Die Spektren der Gasnebel

1. Die Spektren der Gasnebel

W. Huggins (1864): Spektrum des PN NGC 6543

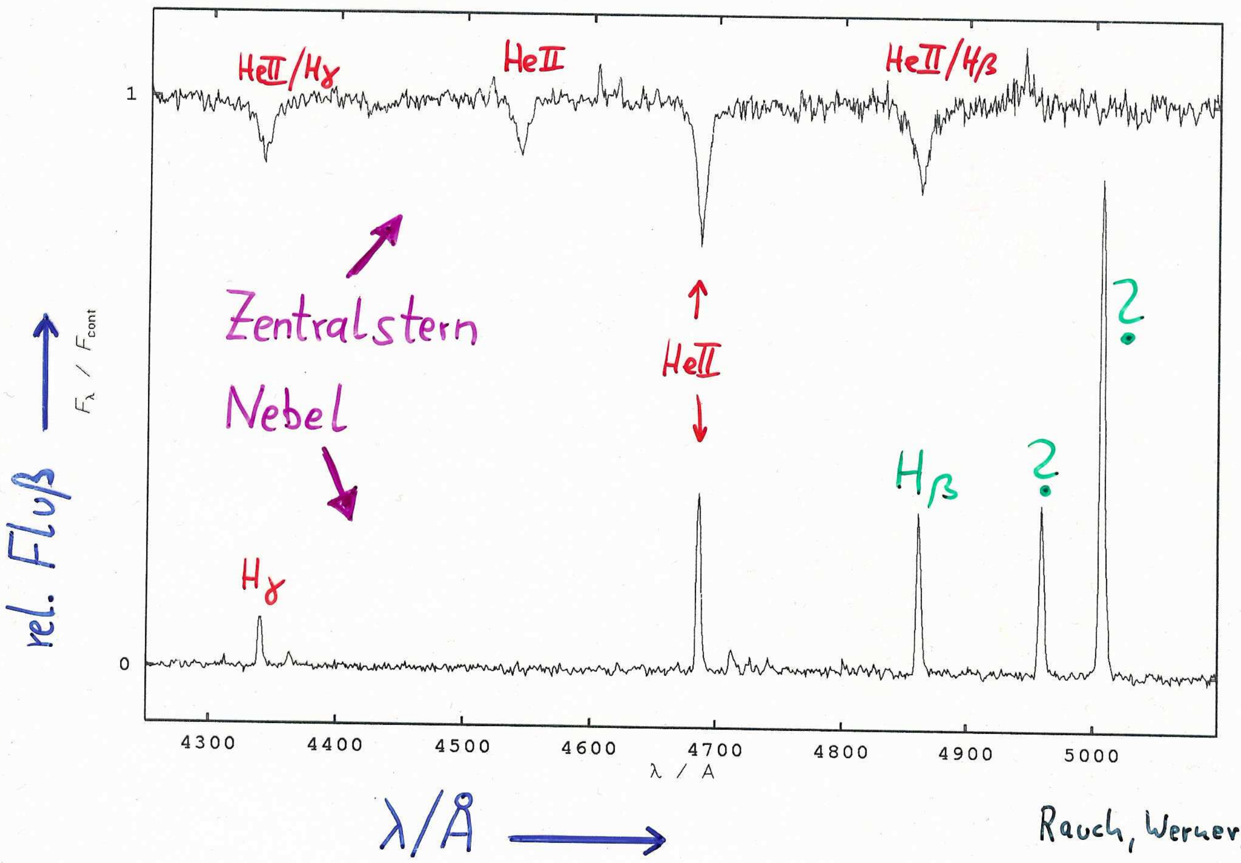
3 Emissionslinien H_β + ? + ?

Linien eines unbekannten chemischen Elementes

Nebulium

analog: Sonnen - Chromosphäre : Helium (1859)
" Korona : Koronium (1869)

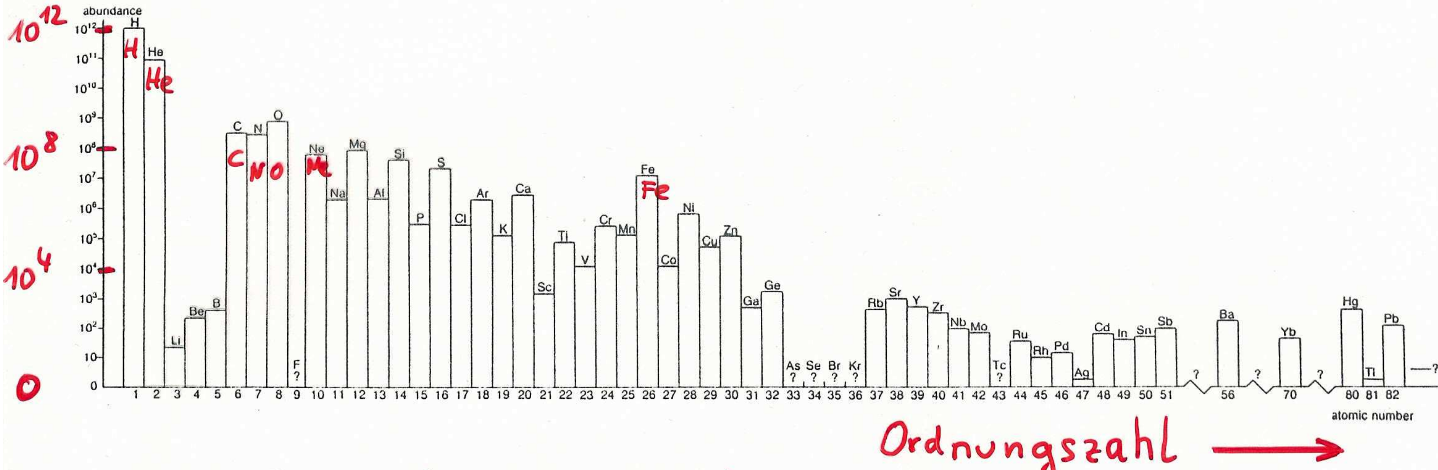
Spektrum des PN LoTr 4



Rauch, Werner, Köppen 199

Identifizierung der "Nebulium"-Linien

Die Häufigkeiten der chemischen Elemente in der Sonne:



universell: Massenbruchteile:

$X = 0.70$ Wasserstoff

$Y = 0.28$ Helium

$Z = 0.02$ alle übrigen Elemente zusammen

gilt für junge Sterne (Population I)

für alte Sterne (Population II, Halopopulation)

$Z = 10^{-4} \ldots 10^{-3}$

HII-Regionen: Kein Grund zur Annahme nicht-normale

Häufigkeiten, denn dort entstehen

normale Sterne

Bowen (1926): Identifizierung als verbotene Übergänge

im Termschema von OIII (zweifach ionisier debates with George Gamow. He has also worked on numerous other problems in theoretical astrophysics and cosmology. The author or coauthor of fourteen novels, a play, and more than twenty nonfiction books, Hoyle has long been a leading popularizer of science. **Photo** courtesy of Caltech.

Edwin Powell Hubble

20 November 1889 **1938 Bruce Medalist** **28 September 1953**

After graduation from the University of Chicago, Edwin Hubble won a Rhodes scholarship and earned a law degree at Oxford University. A year later he returned to Chicago and to astronomy. After obtained his doctorate he spent his career, aside from army service in both world wars, at **Mt. Wilson Observatory**. In 1923 - 25 he identified Cepheid variables in "spiral nebulae" M31 and M33 and proved conclusively that they are outside the Galaxy. His investigation of these objects, which he called extragalactic nebulae and which astronomers today call galaxies, led to his now-standard classification system of elliptical, spiral, and irregular galaxies. With Milton L. Humason he extended **Vesto M. Slipher**'s measurements of redshifts of galaxies, and in 1929 Hubble published the velocity-distance relation which is the basis of modern cosmology. Photos courtesy of **Caltech** and the **American Institute of Physics**. See also **Hubble, Humason, and Hubble's Constant** for more, including an account of **Hubble's achievements** by **Allan Sandage**.

Photo courtesy Mary Lea Shane Archives,
Lick Observatory

William Huggins

7 February 1824 **1904 Bruce Medalist** **12 May 1910**

Huggins was one of the wealthy British "amateurs" who contributed so much to 19th century science. At age 30 he sold the family business and built a private observatory five miles outside London. After Kirchhoff and Bunsen's 1859 discovery that spectral emission and absorption lines could reveal the composition of the source, Huggins took chemicals and batteries into the observatory to compare laboratory spectra with those of stars. First visually and then photographically he explored the spectra of stars, nebulae, and comets. He was the first to show that some nebulae, including the great nebula in Orion, have pure emission spectra and thus must be truly gaseous, while others, such as that in Andromeda, yield spectra characteristic of stars. After 1875 his observations were made jointly with his talented wife, the former Margaret Lindsay Murray. For more, see *Mercury* **19**, 5, 148 (1990) and *Griffith Observer* **50**, 10, 2 (1986).

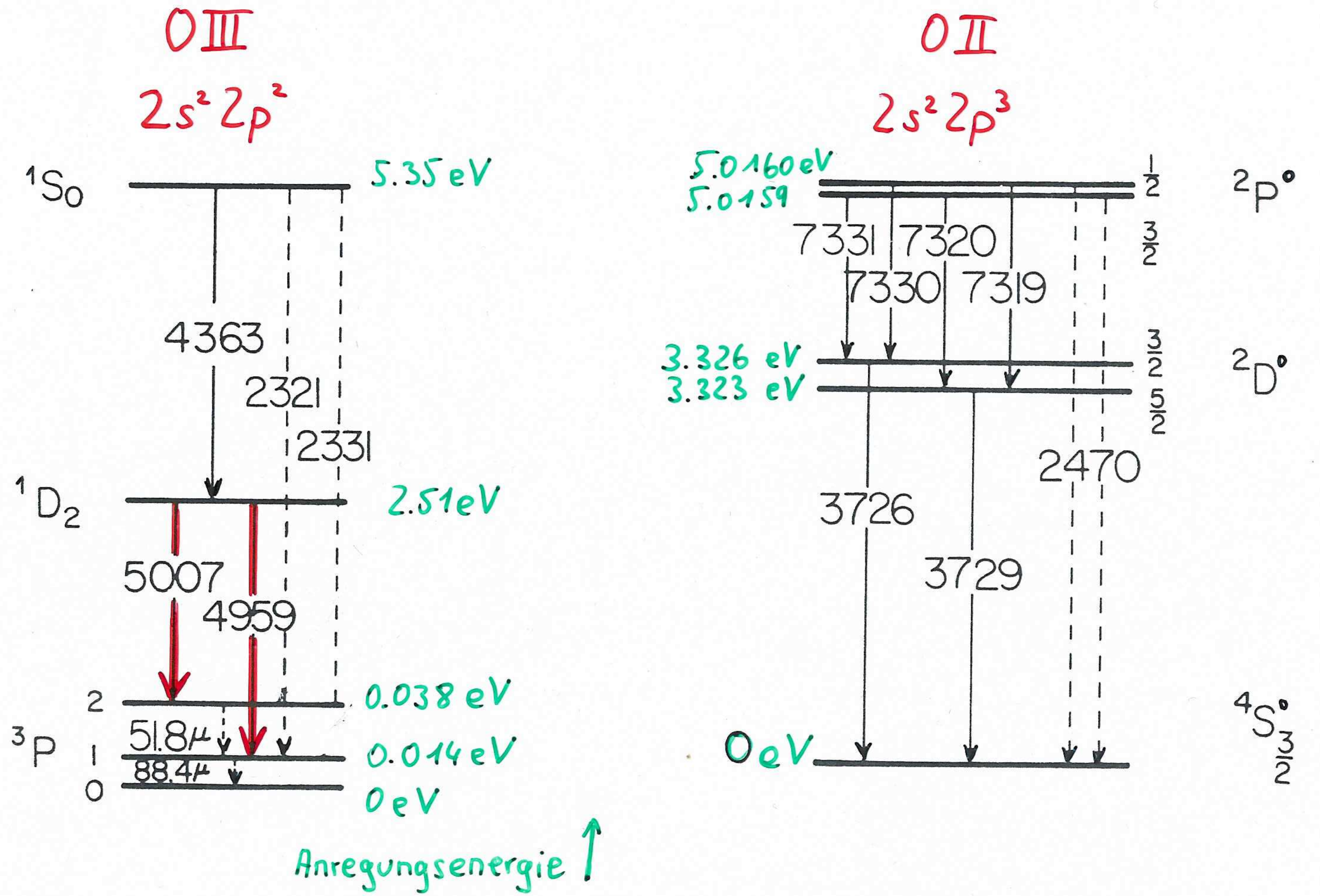
Alfred Harrison Joy

23 Sep1882 **1950 Bruce Medalist** **18 April 1973**

After studies at Greenville College, Illinois, and **Oberlin College**, Ohio, Alfred Joy taught ten years at the American University of Beirut. He spent several summers and one year at **Yerkes Observatory** and then joined the staff of **Mt. Wilson Observatory** in 1915. He remained active there nearly sixty years, although officially retired after 1948. Joy applied **Walter S. Adams**'s method of spectroscopic parallax to determine the distances of thousands of stars. When he retired nearly half of all published radial

http://www.astro.uni-bonn.de/~pbrosche/astoria.html
(Astronomiegeschichte)

Energieniveaus : Sauerstoff



Wellenlängen in Ångstroem

6 Elektronen,
Konfiguration: $1s^2\,2s^2\,2p^2$

7 Elektronen,
Konfiguration: $1s^2\,2s^2\,2p^3$

- Erlaubte Übergänge:

ungefähr:

Übergangswahrscheinlichkeit: $A_{ul} = 10^{8} \, \text{sec}^{-1}$

Lebensdauer: $\tau = 10^{-8} \, \text{sec}$

- "Verbotene" Übergänge: $A_{ul} = 1 \, \text{sec}^{-1}$

Schreibweise: [ ] $\tau = 1 \, \text{sec}$

verboten nach Auswahlregeln der Quantenmechanik (in 1. Näherung, elektr. Dipolstrahlung)

Beispiel: [OIII] 5007 Å $A_{43} = 0.014 \, \text{sec}^{-1}$

[OIII] 4959 Å $A_{42} = 0.007 \, \text{sec}^{-1}$

$$\Longrightarrow \quad \tau = (A_{43} + A_{42})^{-1} = \underline{48 \, \text{s}}$$

Extremes Beispiel: HI, 21cm - Linie

Hyperfeinstruktur übergang

Grundzustand: $F=0 \rightarrow F=1$

$$A_{10} = 2.85 \cdot 10^{-15} \, \text{sec}^{-1}$$

$$\tau = 1{,}1 \cdot 10^{7} \text{ Jahre !!}$$

beobachtet in IC 418

- beobachtete verbotene Linien stammen von Konfigurationen mp^{n} her, mit $m = 2$ oder 3, $n = 1 \dots 5$

Beispiel: OIII: $2p^{2}$ OII: $2p^{3}$ OI: $2p^{4}$

$1s^{2} 2s^{2} \dots$

THE ORIGIN OF THE CHIEF NEBULAR LINES

By I. S. Bowen

Several of the strongest lines in the spectra of the gaseous nebulae have not been observed in terrestrial sources. Since the spectra of the light elements, which are thought to form the chief constituents of nebulae, have been thoroughly studied, this leads to the conclusion that some cause, such as low density, must be operating in the nebulae to bring out lines in addition to those found in laboratory sources.

An atom in an excited state may give up its energy and return to a lower state either by radiating this energy or by transferring it to another atom through a collision of the second kind. If the mean life of the excited state before spontaneous emission is very long, as in the case of a metastable state, and if the mean time between impacts is short (in the most rarified terrestrial sources this is never more than 1/1000 second) practically all of the atoms will return by the second process and no radiation will take place. In the nebulae, however, where the mean time between impacts is estimated at from 10^4 to 10^7 seconds the first process may predominate even in the case of jumps from metastable states. This suggests at once that jumps from metastable states may be the source of lines appearing in nebulae but not in terrestrial sources.

The elements known to exist in the nebulae are H, He, C, N, O. CI, NI, NII, OI, OII, OIII, are the only ions of these elements that have metastable states so placed that jumps from them will produce lines in the range of wavelengths that can be observed in nebulae. Of these CI, NI, and OI can be eliminated because of the high ionization found in nebulae. In NII and OIII, which have similar structures, the metastable states are ^3P, ^1D, ^1S all arising from the normal configuration of two 2s and two 2p electrons. Likewise OII has the states ^4S, ^2D, ^2P due to the normal configuration of two 2s and three 2p electrons.

Originalarbeit von
BOWEN

erschienen 1927 in

Publications of the Astronomical
Society of the Pacific

In only two cases are the differences between these levels accurately known from combinations with a third level[1]. These are $^1D-^1S$ of OIII and $^2D-^2P$ of OII whose differences are 22916 and 13646 frequency units corresponding to wavelengths of 4362.54A and 7326.2A respectively. Two of the strongest nebular lines are found at 4363.21A and 7325.A. Since the differences are calculated from lines in the 500A region, these deviations are well within the error of the predictions.

The ^4S and ^2D levels of OII are known roughly from series formulae, but as no intercombinations between quartets and doublets have been observed the difference between them cannot be determined accurately. This approximate difference predicts a pair[2] which agrees as well as can be expected in both separation and position with two of the strongest nebular lines at 3728.91A and 3726.16A.

Two other strong pairs in the nebular spectrum are found at 5006.84A, 4958.91A, and 6583.6A, 6548.1A. These have separations of 193 and 82.3 frequency units, respectively, while the separation of $^3P_1-^3P_2$ in OIII is 192 and in NII is 82.7. This suggests at once that these lines are $^3P_2-^1D_2$ and $^3P_1-^1D_2$ in these elements. In NII it is possible to check this identification because other singlet terms are known[3] which should combine strongly with this $^1D_2$ term. Calculating the value of $^1D_2$ from the frequency of the red nebular pair one finds that the position of these combinations should be 746.98A and 582.15A. Strong lines are observed in the nitrogen spectrum at 746.97A and 582.16A.

The lines thus far identified on the basis of this hypothesis are collected in Table 1. The table includes all of the lines of an easily observable wavelength which would be excited by this mechanism in NII, OII, and OIII. Only two or three of the strong nebular lines are left unidentified.

---

[1] Bowen, *Phys. Rev.* **29**, 231, 1927.

[2] At 3681.25A and 3678.81A. The position of the pair is subject to an uncertainty of many angstroms.

[3] Fowler, *Proc. Roy. Soc.*, **114**, 662, 1927.

TABLE 1

IDENTIFICATION OF NEBULAR LINES

I. A.	Source	Series Designation
7325.	OII	$^2D-^2P$
6583.6	NII	$^3P_2-^1D$
6548.1	NII	$^3P_1-^1D$
5006.84	OIII	$^3P_2-^1D$
4958.91	OIII	$^3P_1-^1D$
4363.21	OIII	$^1D-^1S$
3728.91	OII	$^4S-^2D_3$
3726.16	OII	$^4S-^2D_2$

A study of the intensities of the nebular lines in various nebulae as given by Wright[4] shows that 5007, 4959, and probably 4363, all identified as OIII, behave in the same manner as 4686 of HeII. This would be expected from the similarity of their ionization potentials (54.8 and 54.2 volts). 3729, 3726 of OII and 6584, 6548 of NII show characteristics similar to the lines of HeI and other atoms of lower ionization potential.

In addition to the above identifications, it may be noted that the lines at 3313, 3342, 3445, and 3759 agree in position with four of the five strongest OIII lines as classified by Mihul[5], the fifth line being obscured by a hydrogen line. The behavior of these lines in the nebulae is in agreement with this identification.

As was recognized by Wright, 3426.2 and 3346 behave in such a way as to indicate a still higher ionization potential than OIII or HeII. The only strong line of NIV to be expected in the 3000-7000 region is 3^3S-3^3P which is predicted at 3460±50, and the only strong line of OIV in this region is 3^2P-3^2D expected at 3440±100. This makes the identification of 3426 as NIV and 3346 as OIV quite probable.

Norman Bridge Laboratory of Physics,
California Institute of Technology
Pasadena.

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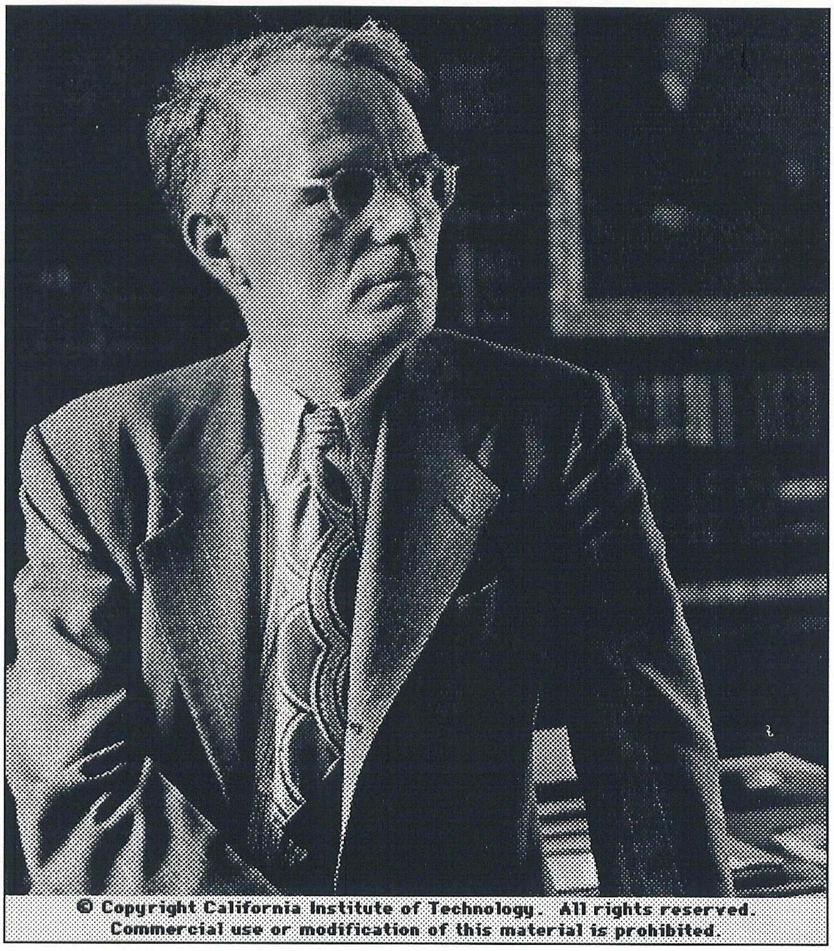
[4] Wright, *Publ. Lick Obs.* **13**, 193, 1918.

[5] Mihul, *C. R.* **183**, 1035; **184**, 89, 874, 1055.

Picture ID: 1.2.2-5

Ira Bowen , formal pose



(credit Life Magazine)

Date: ca 1946 or '47

Negative available: no

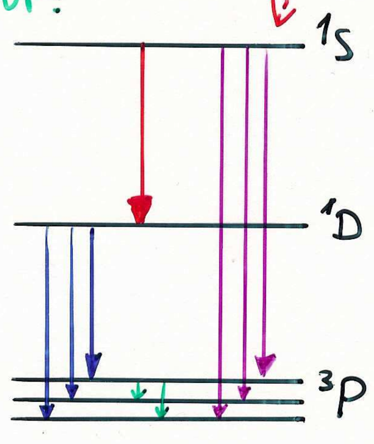
Search for another string, or return to the Caltech Home Page

p^1 und p^5 - Konfigurationen : 2 Niveaus $\searrow {}^2P$ (z.B. SIV

p^2, p^3, p^4 - Konfigurationen : 5 Niveaus z.B. OIII $1s^2 2s$

≙ CI, NII, NeV

Nomenklatur:



↓ Auroraübergang

↓ Transaurora - Übergänge

↓ Nebelübergänge

↓ Feinstrukturübergänge

Auswahlregeln: (LS-Kopplung) $\Pi = \sum_i l_i$

	erlaubte Üb. (= el. Dipol)	el. Quadrupol	mag. Dipol z.B. [OIII] 4959, 5007
1.	Parität $\Delta\Pi \neq 0$ nur odd-even even-odd	$\Delta\Pi = 0$	$\Delta\Pi = 0$
2.	$\Delta L = 0, \pm 1$ ($\hat{=} \Delta l = \pm 1$ für Leuchtelektron)	$\Delta l = 0, \pm 2$	$\Delta l = 0$
3.	$\Delta S = 0$		
4.	$\Delta J = 0, \pm 1$ verboten: $J=0 \rightarrow J'=0$	$\Delta J = 0, \pm 1, \pm 2$ nicht: $0 \rightarrow 0$, $\frac{1}{2} \rightarrow \frac{1}{2}$, $1 \rightleftarrows 0$	$\Delta J = 0, \pm 1$ nicht: $0 \rightarrow 0$
5.	Δn beliebig	Δn beliebig	$\Delta n = 0$

Interkombinationslinien: "halbverbotene" Linien

Schreibweise "]" , z.B. O III] 1666 Å $\Delta S \neq 0$

TABELLE 4-2 Terme äquivalenter Elektronen

Konfiguration	Terme	Konfiguration	Terme
s	^2S	d, d^9	^2D
s^2	^1S	d^2, d^8	^1S, ^1D, ^1G, ^3P, ^3F
p, p^5	^2P	d^3, d^7	^2P, ^2D, ^2F, ^2G, ^2H, ^4P, ^4F
p^2, p^4	^1S, ^1D, ^3P	d^4, d^6	^1S, ^1D, ^1F, ^1G, ^1I, ^3P, ^3D, ^3F, ^3G, ^3H, ^5D
p^3	^4S, ^2P, ^2D	d^5	^2S, ^2P, ^2D, ^2F, ^2G, ^2H, ^2I, ^4P, ^4F, ^4D, ^4G

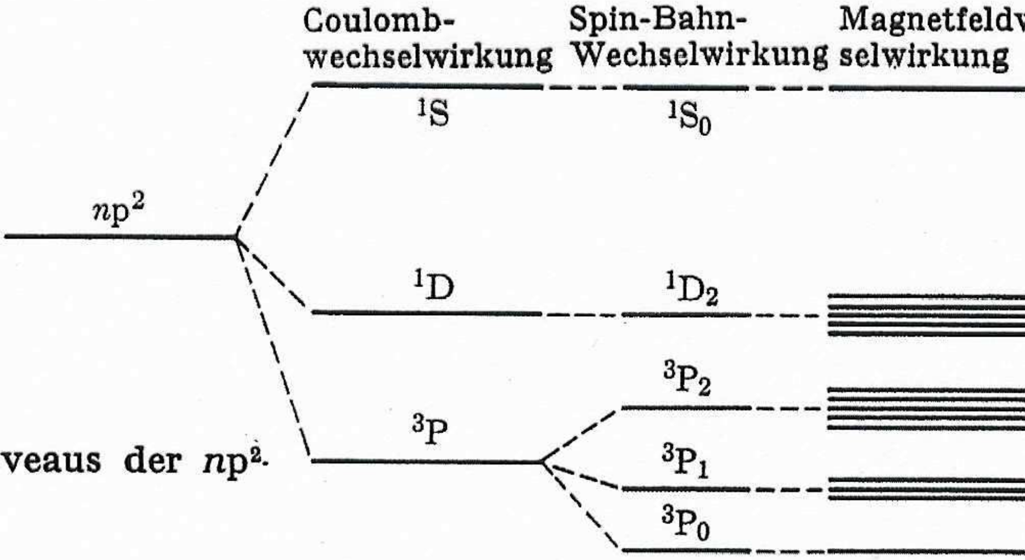


Abb. 4-10. Energieniveaus der np^2-Konfiguration.

TABELLE 4-8 Mögliche m_l- und m_s-Werte für die np^2-Konfiguration

M_L \ M_S	−1	0	+1
+2		(1, +)(1, −)	~~(1, +)(1, +)~~
+1	(1, −)(0, −)	(1, +)(0, −) (1, −)(0, +)	(1, +)(0, +)
0	(1, −)(−1, −)	(1, +)(−1, −) (0, +)(0, −) (1, −)(−1, +)	(1, +)(−1, +)
−1	(0, −)(−1, −)	(0, +)(−1, −) (0, −)(−1, +)	(0, +)(−1, +)
−2		(−1, +)(−1, −)	

Kurs: Atomspektren

hrödingergleichung : $\hat{H}\psi = E\psi$

ösung : $\psi = \psi(\vec{r}_1, \vec{r}_2, \dots, \vec{r}_N, \sigma_1, \dots, \sigma_N, \alpha_1, \dots, \alpha_s)$

α_i = Quantenzahlen $\quad s = 4N$

Bei N Elektronen beschreiben 4N Quantenzahlen die Wellenfunktion bzw. die Energieniveaus.

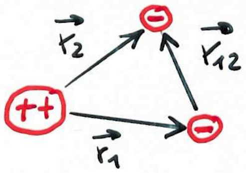
Beispiel Wasserstoff: 1 Elektron n, l, m_l, m_s

$$\hat{H} = -\frac{1}{2}\Delta - \frac{1}{r}$$

(atomare Einheiten : Länge = $\frac{\hbar^2}{m_0 e^2}$

Energie = $\frac{m_0 e}{2\hbar}$

Helium:



Hamiltonoperator für Mehrelektronensysteme :

$$\hat{H} = \underbrace{-\sum_{i=1}^{N}\left(\frac{1}{2}\Delta_i + \frac{1}{r_i}\right)}_{\hat{H}_0} + \underbrace{\sum_{i<j}\frac{1}{r_{ij}} + \sum_{i=1}^{N}\xi(r_i)\,\vec{l}_i\,\vec{s}_i}_{\text{Störterme}}$$

ohne Störterme : „gute“ Quantenzahlen :

$n_1, l_1, m_{l_1}, m_{s_1} \;\dots\; n_N, l_N, m_{l_N}, m_{s_N}$

„[illegible] model“

mit Störtermen: m_{ℓ_i}, s_{ℓ_i} Keine guten Quantenzahlen wegen Wechselwirkung zwischen $\vec{\ell}_i, \vec{\ell}_j$ bzw. $\vec{\ell}_i, \vec{s}_i$

"independent particle model" Ψ_i:

Energiematrix ohne Störterme: $\langle \Psi_M | \hat{H}_0 | \Psi_N \rangle = \langle \Psi_M | E \Psi_N \rangle$

$$= E \cdot \langle \Psi_M | \Psi_N \rangle$$

$$= E \cdot \delta_{MN}$$

Energiematrix mit Störtermen: $\langle \Psi_M | \hat{H} | \Psi_N \rangle \neq E \cdot \delta_{MN}$

nicht-Diagonalelemente zwischen Zuständen verschiedener m_{ℓ_i} und m_{s_i}

Ausweg: Diagonalisierung durch Basiswechsel

Kopplungsschemata (je nach Bedeutung der Störterme)

1) LS-Kopplung (Russell-Saunders-Kopplung)

1. Störterm dominiert (leichte Atome, He, C, N, O...)

$$\left.\begin{aligned} \vec{L} &= \sum_{i=1}^{N} \vec{\ell}_i \\ \vec{S} &= \sum_{i=1}^{N} \vec{s}_i \end{aligned}\right\} \quad \vec{L} + \vec{S} = \vec{J}$$

mit $|L-S| \le J \le L$

2 Elektronen: $n_1 \ell_1 n_2 \ell_2 \; L S J M$

8 gute Quantenzahlen

Bezeichnung: Niveau $n_1 l_1 n_2 l_2 \; {}^{2S+1}L_J$

Term $n_1 l_1 n_2 l_2 \; {}^{2S+1}L$

z.B. Helium:

$$\left.\begin{matrix} n_1 = 1 & l_1 = 0 & n_2 = 2 & l_2 = 1 \\ L = 1 & S = 1 & J = 1 & \end{matrix}\right\} 1s2p \; {}^3P_1$$

$2S+1$ heißt Multiplizität

= 1 Singlet
= 2 Dublet
= 3 Triplet
⋮

2) j-j-Kopplung

2. Störterm dominiert (schwere Atome, z.B. Fe)

$$\vec{j}_i = \vec{l}_i + \vec{s}_i \longrightarrow \vec{J} = \sum_{i=1}^{N} \vec{j}_i$$

2 Elektronen: $n_1 l_1 n_2 l_2 j_1 j_2 J M$

Komplikation: mehr als 2 Elektronen

(LS-Kopplung: $n_1 l_1 n_2 l_2 n_3 l_3 L S J M$ = 10 Quantenzahl

Wir brauchen 12 Quantenzahlen

Elternion:

$$\left.\begin{matrix} \vec{l}_1 + \vec{l}_2 = \vec{L}_0 \\ \vec{s}_1 + \vec{s}_2 = \vec{S}_0 \end{matrix}\right\} \rightarrow \left.\begin{matrix} \vec{L}_0 + \vec{l}_3 = \vec{L} \\ \vec{S}_0 + \vec{s}_3 = \vec{S} \end{matrix}\right\} \rightarrow \vec{L} + \vec{S} =$$

12 Quantenzahlen: $n_1 l_1 n_2 l_2 L_0 S_0 n_3 l_3 L S J M$

Pauli-Prinzip: abgeschlossene Schalen unwichtig für Kopplungsschema

Übergangswahrscheinlichkeit

a) $w \approx \langle \psi | \hat{d} | \phi \rangle$ $\hat{d}$ Dipoloperator

Dipolstrahlung

b) $w \approx \langle \psi | \hat{Q} | \phi \rangle$ $\hat{Q}$ Quadrupoloperator

Quadrupolstrahlung

$\hat{d}$ ist ein ungerader Operator $\hat{d}(-r) = -\hat{d}(r)$

z.B. 1-dimensional $\hat{d} = e \cdot x$

$\hat{Q}$ ist ein gerader Operator $\hat{Q}(r) = \hat{Q}(-r)$

- $\langle \psi | x | \phi \rangle = \int\limits_{-\infty}^{\infty} \psi(x) \cdot x \cdot \phi^*(x)\, dx \neq 0$

  nur wenn Integrand $\psi x \phi^*$ gerade Funktion ist.

  x ist ungerade ⇒ $w \neq 0$ nur für Übergänge
  gerade ↔ ungerade

- Quadrupolstrahlung: Übergänge gerade ↔ gerade
  ungerade ↔ ungerad

  Parität $\Pi = \sum_{i=1}^{N} l_i$ (arithmetische Summe)

Die übrigen Auswahlregeln ergeben sich ebenfalls aus $w \neq 0$

Interkombination: $\Delta S \neq 0$ Abweichung von LS-Koppl

Übergangswahrscheinlichkeit

wächst mit Atomgewicht

Inter Kombination

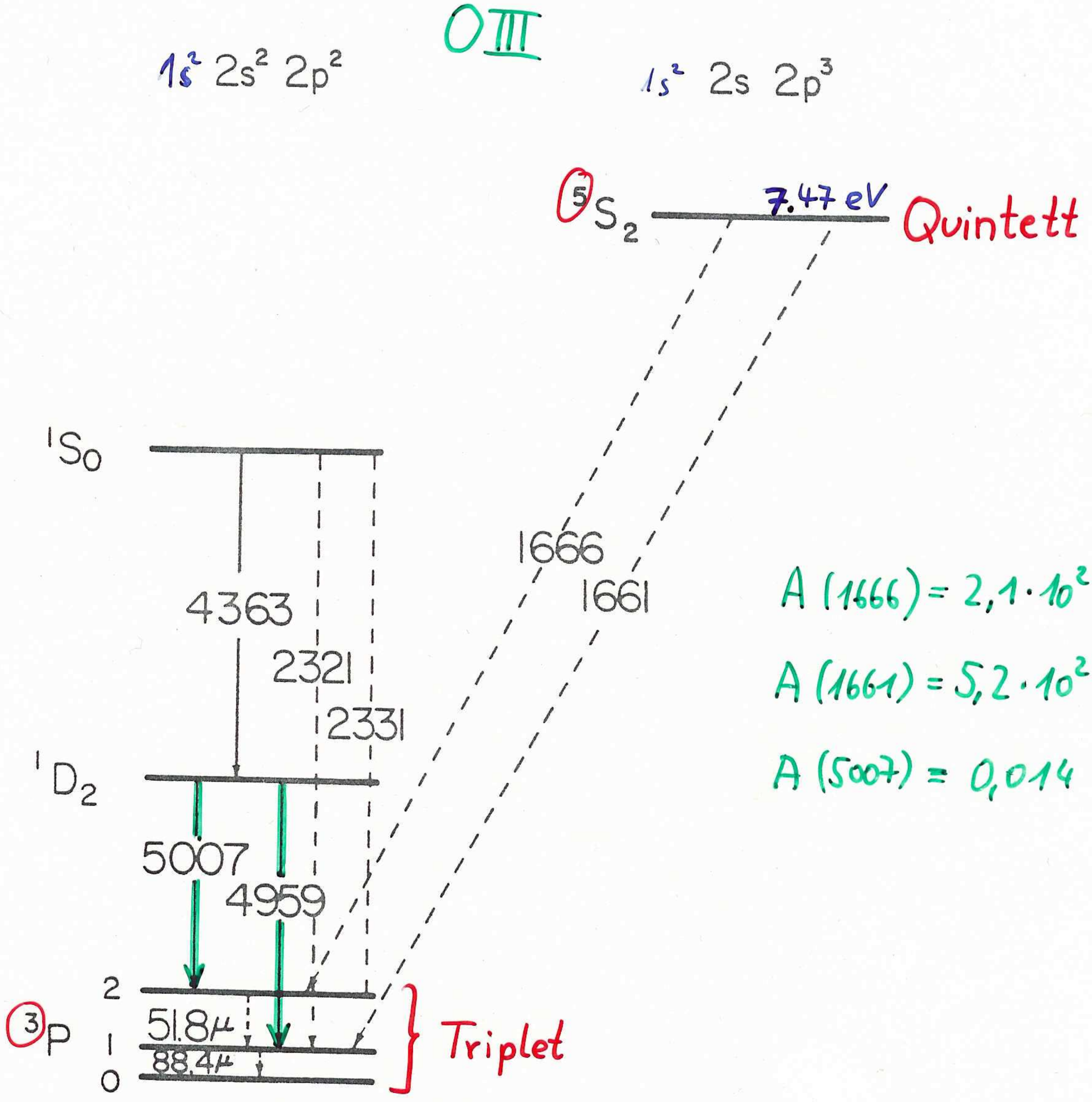


FIG. 1–Energy-level diagram of O III. Optical forbidden lines identified by Bowen shown as solid lines; other forbidden transitions in the ultraviolet and infrared are shown as dashed lines.

$A\,(1666) = 2{,}1 \cdot 10^2$ se

$A\,(1661) = 5{,}2 \cdot 10^2$

$A\,(5007) = 0{,}014$

TERMSCHEMATA

Wasserstoff

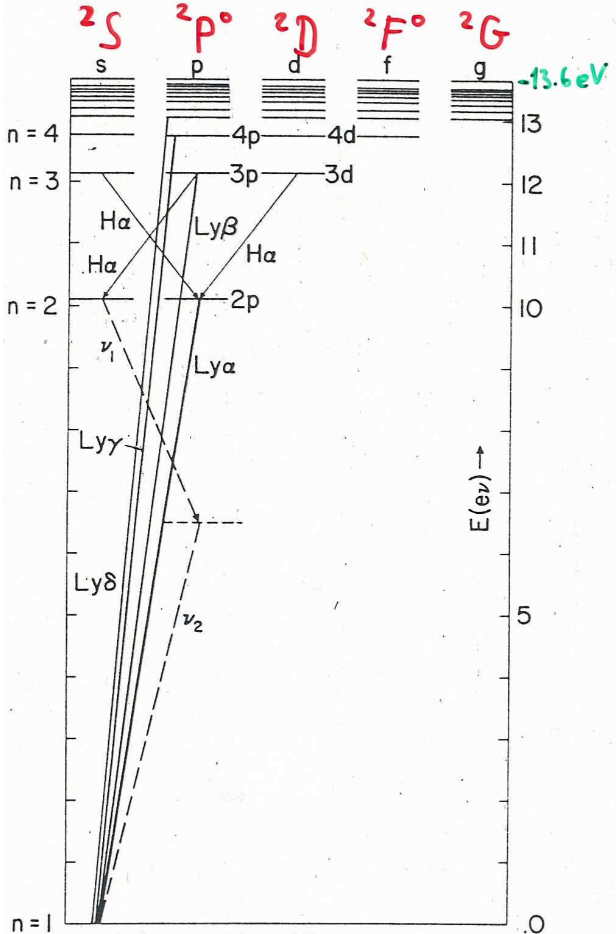
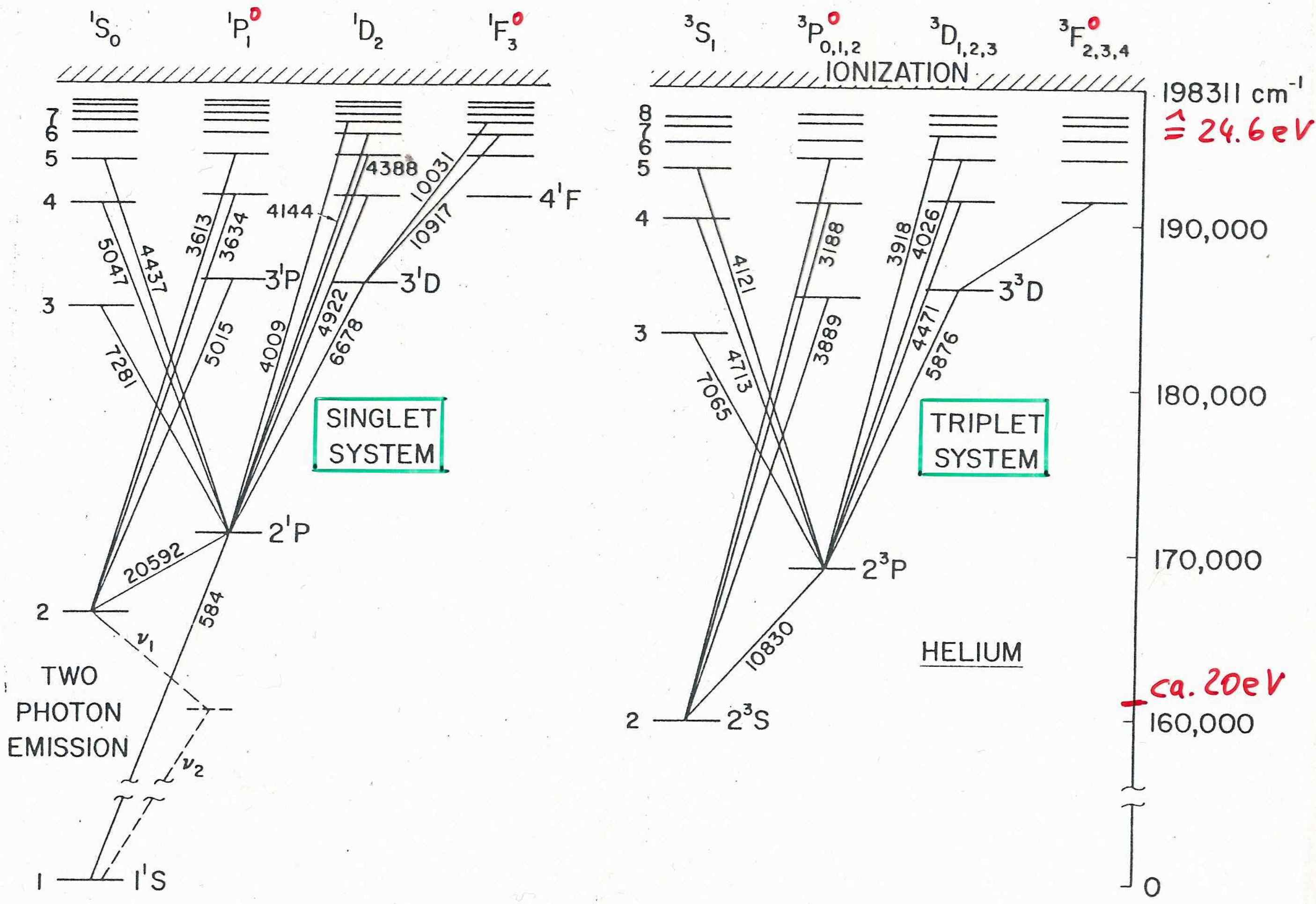


Figure 2-5

Helium



Wellenlängen in Å

Visueller Spektralbereich

erlaubte Übergänge : H I, He I, He II

Keine Metalle (Ausnahme s.u.)

verbotene Übergänge: [O I], [N I], ..., [O III], [N II],

[Ar IV], [Ne V]

Anregungsklassen: 1 bis 10

mit steigendem Ionisationsgrad LoTr 4 : 10

Spezialfall: hochangeregte Nebel (He II stark)

erlaubte Übergänge O III, nur solche, die von dem Niveau $2s^2 2p 3d\ ^3P_2$ ausgehen; (s. 2.6)

ähnliche N III - Linien

Radio - Bereich

Übergänge zwischen sehr hoch angeregten Niveaus von H I und He I

z.B. bei ~6 cm : H 110α (n = 110 → n' = 1

H 138β (n = 138 → n' = 1

H 158γ (n = 158 → n' = 1

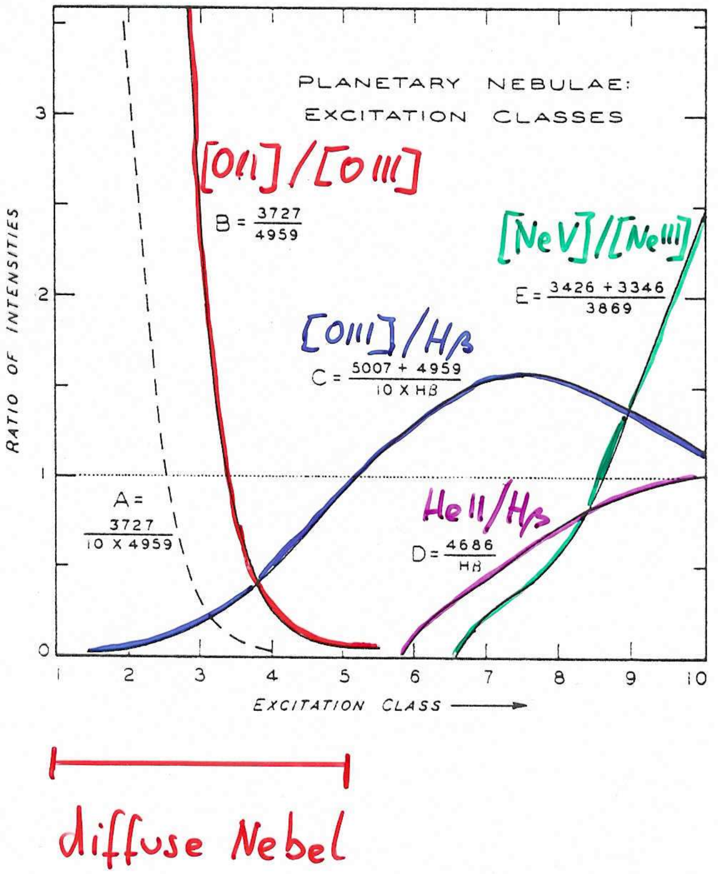
H 186δ (n = 186 → n' = 1

Anregungsklassen nach ALLER

The five curves on this chart represent line-intensity ratios of the following ions:

A, *B*, [O II] / [O III]
C, [O III] / H I
D, He II / H I
E, [Ne V] / [Ne III]

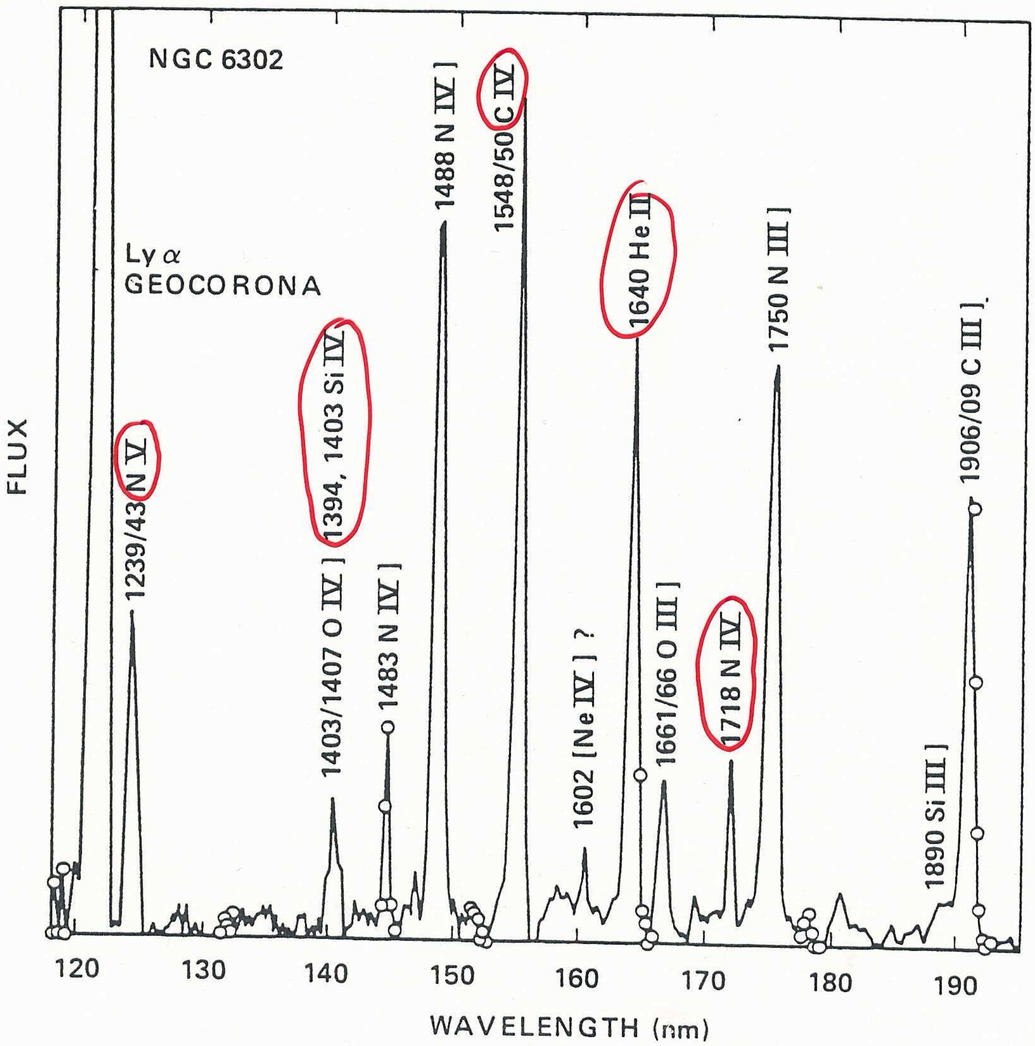
Nebulae of lowest excitation fall at the left, where curve *A* is like *B* but has a 10-times larger denominator. Except in *A*, ratios of less than unity (horizontal dotted line) represent cases where the line or lines in the numerator are less intense than those in the denominator. This holds true for curve *D*, except for planetaries of the very highest excitation.



Für PN: Es gibt eine Korrelation der Anregungsklasse mit dem Spektraltyp des Zentralsterns

(Pottasch 1984, Kapitel

Ultraviolett ("Satelliten-UV:" 1200 Å - 3200 Å)



○ = erlau
Übergä

Interkombinationslinien : C III] 1906/09 Å
O III] 1661/66 Å

erlaubte Übergänge : C IV 1548/50 Å
Si IV 1394/1403 Å
N V 1239/43 Å

Resonanzlinien ($E_{low} = 0\,eV$, $E_{up} \approx 8\,eV$)

Infrarot (bodengebunden und Satelliten)

Feinstrukturlinien [O III], …

Emissions - Features vom Staub (Silikate) s. Kap. 10

Zusammenfassung: Beobachtete Spektren

- H, He : erlaubte Übergänge zwischen hochangeregten Niveaus ($E > 10\,\mathrm{eV}$), bis hinauf zu sehr hohen Quantenzahlen ($n > 100$, Radio)
- "Metalle": nur Übergänge zwischen niedrig angeregten Niveaus (Ausnahme: partikuläre PN mit Linie von O III, N III). $E \lesssim 5-8\,\mathrm{eV}$

entweder : verboten [O III], … (visuell), IR
oder : erlaubt C IV - Resonanzlinien, UV
oder : Interkombination C III], … UV

nebenbei bemerkt:

ähnliche Spektren zeigen Quasare

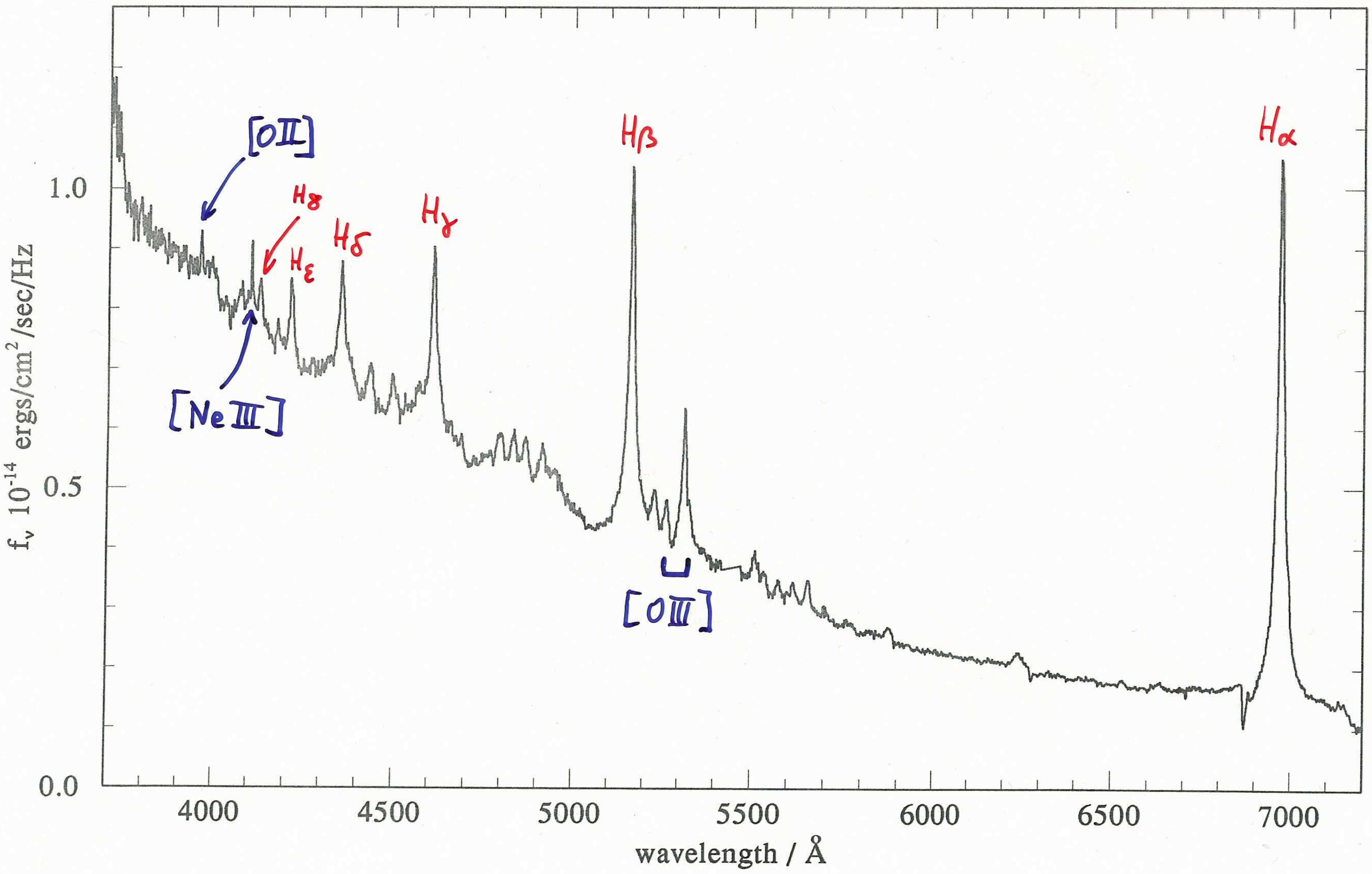
⇒ Gasnebel - Analysetechniken sind wichtiges Mittel zum Verständnis der Quasare

Quasare

Kosmologische Rotverschiebung

$$z = \frac{\Delta\lambda}{\lambda} \approx \frac{v}{c}$$

KUV quasar KUV 00549−2239 $z = 0.06$



Calar Alto
3.5m Teleskop
Sept. 1994