International Atomic Energy Agency INDC(NDS)-309

INDC INTERNATIONAL NUCLEAR DATA COMMITTEE

# Radiative Losses and Electron Cooling Rates of Hydrogen, Helium, Carbon and Oxygen

R. Marchand*, C. Illescas#†, X. Bonnin* and J. Botero#

*INRS-Energie, C.P. 1020, Varennes QC, J3X 1S2, Canada
# International Atomic Energy Agency, P.O. Box 100, A-1400 Vienna, Austria
† Departamento de Química, CIX, Universidad Autónoma de Madrid,
Cantoblanco, E-28049, Spain

Vienna, July, 1995

IAEA NUCLEAR DATA SECTION, WAGRAMERSTRASSE 5, A-1400 VIENNA

INDC(NDS)-309

# Radiative Losses and Electron Cooling Rates of Hydrogen, Helium, Carbon and Oxygen

R. Marchand*, C. Illescas#†, X. Bonnin* and J. Botero#

*INRS-Energie, C.P. 1020, Varennes QC, J3X 1S2, Canada
# International Atomic Energy Agency, P.O. Box 100, A-1400 Vienna, Austria
† Departamento de Química, CIX, Universidad Autónoma de Madrid,
Cantoblanco, E-28049, Spain

Vienna, July, 1995

Reproduced by the IAEA in Austria
July 1995

# Abstract

Atomic rates relevant to fusion plasma modelling are calculated from a simplified collisional radiative model, using recommended atomic data. The rates calculated are the radiative loss and the electron cooling rates for individual ionisation stages of hydrogen, helium, carbon, and oxygen. The results are presented graphically as a function of the temperature, for various electron densities. They are also approximated by analytic fits convenient to use in computer simulation models.

# Contents

# List of Tables

# List of Figures

# 1 Introduction

The physics associated with atomic processes is important to fusion research, particularly with regard to the edge and divertor region of tokamaks which are characterized by low temperatures and potentially high density plasmas. A good understanding, a capacity to model edge plasmas, recycling, and plasma-material interaction necessitates a comprehensive and accurate knowledge of atomic, molecular, and plasma-material processes. These processes can have important physical consequences in the plasma, such as electron cooling associated with inelastic collisions and energy dissipation by radiation. The rate at which the various ion species ionize and recombine is also important as it determines the number of free electrons per nucleus and, hence, fuel dilution. Considering the key role expected from atomic processes in certain scenarios of power exhaust in an eventual fusion reactor it is crucial that computer models of reactor plasmas be equipped with accurate and complete atomic rates. Over the years, several calculations have been made of these rates; the earlier ones being motivated primarily by astrophysical applications [1-3]. More recently, several calculations have been made specifically for fusion applications [4-13]. In this report, we present results of atomic rate calculations for hydrogen and light impurity ions for fusion plasmas. These calculations are based on a simplified collisional radiative model very similar to one already described in Refs. [12,13]. In addition to hydrogen, the ion species considered are those of helium, carbon, and oxygen. The rates calculated are the the radiative loss and electron cooling rates. In each case, the rates are represented graphically as a function of temperature, for various electron densities. Analytic fits are also given, which permit the use of these rates in actual plasma simulation models. The rates presented here are for the most part very close to the ones given in Ref. [13]. The new analytic fits, however, should be used instead of the ones of Ref. [13], because the latter have been found to be systematically in error.

The remainder of this report is organized as follows. In Sec. 2, a brief description of the atomic model is given. In Sec. 3, a brief description of the atomic data base is presented. In Sec. 4 the various rates are presented both graphically, and with analytic fits. Finally, a summary and some concluding remarks are given in Sec. 5.

# 2 Atomic model description

The simplified collisional-radiative model considered here is very close to one already described in Refs. [12,13]. The main points are repeated here for completeness. For more details the reader is referred to aforementioned references.

The radiative loss rate is calculated as

$$P_r = \sum_{i,\alpha} n^i_\alpha P^i_{r,\alpha}, \tag{1}$$

where $n_i$ is the density of a given element in ionisation stage $i$, and $P^i_{r,\alpha}$ is called the radiative loss coefficient. For a given ionisation stage, using the definitions in Table

1, this coefficient is calculated as

$$\begin{aligned} n^i_\alpha P^i_{r,\alpha} &= \sum_\beta n^i_\alpha [A^i_{\beta\alpha}\epsilon^i_{\beta\alpha} + n_e \int d^3v \left(\frac{1}{2}Mv^2 + \epsilon^{i-1}_\beta + \epsilon^i_{0\alpha}\right) v\sigma^{i-1}_{rr,0\alpha} f(v) + \\ & R_{\beta\alpha}\epsilon^{i-1}_{0\beta} + n_e B^i_\alpha] \end{aligned} \tag{2}$$

In Eq. (2), the first term represents line radiation associated with radiative decay. The second term represents continuum radiation associated with radiative recombination. The third term represents the radiative cascade which follows radiative recombination to an excited state, and the last term represents bremsstrahlung. We note that in this approximation, recombined ions are assumed to decay radiatively to the ground state without any possibility of excitation or ionisation from an excited state. That is, recombination is treated in the coronal approximation. The contribution to radiative losses associated with a radiative cascade which would follow charge exchange to an excited stateis not included here for simplicity. This contribution should be calculated separately and added to the radiative loss coefficient calculated here. This contribution would add a dependence of the rates on particle neutral densities.

The electron cooling rate $P_e$ is defined similarly in terms of the densities of ionisation stage $i$ $n_i$ and the electron cooling coefficients $P^i_{e,\alpha}$ as

$$P_e = \sum_{i,\alpha} n^i_\alpha P^i_{e,\alpha}, \tag{3}$$

where

$$\begin{aligned} n^i_\alpha P^i_{e,\alpha} &= \sum_\beta n^i_\alpha n_e [X^i_{\alpha\beta}\epsilon^i_{\alpha\beta} + \int d^3v \frac{1}{2} M v^2 v \sigma^{i-1}_{rr,0\alpha} f(v) + \\ & \sum_\gamma \int d^3v \frac{1}{2} M v^2 v \sigma^{i-1}_{dr,\alpha\beta\gamma} f(v)] + n^i_\alpha n_e \left[S^i_\alpha \epsilon^i_\alpha + B^i_\alpha i\right]. \end{aligned} \tag{4}$$

The first term in this equation represents cooling associated with collisional excitation. The second term represents the loss of energy associated with radiative recombination. The third and fourth terms represent the loss of electron energy associated with collisional ionisation and bremsstrahlung respectively.

The calculation of the expressions given in the above equations requires a knowledge of the densities $n^i_\alpha$ for individual excited states, as well as accurate values for cross sections and rates which appear in the right hand sides. As in Refs. [12,13], the densities are obtained by solving the system of equations

$$\begin{aligned} \frac{\partial n^i_\alpha}{\partial t} &= \sum_\beta [-n^i_\alpha (A^i_{\alpha\beta} + n_e X^i_{\alpha\beta}) \\ & n^i_\alpha (A^i_{\alpha\beta} + n_e X^i_{\alpha\beta})] - n^i_\alpha S^i_\alpha + \delta_{0\alpha} \sum_\beta n^i_\beta n_e S^i_\beta. \end{aligned} \tag{5}$$

This constitutes a simplified collisional radiative model in which the populations of the various excited states are determined by radiative decay, collisional excitation and deexcitation, and by ionisation. The main difference between the model

**Table 1**. Definition of the variables and rates used in the calculations.

| | |
|---|---|
| $A^i_{\alpha\beta}$ | Transition probability for transition $\alpha \rightarrow \beta$ in ionisation stage i. |
| $B^i_{\alpha}$ | Power radiated by bremsstrahlung per unit ion ionisation stage i. |
| $S^i_{\alpha}$ | Rate of ionisation for ionisation stage i in state $\alpha$. |
| $X^i_{\alpha\beta}$ | Rate of excitation (including resonance excitation) for transition $\alpha \rightarrow \beta$ in ionisation stage i. |
| $n^i_{\alpha}$ | Density of ions in ionisation stage i and state $\alpha$. |
| $n_e$ | Electron density. |
| $\epsilon^i_{\alpha}$ | Ionisation energy for ionisation stage i in state $\alpha$. |
| $\epsilon^i_{\alpha\beta}$ | Excitation energy for transition $\alpha \rightarrow \beta$ in ionisation stage i. |
| $\sigma^i_{rr}$ | Cross section for radiative recombination in state $\beta$ from an ion in ionisation stage i and in state $\alpha$. |
| $\sigma^i_{dr,\alpha\beta\gamma}$ | Cross section for dielectronic recombination in Rydberg state $\gamma$ of ionisation stage $\imath$ associated with a core transition $\alpha \rightarrow \beta$. |

considered here and the one presented in Refs. [12,13] is that in these references, multistep processes were considered only for metastable states. Specifically, collisional deexcitation and ionisation from an excited states were considered only from excited metastable states. In practice, this can be imposed by setting $A^i_{\alpha\beta}$, $S^i_{\alpha}$, and $X^i_{\alpha\beta}$ to zero whenever the initial state is not the ground state or a metastable state. In the calculations considered here, multistep processes are considered for both metastable and non metastable states.

# 3 Atomic data base

For carbon and oxygen, the atomic data base used for the detailed rates and cross sections in this calculation is essentially the same as described in Refs. [12,13]. For hydrogen, we use rates and cross sections given by Janev, et al. [14]. For neutral helium, the ionisation rate from the ground state is calculated from fits produced by Lennon, et al. [15]. Ionisation from excited states is calculated from recommended and semiemperical formulas taken from Ref. [14]. For excitation rates, we use rates taken from Refs. [16-20] when available, and rates obtained from Ref. [14] otherwise.

# 4 Analytic Fits

In many applications, plasma modeling for example, cross sections or rate coefficients of different processes are required over a wide energy region. Analytic fits to the data serve this purpose, because with few parameters and a given function, the rate coefficients can be generated easily. Compared to polynomial fits (which are linear in the fitting parameters), non-linear analytic fits do not have spurious oscillations and can represent the low and high energy limits properly.

In this work, we have made analytic fits to all data presented. The functions used are (T refers to temperature in keV):

Expression 1:

$$P_{r,e}(T) = a_1 \frac{e^{-a_2/T^{a_3}}}{T^{a_4} + a_5 T^{a_6}} \tag{6}$$

Expression 2:

$$P_{r,e}(T) = a_1 \frac{e^{-a_2/T^{a_3}}}{1 + a_4 T^{a_5} + a_6 T^{a_7}} \tag{7}$$

Expression 3:

$$P_{r,e}(T) = a_1 \frac{e^{-a_2/T^{a_3}}}{T^{a_4} + a_5 T^{a_6} + a_7 T^{a_8}} + a_9 \frac{e^{-a_{10} T}}{T^{a_{11}}} \tag{8}$$

Expression 4:

$$P_{r,e}(T) = a_1 \frac{e^{-a_2/T^{a_3}}}{T^{a_4} + a_5 T^{a_6}} + a_7 T^{a_8} \tag{9}$$

Expression 5:

$$P_{r,e}(T) = a_1 T^{a_2} + a_3 T^{a_4} \tag{10}$$

Expression 6:

$$P_{r,e}(T) = a_1 T^{a_2} + a_3 T^{a_4} + a_5 T^{a_6} \tag{11}$$

Expression 7:

$$P_{r,e}(T) = a_1 \frac{e^{-a_2/T^{a_3}} ln(1 + T^{a_4})}{T^{a_5} + a_6 T^{a_7}} \tag{12}$$

Expression 8:

$$P_{r,e}(T) = a_1 e^{-a_2/T^{a_3}} (1 + a_4 T^{a_5} + a_6 T^{a_7}) \tag{13}$$

Tables 2-11 give the parameters for the fits shown in Figs. (2)-(37).

# 5 Summary

A simplified collisional radiative model has been used to calculate atomic rate coefficients for radiative loss, and electron cooling associated with atoms and ions in fusion plasmas. The species considered are hydrogen, helium, carbon, and oxygen. The results are presented graphically as a function of temperature, for three densities ($10^{19}$ m$^{-3}$, $10^{20}$ m$^{-3}$, $10^{21}$ m$^{-3}$). They are also expressed in terms of analytic fits, convenient for use in numerical plasma simulation models. The agreement between the actual rates and the analytic fits is generally excellent (within 10%), except at low temperatures ($\approx$1 eV) where some of the fits can be in error by more than a factor two. The density dependence of the rates is found to be generally weak. For densities in the range $10^{19}$ m$^{-3}$, $10^{21}$ m$^{-3}$, this dependence can be well approximated from a logarithmic interpolation of the rates presented. The strongest density dependence is observed for the radiative cooling rate with neutral or weakly ionized species. In comparison, the electron cooling rate is relatively insensitive to the electron density.

## Acknowledgements

One of us (RM) thanks the Natural Sciences and Engineering Research Council of Canada for its financial support.

## References

1. D.H. Menzel and L.H. Aller, Astrophys. J. 94, 30 (1941).
2. L.H. Aller, Astrophys. J. 118, 547 (1953).
3. D.P. Cox and W.H. Tucker, Astrophys. J. 157, 1157 (1969).
4. D.E. Post, R. V. Jensen, C.B. Tarter, W.H. Grasberger, and W.A. Lokke, Atom. Data Nucl. Data Tables 20, 397 (1977).
5. J. Davis, V.L. Jacobs, P.C. Kepple, and M. Blaha, J. Quant. Spectrosc. Radiat. Transfer 17, 139 (1977).
6. V.L. Jacobs, J. Davis, J.E. Rogerson, and M. Blaha, J. Quant. Spectrosc. Radiat. Transfer 19, 591 (1978).
7. C. Breton, C. De Michelis, and M. Mattioli, Nucl. Fusion 16, 891 (1976).
8. H.P. Summers and R.W.P. McWhirter, J. Phys. B 12, 2387 (1979).
9. R. Hulse, Nucl. Technol./Fusion 3, 259 (1983).
10. R.W.P. McWhirter and H.P. Summers, in Applied Atomic Collision Physics, edited by C.F. Barnet and M.F.A. Harrison (Orlando Academic, Orlando, FL, 1984), Vol. 2, p. 51.
11. C. Keane and C.H. Skinner, Phys. Rev. A 33, 4179 (1986).
12. R. Marchand, R.K. Janev, and X. Bonnin, International Atomic Energy Agency Report INDC(NDS)-255 (1992).
13. X. Bonnin, R. Marchand, and R.K. Janev, Nucl. Fusion Supp. Vol. 2 "Atomic and Plasma-Material Interaction Data for Fusion", 117 (1992).
14. R.K. Janev, W.D. Langer, K. Evans, Jr., and D.E. Post, Jr., Elementary Processes in Hydrogen-Helium Plasmas (Springer- Verlag, New York, 1987).
15. M.A. Lennon, K.L. Bell, H.B. Hilbody, J.G. Hughes, E. Kingston, M.J. Murray, and F.J. Smith, J. Phys. Chem. Ref. Data, 17, 1285 (1988).
16. K.A. Berrington and A.E. Kingston, J. Phys. B 20, 6631 (1987).
17. D.C. Cartwright, G. Csanak, S. Trajmar and D.F. Register, Phys. Rev. A 45, 1602 (1992).
18. A.K. Katiyar and R. Srivastava, Phys. Rev. A 38, 2767 (1988).
19. T. Kato and S. Nakazaki, ADNDT 42, 313 (1989).
20. V.P. Shevelko, L.A. Vainshtein and E.A. Yukov, Phys. Scripta T28,39 (1989).

## Table 2: Parameters for the analytic fits: Hydrogen.

**Hydrogen:** $P_e, n = 10^{19} m^{-3}$

| | I | II |
|---|---|---|
| Fit* | 1 | 6 |
| $a_1$ | .1247E+03 | 3180E-03 |
| $a_2$ | 2111 | 2332 |
| $a_3$ | 5982 | - 9388E-02 |
| $a_4$ | .4063 | 8617 |
| $a_5$ | 9640E-03 | 9663E-02 |
| $a_6$ | 1 4523 | 8573 |

**Hydrogen:** $\mathrm{P_e, n = 10^{20} m^{-3}}$

| | I | II |
|---|---|---|
| Fit* | 1 | 6 |
| $a_1$ | .1246E+03 | .3180E-03 |
| $a_2$ | 2078 | 2332 |
| $a_3$ | 6007 | - 9388E-02 |
| $a_4$ | 4071 | 8617 |
| $a_5$ | 8290E-03 | 9663E-02 |
| $a_6$ | 1 4738 | 8573 |

**Hydrogen:** $\mathrm{P_e, n = 10^{21} m^{-3}}$

| | I | II |
|---|---|---|
| Fit* | 1 | 6 |
| $a_1$ | 3184E+03 | .3180E-03 |
| $a_2$ | 2087 | 2332 |
| $a_3$ | 5986 | - 9388E-02 |
| $a_4$ | 4155 | 8617 |
| $a_5$ | 1 5270 | 9663E-02 |
| $a_6$ | 4155 | 8573 |

* Refers to expressions in Eqs (6)-(13)

## **Table 3**: Parameters for the analytic fits.

**Hydrogen: $P_r, n = 10^{19} m^{-3}$**

| | I | II |
|---|---|---|
| Fit* | 1 | 6 |
| $a_1$ | 60.3763 | 1300E-04 |
| $a_2$ | 1795 | - 1775E-02 |
| $a_3$ | 5985 | .9000E-05 |
| $a_4$ | 3382 | - 6615 |
| $a_5$ | 8330E-03 | 5760E-03 |
| $a_6$ | 1 5886 | 5019 |

**Hydrogen: $P_r, n = 10^{20} m^{-3}$**

| | I | II |
|---|---|---|
| Fit* | 1 | 6 |
| $a_1$ | 50.5610 | 1300E-04 |
| $a_2$ | .1667 | - 1775E-02 |
| $a_3$ | 6020 | 9000E-05 |
| $a_4$ | .3109 | - 6615 |
| $a_5$ | .1555E-02 | 5760E-03 |
| $a_6$ | 1 4469 | .5019 |

**Hydrogen: $P_r, n = 10^{21} m^{-3}$**

| | I | II |
|---|---|---|
| Fit* | 1 | 6 |
| $a_1$ | 26 7831 | 1300E-04 |
| $a_2$ | .1017 | -.1775E-02 |
| $a_3$ | 6343 | 9000E-05 |
| $a_4$ | 1250 | - 6615 |
| $a_5$ | 5904E-01 | 5760E-03 |
| $a_6$ | 7304 | 5019 |

* Refers to expressions in Eqs (6)-(13)

Table 4: Parameters for the analytic fits.

**Helium: $P_e, n = 10^{19} m^{-3}$**

| | I | II | III |
|---|---|---|---|
| Fit* | 1 | 4 | 6 |
| $a_1$ | 6623E+03 | 3476E+03 | .2730E-01 |
| $a_2$ | 9476E-01 | 1214 | .6004 |
| $a_3$ | 7456 | 7974 | - 2772E-01 |
| $a_4$ | - 2592 | 4819 | 5925 |
| $a_5$ | 3 8098 | 1 4066 | 3060E-02 |
| $a_6$ | 4026 | - 3639E-02 | 3590 |
| $a_7$ | | 9720E-03 | |
| $a_8$ | | 4078 | |

**Helium: $P_e, n = 10^{20} m^{-3}$**

| | I | II | III |
|---|---|---|---|
| Fit* | 1 | 4 | 6 |
| $a_1$ | .6547E+03 | 2487E+03 | 2730E-01 |
| $a_2$ | 9272E-01 | 1194 | 6004 |
| $a_3$ | 7505 | 8003 | - 2772E-01 |
| $a_4$ | - 2589 | - 8375E-02 | .5925 |
| $a_5$ | 3 7644 | 7251 | .3060E-02 |
| $a_6$ | 4028 | 4797 | 3590 |
| $a_7$ | | 9720E-03 | |
| $a_8$ | | .4078 | |

**Helium: $P_e, n = 10^{21} m^{-3}$**

| | I | II | III |
|---|---|---|---|
| Fit* | 1 | 4 | 6 |
| $a_1$ | 6540E+03 | 3459E+03 | 2730E-01 |
| $a_2$ | 9454E-01 | 1194 | .6004 |
| $a_3$ | 7480 | 8007 | - 2772E-01 |
| $a_4$ | -.2498 | .4812 | 5925 |
| $a_5$ | 3 7483 | 1 4009 | 3060E-02 |
| $a_6$ | 4036 | - 5582E-02 | 3590 |
| $a_7$ | | 9720E-03 | |
| $a_8$ | | .4078 | |

* Refers to expressions in Eqs (6)-(13)

## Table 5: Parameters for the analytic fits.

**Helium: $P_r$, $n = 10^{19} m^{-3}$**

| | I | II | III |
|---|---|---|---|
| Fit* | 1 | 4 | 6 |
| $a_1$ | 1248E+03 | 1263E+03 | 1601E-03 |
| $a_2$ | 5112E-01 | 1213 | -.4784 |
| $a_3$ | 8413 | .8023 | 8600E-04 |
| $a_4$ | -.1881 | 8712E-01 | - 6062 |
| $a_5$ | 3 1032 | 2276 | .2284E-02 |
| $a_6$ | 3749 | .5996 | 5051 |
| $a_7$ | | 1800E-04 | |
| $a_8$ | | - 6236 | |

**Helium: $P_r$, $n = 10^{20} m^{-3}$**

| | I | II | III |
|---|---|---|---|
| Fit* | 1 | 4 | 6 |
| $a_1$ | 88.9673 | .5847E+03 | .1610E-03 |
| $a_2$ | 7567E-01 | 1261 | - 4784 |
| $a_3$ | 7895 | 7963 | .8600E-04 |
| $a_4$ | -.9620E-01 | 6092 | - 6062 |
| $a_5$ | 2 2503 | 4 7760 | .2284E-02 |
| $a_6$ | 3787 | 9214E-01 | 5051 |
| $a_7$ | | 1800E-04 | |
| $a_8$ | | - 6236 | |

**Helium: $P_r$, $n = 10^{21} m^{-3}$**

| | I | II | III |
|---|---|---|---|
| Fit* | 1 | 4 | 6 |
| $a_1$ | 47 7193 | 1253E+03 | 1610E-03 |
| $a_2$ | 7062E-01 | 1283 | - 4784 |
| $a_3$ | 7941 | 7894 | 8600E-04 |
| $a_4$ | - 1261 | 7467E-01 | - 6062 |
| $a_5$ | 1 5861 | 2628 | .2284E-02 |
| $a_6$ | 3484 | .5770 | 5051 |
| $a_7$ | | 1800E-04 | |
| $a_8$ | | - 6236 | |

* Refers to expressions in Eqs (6)-(13)

# Table 6: Parameters for the analytic fits.

**Carbon: $P_e, n = 10^{19} m^{-3}$**

| | I | II | III | IV | V | VI | VII |
|---|---|---|---|---|---|---|---|
| Fit* | 1 | 1 | 2 | 1 | 4 | 4 | 6 |
| $a_1$ | 6448E+03 | .4519E+03 | 4368E+03 | 1738E+03 | 1173E+03 | 52 5191 | 1662 |
| $a_2$ | 3824E-02 | .6083E-01 | 9100E-04 | 1640E-03 | 2612 | 3274 | 8353 |
| $a_3$ | 1 1008 | 7313 | 1 6421 | 1.5417 | 9629 | .9951 | - 1868 |
| $a_4$ | 3730 | 3943 | 2334E-01 | 3624 | -.4263 | - 3099 | 8126 |
| $a_5$ | 2766 | 4318 | -1 1336 | 4363 | 9247 | 7766 | 6259E-01 |
| $a_6$ | - 1836 | - 4402E-01 | 1 1203 | - 2909 | 3279 | 3331 | |
| $a_7$ | | | 4493 | | 6987E-02 | .2229E-01 | |
| $a_8$ | | | | | 2506 | 3049 | |

**Carbon: $P_e, n = 10^{20} m^{-3}$**

| | I | II | III | IV | V | VI | VII |
|---|---|---|---|---|---|---|---|
| Fit* | 1 | 1 | 2 | 1 | 4 | 4 | 5 |
| $a_1$ | 6341E+03 | 4478E+03 | .4327E+03 | 1705E+03 | 1179E+03 | 52.3327 | .1662 |
| $a_2$ | 3301E-02 | .5713E-01 | 1070E-03 | 1540E-03 | 2662 | 3331 | .8353 |
| $a_3$ | 1 1241 | .7411 | 1.6144 | 1 5495 | .9619 | 9924 | - 1868 |
| $a_4$ | 3714 | 3931 | .2300E-01 | 3576 | - 4202 | - 2995 | 8126 |
| $a_5$ | 2852 | 4323 | -1 1340 | 4116 | 9264 | 7610 | 6258E-01 |
| $a_6$ | - 1795 | - 4881E-01 | 1 0992 | -.3073 | .3286 | 3362 | 3902 |
| $a_7$ | | | 4513 | | 6893E-02 | 2211E-01 | |
| $a_8$ | | | | | .2483 | 3034 | |

**Carbon: $P_e; n = 10^{21} m^{-3}$**

| | I | II | III | IV | V | VI | VII |
|---|---|---|---|---|---|---|---|
| Fit* | 1 | 1 | 2 | 1 | 4 | 4 | 6 |
| $a_1$ | .5742E+03 | 4248E+03 | .4112E+03 | 1532E+03 | 1231E+03 | 52 2594 | 1662 |
| $a_2$ | 2407E-02 | 4082E-01 | 3440E-03 | 1450E-03 | .3113 | 3285 | .8353 |
| $a_3$ | 1 1731 | .7937 | 1 4249 | 1.5344 | .9340 | 9982 | - 1868 |
| $a_4$ | 3583 | 3856 | 2365E-01 | 3296 | -.3729 | - 3069 | 8126 |
| $a_5$ | 2523 | 4098 | -1 1104 | 2883 | 9319 | 7675 | 6259E-01 |
| $a_6$ | - 1921 | - 8080E-01 | 1.0141 | - 4230 | 3357 | 3345 | 3902 |
| $a_7$ | | | 4552 | | 6788E-02 | 2195E-01 | |
| $a_8$ | | | | | .2455 | 3020 | |

* Refers to expressions in Eqs (6)-(13)

## Table 7: Parameters for the analytic fits.

**Carbon: $P_r, n = 10^{19} m^{-3}$**

| | I | II | III | IV | V | VI | VII |
|---|---|---|---|---|---|---|---|
| Fit* | 1 | 1 | 2 | 1 | 3 | 3 | 6 |
| $a_1$ | 3355E+03 | 3149E+03 | .3409E+03 | 1061E+03 | 59 5004 | 33 1965 | 2866E-01 |
| $a_2$ | 4649E-02 | 3120E-01 | 2100E-04 | 4890E-03 | 1643E-01 | 4860E-01 | 4204 |
| $a_3$ | 1 0747 | 8327 | 1 8872 | 1.3696 | 1 6944 | 1 4735 | 3 5997 |
| $a_4$ | 3842 | 4229 | 1408E-01 | .3394 | 3499 | 3219 | - 4611 |
| $a_5$ | 2871 | 6912 | -1 1895 | 2132 | 1 2847 | 1 2237 | -3 5712 |
| $a_6$ | - 5545E-01 | 3375E-01 | 1 4539 | -.2981 | - 3530 | - 4093 | - 4598 |
| $a_7$ | | | 4354 | | 2396 | 1113 | |
| $a_8$ | | | | | -1 4526 | -1 7343 | |
| $a_9$ | | | | | 5520E-03 | 7283E-02 | |
| $a_{10}$ | | | | | - 8682E-01 | - 2828E-01 | |
| $a_{11}$ | | | | | 6945 | 7062 | |

**Carbon: $P_r, n = 10^{20} m^{-3}$**

| | I | II | III | IV | V | VI | VII |
|---|---|---|---|---|---|---|---|
| Fit* | 1 | 1 | 2 | 1 | 3 | 3 | 6 |
| $a_1$ | 2833E+03 | 2657E+03 | 3311E+03 | 1046E+03 | 55 6466 | 32 8181 | 2866E-01 |
| $a_2$ | 3145E-02 | 2266E-01 | 2300E-04 | 4830E-03 | 1813E-01 | 5149E-01 | 4204 |
| $a_3$ | 1 1257 | .8745 | 1 8755 | 1 3696 | 1 6565 | 1 4601 | 3 5997 |
| $a_4$ | 3741 | 3982 | 1381E-01 | 3360 | 3377 | .3201 | - 4611 |
| $a_5$ | 3987 | 5639 | -1 1871 | 2061 | 1 1879 | 1 2001 | -3 5712 |
| $a_6$ | - 6201E-01 | - 2280E-01 | 1 4124 | - 3100 | - 4060 | - 4145 | - 4598 |
| $a_7$ | | | 4355 | | 1811 | 1063 | |
| $a_8$ | | | | | -1.5368 | -1 7338 | |
| $a_9$ | | | | | 4470E-03 | .7279E-02 | |
| $a_{10}$ | | | | | 4600E-04 | -.2418E-01 | |
| $a_{11}$ | | | | | 7276 | 7063 | |

**Carbon: $P_r, n = 10^{21} m^{-3}$**

| | I | II | III | IV | V | VI | VII |
|---|---|---|---|---|---|---|---|
| Fit* | 1 | 1 | 2 | 1 | 3 | 3 | 6 |
| $a_1$ | 2246E+03 | 2006E+03 | 2780E+03 | 95.2822 | 59 3701 | 32 9139 | 2866E-01 |
| $a_2$ | 1683E-02 | 9595E-02 | 2400E-04 | 5410E-03 | 1441E-01 | 5305E-01 | 4204 |
| $a_3$ | 1 2048 | 9961 | 1.8652 | 1 3340 | 1 7419 | 1 4521 | 3 5997 |
| $a_4$ | 3635 | 3647 | 1133E-01 | 3155 | 3514 | 3211 | - 4611 |
| $a_5$ | 1 6126 | 5052 | -1.1977 | 1690 | 1.3364 | 1 2109 | -3 5712 |
| $a_6$ | - 4745E-01 | - 9863E-01 | 1 1938 | - 3957 | - 3553 | - 4123 | - 4598 |
| $a_7$ | | | 4354 | | .2434 | 1055 | |
| $a_8$ | | | | | -1 5597 | -1.7384 | |
| $a_9$ | | | | | 5620E-03 | 7269E-02 | |
| $a_{10}$ | | | | | - 9486E-01 | - 2339E-01 | |
| $a_{11}$ | | | | | 6916 | 7065 | |

* Refers to expressions in Eqs (6)-(13)

## Table 8: Parameters for the analytic fits.

**Oxygen: $P_e$, $n = 10^{19} m^{-3}$**

|  | I | II | III | IV | V |
|---|---|---|---|---|---|
| Fit* | 1 | 2 | 2 | 4 | 4 |
| $a_1$ | 4675E+03 | 8565E+03 | .6388E+04 | .3009E+03 | 161 8436 |
| $a_2$ | 3565E-01 | 1319E-01 | 3855 | 4673E-01 | 1130E-01 |
| $a_3$ | 7942 | 1 0022 | 4629 | .7865 | 1.7609 |
| $a_4$ | .3707 | 1209 | 8117E-02 | .3472 | .3169 |
| $a_5$ | 4492 | - 6863 | -1 3193 | .3230 | 1448 |
| $a_6$ | - 1616 | 1.4778 | 10 1092 | - 3553 | - 7023 |
| $a_7$ |  | 4233 | 4055 | .3500E-01 | .200E-02 |
| $a_8$ |  |  |  | .2500E-02 | 200E-01 |

|  | VI | VII | VIII | IX |
|---|---|---|---|---|
| Fit* | 7 | 4 | 4 | 6 |
| $a_1$ | 95 0706 | 62.5956 | 27 8644 | 6100 |
| $a_2$ | 7180E-03 | 3643 | 5154 | 6191E-01 |
| $a_3$ | 1 3730 | 1 0742 | 9911 | .6844E-02 |
| $a_4$ | 9117 | - 5975 | - 4207 | 8010 |
| $a_5$ | 6831 | 6774 | 5982 | - 5485 |
| $a_6$ | - 3251 | 2791 | 3010 | .4822E-01 |
| $a_7$ | 6173 | 2049E-01 | 4235E-01 |  |
| $a_8$ |  | 2504 | 2687 |  |

**Oxygen: $P_e$, $n = 10^{20} m^{-3}$**

|  | I | II | III | IV | V |
|---|---|---|---|---|---|
| Fit* | 1 | 2 | 2 | 4 | 4 |
| $a_1$ | 4614E+03 | .8452E+03 | 6383E+04 | 3045E+03 | 161 5876 |
| $a_2$ | 3625E-01 | 1123E-01 | .3848 | 5247E-01 | 1100E-03 |
| $a_3$ | .7919 | 1 0302 | .4631 | 7688 | 1 7649 |
| $a_4$ | .3696 | 1221 | .8037E-02 | 3518 | 3202 |
| $a_5$ | 4486 | -.6900 | -1 3222 | 3326 | 1462 |
| $a_6$ | - 1633 | 1.4651 | 10 1209 | - 3384 | - 7034 |
| $a_7$ |  | 4228 | 4051 | .2000 | 2000E-02 |
| $a_8$ |  |  |  | 3300 | 2200E-01 |

|  | VI | VII | VIII | IX |
|---|---|---|---|---|
| Fit* | 7 | 4 | 4 | 6 |
| $a_1$ | 1039E+03 | 62.6109 | 28 2469 | 6100 |
| $a_2$ | .3320E-03 | .3628 | 5280 | .6191E-01 |
| $a_3$ | 1 5185 | 1 0770 | 9869 | 6844E-02 |
| $a_4$ | 9160 | - 6024 | - 4111 | 8100 |
| $a_5$ | 7166 | 6815 | 6015 | -.5485 |
| $a_6$ | -.2689 | 2779 | 3024 | 4822E-01 |
| $a_7$ | 7166 | 2044E-01 | 4233E-01 |  |
| $a_8$ |  | 2500 | .2686 |  |

* Refers to expressions in Eqs (6)-(13)

# Table 9: Parameters for the analytic fits.

**Oxygen: $P_e$, $n = 10^{21} m^{-3}$**

| | I | II | III | IV | V |
|---|---|---|---|---|---|
| Fit* | 1 | 2 | 2 | 4 | 4 |
| $a_1$ | 4505E+03 | 8401E+03 | 6356E+04 | 3089E+03 | 161 3996 |
| $a_2$ | .3395E-01 | 8584E-02 | 3847 | 6222E-01 | 1180E-03 |
| $a_3$ | 8009 | 1 0813 | 4622 | 7457 | 1 7511 |
| $a_4$ | 3673 | 1303 | 7127E-02 | 3553 | 3200 |
| $a_5$ | 4348 | - 6774 | -1 3532 | 3397 | 1467 |
| $a_6$ | - 1745 | 1 4928 | 10 1544 | - 3134 | - 7060 |
| $a_7$ | | 4202 | 4039 | 1800 | 2000E-02 |
| $a_8$ | | | | 3900 | 2000E-02 |

| | VI | VII | VIII | IX |
|---|---|---|---|---|
| Fit* | 7 | 4 | 4 | 6 |
| $a_1$ | 1858E+05 | 63 9077 | 28.5565 | 6100 |
| $a_2$ | 4 8333 | 3787 | 5445 | 6191E-01 |
| $a_3$ | 1532 | 1 0640 | 9824 | 6844E-02 |
| $a_4$ | -.1044E-03 | - 5898 | - 3948 | 8100 |
| $a_5$ | 8467 | 6901 | 5955 | - 5485 |
| $a_6$ | 1718E-10 | 2796 | 3062 | 4822E-01 |
| $a_7$ | -3 6156 | 2038E-01 | 4230E-01 | |
| $a_8$ | | 2494 | 2685 | |

**Oxygen: $P_r$, $n = 10^{19} m^{-3}$**

| | I | II | III | IV | V |
|---|---|---|---|---|---|
| Fit* | 1 | 1 | 1 | 4 | 4 |
| $a_1$ | 1606E+05 | 7378E+04 | 3452E+03 | .2647E+04 | 104 4110 |
| $a_2$ | 7736E-01 | 5324E-01 | 3006 | 1235 | 3230E-03 |
| $a_3$ | 6957 | 8260 | 4783 | 6843 | 1 5838 |
| $a_4$ | 1 2057 | 9278 | 3761 | 7279 | 3390 |
| $a_5$ | 2657E+03 | 48 3739 | 8210E-03 | 16 8926 | 9594E-01 |
| $a_6$ | 2327 | 2833 | -1 3370 | 2554 | - 6673 |
| $a_7$ | | | | 9000E-01 | 3600 |
| $a_8$ | | | | - 1000E-01 | 2000 |

| | VI | VII | VIII | IX |
|---|---|---|---|---|
| Fit* | 8 | 3 | 3 | 5 |
| $a_1$ | 6964 | 40 1658 | 20 8457 | 1815E-01 |
| $a_2$ | 2392 | 5266E-01 | 4104 | 7137 |
| $a_3$ | .6039 | 1.7029 | 8141 | 1084 |
| $a_4$ | 5147 | .2631 | - 4310 | - 5546 |
| $a_5$ | -1 8233 | 1 1736 | 1 0111 | |
| $a_6$ | 1218E+03 | - 6624 | .2823 | |
| $a_7$ | - 3048 | 1530 | 4229E-01 | |
| $a_8$ | | -1 9360 | -2 5273 | |
| $a_9$ | | 2412E-02 | .2708E-01 | |
| $a_{10}$ | | - 5328E-01 | - 1033E-01 | |
| $a_{11}$ | | 7565 | 7351 | |

* Refers to expressions in Eqs (6)-(13)

# Table 10: Parameters for the analytic fits.

**Oxygen: $P_r; n = 10^{20} m^{-3}$**

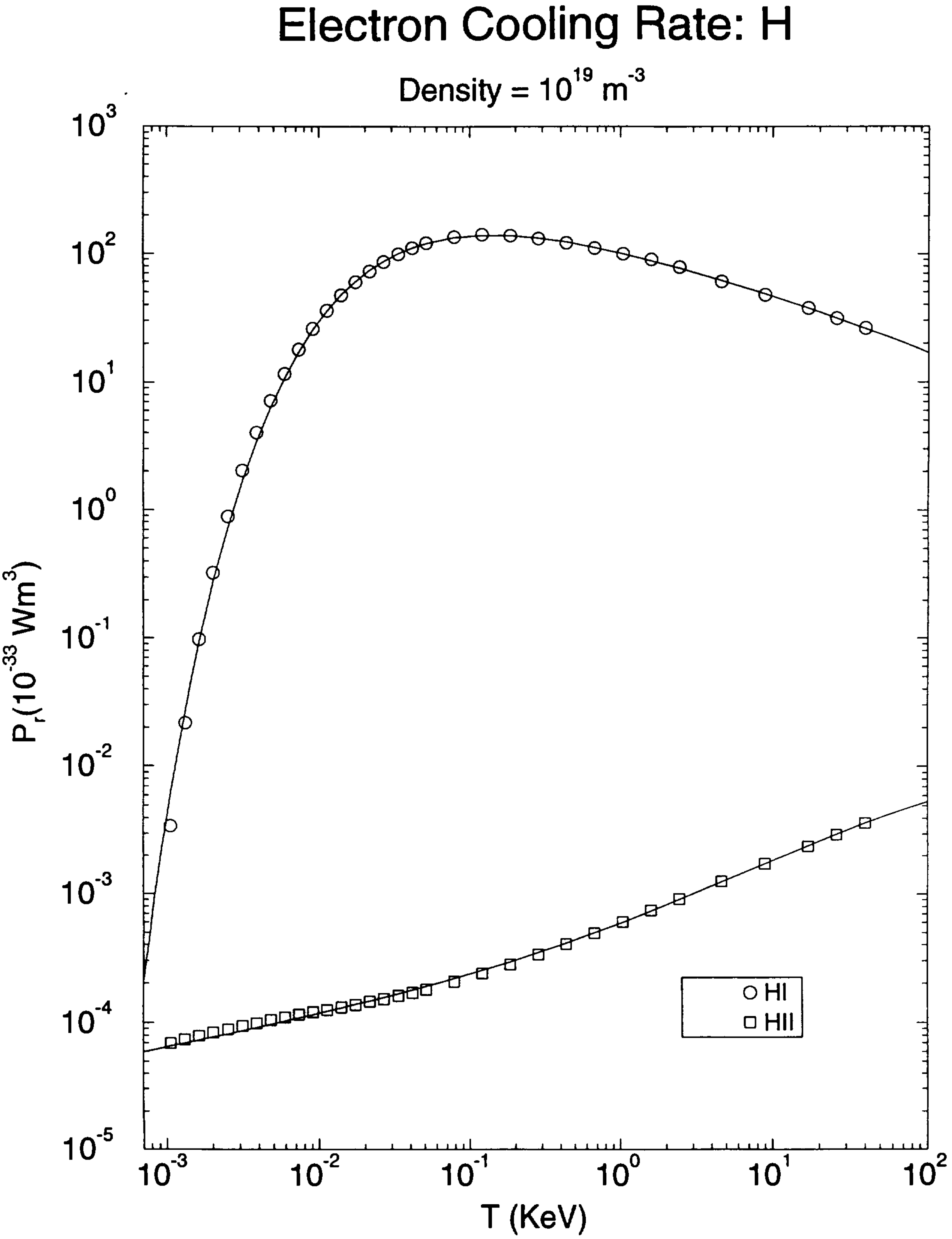
|  | I | II | III | IV | V |
|---|---|---|---|---|---|
| Fit* | 7 | 1 | 1 | 4 | 4 |
| $a_1$ | 39 4024 | 1345E+03 | 3416E+03 | 2654E+04 | 104 0786 |
| $a_2$ | .3864E-02 | 4326E-01 | 3009 | 1228 | 2990E-03 |
| $a_3$ | .9753 | 8545 | 4775 | .6850 | 1 5985 |
| $a_4$ | 4329 | .2597 | 3741 | 7285 | 3424 |
| $a_5$ | 4615 | 2252E-01 | .7840E-03 | 17.0219 | 9792E-01 |
| $a_6$ | 3977E-02 | 9026 | -1 3462 | 2544 | -.6664 |
| $a_7$ | - 9034 |  |  | .7800E-01 | 3500 |
| $a_8$ |  |  |  | -.9500E-02 | .2000 |

|  | VI | VII | VIII | IX |
|---|---|---|---|---|
| Fit* | 8 | 3 | 3 | 5 |
| $a_1$ | 7469 | 39 1740 | 21 2873 | 1815E-01 |
| $a_2$ | .2243 | 5429E-01 | 4270 | 7137 |
| $a_3$ | 6134 | 1 6643 | 8102 | 1084 |
| $a_4$ | 4095 | 2579 | - 4204 | - 4456 |
| $a_5$ | -1 8347 | 1.1645 | 1 0269 |  |
| $a_6$ | 1126E+03 | - 7047 | 2833 |  |
| $a_7$ | - 3030 | 1067 | 4284E-01 |  |
| $a_8$ |  | -2 1320 | -2 5143 |  |
| $a_9$ |  | 2386E-02 | 2708E-01 |  |
| $a_{10}$ |  | 1016E-02 | - 2266E-01 |  |
| $a_{11}$ |  | 7582 | 7351 |  |

**Oxygen: $P_r, n = 10^{21} m-3$**

|  | I | II | III | IV | V |
|---|---|---|---|---|---|
| Fit* | 2 | 1 | 1 | 4 | 4 |
| $a_1$ | 18 0865 | 2751E+04 | 3199E+03 | 2092E+04 | 103 0567 |
| $a_2$ | 9879E-02 | 2563E-01 | 2895 | 1062 | 3120E-03 |
| $a_3$ | 8327 | 9304 | 4798 | 7093 | 1 5909 |
| $a_4$ | 7514 | 7847 | 3640 | 7032 | 3408 |
| $a_5$ | 2978 | 29 0309 | 6440E-03 | 13 8388 | 9837E-01 |
| $a_6$ | 7021E-02 | .2139 | -1 3915 | 2367 | - 6663 |
| $a_7$ | -1 2861 |  |  | 6600E-01 | 3400 |
| $a_8$ |  |  |  | - 8000E-02 | 2000 |

|  | VI | VII | VIII | IX |
|---|---|---|---|---|
| Fit* | 8 | 3 | 3 | 5 |
| $a_1$ | 8581 | 39 6638 | 23 8166 | 1814E-01 |
| $a_2$ | 1325 | 5398E-01 | 4862 | .7137 |
| $a_3$ | 7040 | 1 6911 | 7748 | 1084 |
| $a_4$ | 3782E-01 | .2612 | -.4105 | -.5546 |
| $a_5$ | -2.1886 | 1 1596 | 1 1507 |  |
| $a_6$ | 95 0512 | - 6693 | 2831 |  |
| $a_7$ | - 2953 | 1486 | .4359E-01 |  |
| $a_8$ |  | -1 9502 | -2 5220 |  |
| $a_9$ |  | 2402E-02 | 2709E-01 |  |
| $a_{10}$ |  | -.2655E-01 | -.2156E-01 |  |
| $a_{11}$ |  | 7572 | 7350 |  |



Electron Cooling Rate: H
Density = $10^{19}$ m$^{-3}$
$P_r(10^{-33}$ Wm$^3)$
$10^3$
$10^2$
$10^1$
$10^0$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
$10^0$
$10^1$
$10^2$
T (KeV)
○ HI
□ HII

**Figure 1**

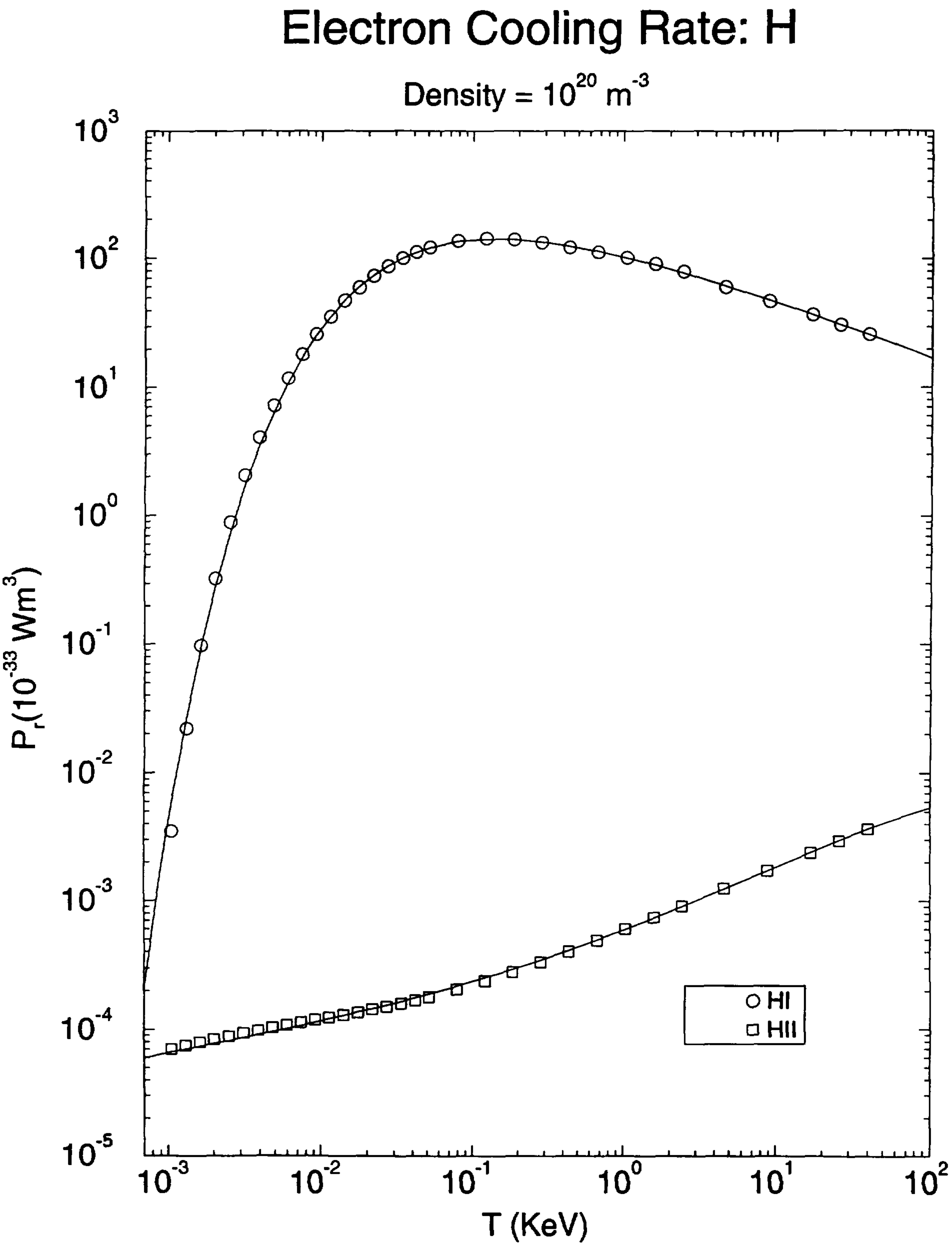

Electron Cooling Rate: H
Density = $10^{20}$ m$^{-3}$
$P_r(10^{-33}$ Wm$^3)$
$10^3$
$10^2$
$10^1$
$10^0$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
$10^0$
$10^1$
$10^2$
T (KeV)
○ HI
□ HII

**Figure 2**

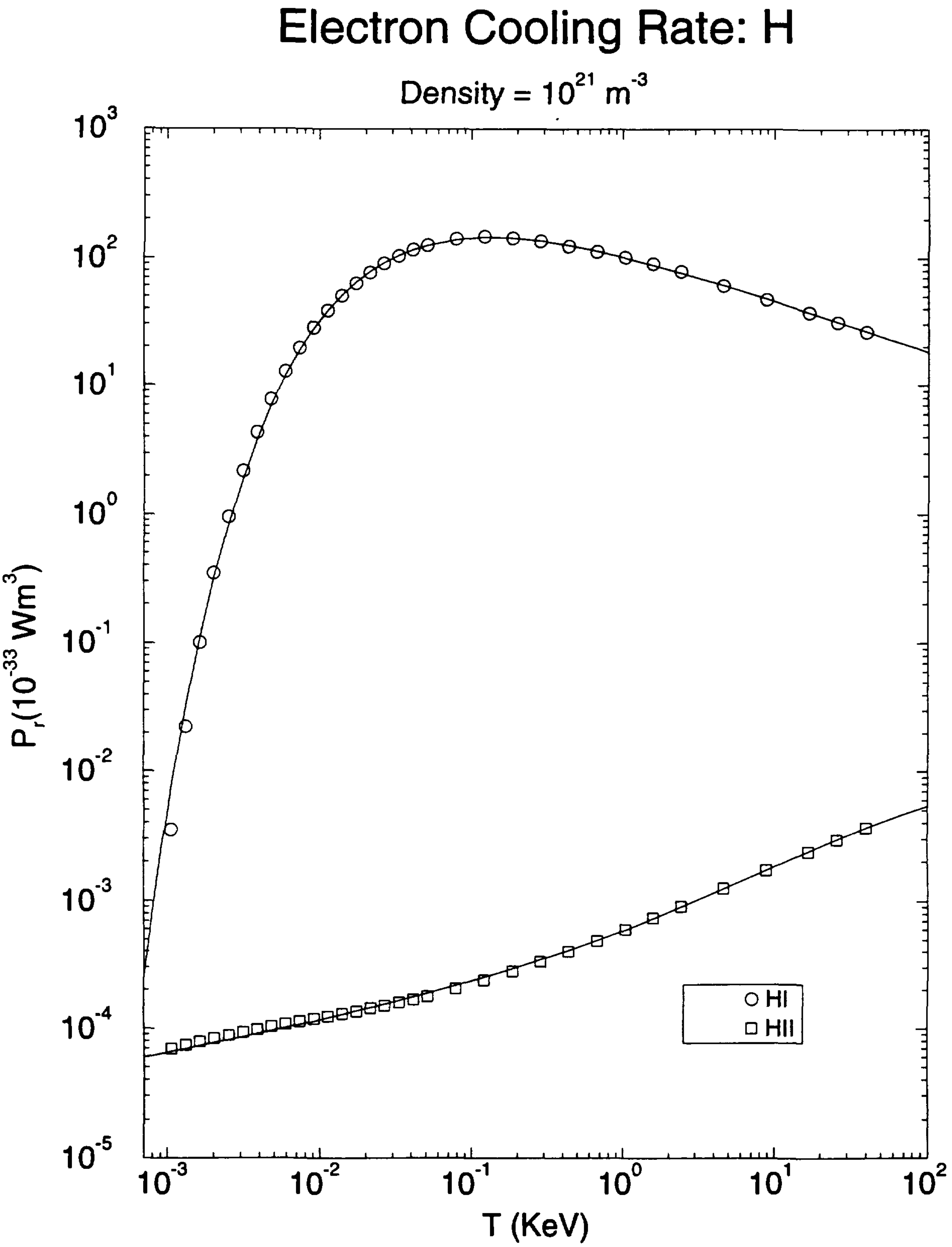

Electron Cooling Rate: H
Density = $10^{21}$ m$^{-3}$
$P_r(10^{-33}\ \mathrm{Wm}^3)$
$10^3$
$10^2$
$10^1$
$10^0$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
$10^0$
$10^1$
$10^2$
T (KeV)
○ HI
□ HII

**Figure 3**

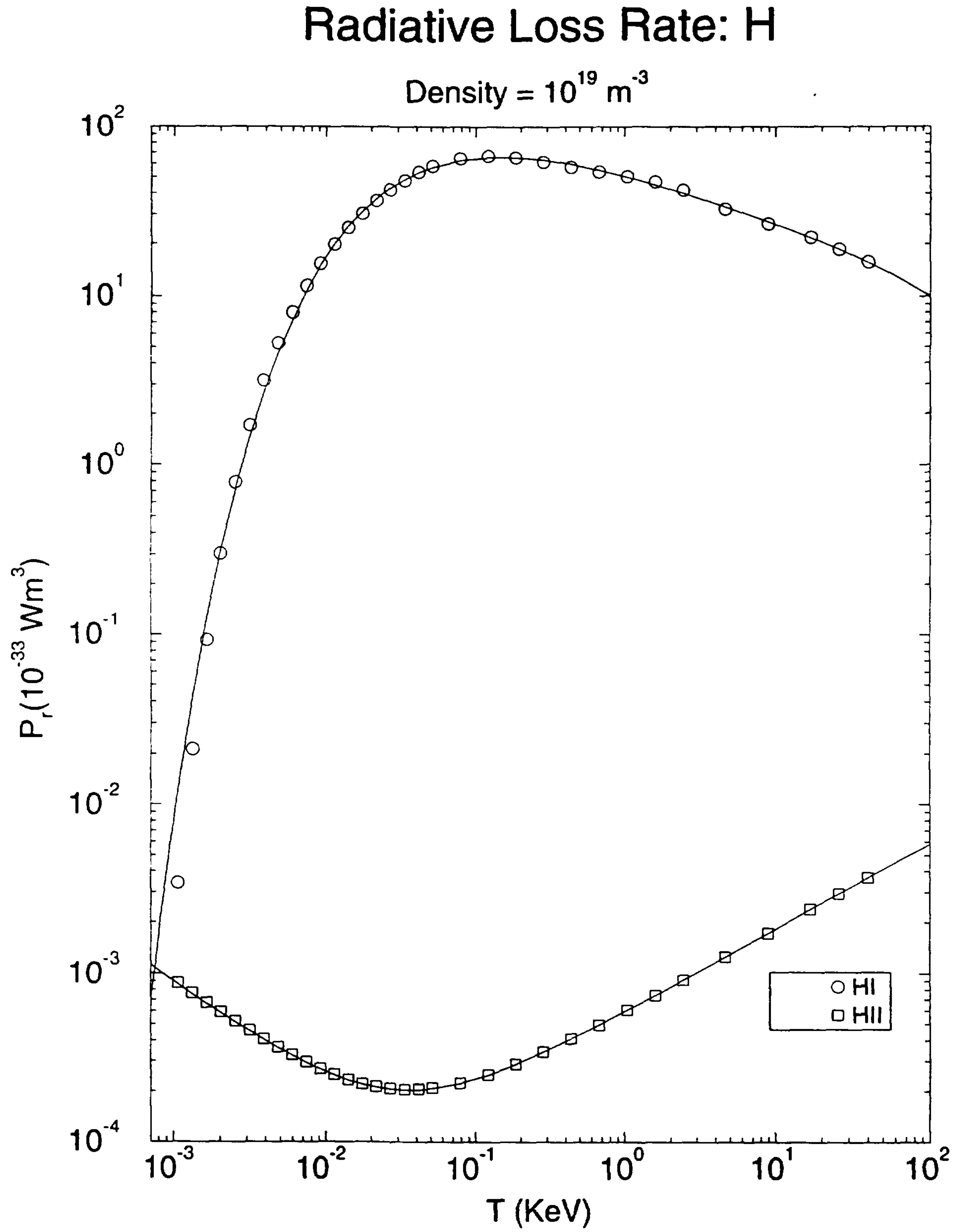

Radiative Loss Rate: H
Density = $10^{19}$ $m^{-3}$
$P_r(10^{-33}\ Wm^3)$
$10^2$
$10^1$
$10^0$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
$10^0$
$10^1$
$10^2$
T (KeV)
○ HI
□ HII

**Figure 4**

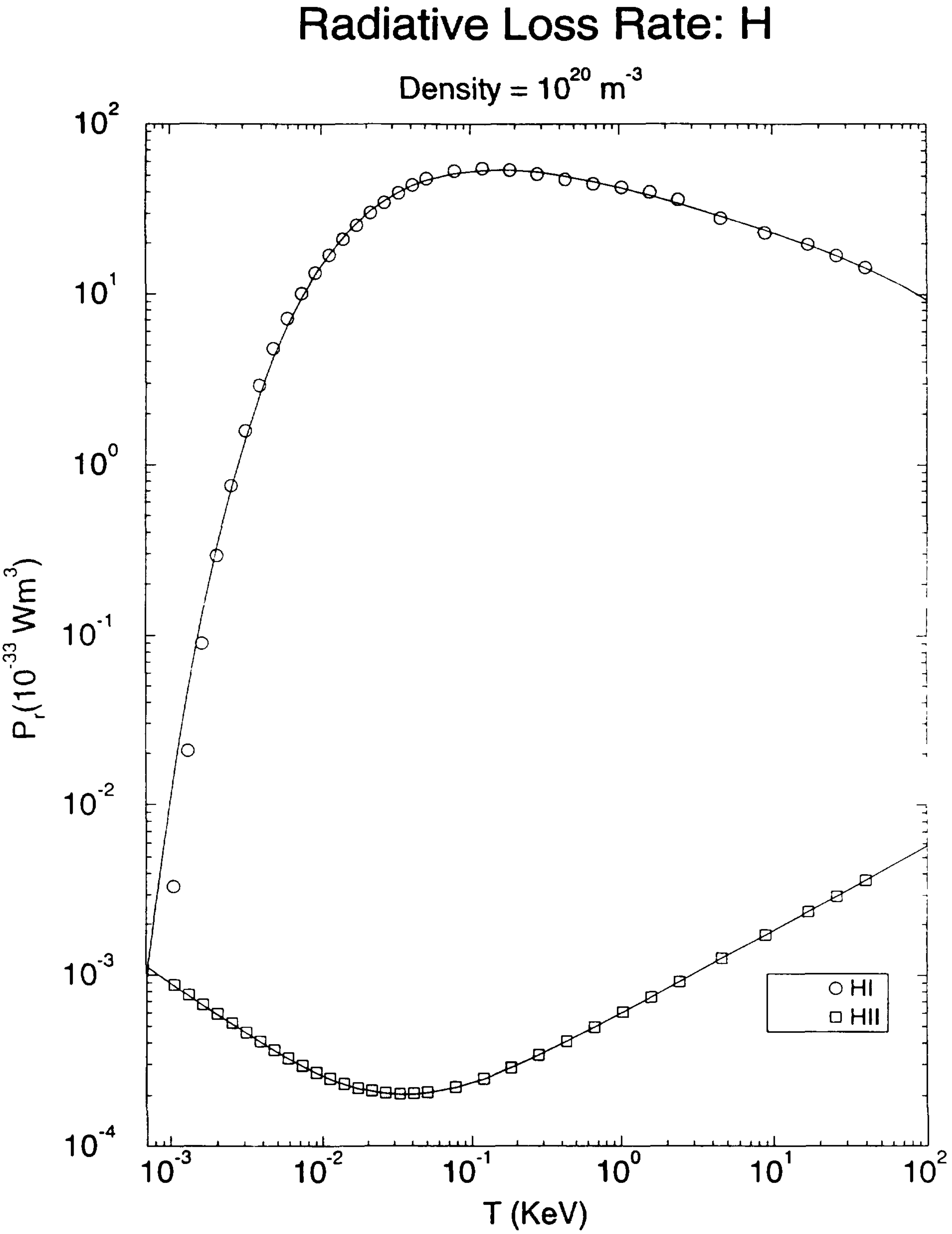

Radiative Loss Rate: H
Density = 10^20 m^-3
P_r(10^-33 Wm^3)
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-3
10^-2
10^-1
10^0
10^1
10^2
T (KeV)
○ HI
□ HII

**Figure 5**

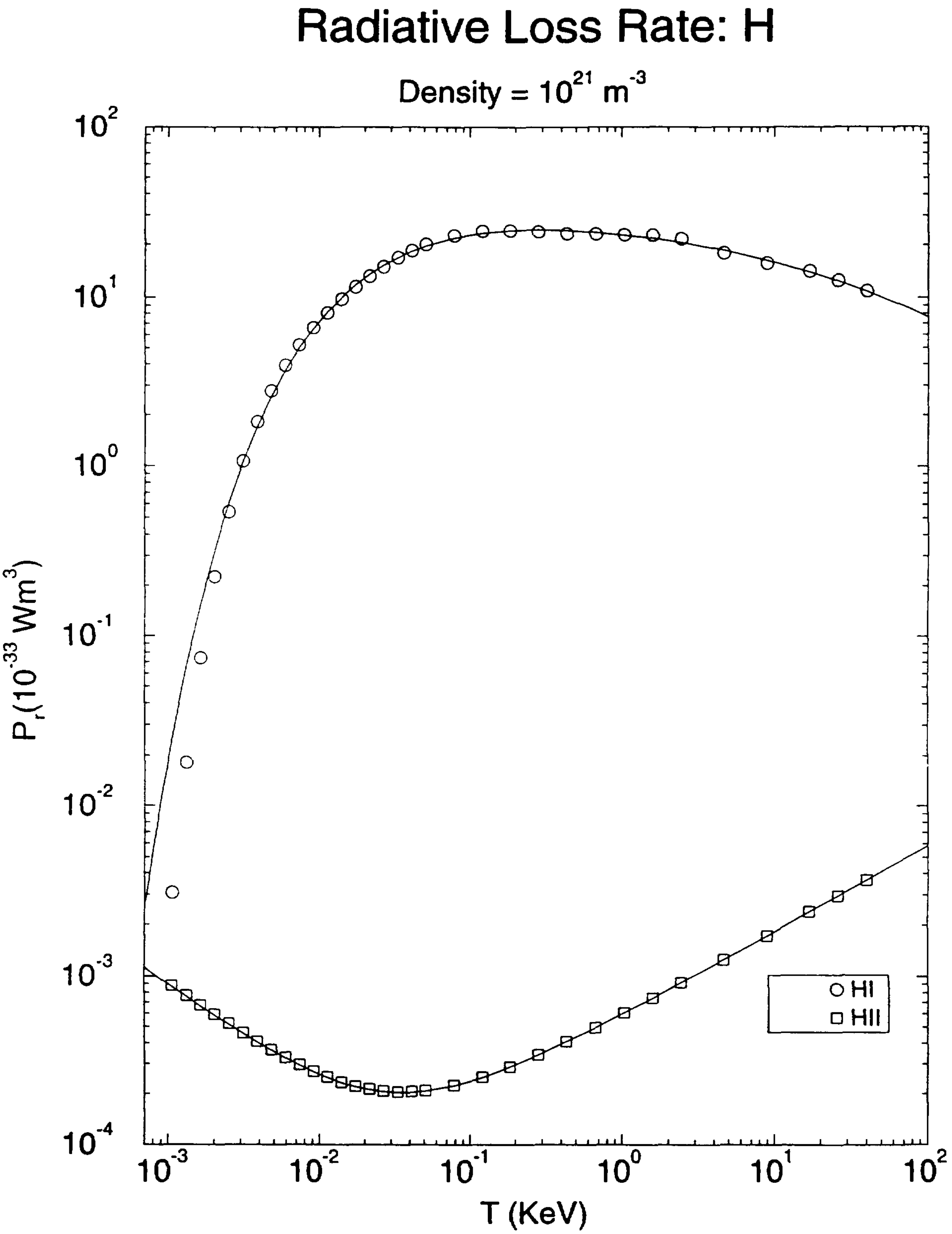

Radiative Loss Rate: H
Density = $10^{21}$ $m^{-3}$
$P_r(10^{-33}\,Wm^3)$
$10^{2}$
$10^{1}$
$10^{0}$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
$10^{0}$
$10^{1}$
$10^{2}$
T (KeV)
○ HI
□ HII

**Figure 6**

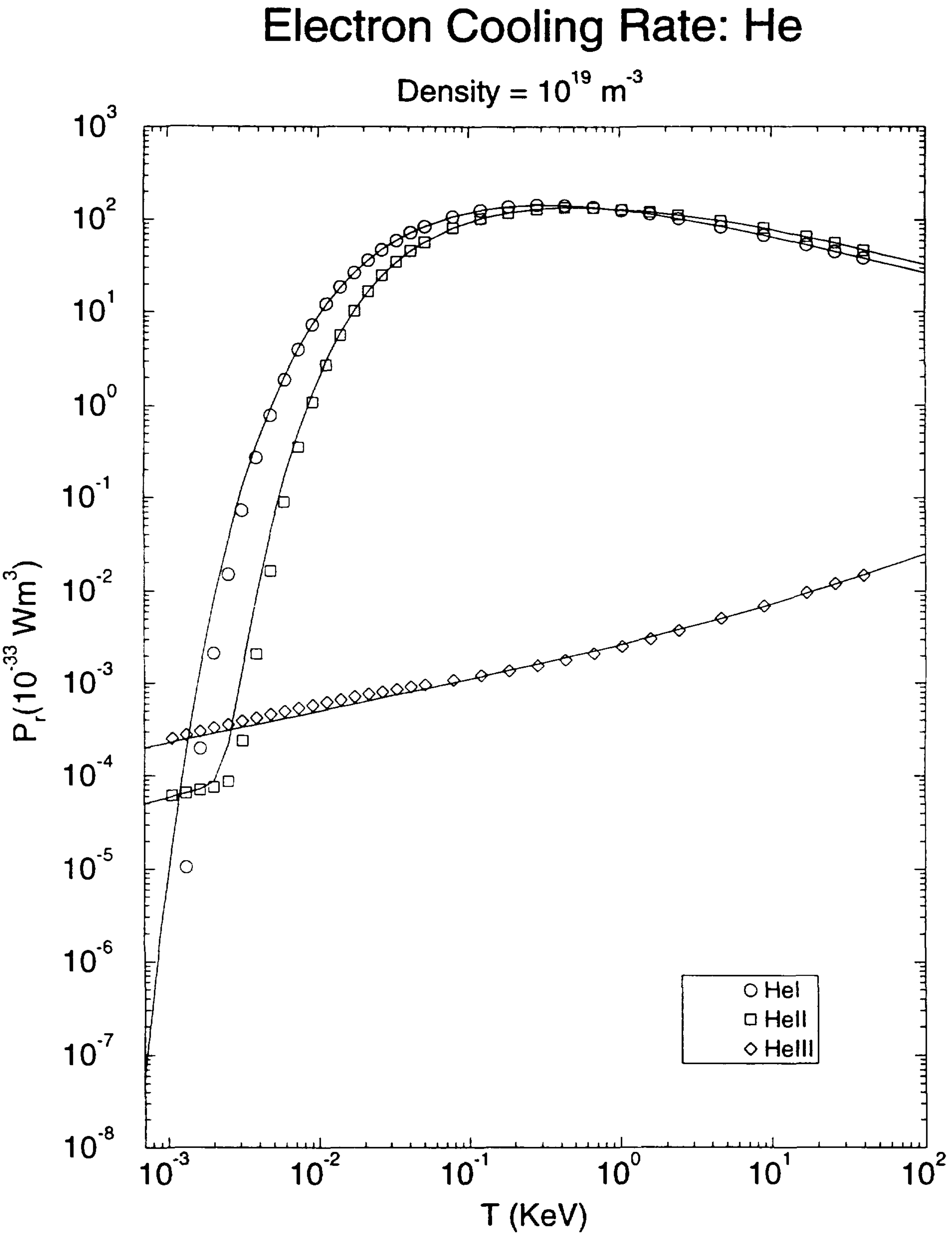
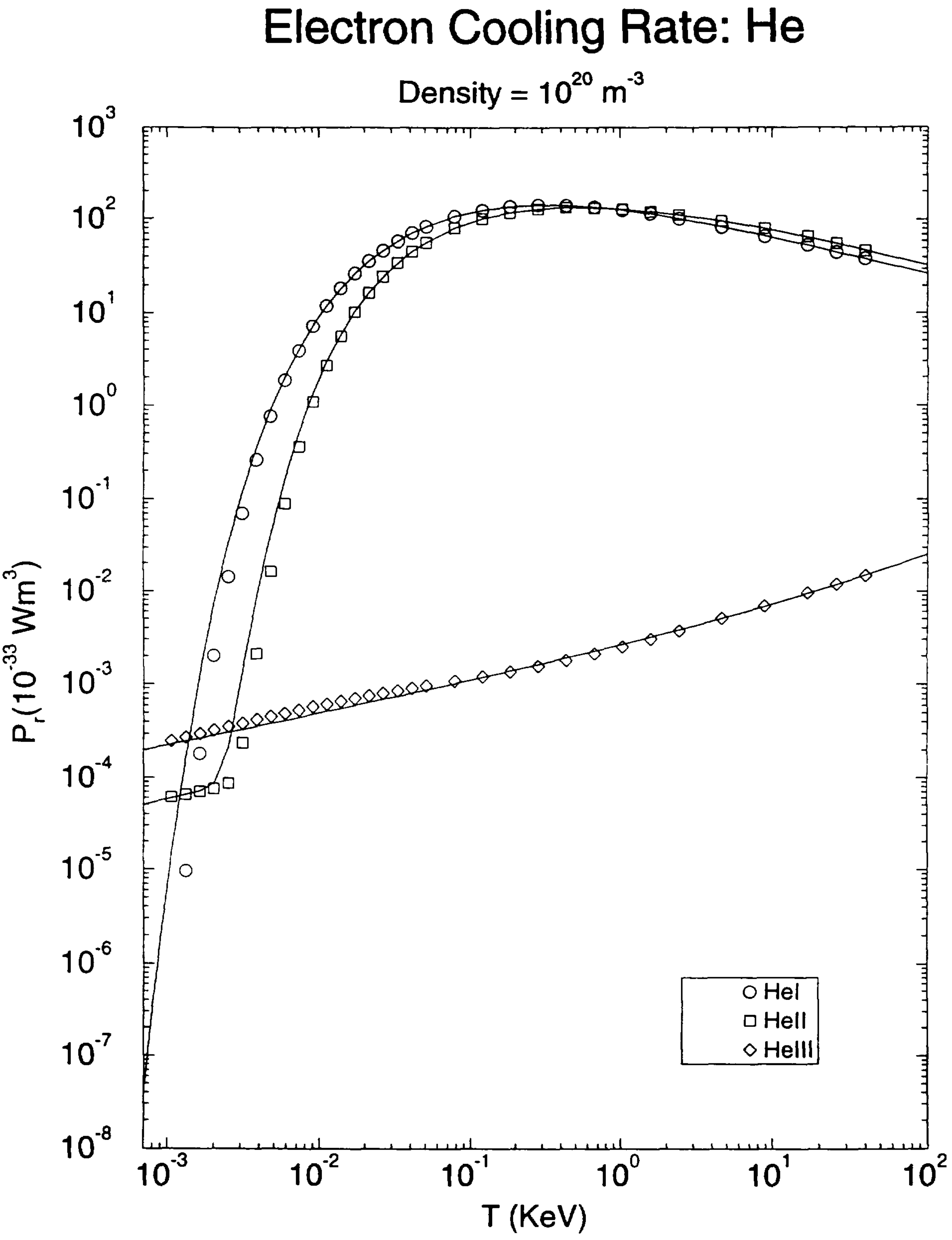
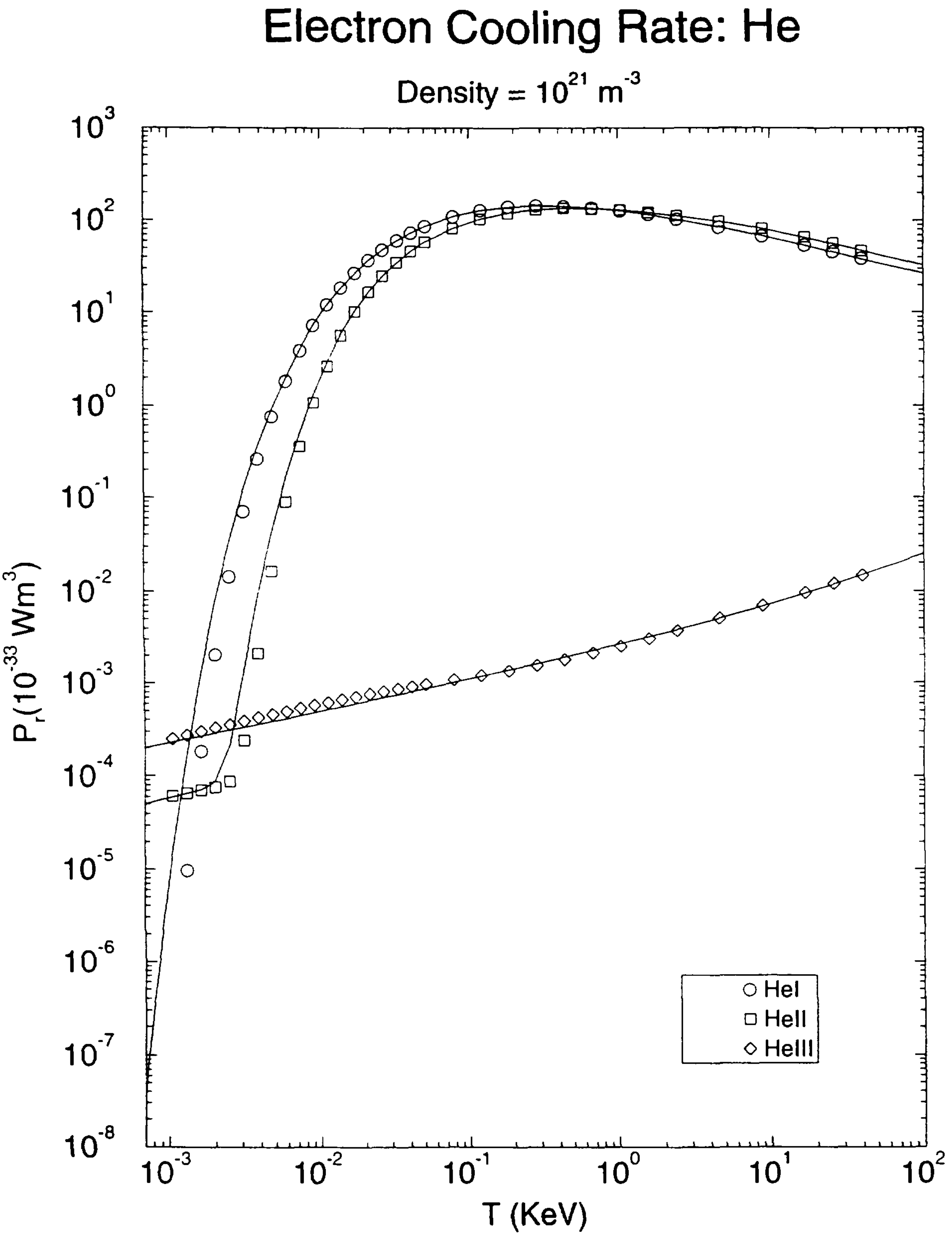

Electron Cooling Rate: He
Density = 10^19 m^-3
P_r(10^-33 Wm^3)
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-3
10^-2
10^-1
10^0
10^1
10^2
T (KeV)
○ HeI
□ HeII
◇ HeIII

**Figure 7**



Electron Cooling Rate: He
Density = $10^{20}$ $m^{-3}$
$P_r(10^{-33}$ $Wm^3)$
$10^3$
$10^2$
$10^1$
$10^0$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
$10^{-8}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
$10^0$
$10^1$
$10^2$
T (KeV)
○ HeI
□ HeII
◇ HeIII

**Figure 8**



Electron Cooling Rate: He
Density = $10^{21}$ m$^{-3}$
$P_r(10^{-33}$ Wm$^3)$
T (KeV)
$10^3$
$10^2$
$10^1$
$10^0$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
$10^{-8}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
$10^0$
$10^1$
$10^2$
○ HeI
□ HeII
◇ HeIII

**Figure 9**

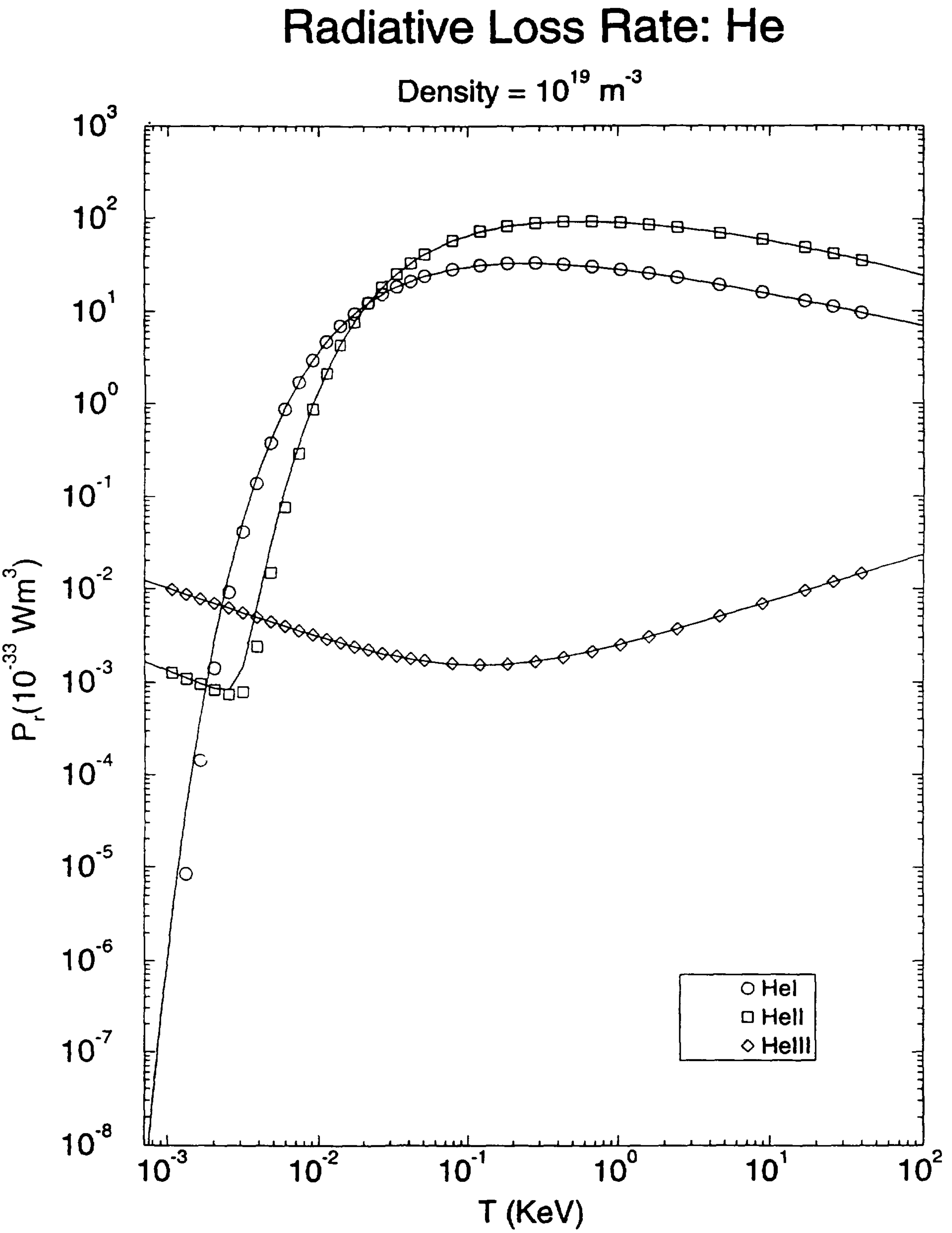

Radiative Loss Rate: He
Density = $10^{19}$ $m^{-3}$
$P_r(10^{-33}\ Wm^3)$
$10^3$
$10^2$
$10^1$
$10^0$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
$10^{-8}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
$10^0$
$10^1$
$10^2$
T (KeV)
○ HeI
□ HeII
◇ HeIII

**Figure 10**

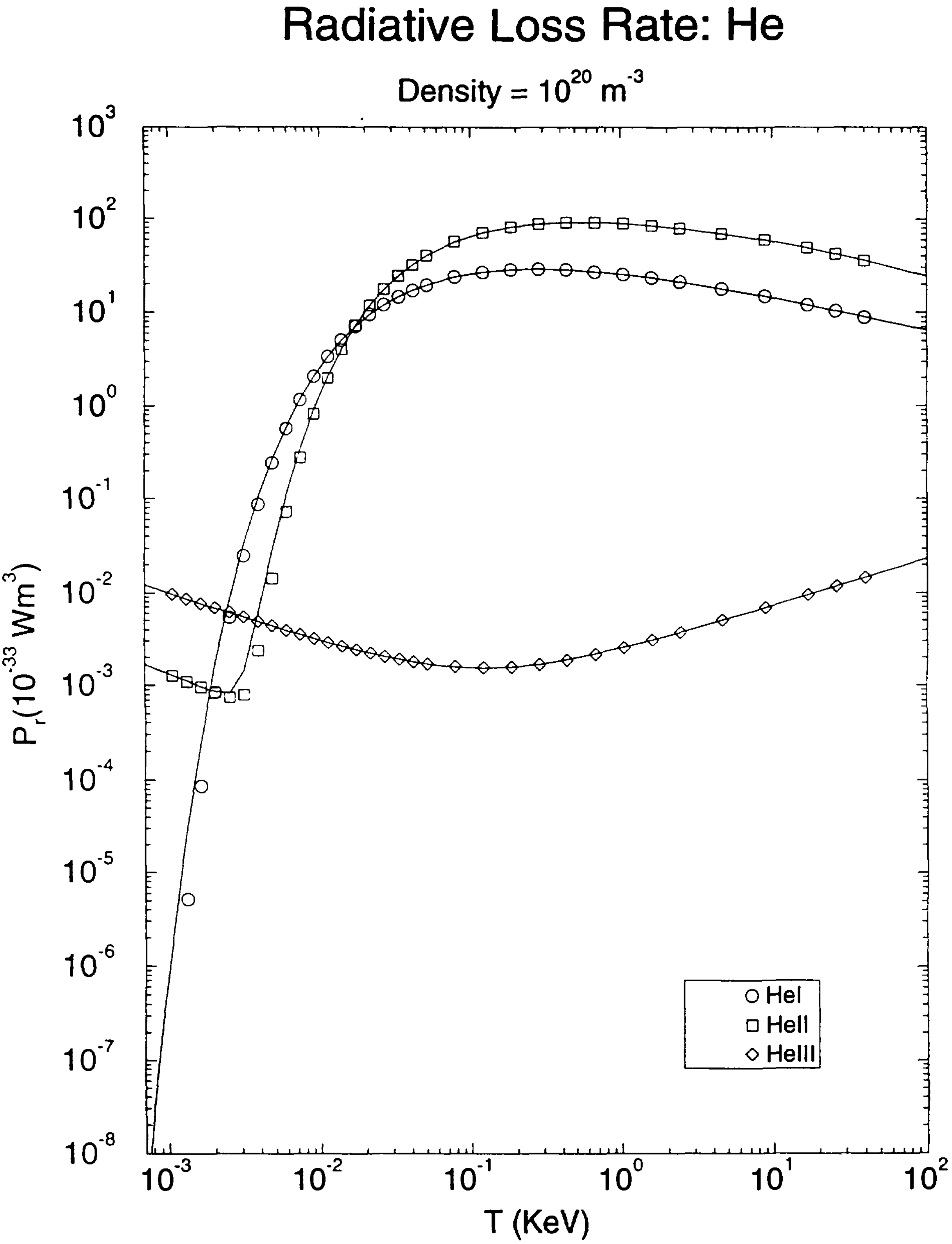

Radiative Loss Rate: He
Density = $10^{20}$ $m^{-3}$
$P_r(10^{-33} Wm^3)$
$10^{3}$
$10^{2}$
$10^{1}$
$10^{0}$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
$10^{-8}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
$10^{0}$
$10^{1}$
$10^{2}$
T (KeV)
○ HeI
□ HeII
◇ HeIII

**Figure 11**

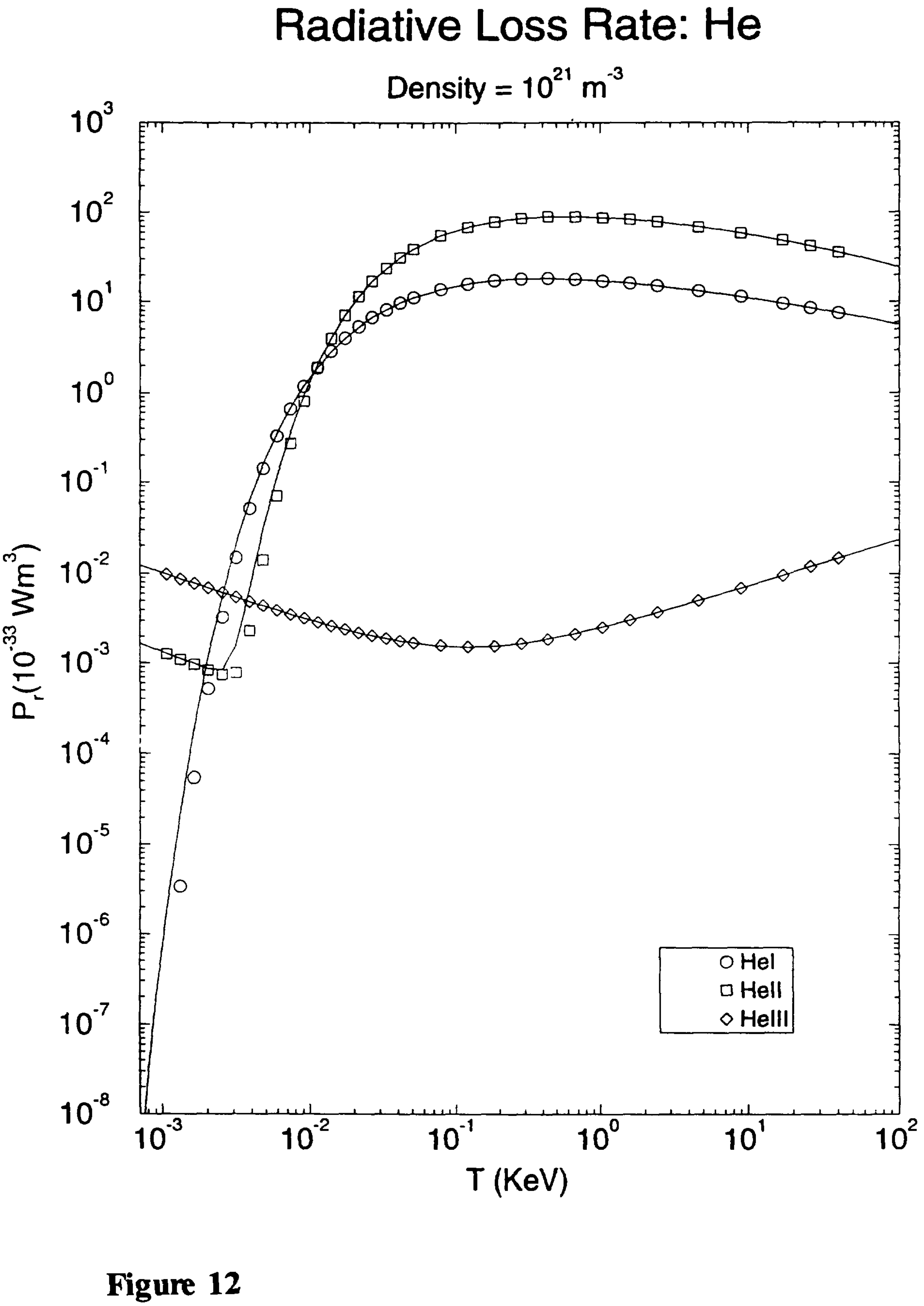

Radiative Loss Rate: He
Density = $10^{21}$ $m^{-3}$
$P_r(10^{-33}$ $Wm^3)$
$10^3$
$10^2$
$10^1$
$10^0$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
$10^{-8}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
$10^0$
$10^1$
$10^2$
T (KeV)
○ HeI
□ HeII
◇ HeIII

**Figure 12**

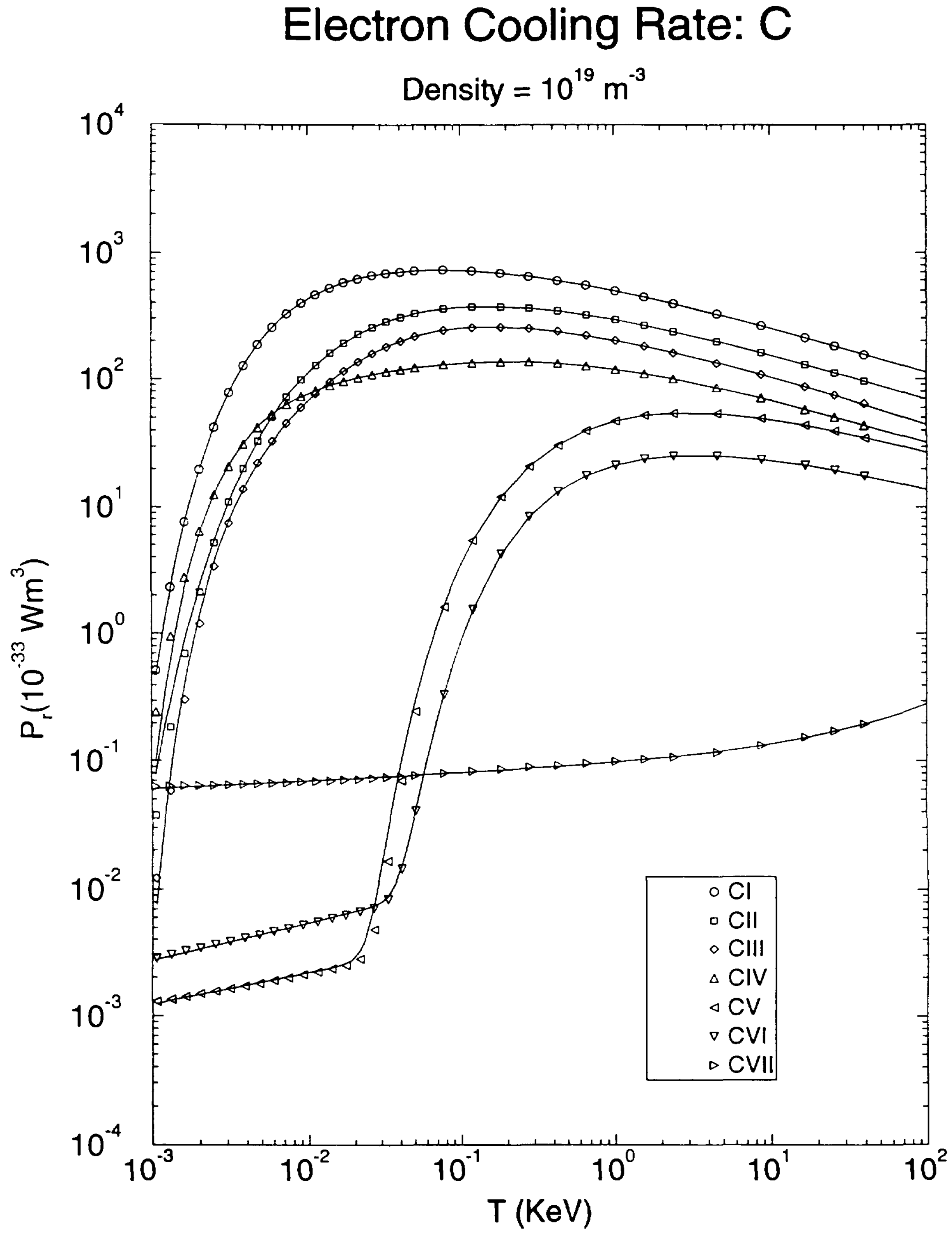

Electron Cooling Rate: C
Density = $10^{19}$ $m^{-3}$
$P_r(10^{-33}\ Wm^3)$
$10^4$
$10^3$
$10^2$
$10^1$
$10^0$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
$10^0$
$10^1$
$10^2$
T (KeV)
○ CI
□ CII
◇ CIII
△ CIV
◁ CV
▽ CVI
▷ CVII

**Figure 13**

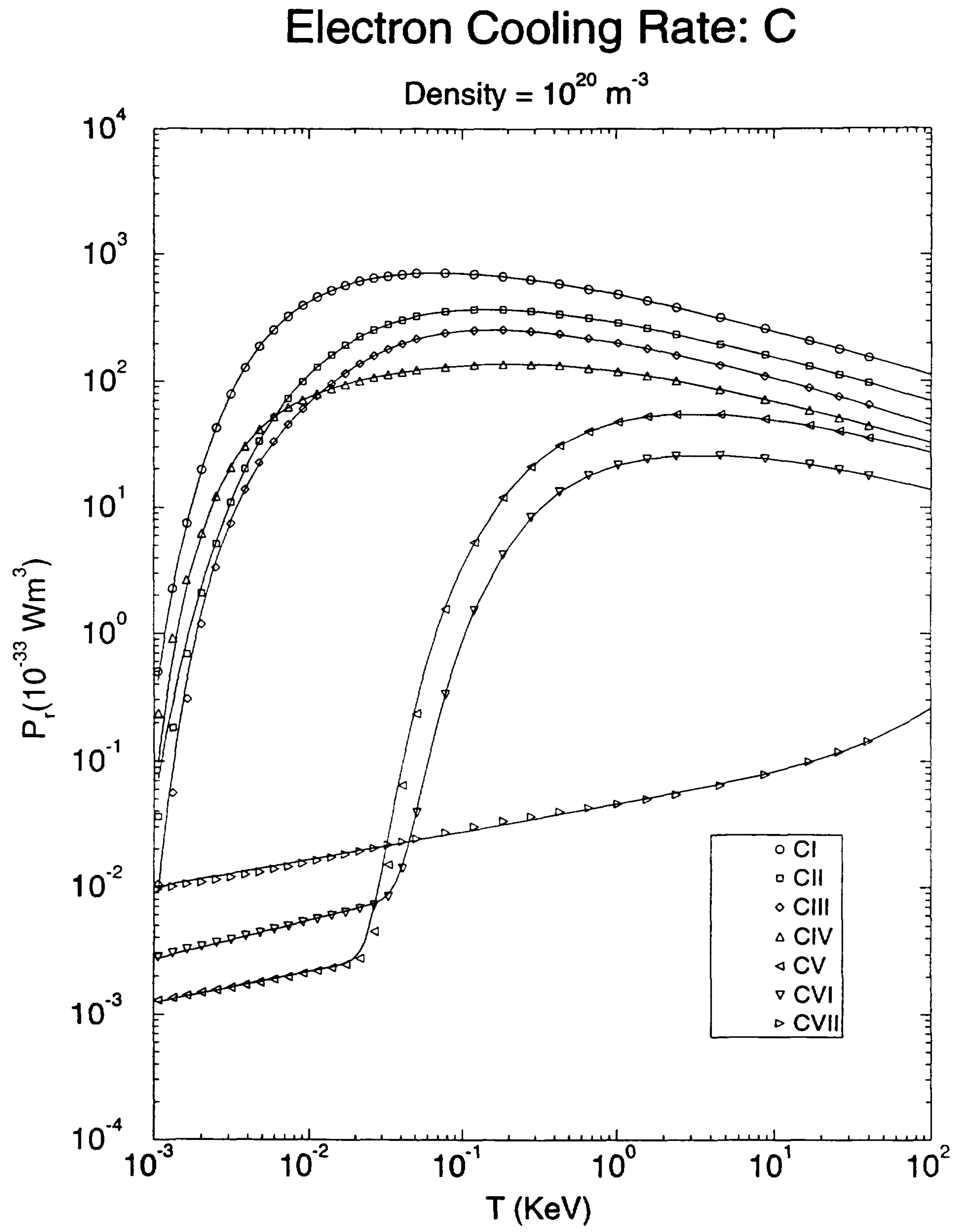
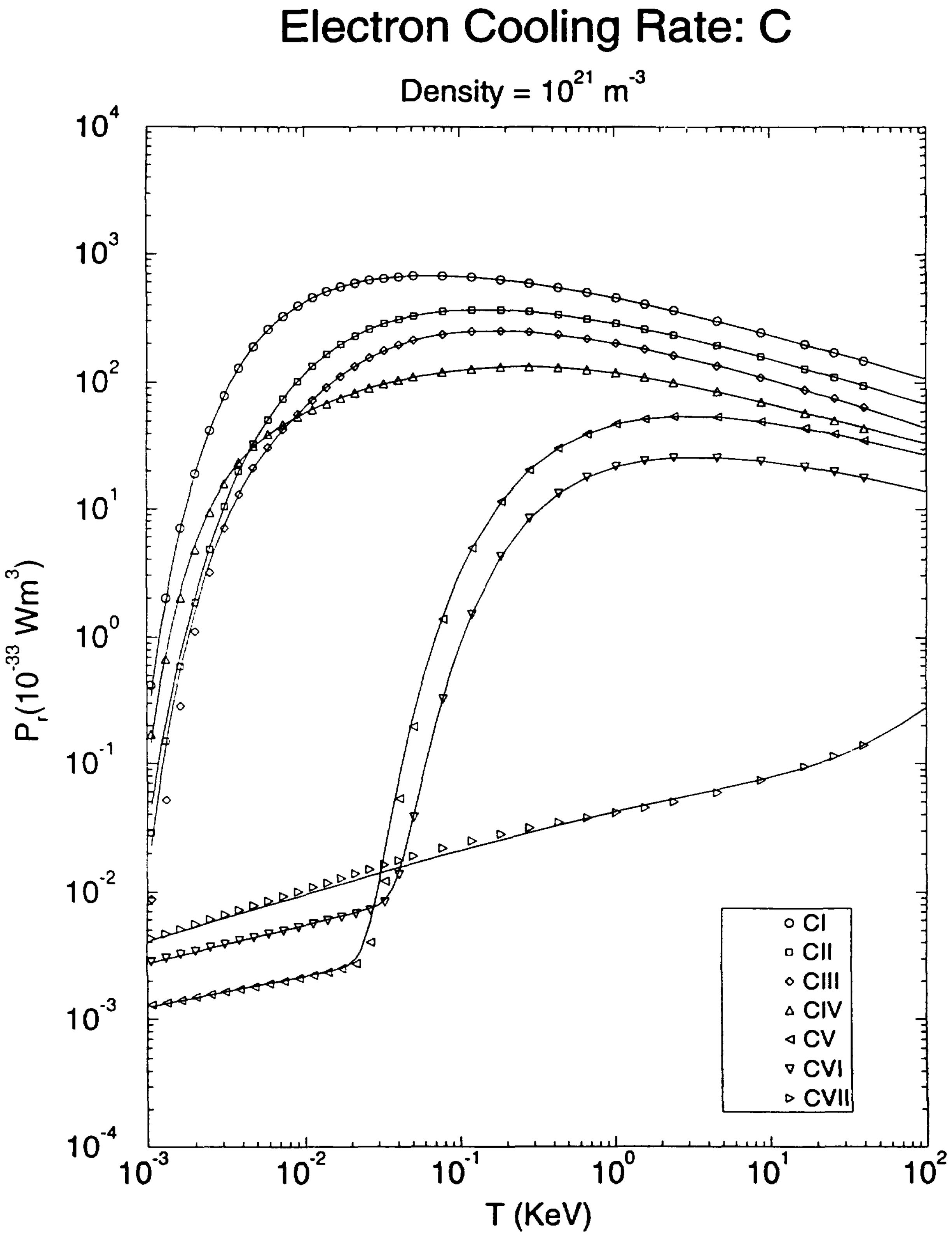

Electron Cooling Rate: C
Density = $10^{20}$ $m^{-3}$
$10^4$
$10^3$
$10^2$
$10^1$
$10^0$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$P_r(10^{-33}\ Wm^3)$
$10^{-3}$
$10^{-2}$
$10^{-1}$
$10^0$
$10^1$
$10^2$
T (KeV)
○ CI
□ CII
◇ CIII
△ CIV
◁ CV
▽ CVI
▷ CVII

**Figure 14**



Electron Cooling Rate: C
Density = 10^21 m^-3
P_r(10^-33 Wm^3)
T (KeV)
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-3
10^-2
10^-1
10^0
10^1
10^2
○ CI
□ CII
◇ CIII
△ CIV
◁ CV
▽ CVI
▷ CVII

**Figure 15**

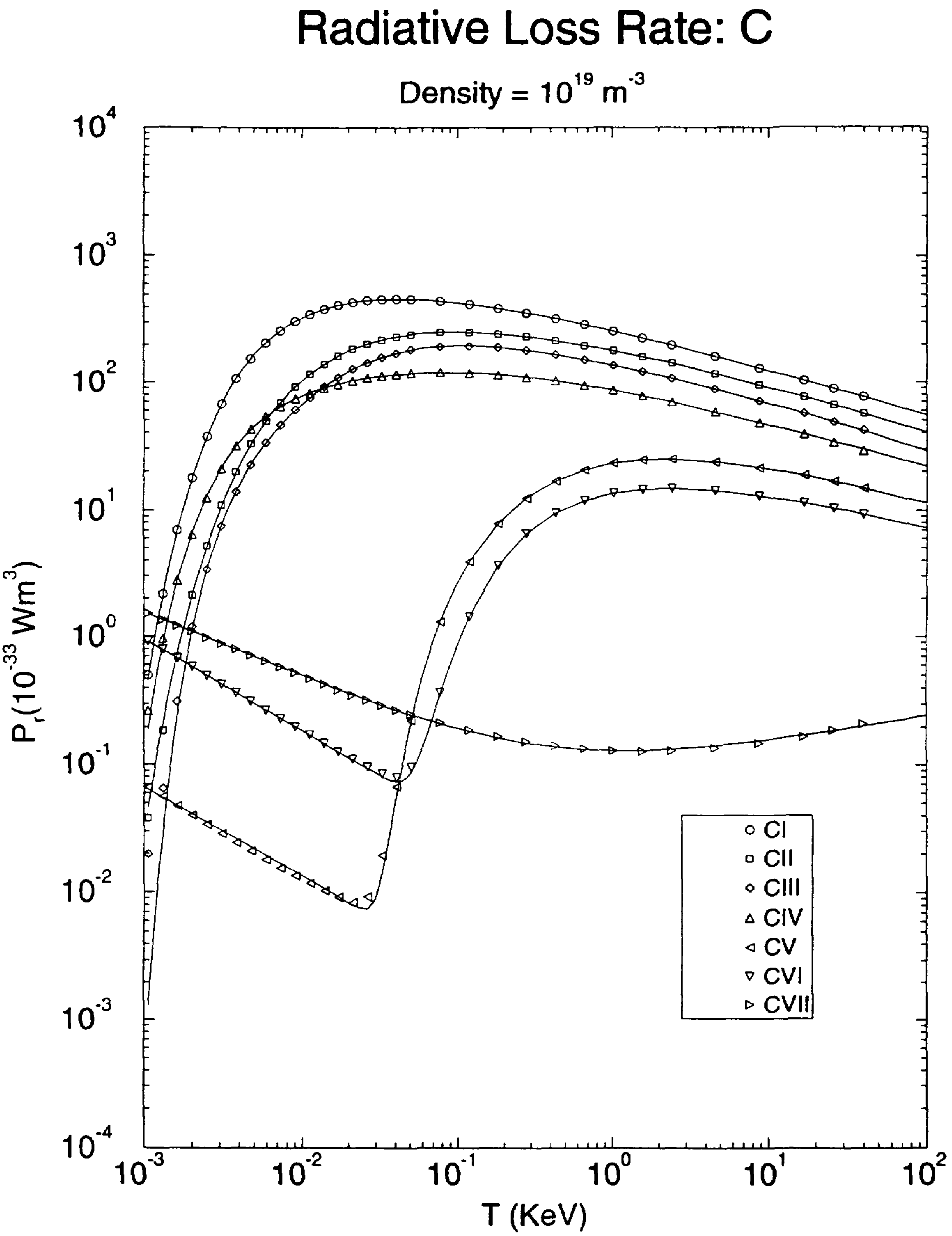

Radiative Loss Rate: C
Density = $10^{19}$ $m^{-3}$
$P_r(10^{-33}$ $Wm^3)$
$10^4$
$10^3$
$10^2$
$10^1$
$10^0$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
$10^0$
$10^1$
$10^2$
T (KeV)
○ CI
□ CII
◇ CIII
△ CIV
◁ CV
▽ CVI
▷ CVII

**Figure 16**

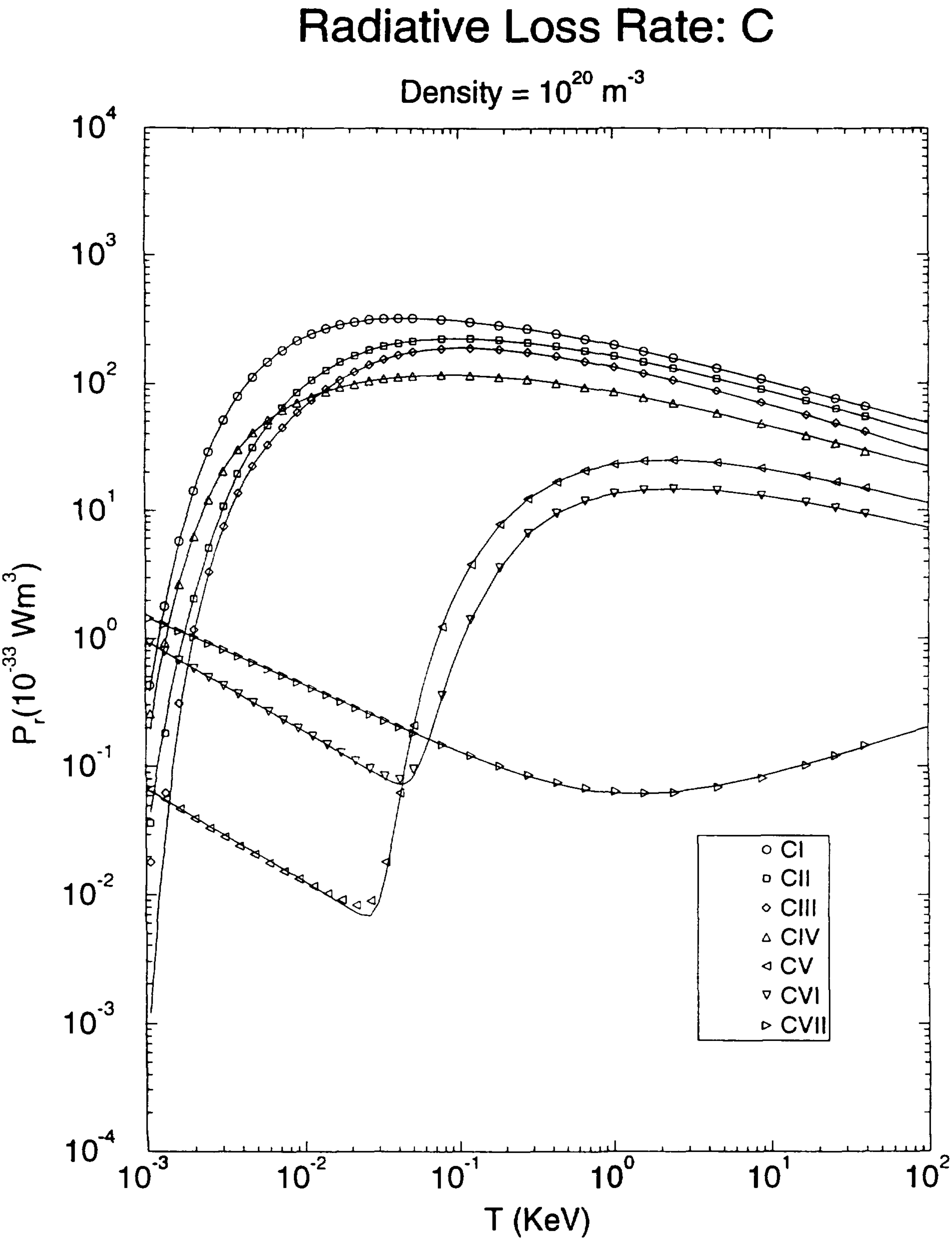
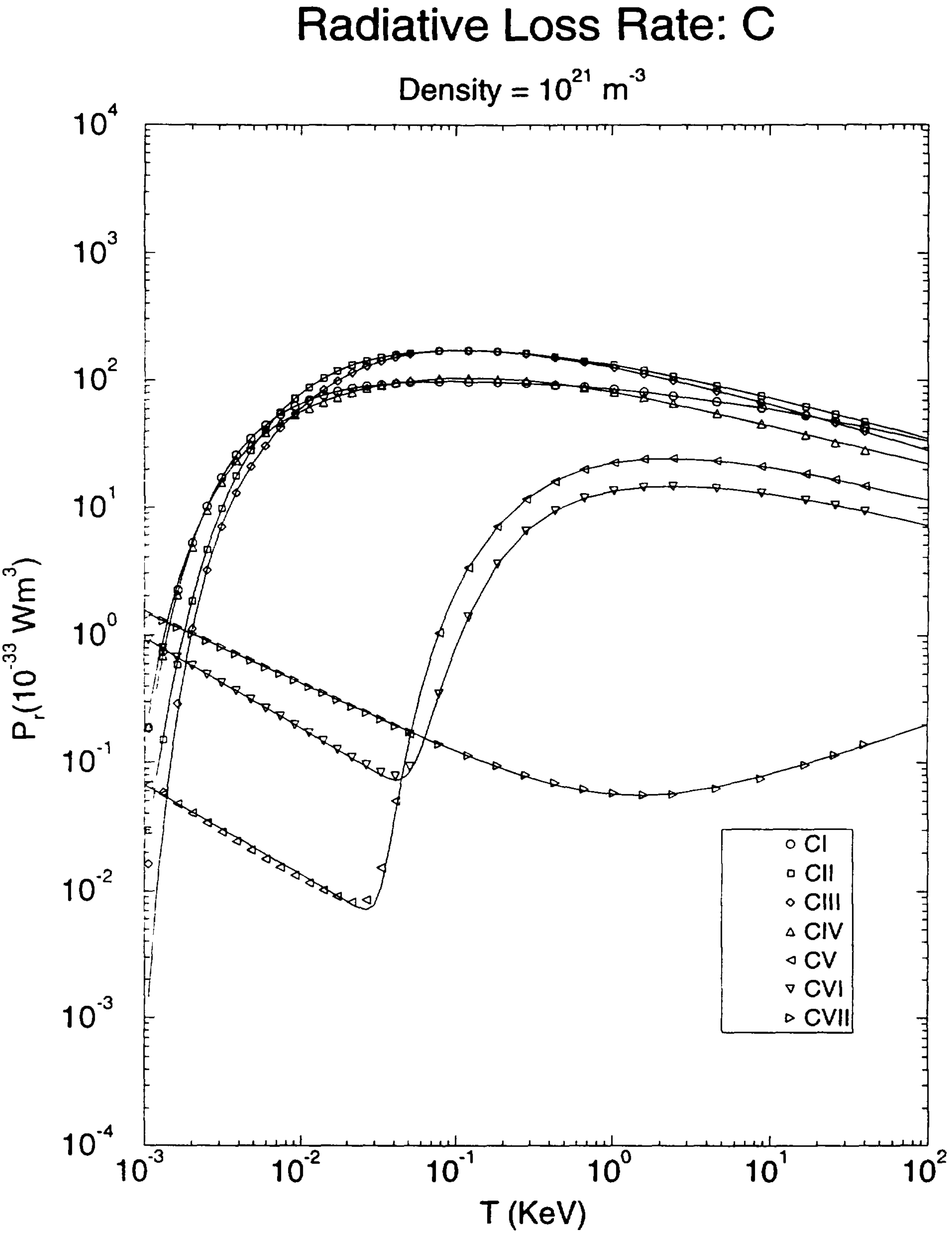

Radiative Loss Rate: C
Density = $10^{20}$ $m^{-3}$
$P_r(10^{-33}$ $Wm^3)$
$10^4$
$10^3$
$10^2$
$10^1$
$10^0$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
$10^0$
$10^1$
$10^2$
T (KeV)
○ CI
□ CII
◇ CIII
△ CIV
◁ CV
▽ CVI
▷ CVII

**Figure 17**



Radiative Loss Rate: C
Density = $10^{21}$ $m^{-3}$
$P_r(10^{-33}$ $Wm^3)$
T (KeV)
$10^{4}$
$10^{3}$
$10^{2}$
$10^{1}$
$10^{0}$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
$10^{0}$
$10^{1}$
$10^{2}$
○ CI
□ CII
◇ CIII
△ CIV
◁ CV
▽ CVI
▷ CVII

**Figure 18**

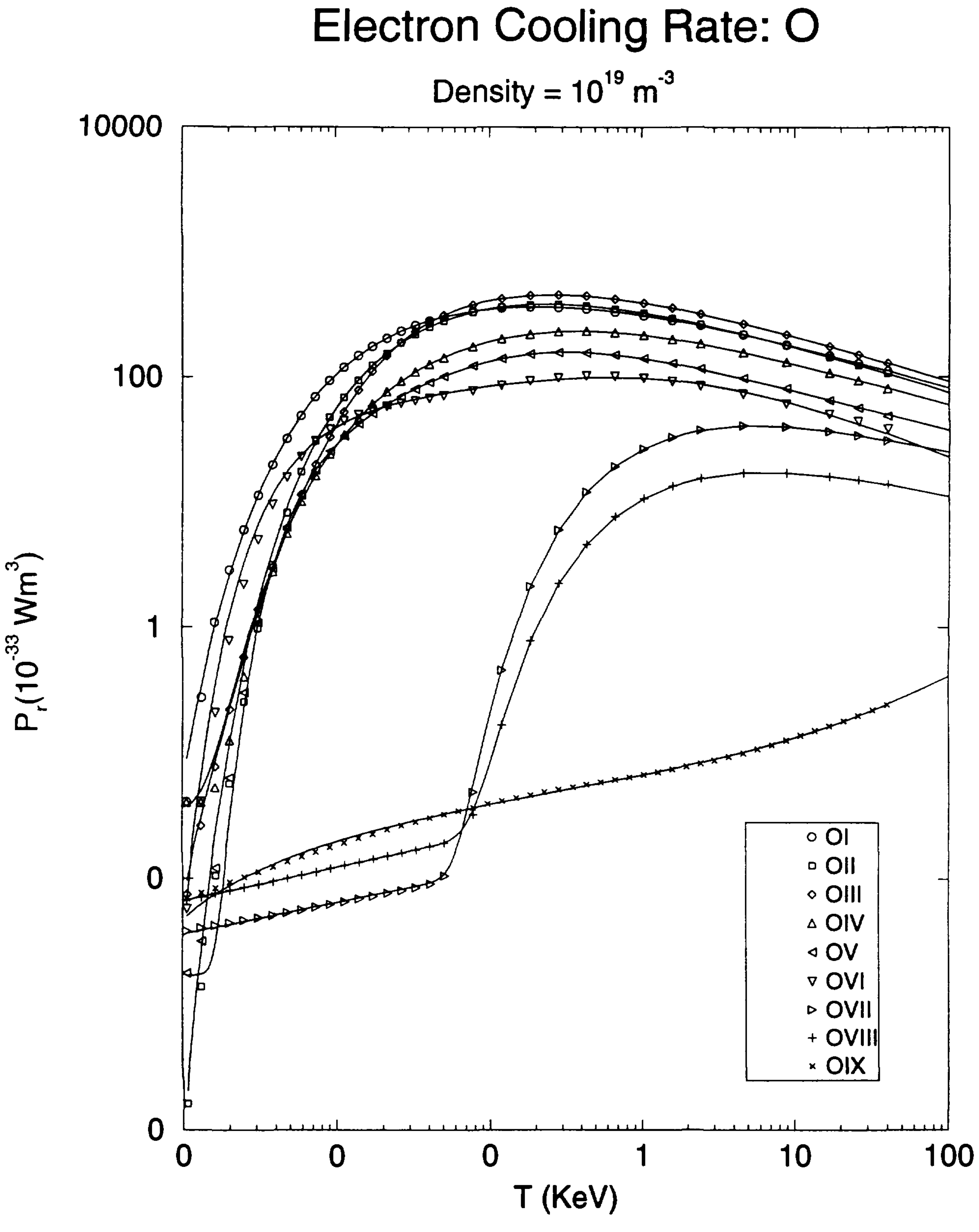

Electron Cooling Rate: O
Density = $10^{19}$ $m^{-3}$
$P_r(10^{-33} Wm^3)$
10000
100
1
0
0
T (KeV)
0
0
0
1
10
100
○ OI
□ OII
◇ OIII
△ OIV
◁ OV
▽ OVI
▷ OVII
+ OVIII
× OIX

Figure 19

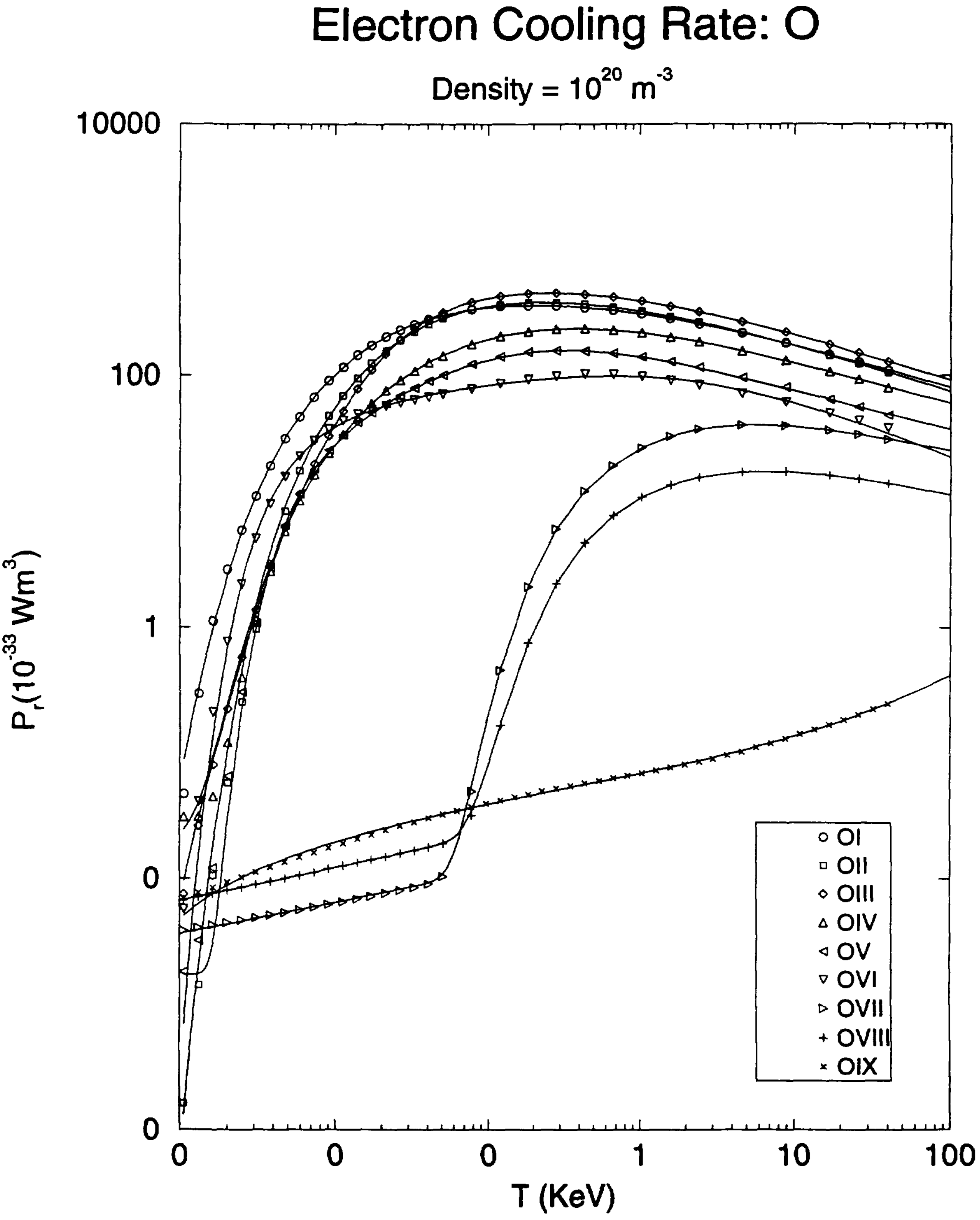

Electron Cooling Rate: O
Density = $10^{20}$ $m^{-3}$
10000
100
1
0
0
$P_r(10^{-33}\ Wm^3)$
0
0
0
1
10
100
T (KeV)
○ OI
□ OII
◇ OIII
△ OIV
◁ OV
▽ OVI
▷ OVII
+ OVIII
× OIX

**Figure 20**

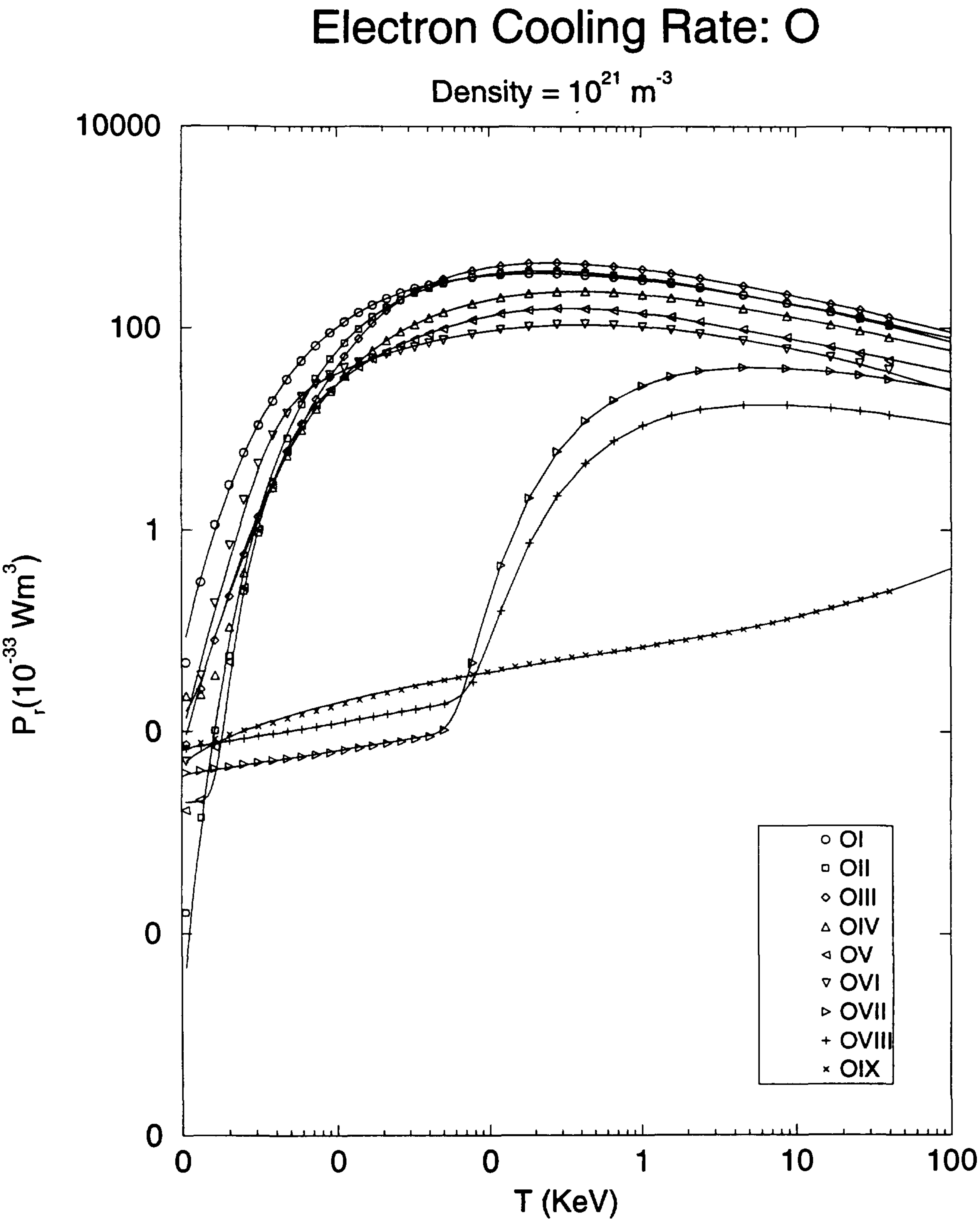

Electron Cooling Rate: O
Density = $10^{21}$ m$^{-3}$
10000
100
1
0
0
0
$P_r(10^{-33}$ Wm$^3)$
0
0
0
1
10
100
T (KeV)
○ OI
□ OII
◇ OIII
△ OIV
◁ OV
▽ OVI
▷ OVII
+ OVIII
× OIX

**Figure 21**

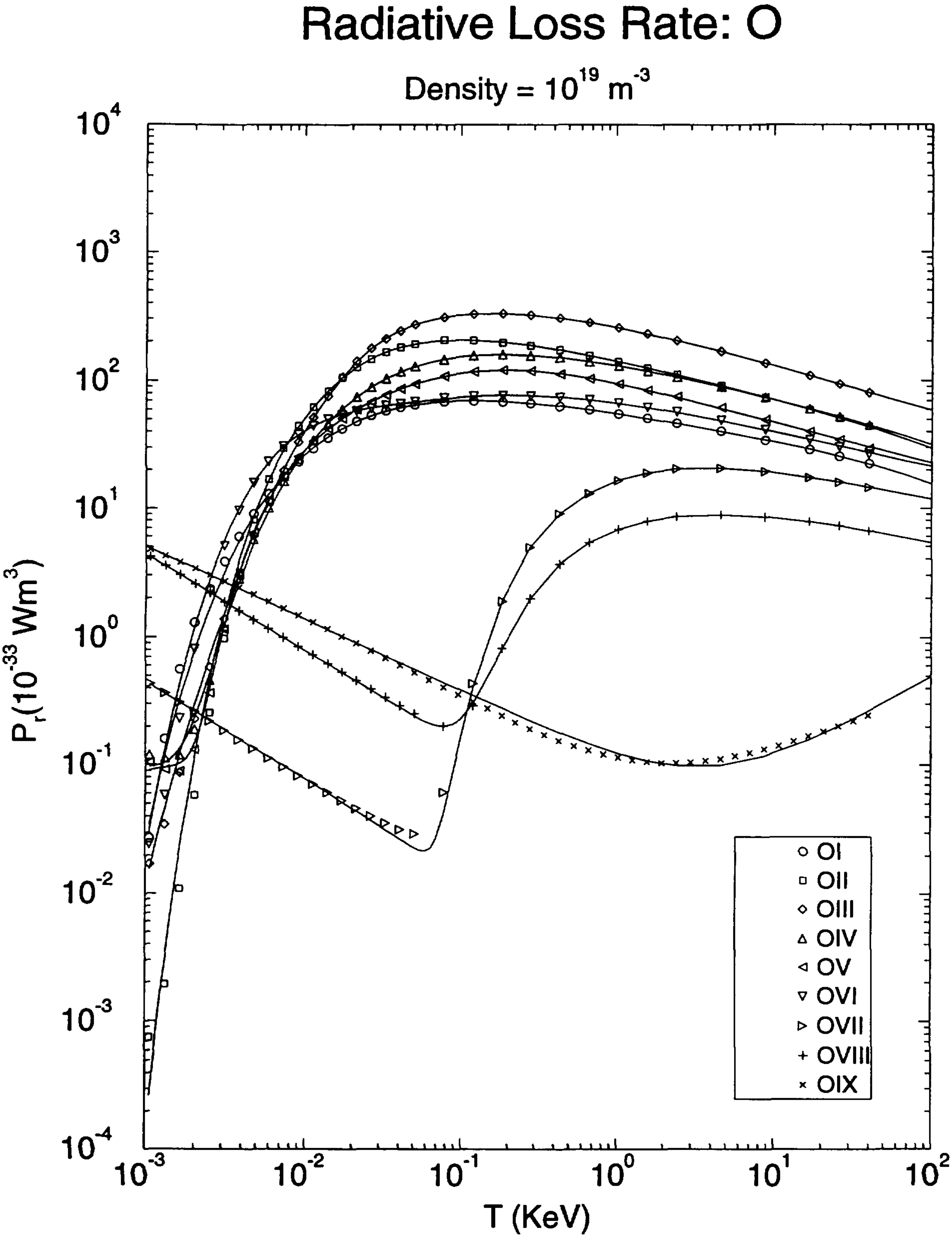

Radiative Loss Rate: O
Density = $10^{19}$ $m^{-3}$
$P_r(10^{-33}\,Wm^3)$
$10^4$
$10^3$
$10^2$
$10^1$
$10^0$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
$10^0$
$10^1$
$10^2$
T (KeV)
○ OI
□ OII
◇ OIII
△ OIV
◁ OV
▽ OVI
▷ OVII
+ OVIII
× OIX

**Figure 22**

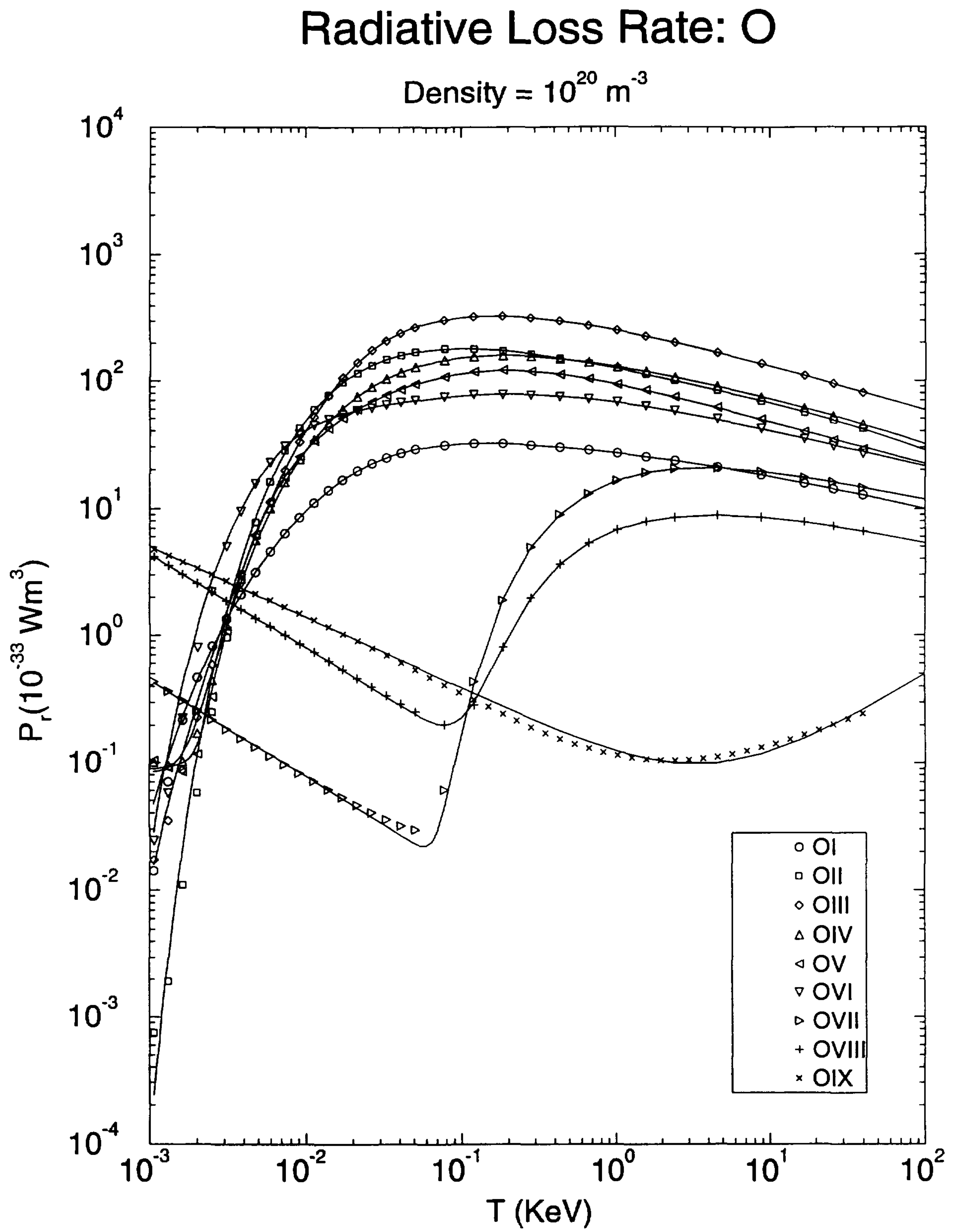

Radiative Loss Rate: O
Density = $10^{20}$ m$^{-3}$
$10^{4}$
$10^{3}$
$10^{2}$
$10^{1}$
$10^{0}$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$P_r(10^{-33}\,Wm^3)$
$10^{-3}$
$10^{-2}$
$10^{-1}$
$10^{0}$
$10^{1}$
$10^{2}$
T (KeV)
OI
OII
OIII
OIV
OV
OVI
OVII
OVIII
OIX

**Figure 23**

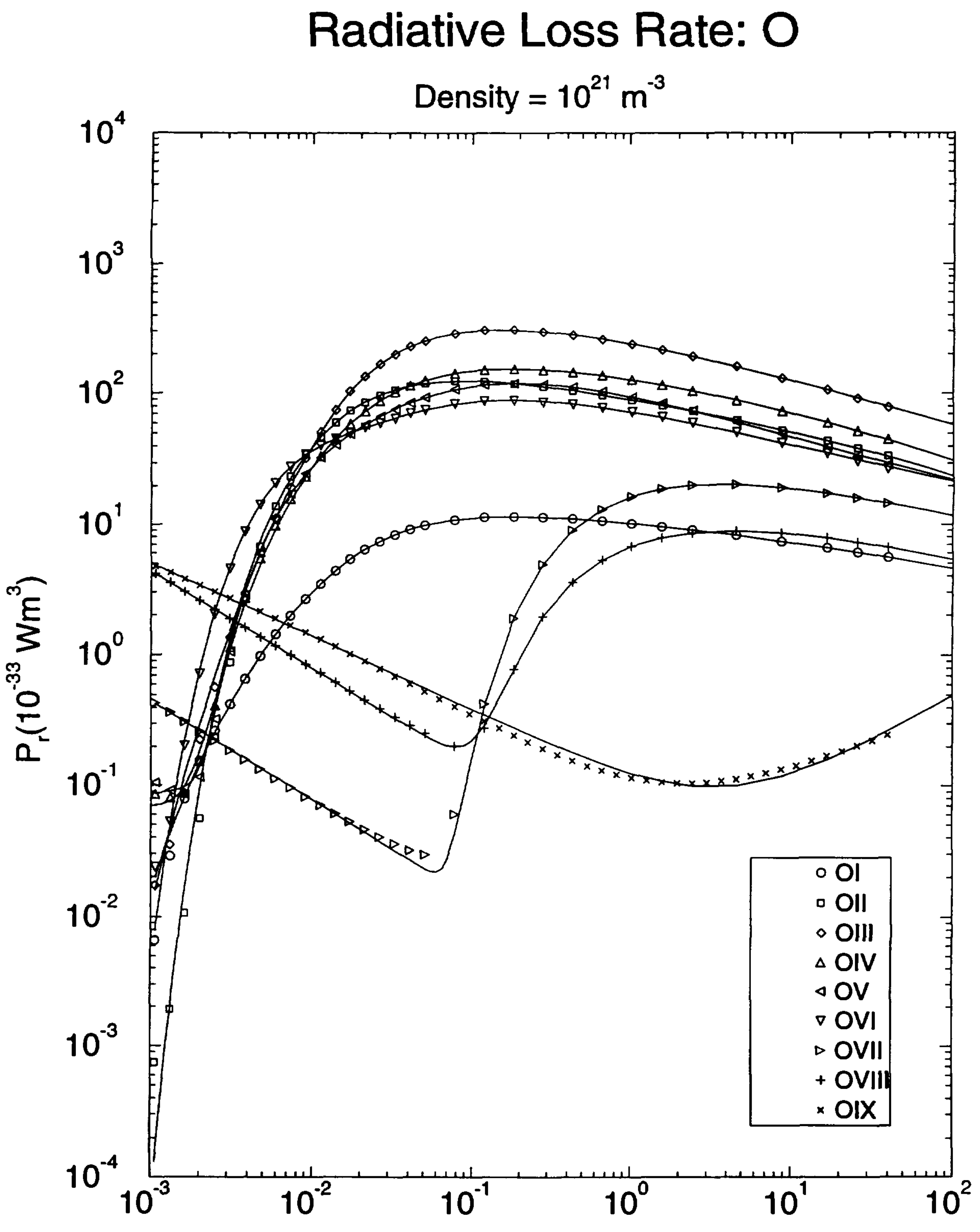

Radiative Loss Rate: O
Density = 10^21 m^-3
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
P_r(10^-33 Wm^3)
10^-3
10^-2
10^-1
10^0
10^1
10^2
T (KeV)
○ OI
□ OII
◇ OIII
△ OIV
◁ OV
▽ OVI
▷ OVII
+ OVIII
× OIX

**Figure 24**