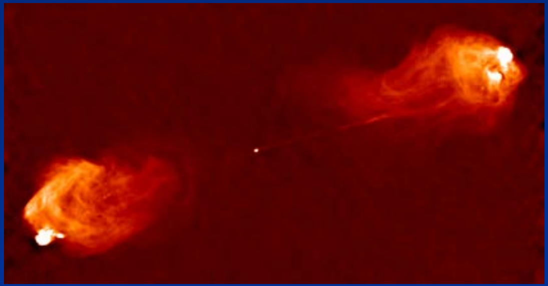
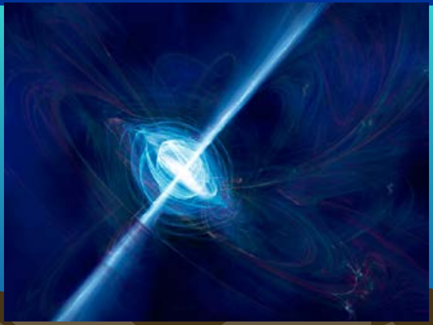
Radio Astronomy

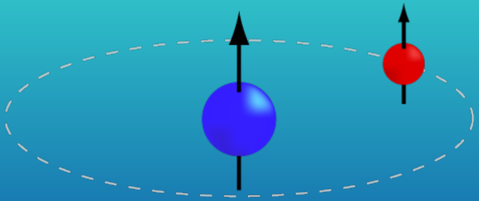
PD Dr. Henrik Beuther and Dr. Hendrik Linz

MPIA Heidelberg

An elective lecture course for the winter term 2012/13 at the Ruperto Carola University Heidelberg







Radio Astronomy

PD Dr. Henrik Beuther and Dr. Hendrik Linz

MPIA Heidelberg

Tentative Schedule:

16.10. Introduction and overview (HL & HB)
23.10. Emission mechanisms, physics of radiation (HB)
30.10. Telescopes – single-dish (HL)
06.11. Telescopes – interferometers (HB)
13.11. Instruments – continuum detection (HL)
20.11. Instruments – line detection (HB)
27.11. Continuous radiation (free-free, synchrotron, dust) (HL)
04.12. Radiation transfer (HB)
11.12. Line radiation (HL)
18.12. Buffer ...
08.01. Molecules and chemistry (HL)
15.01. Physics and kinematics (HB)
22.01. Applications (HL)
29.01. Applications (HB)
05.02. Exam week

Radio Astronomy

PD Dr. Henrik Beuther and Dr. Hendrik Linz

MPIA Heidelberg

Topics for today:

- line radiative transfer and Einstein coefficients (basic)

The derivations on the blackboard followed closely the corresponding chapter in the Condon lecture series on radio atsronomy: http://www.cv.nrao.edu/course/astr534/LineRadxfer.html

Read your notes, read this chapter of the Condon lectures. And if you really want to understand it, follow and redo all the steps there with a pen and a piece of paper.

- different kinds of line emission mechanisms

Optical spectroscopy: already well established in astrophysics at the dawn of radio astronomy

Fraunhofer (1821) and Kirchhoff (1859): absorption line system in the Sun spectrum, and spectral analysis of the Sun and the stars

Kirchhoff and Bunsen

Spectroscopy pioneers in Heidelberg

IN DIESEM HAUSE HAT
KIRCHHOFF
1859 SEINE MIT BUNSEN BEGRÜNDETE
SPEKTRALANALYSE
AUF SONNE UND GESTIRNE GEWANDT
UND DAMIT DIE CHEMIE DES WELTALLS
ERSCHLOSSEN

Gustav Robert Kirchhoff
18.03.1824-17.10.1887

Robert Wilhelm Bunsen
31.03.1811-16.08.1899

Optical spectroscopy: already well established in astrophysics at the dawn of radio astronomy

Material in-between the stars got accessible:

- W. Huggins 1864: “Nebulium” lines towards emission nebulae (1927 reveal as to arise from oxygen ions, “forbidden lines”)
- J. Hartmann 1904: the non-moving Calcium absorption line in the spectra of binary stars

Still, most studies concentrated on stellar spectroscopy, atomic and ion lines.

A. McKellar 1940: spectral evidence for CH and CN in optical spectra … perhaps the first organic molecules ! But not a high impact in subsequent research.

Radio astronomy: first results by the pioneers Jansky and Reber were obtained in the centimeter and meter continuum

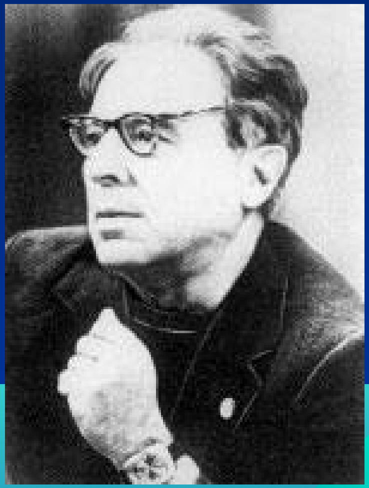
But a few people got excited about the possibility to have spectral lines in the radio!

Access to kinematics in the (cold) interstellar medium (ISM) as an early motivation not directly accessible to optical spectroscopy

Prediction of line emission arising from neutral hydrogen in 1944 – 1949 …

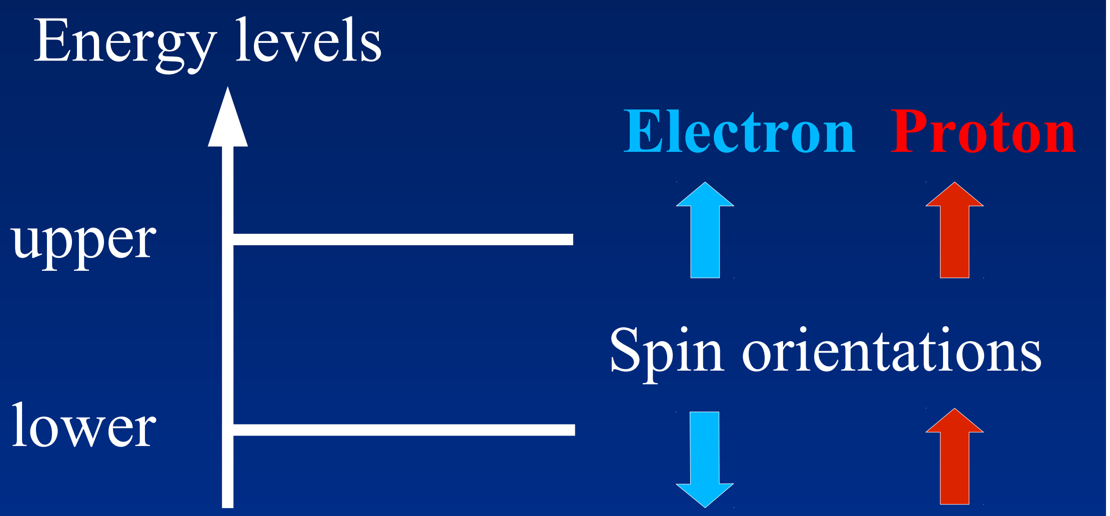
Jan Oort

Hendrik van der Hulst



Iosif Shklovsky

Neutral Hydrogen H I : a hyperfine transition causes the 21 cm line

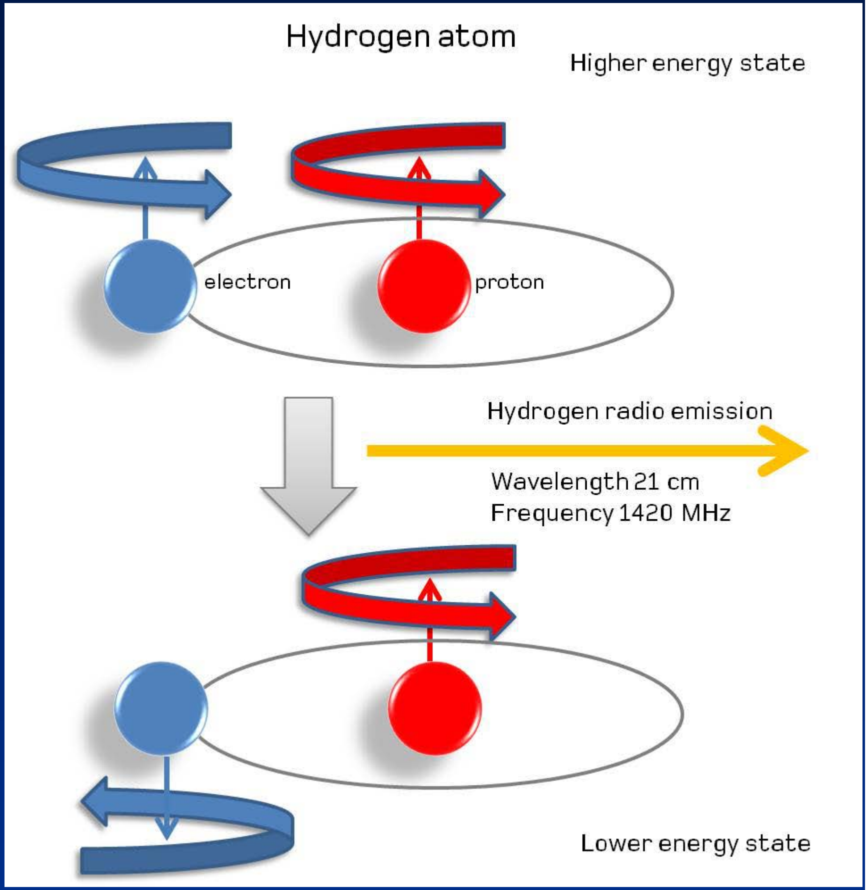

Energy levels

upper

lower

Electron **Proton**

Spin orientations



$$\nu_{10} = \frac{8}{3} g_{\mathrm{I}} \left(\frac{m_{\mathrm{e}}}{m_{\mathrm{p}}}\right) \alpha^2 (R_{\mathrm{M}} c) \approx 1420.405751\ \mathrm{MHz}$$

g_I = 5.58569 nuclear g-factor for the proton

α = fine-structure constant

R_M c = hydrogen Rydberg frequency

$$R_M = R_\infty \left(1 + m_e / M_{\mathbf{nucleus}} \right)^{-1}$$

Fine-structure lines of metal atoms and ions

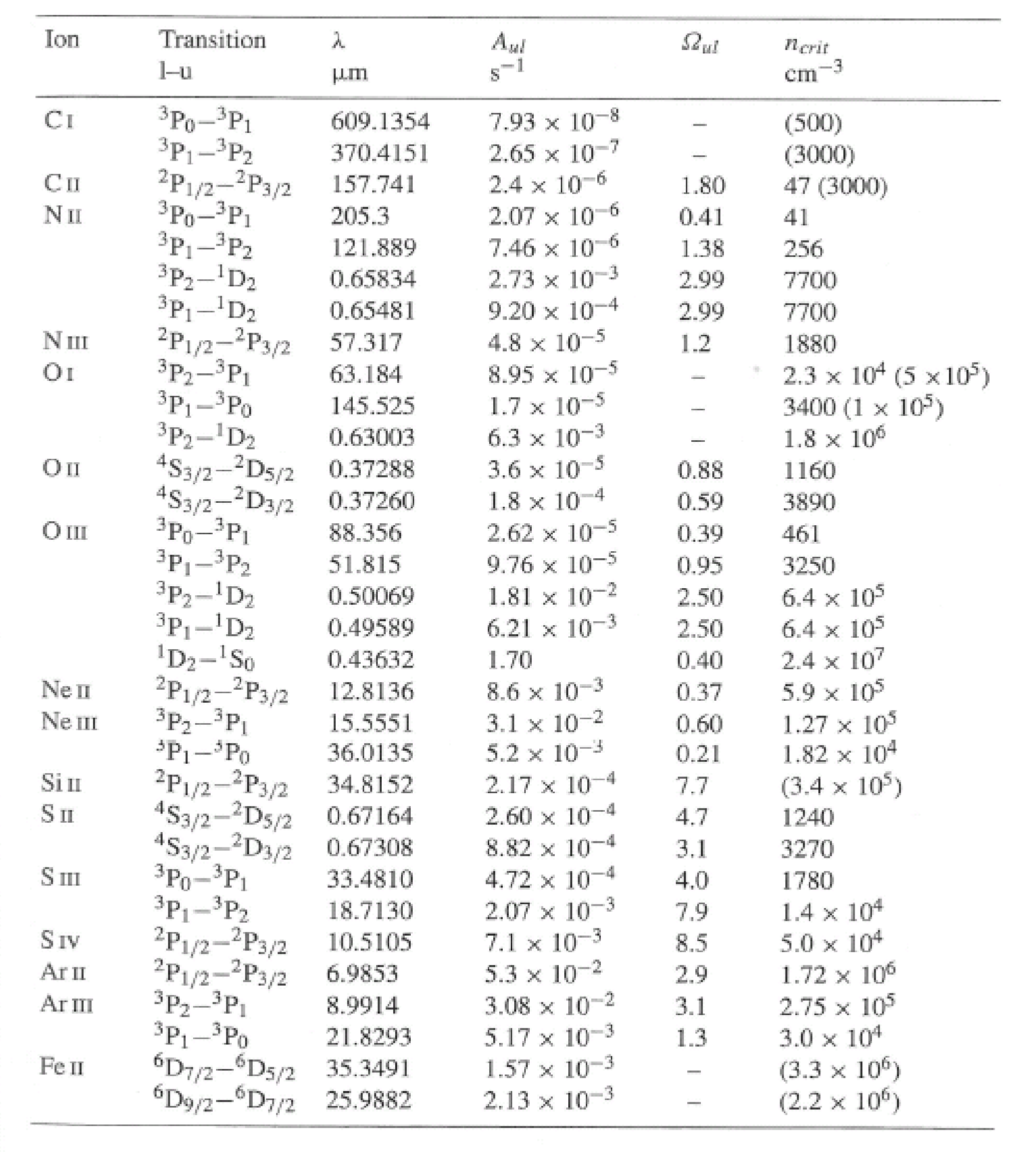
→ *energy levels split by fine-structure interaction between the total orbital momentum of the electrons* **L** *and their total spin* **S**

$\mathbf{J} = \mathbf{L} + \mathbf{S}$ *(if this so-called Russell-Saunders coupling applies)*

Selection rules for electric dipole transitions are $\Delta S = 0$, $\Delta L = +/- 1$, *and* $\Delta J = 0, +/-1$

It turns out that often, important fine-structure lines of astrophysical relevance violate one or the other relation …

→ These have to be magnetic dipole transitions then, or even electric quadrupole transitions (much weaker than electric dipole ones)

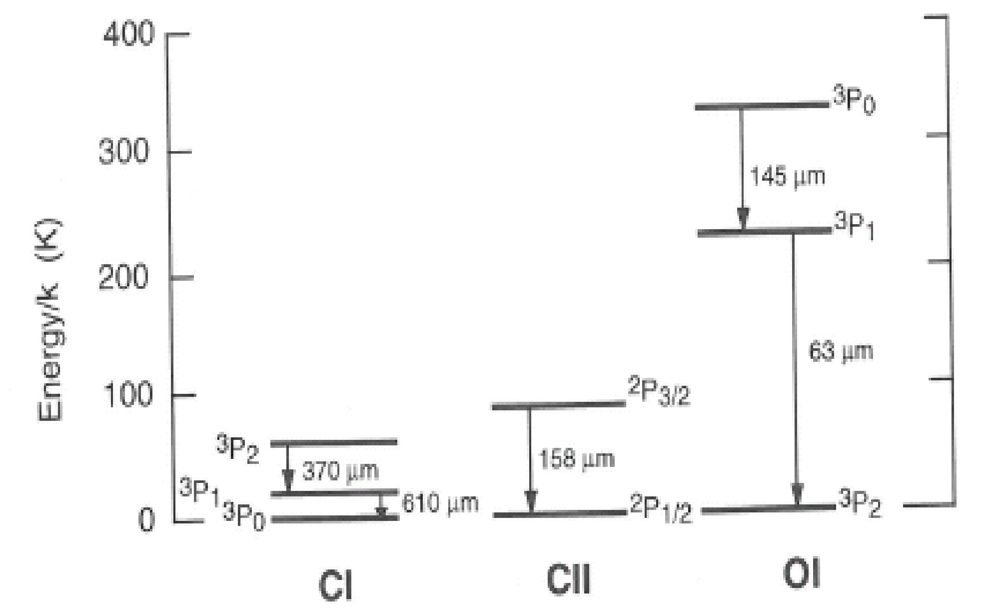


Ion	Transition l–u	λ µm	A_{ul} s^{-1}	Ω_{ul}	n_{crit} cm^{-3}
C I	$^3P_0-^3P_1$	609.1354	7.93×10^{-8}	–	(500)
	$^3P_1-^3P_2$	370.4151	2.65×10^{-7}	–	(3000)
C II	$^2P_{1/2}-^2P_{3/2}$	157.741	2.4×10^{-6}	1.80	47 (3000)
N II	$^3P_0-^3P_1$	205.3	2.07×10^{-6}	0.41	41
	$^3P_1-^3P_2$	121.889	7.46×10^{-6}	1.38	256
	$^3P_2-^1D_2$	0.65834	2.73×10^{-3}	2.99	7700
	$^3P_1-^1D_2$	0.65481	9.20×10^{-4}	2.99	7700
N III	$^2P_{1/2}-^2P_{3/2}$	57.317	4.8×10^{-5}	1.2	1880
O I	$^3P_2-^3P_1$	63.184	8.95×10^{-5}	–	2.3×10^4 (5×10^5)
	$^3P_1-^3P_0$	145.525	1.7×10^{-5}	–	3400 (1×10^5)
	$^3P_2-^1D_2$	0.63003	6.3×10^{-3}	–	1.8×10^6
O II	$^4S_{3/2}-^2D_{5/2}$	0.37288	3.6×10^{-5}	0.88	1160
	$^4S_{3/2}-^2D_{3/2}$	0.37260	1.8×10^{-4}	0.59	3890
O III	$^3P_0-^3P_1$	88.356	2.62×10^{-5}	0.39	461
	$^3P_1-^3P_2$	51.815	9.76×10^{-5}	0.95	3250
	$^3P_2-^1D_2$	0.50069	1.81×10^{-2}	2.50	6.4×10^5
	$^3P_1-^1D_2$	0.49589	6.21×10^{-3}	2.50	6.4×10^5
	$^1D_2-^1S_0$	0.43632	1.70	0.40	2.4×10^7
Ne II	$^2P_{1/2}-^2P_{3/2}$	12.8136	8.6×10^{-3}	0.37	5.9×10^5
Ne III	$^3P_2-^3P_1$	15.5551	3.1×10^{-2}	0.60	1.27×10^5
	$^3P_1-^3P_0$	36.0135	5.2×10^{-3}	0.21	1.82×10^4
Si II	$^2P_{1/2}-^2P_{3/2}$	34.8152	2.17×10^{-4}	7.7	(3.4×10^5)
S II	$^4S_{3/2}-^2D_{5/2}$	0.67164	2.60×10^{-4}	4.7	1240
	$^4S_{3/2}-^2D_{3/2}$	0.67308	8.82×10^{-4}	3.1	3270
S III	$^3P_0-^3P_1$	33.4810	4.72×10^{-4}	4.0	1780
	$^3P_1-^3P_2$	18.7130	2.07×10^{-3}	7.9	1.4×10^4
S IV	$^2P_{1/2}-^2P_{3/2}$	10.5105	7.1×10^{-3}	8.5	5.0×10^4
Ar II	$^2P_{1/2}-^2P_{3/2}$	6.9853	5.3×10^{-2}	2.9	1.72×10^6
Ar III	$^3P_2-^3P_1$	8.9914	3.08×10^{-2}	3.1	2.75×10^5
	$^3P_1-^3P_0$	21.8293	5.17×10^{-3}	1.3	3.0×10^4
Fe II	$^6D_{7/2}-^6D_{5/2}$	35.3491	1.57×10^{-3}	–	(3.3×10^6)
	$^6D_{9/2}-^6D_{7/2}$	25.9882	2.13×10^{-3}	–	(2.2×10^6)

This sort of lines gives a kind of continuity wrt the optical and infrared wavelength range ...

It turns out that often, important fine-structure lines of astrophysical relevance violate one or the other relation …

→ These have to be magnetic dipole transitions then, or even electric quadrupole transitions (much weaker than electric dipole ones)



These lines, especially the 158 µm CII line and the 63 µm OI line, are the most important "cooling" lines in the denser neutral and cooler ionised medium.

→ now accessible with heterodyne "radio" instrumentation (HIFI@Herschel and GREAT@SOFIA)

Notation for the energy levels:

Fundamental state as → $^{X}Y_{J}$

With X = 2S+1 ,
Y = S, P, D, … for L = 0, 1, 2, …

electric dipole transitions are
$\Delta S = 0$, $\Delta L = +/- 1$, ***and*** $\Delta J = 0, +/-1$

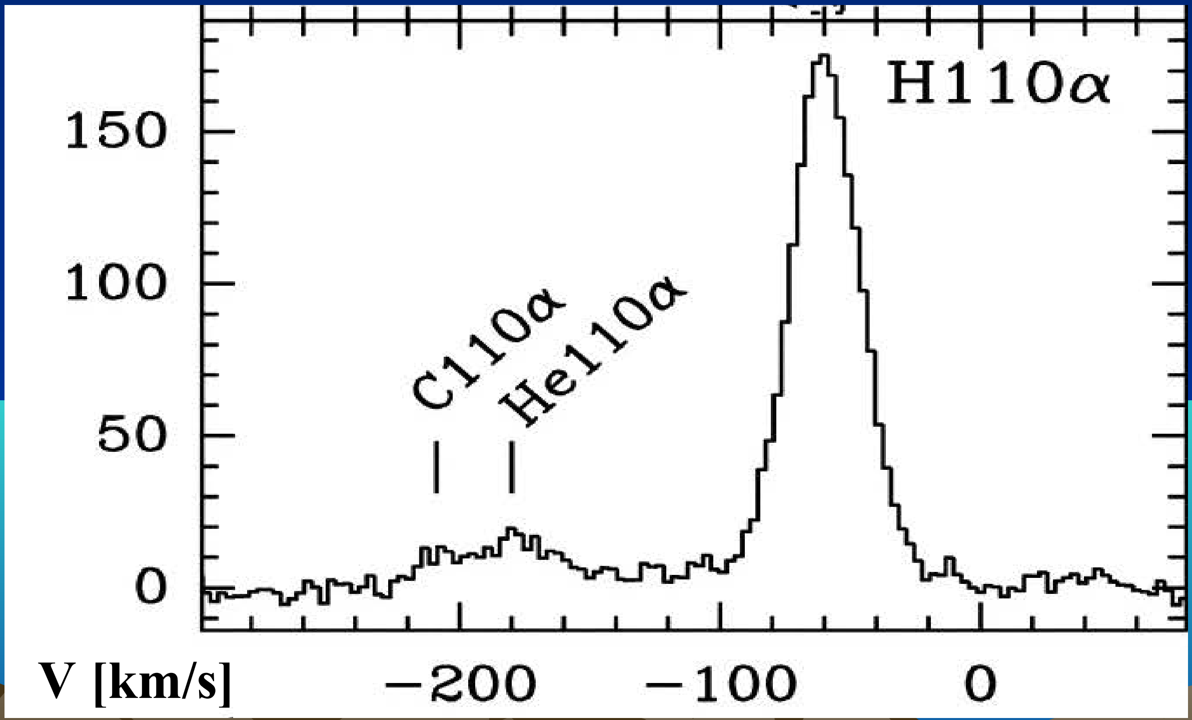
All shown transitions violate the $\Delta L = +/- 1$ ***rule, i.e., they are much weaker magnetic dipole transitions.***

Radio Recombination lines

Prerequisite: presence of ionised gas

a.) Occasional recombination of free electrons with ions (i.e., a free-bound transition, giving a quasi-continuous spectrum, into high energy levels within the electron shell)

b.) A subsequent level transition from one high to a slightly lower level, hence, a line radiation event.



Recomb lines for the elements H, He, and C at around 4.9 GHz (taken from Araya et al. 2007, ApJS 170:152-174)

110α means a transition from level 111 → 110

Radio Recombination lines

1.) *Recomb lines will always sit on a free-free continuum.*

2.) *Radio recomb lines arise from high energy levels (Rydberg states), and the atoms behave almost quasi-classical (a point charge in the middle with a single electron orbiting at a large distance …*
→ Correspondence Principle)
Rydberg atoms in thin interstellar space can extent to almost macroscopic proportions (up to almost 1 mm!) not quickly destroyed by collisions

3.) *radio recomb lines as a way to assess the kinematics of the ionised gas also in regions not accessible for optical spectroscopy due to (dust extinction)*

2 atoms
H2
AlF
AlCl
C2**
CH
CH+
CN
CO
CO+
CP
SiC
HCl
KCl
NH
NO
NS
NaCl
OH
PN
SO
SO+
SiN
SiO
SiS
CS
HF
HD
FeO ?
O2
CF+
SiH ?
PO
AlO
OH+
CN–
SH+
SH
HCl+

3 atoms
C3 *
C2H
C2O
C2S
CH2
HCN
HCO
HCO+
HCS+
HOC+
H2O
H2S
HNC
HNO
MgCN
MgNC
N2H+
N2O
NaCN
OCS
SO2
c-SiC2
CO2 *
NH2
H3+ *
H2D+
SiCN
AlNC
SiNC
HCP
CCP
AlOH
H2O+
H2Cl+
KCN
HO2
FeCN

4 atoms
c-C3H
l-C3H
C3N
C3O
C3S
C2H2*
NH3
HCCN
HCNH+
HNCO
HNCS
HOCO+
H2CO
H2CN
H2CS
H3O+
c-SiC3
CH3 *
C3N–
PH3 ?
HCNO
HOCN
HSCN
H2O2
C3H+

5 atoms
C5 *
C4H
C4Si
l-C3H2
c-C3H2
H2CCN
CH4 *
HC3N
HC2NC
HCOOH
H2CNH
H2C2O
H2NCN
HNC3
SiH4 *
H2COH+
C4H–
HC(O)CN
HNCNH
CH3O

6 atoms
C5H
l-H2C4
C2H4*
CH3CN
CH3NC
CH3OH
CH3SH
HC3NH+
HC2CHO
NH2CHO
C5N
l-HC4H *
l-HC4N
c-H2C3O
H2CCNH (?)
C5N–

7 atoms
C6H
CH2CHCN
CH3C2H
HC5N
CH3CHO
CH3NH2
c-C2H4O
H2CCHOH
C6H–

8 atoms
CH3C3N
HC(O)OCH3
CH3COOH
C7H
C6H2
CH2OHCHO
l-HC6H *
CH2CHCHO (?)
CH2CCHCN
H2NCH2CN

9 atoms
CH3C4H
CH3CH2CN
(CH3)2O
CH3CH2OH
HC7N
C8H
CH3C(O)NH2
C8H–
C3H6

10 atoms
CH3C5N
(CH3)2CO
(CH2OH)2
CH3CH2CHO

11 atoms
HC9N
CH3C6H
C2H5OCHO

12 atoms
c-C6H6 *
C2H5OCH3 ?
n-C3H7CN

>12 atoms
HC11N
C60 *
C70 *

Detected molecules in space (outside of stellar atmospheres): > 170 (as of 11/2012)

Taken from the CDMS (Cologne Database of Molecular Spectroscopy)
http://www.astro.uni-koeln.de/cdms

Line emission from molecules

Molecules can exhibit more degrees of freedom and more possibilities of quantised energy levels than simple atoms.

There can be energy transitions due to:

– electronic transitions
– vibrations of different kinds (bending, stretching of molecular bonds)
– molecular rotations
– inversion transitions

All will lead to line emission/absorption of one kind or the other.

To be continued in the next lecture ...

Radio Astronomy

PD Dr. Henrik Beuther and Dr. Hendrik Linz

MPIA Heidelberg

Scripts at : http://www.mpia.de/homes/beuther/lecture_ws1213.html

Tentative Schedule:
16.10. Introduction and overview (HL & HB)
23.10. Emission mechanisms, physics of radiation (HB)
30.10. Telescopes – single-dish (HL)
06.11. Telescopes – interferometers (HB)
13.11. Instruments – continuum detection (HL)
20.11. Instruments – line detection (HB)
27.11. Continuous radiation (free-free, synchrotron, dust) (HL)
04.12. Radiation transfer (HL)
11.12. Line radiation (HL)
18.12. Visiting the Effelsberg Telescope (all)
08.01. Molecules and chemistry (HL)
15.01. Physics and kinematics (HB)
22.01. Applications (HL)
29.01. Applications (HB)
05.02. Exam week

Radio Astronomy

PD Dr. Henrik Beuther and Dr. Hendrik Linz

MPIA Heidelberg

18.12. Visiting the Effelsberg Telescope (all)

Have you indicated in the separate list whether you will come?

Meeting point and time for the day trip: 8:00 h (sharp) in front of ARI

In case something happens with your plan to participate:
→ please send us an email in time

To: beuther @ mpia.de
Cc: linz @ mpia.de