Chapter #: CR Model for Argon I

#.# The Model

The collisional-radiative model for neutral argon (AR I) under evaluation originated in 1988 by J. Vlcek and was extended in 1998 by A. Bogaerts and R. Gijbels. The code implementing this model was received from E. Sciamma who in turn received it from A. Keesee.

The model consists of 65 effective levels. Each model level represents one or more physical levels. All included levels can be seen in Table #.# and Figure #.#. Some levels of similar energy and quantum numbers are grouped together to reduce the amount of atomic data needed and the number of equations needed to solve for the level populations.

The radiative processes included are spontaneous emissions, and recombination from the Ar II ground level. Photo-excitation is accounted for by an escape factor $\Lambda_{i1} \leq 1$ for spontaneous emissions to the ground level which reduces the rate of transitions, and $\Lambda_{ij} = 1$ for $j \neq 1$.

The collisional processes included are electron impact excitation, de-excitation, ionization, two-body and three-body recombination from the Ar II ground state.

Table #.# List of Ar I Model levels [ref]

Effective level number: n	Designation	Excitation energy (eV)	Statistical weight
1	$3p^6\,{}^1S$	0.0	1
2	$4s[3/2]_2$	11.548	5
3	$4s[3/2]_1$	11.624	3
4	$4s'[1/2]_0$	11.723	1
5	$4s'[1/2]_1$	11.828	3
6	$4p[1/2]_1$	12.907	3
7	$4p[3/2]_{1,2}+[5/2]_{2,3}$	13.116	20
8	$4p'[3/2]_{1,2}$	13.295	8
9	$4p'[1/2]_1$	13.328	3
10	$4p[1/2]_0$	13.273	1
11	$4p'[1/2]_0$	13.480	1
12	$3d[1/2]_{0,1}+[3/2]_2$	13.884	9
13	$3d[7/2]_{3,4}$	13.994	16
14	$3d'[3/2]_2+[5/2]_{2,3}$	14.229	17
15	$5s'$	14.252	4
16	$3d[3/2]_1+[5/2]_{2,3}+5s$	14.090	23
17	$3d'[3/2]_1$	14.304	3
18	$5p$	14.509	24
19	$5p'$	14.690	12
20	$4d+6s$	14.792	48
21	$4d'+6s'$	14.976	24
22	$4f'$	15.083	28
23	$4f$	14.906	56
24	$6p'$	15.205	12
25	$6p$	15.028	24
26	$5d'+7s'$	15.324	24
27	$5d+7s$	15.153	48
28	$5f',g'$	15.393	64
29	$5f,g$	15.215	128
30	$7p'$	15.461	12
31	$7p$	15.282	24
32	$6d'+8s'$	15.520	24
33	$6d+8s$	15.347	48
34	$6f',g',h'$	15.560	108
35	$6f,g,h$	15.382	216
36	$8p'$	15.600	12
37	$8p$	15.423	24
38	$7d'+9s'$	15.636	24
39	$7d+9s$	15.460	48
40	$7f',g',h',i'$	15.659	160
41	$7f,g,h,i$	15.482	320
42	$8d',f',\ldots$	15.725	240
43	$8d,f,\ldots$	15.548	480
44	$9p',d',f',\ldots$	15.769	320
45	$9p,d,f,\ldots$	15.592	640
46	$10s',p',d',f',\ldots$	15.801	400
47	$10s,p,d,f,\ldots$	15.624	800
48	$11s',p',d',f',\ldots$	15.825	484
49	$11s,p,d,f,\ldots$	15.648	968
50	$12s',p',d',f',\ldots$	15.843	576
51	$12s,p,d,f,\ldots$	15.666	1152
52	$13s',p',d',f',\ldots$	15.857	676
53	$13s,p,d,f,\ldots$	15.680	1352
54	$14s',p',d',f',\ldots$	15.868	784
55	$14s,p,d,f,\ldots$	15.691	1568
56	$15s',p',d',f',\ldots$	15.877	900
57	$15s,p,d,f,\ldots$	15.700	1800
58	$16s',p',d',f',\ldots$	15.884	1024
59	$16s,p,d,f,\ldots$	15.707	2048
60	$17s',p',d',f',\ldots$	15.890	1156
61	$17s,p,d,f,\ldots$	15.713	2312
62	$18s',p',d',f',\ldots$	15.895	1296
63	$18s,p,d,f,\ldots$	15.718	2592
64	$19s',p',d',f',\ldots$	15.899	1444
65	$19s,p,d,f,\ldots$	15.722	2888

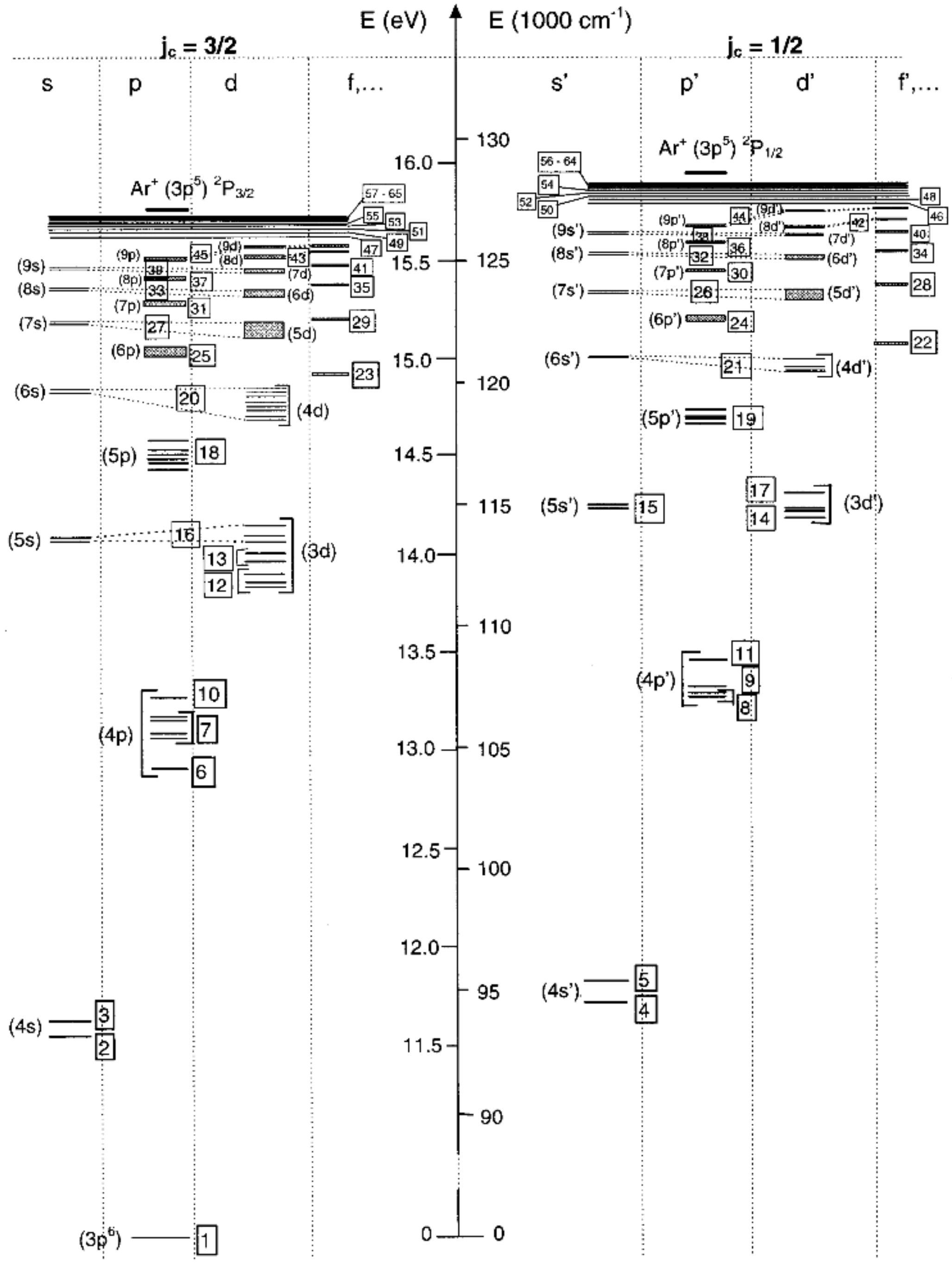

Figure #.#: Ar I model energy level diagram. [ref]

#.# Equilibrium

In the Texas Helimak, the neutral-neutral collision time for Argon is estimated to be $(\sqrt{2} n \sigma v_{th})^{-1} = 4.6ms$, where $n = 10^{12} cm^{-3}$, $\sigma = 0.36 \times 10^{-18} m^2$ [ref], $v_{th} = \sqrt{3kT/m}$, and $T = 300K$.

The transit time is estimated to be $L/v_{th} = 2.4ms$ ($L = 1m$). Therefore it is expected that the longest possible time-scale is limited by the transit time. The collisional-radiative model was used to estimate the typical life-time of levels of Argon I seen in figure #.#.

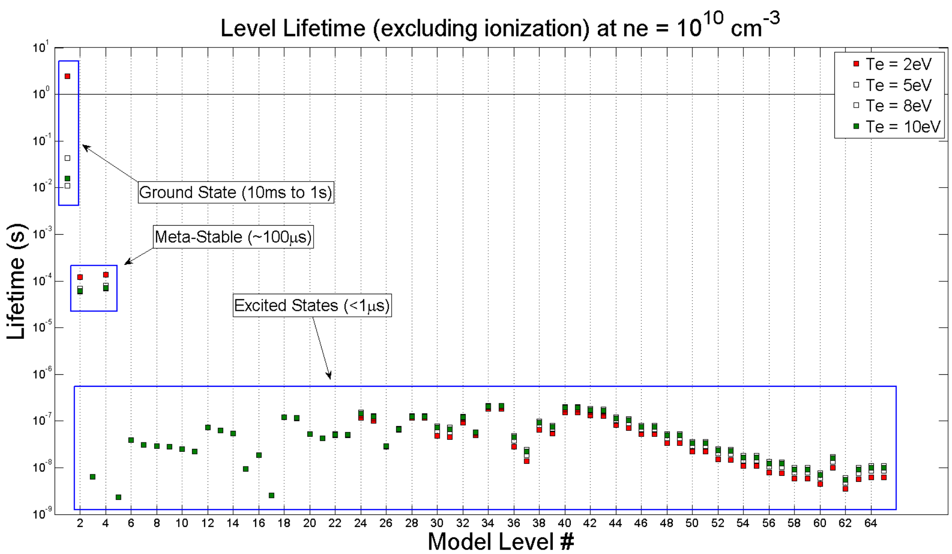

Figure #.#: AR I Level Lifetimes

As can be seen, the ground state has a lifetime much longer than the transit time, while all other levels have lifetimes much shorter than the transit time. Care will be taken to ensure that the model gives sensible results given a true equilibrium cannot be reached between all levels.

The dominate process for each model level (collisional versus radiative) can be determined from figure #.#. For example, given $n_e = 10^{10} cm^{-3}$, radiative processes dominate (>90%) the levels below approximately level 20 while collisional processes dominate levels above approximately level 46.

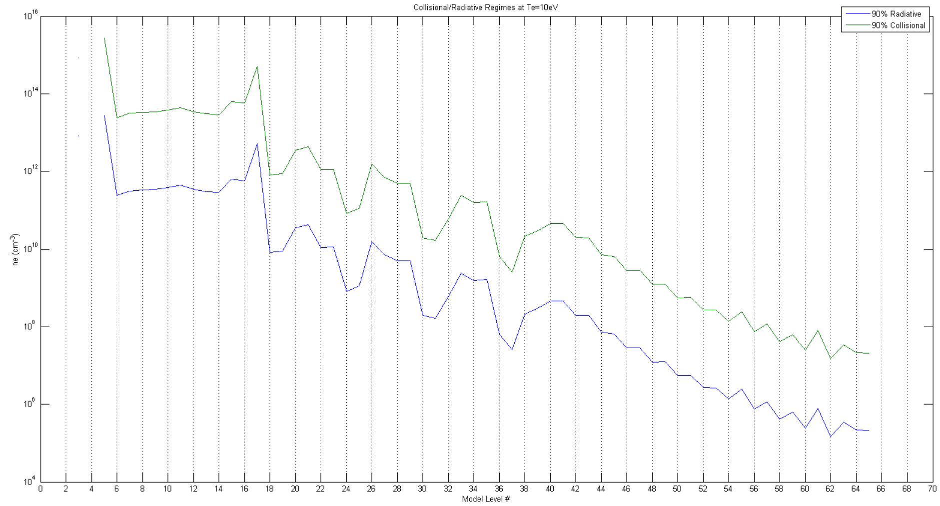

Figure #.#: Dominant Processes

This result indicates that levels above ~46 will not significantly impact this evaluation given that the transitions will be predominantly to the other levels nearby in energy. Whereas the lower lying levels, which have significant radiative transitions, may cause cascade to the levels being measured.

#.# Non-Local Effects

Given that Ar I does not come to a true equilibrium, the code was extended to estimate the magnitude of departure from local equilibrium. This was done by using a single velocity 1D kinetic model described by distribution and source in eq. #.# and #.#, and the boundary condition that atoms coming from the walls are in the ground state in eq. #.# and #.#.

$$f_i = n_i^+(x)\delta(v - v_{th}) + n_i^-(x)\delta(v + v_{th}) \quad \text{(#.#)}$$

$$s_i = S_i^+(x)\delta(v - v_{th}) + S_i^-(x)\delta(v + v_{th}) \quad \text{(#.#)}$$

$$S^\pm = G_i^\pm - n_i^\pm L_i$$

$$G_i^\pm = \Sigma_j n_j^\pm (R_{ji} + \Lambda_{ji} A_{ji}) + \tfrac{1}{2} n_{ion} (R_i^{2B-recomb} + R_i^{3B-recomb})$$

$$L_i = \Sigma_j (R_{ij} + \Lambda_{ij} A_{ij}) + R_i^{ion}$$

$$n_i^+(0) = \tfrac{1}{2} n_0 \quad \text{(#.#)}$$

$$n_i^-(L) = \tfrac{1}{2} n_0 \quad \text{(#.#)}$$

$$n_0 = \frac{p}{kT}$$

This set of distributions are used with the Boltzmann equation with sources eq. #.#, neglecting force and collision terms, and seeking equilibrium $\frac{\partial f}{\partial t} = 0$. This allows the equation to be split the $\pm$ terms into independent equations.

$$\frac{\partial n_i^{\pm}}{\partial x} v_{th} = S_i^{\pm} \longrightarrow \frac{\partial n_i^{\pm}}{\partial x} = \frac{1}{v_{th}} S_i^{\pm} \quad (\#.\#)$$

For the purpose of this analysis, a triangular profile was used for the electron density and temperature to compute both the kinetic and the local equilibrium solutions seen in Figure #.#.

#.# Comparison to ADAS Ar I Model