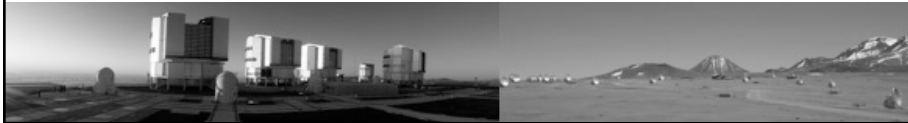


# Atomic Processes and the Interstellar Medium

Extracting quantitative measurements from astronomical observations

Patrick Roche



## Astrophysics seminars

Usually Monday afternoons, 2pm:

Today: Dr. S.-J. Paardekooper, Queen Mary University of London

Migration of Rocks, Planets and Hurricanes in Protoplanetary Discs

But note that the Hintze Lecture is on Tuesday May 10 and the Halley Lecture on Wednesday June 8 at 5pm

University of Oxford  
The Hintze Lecture Series  
Professor Robert Kennicutt  
Plumian Professor of Astronomy and Experimental Philosophy  
Institute of Astronomy, University of Cambridge

'Unveiling the Birth of Stars and Galaxies'  
Tuesday 10<sup>th</sup> May 2016 at 5:00pm  
(to be seated by 4:50pm)

Martin Wood Lecture Theatre  
Clarendon Laboratory, Parks Road, Oxford

Followed by a reception in the foyer of the Martin Wood Lecture Theatre

Abstract: Understanding the birth of stars is one of grand challenges of 21<sup>st</sup> century astrophysics, with impacts extending from the formation of planets to the birth and shaping of galaxies themselves. The challenge has been all the more difficult because the most active birth sites are largely hidden in visible light. Thanks to a new generation of infrared and submillimetre space telescopes this veil has been lifted, and a complete picture of starbirth in the Universe is emerging. They reveal an extraordinary diversity of activities in galaxies, and an emerging history of star formation cosmic time, extending back to some of the first stars and seeds of galaxies. This talk will summarise what we have learnt about starbirth on cosmic scales, and highlight the challenges and opportunities which lie ahead.

## Synopsis

- Astronomical spectroscopy, lines in different spectral regions, recap of atomic physics and selection rules, forbidden and allowed transitions, cosmic abundances
- The two level atom, A, B and C coefficients and their useful regimes, thermal populations, IR fine structure lines, critical density, mass estimates
- Recombination and ionization processes, the Stromgren sphere, ionization balance, effective temperature estimates.
- The 3 level atom: diagnostics of electron temperature and electron density.
- Absorption lines, equivalent width and the curve of growth. Column densities and abundances
- The interstellar medium. Atomic and ionic absorption lines, abundance of gas, molecules and dust. Hyperfine transitions: 21cm line of H, Galactic structure
- Interstellar extinction, dust components, thermal emission, equilibrium and stochastic processes
- The sun. Ionization and sources of opacity, radiative transfer, the Gray atmosphere limb darkening, absorption line formation

## Some typical conditions

- 90% H atoms, ~9% He, ~1% everything else (by number)
- Stellar surface temperatures  $2000 < T < 40000$  K  
Densities  $\sim$  few gram/m<sup>3</sup> for main sequence stars
- Ionized nebulae e.g. HII regions, planetary nebulae
  - T(electron)  $\sim$  10000K,
  - n(electron)  $\sim$  N(proton)  $10^6 - 10^{12}$  m<sup>-3</sup>
  - T(dust)  $\sim$  50K
- Cold and denser molecular clouds ( $T \ll 100$  K)
- Hot and lower-density plasmas - e.g. shock heated gas,  $T \sim 10^6$  K,  $n < 100$
- Velocities: cold ISM 1km/s - SN outflows  $10^4$  km/s
- Overall density of the Universe is  $\sim$  10 orders of magnitude lower than the best lab vacuum

## Astronomical Spectroscopy

Imaging provides information about structure and morphology, Whilst photometry permits estimates of luminosity and variability.

We have to analyse spectra to understand the composition and physical conditions (temperature, density, excitation) of galaxies, stars and nebulae and the intervening material between the Earth and the object

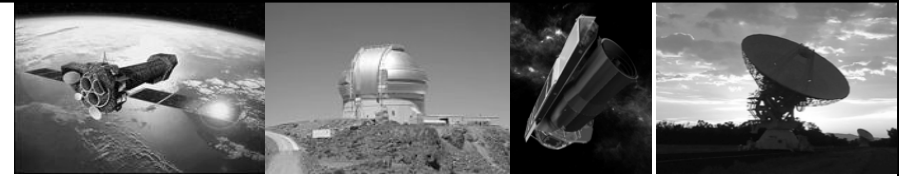
Spectra provide information on the structure and dynamics of stars, planets and galaxies – and have provided evidence for the Big Bang, expansion of the Universe, dark matter, exosolar planets

In fact almost everything interesting in astrophysics!

To first order, astronomical objects have very similar compositions, but their appearances vary dramatically

e.g. the surface of the sun and a nebula

Quantitative analysis allows us to probe and understand this



Observations across the electromagnetic spectrum probe: e.g.

High energy processes e.g. accretion onto compact objects; K-shell X-ray transitions

Photo-ionised gas, recombination and forbidden lines, stellar atmospheres in UV, optical, Infrared

Rotational-vibrational molecular transitions, fine-structure line transitions, dust emission in the IR

Molecular rotational lines, synchrotron and free-free emission in the microwave and radio, 21cm line tracing atomic H

Different techniques using a range of ground-based and space facilities

Here I will concentrate on optical/infrared transitions, but the same principles apply to other wavelength regimes

## A brief history of astronomical spectroscopy

1672 Newton's prism – sunlight split into constituent colours

1800 Herschel noted that infrared light is present beyond the visible red bands

1804 Wollaston noted dark lines in the solar spectrum

1814 Fraunhofer rediscovered them and identified 475 dark lines including one coincident with that produced by salt in flame

1870 Kirchoff and Bunsen identified 70 lines with iron vapour

1864 Nebulium was proposed by Huggins to explain a green line seen in nebula

1869 Coronium invoked to explain a green line seen in solar prominences

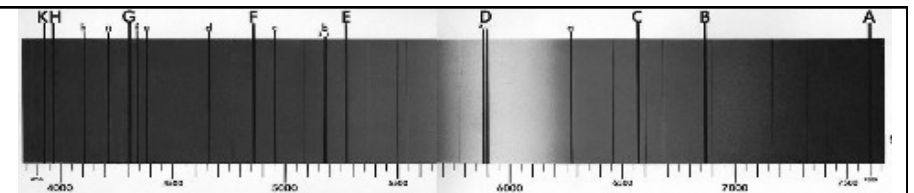
1870 Lockyer and Janssen proposed a new element Helium from solar spectra

Helium was confirmed in 1895 by Ramsay.

The explanation for Nebulium did not emerge until 1928 when Bowen demonstrated that the lines at 4959 and 5007Å arise from the  $^1D_2 - ^3P_2$  forbidden transition in OIII

Coronium was identified by Edlen and Grotrian in 1939 as a transition from Fe XIV, arising from an ion with an ionization potential of 361eV.

Since then, many other unexpected phenomena have been discovered – masers, transitions from short-lived species, highly relativistic motions etc, there are still many as-yet unidentified lines from ions and molecules.



Fraunhofer Spectrum of the Sun

A,B – telluric atmospheric absorption bands by ozone

C – Hydrogen (Balmer alpha)

D – Sodium Doublet

E – Iron

F,G – Hydrogen (Balmer beta, gamma)

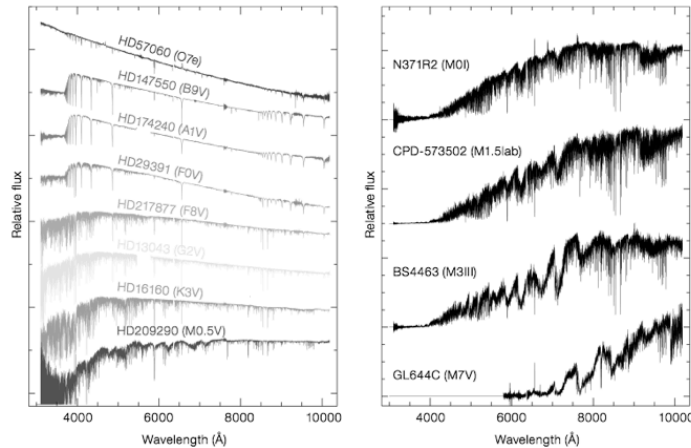
H,K - Ca+

Note that although Hydrogen is by far the most abundant element, the strongest lines are due to 'trace' elements – we need to use Atomic Physics and statistical mechanics to understand this. The presence of dark lines, suggests a temperature gradient in the surface layers

Note also that for accurate analysis, we need to calibrate the spectra – compensate for the effects of transmission through the atmosphere and instrument (and in more distant objects, the effects of the interstellar medium).

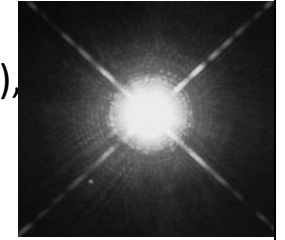
## Stellar Spectra

Examples of stellar spectra with  $T_{\text{eff}}$  ranging from 30000 - 2800 K (Y-P Chen et al 2014)



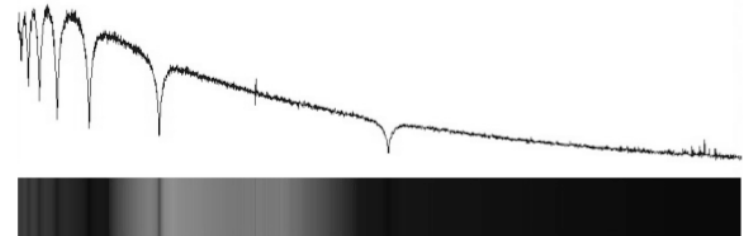
- Strong quasi-blackbody continuum emission but with marked spectral structure and absorption lines: the break at  $\sim 350\text{nm}$  (the 'Balmer Jump' due to an excitation edge in H), narrow atomic lines and broader molecular bands
- Note the increasingly prominent absorption as temperature decreases

Detailed spectral characteristics depend on pressure (surface gravity), element abundances etc.



Sirius A and B

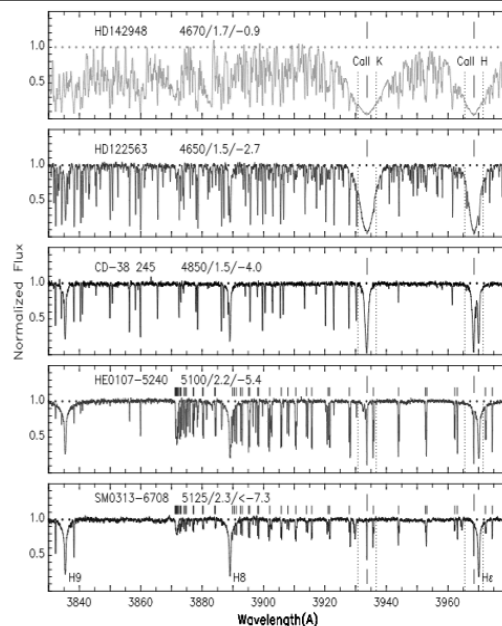
- E.g. White dwarf : the end product of intermediate mass star evolution after going through planetary nebula phase.
- Dense. High surface gravity leads to pressure-broadening of lines



## Effects of Metallicity

Stars with reduced heavy element abundances show fewer and narrower absorption bands. Spectroscopic surveys have identified stars in the halo of our galaxy with very low abundances of heavy elements.

Element abundance patterns in the most metal-poor stars reflect pollution from first generation of stars formed: SMSS 0313-6708 has  $[\text{Fe}/\text{H}] < -7.1$  and  $[\text{C}/\text{H}] = -2.6$  and may show the imprint of a single early-time Supernova (Keller et al 2014) Figure from Frebel & Norris 2015.



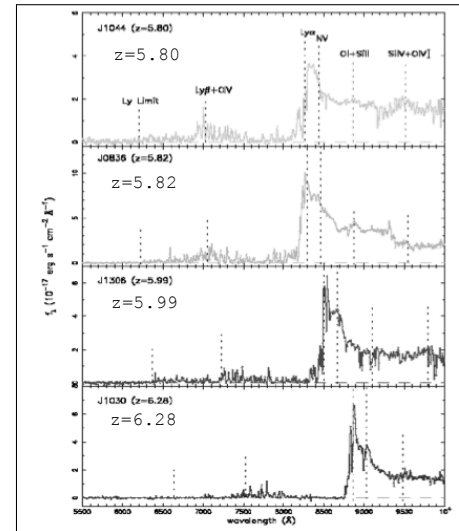
## Interpretation of Spectra

- Continuum with emission and/or absorption lines (and molecular bands and solid state dust features in the infrared)
- Continuum due to a range of processes,
  - thermal emission (characteristic of the temperature of a star, nebula or dust) :  $\lambda_{\text{max}}T = 2898$  [ T in K,  $\lambda$  in  $\mu\text{m}$  ]
  - Bremsstrahlung from electron-electron interactions in plasma
  - Non-thermal (synchrotron) emission at long wavelengths
  - Non-thermal (compton) emission at short wavelengths
- In the simplest case, a cold layer in front of a hot star will produce absorption lines, while
- A hot gas will produce emission lines from atoms and ions (see arc lamps) ; a cool gas may produce emission from molecules and neutral atoms.
  - In astronomical objects, conditions are often very different from those in terrestrial laboratories.

## Information from observations of lines

- Radial velocities and velocity components and distributions and hence dynamics, rotation, expansion and/or contraction, bulk or turbulent motions, outflow and/or accretion, pulsations, flares, astroseismology
- The physical conditions of astronomical bodies:
  - density, temperature, ionization state etc
- Ionic and element abundances, isotopic ratios in some cases
- Magnetic field strengths (Zeeman effect)
- Molecule (gas and condensed phases) and dust species, astrochemistry

## The search for the most distant objects



For some purposes, identification of lines and wavelengths may be sufficient, e.g. redshift determination. But even here, need to know which lines have been detected (e.g. Lyman Alpha in these high-z QSOs)

## Interstellar Absorption lines towards nearby stars

Observations of absorption lines produced by ions and atoms in the interstellar medium between the Earth and nearby stars are used to estimate the amounts of different species in the gas phase of the ISM.

High spectral resolution observations isolate different velocity components (along the line of sight), and the identification of different clumps of material

With narrow lines, and high quality spectra, may pick up hyperfine structure due to different isotopes

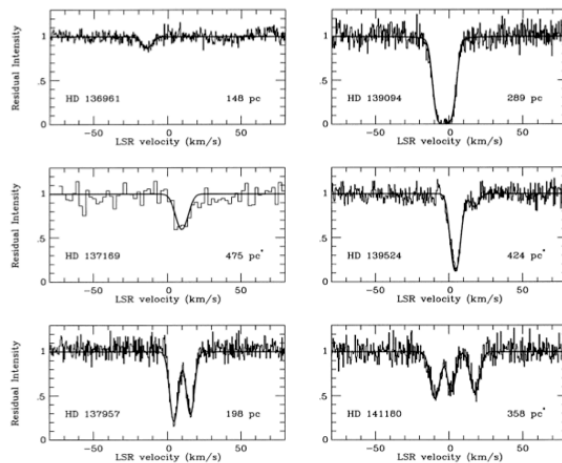
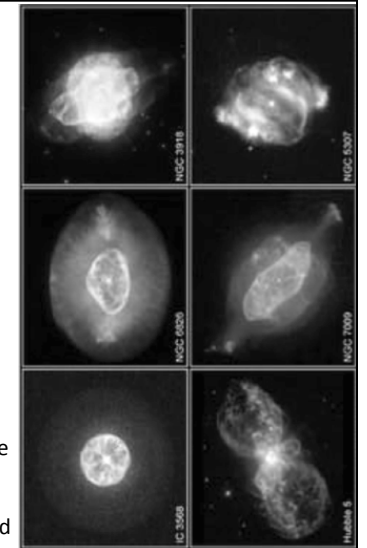


Figure 2. The interstellar Na D<sub>2</sub> lines towards the observed stars. The observed data are plotted as histograms, and the theoretical line profiles with the parameters given in Table 1 are shown superimposed. Distances are from Hipparcos, unless marked \*, in which case they are less certain photometric values

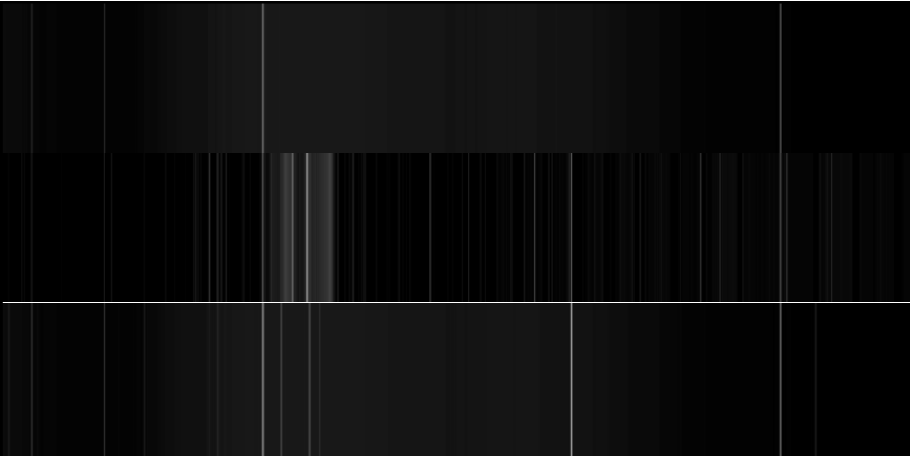
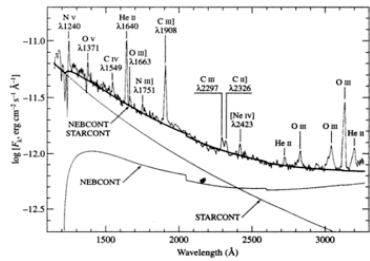
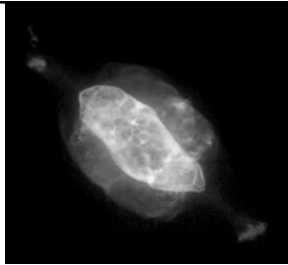
## Planetary nebulae and Photoionized gas

- laboratories for understanding atomic processes and photoionization by hot stars
  - Isolated systems
  - Single (or at least a small number of stars)
  - Central star excites gas ejected by the precursor
- Clues to stellar evolution
  - End point of red giants
  - Enrichment of the ISM
  - Production of white dwarfs
- Central stars have  $30,000 \text{ K} < T < 250,000 \text{ K}$ 
  - Ionization state of gas reflects stellar temperature
  - Chemical abundances reflect stellar evolution:
    - nuclear processing and dredge-up
  - Density structure reflects ejection mechanism and protoplanetary structure
  - Formation and processing of molecules and dust



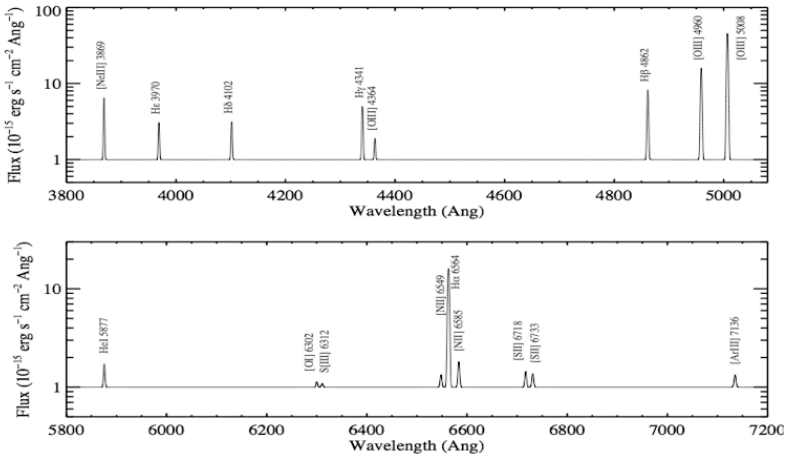
# Planetary Nebula NGC 7009

- Photo-ionised gas emission spectrum
  - Bright emission lines from hydrogen, helium, oxygen, nitrogen etc.
- Recombination lines of Hydrogen (and Helium): protons capture electrons in excited states which then cascade down
- Collisionally excited forbidden states in heavy elements, which have low transition probabilities, but can decay radiatively at low densities, cooling and acting as a thermostat for the gas

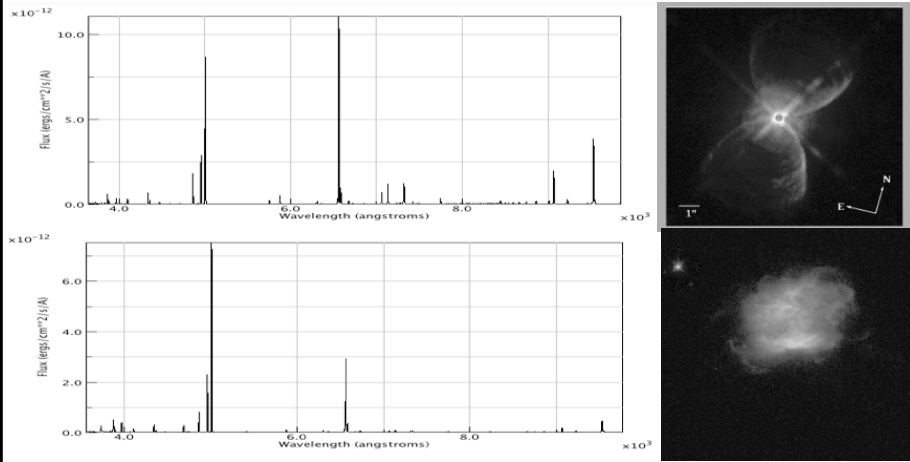


Visible spectrum of Planetary Nebula NGC 7027 flanked by the spectra of Hydrogen (top) and H + He (bottom) – with logarithmic scaling [from Kevin Volk]

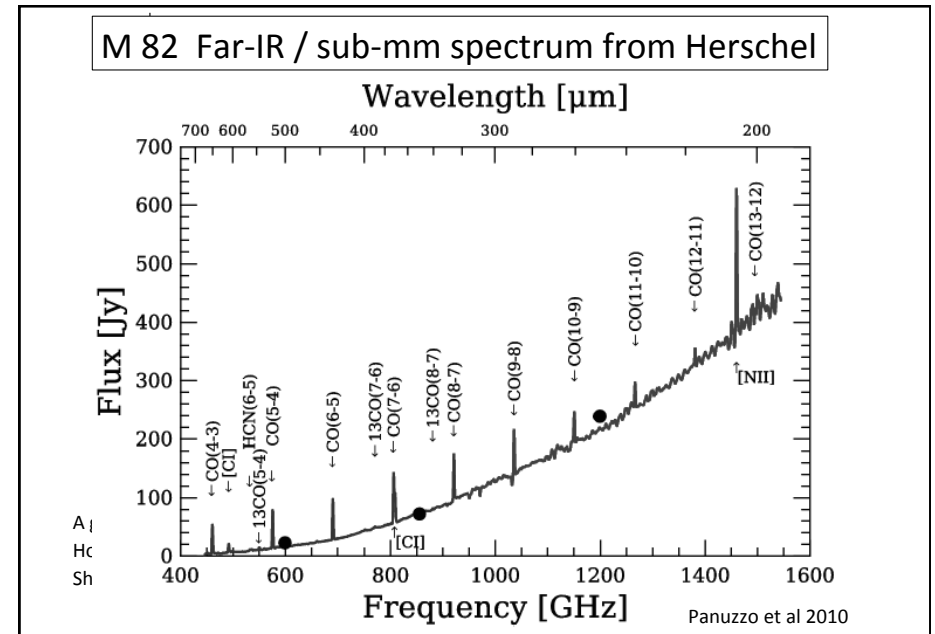
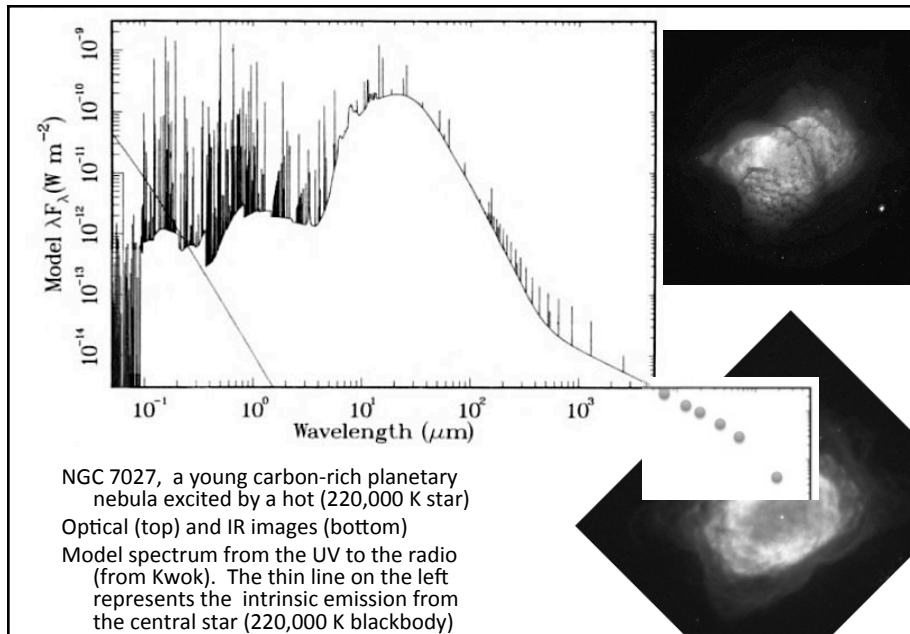
## Zoom in to the optical spectrum showing line identifications



## Spectra of Planetary Nebulae



Planetary nebulae spectra: Hubble 12 (top), Jonckhere 900. ejected material from evolved stars excited by the remnant stellar core (white dwarf) In high-excitation PN, most photons may emerge at 5007Å from the [OIII] forbidden line



## Recap on Atomic Physics

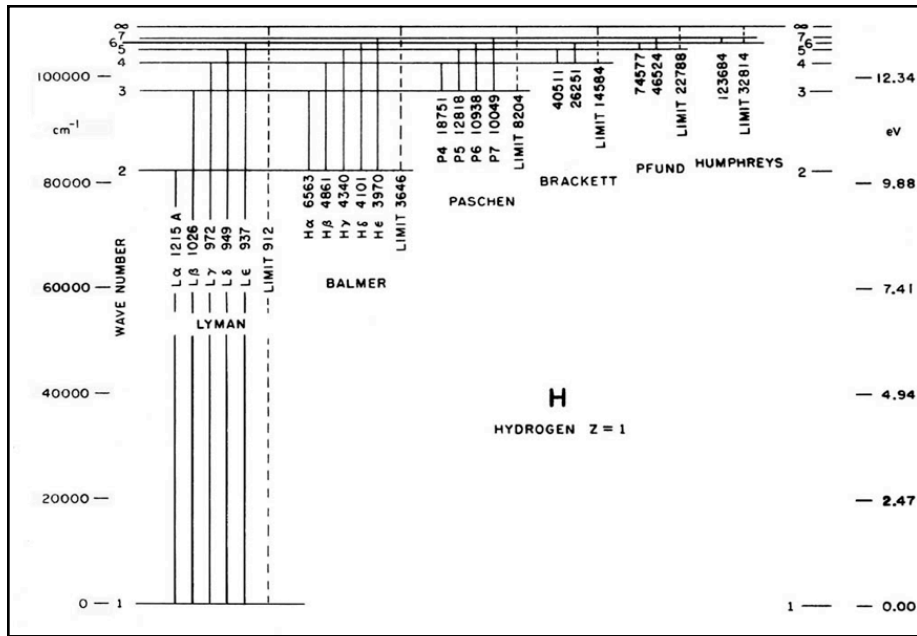
- Nomenclature: Ionization state denoted by roman numerals :
    - e.g. O III denotes  $\text{O}^{2+}$ , O I denotes neutral oxygen
  - Selection Rules – electric dipole transitions
    - Seen under lab conditions, with high densities
  - In astronomy, densities are often very low; intervals between collisions are long and we see Forbidden Lines – denoted by [ ]
    - e.g. [OIII] Forbidden transition in  $\text{O}^{2+}$
    - magnetic dipole or electric quadrupole transition, usually in the lowest electron configuration, with low transition probabilities
    - Generally arise in low lying levels as higher levels have more possible allowed transitions
- Also have electric dipole lines with  $\Delta s \neq 0$ ,
- semi-forbidden lines, one square bracket e.g. C III]

## Selection Rules

(from J Tennyson 2005)

Table 5.1. Selection rules for atomic spectra. Rules 1, 2 and 3 must always be obeyed. For electric dipole transitions, intercombination lines violate rule 4 and forbidden lines violate rule 5 and/or 6. Electric quadrupole and magnetic dipole transitions are also described as forbidden.

	Electric dipole	Electric quadrupole	Magnetic dipole
1.	$\Delta J = 0, \pm 1$ Not $J = 0 - 0$	$\Delta J = 0, \pm 1, \pm 2$ Not $J = 0 - 0, \frac{1}{2} - \frac{1}{2}, 0 - 1$	$\Delta J = 0, \pm 1$ Not $J = 0 - 0$
2.	$\Delta M_J = 0, \pm 1$	$\Delta M_J = 0, \pm 1, \pm 2$	$\Delta M_J = 0, \pm 1$
3.	Parity changes	Parity unchanged	Parity unchanged
4.	$\Delta S = 0$	$\Delta S = 0$	$\Delta S = 0$
5.	One electron jumps $\Delta n$ any $\Delta l = \pm 1$	One or no electron jumps $\Delta n$ any $\Delta l = 0, \pm 2$	No electron jumps $\Delta n = 0$ $\Delta l = 0$
6.	$\Delta L = 0, \pm 1$ Not $L = 0 - 0$	$\Delta L = 0, \pm 1, \pm 2$ Not $L = 0 - 0, 0 - 1$	$\Delta L = 0$



## 21cm Hyperfine transition in H

- Spin-flip transition in the ground state of Hydrogen. 1420MHz, 21cm
- Very low probability:  $A \sim 3 \times 10^{-15} \text{ sec}^{-1}$
- Predicted in 1944, first detected in 1951
- But vast clouds of Hydrogen make it easily detectable – a tracer of neutral Hydrogen in our (and other) Galaxy
- Potentially very important for tracing the ionization conditions in the early Universe

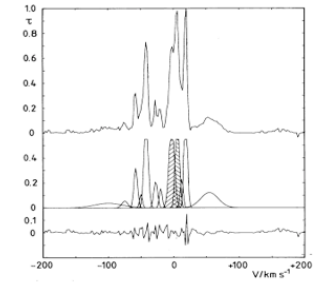
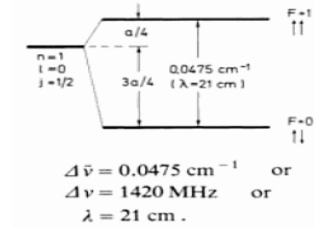
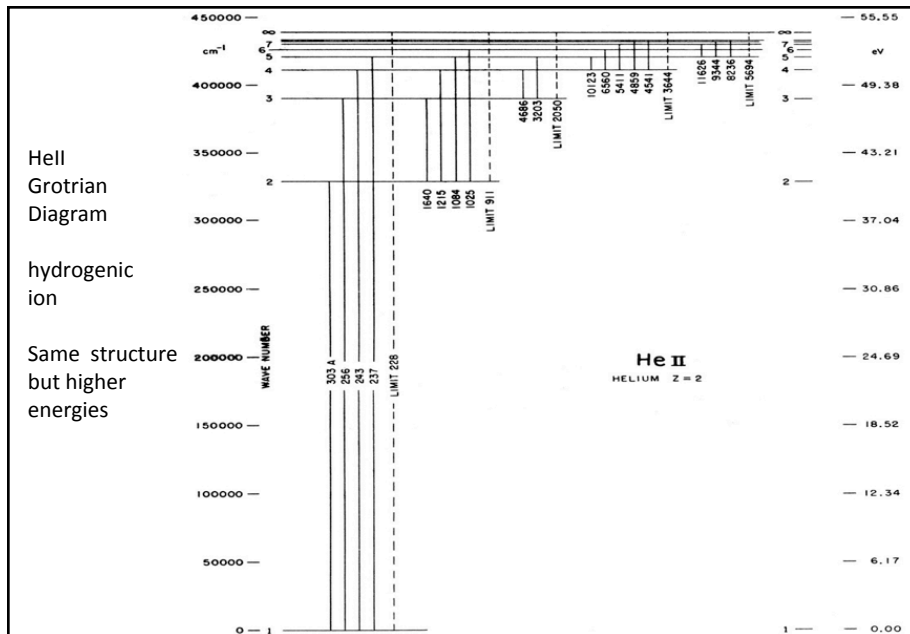
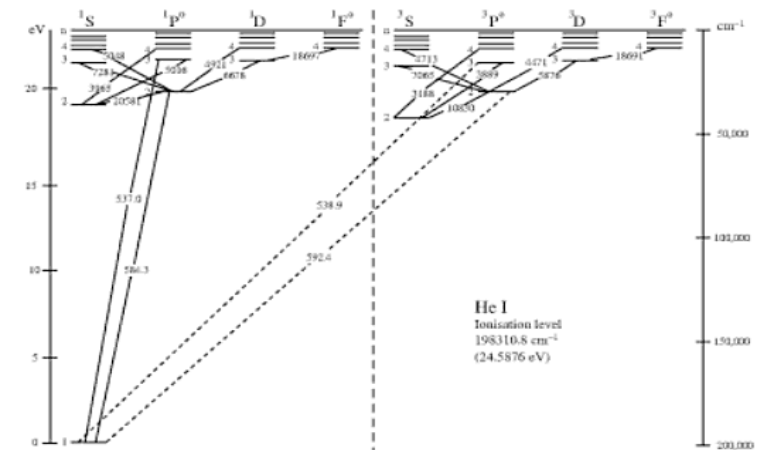


Fig. 4. The absorption profile of SgrB2 and its Gaussian analysis.



## Helium I Grotrian Diagram

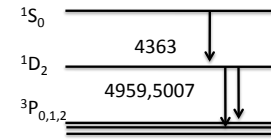
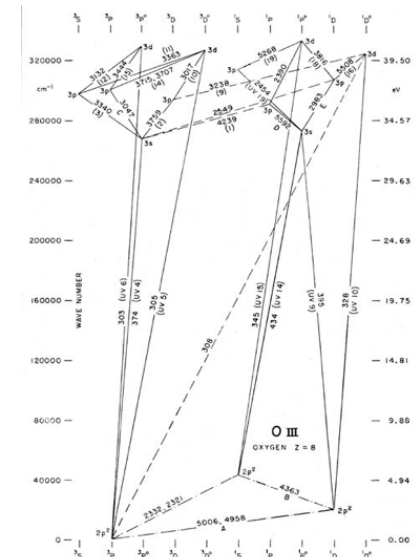
Singlet and triplet spectra due to electrons with parallel or antiparallel spin



# Ionization Potentials

Atom	Stage of ionization													
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV
1 H	13.59844													
2 He	24.58741	54.41778												
3 Li	5.39172	75.64018												
4 Be	9.32263	18.21116	153.897											
5 B	8.29803	25.15484	37.931	259.366	340.22									
6 C	11.26030	24.38332	47.888	64.492	392.08	489.98								
7 N	14.53414	29.6013	47.449	77.472	97.89	552.06	667.03							
8 O	13.61806	35.11730	54.936	77.413	113.90	138.12	739.29	871.41						
9 F	17.42282	34.97082	62.708	87.140	114.24	157.17	185.19	953.91	1103.1					
10 Ne	21.56454	40.96328	63.45	97.12	126.21	157.93	207.28	239.10	1195.8	1362.2				
11 Na	5.13908	47.2864	71.620	98.91	138.40	172.18	208.50	264.25	299.9	1465.1	1648.7			
12 Mg	7.64624	15.03528	80.144	109.265	141.27	186.76	225.02	265.96	328.1	367.5	1761.8	1963		
13 Al	5.98577	18.82856	28.448	119.99	153.83	190.49	241.76	284.66	330.1	398.8	442.0	2086	2304	
14 Si	8.15169	16.34585	33.493	45.142	166.77	205.27	246.49	303.54	351.1	401.4	476.4	523	2438	2673
15 P	10.48669	19.7694	30.203	51.444	65.03	220.42	263.57	309.60	372.1	424.4	479.5	561	612	2817
16 S	10.36001	23.3379	34.79	47.222	72.59	88.05	280.95	328.75	379.6	447.5	504.8	564	652	707
17 Cl	12.96764	23.814	39.61	53.465	67.8	97.03	114.20	348.28	400.1	455.6	529.3	592	657	750
18 Ar	15.75962	27.62967	40.74	59.81	75.02	91.01	124.32	143.46	422.5	478.7	539.0	618	686	756
19 K	4.34066	31.63	45.806	60.91	82.66	99.4	117.56	154.88	175.8	503.8	564.7	629	715	787
20 Ca	6.11316	11.87172	50.913	67.27	84.50	108.78	127.2	147.24	188.5	211.3	591.9	657	727	818
21 Sc	6.56144	12.79967	24.757	73.489	91.65	111.68	138.0	158.1	180.0	225.2	249.8	688	757	831
22 Ti	6.8282	13.5755	27.492	43.267	99.30	119.53	140.8	170.4	192.1	215.9	265.1	292	788	863
23 V	6.7463	14.66	29.311	46.71	65.28	128.1	150.6	173.4	205.8	230.5	255.1	308	336	896
24 Cr	6.76664	16.4857	30.96	49.16	69.46	90.64	161.18	184.7	209.3	244.4	270.7	298	355	384
25 Mn	7.43402	15.63999	33.668	51.2	72.4	95.6	119.20	194.5	221.8	248.3	286.0	314	344	404
26 Fe	7.9024	16.1878	30.652	54.8	75.0	99.1	124.98	151.06	233.6	262.1	290.2	331	361	392
27 Co	7.8810	17.083	33.50	51.3	79.5	103	131	160	186.2	272.6	305	336	379	411
28 Ni	7.6398	18.16884	35.19	54.9	75.5	108	134	164	193	224.6	321	352	384	430
29 Cu	7.72638	20.29240	36.841	55.2	79.9	103	139	167	199	232	266	369	401	435
30 Zn	9.39405	17.96440	39.723	59.4	82.6	108	136	175	203	238	274	311	412	454

- O III (O<sup>++</sup>) energy level (Grotrian) diagram
- Transitions within the ground state are forbidden by electric dipole transition rules, but allowed at low probability as electric quadrupole, magnetic dipole transitions
- Populated by electron collisions



Transitions between the  $^3P_{0,1,2}$  ground state levels give rise to bright lines in the far Infrared.

Neutral Aluminium  
 $1s^2 2s^2 2p^6 3s^2 3p^1$

Al I Grotrian diagram

- The separation of the  $^2P_{3/2} - ^2P_{1/2}$  fine structure levels in the ground state is  $112 \text{ cm}^{-1}$ , giving a line at  $\lambda \sim 90 \text{ nm}$
- FeXIV has the same electronic structure but the  $Z^4$  dependence puts the transition at 503 nm

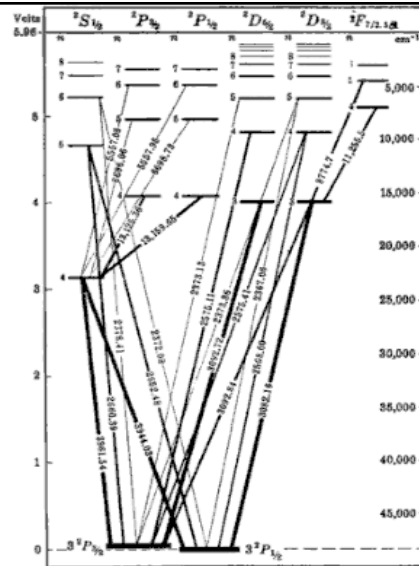


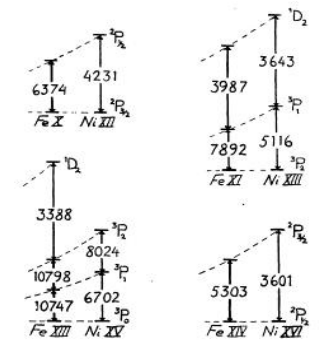
Fig. 73. Energy Level Diagram of Al I [Grotrian (8)].  $n$  is the true principal quantum number of the emission electron. Only the normal doublet terms are indicated, all of which go to the same limit. Series of anomalous  $^2P_{3/2}$  levels are shown by dashed lines.

## FeXIV Coronium at 530.3nm

By extrapolating along the isoelectronic sequence from Al I, Si II, P III, S IV, Cl V, Ar VI ....

$z = 13, 14, 15, 16, 17, 18 \dots$

Edlen & Grotrian identified the 'Coronium' line with the  $^2P_{3/2} - ^2P_{1/2}$  transition in Fe XIV ( $z=26$ )





## Solar Abundances

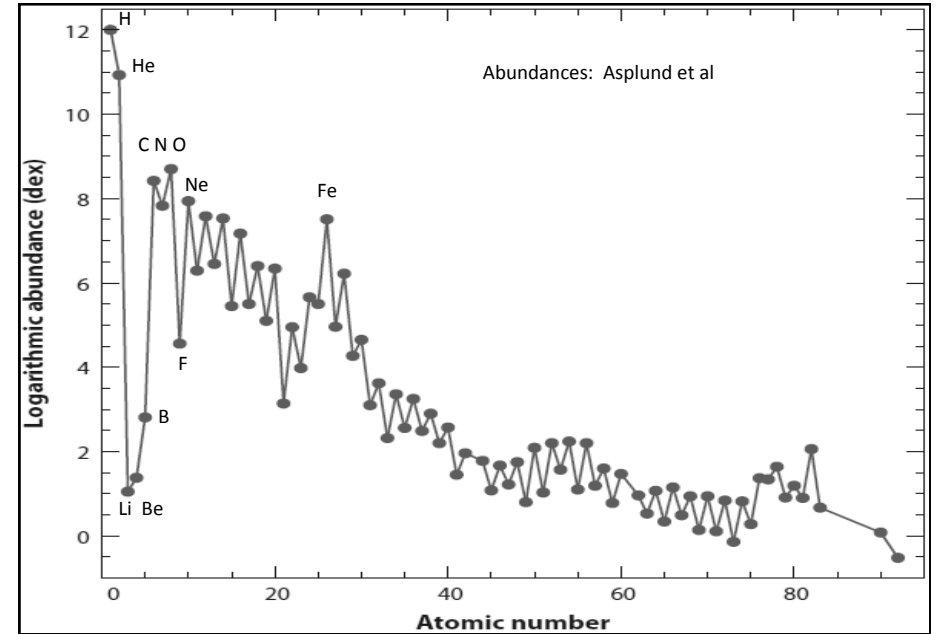
(Asplund et al 2009)

Abundances are often expressed as logarithmic abundances with respect to H = 12.00

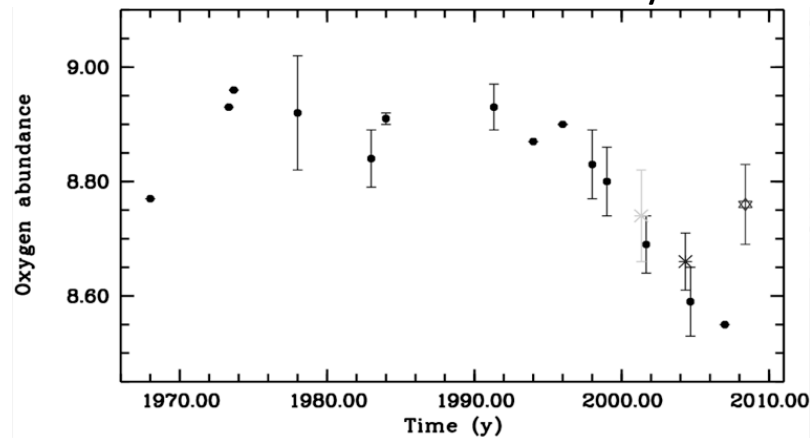
How is it that trace elements have prominent spectral features in stars and nebulae?

We need to understand the energy level structure and level populations at different temperatures in different elements in their atomic and ionic states

Atom (X)	log n	n(X)/n(H) (by number)	n(X)/n(He) (by number)	mass fraction	
H	1	12.00	1.000E+00	1.175E+01	7.347E-01
He	2	10.93	8.511E-02	1.000E+00	2.483E-01
Li	3	1.05	1.122E-11	1.318E-10	5.675E-11
Be	4	1.38	2.399E-11	2.818E-10	1.576E-10
B	5	2.70	5.012E-10	5.888E-09	3.949E-09
C	6	8.39	2.455E-04	2.884E-03	2.149E-03
N	7	7.78	6.026E-05	7.079E-04	6.153E-04
O	8	8.66	4.571E-04	5.370E-03	5.331E-03
F	9	4.56	3.631E-08	4.266E-07	5.028E-07
Ne	10	7.84	6.918E-05	8.128E-04	1.018E-03
Na	11	6.17	1.479E-06	1.738E-05	2.480E-05
Mg	12	7.53	3.388E-05	3.981E-04	6.004E-04
Al	13	6.37	2.344E-06	2.754E-05	4.610E-05
Si	14	7.51	3.236E-05	3.802E-04	6.625E-04
P	15	5.36	2.291E-07	2.692E-06	5.171E-06
S	16	7.14	1.380E-05	1.622E-04	3.226E-04
Cl	17	5.50	3.162E-07	3.715E-06	8.171E-06
Ar	18	6.18	1.514E-06	1.778E-05	4.407E-05
K	19	5.08	1.202E-07	1.413E-06	3.426E-06
Ca	20	6.31	2.042E-06	2.399E-05	5.965E-05
Sc	21	3.05	1.122E-09	1.318E-08	3.677E-08
Ti	22	4.90	7.943E-08	9.333E-07	2.773E-06
V	23	4.00	1.000E-08	1.175E-07	3.713E-07
Cr	24	5.64	4.365E-07	5.129E-06	1.655E-05
Mn	25	5.39	2.455E-07	2.884E-06	9.830E-06
Fe	26	7.45	2.818E-05	3.311E-04	1.147E-03
Co	27	4.92	8.318E-08	9.772E-07	3.573E-06
Ni	28	6.23	1.698E-06	1.995E-05	7.267E-05



## Determinations of the solar Oxygen abundance over the last 40 years



Now seems to have stabilised at O/H = 8.69 (Grevesse et al 2013), with previous discrepancies ascribed to use of 1D rather than 3D models, non-LTE analyses and careful attention to blended lines

Copies of Lecture Slides

and problem sets

[www-astro.physics.ox.ac.uk/~pfr/C1.htm](http://www-astro.physics.ox.ac.uk/~pfr/C1.htm)

Text books: various but

"Physics and Chemistry of the Interstellar Medium" by Sun Kwok

"Physics of the Interstellar and Intergalactic Medium" by Bruce Draine

are recent and comprehensive