

Laboratory Spectroscopy for near-Infrared Astrophysics

SOLVAY WORKSHOP, BRUSSELS NOVEMBER 2019

by

Henrik Hartman

Collaborators and thanks

Madeleine Burheim *Malmö University and Lund Observatory*

Hampus Nilsson *Malmö Observatory*

Lars Engström *Physics, Lund University*

Asli Pehlivan Rhodin *Malmö University and Lund Observatory (until 2018)*

Asimina Papoulia *Malmö University and Lund University*

Jörgen Ekman *Malmö University*

Per Jönsson *Malmö University*

LUMCAS, CompAS, Imperial College London, Mons group, NIST and Uppsala university



The Crafoord Foundation
ESTABLISHED BY BOUGELCKRAFOORD IN 1989

Conclusion

The aim of our program is to provide evaluated sets of transition data with realistic uncertainties for selected atoms and ions with a range in wavelength, strength and excitation potential.

Laboratory measurements and calculations can provide the data needed to analyse the expensively required astronomical observations.

Optical vs near-IR observations

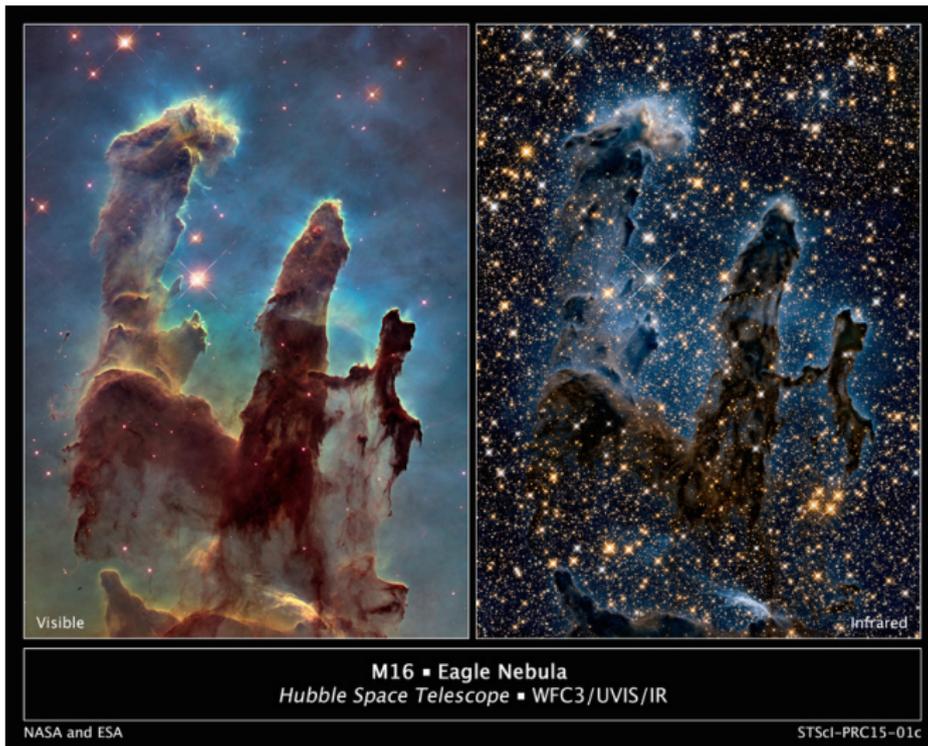


M16 • Eagle Nebula
Hubble Space Telescope • WFC3/UVIS/IR

NASA and ESA

STScI-PRC15-01c

Optical vs near-IR observations



near-IR stellar spectroscopy, 1-5 μm

Motivations for near-infrared observations:

- ❖ Several orders of magnitude less extinction
- ❖ Atmospheric transmission bands
- ❖ Cool stars

Consequences:

- ❖ Astronomical observatories are designed for this region.
- ❖ Coming ELTs deigned to observe 1-2.5 μm .
- ❖ The atomic data base above 1 micron is sparse.
- ❖ Numerous atomic lines in the stellar spectra

near-IR atomic transitions

near-IR transitions from an atomic physicists point of view:

- ❖ High-excitation transitions; Rydberg states
- ❖ Lower excitation transitions in complex atomic spectra
- ❖ Resonance lines in heavier elements, e.g. third spectra of rare-earth elements

PERIODIC TABLE

Atomic Properties of the Elements

NIST
National Institute of
Standards and Technology
U.S. Department of Commerce

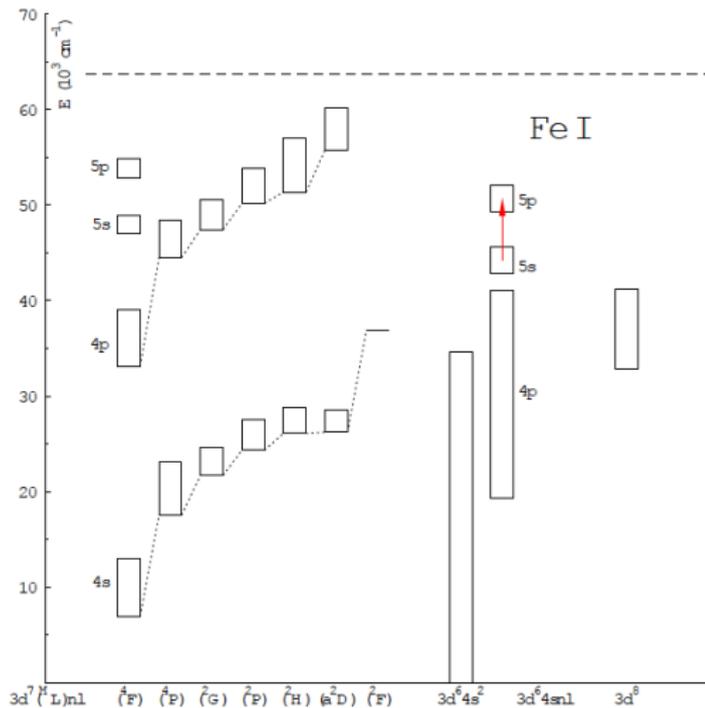
Group 1 IA		Frequently used fundamental physical constants										Physical Measurement Laboratory www.nist.gov/pml				Standard Reference Data www.nist.gov/srd				18 VIIIA	
1 H		For the most accurate values of these and other constants, visit physics.nist.gov/constants										13 IIIA				15 VA				2 He	
2 IA		1 second = 0.192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of ¹³³ Cs										14 IVA				16 VIA				10 VIIA	
3 IIA		speed of light in vacuum $c = 299\,792\,458\ \text{m s}^{-1}$ (exact)										5 B				7 P				8 O	
4 IIIA		Planck constant $h = 6.626\,07 \times 10^{-34}\ \text{J s}$ ($h = h/2\pi$)										6 C				8 S				9 F	
5 IIA		elementary charge $e = 1.602\,177 \times 10^{-19}\ \text{C}$										9 Al				10 Si				11 P	
6 IIIA		electron mass $m_e = 9.109\,383 \times 10^{-31}\ \text{kg}$										11 Ga				12 Ge				13 As	
7 IIIA		proton mass $m_p = 1.672\,622 \times 10^{-27}\ \text{kg}$										13 In				14 Sn				15 Sb	
8 IIIA		fine-structure constant $\alpha = 1/137.035\,999$										14 Zn				15 Cd				16 In	
9 IIIA		Rydberg constant $R_\infty = 10\,973\,731.568\ \text{m}^{-1}$										15 Cu				16 Ag				17 Au	
10 IIIA		Bohr magneton $\mu_B = 9.274\,010 \times 10^{-24}\ \text{J T}^{-1}$										16 Ni				17 Pd				18 Pt	
11 IIIA		Boltzmann constant $k = 1.380\,65 \times 10^{-23}\ \text{J K}^{-1}$										17 Co				18 Rh				19 Ir	
12 IIIA		Sodium										18 Ni				19 Pd				20 Pt	
13 IIIB		Sulfur										19 Cu				20 Zn				21 Ga	
14 IIIB		Chromium										20 Zn				21 Ga				22 Ge	
15 IIIB		Manganese										21 Ga				22 Ge				23 As	
16 IIIB		Iron										22 Ge				23 As				24 Se	
17 IIIB		Cobalt										23 As				24 Se				25 Br	
18 IIIB		Nickel										24 Se				25 Br				26 Kr	
19 IIIB		Copper										25 Br				26 Kr				27 Rb	
20 IIIB		Zinc										26 Kr				27 Rb				28 Sr	
21 IIIB		Gallium										27 Rb				28 Sr				29 Y	
22 IIIB		Germanium										28 Sr				29 Y				30 Zr	
23 IIIB		Arsenic										29 Y				30 Zr				31 Nb	
24 IIIB		Selenium										30 Zr				31 Nb				32 Mo	
25 IIIB		Bromine										31 Nb				32 Mo				33 Tc	
26 IIIB		Krypton										32 Mo				33 Tc				34 Ru	
27 IIIB		Rubidium										33 Tc				34 Ru				35 Rh	
28 IIIB		Strontium										34 Ru				35 Rh				36 Pd	
29 IIIB		Yttrium										35 Rh				36 Pd				37 Ag	
30 IIIB		Zirconium										36 Pd				37 Ag				38 Cd	
31 IIIB		Niobium										37 Ag				38 Cd				39 In	
32 IIIB		Molybdenum										38 Cd				39 In				40 Sn	
33 IIIB		Technetium										39 In				40 Sn				41 Sb	
34 IIIB		Ruthenium										40 Sn				41 Sb				42 Te	
35 IIIB		Rhodium										41 Sb				42 Te				43 I	
36 IIIB		Palladium										42 Te				43 I				44 Xe	
37 IIIB		Silver										43 I				44 Xe				45 Ba	
38 IIIB		Cadmium										44 Xe				45 Ba				46 La	
39 IIIB		Indium										45 Ba				46 La				47 Ce	
40 IIIB		Tin										46 La				47 Ce				48 Pr	
41 IIIB		Antimony										47 Ce				48 Pr				49 Nd	
42 IIIB		Tellurium										48 Pr				49 Nd				50 Pm	
43 IIIB		Iodine										49 Nd				50 Pm				51 Sm	
44 IIIB		Xenon										50 Pm				51 Sm				52 Eu	
45 IIIB		Barium										51 Sm				52 Eu				53 Gd	
46 IIIB		Lanthanum										52 Eu				53 Gd				54 Tb	
47 IIIB		Cerium										53 Gd				54 Tb				55 Dy	
48 IIIB		Praseodymium										54 Tb				55 Dy				56 Ho	
49 IIIB		Neodymium										55 Dy				56 Ho				57 Er	
50 IIIB		Promethium										56 Ho				57 Er				58 Tm	
51 IIIB		Samarium										57 Er				58 Tm				59 Yb	
52 IIIB		Europium										58 Tm				59 Yb				60 Lu	
53 IIIB		Terbium										59 Yb				60 Lu				61 Hf	
54 IIIB		Dysprosium										60 Lu				61 Hf				62 Ta	
55 IIIB		Holmium										61 Hf				62 Ta				63 W	
56 IIIB		Erbium										62 Ta				63 W				64 Re	
57 IIIB		Thulium										63 W				64 Re				65 Os	
58 IIIB		Ytterbium										64 Re				65 Os				66 Ir	
59 IIIB		Lutetium										65 Os				66 Ir				67 Pt	
60 IIIB		Hafnium										66 Ir				67 Pt				68 Au	
61 IIIB		Tantalum										67 Pt				68 Au				69 Hg	
62 IIIB		Tungsten										68 Au				69 Hg				70 Tl	
63 IIIB		Rhenium										69 Hg				70 Tl				71 Pb	
64 IIIB		Osmium										70 Tl				71 Pb				72 Bi	
65 IIIB		Iridium										71 Pb				72 Bi				73 Po	
66 IIIB		Platinum										72 Bi				73 Po				74 At	
67 IIIB		Gold										73 Po				74 At				75 Rn	
68 IIIB		Mercury										74 At				75 Rn				76 Fr	
69 IIIB		Thallium										75 Rn				76 Fr				77 Ra	
70 IIIB		Lead										76 Fr				77 Ra				78 Ac	
71 IIIB		Bismuth										77 Ra				78 Ac				79 Th	
72 IIIB		Polonium										78 Ac				79 Th				80 Pa	
73 IIIB		Astatine										79 Th				80 Pa				81 U	
74 IIIB		Radon										80 Pa				81 U				82 Np	
75 IIIB		Francium										81 U				82 Np				83 Pu	
76 IIIB		Radium										82 Np				83 Pu				84 Am	
77 IIIB		Actinium										83 Pu				84 Am				85 Cm	
78 IIIB		Thorium										84 Am				85 Cm				86 Bk	
79 IIIB		Protactinium										85 Cm				86 Bk				87 Cf	
80 IIIB		Uranium										86 Bk				87 Cf				88 Es	
81 IIIB		Neptunium										87 Cf				88 Es				89 Fm	
82 IIIB		Plutonium										88 Es				89 Fm				90 Md	
83 IIIB		Americium										89 Fm				90 Md				91 No	
84 IIIB		Curium										90 Md				91 No				92 Lr	
85 IIIB		Berkelium										91 No				92 Lr				93 La	
86 IIIB		Californium										92 Lr				93 La				94 Ce	
87 IIIB		Einsteinium										93 La				94 Ce				95 Pr	
88 IIIB		Fermium										94 Ce				95 Pr				96 Nd	
89 IIIB		Mendelevium										95 Pr				96 Nd				97 Pm	
90 IIIB		Nobelium										96 Nd				97 Pm				98 Sm	
91 IIIB		Lawrencium										97 Pm				98 Sm				99 Eu	
92 IIIB		Ununennium										98 Sm				99 Eu				100 Gd	
93 IIIB		Unbinilium										99 Eu				100 Gd				101 Tb	
94 IIIB		Untrium										100 Gd				101 Tb				102 Dy	
95 IIIB		Unquadium										101 Tb				102 Dy				103 Ho	
96 IIIB		Unpentium										102 Dy				103 Ho				104 Er	
97 IIIB		Unsexium										103 Ho				104 Er				105 Tm	
98 IIIB		Unseptium										104 Er				105 Tm				106 Yb	
99 IIIB		Unoctium										105 Tm				106 Yb				107 Lu	
100 IIIB		Unnennium										106 Yb				107 Lu				108 Hf	

*Based upon ¹²C. (C) indicates the mass number of the longest-lived isotope. [†]IUPAC conventional atomic weights; standard atomic weights for these elements are expressed in intervals; see www.iupac.org for an explanation and values. For a description of the data, visit physics.nist.gov/data NIST SP 966 (September 2014)

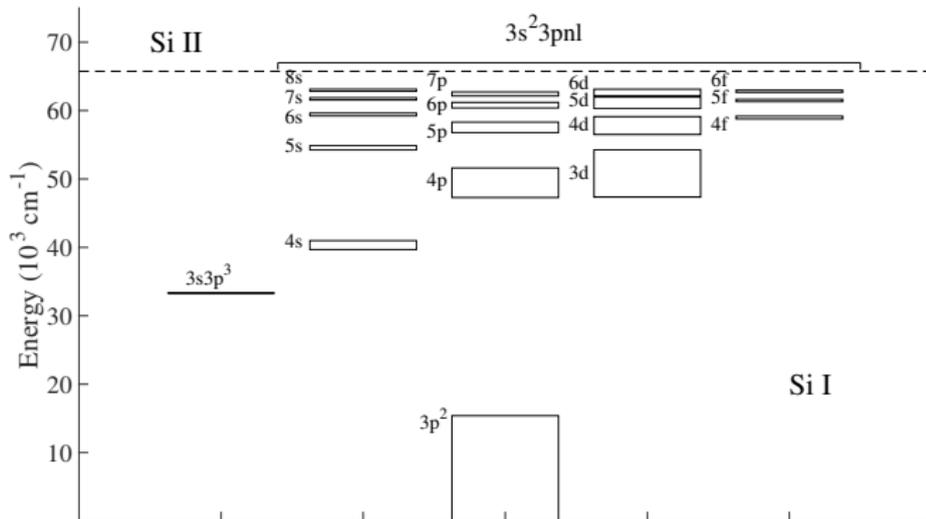
High excitation transitions

PERIODIC TABLE																		NIST National Institute of Standards and Technology U.S. Department of Commerce																																	
Atomic Properties of the Elements																		18 VIIIA																																	
Frequently used fundamental physical constants																		Physical Measurement Laboratory www.nist.gov/pml		Standard Reference Data www.nist.gov/srd																															
For the most accurate values of these and other constants, visit physics.nist.gov/constants																		13 IIIA		14 IVA		15 VA		16 VIA		17 VIIA		18 VIIIA																							
1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of ^{133}Cs																		5 B		6 C		7 N		8 O		9 F		10 Ne																							
speed of light in vacuum c 299 792 458 m s $^{-1}$ (exact)																		13 Al		14 Si		15 P		16 S		17 Cl		18 Ar																							
Planck constant h 6.626 070 15 × 10 $^{-34}$ J s ($n = n/202$)																		13 Ga		14 Ge		15 As		16 Se		17 Br		18 Kr																							
elementary charge e 1.602 177 × 10 $^{-19}$ C																		13 In		14 Sn		15 Sb		16 Te		17 I		18 Xe																							
electron mass m_e 9.109 383 56 × 10 $^{-31}$ kg																		13 Tl		14 Pb		15 Bi		16 Po		17 At		18 Rn																							
proton mass m_p 1.672 621 923 × 10 $^{-27}$ kg																		13 Pb		14 Bi		15 Po		16 At		17 Rn		18 Fr																							
fine structure constant α 1/137.035 999																		13 Tl		14 Pb		15 Bi		16 Po		17 At		18 Rn																							
Rydberg constant R_∞ 10 973 731.568 m $^{-1}$																		13 Tl		14 Pb		15 Bi		16 Po		17 At		18 Rn																							
Bohr radius a_0 5.291 772 109 × 10 $^{-11}$ m																		13 Tl		14 Pb		15 Bi		16 Po		17 At		18 Rn																							
Boltzmann constant k_B 1.380 658 × 10 $^{-23}$ J K $^{-1}$																		13 Tl		14 Pb		15 Bi		16 Po		17 At		18 Rn																							
1	1A	1	2	IIA											10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36										
1	1A	2	IIA											10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36											
2	1A	2	IIA											10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36											
3	1A	2	IIA	3	IIIB	4	IVB	5	VB	6	VIB	7	VII B	8	VIII	9	IX	10	X	11	XI	12	XII	13	XIIIA	14	XIIIV	15	XIVB	16	XVB	17	XVIB	18	XVII B	19	XVIII	20	XIIIA	21	XIIIV	22	XIVB	23	XVIB	24	XVIB	25	XVII B	26	XVIII
4	1A	2	IIA	3	IIIB	4	IVB	5	VB	6	VIB	7	VII B	8	VIII	9	IX	10	X	11	XI	12	XII	13	XIIIA	14	XIIIV	15	XIVB	16	XVB	17	XVIB	18	XVII B	19	XVIII	20	XIIIA	21	XIIIV	22	XIVB	23	XVIB	24	XVIB	25	XVII B	26	XVIII
5	1A	2	IIA	3	IIIB	4	IVB	5	VB	6	VIB	7	VII B	8	VIII	9	IX	10	X	11	XI	12	XII	13	XIIIA	14	XIIIV	15	XIVB	16	XVB	17	XVIB	18	XVII B	19	XVIII	20	XIIIA	21	XIIIV	22	XIVB	23	XVIB	24	XVIB	25	XVII B	26	XVIII
6	1A	2	IIA	3	IIIB	4	IVB	5	VB	6	VIB	7	VII B	8	VIII	9	IX	10	X	11	XI	12	XII	13	XIIIA	14	XIIIV	15	XIVB	16	XVB	17	XVIB	18	XVII B	19	XVIII	20	XIIIA	21	XIIIV	22	XIVB	23	XVIB	24	XVIB	25	XVII B	26	XVIII
7	1A	2	IIA	3	IIIB	4	IVB	5	VB	6	VIB	7	VII B	8	VIII	9	IX	10	X	11	XI	12	XII	13	XIIIA	14	XIIIV	15	XIVB	16	XVB	17	XVIB	18	XVII B	19	XVIII	20	XIIIA	21	XIIIV	22	XIVB	23	XVIB	24	XVIB	25	XVII B	26	XVIII
8	1A	2	IIA	3	IIIB	4	IVB	5	VB	6	VIB	7	VII B	8	VIII	9	IX	10	X	11	XI	12	XII	13	XIIIA	14	XIIIV	15	XIVB	16	XVB	17	XVIB	18	XVII B	19	XVIII	20	XIIIA	21	XIIIV	22	XIVB	23	XVIB	24	XVIB	25	XVII B	26	XVIII
9	1A	2	IIA	3	IIIB	4	IVB	5	VB	6	VIB	7	VII B	8	VIII	9	IX	10	X	11	XI	12	XII	13	XIIIA	14	XIIIV	15	XIVB	16	XVB	17	XVIB	18	XVII B	19	XVIII	20	XIIIA	21	XIIIV	22	XIVB	23	XVIB	24	XVIB	25	XVII B	26	XVIII
10	1A	2	IIA	3	IIIB	4	IVB	5	VB	6	VIB	7	VII B	8	VIII	9	IX	10	X	11	XI	12	XII	13	XIIIA	14	XIIIV	15	XIVB	16	XVB	17	XVIB	18	XVII B	19	XVIII	20	XIIIA	21	XIIIV	22	XIVB	23	XVIB	24	XVIB	25	XVII B	26	XVIII
11	1A	2	IIA	3	IIIB	4	IVB	5	VB	6	VIB	7	VII B	8	VIII	9	IX	10	X	11	XI	12	XII	13	XIIIA	14	XIIIV	15	XIVB	16	XVB	17	XVIB	18	XVII B	19	XVIII	20	XIIIA	21	XIIIV	22	XIVB	23	XVIB	24	XVIB	25	XVII B	26	XVIII
12	1A	2	IIA	3	IIIB	4	IVB	5	VB	6	VIB	7	VII B	8	VIII	9	IX	10	X	11	XI	12	XII	13	XIIIA	14	XIIIV	15	XIVB	16	XVB	17	XVIB	18	XVII B	19	XVIII	20	XIIIA	21	XIIIV	22	XIVB	23	XVIB	24	XVIB	25	XVII B	26	XVIII
13	1A	2	IIA	3	IIIB	4	IVB	5	VB	6	VIB	7	VII B	8	VIII	9	IX	10	X	11	XI	12	XII	13	XIIIA	14	XIIIV	15	XIVB	16	XVB	17	XVIB	18	XVII B	19	XVIII	20	XIIIA	21	XIIIV	22	XIVB	23	XVIB	24	XVIB	25	XVII B	26	XVIII
14	1A	2	IIA	3	IIIB	4	IVB	5	VB	6	VIB	7	VII B	8	VIII	9	IX	10	X	11	XI	12	XII	13	XIIIA	14	XIIIV	15	XIVB	16	XVB	17	XVIB	18	XVII B	19	XVIII	20	XIIIA	21	XIIIV	22	XIVB	23	XVIB	24	XVIB	25	XVII B	26	XVIII
15	1A	2	IIA	3	IIIB	4	IVB	5	VB	6	VIB	7	VII B	8	VIII	9	IX	10	X	11	XI	12	XII	13	XIIIA	14	XIIIV	15	XIVB	16	XVB	17	XVIB	18	XVII B	19	XVIII	20	XIIIA	21	XIIIV	22	XIVB	23	XVIB	24	XVIB	25	XVII B	26	XVIII
16	1A	2	IIA	3	IIIB	4	IVB	5	VB	6	VIB	7	VII B	8	VIII	9	IX	10	X	11	XI	12	XII	13	XIIIA	14	XIIIV	15	XIVB	16	XVB	17	XVIB	18	XVII B	19	XVIII	20	XIIIA	21	XIIIV	22	XIVB	23	XVIB	24	XVIB	25	XVII B	26	XVIII
17	1A	2	IIA	3	IIIB	4	IVB	5	VB	6	VIB	7	VII B	8	VIII	9	IX	10	X	11	XI	12	XII	13	XIIIA	14	XIIIV	15	XIVB	16	XVB	17	XVIB	18	XVII B	19	XVIII	20	XIIIA	21	XIIIV	22	XIVB	23	XVIB	24	XVIB	25	XVII B	26	XVIII
18	1A	2	IIA	3	IIIB	4	IVB	5	VB	6	VIB	7	VII B	8	VIII	9	IX	10	X	11	XI	12	XII	13	XIIIA	14	XIIIV	15	XIVB	16	XVB	17	XVIB	18	XVII B	19	XVIII	20	XIIIA	21	XIIIV	22	XIVB	23	XVIB	24	XVIB	25	XVII B	26	XVIII
19	1A	2	IIA	3	IIIB	4	IVB	5	VB	6	VIB	7	VII B	8	VIII	9	IX	10	X	11	XI	12	XII	13	XIIIA	14	XIIIV	15	XIVB	16	XVB	17	XVIB	18	XVII B	19	XVIII	20	XIIIA	21	XIIIV	22	XIVB	23	XVIB	24	XVIB	25	XVII B	26	XVIII
20	1A	2	IIA	3	IIIB	4	IVB	5	VB	6	VIB	7	VII B	8	VIII	9	IX	10	X	11	XI	12	XII	13	XIIIA	14	XIIIV	15	XIVB	16	XVB	17	XVIB	18	XVII B	19	XVIII	20	XIIIA	21	XIIIV	22	XIVB	23	XVIB	24	XVIB	25	XVII B	26	XVIII
21	1A	2	IIA	3	IIIB	4	IVB	5	VB	6	VIB	7	VII B	8	VIII	9	IX	10	X	11	XI	12	XII	13	XIIIA	14	XIIIV	15	XIVB	16	XVB	17	XVIB	18	XVII B	19	XVIII	20	XIIIA	21	XIIIV	22	XIVB	23	XVIB	24	XVIB	25	XVII B	26	XVIII
22	1A	2	IIA	3	IIIB	4	IVB	5	VB	6	VIB	7	VII B	8	VIII	9	IX	10	X	11	XI	12	XII	13	XIIIA	14	XIIIV	15	XIVB	16	XVB	17	XVIB	18	XVII B	19	XVIII	20	XIIIA	21	XIIIV	22	XIVB	23	XVIB	24	XVIB	25	XVII B	26	XVIII
23	1A	2	IIA	3	IIIB	4	IVB	5	VB	6	VIB	7	VII B	8	VIII	9	IX	10	X	11	XI	12	XII	13	XIIIA	14	XIIIV	15	XIVB	16	XVB	17	XVIB	18	XVII B	19	XVIII	20	XIIIA	21	XIIIV	22	XIVB	23	XVIB	24	XVIB	25	XVII B	26	XVIII
24	1A	2	IIA	3	IIIB	4	IVB	5	VB	6	VIB	7	VII B	8	VIII	9	IX	10	X	11	XI	12	XII	13	XIIIA	14	XIIIV	15	XIVB	16	XVB	17	XVIB	18	XVII B	19	XVIII	20	XIIIA	21	XIIIV	22	XIVB	23	XVIB	24	XVIB	25	XVII B	26	XVIII
25	1A	2	IIA	3	IIIB	4	IVB	5	VB	6	VIB	7	VII B	8	VIII	9	IX	10	X	11	XI	12	XII	13	XIIIA	14	XIIIV	15	XIVB	16	XVB	17	XVIB	18	XVII B	19	XVIII	20	XIIIA	21	XIIIV	22	XIVB	23	XVIB	24	XVIB	25	XVII B	26	XVIII
26	1A	2	IIA	3	IIIB	4	IVB	5	VB	6	VIB	7	VII B	8	VIII	9	IX	10	X	11	XI	12	XII	13	XIIIA	14	XIIIV	15	XIVB	16	XVB	17	XVIB	18	XVII B	19	XVIII	20	XIIIA	21	XIIIV	22	XIVB	23	XVIB	24	XVIB	25	XVII B	26	XVIII
27	1A	2	IIA	3	IIIB	4	IVB	5	VB	6	VIB	7	VII B	8	VIII	9																																			

High-excitation transitions- Fe I



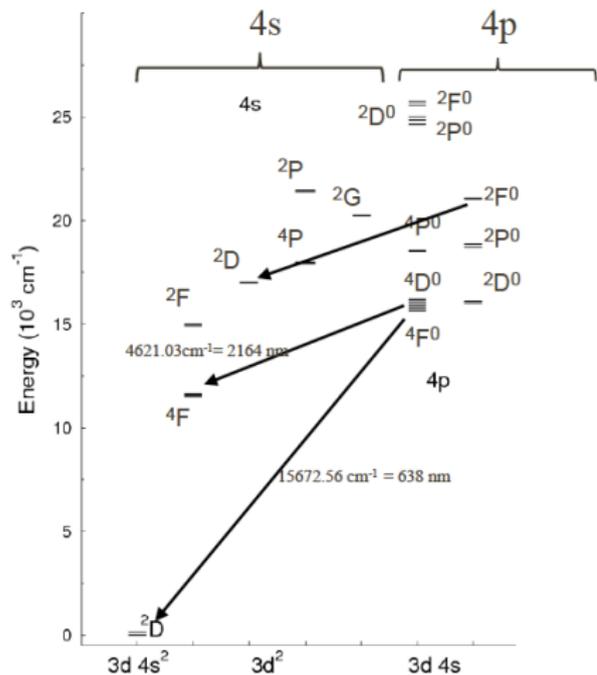
Silicon



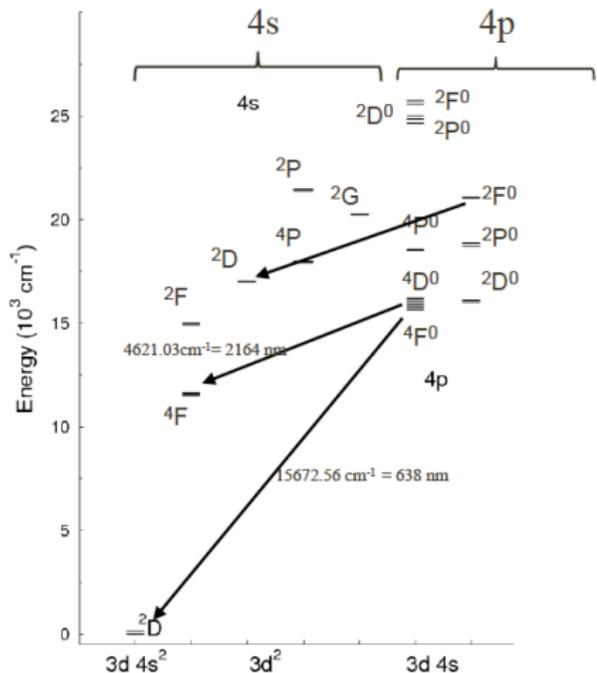
Low excitation lines - Sc, Ti, V, La I

PERIODIC TABLE																	
Atomic Properties of the Elements																	
Frequently used fundamental physical constants																	
For the most accurate values of these and other constants, visit physics.nist.gov/constants																	
1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of ^{133}Cs																	
speed of light in vacuum c 299 792 458 m s ⁻¹ (exact)																	
Planck constant h 6.626 07 × 10 ⁻³⁴ J s ($n = n/2\pi$)																	
elementary charge e 1.602 177 × 10 ⁻¹⁹ C																	
electron mass m_e 9.109 38 × 10 ⁻³¹ kg																	
proton mass m_p 1.672 622 × 10 ⁻²⁷ kg																	
fine-structure constant α 1/137.035 999																	
Rydberg constant R_∞ 10 973 731.569 m ⁻¹																	
$R_\infty c$ 3.299 841 960 × 10 ¹⁵ Hz																	
$R_\infty h c$ 13.605 69 eV																	
Boltzmann constant k 1.380 6 × 10 ⁻²³ J K ⁻¹																	
Physical Measurement Laboratory www.nist.gov/pml																	
Standard Reference Data www.nist.gov/srd																	
Legend: Solids (blue), Liquids (green), Gases (red), Artificially Prepared (yellow)																	
Group																	
1 IA																	
1	2 IIA																18 VIII
1	2																18
2	3																18
3	4																18
4	5																18
5	6																18
6	7																18
7	8																18
8	9																18
9	10																18
10	11																18
11	12																18
12	13																18
13	14																18
14	15																18
15	16																18
16	17																18
17	18																18
18	19																18
19	20																18
20	21																18
21	22																18
22	23																18
23	24																18
24	25																18
25	26																18
26	27																18
27	28																18
28	29																18
29	30																18
30	31																18
31	32																18
32	33																18
33	34																18
34	35																18
35	36																18
36	37																18
37	38																18
38	39																18
39	40																18
40	41																18
41	42																18
42	43																18
43	44																18
44	45																18
45	46																18
46	47																18
47	48																18
48	49																18
49	50																18
50	51																18
51	52																18
52	53																18
53	54																18
54	55																18
55	56																18
56	57																18
57	58																18
58	59																18
59	60																18
60	61																18
61	62																18
62	63																18
63	64																18
64	65																18
65	66																18
66	67																18
67	68																18
68	69																18
69	70																18
70	71																18
71	72																18
72	73																18
73	74																18
74	75																18
75	76																18
76	77																18
77	78																18
78	79																18
79	80																18
80	81																18
81	82																18
82	83																18
83	84																18
84	85																18
85	86																18
86	87																18
87	88																18
88	89																18
89	90																18
90	91																18
91	92																18
92	93																18
93	94																18
94	95																18
95	96																18
96	97																18
97	98																18
98	99																18
99	100																18
100	101																18
101	102																18
102	103																18
103	104																18
104	105																18
105	106																18
106	107																18
107	108																18
108	109																18
109	110																18
110	111																18
111	112																18
112	113																18
113	114																18
114	115																18
115	116																18
116	117																18
117	118																18
118	119																18
119	120																18
120	121																18
121	122																18
122	123																18
123	124																18
124	125																18
125	126																18
126	127																18
127	128																18
128	129																18
129	130																18
130	131																18
131	132																18
132	133																18
133	134																18
134	135																18
135	136																18
136	137																18
137	138																18
138	139																18
139	140																18
140	141																18
141	142																18
142	143																18
143	144																18
144	145																18
145	146																18
146	147																18
147	148																18
148	149																18
149	150																18
150	151																18
151	152																18
152	153																18
153	154																18
154	155																18
155	156																18
156	157																18
157	158																18
158	159																18
159	160																18
160	161																18
161	162																18
162	163																18
163	164																18
164	165																18
165	166																18
166	167																18
167	168																18
168	169																18
169	170																18
170	171																18
171	172																18
172	173																18
173	174																18
174	175																18
175	176																18
176	177																18
177	178																18
178	179																18
179	180																18
180	181																18
181	182																18
182	183																18
183	184																18
184	185																18
185	186																18
186	187																18
187	188																18
188	189																18
189	190																18
190	191																18
191	192																18
192	193																18
193	194																18
194	195																18
195	196																18
196	197																18
197	198																18
198	199																18
199	200																18
200	201																18
201	202																18
202	203																18
203	204																18
204	205																18
205	206																18
206	207																18
207	208																18
208	209																18
209	210																18
210	211																18
211	212																18
212	213																18
213	214																18
214	215																18
215	216																18
216	217																18
217	218																18
218	219																18
219	220																18
220	221																18
221	222																18
222	223																18
223	224																18
224	225																18
225	226																18
226	227																18
227	228																18
228	229																18
229	230																18
230	231																18
231	232																18
232	233																18
233	234																18
234	235																18
235	236																18
236	237																18
237	238																18
238	239																18
239	240																18
240	241																18
241	242																18
242	243																18
243	244																18
244	245																18
245	246																18
246	247																18
247	248																18
248	249																18
249	250																18
250	251																18
251	252																18
252	253																18
253	254																18
254	255																18
255	256																18
256	257																18
257	258																18
258	259																18
259	260																18
260	261																18
261	262																18
262	263																18
263	264																18
264	265																18
265	266																18
266	267																18
267	268																18
268	269																18
269	270																18
270	271																18
271	272																18
272	273																18
273	274																18
274	275																18
275	276																18
276	277																18
277	278																18
278	279																18
279	280																18
280	281																18
281	282																18
282	283																18
283	284																18
284	285																18
285	286																18
286	287																18
287	288																18
288	289																18
289	290																18
290	291																18
291	292																18
292	293																18
293	294																18
294	295																18
295	296																18
296	297																18
297	298																18
298	299																18
299	300																18
300	301																18
301	302																18
302	303																18
303	304																18
304	305																18
305	306																18
306	307																18
307	308																18
308	309																18
309	310																18
310	311																18
311	312																18
312	313																18
313	314																18
314	315																18
315																	

Low excitation lines - Sc I, Y I, La I



Low excitation lines - Sc I, Y I, La I



The energy level structure for Sc I, Y I and La I are similar with the energy levels for $nd(n+1)s^2$ and $nd^2(n+1)s$

Sc I : $3d4s^2, 3d^24s$

Y I : $4d5s^2, 4d^25s$

La I : $5d6s^2, 5d^26s$

Infrared transitions between $nd^2(n+1)s - nd(n+1)s(n+1)p$

Experimental transition rates

The A-values is derived from the measured quantities branching fraction (BF) and radiative lifetime (τ) of the upper level.

$$A_{ul} = \frac{BF_{ul}}{\tau_u}$$

where

$$BF_{ul} = \frac{I_{ul}}{\sum_l I_{ul}}$$

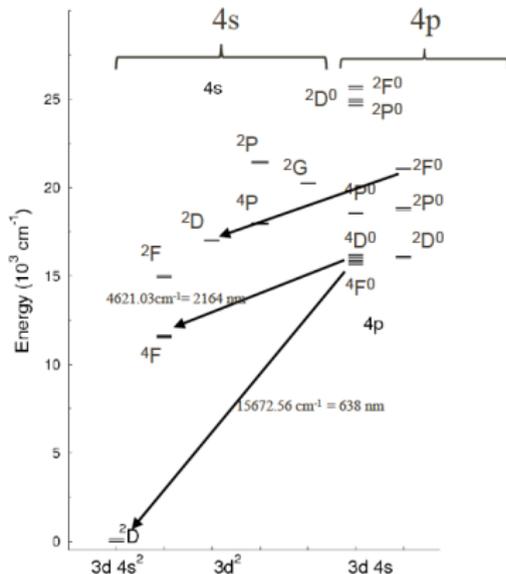
Experimental transition rates

The A-values is derived from the measured quantities branching fraction (BF) and radiative lifetime (τ) of the upper level.

$$A_{ul} = \frac{BF_{ul}}{\tau_u}$$

where

$$BF_{ul} = \frac{I_{ul}}{\sum_l I_{ul}}$$



Experimental transition rates

The A-values is derived from the measured quantities

- branching fraction (BF) and
- radiative lifetime (τ) of the upper level.

$$A_{ul} = \frac{BF_{ul}}{\tau_u}$$

where

$$BF_{ul} = \frac{I_{ul}}{\sum_l I_{ul}}$$

<i>Decay region</i>	<i>BF spread</i>	<i>lifetime</i>
only optical	narrow	1-20 ns
optical + nIR	wide	1-20 ns
only nIR	narrow	1-10 μ s

Experimental transition rates

The A-values is derived from the measured quantities

- branching fraction (BF) and
- radiative lifetime (τ) of the upper level.

$$A_{ul} = \frac{BF_{ul}}{\tau_u}$$

where

$$BF_{ul} = \frac{I_{ul}}{\sum_l I_{ul}}$$

<i>Decay region</i>	<i>BF spread</i>	<i>lifetime</i>
only optical	narrow 👍	1-20 ns 👍
optical + nIR	wide	1-20 ns
only nIR	narrow	1-10 μ s

Experimental transition rates

The A-values is derived from the measured quantities

- branching fraction (BF) and
- radiative lifetime (τ) of the upper level.

$$A_{ul} = \frac{BF_{ul}}{\tau_u}$$

where

$$BF_{ul} = \frac{I_{ul}}{\sum_l I_{ul}}$$

<i>Decay region</i>	<i>BF spread</i>	<i>lifetime</i>
only optical	narrow 	1-20 ns 
optical + nIR	wide 	1-20 ns 
only nIR	narrow	1-10 μ s

Experimental transition rates

The A-values is derived from the measured quantities

- branching fraction (BF) and
- radiative lifetime (τ) of the upper level.

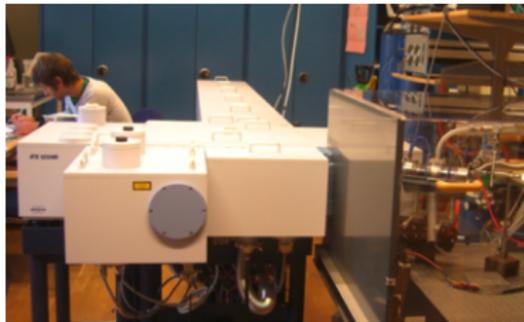
$$A_{ul} = \frac{BF_{ul}}{\tau_u}$$

where

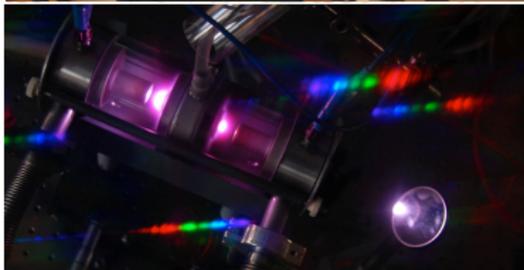
$$BF_{ul} = \frac{I_{ul}}{\sum_l I_{ul}}$$

<i>Decay region</i>	<i>BF spread</i>	<i>lifetime</i>
only optical	narrow 	1-20 ns 
optical + nIR	wide 	1-20 ns 
only nIR	narrow 	1-10 μ s 

The Edlén laboratory

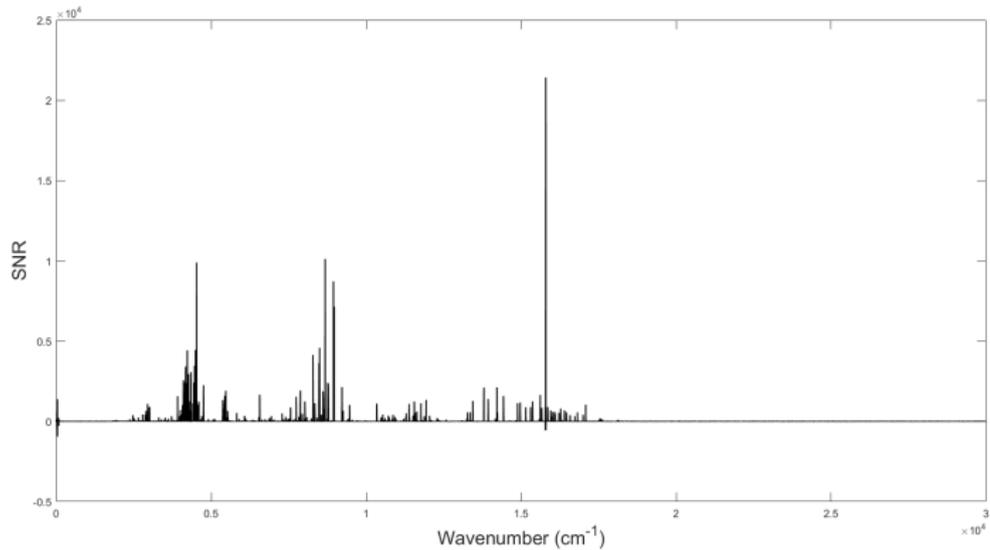


FTS Bruker IFS125
Coverage: 4000 Å- 5 μm
HC lamp produces neutral and
singly ionised atoms and ions.
Resolving power 10^6

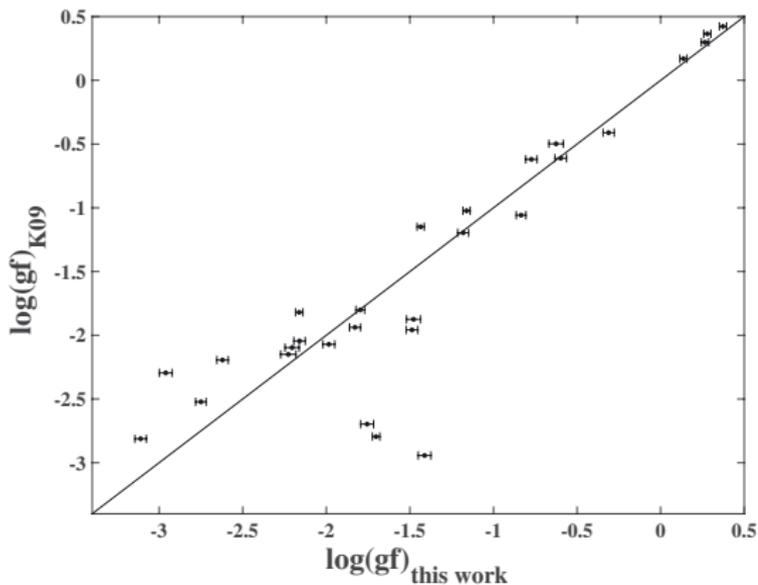


Lifetimes measured at Lund
High Power Laser Facility
(closed 2018).

FTS spectrum of Sc I



Results for Sc I

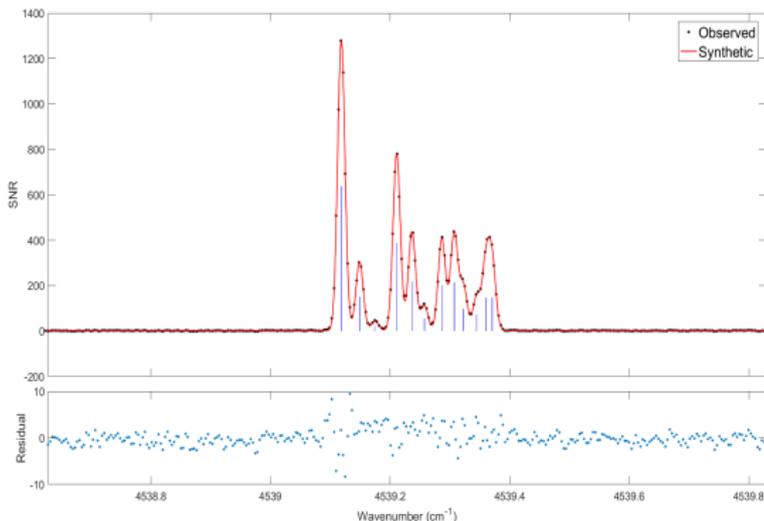


Results from Sc I : Pehlivan et al. (2015)

Lifetimes and branching fraction for Y I and La I have been measured, and are being analysed.

Hyperfine structure

The interaction with the nuclear spin splits the fine structure. More important for near-IR lines.



Spectrum of Sc I observed with the IRFTS at Edlen laboratory, van Deelen 2017.

Hyperfine structure

Physica Scripta. Vol. 53, 28–32, 1996

Hyperfine Structure of Sc I by Infrared Fourier Transform Spectroscopy

A. Aboussaid,^a M. Carleer,^a D. Hurtmans,^a E. Biémont^b and M. R. Godefroid^{a*}

^a Laboratoire de Chimie Physique Moléculaire, CP160/09, Université Libre de Bruxelles, 50, av. F.D. Roosevelt, B-1050 Bruxelles, Belgium

^b Institut d'Astrophysique, Université de Liège, 5, Avenue de Coïnte, B-4000 Liège, Belgium

Received March 5, 1995; Accepted in revised form May 29, 1995

Hyperfine Structure of Sc I by Infrared Fourier Transform Spectroscopy 29

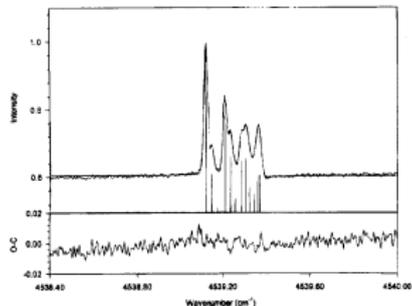


Fig. 1. Observed and fitted hyperfine patterns for the Sc I 3d4s(3D)4p 2D_{3/2} - 3d²(1F)4s 4F_{5/2} at $\tilde{\nu} = 4539.227 \text{ cm}^{-1}$. The theoretical components of the profiles with their relative intensities are also shown for comparison. The lower part of the figure shows the (observed-calculated) signal corresponding to the final fit of the line profile.

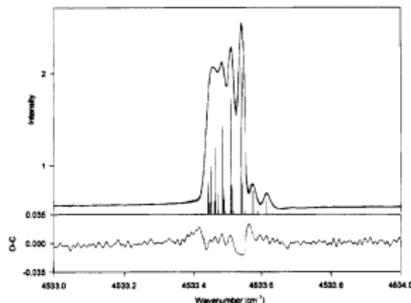
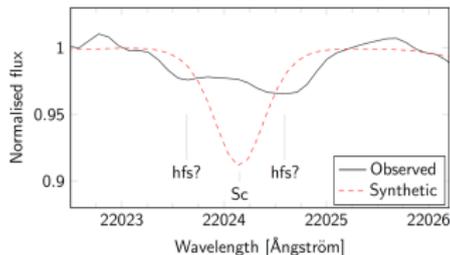


Fig. 2. Observed and fitted hyperfine patterns for the Sc I 3d4s(3D)4p 4D_{5/2} - 3d²(1F)4s 4F_{5/2} at $\tilde{\nu} = 4533.502 \text{ cm}^{-1}$. The theoretical components of the profiles with their relative intensities are also shown for comparison. The lower part of the figure shows the (observed-calculated) signal corresponding to the final fit of the line profile.

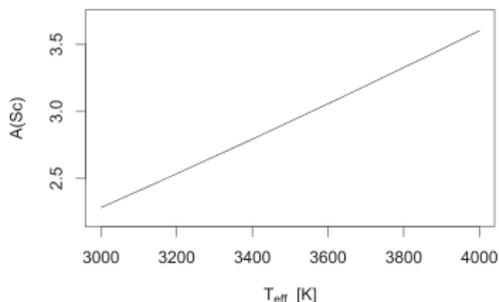
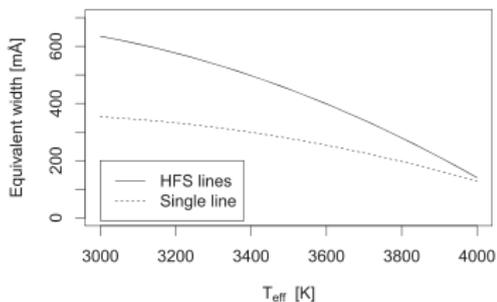
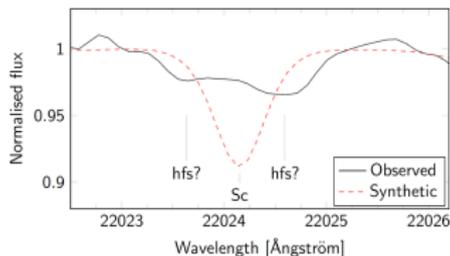
Hyperfine structure

Omitting the inclusion of the hyperfine structure can result in significant deviations in the abundance.



Hyperfine structure

Omitting the inclusion of the hyperfine structure can result in significant deviations in the abundance.



Simulations by Thorsbro+, ApJS (2018).

Approach for Mg, Si and Al

Approach to retrieve an evaluated set of infrared Mg I, Al I and Si I transition data:

Experimental data

FTS measurements combined with lifetime data

Theoretical data

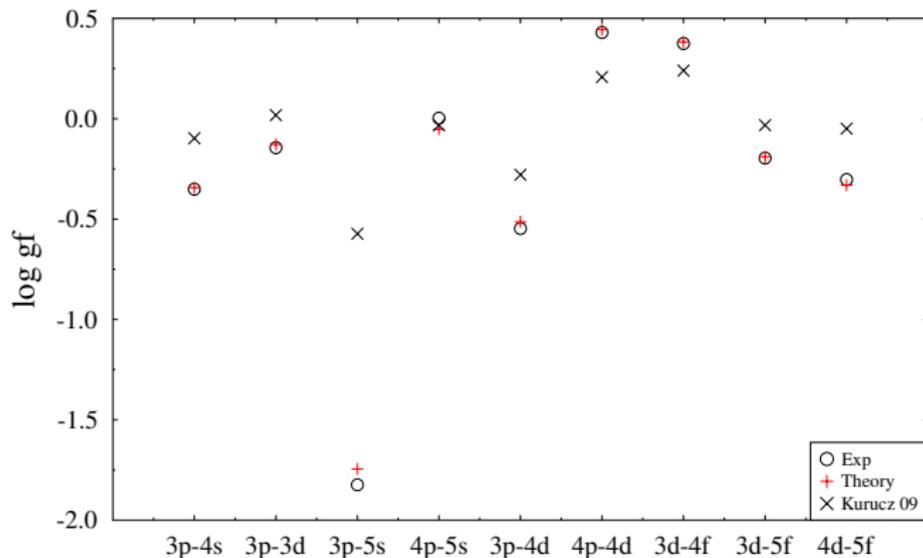
ATSP2k calculations for additional states

Stellar spectra

For benchmarking and application

Combined with collisional data by P Barklem and J Grumer (Uppsala) to provide '*atomic data to the limit*'. Calculations by P Jönsson, A Papoulia, J Ekman.

Results for Magnesium



Results from Mg I : Pehlivan et al. (2017)

Studies for Silicon (Pehlivan Rhodin et al., in review) and Aluminium (Papoulia et al., 2018 and Burheim et al., in preparation). See Posters.

Note that the uncertainty in the data directly translates to an uncertainty in derived stellar abundance.

Uncertainties

Remember:

$$A_{ul} = \frac{BF_{ul}}{\tau_u}$$

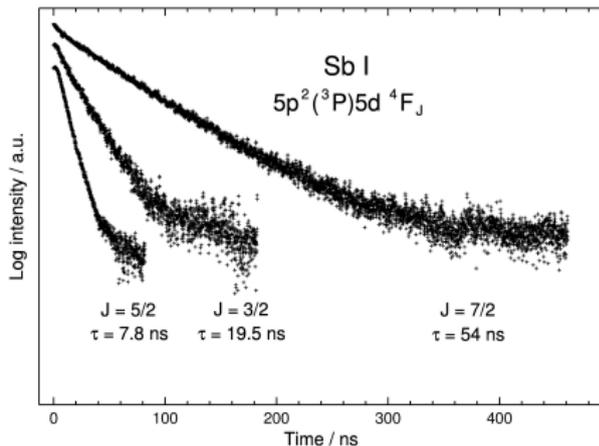
where

$$BF_{ul} = \frac{I_{ul}}{\sum_l I_{ul}}$$

and

$$f \propto \lambda^2 \cdot A$$

Systematic and statistical effects contribute to the uncertainty.



Uncertainties

Sources of uncertainties for experimental data:

- *Branching fractions*: calibration, self absorption (radiative transfer), unobserved lines. 0-30%.

- *Radiative lifetime*: statistical and systematic errors. 5-15%

Experimental f -values can be obtained with uncertainties down to 5%.

near-IR *forbidden* transitions

An important class of infrared lines are parity forbidden transitions (E2 and M1), observed in nebula and low density plasmas.

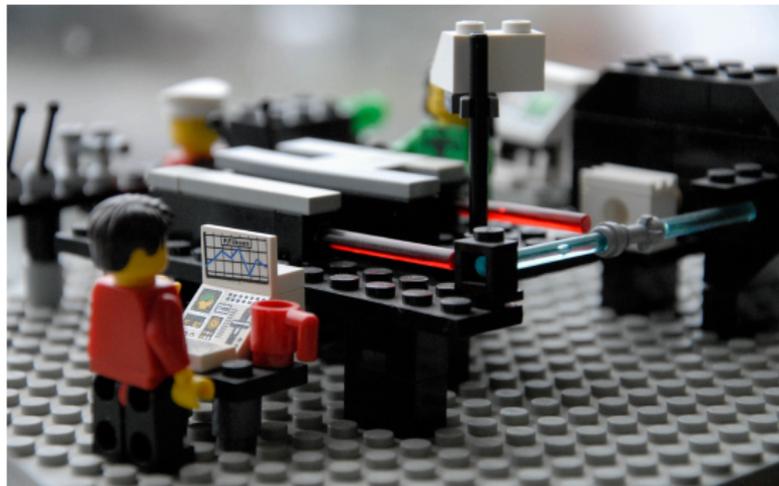
- ❖ Low transition rates ($\sim 1 \text{ s}^{-1}$)
- ❖ Long radiative lifetimes
- ❖ Sensitive to collisions

Have relied on calculated transition rates, but can now be measured using selective methods at storage rings (e.g. DESIREE @ Stockholm university, Sweden) combined with astronomical observations of low-density plasmas (Eta Carinae).



Summary

- ❖ near-IR atomic data is crucial to meet the demands from new observatories.
- ❖ Lab spectroscopy and calculations can provide evaluated sets of near-infrared atomic data with uncertainties down to 5%





THIS WEEK

EDITORIALS

MENTORING The heavy responsibility to the next generation **p.438**

WORLD VIEW Beware the real risk of World Cup fever **p.439**



POISON Strawberry-frog parents give protection to kids **p.441**

Nailing fingerprints in the stars

Laboratory-based experiments are sorely needed to complement the rapidly proliferating spectral data originating from observations by the latest space telescopes.

What are stars made of? After astronomers detected a bright-yellow, unknown spectral line in sunlight in 1868, they named the new element helium after the Greek Sun god

quantum mechanics. But heavier elements have many electrons that can participate in transitions — iron has 26, making the probabilities of possible transitions between levels too complex to calculate accu-

Periodic table - Rare earth elements

PERIODIC TABLE
Atomic Properties of the Elements

Frequently used fundamental physical constants
For the most accurate values of these and other constants, visit physics.nist.gov/constants
1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of ^{133}Cs

speed of light in vacuum c 299 792 458 m s⁻¹ (exact)
Planck constant h 6.626 07 × 10⁻³⁴ J s ($n = n/227$)
elementary charge e 1.602 177 × 10⁻¹⁹ C
electron mass m_e 9.109 38 × 10⁻³¹ kg
 m_p/m_e 1.836 152 673 × 10³
proton mass m_p 1.672 622 × 10⁻²⁷ kg
fine-structure constant α 1/137.035 999
Rydberg constant R_∞ 10 973 731.569 m⁻¹
 R_H/c 3.299 841 960 × 10¹⁰ Hz
 R_H/h 13.605 69 eV
Boltzmann constant k_B 1.380 65 × 10⁻²³ J K⁻¹

Physical Measurement Laboratory
www.nist.gov/pml

Standard Reference Data
www.nist.gov/srd

13 IIA **14 IVA** **15 VA** **16 VIA** **17 VIIA**

5 B **6 C** **7 N** **8 O** **9 F** **10 Ne**

11 Na **12 Mg** **13 Al** **14 Si** **15 P** **16 S** **17 Cl** **18 Ar**

19 K **20 Ca** **21 Sc** **22 Ti** **23 V** **24 Cr** **25 Mn** **26 Fe** **27 Co** **28 Ni** **29 Cu** **30 Zn** **31 Ga** **32 Ge** **33 As** **34 Se** **35 Br** **36 Kr**

37 Rb **38 Sr** **39 Y** **40 Zr** **41 Nb** **42 Mo** **43 Tc** **44 Ru** **45 Rh** **46 Pd** **47 Ag** **48 Cd** **49 In** **50 Sn** **51 Sb** **52 Te** **53 I** **54 Xe**

55 Cs **56 Ba** **57 La** **58 Ce** **59 Pr** **60 Nd** **61 Pm** **62 Sm** **63 Eu** **64 Gd** **65 Tb** **66 Dy** **67 Ho** **68 Er** **69 Tm** **70 Yb** **71 Lu**

87 Fr **88 Ra** **89 Ac** **90 Th** **91 Pa** **92 U** **93 Np** **94 Pu** **95 Am** **96 Cm** **97 Bk** **98 Cf** **99 Es** **100 Fm** **101 Md** **102 No** **103 Lr**

Legend:
 Solids
 Liquids
 Gases
 Artificially Prepared

Group 1 IA **2 IIA** **3 IIIB** **4 IVB** **5 VB** **6 VIB** **7 VIIB** **8 VIII** **9 VIII** **10 VIII** **11 IB** **12 IIB** **13 IIIA** **14 IVA** **15 VA** **16 VIA** **17 VIIA** **18 VIIIA**

Period 1 2 3 4 5 6 7 8 9 10 11 12

Atomic Number 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100 101 102 103 104 105 106 107 108 109 110 111 112 113 114 115 116 117 118 119 120 121 122 123 124 125 126 127 128 129 130 131 132 133 134 135 136 137 138 139 140 141 142 143 144 145 146 147 148 149 150 151 152 153 154 155 156 157 158 159 160 161 162 163 164 165 166 167 168 169 170 171 172 173 174 175 176 177 178 179 180 181 182 183 184 185 186 187 188 189 190 191 192 193 194 195 196 197 198 199 200 201 202 203 204 205 206 207 208 209 210 211 212 213 214 215 216 217 218 219 220 221 222 223 224 225 226 227 228 229 230 231 232 233 234 235 236 237 238 239 240 241 242 243 244 245 246 247 248 249 250 251 252 253 254 255 256 257 258 259 260 261 262 263 264 265 266 267 268 269 270 271 272 273 274 275 276 277 278 279 280 281 282 283 284 285 286 287 288 289 290 291 292 293 294 295 296 297 298 299 300 301 302 303 304 305 306 307 308 309 310 311 312 313 314 315 316 317 318 319 320 321 322 323 324 325 326 327 328 329 330 331 332 333 334 335 336 337 338 339 340 341 342 343 344 345 346 347 348 349 350 351 352 353 354 355 356 357 358 359 360 361 362 363 364 365 366 367 368 369 370 371 372 373 374 375 376 377 378 379 380 381 382 383 384 385 386 387 388 389 390 391 392 393 394 395 396 397 398 399 400 401 402 403 404 405 406 407 408 409 410 411 412 413 414 415 416 417 418 419 420 421 422 423 424 425 426 427 428 429 430 431 432 433 434 435 436 437 438 439 440 441 442 443 444 445 446 447 448 449 450 451 452 453 454 455 456 457 458 459 460 461 462 463 464 465 466 467 468 469 470 471 472 473 474 475 476 477 478 479 480 481 482 483 484 485 486 487 488 489 490 491 492 493 494 495 496 497 498 499 500 501 502 503 504 505 506 507 508 509 510 511 512 513 514 515 516 517 518 519 520 521 522 523 524 525 526 527 528 529 530 531 532 533 534 535 536 537 538 539 540 541 542 543 544 545 546 547 548 549 550 551 552 553 554 555 556 557 558 559 560 561 562 563 564 565 566 567 568 569 570 571 572 573 574 575 576 577 578 579 580 581 582 583 584 585 586 587 588 589 590 591 592 593 594 595 596 597 598 599 600 601 602 603 604 605 606 607 608 609 610 611 612 613 614 615 616 617 618 619 620 621 622 623 624 625 626 627 628 629 630 631 632 633 634 635 636 637 638 639 640 641 642 643 644 645 646 647 648 649 650 651 652 653 654 655 656 657 658 659 660 661 662 663 664 665 666 667 668 669 670 671 672 673 674 675 676 677 678 679 680 681 682 683 684 685 686 687 688 689 690 691 692 693 694 695 696 697 698 699 700 701 702 703 704 705 706 707 708 709 710 711 712 713 714 715 716 717 718 719 720 721 722 723 724 725 726 727 728 729 730 731 732 733 734 735 736 737 738 739 740 741 742 743 744 745 746 747 748 749 750 751 752 753 754 755 756 757 758 759 760 761 762 763 764 765 766 767 768 769 770 771 772 773 774 775 776 777 778 779 780 781 782 783 784 785 786 787 788 789 790 791 792 793 794 795 796 797 798 799 800 801 802 803 804 805 806 807 808 809 810 811 812 813 814 815 816 817 818 819 820 821 822 823 824 825 826 827 828 829 830 831 832 833 834 835 836 837 838 839 840 841 842 843 844 845 846 847 848 849 850 851 852 853 854 855 856 857 858 859 860 861 862 863 864 865 866 867 868 869 870 871 872 873 874 875 876 877 878 879 880 881 882 883 884 885 886 887 888 889 890 891 892 893 894 895 896 897 898 899 900 901 902 903 904 905 906 907 908 909 910 911 912 913 914 915 916 917 918 919 920 921 922 923 924 925 926 927 928 929 930 931 932 933 934 935 936 937 938 939 940 941 942 943 944 945 946 947 948 949 950 951 952 953 954 955 956 957 958 959 960 961 962 963 964 965 966 967 968 969 970 971 972 973 974 975 976 977 978 979 980 981 982 983 984 985 986 987 988 989 990 991 992 993 994 995 996 997 998 999 1000

Symbol H He Li Be B C N O F Ne Na Mg Al Si P S Cl Ar K Ca Sc Ti V Cr Mn Fe Co Ni Cu Zn Ga Ge As Se Br Kr Rb Sr Y Zr Nb Mo Tc Ru Rh Pd Ag Cd In Sn Sb Te I Xe Cs Ba La Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb Lu Fr Ra Ac Th Pa U Np Pu Am Cm Bk Cf Es Fm Md No Lr

Name Hydrogen Helium Lithium Beryllium Boron Carbon Nitrogen Oxygen Fluorine Neon Sodium Magnesium Aluminum Silicon Phosphorus Sulfur Chlorine Argon Potassium Calcium Scandium Titanium Vanadium Chromium Manganese Iron Cobalt Nickel Copper Zinc Gallium Germanium Arsenic Selenium Bromine Krypton Rubidium Strontium Yttrium Zirconium Niobium Molybdenum Technetium Ruthenium Rhodium Palladium Silver Cadmium Indium Tin Antimony Tellurium Iodine Xenon Cesium Barium Lanthanum Cerium Praseodymium Neodymium Promethium Samarium Europium Gadolinium Terbium Dysprosium Holmium Thulium Ytterbium Lutetium Francium Radium Actinium Thorium Protactinium Uranium Neptunium Plutonium Americium Curium Berkelium Californium Einsteinium Fermium Mendelevium Nobelium Lawrencium

Standard Atomic Weight 1.008 4.002 6.941 9.012 10.81 12.011 14.007 15.999 18.998 22.990 24.305 26.982 28.086 30.974 32.06 35.45 39.098 40.078 44.956 47.88 50.94 51.996 52.004 55.845 58.933 63.546 65.38 69.723 72.630 74.922 78.971 81.07 85.468 87.62 91.224 92.906 95.94 98.906 101.07 102.905 106.42 107.868 112.414 114.913 118.710 121.754 124.608 127.603 132.905 137.327 138.905 140.12 140.908 144.24 146.907 150.36 151.964 157.25 158.925 162.50 164.930 167.259 168.934 171.954 174.967 176.487 178.487 180.948 183.848 186.207 188.906 191.224 192.222 194.04 196.967 198.906 200.97 202.07 204.38 206.97 208.98 210.987 212.91 214.904 216.904 218.905 220.911 222.914 225.023 227.027 229.031 231.036 232.037 233.04 235.044 237.047 238.029 239.052 241.056 243.061 245.063 247.065 249.067 251.069 253.071 255.073 257.075 259.077 261.079 263.081 265.083 267.085 269.087 271.089 273.091 275.093 277.095 279.097 281.099 283.101 285.103 287.105 289.107 291.109 293.111 295.113 297.115 299.117 301.119 303.121 305.123 307.125 309.127 311.129 313.131 315.133 317.135 319.137 321.139 323.141 325.143 327.145 329.147 331.149 333.151 335.153 337.155 339.157 341.159 343.161 345.163 347.165 349.167 351.169 353.171 355.173 357.175 359.177 361.179 363.181 365.183 367.185 369.187 371.189 373.191 375.193 377.195 379.197 381.199 383.201 385.203 387.205 389.207 391.209 393.211 395.213 397.215 399.217 401.219 403.221 405.223 407.225 409.227 411.229 413.231 415.233 417.235 419.237 421.239 423.241 425.243 427.245 429.247 431.249 433.251 435.253 437.255 439.257 441.259 443.261 445.263 447.265 449.267 451.269 453.271 455.273 457.275 459.277 461.279 463.281 465.283 467.285 469.287 471.289 473.291 475.293 477.295 479.297 481.299 483.301 485.303 487.305 489.307 491.309 493.311 495.313 497.315 499.317 501.319 503.321 505.323 507.325 509.327 511.329 513.331 515.333 517.335 519.337 521.339 523.341 525.343 527.345 529.347 531.349 533.351 535.353 537.355 539.357 541.359 543.361 545.363 547.365 549.367 551.369 553.371 555.373 557.375 559.377 561.379 563.381 565.383 567.385 569.387 571.389 573.391 575.393 577.395 579.397 581.399 583.401 585.403 587.405 589.407 591.409 593.411 595.413 597.415 599.417 601.419 603.421 605.423 607.425 609.427 611.429 613.431 615.433 617.435 619.437 621.439 623.441 625.443 627.445 629.447 631.449 633.451 635.453 637.455 639.457 641.459 643.461 645.463 647.465 649.467 651.469 653.471 655.473 657.475 659.477 661.479 663.481 665.483 667.485 669.487 671.489 673.491 675.493 677.495 679.497 681.499 683.501 685.503 687.505 689.507 691.509 693.511 695.513 697.515 699.517 701.519 703.521 705.523 707.525 709.527 711.529 713.531 715.533 717.535 719.537 721.539 723.541 725.543 727.545 729.547 731.549 733.551 735.553 737.555 739.557 741.559 743.561 745.563 747.565 749.567 751.569 753.571 755.573 757.575 759.577 761.579 763.581 765.583 767.585 769.587 771.589 773.591 775.593 777.595 779.597 781.599 783.601 785.603 787.605 789.607 791.609 793.611 795.613 797.615 799.617 801.619 803.621 805.623 807.625 809.627 811.629 813.631 815.633 817.635 819.637 821.639 823.641 825.643 827.645 829.647 831.649 833.651 835.653 837.655 839.657 841.659 843.661 845.663 847.665 849.667 851.669 853.671 855.673 857.675 859.677 861.679 863.681 865.683 867.685 869.687 871.689 873.691 875.693 877.695 879.697 881.699 883.701 885.703 887.705 889.707 891.709 893.711 895.713 897.715 899.717 901.719 903.721 905.723 907.725 909.727 911.729 913.731 915.733 917.735 919.737 921.739 923.741 925.743 927.745 929.747 931.749 933.751 935.753 937.755 939.757 941.759 943.761 945.763 947.765 949.767 951.769 953.771 955.773 957.775 959.777 961.779 963.781 965.783 967.785 969.787 971.789 973.791 975.793 977.795 979.797 981.799 983.801 985.803 987.805 989.807 991.809 993.811 995.813 997.815 999.817 1001.819 1003.821 1005.823 1007.825 1009.827 1011.829 1013.831 1015.833 1017.835 1019.837 1021.839 1023.841 1025.843 1027.845 1029.847 1031.849 1033.851 1035.853 1037.855 1039.857 1041.859 1043.861 1045.863 1047.865 1049.867 1051.869 1053.871 1055.873 1057.875 1059.877 1061.879 1063.881 1065.883 1067.885 1069.887 1071.889 1073.891 1075.893 1077.895 1079.897 1081.899 1083.901 1085.903 1087.905 1089.907 1091.909 1093.911 1095.913 1097.915 1099.917 1101.919 1103.921 1105.923 1107.925 1109.927 1111.929 1113.931 1115.933 1117.935 1119.937 1121.939 1123.941 1125.943 1127.945 1129.947 1131.949 1133.951 1135.953 1137.955 1139.957 1141.959 1143.961 1145.963 1147.965 1149.967 1151.969 1153.971 1155.973 1157.975 1159.977 1161.979 1163.981 1165.983 1167.985 1169.987 1171.989 1173.991 1175.993 1177.995 1179.997 1181.999 1183.001 1185.003 1187.005 1189.007 1191.009 1193.011 1195.013 1197.015 1199.017 1201.019 1203.021 1205.023 1207.025 1209.027 1211.029 1213.031 1215.033 1217.035 1219.037 1221.039 1223.041 1225.043 1227.045 1229.047 1231.049 1233.051 1235.053 1237.055 1239.057 1241.059 1243.061 1245.063 1247.065 1249.067 1251.069 1253.071 1255.073 1257.075 1259.077 1261.079 1263.081 1265.083 1267.085 1269.087 1271.089 1273.091 1275.093 1277.095 1279.097 1281.099 1283.101 1285.103 1287.105 1289.107 1291.109 1293.111 1295.113 1297.115 1299.117 1301.119 1303.121 1305.123 1307.125 1309.127 1311.129 1313.131 1315.133 1317.135 1319.137 1321.139 1323.141 1325.143 1327.145 1329.147 1331.149 1333.151 1335.153 1337.155 1339.157 1341.159 1343.161 1345.163 1347.165 1349.167 1351.169 1353.171 1355.173 1357.175 1359.177 1361.179 1363.181 1365.183 1367.185 1369.187 1371.189 1373.191 1375.193 1377.195 1379.197 1381.199 1383.201 1385.203 1387.205 1389.207 1391.209 1393.211 1395.213 1397.215 1399.217 1401.219 1403.221 1405.223 1407.225 1409.227 1411.229 1413.231 1415.233 1417.235 1419.237 1421.239 1423.241 1425.243 1427.245 1429.247 1431.249 1433.251 1435.253 1437.255 1439.257 1441.259 1443.261 1445.263 1447.265 1449.267 1451.269 1453.271 1455.273 1457.275 1459.277 1461.279 1463.281 1465.283 1467.285 1469.287 1471.289 1473.291 1475.293 1477.295 1479.297 1481.299 1483.301 1485.303 1487.305 1489.307 1491.309 1493.311 1495.313 1497.315 1499.317 1501.319 1503.321 1505.323 1507.325 1509.327 1511.329 1513.331 1515.333 1517.335 1519.337 1521.339 1523.341 1525.343 1527.345 1529.347 1531.349 1533.351 1535.353 1537.355 1539.357 1541.359 154

Rare-Earth Elements - La III

