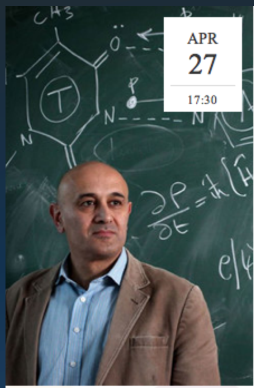
Oxford May Music

- The annual May Music Festival begins on Wednesday 27th April
- Free participation for all events to all undergraduate and postgraduate students in physics.
- Email Brian Foster

- Note 1st May 17:30 The Dark Universe : Jo Dunkley



Life on the Edge: the coming of age of quantum biology

Wednesday, April 27, 2016
17:30 – 18:30
Holywell Music Room (map)

Prof Jim Al-Khalili
University of Surrey

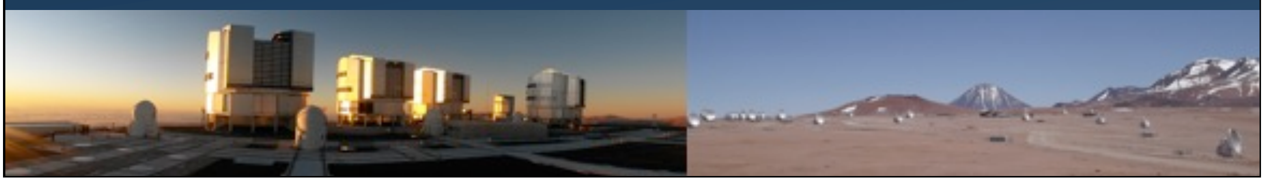
For almost a century, physicists and chemists have developed and learned to harness and apply the strange rules of quantum mechanics to explain the microscopic world of atoms and molecules and the elementary building blocks of our universe. But biologists have thus far not needed to learn about this powerful yet counterintuitive field. Now, experimental evidence and theoretical advances have pushed quantum biology to the forefront of research. This talk will shed light on some familiar phenomena in biology, from photosynthesis to smell, that seem to require quantum mechanics in order to be full understood.

http://www.oxfordmaymusic.co.uk/2016prog/

Atomic Processes and the Interstellar Medium

Extracting quantitative measurements from astronomical observations

Patrick Roche



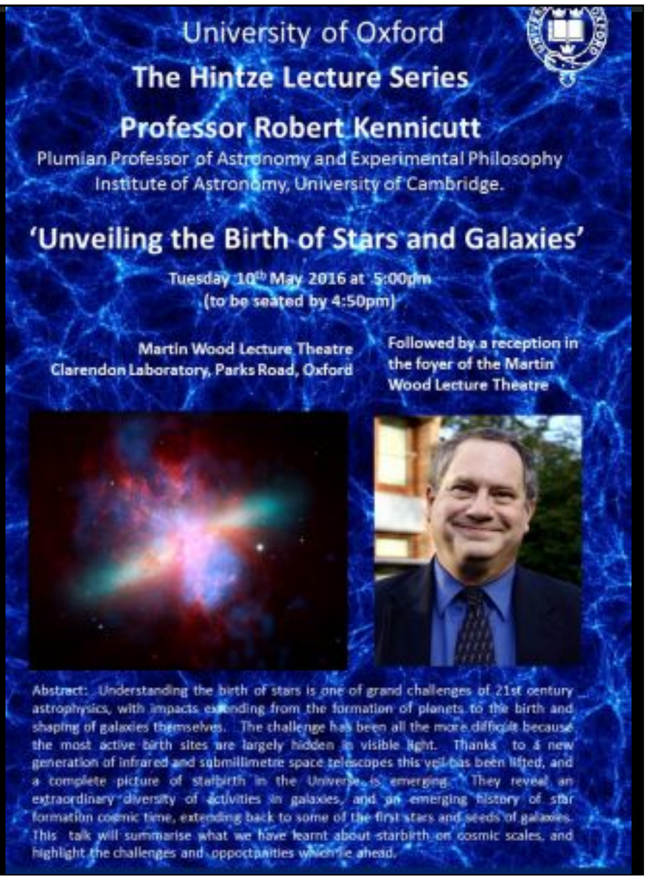
Astrophysics seminars

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



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 ~ few gram/m^3 for main sequence stars
- Ionized nebulae e.g. HII regions, planetary nebulae
  - T(electron) ~ 10000K,
  - n(electron)~ N(proton) 10^6 - 10^{12} m^{-3}
  - T(dust) ~ 50K
- Cold and denser molecular clouds (T<< 100 K)
- Hot and lower-density plasmas - e.g. shock heated gas, T~10^6K, n<100
- Velocities: cold ISM 1km/s - SN outflows 10^4 km/s
- Overall density of the Universe is ~ 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

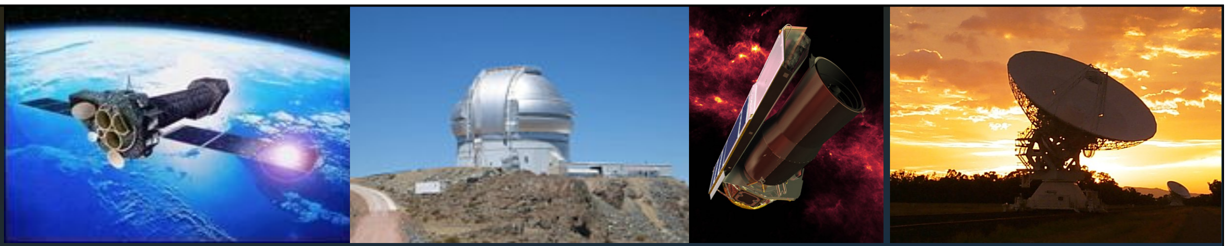
Spectra provide information on the structure and dynamics of stars, planets and galaxies – and have provided evidence for the Big Bang, expansion of the Universe, dark matter, exosolar planets

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

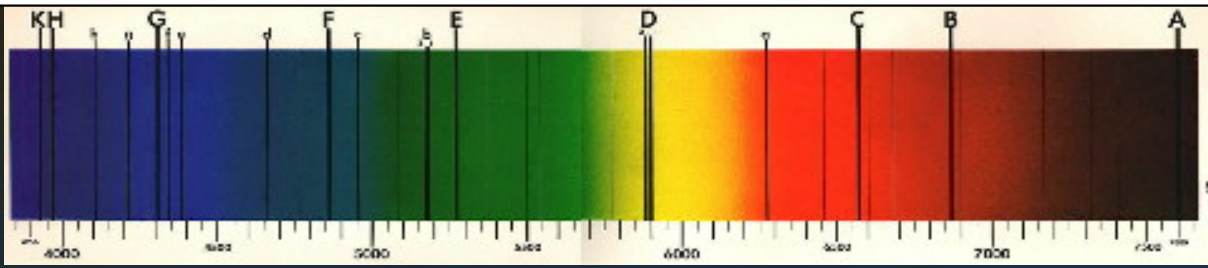
1870 Lockyer and Janssen proposed a new element Helium from solar spectra

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 5007A 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.



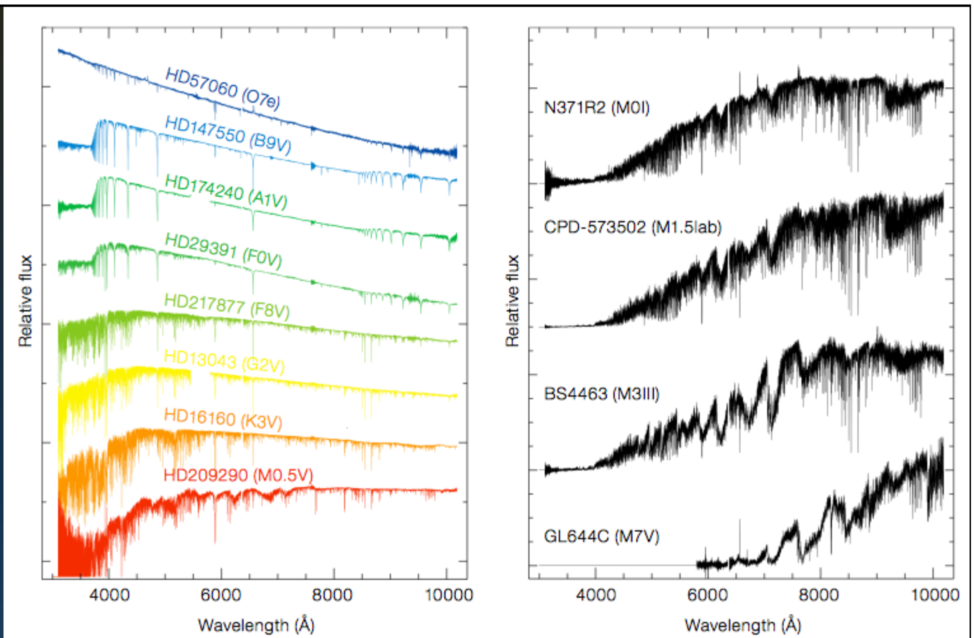
Fraunhofer Spectrum of the Sun
A,B – telluric atmospheric absorption bands by ozone
C – Hydrogen (Balmer alpha)
D – Sodium Doublet
E – Iron
F,G – Hydrogen (Balmer beta, gamma)
H,K - Ca+

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).

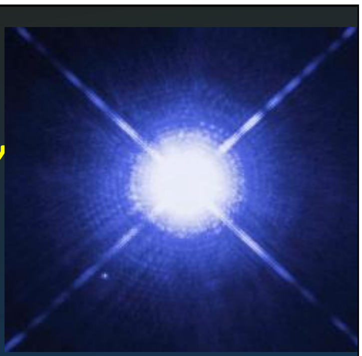
Stellar Spectra

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



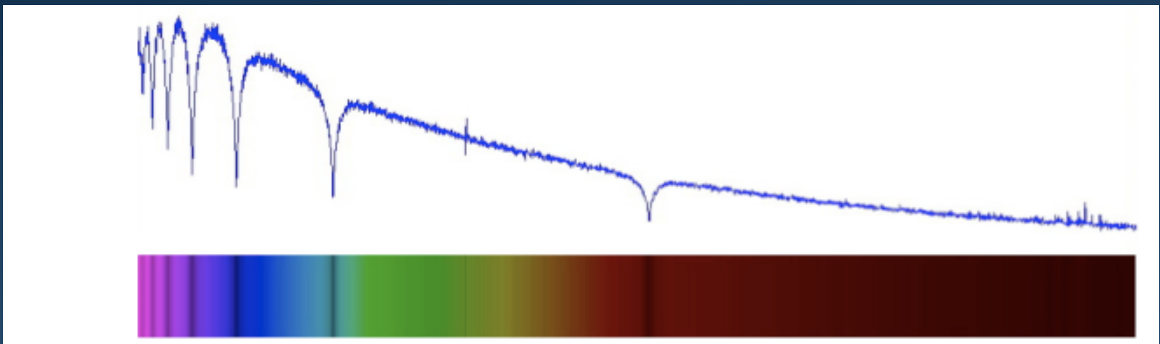
- Strong quasi-blackbody continuum emission but with marked spectral structure and absorption lines: the break at ~350nm (the 'Balmer Jump' due to an excitation edge in H), narrow atomic lines and broader molecular bands
- Note the increasingly prominent absorption as temperature decreases

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



Sirius A and B

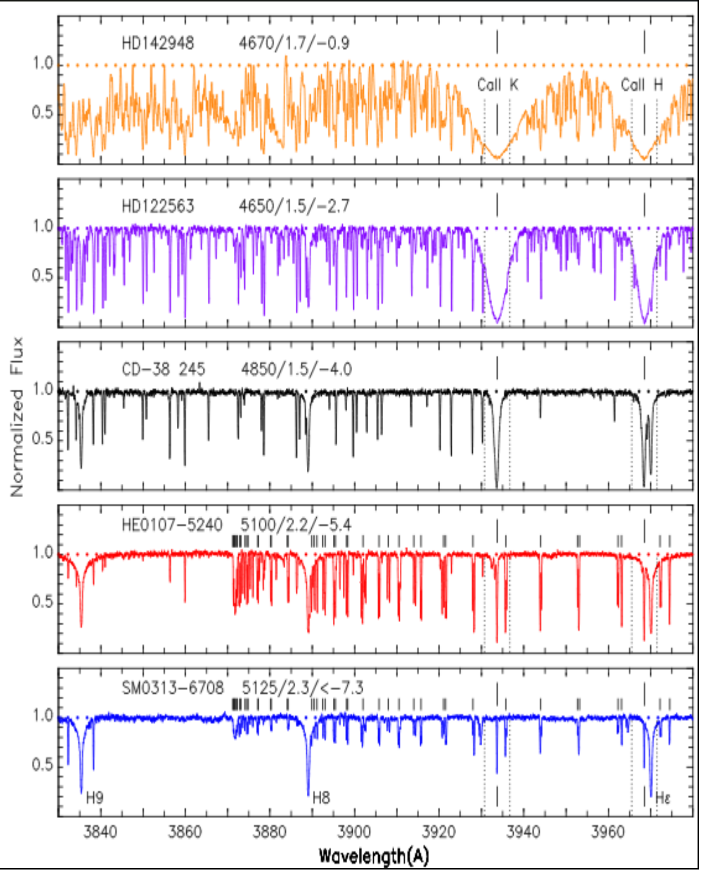
- E.g. White dwarf : the end product of intermediate mass star evolution after going through planetary nebula phase.
- Dense. High surface gravity leads to pressure-broadening of lines



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 [Fe/H] < -7.1 and [C/H] = -2.6 and may show the imprint of a single early-time Supernova (Keller et al 2014) Figure from Frebel & Norris 2015.



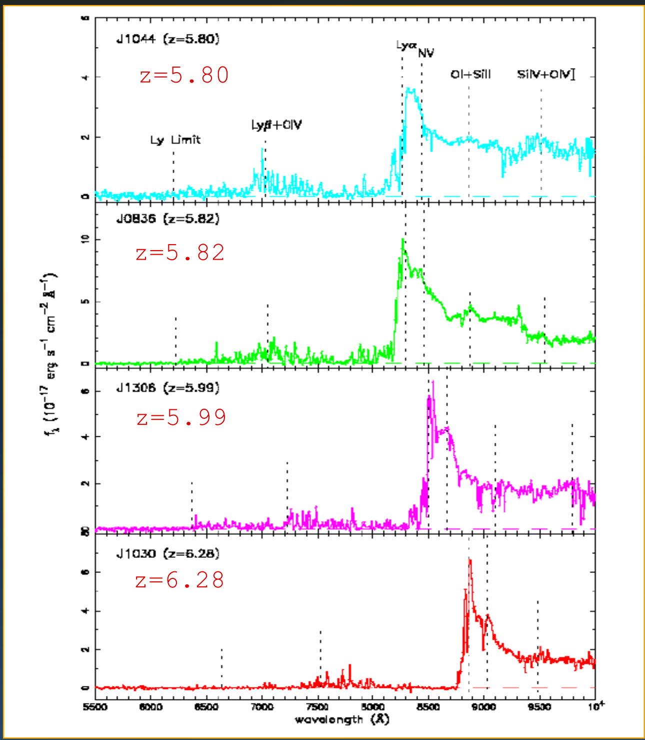
Interpretation of Spectra

- 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) : $\lambda_{max}T = 2898$ [T in K, λ in μm]
  - 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

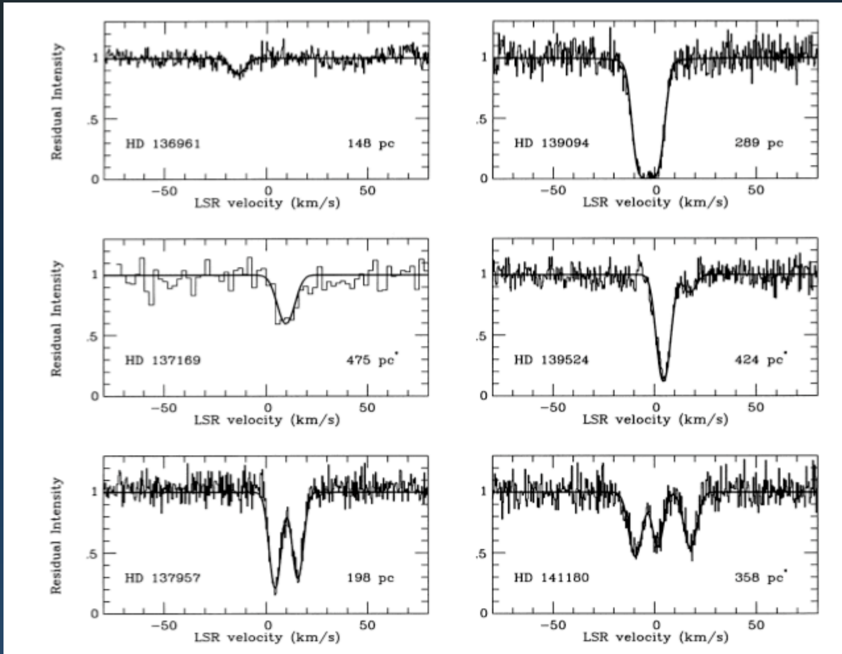
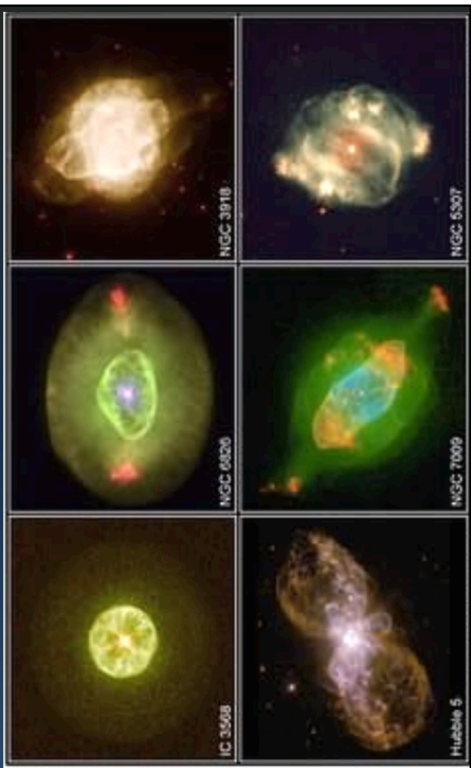


Figure 2. The interstellar Na D_2 lines towards the observed stars. The observed data are plotted as histograms, and the theoretical line profiles with the parameters given in Table 1 are shown superimposed. Distances are from *Hipparcos*, unless marked *, in which case they are less certain photometric values (Table 1).

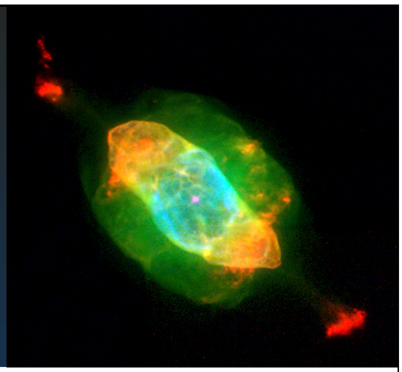
Planetary nebulae and Photoionized gas

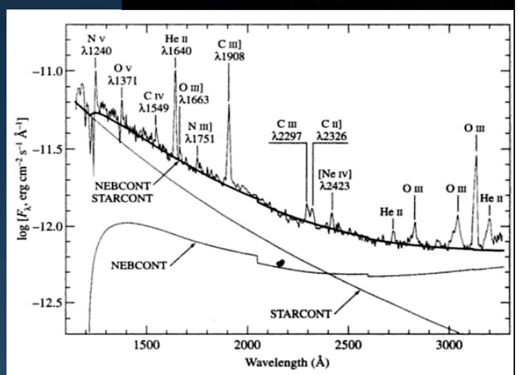
- laboratories for understanding atomic processes and photoionization by hot stars
  - Isolated systems
  - Single (or at least a small number of stars)
  - Central star excites gas ejected by the precursor
- Clues to stellar evolution
  - End point of red giants
  - Enrichment of the ISM
  - Production of white dwarfs
- Central stars have 30,000 K < T < 250,000 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

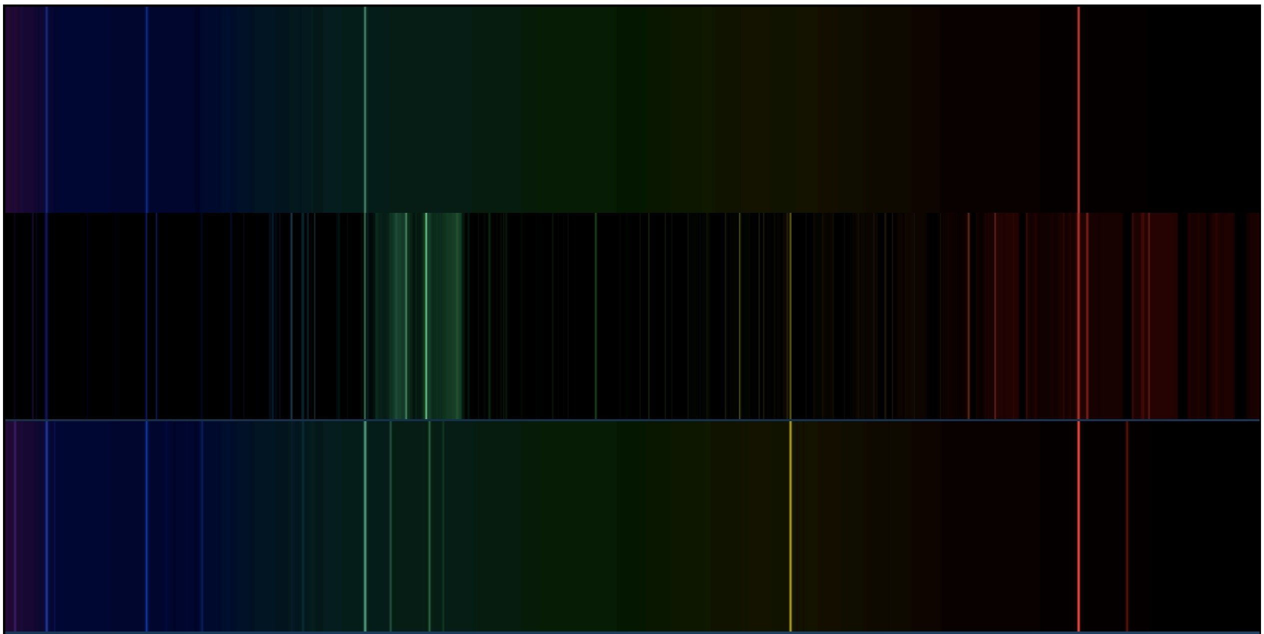


Planetary Nebula NGC 7009

- 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

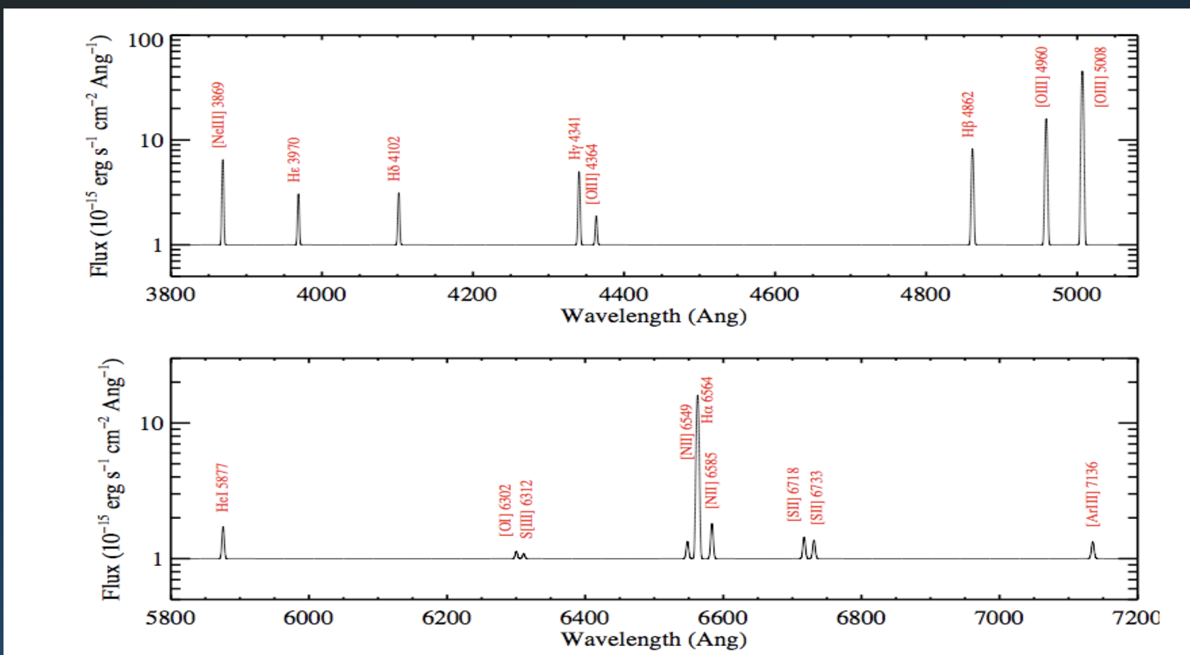




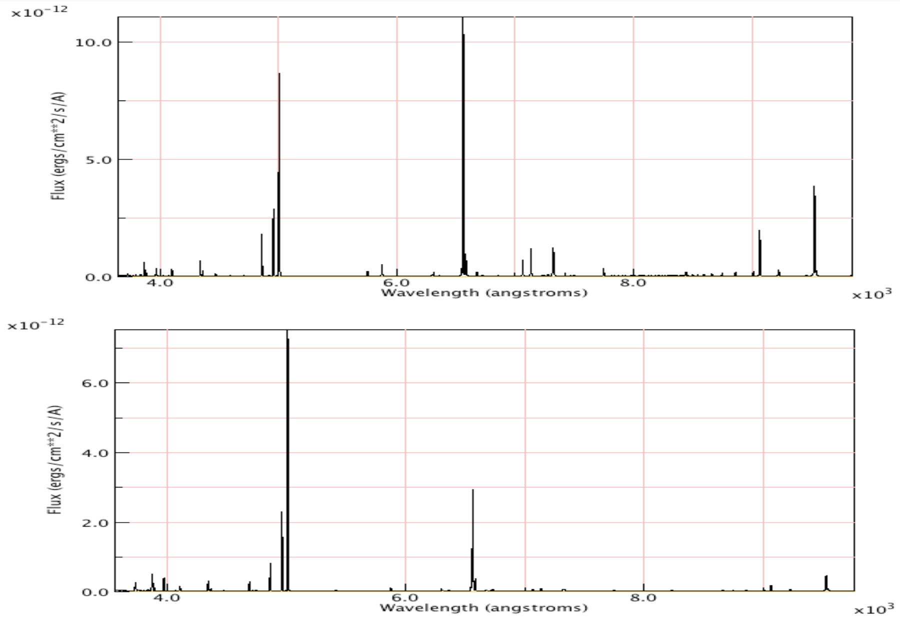


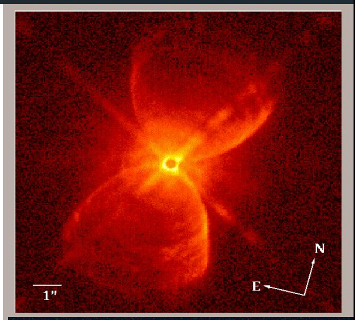
Visible spectrum of Planetary Nebula NGC 7027 flanked by the spectra of Hydrogen (top) and H + He (bottom) – with logarithmic scaling
[from Kevin Volk]

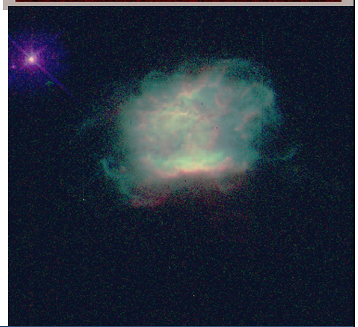
Zoom in to the optical spectrum showing line identifications



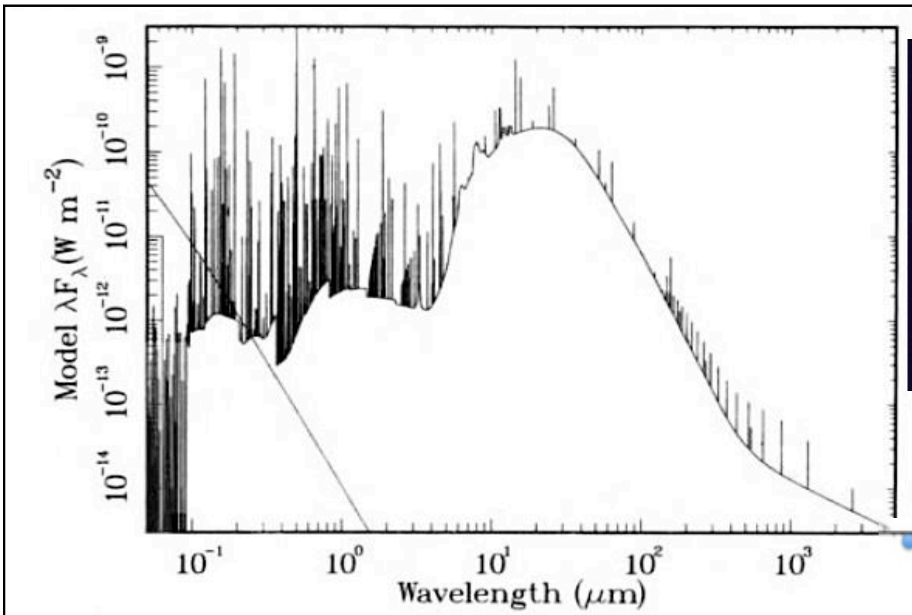
Spectra of Planetary Nebulae

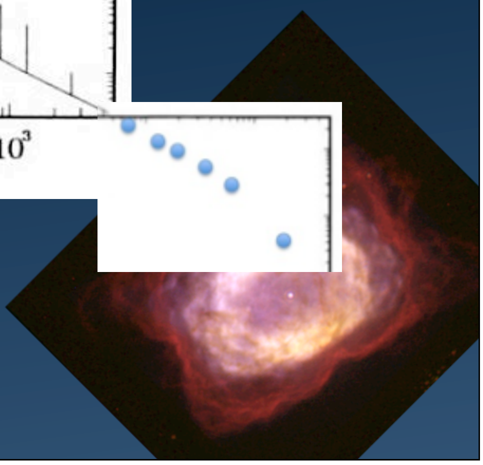






Planetary nebulae spectra: Hubble 12 (top), Jonckhere 900.
ejected material from evolved stars excited by the remanant stellar core (white dwarf)
In high-excitation PN, most photons may emerge at 5007A from the [OIII] forbidden line



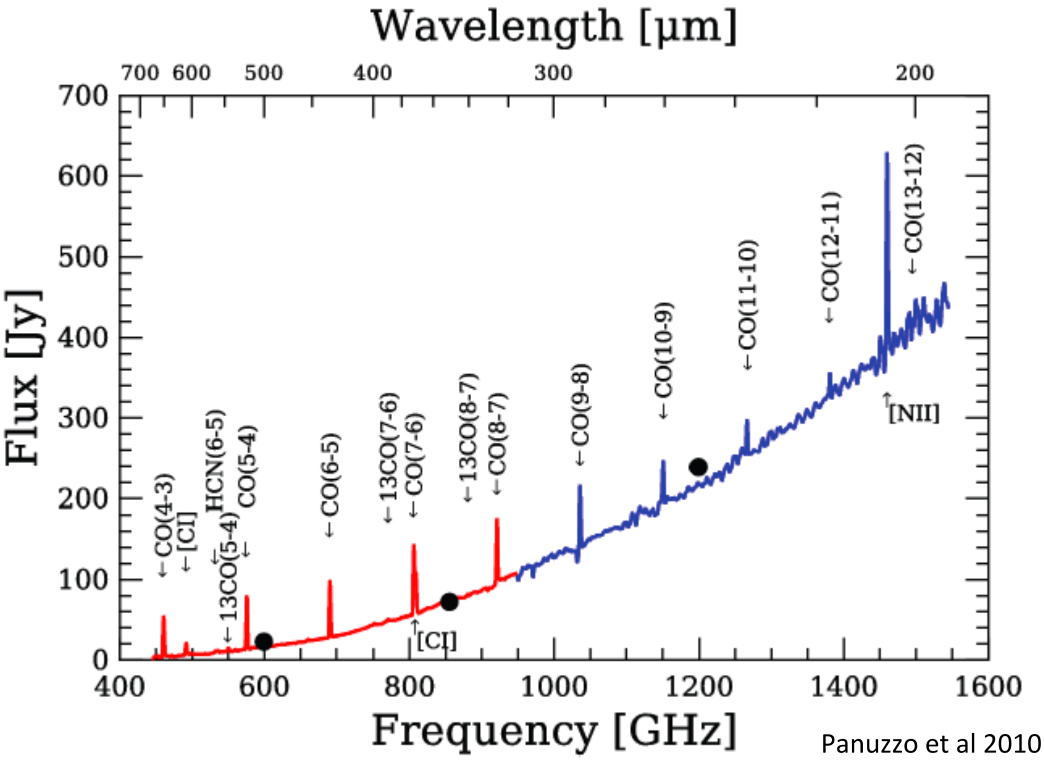


NGC 7027, a young carbon-rich planetary nebula excited by a hot (220,000 K star)

Optical (top) and IR images (bottom)

Model spectrum from the UV to the radio (from Kwok). The thin line on the left represents the intrinsic emission from the central star (220,000 K blackbody)

M 82 Far-IR / sub-mm spectrum from Herschel



Panuzzo et al 2010

Recap on Atomic Physics

- Nomenclature: Ionization state denoted by roman numerals :
  - e.g O III denotes 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 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

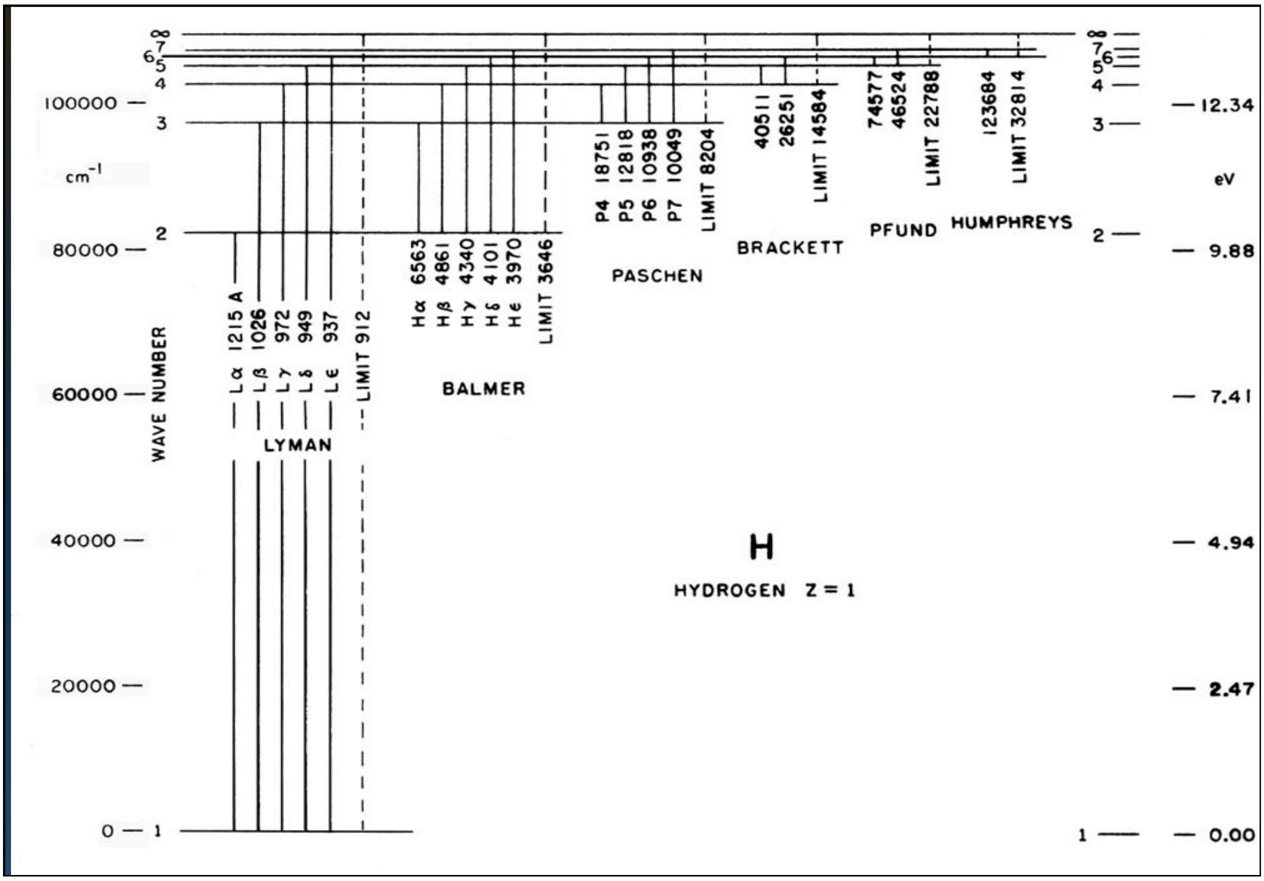
  Also have electric dipole lines with $\Delta s \neq 0$,
  - semi-forbidden lines, one square bracket e.g. C III]

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 Δn any $\Delta l = \pm 1$	One or no electron jumps Δn 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 ~3 x 10 $^{-15}$ 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

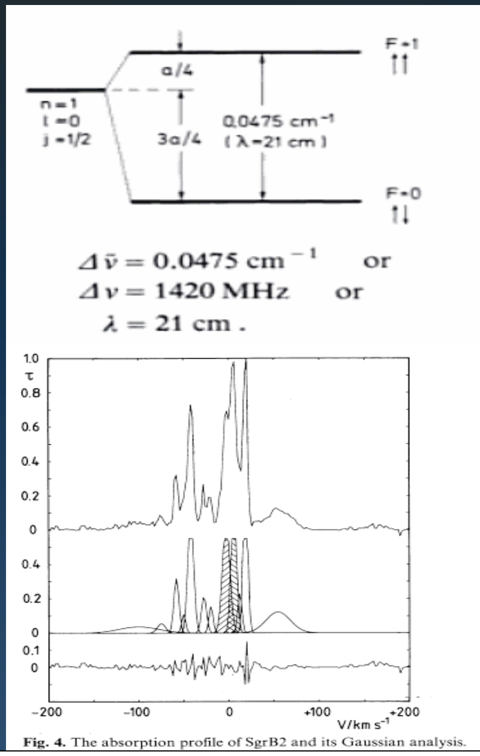
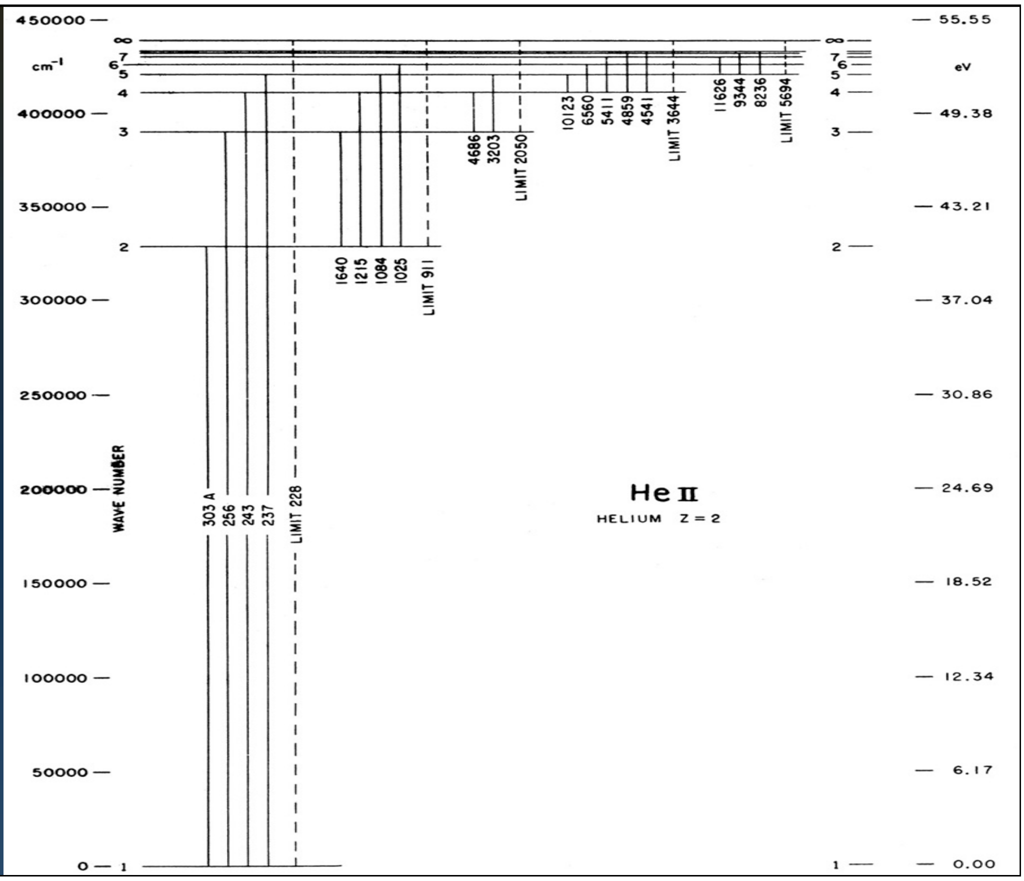


Fig. 4. The absorption profile of SgrB2 and its Gaussian analysis.

HeII Grotrian Diagram

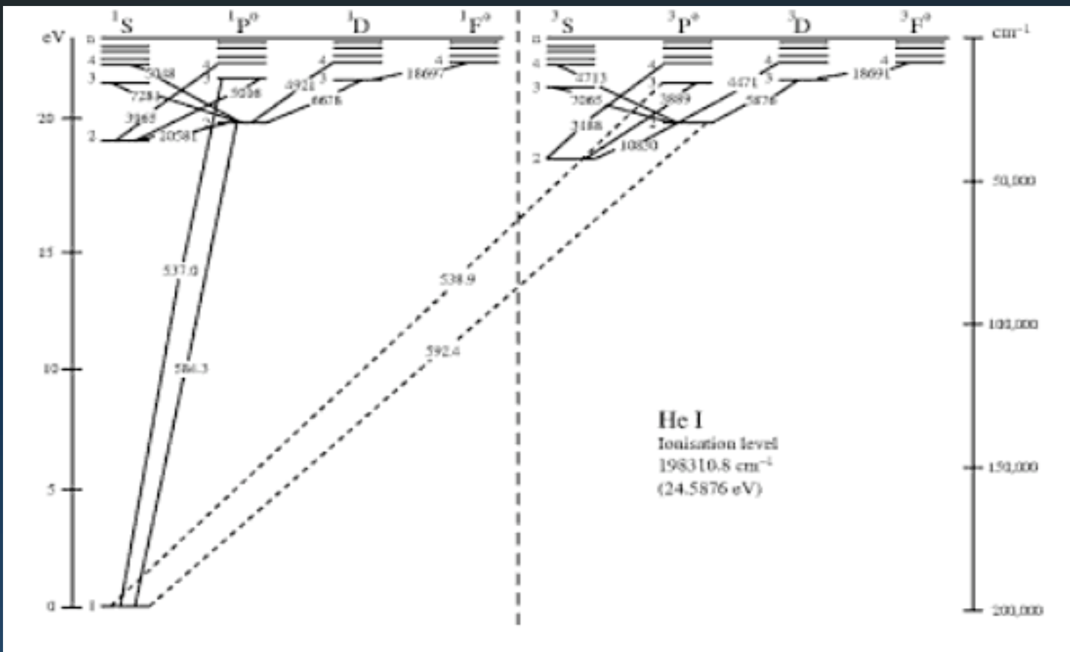
hydrogenic ion

Same structure but higher energies



Helium I Grotrian Diagram

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

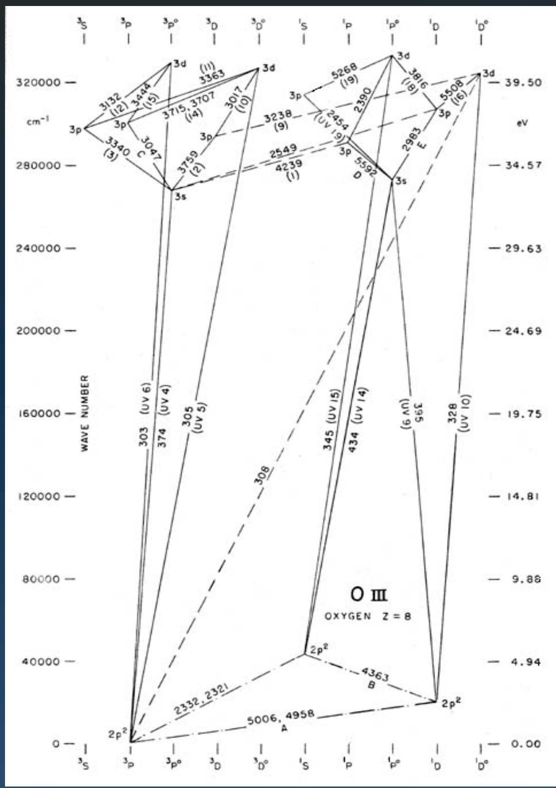


Ionization Potentials (eV)

		Stage of ionization													
Atom		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV
1	H	13.598 44													
2	He	24.587 41	54.417 78												
3	Li	5.391 72	75.640 18	122.454											
4	Be	9.322 63	18.211 16	153.897	217.713										
5	B	8.298 03	25.154 84	37.931	259.366	340.22									
6	C	11.260 30	24.383 32	47.888	64.492	392.08	489.98								
7	N	14.534 14	29.601 3	47.449	77.472	97.89	552.06	667.03							
8	O	13.618 06	35.117 30	54.936	77.413	113.90	138.12	739.29	871.41						
9	F	17.422 82	34.970 82	62.708	87.140	114.24	157.17	185.19	953.91	1 103.1					
10	Ne	21.564 54	40.963 28	63.45	97.12	126.21	157.93	207.28	239.10	1 195.8	1 362.2				
11	Na	5.139 08	47.286 4	71.620	98.91	138.40	172.18	208.50	264.25	299.9	1 465.1	1 648.7			
12	Mg	7.646 24	15.035 28	80.144	109.265	141.27	186.76	225.02	265.96	328.1	367.5	1 761.8	1 963		
13	Al	5.985 77	18.828 56	28.448	119.99	153.83	190.49	241.76	284.66	330.1	398.8	442.0	2 086	2 304	
14	Si	8.151 69	16.345 85	33.493	45.142	166.77	205.27	246.49	303.54	351.1	401.4	476.4	523	2 438	2 673
15	P	10.486 69	19.769 4	30.203	51.444	65.03	220.42	263.57	309.60	372.1	424.4	479.5	561	612	2 817
16	S	10.360 01	23.337 9	34.79	47.222	72.59	88.05	280.95	328.75	379.6	447.5	504.8	564	652	707
17	Cl	12.967 64	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	15.759 62	27.629 67	40.74	59.81	75.02	91.01	124.32	143.46	422.5	478.7	539.0	618	686	756
19	K	4.340 66	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	6.113 16	11.871 72	50.913	67.27	84.50	108.78	127.2	147.24	188.5	211.3	591.9	657	727	818
21	Sc	6.561 44	12.799 67	24.757	73.489	91.65	111.68	138.0	158.1	180.0	225.2	249.8	688	757	831
22	Ti	6.828 2	13.575 5	27.492	43.267	99.30	119.53	140.8	170.4	192.1	215.9	265.1	292	788	863
23	V	6.746 3	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	6.766 64	16.485 7	30.96	49.16	69.46	90.64	161.18	184.7	209.3	244.4	270.7	298	355	384
25	Mn	7.434 02	15.639 99	33.668	51.2	72.4	95.6	119.20	194.5	221.8	248.3	286.0	314	344	404
26	Fe	7.902 4	16.187 8	30.652	54.8	75.0	99.1	124.98	151.06	233.6	262.1	290.2	331	361	392
27	Co	7.881 0	17.083	33.50	51.3	79.5	103	131	160	186.2	276.2	305	336	379	411
28	Ni	7.639 8	18.168 84	35.19	54.9	75.5	108	134	164	193	224.6	321	352	384	430
29	Cu	7.726 38	20.292 40	36.841	55.2	79.9	103	139	167	199	232	266	369	401	435
30	Zn	9.394 05	17.964 40	39.723	59.4	82.6	108	136	175	203	238	274	311	412	454

- O III (O^{++}) 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 cm^{-1}, giving a line at $\lambda \sim 90\ \mu m$
- FeXIV has the same electronic structure but the Z^4 dependence puts the transition at 503 nm

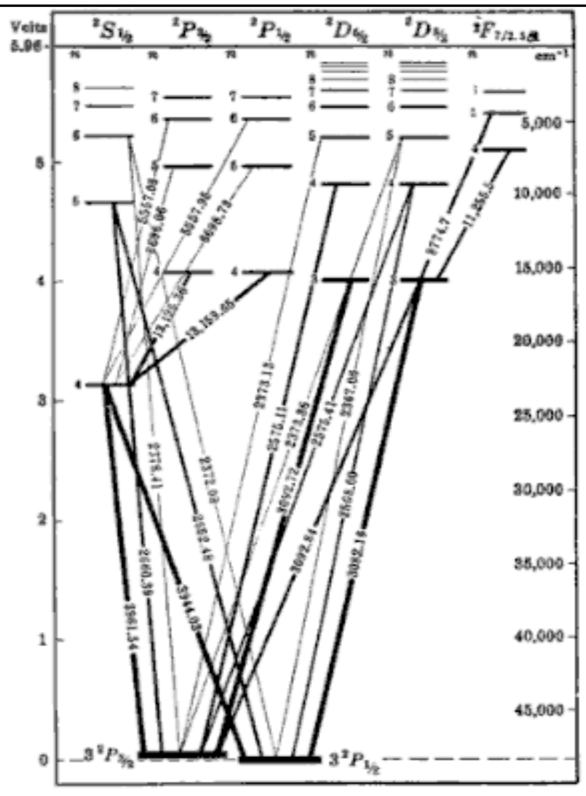


Fig. 73. Energy Level Diagram of Al I [Grotrian (8)]. n is the true principal quantum number of the emission electron. Only the normal doublet terms are indicated, all of which go to the same limit. Series of anomalous

FeXIV Coronium at 530.3nm

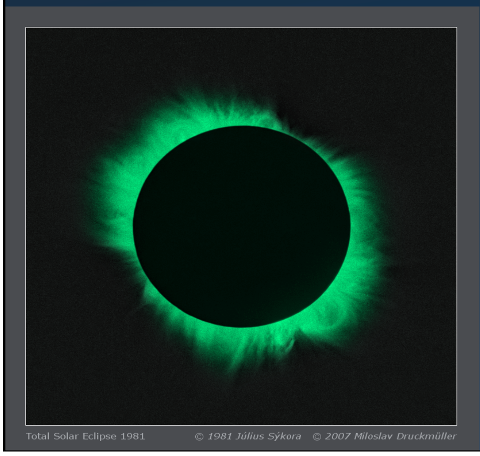
By extrapolating along the isoelectronic sequence from

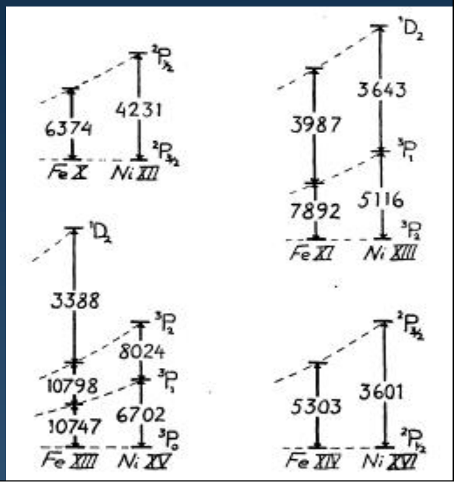
Al I, Si II, P III, S IV, Cl V, Ar VI ….

z= 13, 14, 15, 16, 17, 18 …..

Edlen & Grotrian identified the 'Coronium' line with the

$^2P_{3/2} - {}^2P_{1/2}$ transition in Fe XIV (z=26)





Solar Abundances

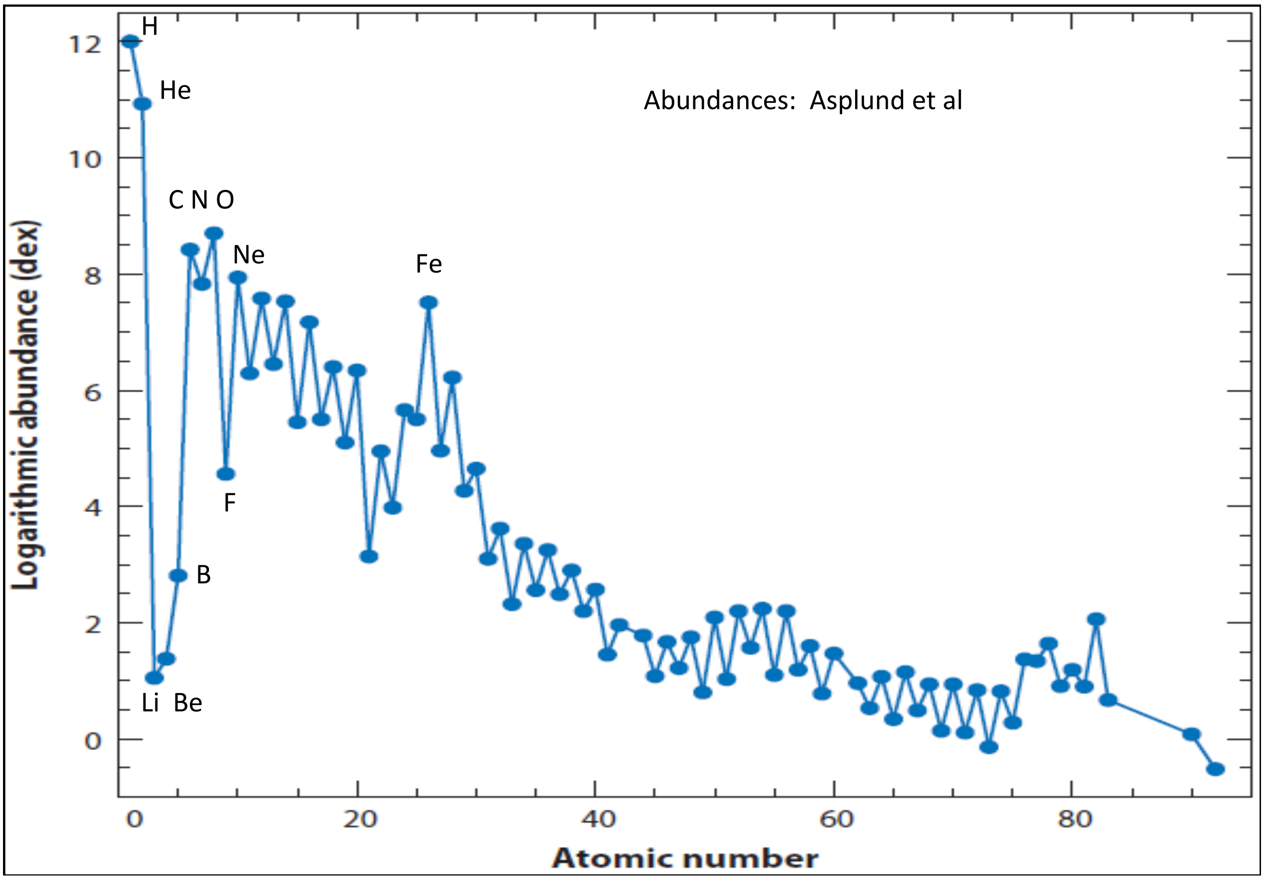
(Asplund et al 2009)

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

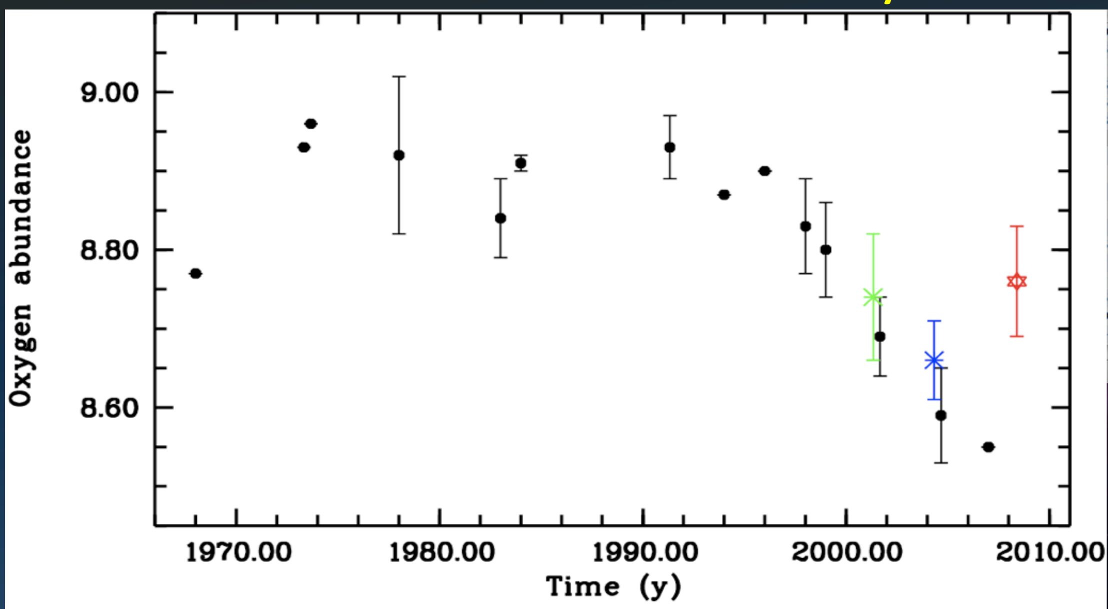
How is it that trace elements have prominent spectral features in stars and nebulae?

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

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