Differential Emission Measure (DEM) analysis

- One of the most widely used methods available for the interpretation of astronomical spectral lines is the Differential Emission Measure (DEM) technique.

- Although this method is less familiar in spectroscopic studies of fusion plasma, it can be applied to determine impurity concentration, impurity variation in time and impurity influx in fusion.

What is DEM

Intensity of spectral line of optically thin plasma:

DEM

$$I_{j\to k} = \frac{A(Z)}{4\pi} \int G_{j\to k}(T_e)\,\Phi(T_e)\,dT_e$$

A realistic study of line emission through DEM requires:

- **Measurements** $\Longrightarrow$ $I_{j\to k}$

- **Atomic model** $\Longrightarrow$ $\begin{cases} G_{j\to k}(T_e) = A_{j\to k} \dfrac{N_H}{N_e} \displaystyle\sum_{\rho=1}^{M_Z} F_{j\rho}^{(exc)} \dfrac{N_\rho}{N_{TOT}} \\ \Phi(T_e)\, dT_e \propto N_e^2\, dV \end{cases}$

Requirements for a DEM analysis

<u>ADAS601</u>: DEM estimated by *data adaptive smoothing approach*, using the integral inversion algorithm of Thompson (1990, 1991).

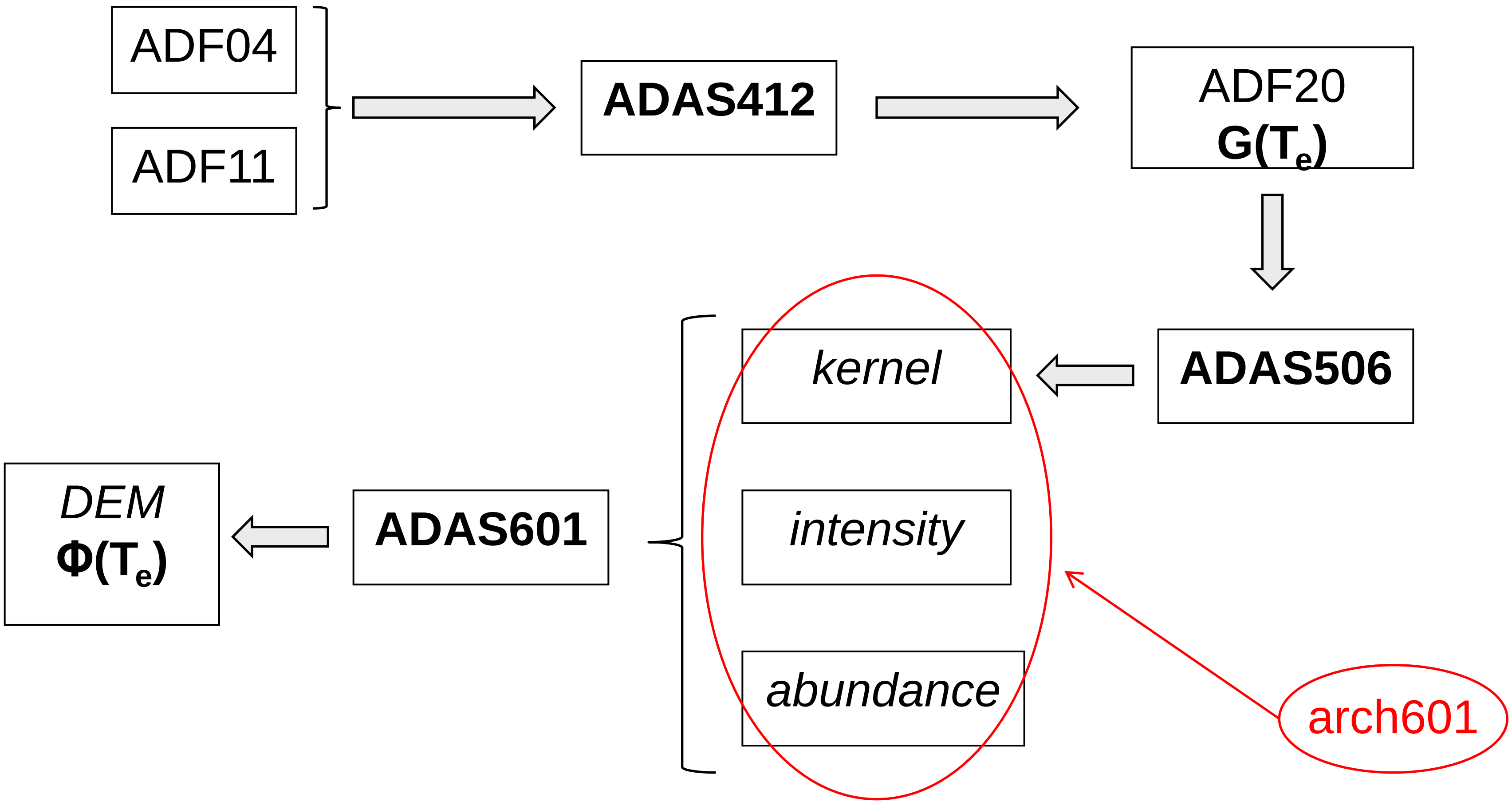
Input data

$$I_i = \frac{A(Z)}{4\pi} \int_{T_1}^{T_2} G_i(T)\, \Phi(T)\, dT$$

$$i = 1, 2, \ldots, m$$

- Set of observed intensities I_i
- Elemental abundances $A(Z)$
- Contribution functions $G_i(T)$

Scheme of DEM analysis in ADAS

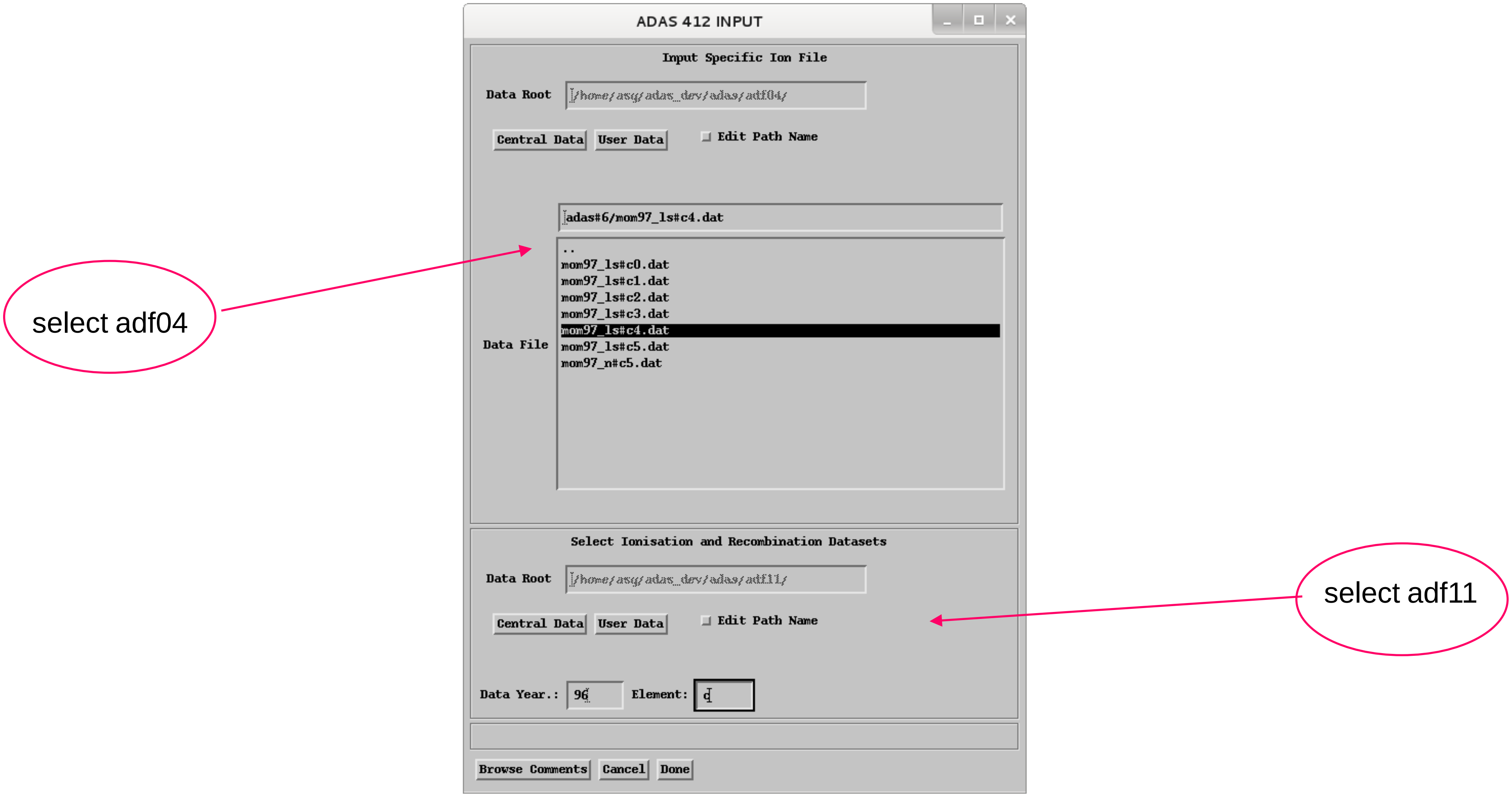


Generating ADF20

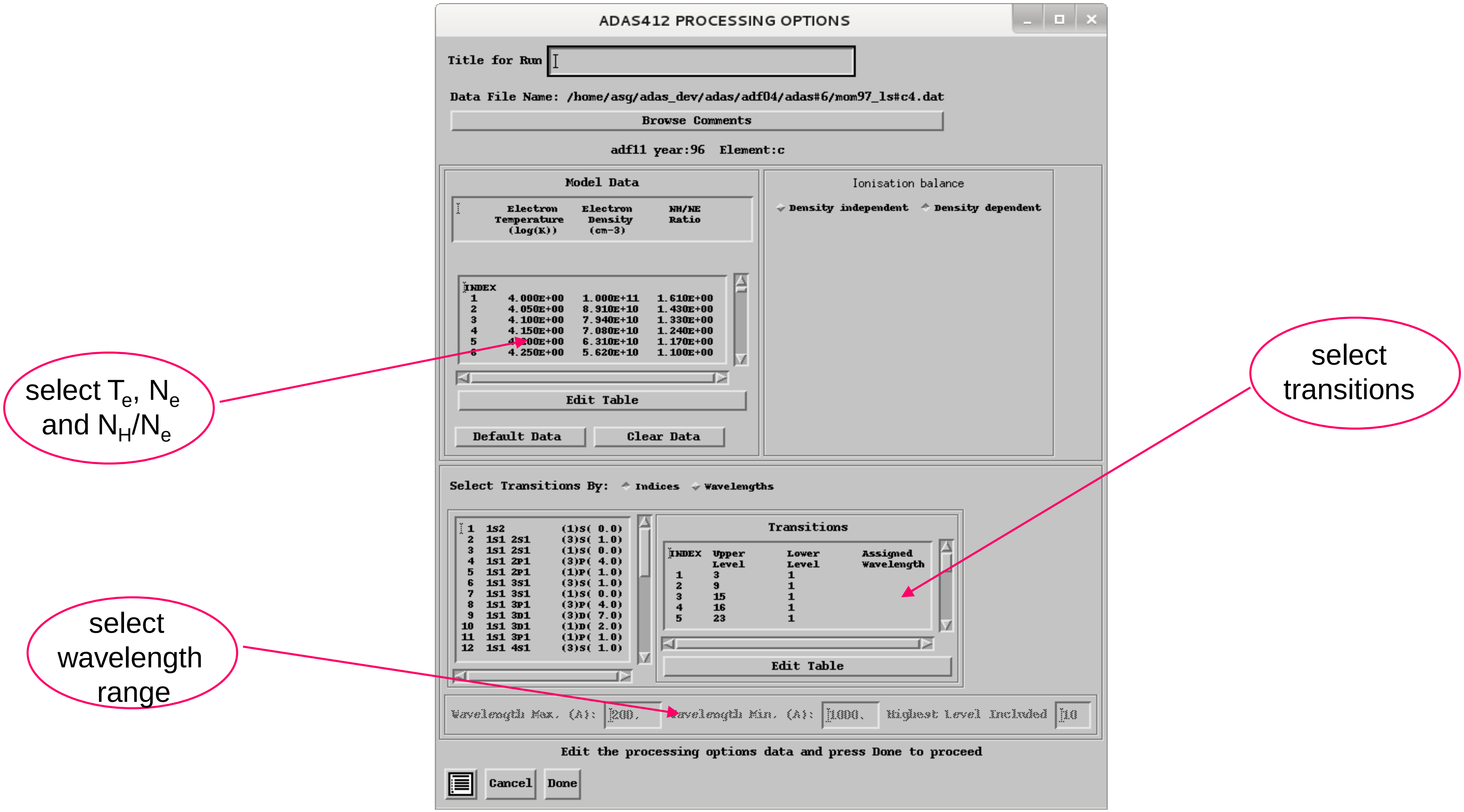
- Code ADAS412 allows the calculation of G(Te) functions and collects them in the ADF20 format.

- It does this by carrying out the excited population calculation from an ADF04 dataset in the manner of ADAS205 and generating an ionisation balance from ADF11 datasets in the manner of ADAS405. Finally it assembles the G(Te) functions.

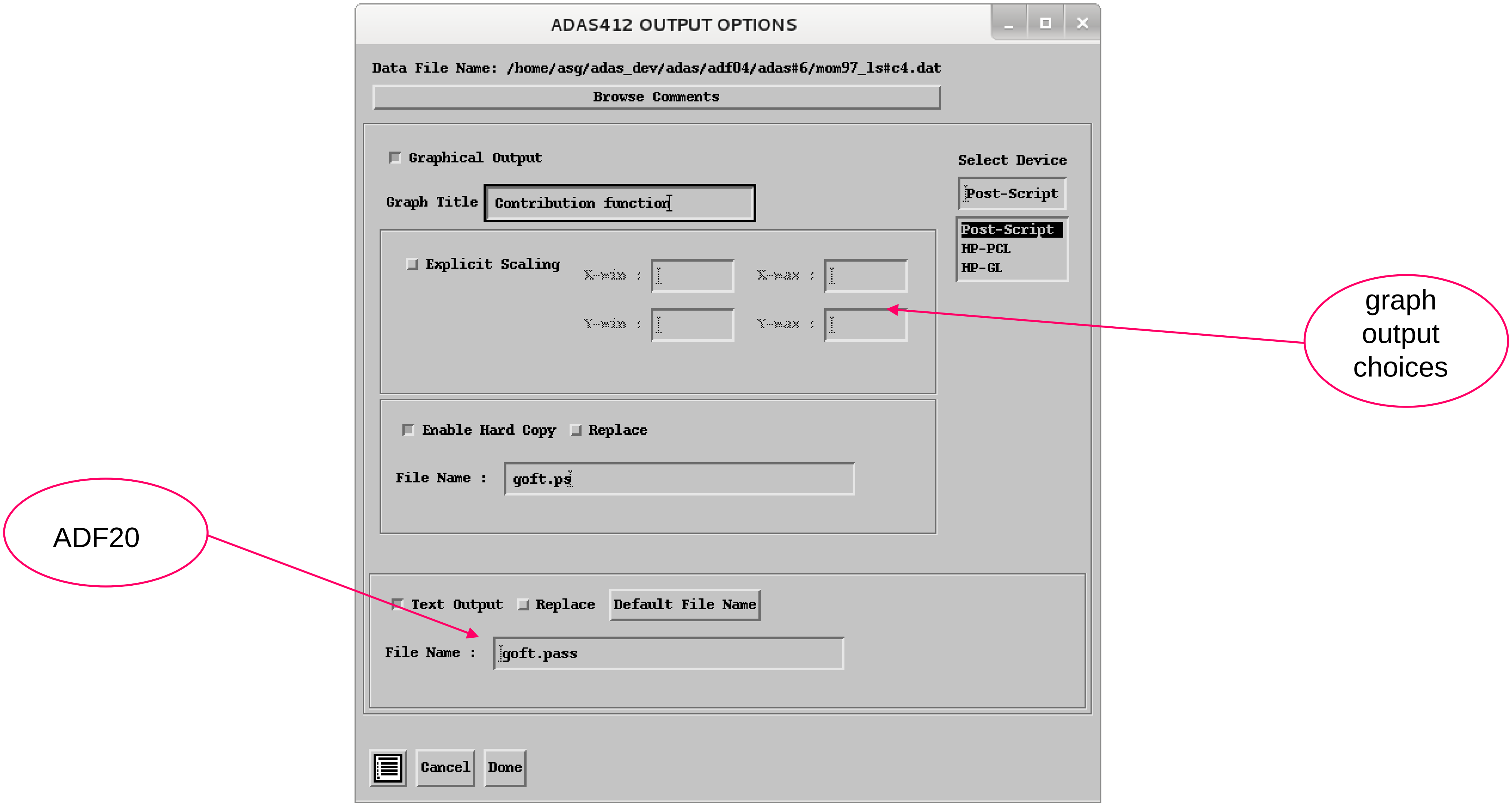
ADAS412 input



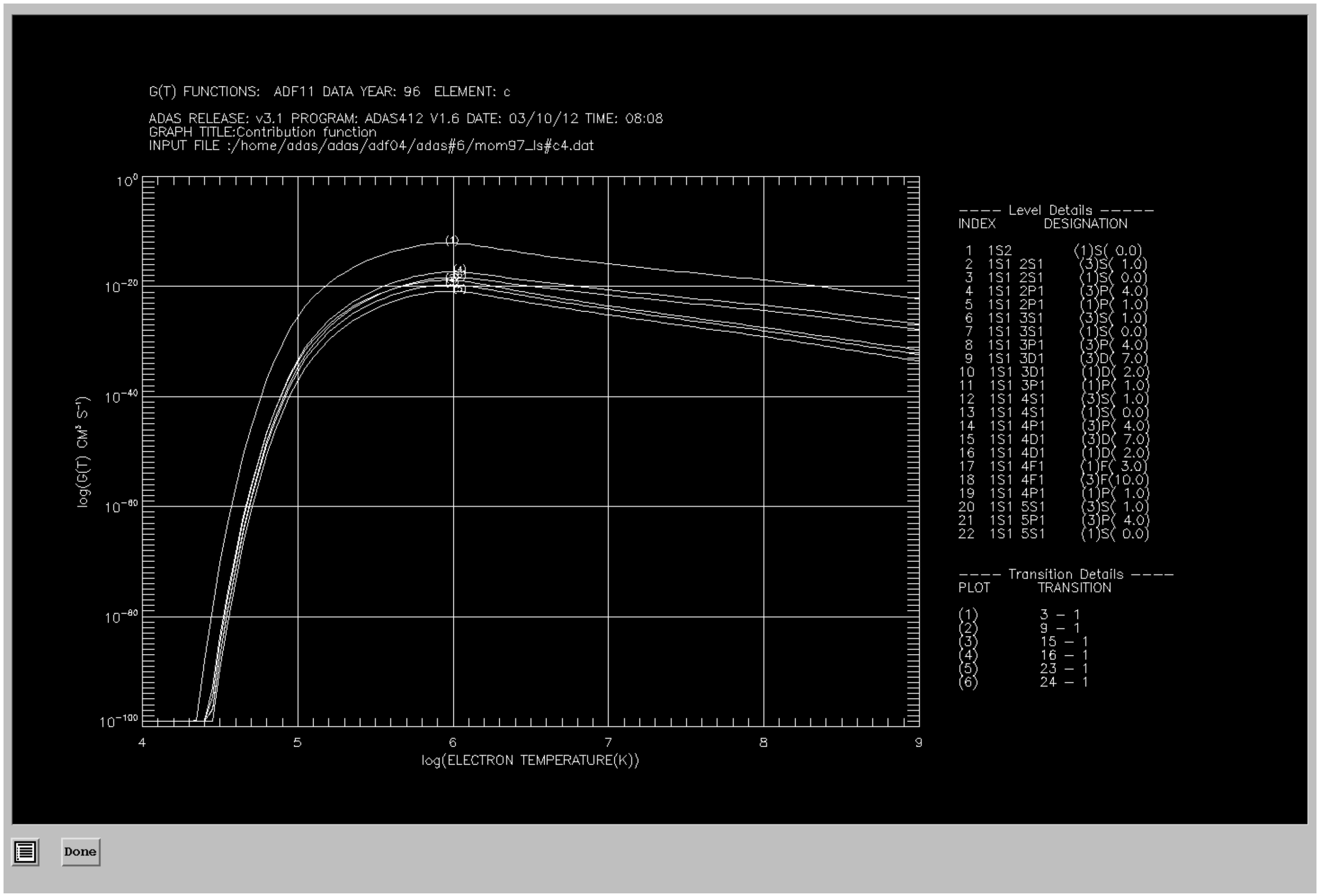
ADAS412 processing



ADAS412 output



ADAS412 graph



Example of ADF20

```
+ 4  /NLEVELS=  11/NKNOTS=  94/NLINES=   6/

SOURCE FILES:
-------------
IONISATION BALANCE DATA   - /ADAS/adas/adf11.<>cd85#C.dat
SPECIFIC ION FILE DATA    - /ADAS/adas/adf04/helike/helike_wjd92#c.dat

PROCESSING CODE                     DATE          USER IDENTIFIER
------------------------------      ---------     ---------------
 GOFT V2.0                          18-Jul-96      Alessandro Lanzafame

ENERGY LEVEL INDEXING
---------------------
INDX     CODE                  S L  IJ
----     ---------------       - -  --
  1      1S2                   1(0) 0.0
  2      1S1 2S1               3(0) 1.0
...................................................................................
 10      1S1 3D1               1(2) 2.0
 11      1S1 3P1               1(1) 1.0

PLASMA MODEL   (FINITE DENSITY IONISATION BALANCE =YES)
------------
TE(K)       NE(CM-3)   P(KCM-3)   NH/NE      TIME(S)   LOG(TE)   LOG(NE)   LOG(P)
--------    --------   --------   --------   -------   -------   -------   -------
2.24D+04    1.00D+10   2.24D+14   1.03D+00              4.35     10.00     14.35
...................................................................................
8.91D+08    1.00D+10   8.91D+18   8.27D-01              8.95     10.00     18.95
1.00D+09    1.00D+10   1.00D+19   8.27D-01              9.00     10.00     19.00

TABLE OF G(T) VALUES (CM3 S-1) FOR C  V
----------------------------------------------
TRANS INDEX         1          2          3          4          5          6          7          8          9          10
APPROX WLENGTH    260.2      271.9      227.2      248.7      267.3      247.3        0.0        0.0        0.0        0.0
SPECTR WLENGTH      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000
TRANSITION         4- 6       5- 7       2- 8       4- 9       5-10       3-11       0- 0       0- 0       0- 0       0- 0
LOG(TE(K))
----------
    5.60       3.366D-15  8.406D-16  5.233D-15  5.167D-15  7.630D-16  1.869D-16  0.000D+00  0.000D+00  0.000D+00  0.000D+00
    5.65       9.269D-15  2.409D-15  1.483D-14  1.443D-14  2.075D-15  5.426D-16  0.000D+00  0.000D+00  0.000D+00  0.000D+00
...................................................................................
    5.90       1.757D-13  5.660D-14  3.243D-13  2.902D-13  3.772D-14  1.383D-14  0.000D+00  0.000D+00  0.000D+00  0.000D+00
    5.95       1.993D-13  6.748D-14  3.789D-13  3.325D-13  4.279D-14  1.683D-14  0.000D+00  0.000D+00  0.000D+00  0.000D+00
-------------------------------------------------------------------------------------------------------------------------

 TRANSITION LIST FOR C  V
--------------------------------
 IND   TRANSITION     APP. WVL.(A)    EXACT WVL.(A)     LOWER ST.     UPPER ST.
 ---   ----------     ------------    -------------     ---------     ---------
  1     4 -   6          260.2             0.0          3(1) 4.0      3(0) 1.0
  2     5 -   7          271.9             0.0          1(1) 1.0      1(0) 0.0
  3     2 -   8          227.2             0.0          3(0) 1.0      3(1) 4.0
  4     4 -   9          248.7             0.0          3(1) 4.0      3(2) 7.0
  5     5 -  10          267.3             0.0          1(1) 1.0      1(2) 2.0
  6     3 -  11          247.3             0.0          1(0) 0.0      1(1) 1.0
```

energy levels

plasma model: N_e =const. or T_eN_e=P_e = const.

line specification

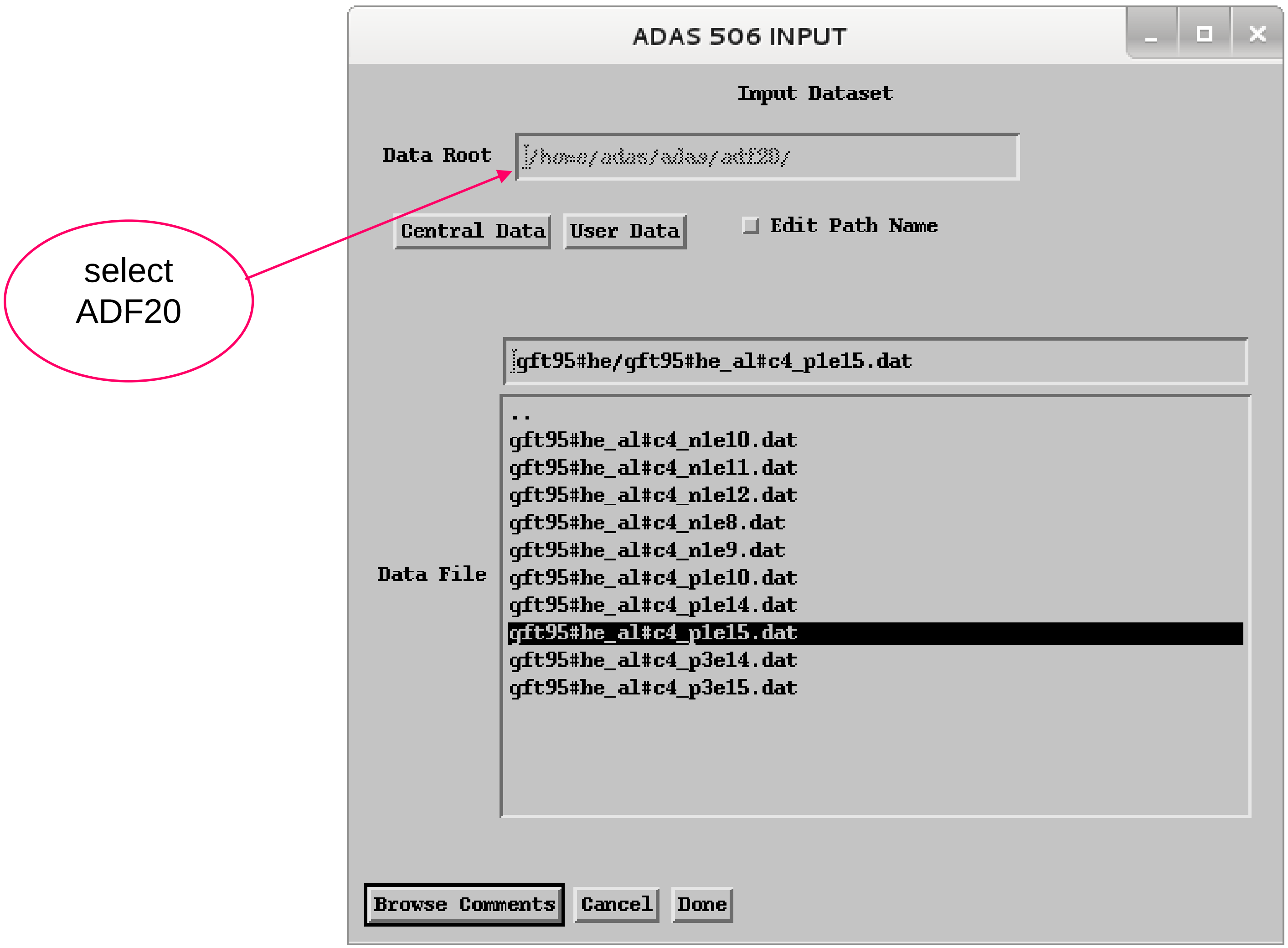
contribution functions versus T_e

Creating the collection file (kernel)

- Code ADAS506 interrogates G(Te) files of the type ADF20.

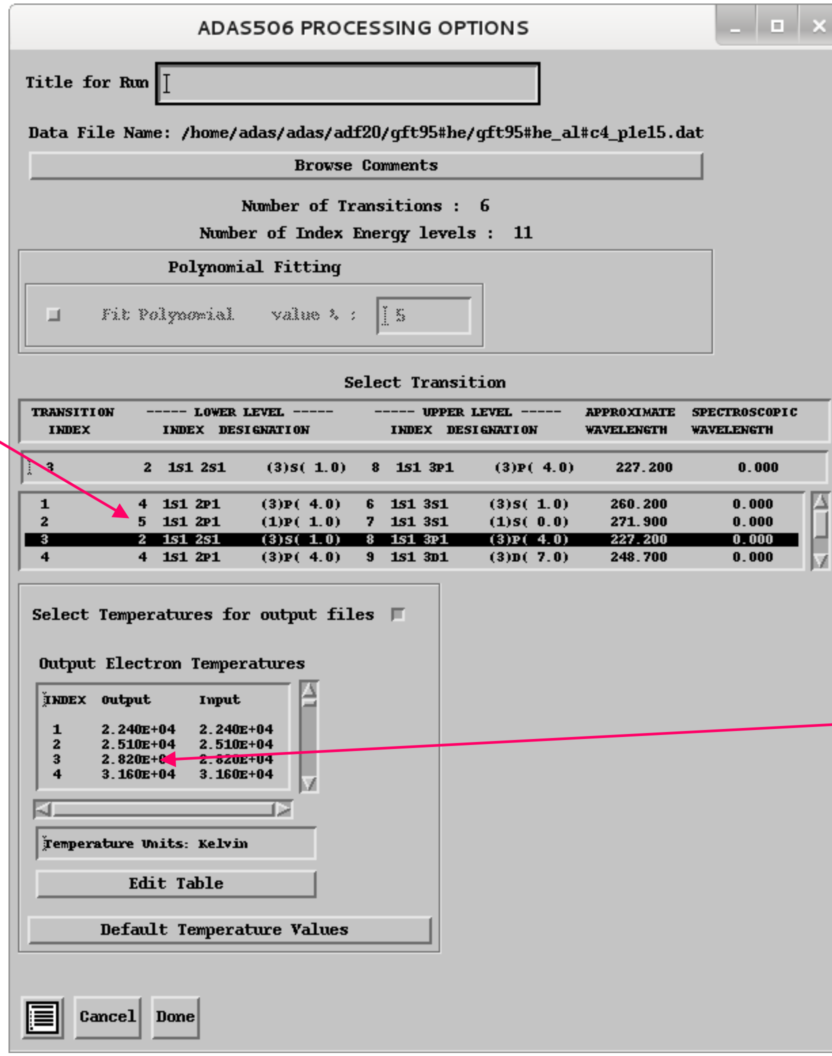
- It gives the collection file (archived in ARCH601) which is composed of blocks of data for each spectrum line. This is one of the input for the differential emission measure analysis performed by ADAS601.

ADAS506 input



ADAS506 processing

select line



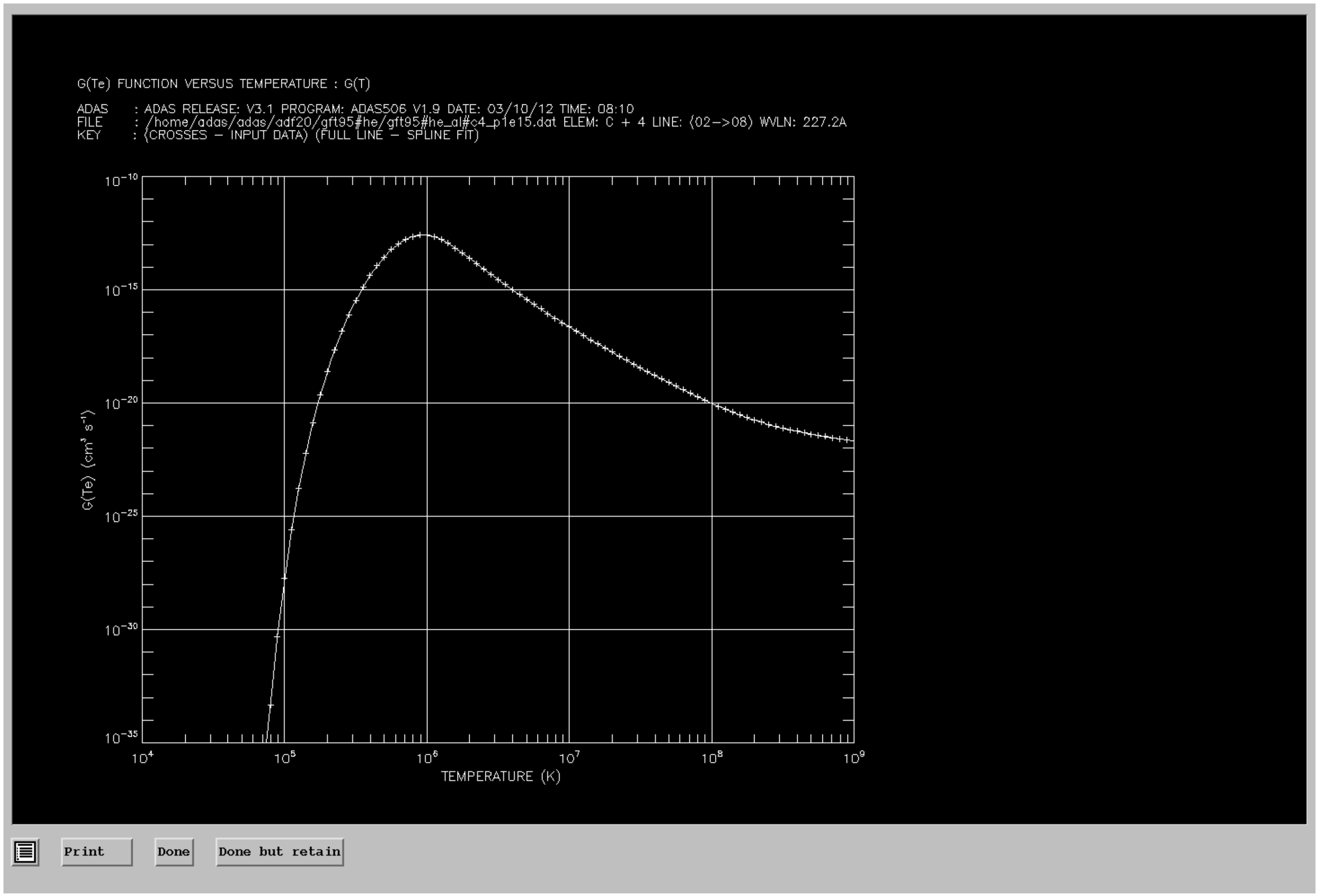
Select output T_e

ADAS506 output

graphical setup

creating collection file for archiving in ARCH601

ADAS506 graph



Example of collection file (kernel)

```
FE+10  /ITRANS=  14/NTEMP=  88/APPWAV=     308.500/SPWAV=     308.515/
/home95/acl/adas/adf20/gft95#s/gft95#s_al#fe10_n1e10.dat
 4.65 4.70 4.75 4.80 4.85 4.90 4.95 5.00 5.05 5.10 5.15 5.20 5.25 5.30 5.35 5.40 5.45 5.50 5.55 5.60 5.65 5.70 5.75
 1.0000E-99 2.5650E-98 6.9770E-87 8.4490E-77 6.0270E-68 3.3460E-60 1.8910E-53 1.3540E-47 1.5400E-42 3.6250E-38 2.304
FE+12  /ITRANS=  22/NTEMP=  84/APPWAV=     311.600/SPWAV=     311.552/
/home95/acl/adas/adf20/gft95#si/gft95#si_al#fe12_n1e10.dat
 4.85 4.90 4.95 5.00 5.05 5.10 5.15 5.20 5.25 5.30 5.35 5.40 5.45 5.50 5.55 5.60 5.65 5.70 5.75 5.80 5.85 5.90 5.95
 1.0000E-99 2.5190E-97 3.3010E-86 1.7300E-76 4.9700E-68 1.1270E-60 2.9150E-54 1.1890E-48 1.0270E-43 2.3140E-39 1.622
MG+ 7  /ITRANS=  13/NTEMP=  90/APPWAV=     311.800/SPWAV=     311.772/
/home95/acl/adas/adf20/gft95#b/gft95#b_al#mg7_n1e10.dat
 4.55 4.60 4.65 4.70 4.75 4.80 4.85 4.90 4.95 5.00 5.05 5.10 5.15 5.20 5.25 5.30 5.35 5.40 5.45 5.50 5.55 5.60 5.65
 1.0000E-99 2.3230E-96 1.9580E-85 1.0250E-75 4.5730E-67 1.9330E-59 8.4180E-53 5.1930E-47 6.4010E-42 1.9340E-37 1.680
MG+ 7  /ITRANS=  11/NTEMP=  90/APPWAV=     313.700/SPWAV=     313.743/
/home95/acl/adas/adf20/gft95#b/gft95#b_al#mg7_n1e10.dat
 4.55 4.60 4.65 4.70 4.75 4.80 4.85 4.90 4.95 5.00 5.05 5.10 5.15 5.20 5.25 5.30 5.35 5.40 5.45 5.50 5.55 5.60 5.65
 1.0000E-99 4.6340E-96 3.8750E-85 2.0130E-75 8.9200E-67 3.7460E-59 1.6210E-52 9.9460E-47 1.2200E-41 3.6700E-37 3.177
SI+ 7  /ITRANS=  13/NTEMP=  91/APPWAV=     314.300/SPWAV=     314.356/
/home95/acl/adas/adf20/gft95#n/gft95#n_al#si7_n1e10.dat
 4.50 4.55 4.60 4.65 4.70 4.75 4.80 4.85 4.90 4.95 5.00 5.05 5.10 5.15 5.20 5.25 5.30 5.35 5.40 5.45 5.50 5.55 5.60
 1.0000E-99 1.0000E-99 5.2670E-90 1.0810E-79 1.5450E-70 1.9730E-62 2.4700E-55 3.1930E-49 5.6070E-44 2.0290E-39 2.069
MG+ 7  /ITRANS=  14/NTEMP=  90/APPWAV=     315.000/SPWAV=     315.015/
/home95/acl/adas/adf20/gft95#b/gft95#b_al#mg7_n1e10.dat
 4.55 4.60 4.65 4.70 4.75 4.80 4.85 4.90 4.95 5.00 5.05 5.10 5.15 5.20 5.25 5.30 5.35 5.40 5.45 5.50 5.55 5.60 5.65
 1.0000E-99 1.1770E-95 9.9210E-85 5.1910E-75 2.3170E-66 9.7930E-59 4.2640E-52 2.6310E-46 3.2430E-41 9.7970E-37 8.512
SI+ 7  /ITRANS=   9/NTEMP=  91/APPWAV=     316.200/SPWAV=     316.218/
/home95/acl/adas/adf20/gft95#n/gft95#n_al#si7_n1e10.dat
 4.50 4.55 4.60 4.65 4.70 4.75 4.80 4.85 4.90 4.95 5.00 5.05 5.10 5.15 5.20 5.25 5.30 5.35 5.40 5.45 5.50 5.55 5.60
 1.0000E-99 1.0000E-99 1.0430E-89 2.1240E-79 3.0120E-70 3.8220E-62 4.7610E-55 6.1270E-49 1.0720E-43 3.8700E-39 3.937
MG+ 7  /ITRANS=  12/NTEMP=  90/APPWAV=     317.000/SPWAV=     317.028/
/home95/acl/adas/adf20/gft95#b/gft95#b_al#mg7_n1e10.dat
 4.55 4.60 4.65 4.70 4.75 4.80 4.85 4.90 4.95 5.00 5.05 5.10 5.15 5.20 5.25 5.30 5.35 5.40 5.45 5.50 5.55 5.60 5.65
 1.0000E-99 2.9510E-96 2.4680E-85 1.2820E-75 5.6800E-67 2.3850E-59 1.0320E-52 6.3340E-47 7.7690E-42 2.3370E-37 2.023
MG+ 6  /ITRANS=  27/NTEMP=  93/APPWAV=     319.000/SPWAV=     319.018/
/home95/acl/adas/adf20/gft95#c/gft95#c_al#mg6_n1e10.dat
 4.40 4.45 4.50 4.55 4.60 4.65 4.70 4.75 4.80 4.85 4.90 4.95 5.00 5.05 5.10 5.15 5.20 5.25 5.30 5.35 5.40 5.45 5.50
 1.0000E-99 4.6500E-99 5.8970E-88 4.5910E-78 2.8670E-69 1.9290E-61 1.8370E-54 3.0770E-48 9.4210E-43 5.3860E-38 7.297
SI+ 7  /ITRANS=   5/NTEMP=  91/APPWAV=     319.800/SPWAV=     319.839/
/home95/acl/adas/adf20/gft95#n/gft95#n_al#si7_n1e10.dat
 4.50 4.55 4.60 4.65 4.70 4.75 4.80 4.85 4.90 4.95 5.00 5.05 5.10 5.15 5.20 5.25 5.30 5.35 5.40 5.45 5.50 5.55 5.60
 1.0000E-99 1.0000E-99 1.7740E-89 3.5680E-79 5.0070E-70 6.2910E-62 7.7670E-55 9.9100E-49 1.7210E-43 6.1670E-39 6.233
```

line specification

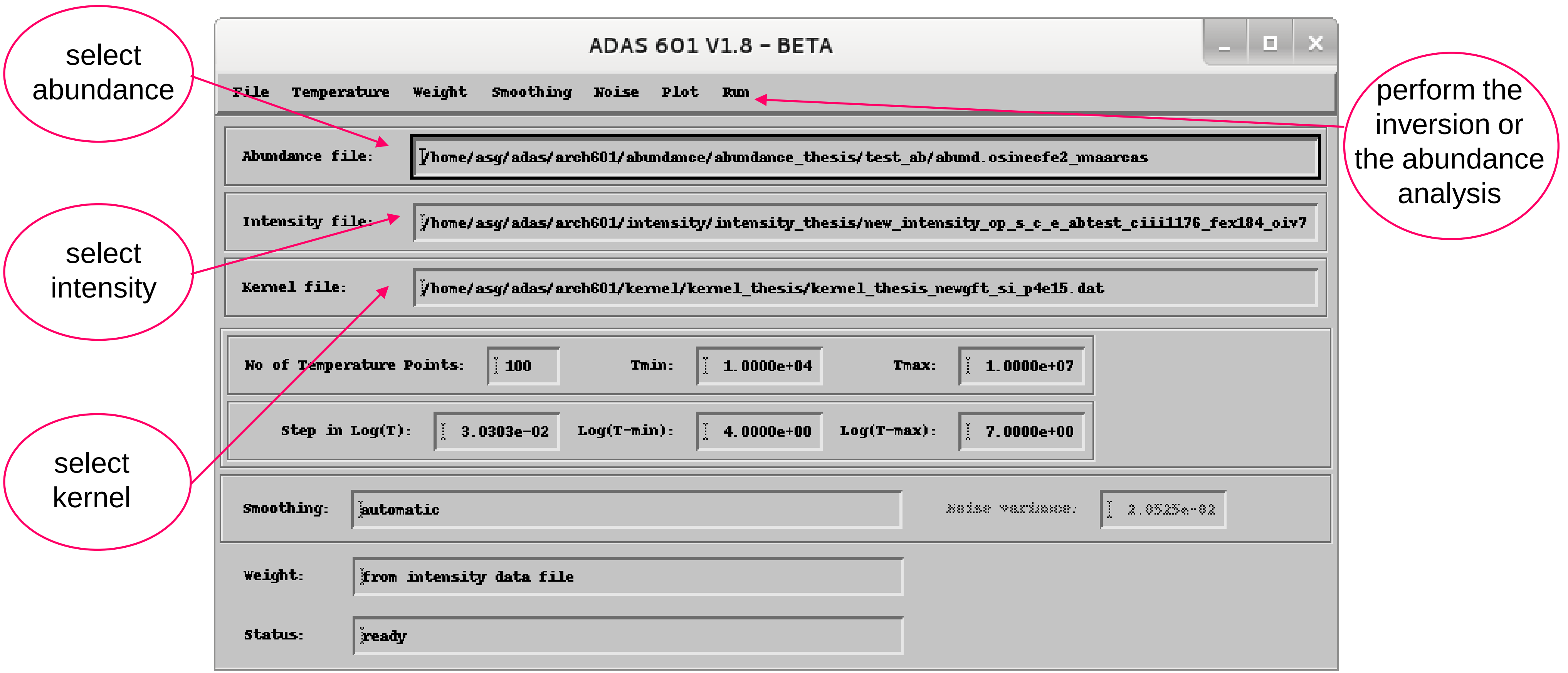
ADF20 source

Performing DEM

- Given a set of observed spectral line intensities, G(Te) functions and elemental abundances, ADAS601 evaluates an estimate for the differential emission measure in temperature.

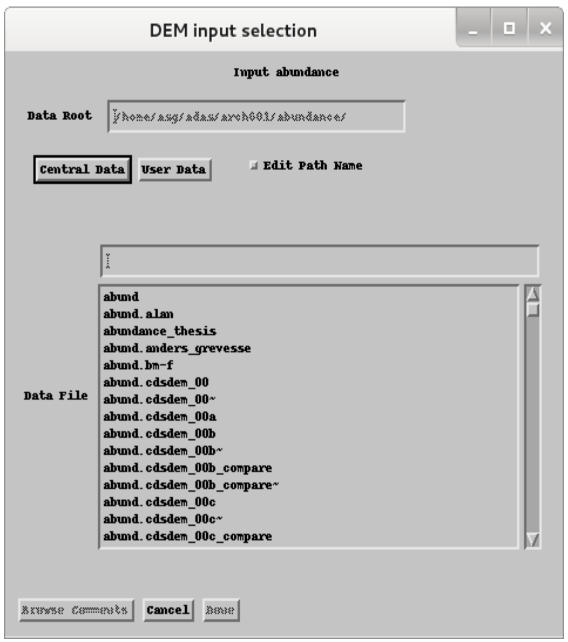
- The output consists of a graphical display of the DEM as a function of electron temperature and a text file which includes also a list of the lines used for the integral inversion and the ratios between reconstructed and observed spectral intensities.

ADAS601 input



Selection of abundance

select abundance



logarithmic scale:
A(H)=logN(H)=12
A(E)=logN(E)=
log[N(E)/N(H)]+12

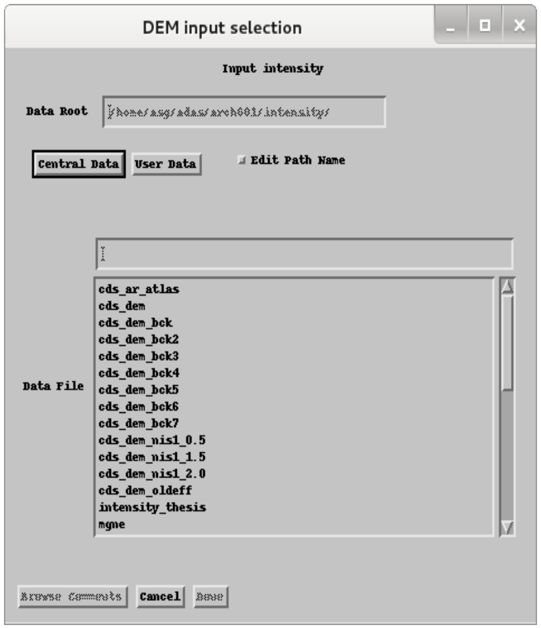
Examples of abundance input file

H	12.0
HE	10.9
C	8.59
N	8.00
O	8.89
NE	8.08
NA	6.93
MG	7.90
AL	7.00
SI	7.65
S	7.27
AR	6.58
CA	7.00
FE	7.67
NI	6.84

H	1.000E+00
K	2.790E-07
Na	4.250E-06
Al	6.300E-06
Ca	4.540E-06
Cr	1.000E-06
Ti	1.780E-07
Mg	7.940E-05
Ni	3.650E-06
Fe	6.740E-05
Si	7.420E-05
Zn	8.010E-08
S	2.080E-05
P	2.750E-07
C	2.570E-04
Cl	1.200E-07
O	5.480E-04
N	6.470E-05
Ar	2.310E-06
Ne	8.830E-05
He	6.310E-02

Selection of intensity

select
intensity

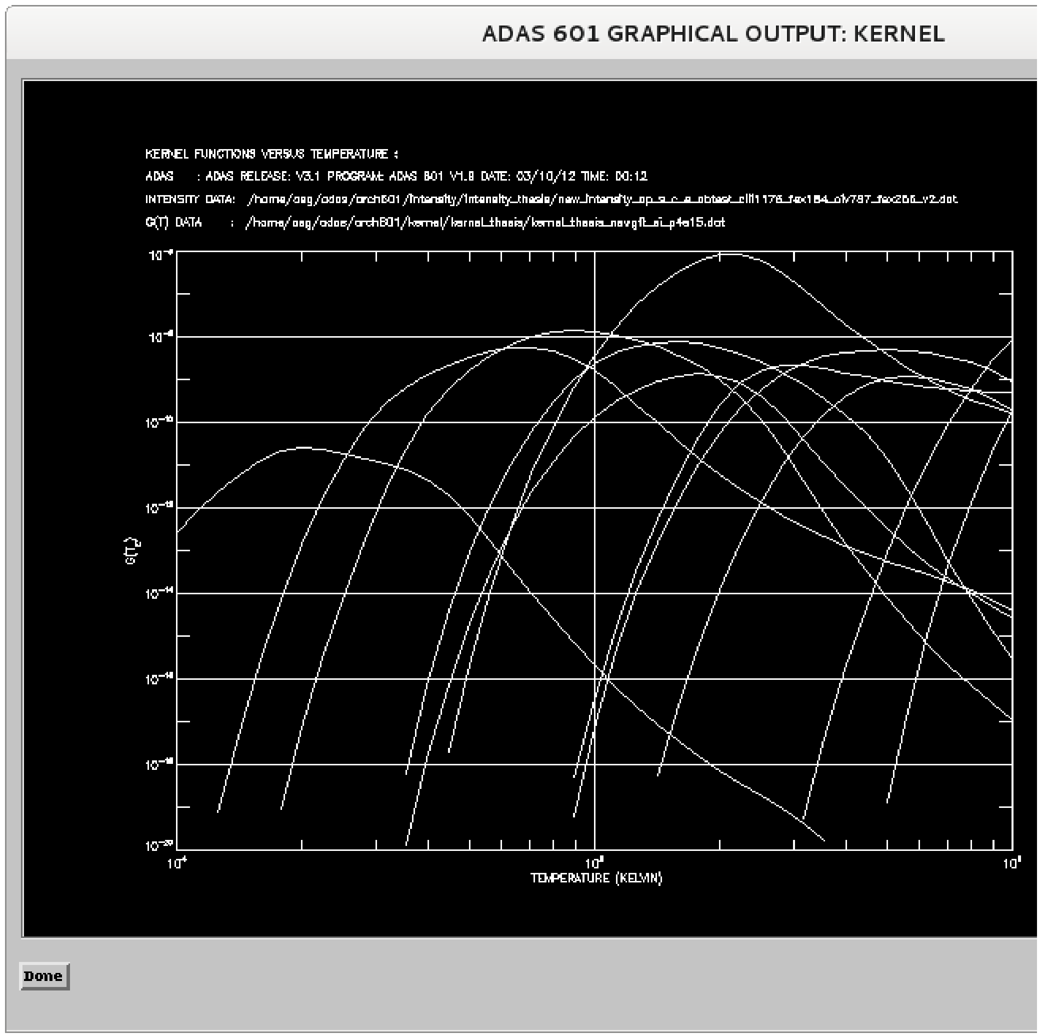


Examples of intensity input file

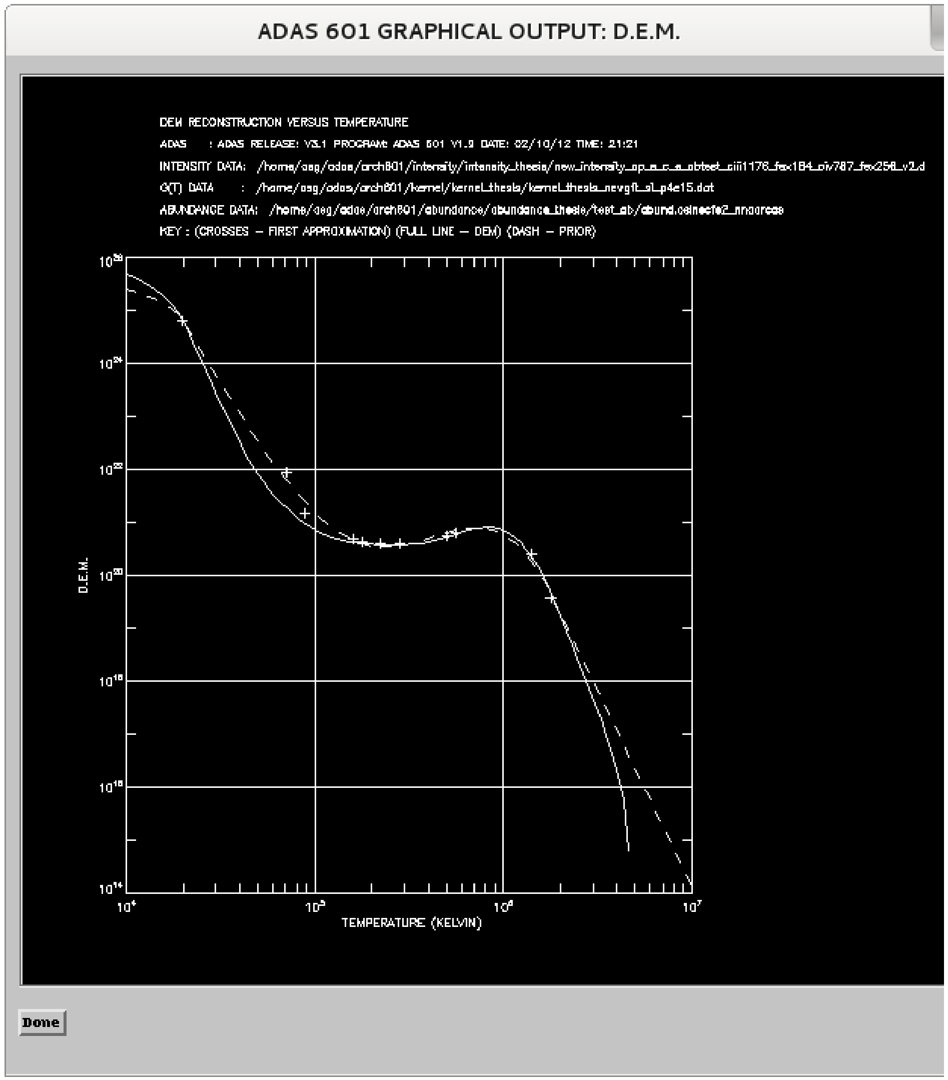
```
|------------------------------------------------------------------------------------------------------------------------|
                  spectr.         configuration              configuration          G-in blnd  observed     observed     uncert.
   |          | wavelength |                          |                          |    |    | wavelength | intensity  |
---|----------|R-----------|--------------------------|--------------------------|----|----|------------|------------|------------|------|
\UNITS=COUNTS/SEC/PIX
 O +2        N    599.598       $2s^22p^2~^1D_{2}-2s2p^3~^1D_{2}      18    0      599.611   1.2596e+00   3.3676e-02
 Ne+3        E    543.886      $2s^22p^3~^4S_{3/2}-2s^22p^4~^4P_{5/2}   12    0      543.941   3.2397e-01   8.4847e-03
 O +4        N    629.732          $2s^2~^1S_{0}-2s2p~^1P_{1}          3    0      629.817   1.1295e+01   1.9724e-01
 Ne+4        E    359.375      2s^22p^2$ $^3$P$_2$-$2s2p^3$ $^3$S$_1$   30    0      359.357   8.0133e-02   4.1755e-03
 Ne+6        E    561.720           2s2p~^3P_{2}-2p^2~^3P_{2}          11    0      561.754   3.2164e-01   1.9390e-02
 Ca+9        E    557.759          $3s~^2S_{1/2}-3p~^2P_{3/2}          2    0      557.810   6.4224e-01   1.5114e-02
 O +3        N    555.263       $2s^22p~^2P_{3/2}-2s2p^2~^2P_{1/2}     12    0      555.319   9.6139e-01   2.6456e-02
 Si+8        E    341.950      2s^22p^2$ $^3$P$_0$-$2s2p^3$ $^3$D$_1$   13    0      341.933   1.0600e-01   5.5169e-03
 Si+11       E    520.662          $2s~^2S_{1/2}-2p~^2P_{1/2}          1    0      520.755   2.1358e-02   5.2103e-03
 O +2        N    525.797        2s^22p^2~^1D_{2}-2s2p^3~^1P_{1}      -25    0      525.855   6.8039e-01   1.2309e-02
 O +3        N    553.329       $2s^22p~^2P_{1/2}-2s2p^2~^2P_{3/2}    -13    0      553.405   8.9942e-01   2.4394e-02
 O +3        N    554.076       $2s^22p~^2P_{1/2}-2s2p^2~^2P_{1/2}    -11    0      554.143   1.6043e+00   8.0473e-02
 Al+7        E    328.230      2s^22p^2$ $^3$P$_2$-$2s2p^3$ $^3$P$_1$  -19    3
 Fe+13            334.178   $ 3s^23p$ $^2$P$_{1/2}$-$3s3p^2$ $^2$D$_{3/2}$   -6    0
 Fe+11       O    338.263  3s ^23p^3$ $^2$D$_{5/2}$-$3s3p^4$ $^2$D$_{5/2}$  -23    0      338.298   1.7945e-02   4.3500e-03
 Ca+6        K    339.965      3s^23p^2$ $^3$P$_1$-$3s^23p3d$ $^3$D$_2$  -159    0
 Fe+10       O    341.113      3s^23p^4$ $^3$P$_2$-$3s3p^5$ $^3$P$_1$   -6    0      341.163   6.5387e-02   3.9576e-03
 Ca+6        K    342.394      3s^23p^2$ $^3$P$_2$-$3s^23p3d$ $^3$D$_3$  -173    0
 Si+8        E    344.954      2s^22p^2$ $^3$P$_1$-$2s2p^3$ $^3$D$_1$  -14    4      345.092   2.6861e-01   1.1433e-02
.................................................................................................................
```

Lines used for the integral inversion

ADAS601 kernel graph



ADAS601 DEM graph



Example of DEM text output

```
 ADAS RELEASE: v3.1 PROGRAM: ADAS 601 V1.9 - BETA DATE: 07/08/12 TIME: 10:52
******************* TABULAR OUTPUT FROM INTEGRAL INVERSION - PROGRAM: ADAS 601 V1.9 - BETA - DATE: 07/08/12 *******************

INTENSITY DATA FILE NAME: /home/asg/adas/arch601/intensity/intensity_thesis/new_intensity_op_s_c_e_abtest_ciii1176_fex184_oiv787_fex256_v2.dat
   KERNEL DATA FILE NAME: /home/asg/adas/arch601/kernel/kernel_thesis/kernel_thesis_newgft_si_p1e15.dat
ABUNDANCE DATA FILE NAME: /home/asg/adas/arch601/abundance/abundance_thesis/test_ab/abund.osinecfe2_nnaarcas


  CONSTANT VARIANCE =       0.24283086
SMOOTHING PARAMETER =        3.1511096

-------------------------------------------------- SINGLE LINES ----------------------------------------------------
 ION   SPECTROSCOP. PEAK     RECONSTR.  OBSERVED            RECONSTR.    OBSERVED
        WAVELENGTH  TEMP     INTENSITY  INTENSITY   QFR     INTENSITY    INTENSITY     EPS          SIG          DEV
                    log(T)   erg/cm2/s  erg/cm2/s           ph/cm2/s     ph/cm2/s
---------------------------------------------------------------------------------------------------------------------
 Si+ 1     1309.276  4.30      131.890     131.889  1.000   8.693e+12    8.693e+12   9.172e+11    8.777e+10    8.531e-09
 C + 2     1174.933  4.85       46.364      46.395  0.999   2.742e+12    2.744e+12   7.195e+11    4.849e+10    3.302e-04
.....................................................................................................................
 Si+ 6      275.667  5.75        2.814       2.776  1.013   3.905e+10    3.853e+10   3.287e+09    2.297e+09    1.230e-02
 Fe+11      193.509  6.15       43.185      43.276  0.998   4.207e+11    4.216e+11   2.690e+10    4.240e+09    1.075e-02
 Si+11      520.662  6.25        3.702       3.663  1.011   9.704e+10    9.600e+10   6.093e+09    2.725e+09    3.548e-02
---------------------------------------------------------------------------------------------------------------------

-------------------------------------------------------------------------

CHISQUARE =       2.93811
NUMBER OF TRANSITION USED FOR THE INTEGRAL INVERSION =       11

-------------------------------------------------------------------------

----------------------------------- PREDICTED  INTENSITIES -------------------------------------
 ION   SPECTROSCOP. PEAK     RECONSTR.  OBSERVED            RECONSTR.    OBSERVED
        WAVELENGTH  TEMP     INTENSITY  INTENSITY   QFR     INTENSITY    INTENSITY     DEV
                    log(T)   erg/cm2/s  erg/cm2/s           ph/cm2/s     ph/cm2/s
-------------------------------------------------------------------------------------------------
 C + 1     1334.532  4.45     1478.155    1114.748  1.326   9.930e+13    7.489e+13   1.179e+02
 C + 2     1174.933  4.80       46.364      46.395  0.999   2.742e+12    2.744e+12   3.302e-04
 O + 3      787.711  5.15       92.726      75.372  1.230   3.677e+12    2.989e+12   6.216e+00
 Ne+ 7      770.409  5.75      104.051      96.682  1.076   4.035e+12    3.750e+12   5.470e+01
 O + 2      525.797  4.95       18.463      23.685  0.780   4.887e+11    6.269e+11   1.542e+02
 O + 4      629.732  5.30      457.300     401.595  1.139   1.450e+13    1.273e+13   5.096e+01
 Ar+ 6      585.754  5.50        5.736       5.325  1.077   1.691e+11    1.570e+11   3.692e-02
 Ar+ 7      526.496  5.55        0.130       0.697  0.187   3.445e+09    1.847e+10   8.268e+00
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--------------------------------------- DIFFERENTIAL EMISSION MEASURE --------------------------------------
   N   TEMP      DEM        N   TEMP      DEM        N   TEMP      DEM        N   TEMP      DEM        N   TEMP      DEM
------------------------------------------------------------------------------------------------------------


   1 1.00e+04 2.17e+26   11 2.01e+04 3.91e+24   21 4.04e+04 3.62e+22   31 8.11e+04 1.11e+21   41 1.63e+05 3.77e+20
   2 1.07e+04 1.46e+26   12 2.15e+04 2.56e+24   22 4.33e+04 2.19e+22   32 8.70e+04 9.51e+20   42 1.75e+05 3.65e+20
   3 1.15e+04 9.85e+25   13 2.31e+04 1.66e+24   23 4.64e+04 1.34e+22   33 9.33e+04 8.23e+20   43 1.87e+05 3.59e+20
   4 1.23e+04 6.63e+25   14 2.48e+04 1.06e+24   24 4.98e+04 8.41e+21   34 1.00e+05 7.19e+20   44 2.01e+05 3.59e+20
   5 1.32e+04 4.45e+25   15 2.66e+04 6.75e+23   25 5.34e+04 5.46e+21   35 1.07e+05 6.34e+20   45 2.15e+05 3.62e+20
.....................................................................................................................
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lines used for the inversion

Ratios between reconstructed and observed intensities

set of reconstructed intensities

DEM versus T_e