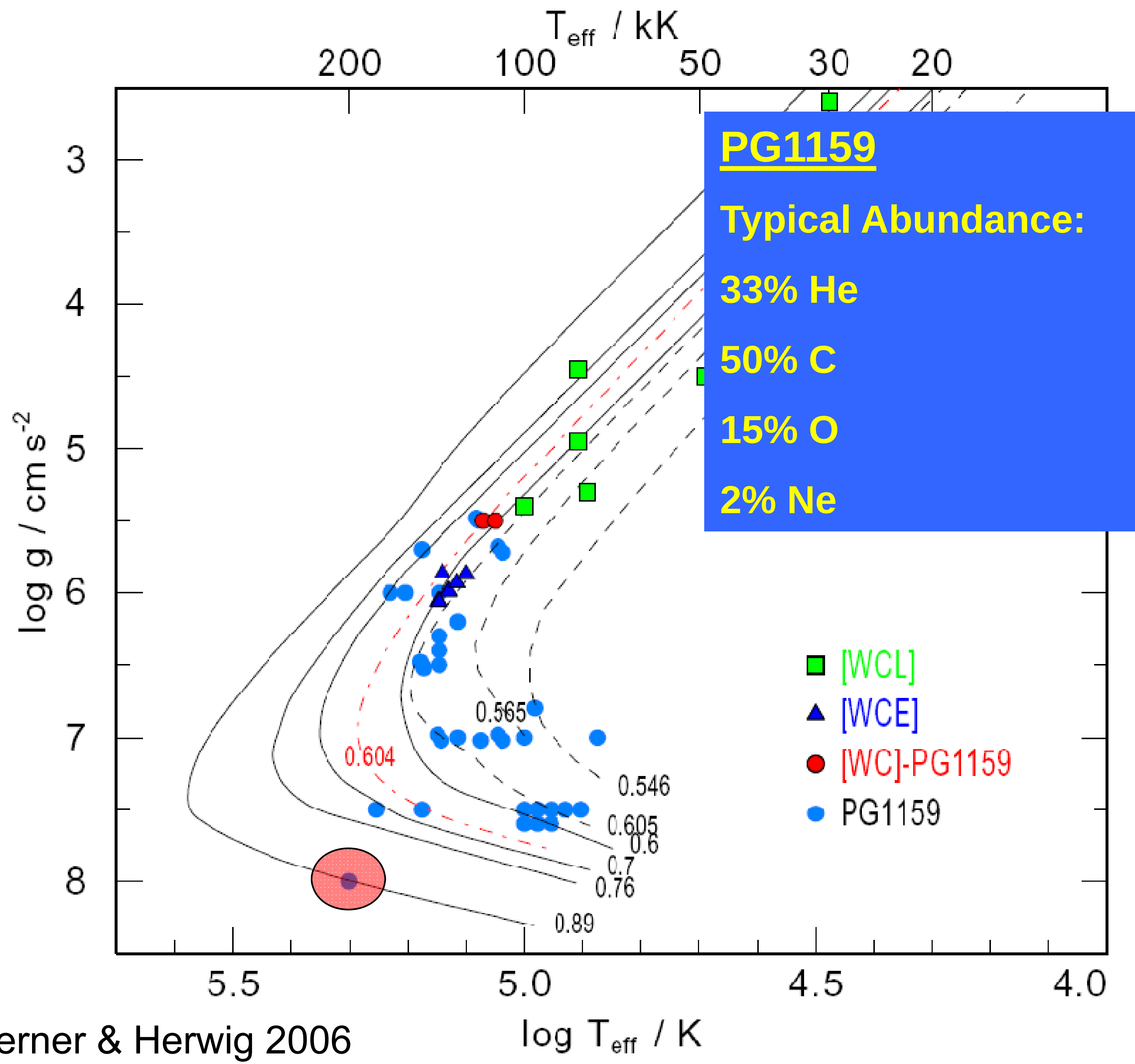
Pure Carbon, T_{eff} = 30,000 K



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

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





Werner & Herwig 2006

PG1159

Typical Abundance:

33% He

50% C

15% O

2% Ne

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

HeHuamdrilde poor

DA

150,000 K

DC

~4000 K

H1504+65

DO

DB

?

Hot DQ

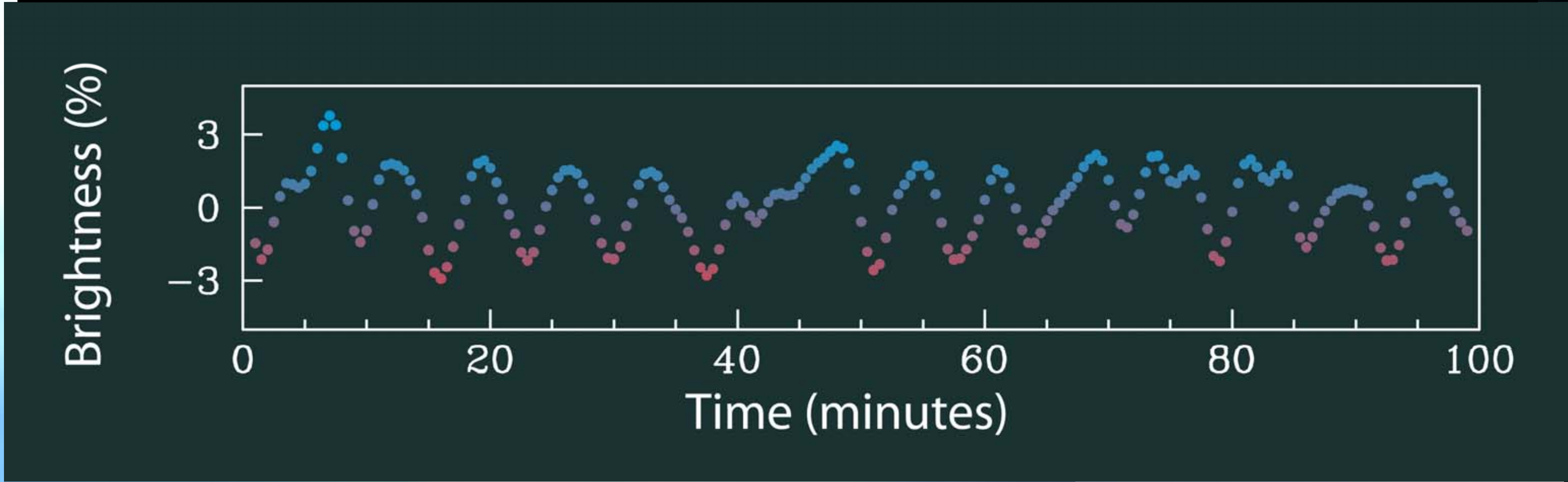
DQ (2nd sequence ?)

Pulsation ?

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

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

Carbone/Oxygen → ???

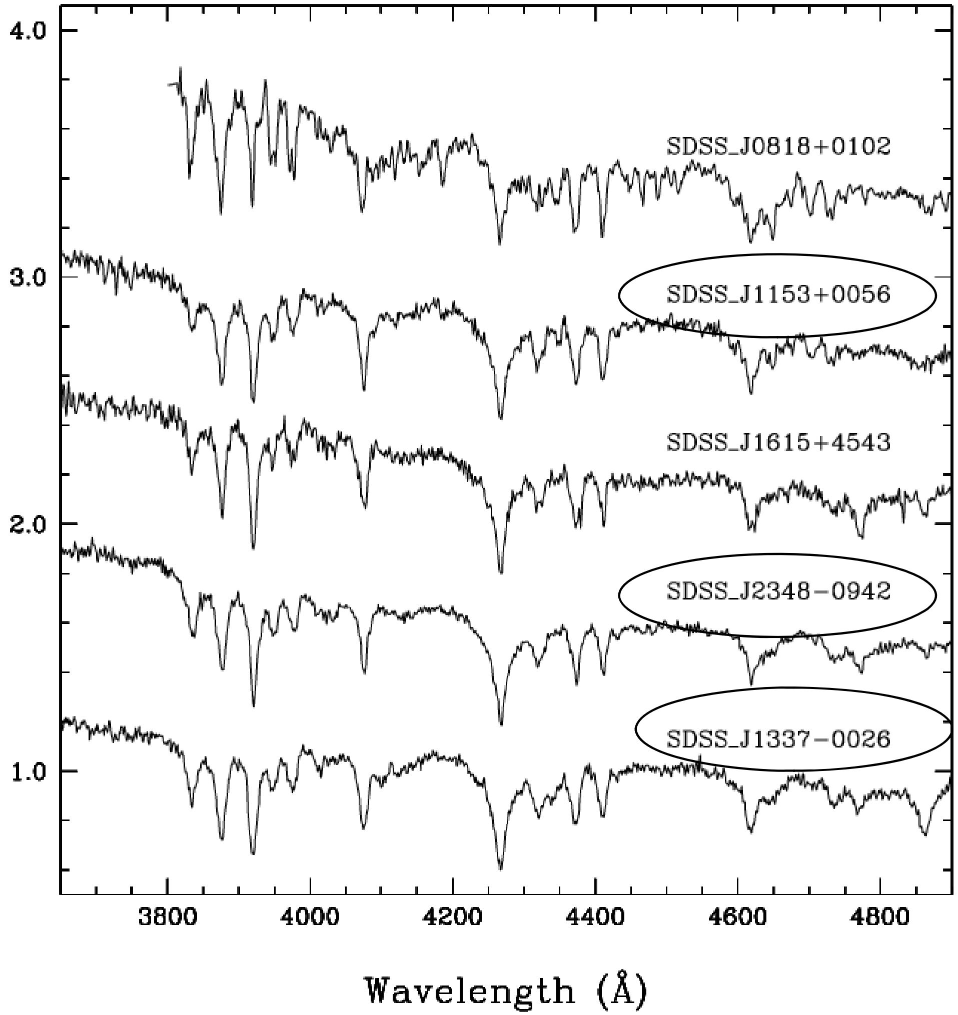


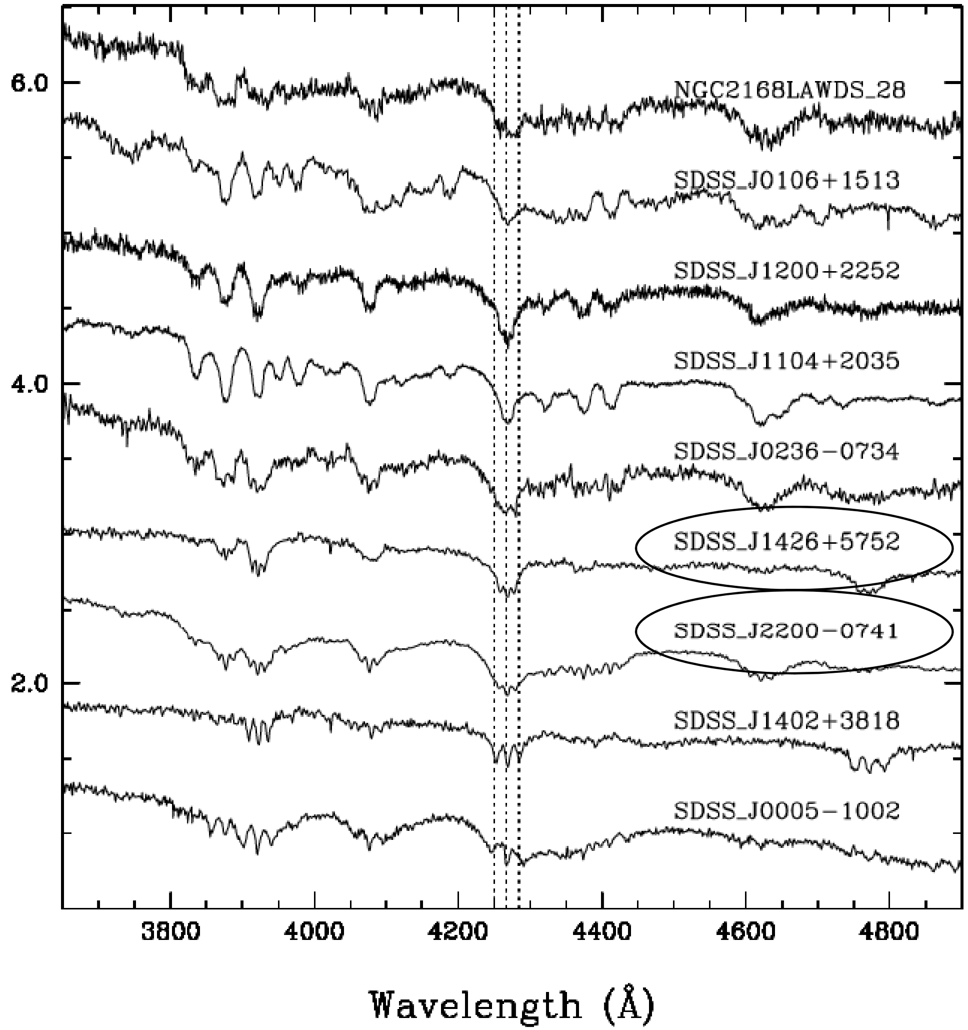
Discovery of a new pulsating star class!

-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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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
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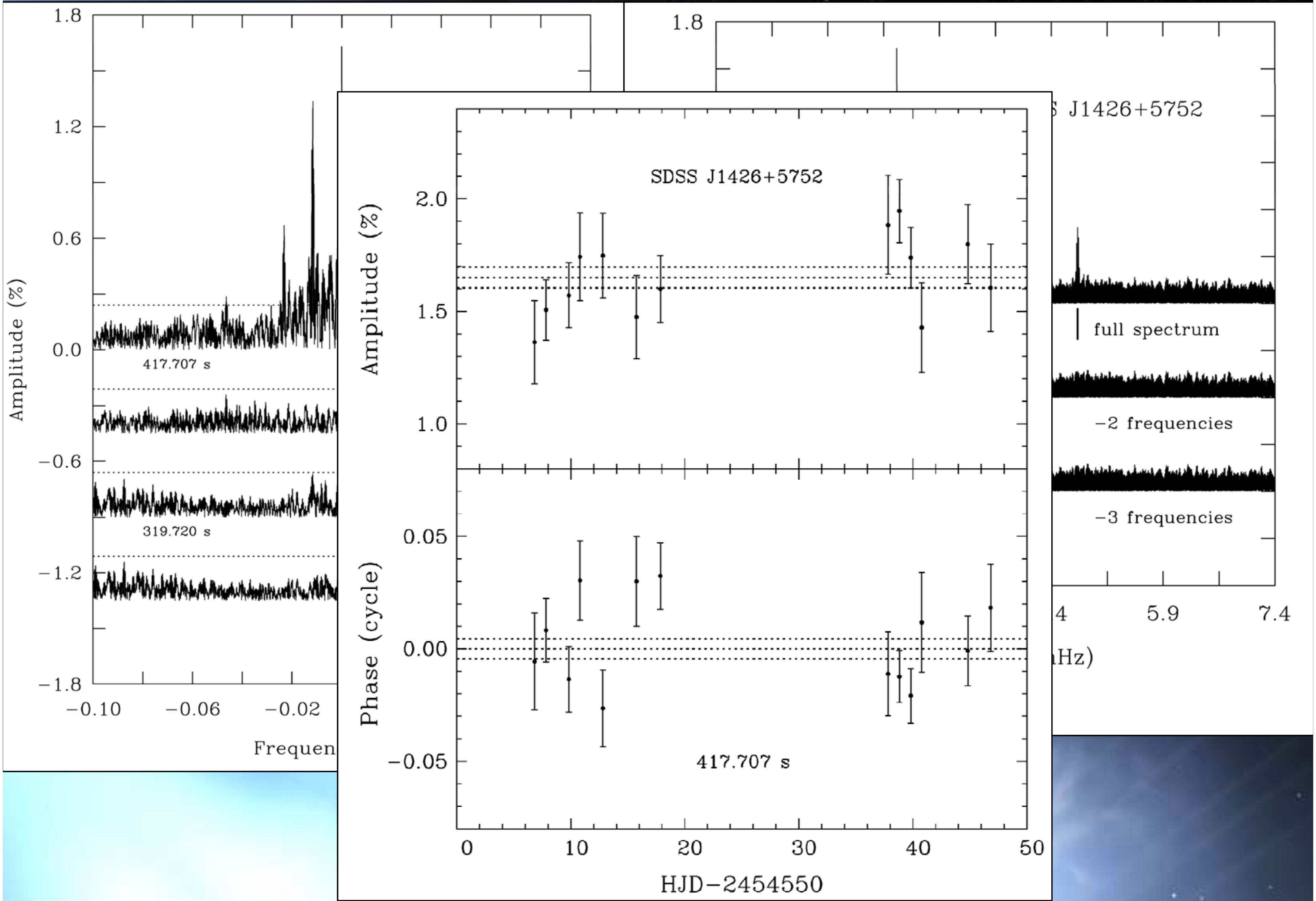
Received 2009 March 24; accepted 2009 July 13; published 2009 August 24

Kuiper Telescope, Mont Bigelow, Arizona (1.6m)


SDSS J1426+5752
Amplitude (%)
Phase (cycle)
417.707 s
HJD−2454550
319.720 s
full spectrum
−2 frequencies
−3 frequencies
Frequen
S J1426+5752
Hz)

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)

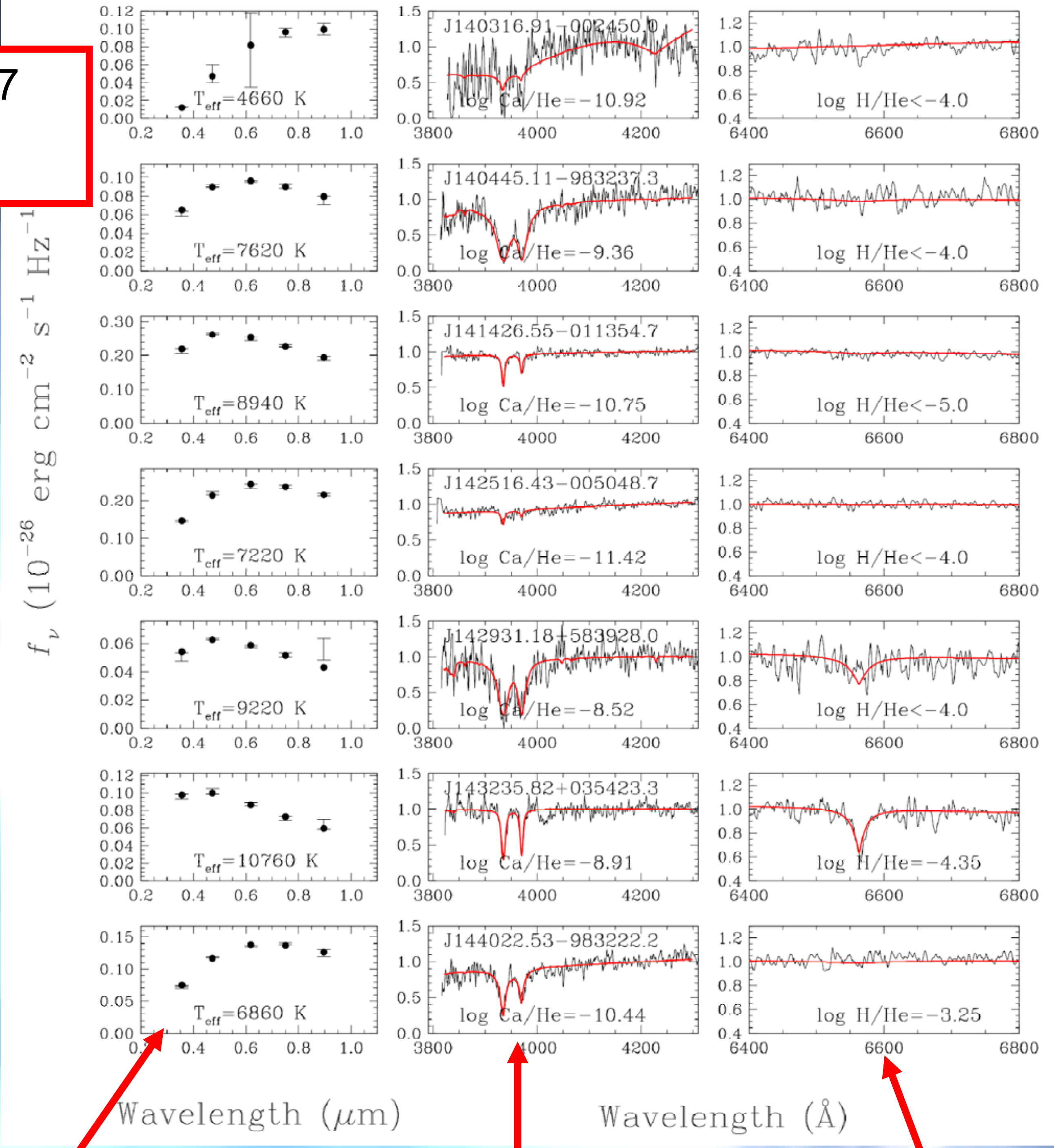
-Pulsations / magnétism

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

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Département de Physique, Université de Montréal, CP 6128, Succursale Centre-Ville, Montreal, PQ H3C 3J7, Canada;
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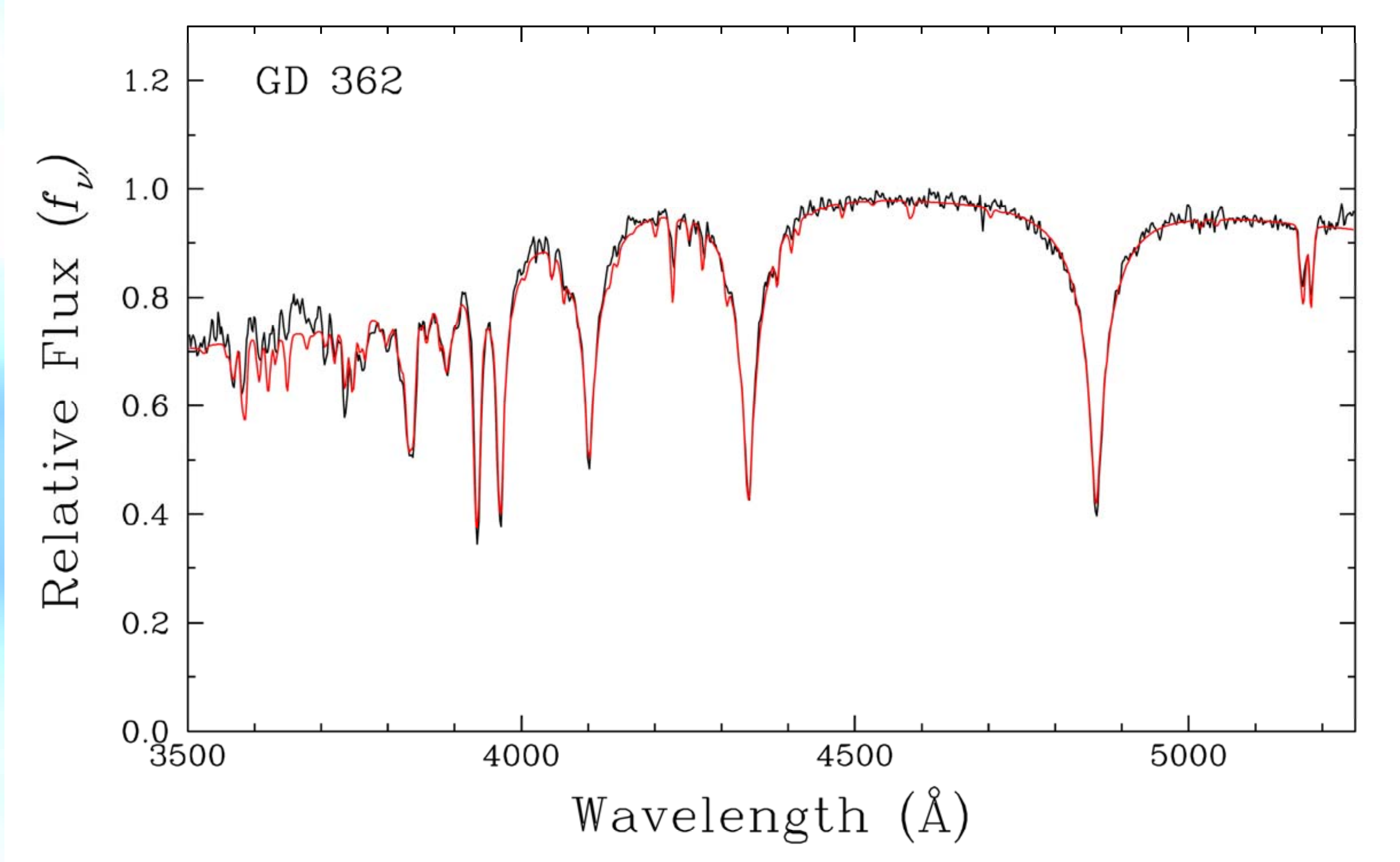
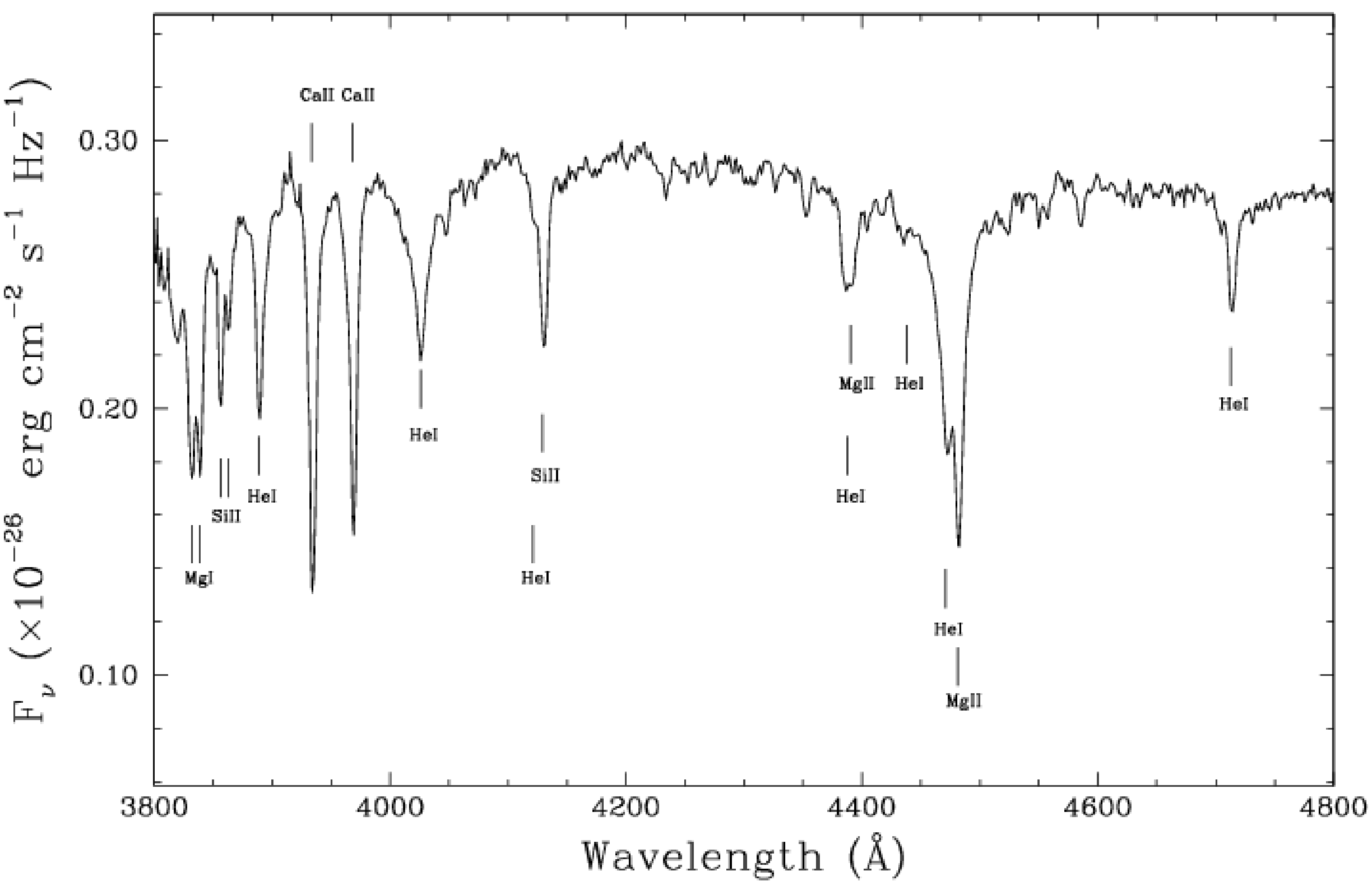
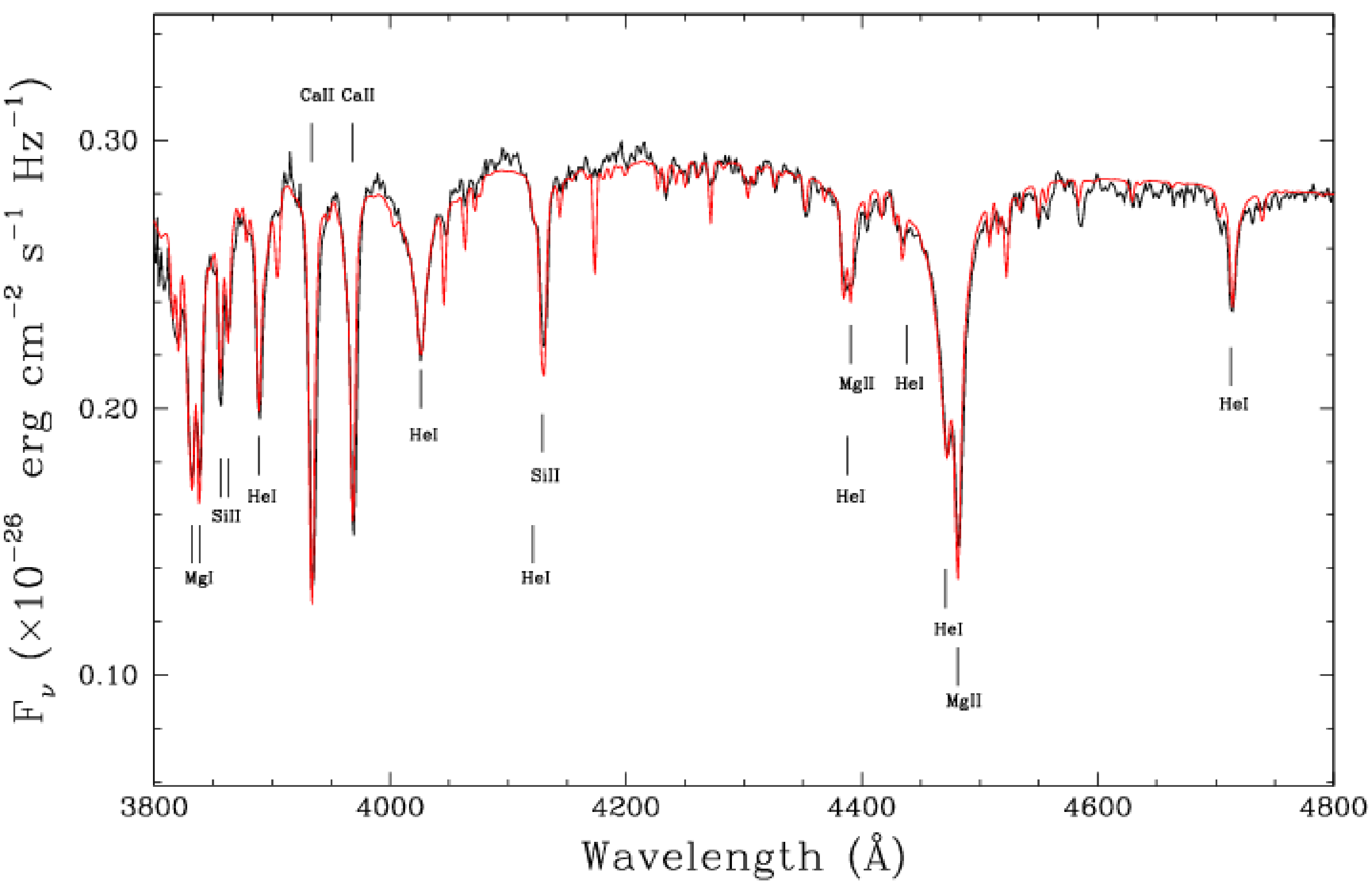
Received 2004 October 7; accepted 2004 October 28; published 2004 November 3





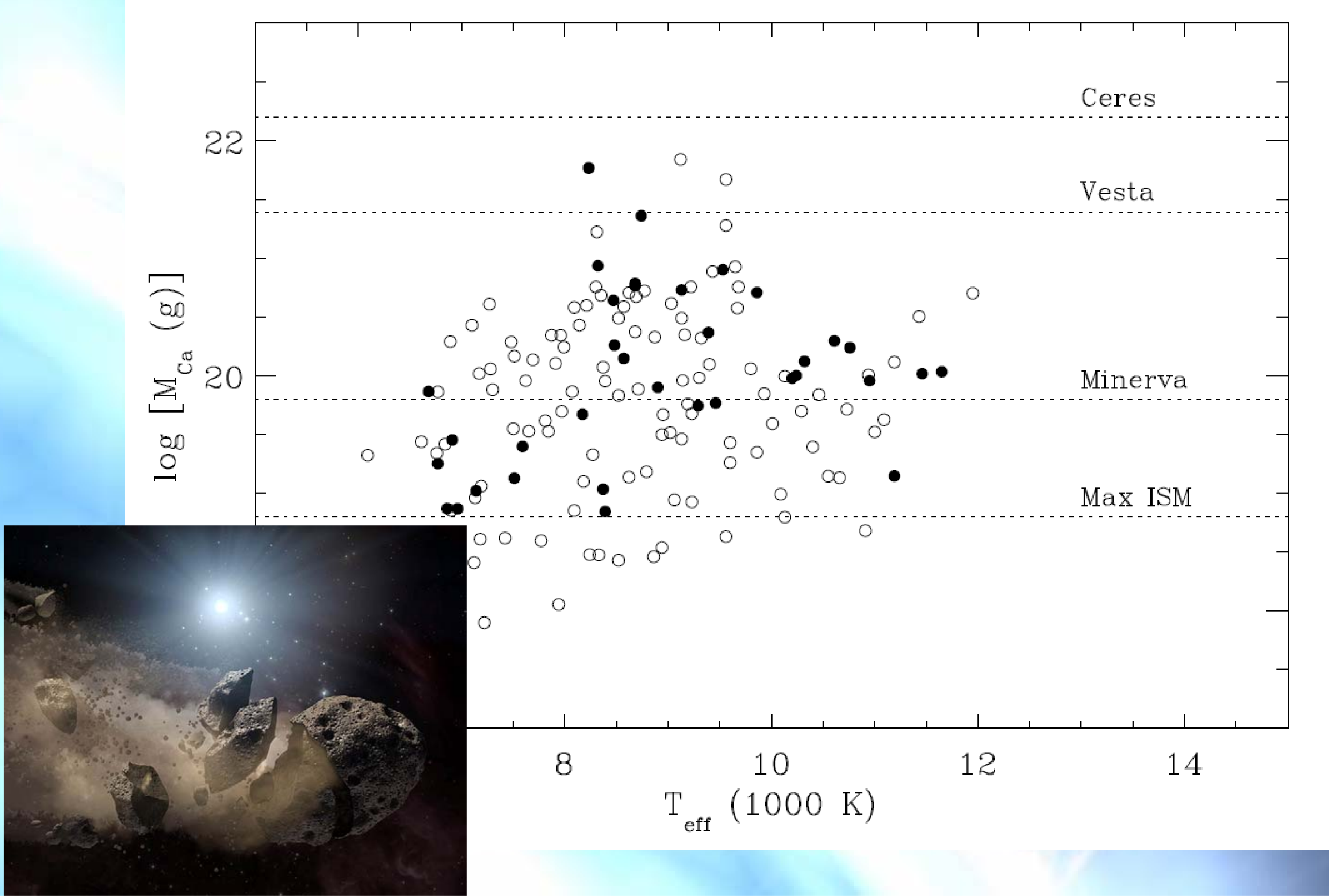
CaII CaII
HeI
SiII
MgI
SiII
HeI
HeI
MgII HeI
HeI
HeI
HeI
MgII
HeI
0.30
0.20
0.10
3800
4000
4200
4400
4600
4800
Wavelength (Å)
F_ν (×10^-26 erg cm^-2 s^-1 Hz^-1)

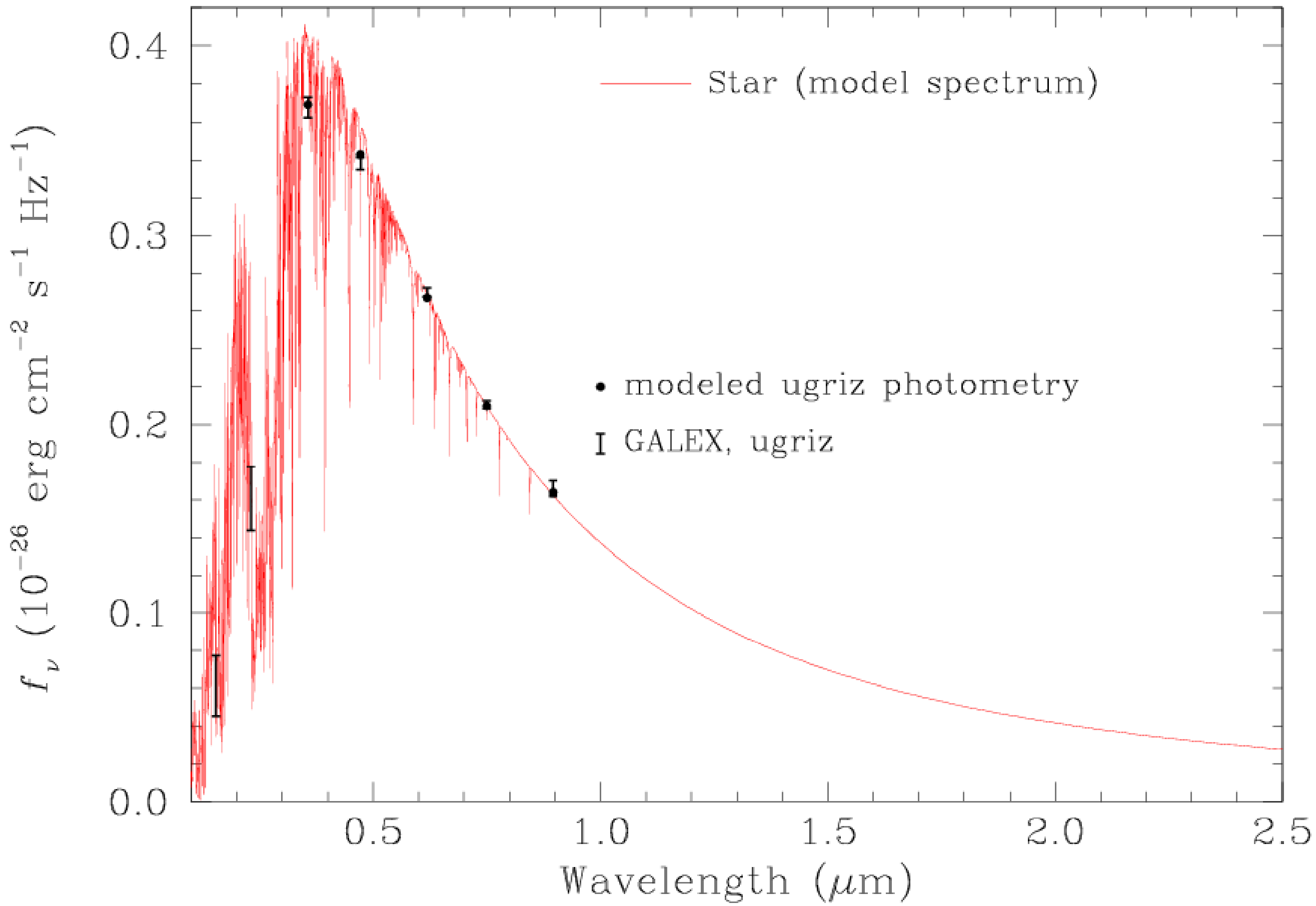


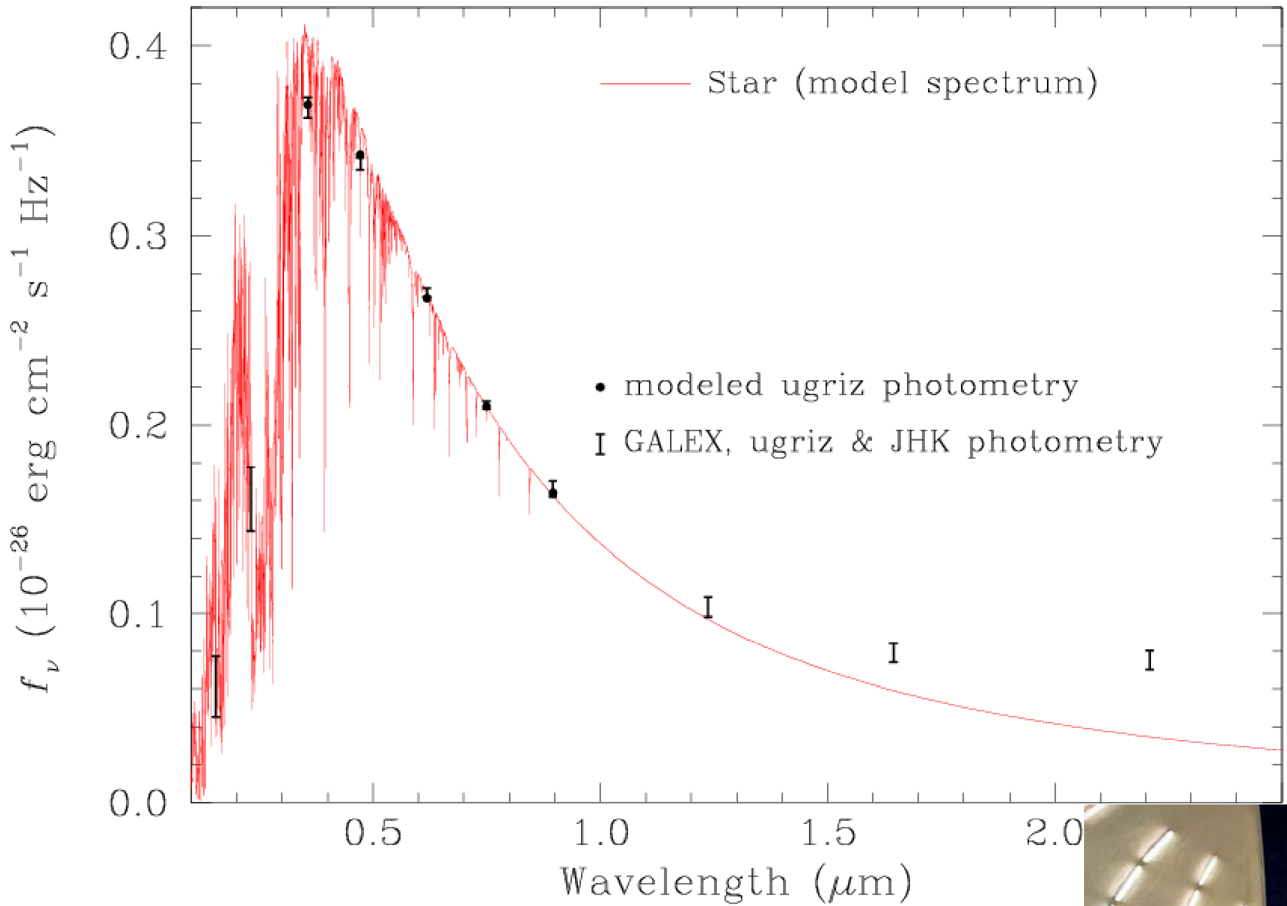
CaII CaII
MgI
SiII
HeI
HeI
SiII
HeI
MgII
HeI
HeI
HeI
MgII
HeI
0.30
0.20
0.10
F_ν ($\times 10^{-26}$ erg cm^{-2} s^{-1} Hz^{-1})
3800
4000
4200
4400
4600
4800
Wavelength (Å)

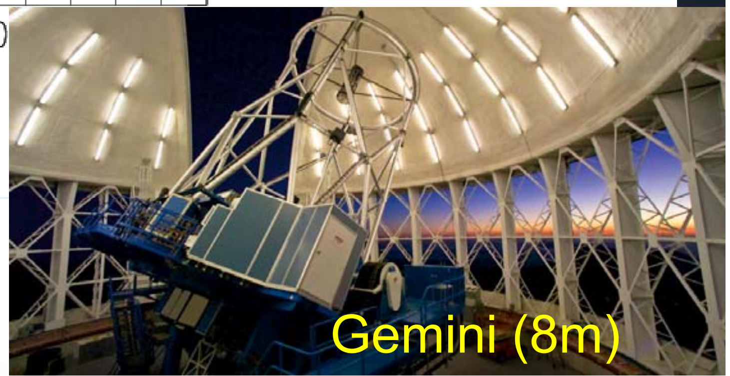
Statistical analysis of **142 DC** et **146 DZ**:

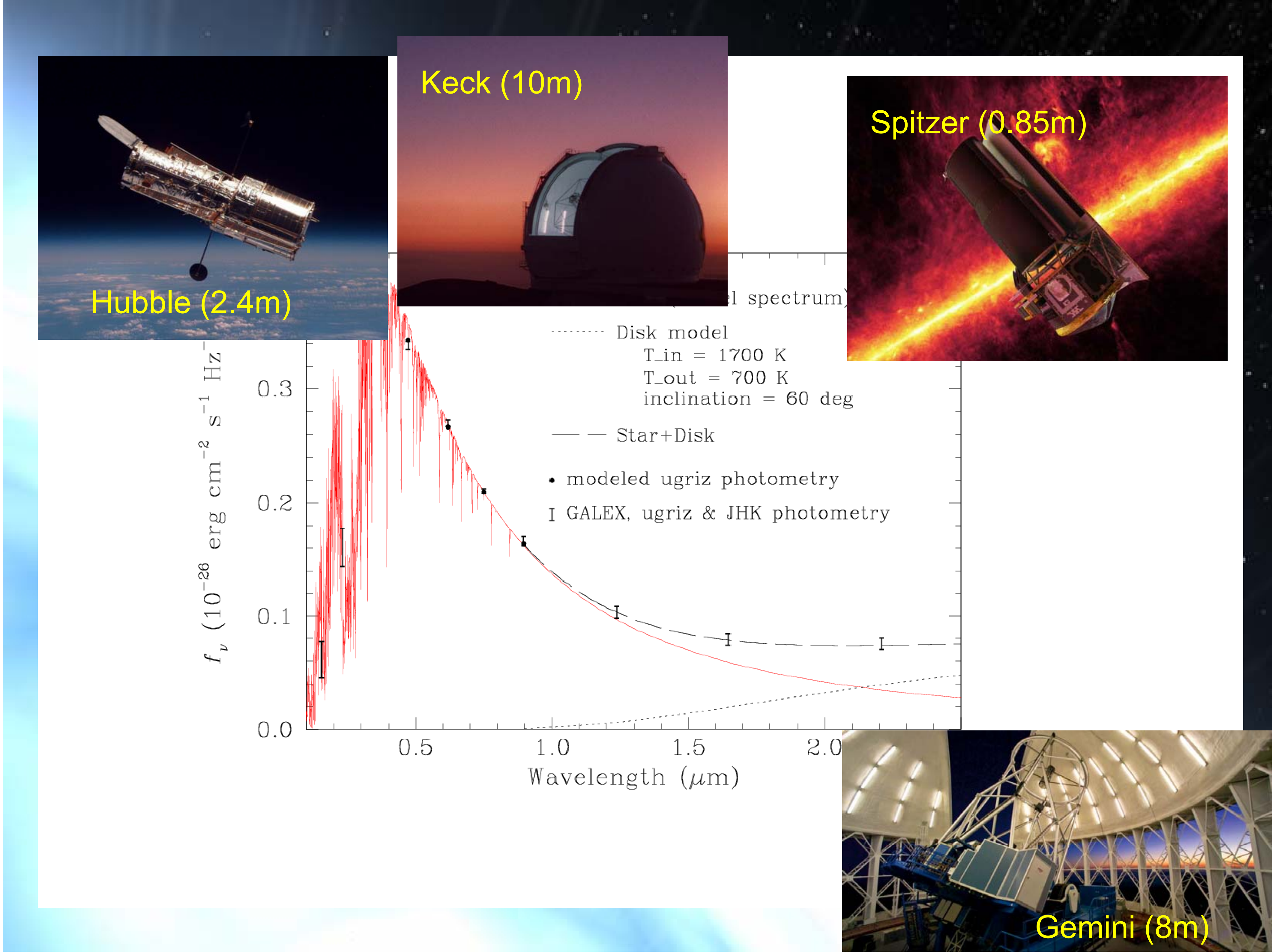
No correlation between the position of WD with and without metals vs Interstellar medium




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


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


Gemini (8m)



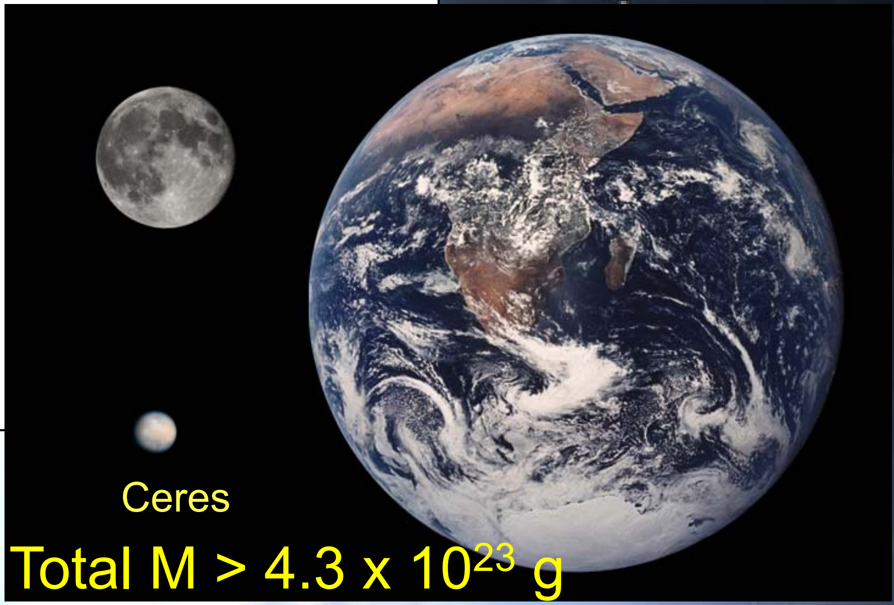
Hubble (2.4m)
Keck (10m)
Spitzer (0.85m)
Gemini (8m)
l spectrum)
Disk model
T_in = 1700 K
T_out = 700 K
inclination = 60 deg
Star+Disk
modeled ugriz photometry
GALEX, ugriz & JHK photometry
f_ν (10^{-26} erg cm^{-2} s^{-1} Hz
0.0
0.1
0.2
0.3
0.5
1.0
1.5
2.0
Wavelength (μm)

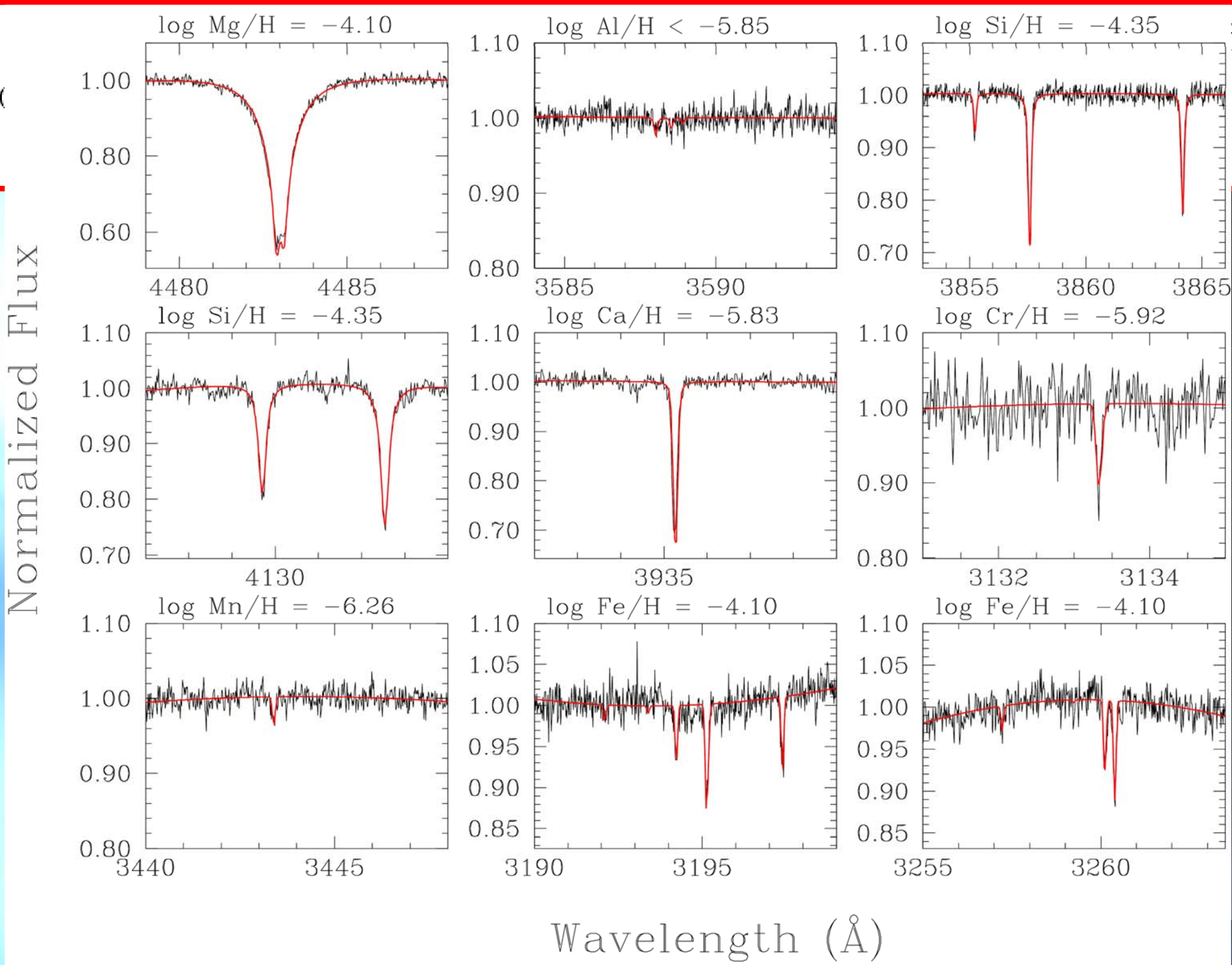
THE DISCOVERY OF THE MOST METAL-RICH WHITE DWARF: COMPOSITION OF A TIDALLY DISRUPTED EXTRASOLAR DWARF PLANET

P. Dufour[1], M. Kilic[2], G. Fontaine[1], P. Bergeron[1], F.-R. Lachapelle[1], S. J. Kleinman[3], S. K. Leggett[3]

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 =0.966R_{Terre}
$\log L/L_\odot$	−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





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

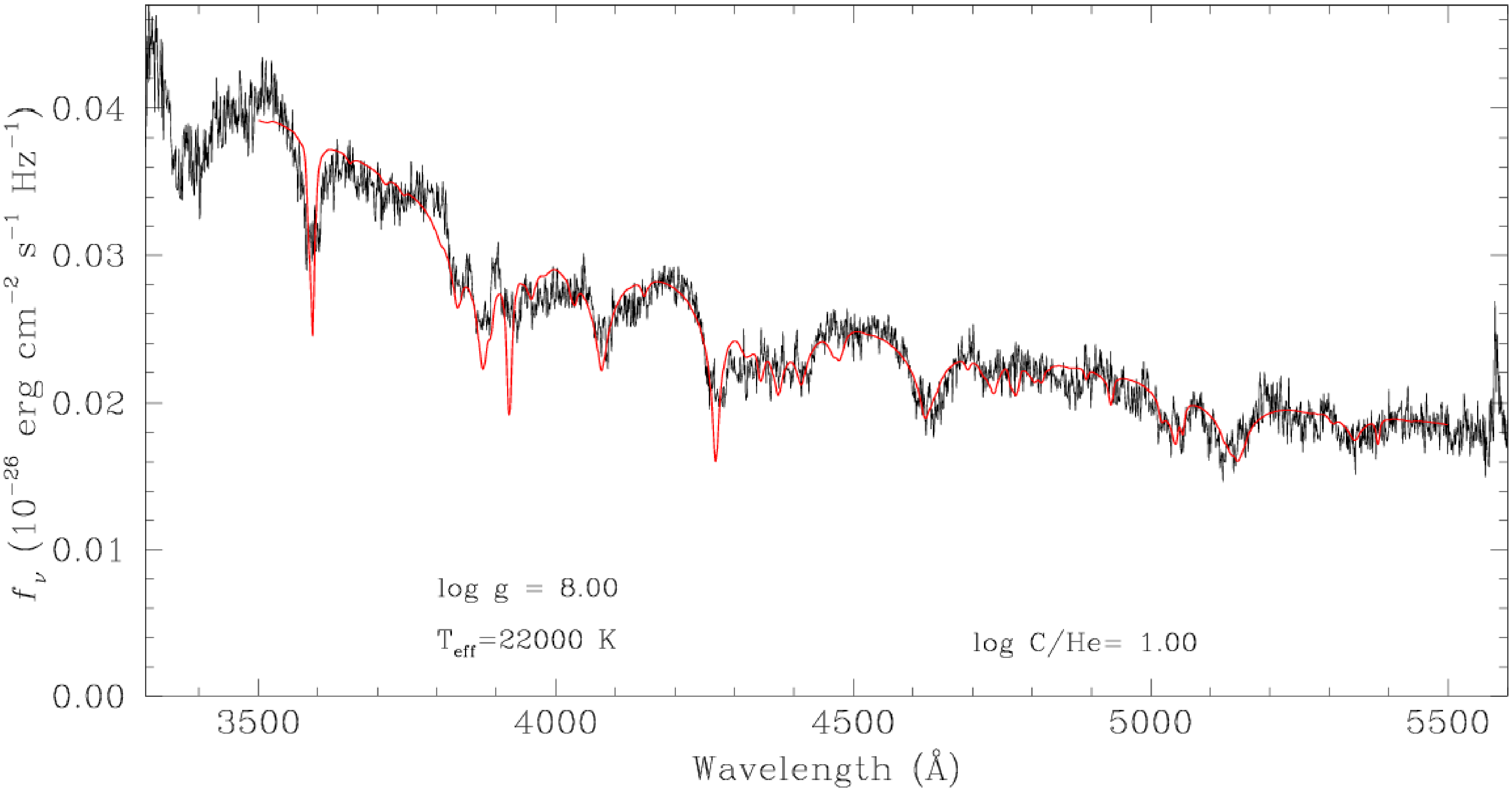
The study of white dwarfs with extreme metal polution is the **ONLY** known technique (other than go there and dig!) to obtain the internal chemical compositions of extrasolar planetesimals/planets.


Thank You

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

Masse du progéniteur

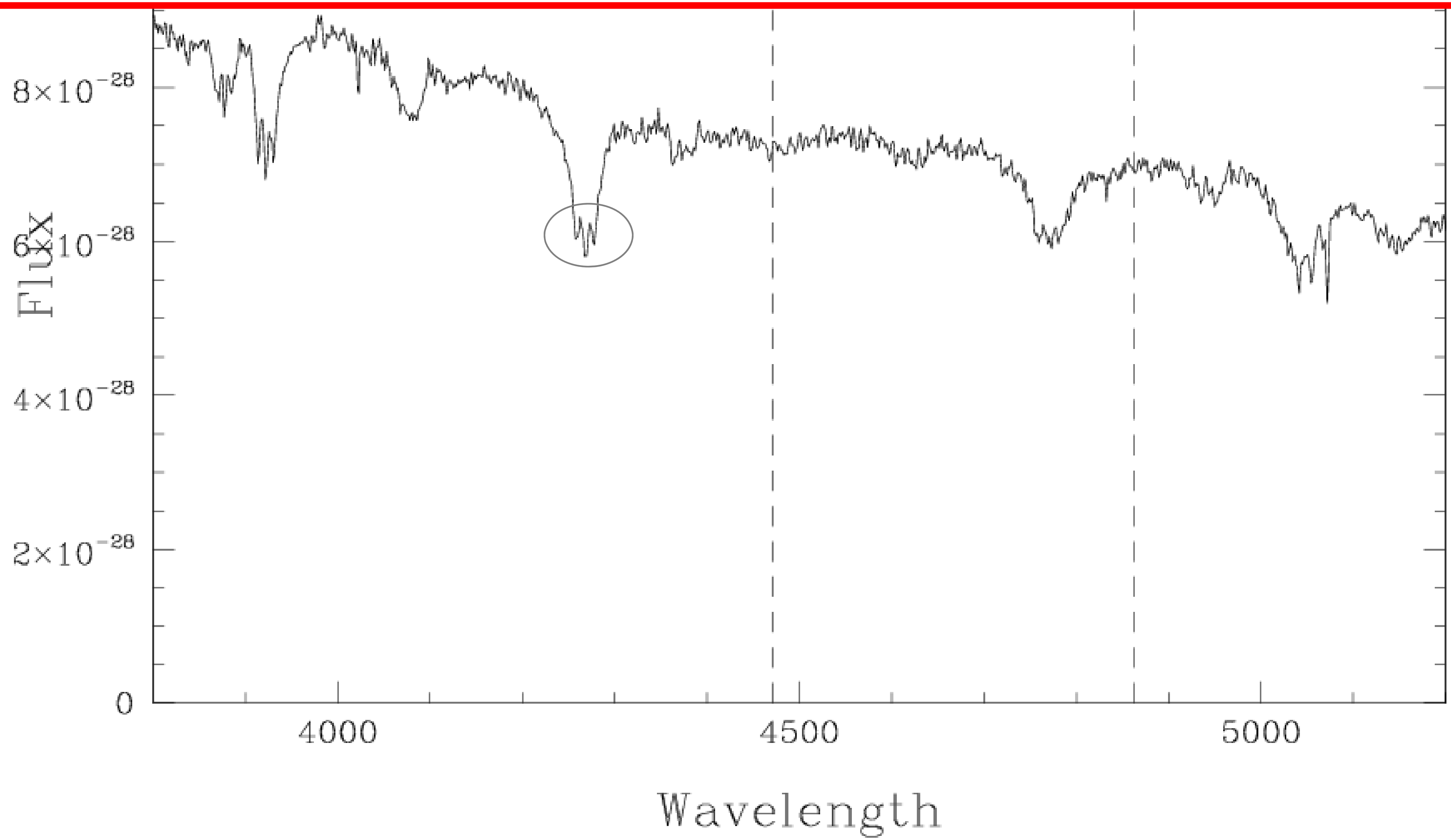
M35

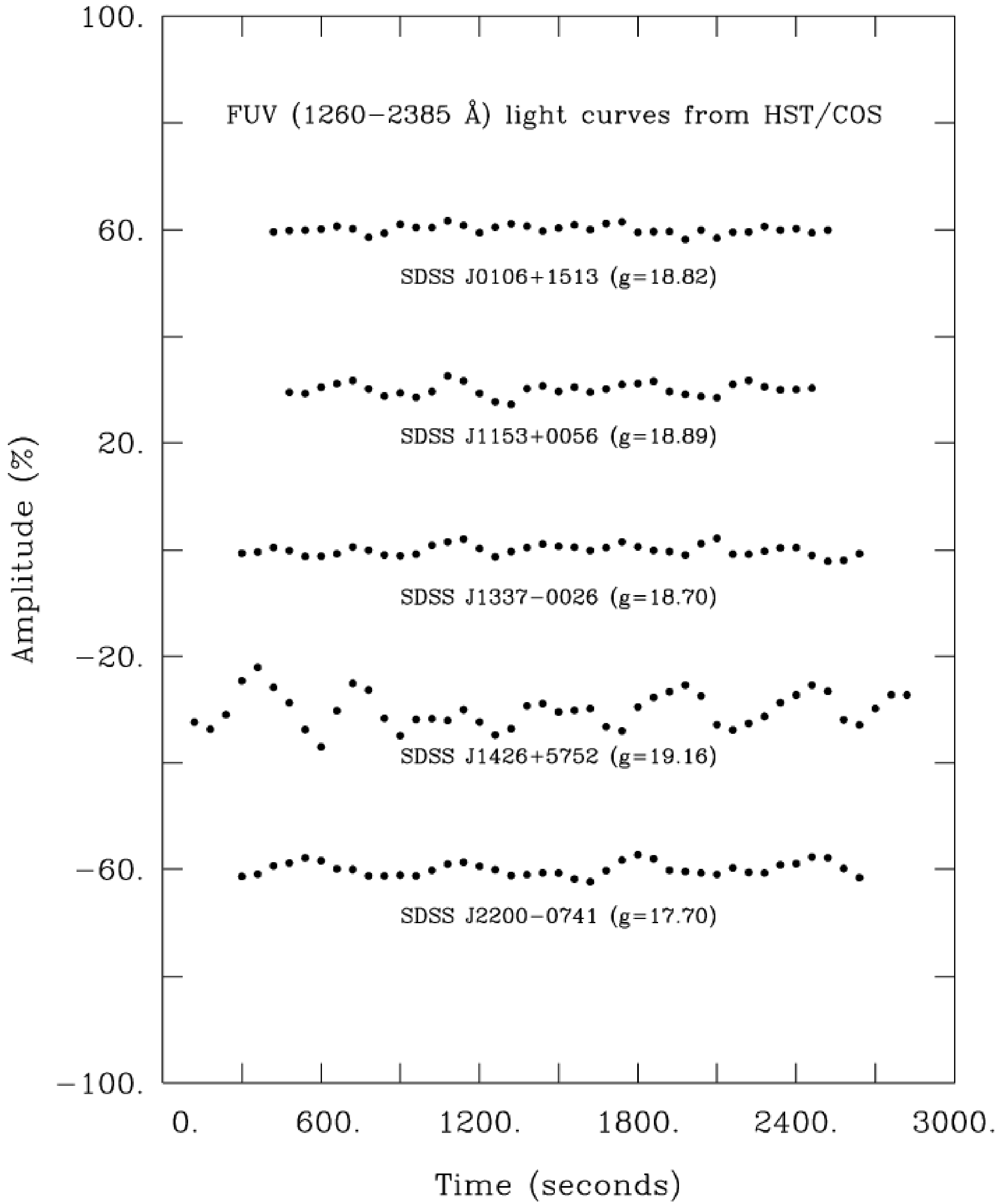


The Astrophysical Journal, 683:L167–L170, 2008 August 20

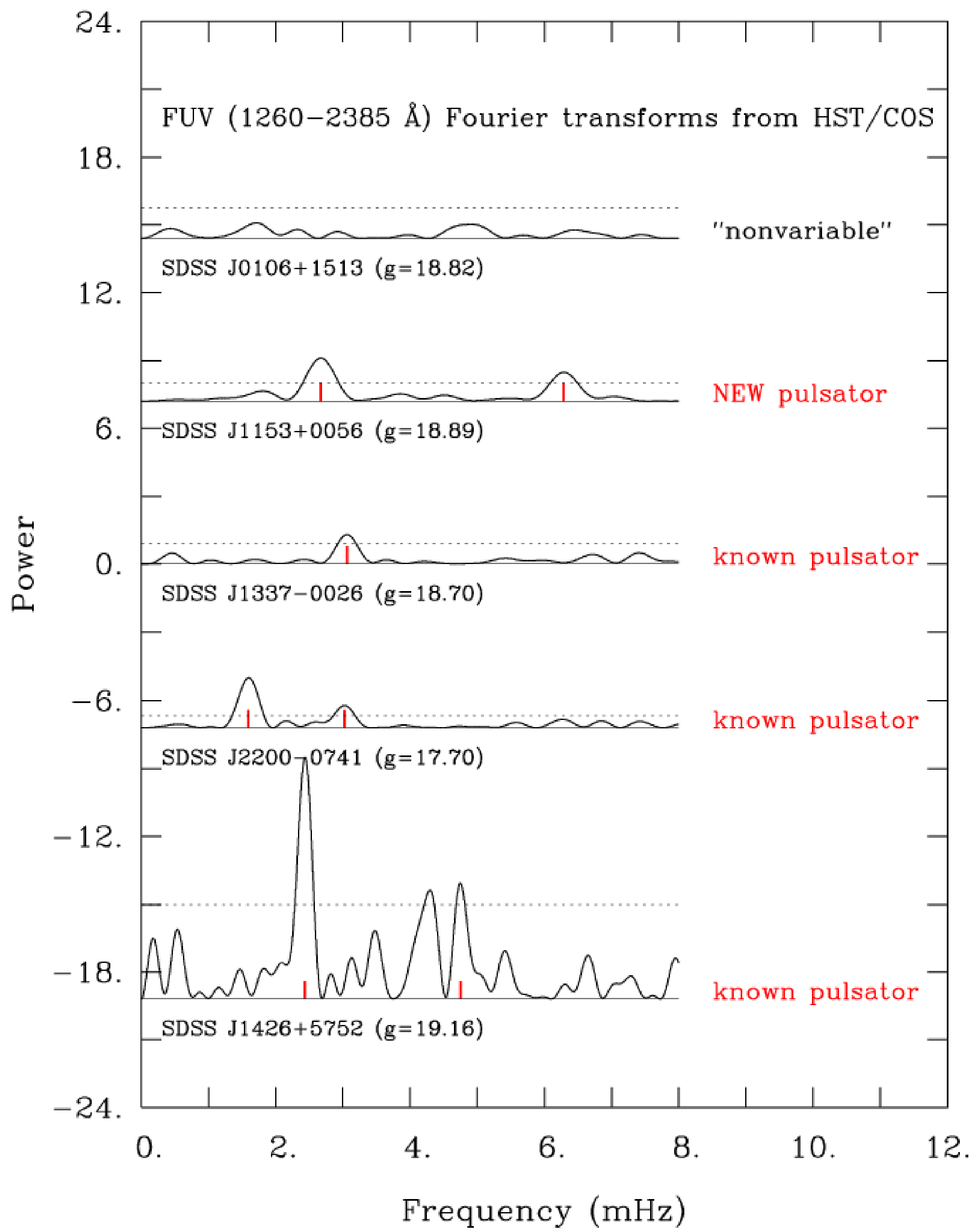
SDSS J142625.71+575218.3: THE FIRST PULSATING WHITE DWARF WITH A LARGE DETECTABLE MAGNETIC FIELD

P. Dufour,[1] G. Fontaine,[2] James Liebert,[1] Kurtis Williams,[3,4] and David K. Lai[5]
Received 2008 June 9; accepted 2008 July 9; published 2008 August 1

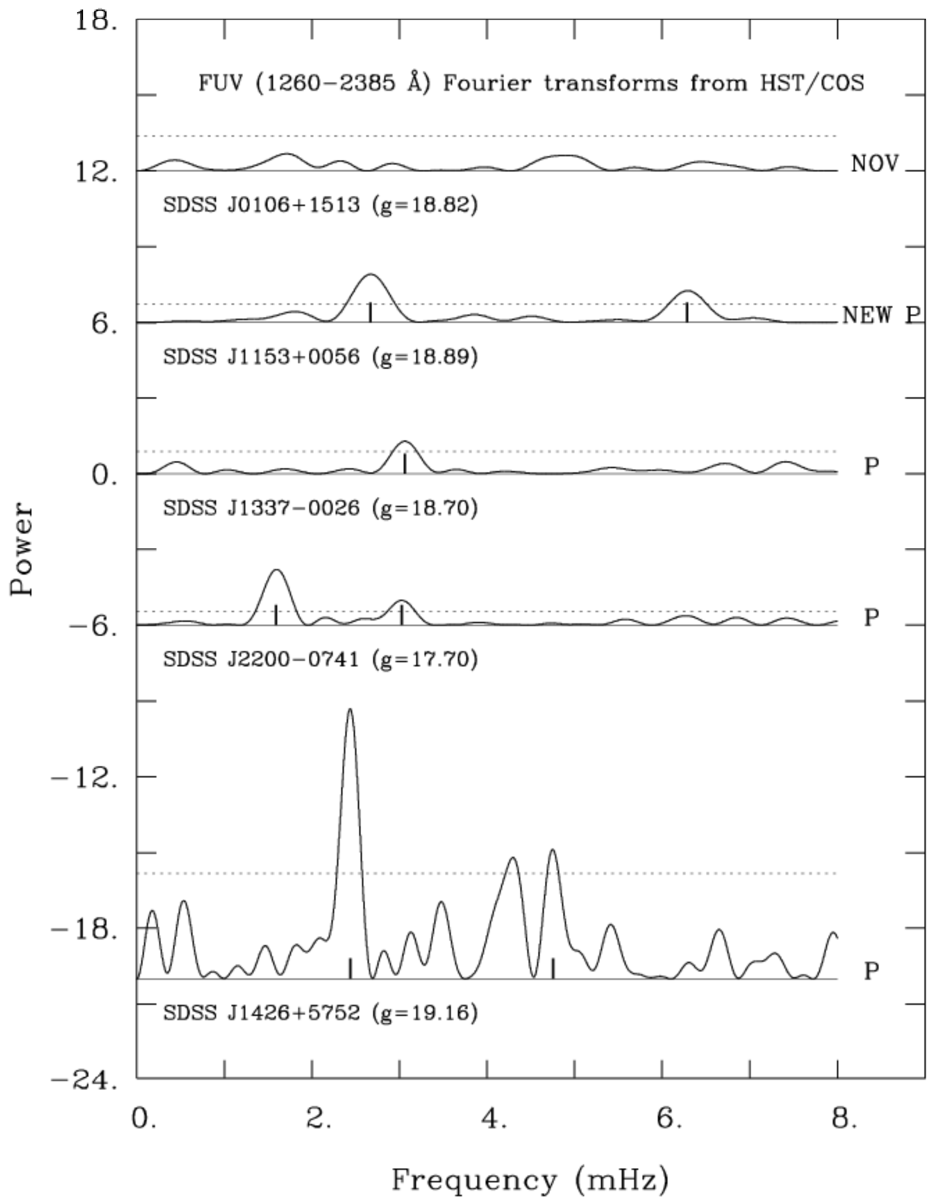




FUV (1260−2385 Å) light curves from HST/COS
SDSS J0106+1513 (g=18.82)
SDSS J1153+0056 (g=18.89)
SDSS J1337−0026 (g=18.70)
SDSS J1426+5752 (g=19.16)
SDSS J2200−0741 (g=17.70)
Amplitude (%)
100.
60.
20.
−20.
−60.
−100.
0.
600.
1200.
1800.
2400.
3000.
Time (seconds)



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
NOV
SDSS J0106+1513 (g=18.82)
NEW P
SDSS J1153+0056 (g=18.89)
P
SDSS J1337−0026 (g=18.70)
P
SDSS J2200−0741 (g=17.70)
P
SDSS J1426+5752 (g=19.16)
Power
Frequency (mHz)
18.
12.
6.
0.
−6.
−12.
−18.
−24.
0.
2.
4.
6.
8.

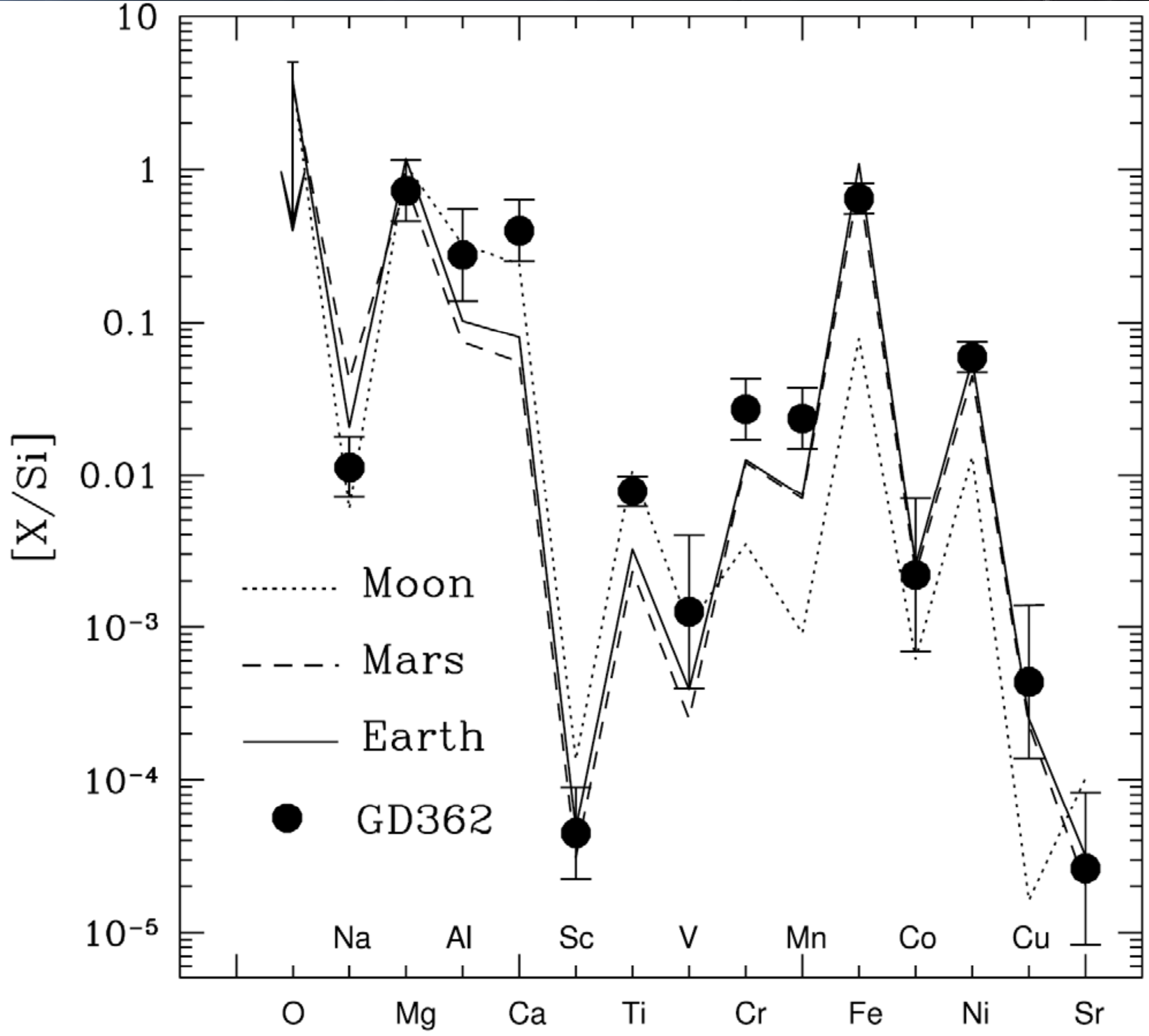


FIG. 3.—Elemental abundances by number relative to silicon. The GD 362 data are from Table 2, and those for Earth, Moon, and Mars are from Lodders & Fegley (1998).

On the formation of hot DQ white dwarfs

L. G. Althaus[1,2]

E. García–Berro[3,4]

A. H. Córsico[1,2]

M. M. Miller Bertolami[1,5]

A. D. Romero[1,5]

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[4] *Institut d'Estudis Espacials de Catalunya, c/ Gran Capità 2–4, 08034 Barcelona, Spain*
[5] *Fellow of CONICET*

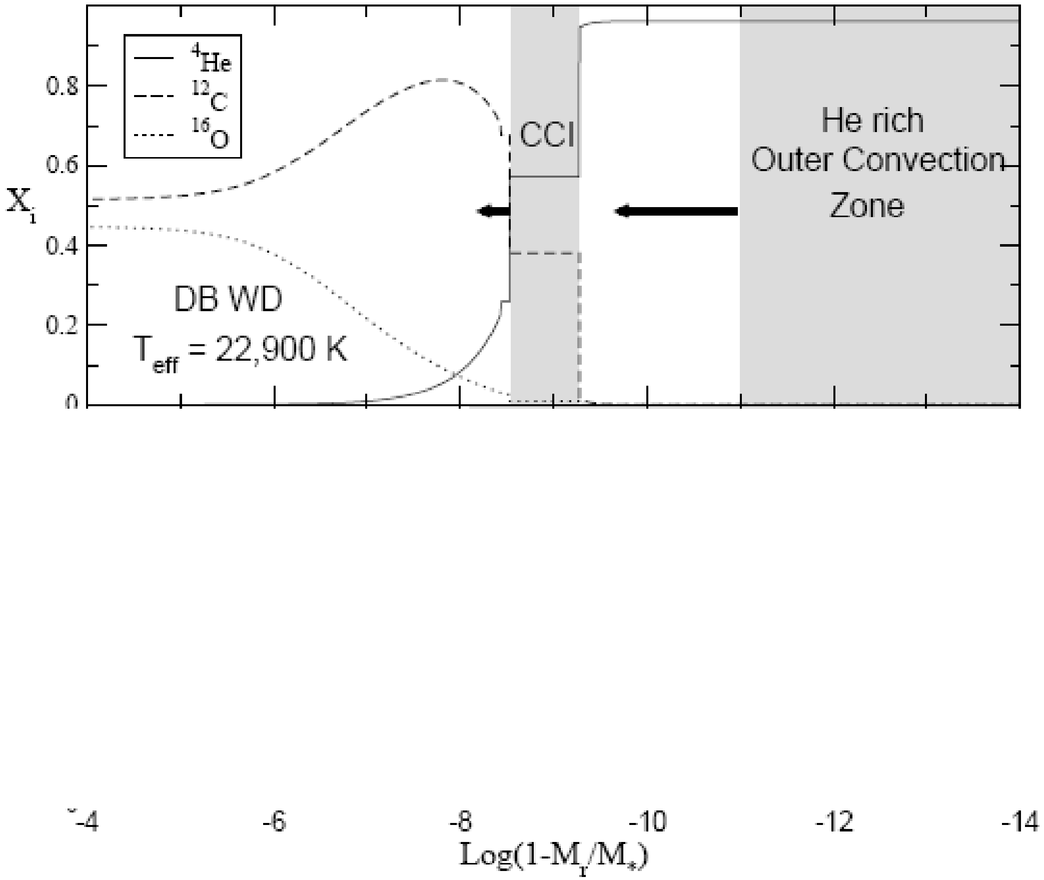

Fig. 1.— Abundance distribution of ^{4}He, ^{12}C, and ^{16}O as a function of the outer mass fraction at two selected effective temperatures for the 0.87 $M_\odot$ white dwarf with $M_{\rm He} = 10^{-8}\, M_{\rm WD}$. Gray areas denote convectively unstable zones. The inward-growing outer convection 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).