Astrophysical Collisional Plasma Test Suite

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Version 0.4.0

1 Introduction

At the 2016 Lorentz workshop on "High Energy Astrophysical Model Comparison", the attendees developed recommendations for a baseline set of model calculations that could be achieved by all or most plasma models. These recommendations are described below, including the temperatures, densities, and compositions of the plasmas and the output formats. To simplify discussion, we define a proto-Solar gas as one where the elements H, He, C, N, O, Ne, Mg, Si, S, Ar, Ca, Fe, Ni (and only these elements) occur with relative abundances given by Lodders et al. (2009, `https://arxiv.org/abs/0901.1149`) in their Table 6 with proto-Solar corrections in their Table 9 (see summary below in Table 1).

These standard tests do not comprise a complete set of possible models, but are intended to represent common astrophysical cases. Variation between codes is to be expected, based both on varying goals (*e.g.* fast operation within a MHD code vs detailed spectral comparisons) and different choices for the underlying atomic data. Variation within 30% is entirely normal based on the current status of experimental and theoretical data. However, disagreements beyond a factor of two likely indicate an aspect that should be investigated. The recommended tests are:

CIE-CSD Charge State Distribution of proto-Solar gas elements in equilibrium with electron density $10^6\,\mathrm{m}^{-3}$ and three temperatures: 10^6K, 6×10^6K, and 4.642×10^7K (=4 keV). These temperatures correspond to typical temperatures of the Sun, Capella, and the Perseus clusters.

Power The total radiative power in ergs s^{-1} from a 1 m^3 plasma with electron density $10^6\,\mathrm{m}^{-3}$ for proto-Solar gas over the spectral range 13.6 eV to 13.6 keV. This should be given per element, for the range $T=10^4-10^9$ K in 51 logarithmic steps (*i.e.* $10^4, 10^{4.1}, 10^{4.2}\ldots10^9$K).

StrongLines The 100 strongest lines with $\lambda < 1000$Å, in photons s^{-1}, from a 1 m^3 plasma with electron density $10^6\,\mathrm{m}^{-3}$ for proto-Solar gas. This should be calculated at three temperatures: 10^6K, 6×10^6K, and 4.642×10^7K (=4 keV)

NEI-CSD Charge State Distribution of proto-Solar gas from a non-equilibrium plasma at constant volume and electron density $10^6\,\mathrm{m}^{-3}$ ($= 1\ \mathrm{cm}^{-3}$) that was initially at 10^4K, raised to 2.321×10^7K (=2 keV) and allowed to evolve for a fluence $n_e \times t = 10^{10}\,\mathrm{cm}^{-3}$s. This corresponds, roughly, to a Cas A-type supernova remnant.

NEI-Lines The 100 strongest lines with $\lambda < 1000\mathring{A}$ from a 1 m^3 plasma with electron density $10^6\,\mathrm{m}^{-3}$ ($= 1\ \mathrm{cm}^{-3}$) for proto-Solar gas. This should be from a non-equilibrium plasma at constant volume and electron density $10^6\,\mathrm{m}^{-3}$ in two cases. The first assumes the plasma is initially in equilibrium at $T_e = 10^4$K, then raised to $T_e = 2.321 \times 10^7$K (=2 keV) and allowed to evolve for a fluence time $n_e \times t = 10^{10}\,\mathrm{cm}^{-3}$s.

NEI-Cont The full spectrum from 10 eV to 10 keV of a 1 m^3 plasma with electron density $10^6\,\mathrm{m}^{-3}$ ($= 1\ \mathrm{cm}^{-3}$) for proto-Solar gas that starts in equilibrium at $T_e = 3.5\,\mathrm{keV}$, then jumps to $T_e = 1.5\,\mathrm{keV}$ and the plasma evolves to a fluence $n_e \times t = 10^{10}\,\mathrm{cm}^{-3}$s. This model corresponds, roughly, to the recombining SNR W49B.

LevelPop For the lines in Table 2, the line flux and formation method in photons s^{-1}, from a 1 m^3 proto-Solar gas plasma with densities $10^6\,\mathrm{m}^{-3}$ ($= 1\,\mathrm{cm}^{-3}$) and $10^{18}\,\mathrm{m}^{-3}$ (=$10^{12}\,\mathrm{cm}^{-3}$). This should each be calculated at three temperatures: 10^6K, $6{\times}10^6$K, and $4.642{\times}10^7$K (=4 keV). Formation methods to be considered include direct electron [de-]excitation, direct proton [de-]excitation, radiative decay into the level, and out of the level, radiative recombination into the level, dielectronic recombination into the level, and inner shell ionization/excitation into the level.

PI-CSD The CSD and electron temperature at $\log(\xi) = 1, 2, 3$ for an optically thin $10^8\,\mathrm{cm}^{-3}$ proto-Solar plasma excited by a single power law ionizing continuum with $\Gamma = 2$ and low and high energy cutoffs are 0.1 eV and 1 MeV, with bolometric luminosity of the central source 2.76×10^{43} erg s^{-1}.

PI-Lines The lines with the largest optical depth from each ion at $\log(\xi) = 1, 2, 3$ for an optically thin $10^8\,\mathrm{cm}^{-3}$ proto-Solar plasma excited by a single power law ionizing continuum with $\Gamma = 2$ and low and high energy cutoffs are 0.1 eV and 1 MeV, with bolometric luminosity of the central source 2.76×10^{43} erg s^{-1}.

PI-HeatCool The heating and cooling rates (both total and broken down by contributing process) at $\log(\xi) = 1, 2, 3$ for an optically thin $10^8\,\mathrm{cm}^{-3}$ proto-Solar plasma excited by a single power law ionizing continuum with $\Gamma = 2$ and low and high energy cutoffs are 0.1 eV and 1 MeV, with bolometric luminosity of the central source 2.76×10^{43} erg s^{-1} erg/s.

PI-Abs The absorption spectra at $\log(\xi) = 1, 2, 3$ for an optically thin $10^8\,\mathrm{cm}^{-3}$ proto-Solar plasma excited by a single power law ionizing continuum with $\Gamma = 2$ and low and high energy cutoffs are 0.1 eV and 1 MeV, with bolometric luminosity of the central source 2.76×10^{43} erg s^{-1}.

2 Formats

The name for each file should begin with the descriptor (*e.g.* CIE-CSD, StrongLines, etc, but after that can contain any desired version or naming convention. Within a file, in all cases, text following a # is ignored to the end of the line.

CIE-CSD An ASCII table with five columns. The first line should describe the columns, with the line "Z Ion 1e6K 6e6K 4.642e7K", with each element separated by a whitespace character. Each following line should list the elemental Z value (1, 2, 6, 7, 8, 10, 12, 14, 16, 18, 20, 26, or 28), the ion (0 = neutral, Z = fully ionized) followed by the fractional population in log10 in that element and ion at the three temperatures; zero population can be given as -20. Any standard numerical format can be used, but each should be separated by whitespace character[s].

Power An ASCII table with 52 columns. The first line should describe the columns, with the line "Z 4.1 4.2 ... 8.9 9.0", with each component separated by whitespace character[s]. Each following line should list the elemental Z value (1, 2, 6, 7, 8, 10, 12, 14, 16, 18, 20, 26, or 28) followed by the logarithm (base 10) of the radiative power in each of the 51 requested temperatures. Any standard numerical format can be used, but each should be separated by a whitespace character.

StrongLines Three ASCII tables, with names starting with StrongLines1, StrongLines2, and StrongLines3 (for 1e6 K, 6e6K, and 4.642×10^7K (=4 keV), respectively), each with five columns. The first line should describe the columns, with the line "Indx Lambda Z Ion Flux", with each element separated by whitespace[s] character. Each following line should list the line index (starting at 1, sorted to put highest flux first and lowest last), the wavelength of the line (in Angstroms), the elemental Z value (1, 2, 6, 7, 8, 10, 12, 14, 16, 18, 20, 26, or 28), the Ion stage (0 for neutral, Z-1 for hydrogen-like) and the flux (in log base 10) at the requested temperatures. Any standard numerical format can be used, but each should be separated by a whitespace character.

NEI-CSD An ASCII table with four columns. The first line should describe the columns, with the line "Z Ion Pop", with each element separated by a whitespace character. Each following line should list the elemental Z value (1, 2, 6, 7, 8, 10, 12, 14, 16, 18, 20, 26, or 28), the ion (0 = neutral, Z = fully ionized) followed by the fractional population in that element and ion at the requested plasma conditions. Any standard numerical format can be used, but each should be separated by a whitespace character.

NEI-Lines An ASCII table with four columns. The first line should describe the columns, with the line "Lambda Z Ion Flux", with each element separated by whitespace characters. Each following line should list the wavelength of the line (in Angstroms), the elemental Z value (1, 2, 6, 7, 8, 10, 12, 14, 16, 18, 20, 26, or 28), the Ion stage (0 for neutral, Z-1 for hydrogen-like) and the flux (in log base 10) at the requested plasma state. Any standard numerical format can be used, but each should be separated by whitespace character(s).

NEI-Cont An ASCII table with three columns, labelled "BinLo BinHi Flux". The BinLo and BinHi values should be in keV, running from 0.01 to 10 keV in units of 1 eV with each row giving the flux in that bin in units of photons cm^3 s^{-1}.

LevelPop An ASCII Table with 10 columns. The first line should describe the columns, with the line "Num Te Ne EExc EDeExc PExc PDeExc CascadeTo RadiativeOut RRin DRin ISion", indicated the line number (see Table 2), the electron temperature in K, the electron density in cm^{-3}, and then the population rate for the relevant For line X have for each of the 7 processes: Te, Ne, excitation, de-excitation, inner-shell ionization, radiative decay (incl cascade) into the level, radiative decay out of the level, DR, RR.

PI-CSD An ASCII table with five columns. The first line should describe the columns, with the line "Z Ion 1 2 3", with each element separated by a whitespace character. The second line gives the electron temperature of the plasmas for $\log(\xi) = 1, 2, 3$ in columns 3, 4, and 5, with the first two columns given as 0. Each following line should list the elemental Z value (1, 2, 6, 7, 8, 10, 12, 14, 16, 18, 20, 26, or 28), the ion (0 = neutral, Z = fully ionized) followed by the fractional population in log10 in that element and ion at the three $\log(\xi)$ values. Any standard numerical format can be used, but each should be separated by whitespace character[s].

PI-Lines Three ASCII tables, with names starting with PI-Lines1, PI-Lines2, and PI-Lines3 (for $\log(\xi) = 1, 2, 3$, respectively), each with five columns. The first line should describe the columns, with the line "Indx Lambda Z Ion Tau", with each element separated by whitespace[s] character. Each following line should list the line index (starting at 1, sorted to put highest flux first and lowest last), the wavelength of the line (in Angstroms), the elemental Z value (1, 2, 6, 7, 8, 10, 12, 14, 16, 18, 20, 26, or 28), the ion (0 = neutral, Z = fully ionized) and the optical depth τ of the line with the largest optical depth from each ion. Any standard numerical format can be used, but each should be separated by a whitespace character.

PI-HeatCool An ASCII table with eight columns. The first line should describe the columns, with the line "LogXi HeatCompton HeatPhotoIon HeatTotal CoolCompton CoolBrems CoolRecAndLine CoolTotal". Each following line should give the value of $\log(\xi)$ (=1, 2, or 3), and then the log base 10 of the heating and cooling rates in units of erg cm^{-3}s^{-1}; for 0, use -99. The different heating processes include that due to Compton scattering, due to photoionization, and the total heating. The cooling processes include Compton scattering, bremsstrahlung, and recombination plus direct line excitation, along with a total cooling term.

PI-Abs An ASCII table with three columns, labelled "BinLo BinHi Flux". The BinLo and BinHi values should be in keV, running from 0.01 to 10 keV in units of 1 eV with each row giving the flux in that bin in units of photons cm^3 s^{-1}.

Table 1: Proto-Solar Abundances by number, scaled to H=1 (Lodders et al. 2009)

Z	elem	LogAb	Linear	Z	elem	LogAb	Linear
1	H	12.000	1	16	S	7.210	1.6218e-5
2	He	10.987	0.09705	17	Cl	5.299	1.9907e-7
3	Li	3.331	2.1429e-9	18	Ar	6.553	3.5727e-6
4	Be	1.373	2.3605e-11	19	K	5.161	1.4488e-7
5	B	2.860	7.2444e-10	20	Ca	6.367	2.3281e-6
6	C	8.443	2.7733e-4	21	Sc	3.123	1.3274e-9
7	N	7.912	8.1658e-5	22	Ti	4.979	9.528e-8
8	O	8.782	6.0534e-4	23	V	4.042	1.1015e-8
9	F	4.491	3.0974e-8	24	Cr	5.703	5.0466e-7
10	Ne	8.103	1.2677e-4	25	Mn	5.551	3.5563e-7
11	Na	6.347	2.2233e-6	26	Fe	7.514	3.2659e-5
12	Mg	7.599	3.9719e-5	27	Co	4.957	9.0573e-8
13	Al	6.513	3.2584-6	28	Ni	6.276	1.888e-6
14	Si	7.586	3.8548e-5	29	Cu	4.319	2.0845e-8
15	P	5.505	3.1989e-7	30	Zn	4.700	5.0119e-8

Table 2: Key Lines for output

#	Ion	λ	Name
1	Fe XVII	15.014Å	3C
2	Fe XVII	15.261Å	3D
3	Fe XVII	16.780Å	3F
4	Fe XVII	17.051Å	3G
5	Fe XVII	17.096Å	M2
6	O VII	21.602Å	w
7	O VII	21.801Å	x
8	O VII	21.804Å	y
9	O VII	22.101Å	z
10	Fe XXV	1.8504Å	w
11	Fe XXV	1.8554Å	x
12	Fe XXV	1.8595Å	y
13	Fe XXV	1.6036Å	z
14	O VIII	18.967Å	Lyα_1
15	O VIII	18.9723Å	Lyα_2
16	Fe XXVI	1.7780Å	Lyα_1
17	Fe XXVI	1.7834Å	Lyα_2