ξ

γ

-1

$\sqrt{Ln}$

L

n

$\geq 10^9 K$

$\leq 3000K$

10^9K

10^{18}

-3

10^{12}

10^{16}

1.5×10^{24}

-2

10^{34}

-5

$10^4 K$

cm^{-3}

10^7

E^{α}

10^{38}

$n = P/(kT)$

$\Delta R_{max} = N/n$

$2.3n$

ε

α

$L_\varepsilon \sim \varepsilon^\alpha$

L_ε

$\varepsilon L_\varepsilon$

νF_ν

N

10^{21}

$\xi = L/(nR^2)$

$\Xi = L/(4\pi c R^2 P)$

1.0

$(0.0 \ldots 100.0)$

$$A(\varepsilon) = \varepsilon^3/(\exp(\varepsilon/kT) - 1)$$

$e - e$

$A(\varepsilon) = \varepsilon^{\alpha}$

ε^{-1}

$$\Delta R = min(\text{emult}/\kappa_max(\varepsilon), R/\text{nsteps})$$

$\kappa_m ax(\varepsilon)$

$\geq$

10^{-8}

$(v_{turb}^2 + v_{therm}^2)^{1/2}$

v_{therm}

$$n = n_0 (R/R_0)^{\mathrm{radexp}}$$

n_0

R_0

$\leq$

$$\Delta\varepsilon/\varepsilon = (40\mathrm{keV}/0.1\mathrm{eV})^{1/(0.49\mathrm{ncn}2)}$$

$\mathring{A}$

-10

$\Delta R/R$

−15

%

$(\varepsilon_{max} - \varepsilon_{min})/(4\ln(\varepsilon_{max}/\varepsilon_{min}))$

21.3

5.13

N_I

i

n_i

$(1 \leq i \leq \mathrm{N_I})$

$$\prod_{\mathrm{i=1}}^{\mathrm{N_I}} n_i$$

N_A

$$(\mathrm{N_A} + 1) \prod_{\mathrm{i=1}}^{\mathrm{N_I}} n_i$$

$(8+1)(5)(4) = 180 calls$

$M_i(x_j)$

ε_i

x_j

$$M_i(x) = \Sigma_j M_i(x_j)\omega_j$$

ω_j

y

y_{max}

$$M_i(y) = (M_i(y_{max}) - M_i(0))\frac{y}{y_{max}} + M_i(0)$$

M

$M_i(y) = e^{-\tau_i(y)}$

$\tau_i(y)$

$M_i(0)$

x_{ij}

$M_i = M_i^0 + \Sigma_j x_j M_i^j$

M_i^0

M_i^j

M_i

$$M_i = exp(-(E_i^0 + \Sigma_j x_j E_i^j))$$

$$E_i^0 = -\ln(M_i^0)$$

E_i^j

$\xi) >$

>

$/xi$

F_n^{mod}

L_{tot}^{xstar}

$$F_n^{mod} = \frac{L_\varepsilon^{xstar}}{L_{tot}^{xstar}} \frac{10^{38}}{4\pi(1\mathrm{kpc})^2} \left(\frac{\Delta\varepsilon}{\varepsilon}\right)$$

$$F_n^{mod} = \frac{L_\varepsilon^{xstar}}{L_{tot}^{xstar}} \left(\frac{\Delta\varepsilon}{\varepsilon} \right) 8.356 \times 10^{-7}$$

$$\left(\frac{\Delta\varepsilon}{\varepsilon}\right)$$

A_{nm}

κ

$$C_m^{mod} = \kappa \Sigma_n F_n^{mod} A_{nm}$$

C_m^{obs}

F_{ε}^{obs}

$$C_m^{obs} = \Sigma_n F_\varepsilon^{obs} A_{nm} \left(\frac{\Delta\varepsilon}{\varepsilon} \right)$$

$$C_m^{obs} = C_m^{mod}$$

$$\kappa = \frac{C_m^{obs}}{C_m^{mod}}$$

$$\kappa = \frac{F_{\varepsilon}^{obs}\left(\frac{\Delta\varepsilon}{\varepsilon}\right)}{F_{n}^{mod}}$$

f

$F_{\varepsilon}^{obs} = fL_{\varepsilon}^{source}/(4\pi D^2)$

L_{ε}^{source}

D

$$\kappa = f\,\frac{L_{\varepsilon}^{source}/10^{38}}{L_{\varepsilon}^{xstar}/L_{tot}^{xstar}}\,\frac{1}{D_{kpc}^{2}}$$

$$L_{\varepsilon}^{source} = L_{\varepsilon}^{xstar}$$

$$L_{tot}^{source} = L_{tot}^{xstar}$$

$$\kappa = f\,\frac{L_{tot}^{xstar}/10^{38}}{D_{kpc}^{2}}$$

$$L_{\varepsilon}^{source} = L_{\varepsilon}^{xstar} L_{tot}^{source} / L_{tot}^{xstar}$$

$$\kappa = f\,\frac{L_{tot}^{source}/10^{38}}{D_{kpc}^{2}}$$

Γ

$LMODDIR:$

$$\kappa = \frac{\mathrm{EM}}{4\pi D^2} \times 10^{-10}$$

C

$\leq C \leq$

$C \geq$

$2 - C$

$C = 2$

$\sim$

$\Gamma = 2$

$L_{0\varepsilon} = Lf_{\varepsilon}$

f_ε

$\int_0^\infty f_\varepsilon d\varepsilon = 1$

$f_\varepsilon \sim \exp(-\varepsilon/kT)$

$f_\varepsilon \sim \varepsilon^3/[\exp(\varepsilon/kT) - 1]$

$f_\varepsilon \sim \varepsilon^\alpha$

$\xi = L/nR^2$

R

$U_H = F_H/n$

F_H

$\Gamma = F_\nu(\nu_L)/(2hcn)$

$F_{\nu}(\nu_L)$

$\Xi = L/(4\pi R^2 cnkT)$

P

$(Ln)^{1/2}$

Ln

τ_e

$\tau_e \leq 0.3$

$\leq 10^{24}$

ϵ

$\epsilon = 10^{-8}$

$$(rate\ in) = (rate\ out)$$

$\sim \kappa^{-1}$

$$R_{lu} = \sigma_{line} F_{\varepsilon}$$

σ_{line}

F_ε

$(Heating) = (Cooling)$.

$$n_e\Gamma_e = \frac{\sigma_T}{m_e c^2}\left(\int \varepsilon J_\varepsilon d\varepsilon - 4kT\int J_\varepsilon d\varepsilon\right)(1)$$

σ_T

n_e

J_ε

$$n_e\Gamma_e = 1.42 \times 10^{-27} T^{1/2} z^2 n_e n_z \text{ ergs cm}^{-3}\text{s}^{-1}, (2)$$

n_z

$T^{1/2}$

n_∞

$$\alpha_i = (\frac{n_i}{n_{i+1}n_e})^* \int_{\varepsilon_{th}}^{\infty} \frac{d\varepsilon}{\varepsilon} \frac{\varepsilon^3}{h^3 c^2} \sigma_{pi} e^{(\varepsilon_{th}-\varepsilon)/kT} (3)$$

$n_i{}^*$

$$j_\varepsilon = n_{upper} n_e (\frac{n_i}{n_{i+1} n_e})^* \frac{\varepsilon^3}{h^3 c^2} \sigma_{pi} e^{(\varepsilon_{th} - \varepsilon)/kT} (4)$$

n_{upper}

σ_{pi}

$$P_{esc.,cont.} = \frac{1}{1000\tau_{cont.} + 1} \quad (5)$$

τ_{cont}.

τ_0

$1 \leq \tau_0 \leq 10^6$

$\tau_0 \geq 10^6$

$$P_{esc.,line}(\tau_{line}) = \frac{1}{\tau_{line}\sqrt{\pi}(1.2+b)}(\tau_{line} \geq 1)(6)$$

$$P_{esc.,line}(\tau_{line}) = \frac{1 - e^{-2\tau_{line}}}{2\tau_{line}}(\tau_{line} \leq 1)(7)$$

$$b = \frac{\sqrt{\log(\tau_{line})}}{1 + \tau_{line}/\tau_w} (8)$$

τ_{line}

$\tau_w = 10^5$

$$j_\varepsilon = \frac{1}{4\pi} n_z n_e \frac{32 Z^2 e^4 h}{3 m^2 c^3} \left(\frac{\pi h \nu_0}{3kT}\right)^{1/2} e^{-h\nu/kT} g_{ff}(T, Z, r) (9)$$

g_{ff}

$$H\left(\frac{\varepsilon}{\varepsilon_0}\right) = 12\left(\frac{\varepsilon}{\varepsilon_0}\right)^2\left(1 - \frac{\varepsilon}{\varepsilon_0}\right) \quad (10)$$

ε_0

$\sim 10^5$

$m_e c^2$

$\sim 10^{23}$

$\kappa(\varepsilon)$

$$L_\varepsilon = \int_{R_{inner}}^{R_{outer}} 4\pi R^2 j_\varepsilon(R) e^{-\tau_{cont.}(R,\varepsilon)} dR (11)$$

$\tau_{cont.}(R, \varepsilon)$

j_ε

$j_\varepsilon(R)$

L_i

$L_{\varepsilon}^{(1)}$

$$\frac{\mathrm{d}L_{\varepsilon}^{(1)}}{\mathrm{d}R} = -\kappa_{cont}(\varepsilon)L_{\varepsilon}^{(1)} + 4\pi R^2 j_{\varepsilon}(R)(12)$$

$L_{\varepsilon}^{(1)} = L_{\varepsilon}^{(inc)}$

$\kappa_{cont}(\varepsilon)$

j_ε

$L_{\varepsilon}^{(inc)}$

$$L_{\varepsilon}^{(2)} = L_{\varepsilon}^{(inc)} e^{-\tau_{cont}^{(tot)}(\varepsilon)} (13)$$

$\tau^{(tot)}_{cont}(\varepsilon)$

$$\tau_{cont}^{(tot)}(\varepsilon) = \int_{R_{inner}}^{R_{outer}} \kappa_{cont}(\varepsilon) dR (14)$$

$$L_{\varepsilon}^{(3)} = \int_{R_{inner}}^{R_{outer}} 4\pi R^2 j_{\varepsilon}(R) e^{-\tau_{cont}^{(in)}(\varepsilon)} P_{esc,cont.}^{(in)}(R) dR \quad (15)$$

$$L_\varepsilon^{(4)} = \int_{R_{inner}}^{R_{outer}} 4\pi R^2 j_\varepsilon(R) e^{-\tau_{cont}^{(out)}(\varepsilon)} P_{esc,cont.}^{(out)}(R) dR (16)$$

$P^{(in)}_{esc,cont.}(R) = (1 - C)/2$

$$P^{(out)}_{esc,cont.}(R) = (1 + C)/2$$

$\tau_{cont}^{(out)}(\varepsilon)$

$$\frac{dL_i^{(1)}}{dR} = -\kappa_{cont}(\varepsilon)L_i^{(1)} + 4\pi R^2 j_i(R) P_{esc,line}^{(in)} \quad (16)$$

$$\frac{dL_i^{(2)}}{dR} = -\kappa_{cont}(\varepsilon) L_i^{(2)} + 4\pi R^2 j_i(R) P_{esc,line}^{(out)} (17)$$

$L_i^{(1)}$

$L_i^{(2)}$

$P_{esc.,line}(\tau_{line})$

$$P^{(in)}_{esc.,line} = (1 - C)P_{esc.,line}(\tau^{(in)}_i)$$

$$P^{(out)}_{esc,line} = (1 - C)P_{esc.,line}(\tau^{(out)}_i) + CP_{esc.,line}(\tau^{(out)}_i + \tau^{(in)}_i)/2$$

$\tau_i^{(in)}$

$\tau_i^{(out)}$

$$\tau_i^{(in)}(R) = \int_{R_{inner}}^{R} \kappa_i \mathrm{dR} \quad (18)$$

$$\tau_i^{(out)}(R) = \int_R^{R_{outer}} \kappa_i \mathrm{dR} (19)$$

κ_i

$$L_{line,\varepsilon}^{(in)} = \Sigma_{i \ni |\varepsilon_i - \varepsilon| \leq \Delta\varepsilon} \frac{L_i^{(1)} \phi(\varepsilon - \varepsilon_i)}{\Delta\varepsilon} (20)$$

$$L_{line,\varepsilon}^{(out)} = \Sigma_{i \ni |\varepsilon_i - \varepsilon| \leq \Delta\varepsilon} \frac{L_i^{(2)} \phi(\varepsilon - \varepsilon_i)}{\Delta\varepsilon} (21)$$

$$\kappa_{line}(\varepsilon) = \Sigma_{i \ni |\varepsilon_i - \varepsilon| \leq \Delta\varepsilon} \kappa_i \phi(\varepsilon - \varepsilon_i) (22)$$

ε

$\Delta\varepsilon$

$\phi(\varepsilon - \varepsilon_i)$

$$\tau^{(tot)}(\varepsilon) = \int_{R_{inner}}^{R_{outer}} (\kappa_{cont}(\varepsilon) + \kappa_{line}(\varepsilon))\mathrm{dR}(23)$$

$$L_\varepsilon^{(5)} = L_\varepsilon^{(inc)} e^{-\tau^{(tot)}(\varepsilon)} (24)$$

$$L_{\varepsilon}^{(6)} = L_{\varepsilon}^{(3)} + L_{line,\varepsilon}^{(in)} \quad (25)$$

$$L_{\varepsilon}^{(7)} = L_{\varepsilon}^{(4)} + L_{line,\varepsilon}^{(out)} \quad (26)$$

$L_\varepsilon^{(inc)}$

$L_{\varepsilon}^{(5)}$

$L_{\varepsilon}^{(6)}$

$L_{\varepsilon}^{(7)}$

$L_{\varepsilon}^{(3)}$

$L_{\varepsilon}^{(4)}$

$$\frac{\mathrm{d}L_\varepsilon^{(1')}}{\mathrm{d}R} = -\kappa_{cont}(\varepsilon)L_\varepsilon^{(1')} + 4\pi R^2 j_\varepsilon(R) + 4\pi R^2 \Sigma_{i \ni |\varepsilon_i - \varepsilon| \leq \Delta\varepsilon} \frac{j_i(R) P_{esc,line}^{(out)} \phi(\varepsilon - \varepsilon_i)}{\Delta\varepsilon} \quad (27)$$

$L_{\varepsilon}^{(1')}$

$\tau_i^{(in)}$

$\tau_i^{(out)}$

$L_{\varepsilon}^{(1')}$

$\tau^{(in)}_{cont}(\varepsilon)$

$$\int (L_\varepsilon^{(inc)} - L_\varepsilon^{(1)}) d\varepsilon - \Sigma_i (L_i^{(1)} + L_i^{(2)})$$

$L_{\varepsilon}^{(5)}$

$L_{\varepsilon}^{(6)} + L_{\varepsilon}^{(7)}$

Λ

&

10^x

χ^2

%%%%

10^4

$$rate = r1/T^{r2}$$

H^0

$$rate = r1 * e^{r2/kT}/T^{1/2}$$

ε_{line}

Z

$effective$

#

$$rate = r1 * 10^{-6} * e^{-r2/T} * (1 + r3 * e^{-r4/T})/T^{3/2}$$

$$rate = r1 * e^{-r2/kT} + r3 * (T^{-r4 - r5 * ln(T)})$$

He^0

$$rate = r1 * t * * r2 * (1. + r3 * expo(r4 * t)) * expo(-eex/t) * (1.e - 9) * xh1$$

H^+

$$\sigma = r1 * (\varepsilon / r5)^{r2}$$

$$crosssection = 10^{\Sigma_{n=1}^{n=12} C_n (ln(\varepsilon/\varepsilon_0))^{n-1} - 18}$$

$\varepsilon \leq$

Δ

C_1

C_2

$$rate = 10^{r1+r2*(log_{10}(T)+4.-r3)^2}$$

$$rate = 10^{-12} * (r1/T + r2 + T * (r3 + T * r4)) * T^{3/2} * e^{-r5/T}$$

$ch = 1./chi$

$$fchi = 0.3 * ch * (a + b * (1. + ch) + (c - (a + b * (2. + ch)) * ch) * alpha + d * beta * ch)$$

$$rate = 2.2e - 6 * sqrt(chir) * fchi * expo(-1./chir)/(e * sqrt(e))$$

$$rate = (4.1416e - 9) * r1 * t * *r2 * exp(-edelt/ekt)/gglo$$

$$rate = 2 * (2.105 \times 10^{-22}) * vth * y * \phi$$

$$term1 = (T/T0) * *(0.5)$$

$$term2 = (1. + (T/T0) * *(0.5)) * *(1. - b)$$

$$term3 = (1. + (T/T1) * *(0.5)) * *(1. + b)$$

$$rrrt = a/(1.d - 48 + term1 * term2 * term3)$$

$rate = rrrt * xnx$

$$rate = r1 * exp(-r5/1.e + 4/t) + r2 * exp(-r6/1.e + 4/t) + ...$$

$rate = rate * T^{-3/2}$

ϒ

$radiative$
ij

$Auger$
ij

$total$
ij

$Threshold$

ij

$$rate = 1.d - 6 * e1 * rho/sqrt(tt * ee * *3)$$

$e1 = E_1(E_{Th}/kT)$

rho

$r1$

rn

LS

J

nlm

nl

m

$m = 0$

0

n_{core}

l

$$n_{core} = \frac{1}{3}n(n-1)(2n-1) + 2l^2.$$

$n = 4$

$l = 1$

$n_{core} = 30$

$2S + 1$

$S = 1/2$

$L = 1$

$n \leq$

+3

$\xi \geq 2$

$\xi) \leq 1$

fig1a-eps-converted-to.pdf

fig1b-eps-converted-to.pdf

fig2-eps-converted-to.pdf

fig3a-eps-converted-to.pdf

fig3b-eps-converted-to.pdf

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fig15b-eps-converted-to.pdf

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fig16b-eps-converted-to.pdf

β

th

$\leq \log(\xi) \leq$

$Z \leq 19$

$Z \geq 21$