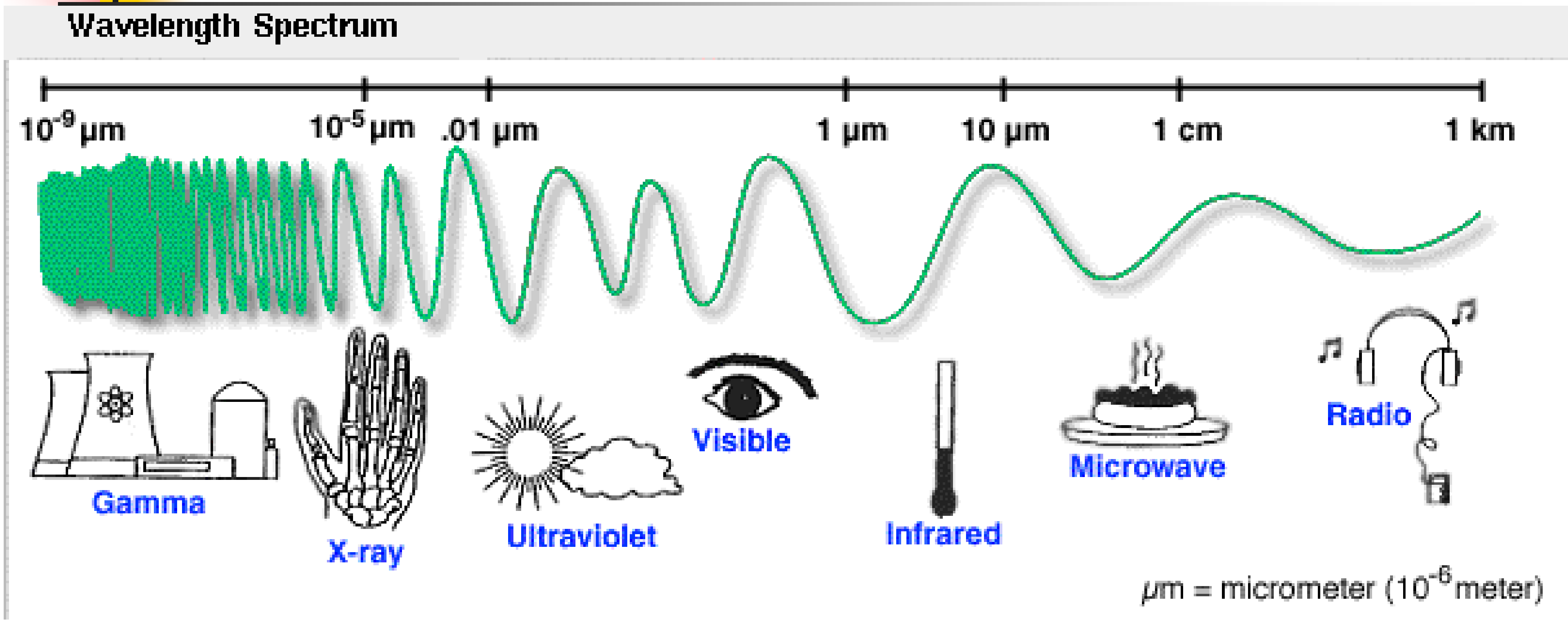
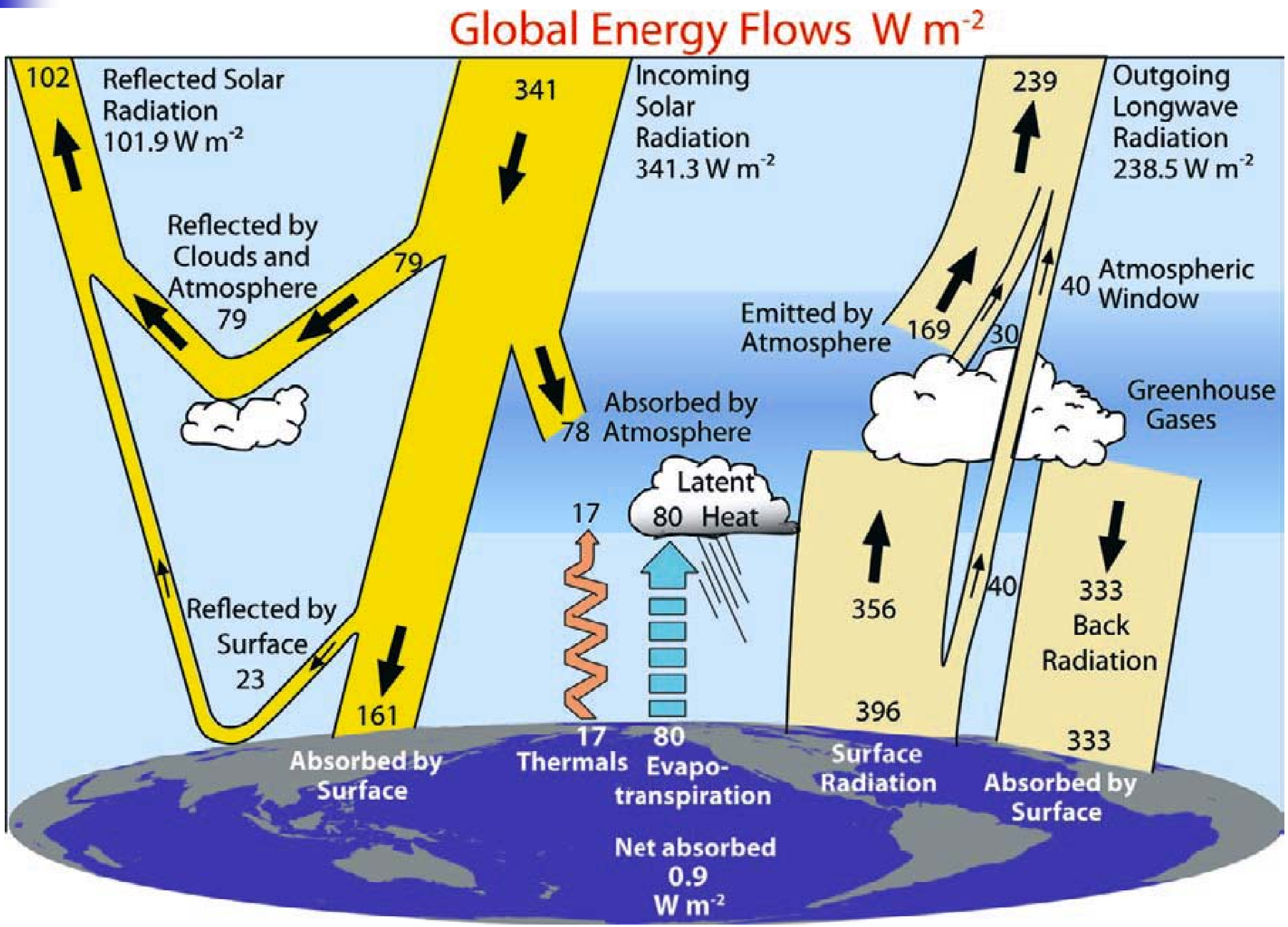
大气短波辐射传输
气溶胶的辐射效应

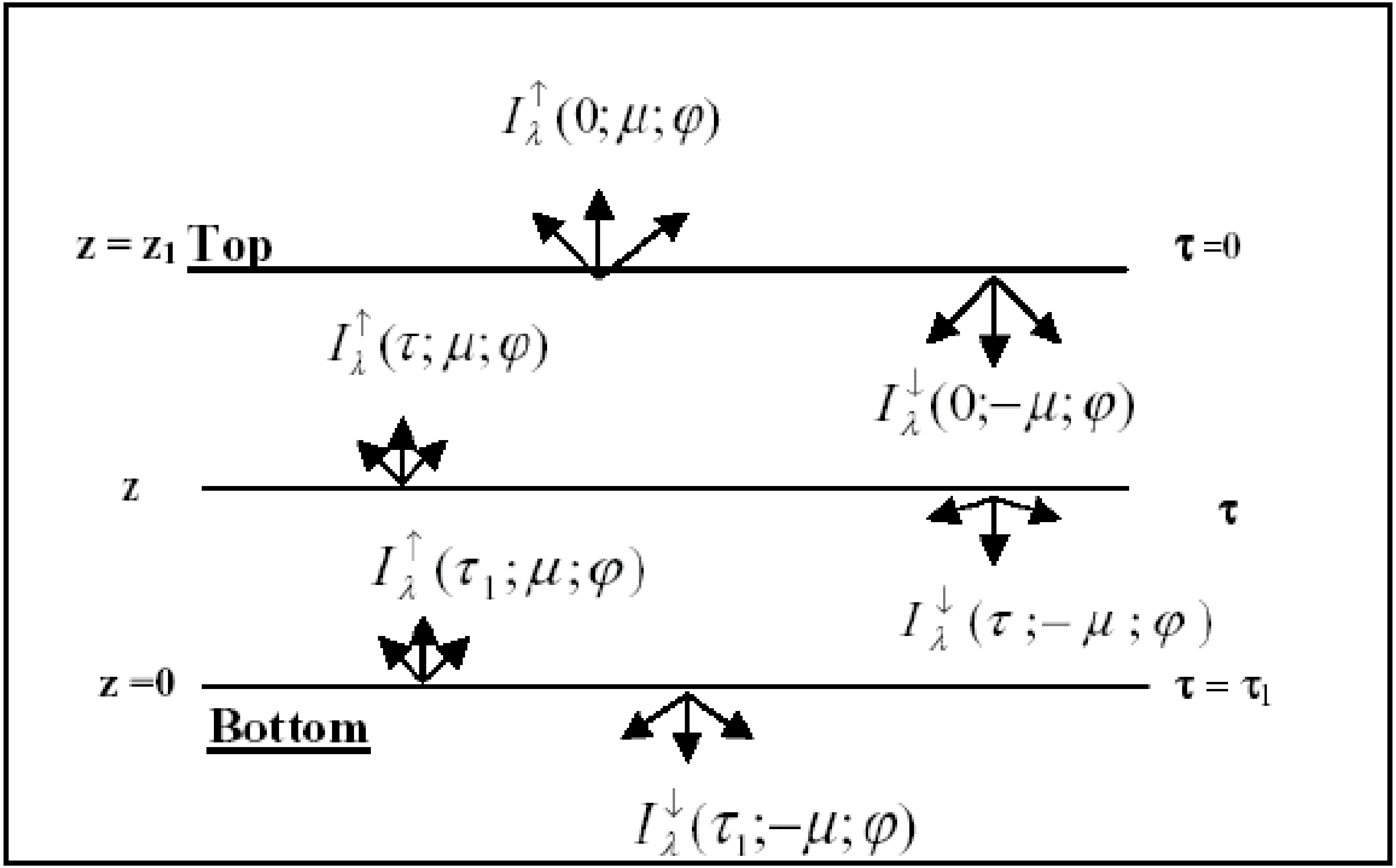
杨军 (jyang@nuist.edu.cn)





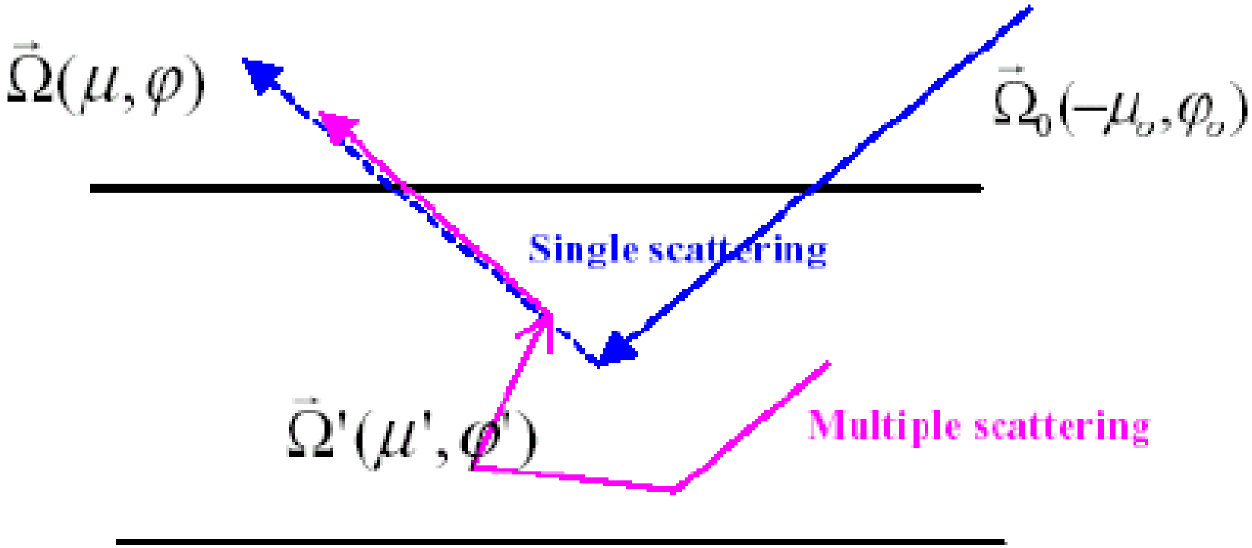
（2000.03- 2004.05，单位： W m^{-2} Trenberth等，2009）

平面平行大气

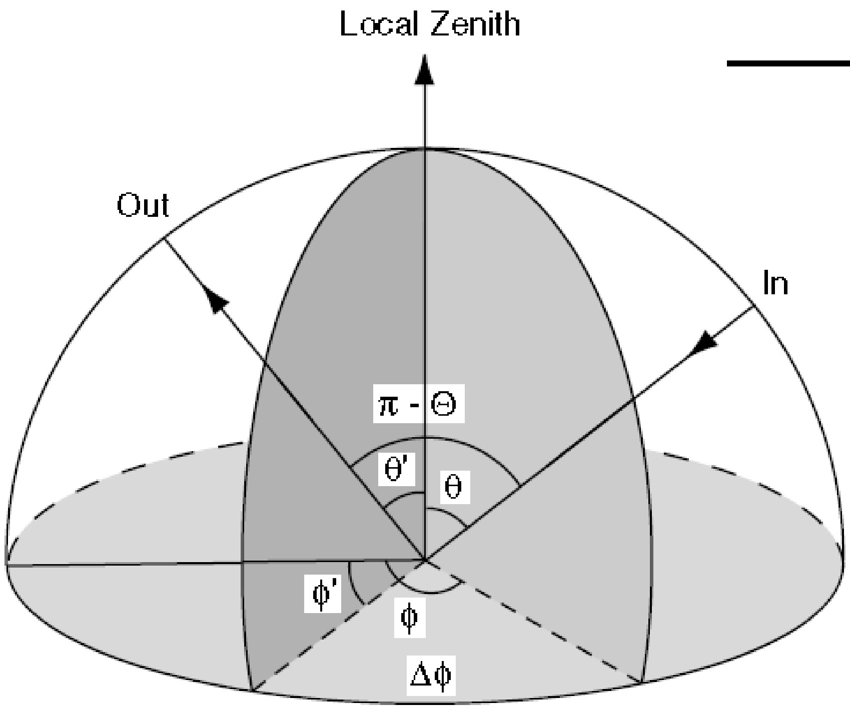


$I_\lambda^\uparrow(0;\mu;\varphi)$
z = z1 Top
τ =0
$I_\lambda^\uparrow(\tau;\mu;\varphi)$
$I_\lambda^\downarrow(0;-\mu;\varphi)$
z
τ
$I_\lambda^\uparrow(\tau_1;\mu;\varphi)$
$I_\lambda^\downarrow(\tau;-\mu;\varphi)$
z =0
τ = τ1
Bottom
$I_\lambda^\downarrow(\tau_1;-\mu;\varphi)$

多次散射的一般方程



$\vec{\Omega}(\mu,\varphi)$
$\vec{\Omega}_0(-\mu_o,\varphi_o)$
Single scattering
$\vec{\Omega}'(\mu',\varphi')$
Multiple scattering



Local Zenith
Out
In
π - Θ
θ'
θ
φ'
φ
Δφ

多次散射的一般方程

$$\mu\frac{dI(\tau,\mu)}{d\tau}=I(\tau,\mu)-\frac{\omega}{2}\int_{-1}^{1}I(\tau,\mu')P(\mu,\mu')d\mu'$$
$$-\frac{\omega}{4\pi}SP(\mu,-\mu_0)e^{-\tau/\mu_0}$$

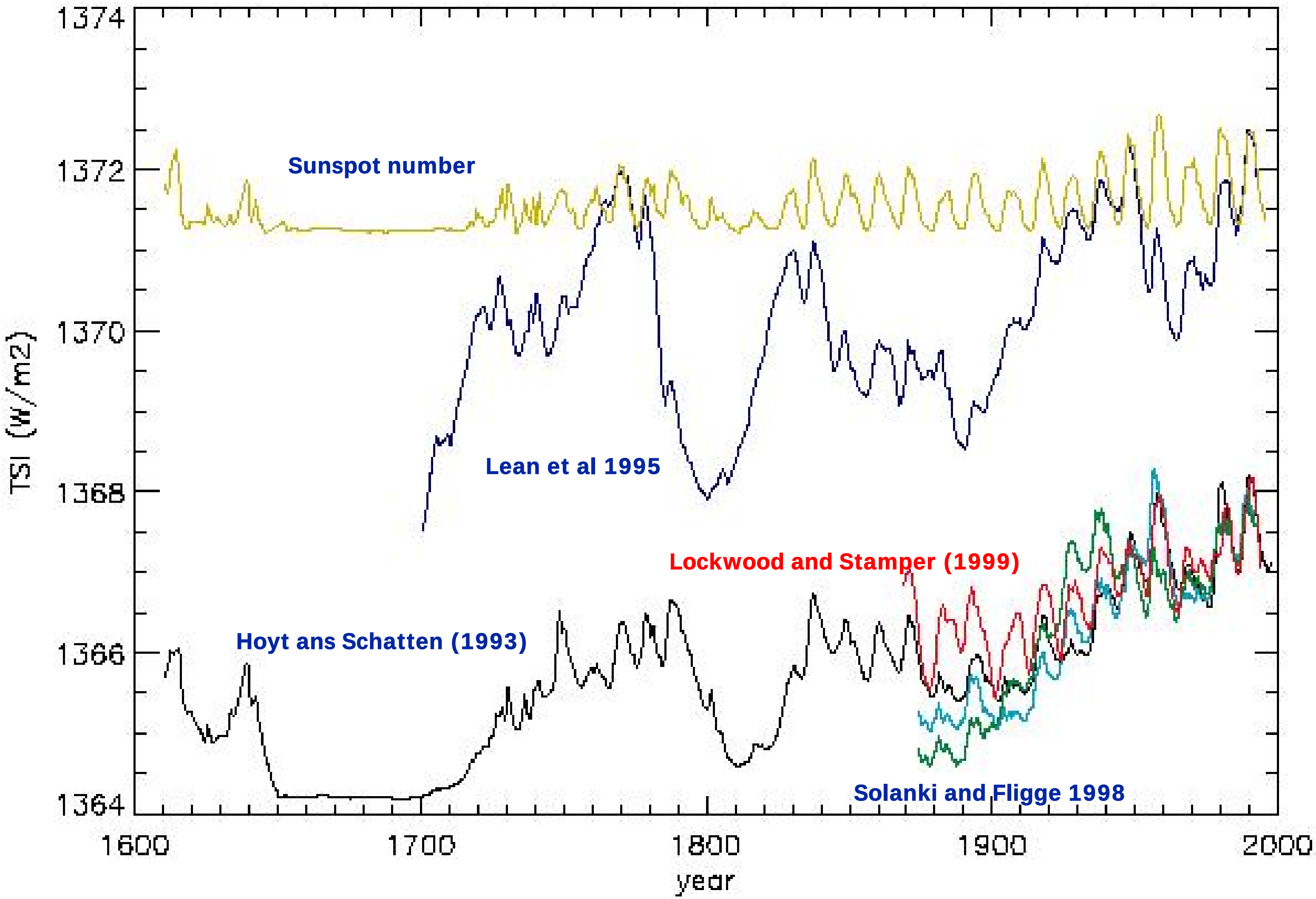
1）单次散射和粒子吸收造成的减弱，即对入射辐射的消光；

2）来自其它方向的散射辐射的再散射，即多次散射，可引起的增强；

3）直接太阳辐射的单次散射引起的增强；

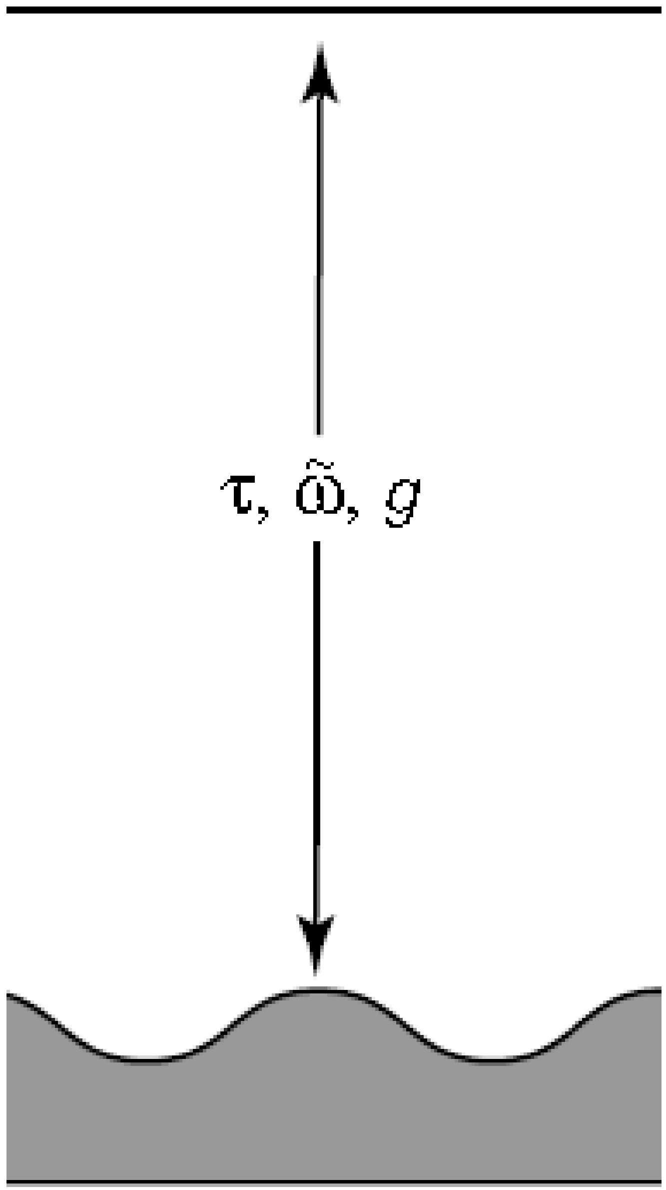
太阳常数的变化

Plot from IPCC TAR



1、方程求解一算法

2、大气性质



常用算法

Discrete-Ordinates Method

对天顶角的积分转换为有限求和→一阶线性微分方程组

最简单形式：Two-Stream Approximations

Spherical Harmonics Methods

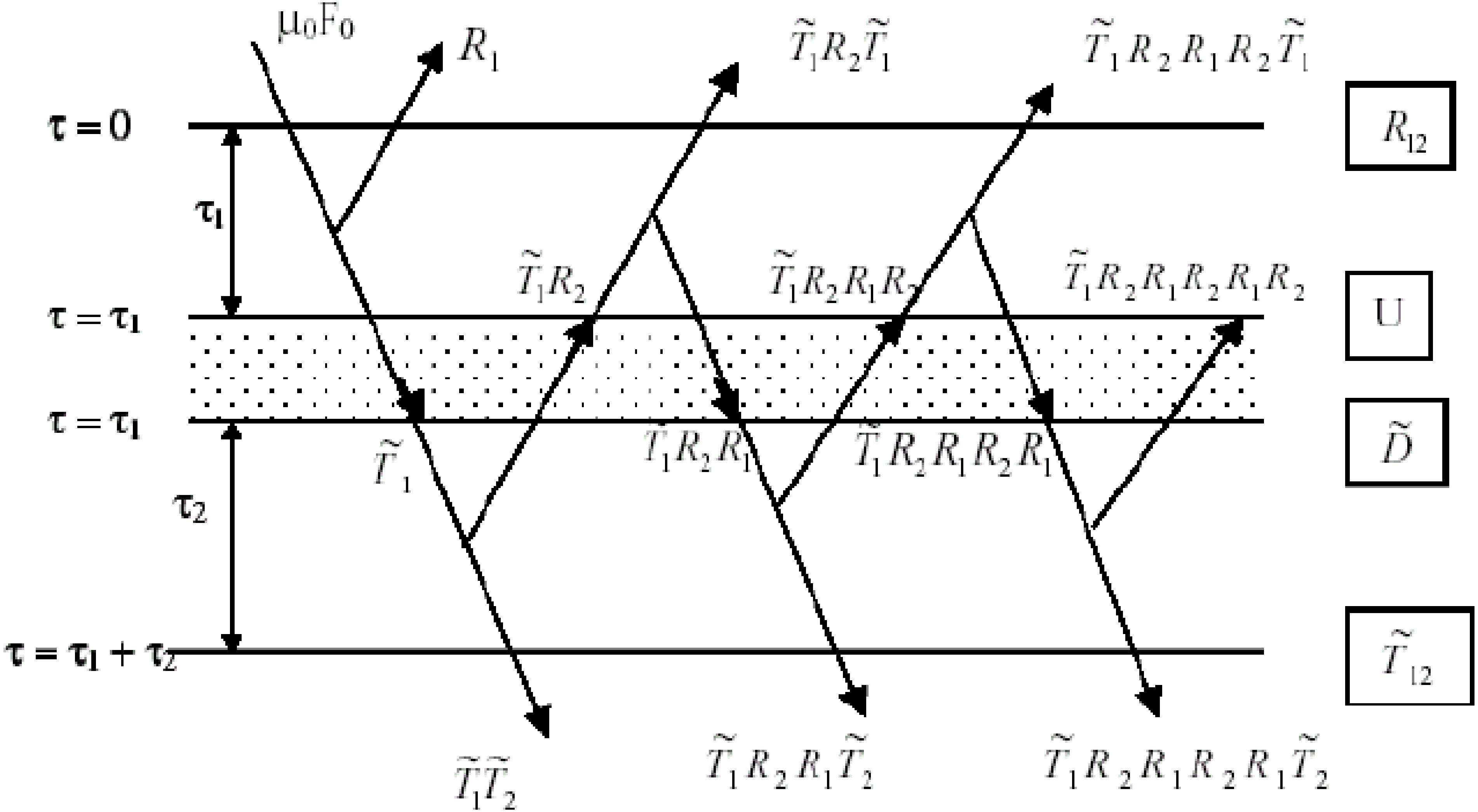
将辐射强度展开为球谐函数→一阶线性微分方程组

“二流”形式退化为：Eddington Approximations

Adding Method

Monte Carlo Method

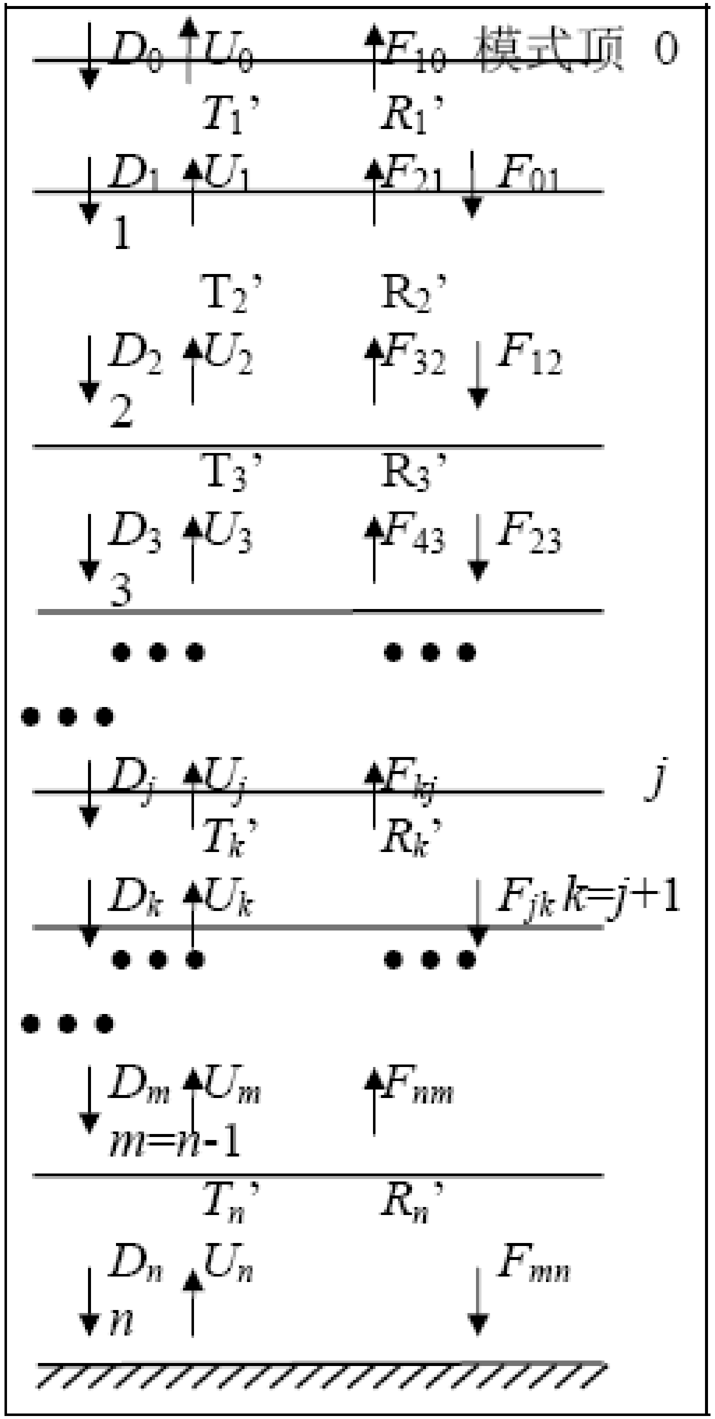
累加法



$\mu_0 F_0$
R_1
$\tilde{T}_1 R_2 \tilde{T}_1$
$\tilde{T}_1 R_2 R_1 R_2 \tilde{T}_1$
$\tau = 0$
R_{12}
τ_1
$\tilde{T}_1 R_2$
$\tilde{T}_1 R_2 R_1 R_2$
$\tilde{T}_1 R_2 R_1 R_2 R_1 R_2$
$\tau = \tau_1$
U
$\tau = \tau_1$
$\tilde{T}_1$
$\tilde{T}_1 R_2 R_1$
$\tilde{T}_1 R_2 R_1 R_2 R_1$
$\tilde{D}$
τ_2
$\tau = \tau_1 + \tau_2$
$\tilde{T}_{12}$
$\tilde{T}_1 \tilde{T}_2$
$\tilde{T}_1 R_2 R_1 \tilde{T}_2$
$\tilde{T}_1 R_2 R_1 R_2 R_1 \tilde{T}_2$

累加法

$$\begin{cases} U_0 = R_1' D_0 + T_1' U_1 + F_{10} \\ D_1 = T_1' D_0 + R_1' U_1 + F_{01} \\ U_1 = R_2' D_1 + T_2' U_2 + F_{12} \\ D_2 = T_2' D_1 + R_2' U_2 + F_{21} \\ \quad \cdots \quad \cdots \quad \cdots \\ U_j = R_k' D_j + T_k' U_k + F_{kj} \\ D_k = T_k' D_j + R_k' U_k + F_{jk} \\ \quad \cdots \quad \cdots \quad \cdots \\ U_m = R_n' D_m + T_n' U_n + F_{nm} \\ D_n = T_n' D_m + R_n' U_n + F_{mn} \end{cases}$$



累加法

$$
\begin{bmatrix}
1 & 0 & -T_1' & & & & & & & \\
0 & 1 & -R_1' & 0 & & & & & & \\
0 & -R_2' & 1 & 0 & \cdots & & & & & \\
 & -T_2' & 0 & 1 & \cdots & \cdots & & & & \\
 & & \cdots & \cdots & \cdots & \cdots & \cdots & & & \\
 & & & \cdots & \cdots & 1 & 0 & \cdots & & \\
 & & & & \cdots & 0 & 1 & \cdots & \cdots & \\
 & & & & & \cdots & \cdots & \cdots & \cdots & \cdots \\
 & & & & & & \cdots & \cdots & 1 & 0 \\
 & & & & & & & \cdots & 0 & 1
\end{bmatrix}
\begin{bmatrix}
U_0 \\ D_1 \\ U_1 \\ D_2 \\ \cdots \\ U_j \\ D_k \\ \cdots \\ U_m \\ D_n
\end{bmatrix}
=
\begin{bmatrix}
F_{10} \\ F_{01} \\ F_{21} \\ F_{12} \\ \cdots \\ F_{kj} \\ F_{jk} \\ \cdots \\ F_{nm} + T_n' \alpha S_{t\lambda} \mu_0 \exp(-\tau_n / \mu_0) \\ F_{mn} + R_n' \alpha S_{t\lambda} \mu_0 \exp(-\tau_n / \mu_0)
\end{bmatrix}
$$

累加法

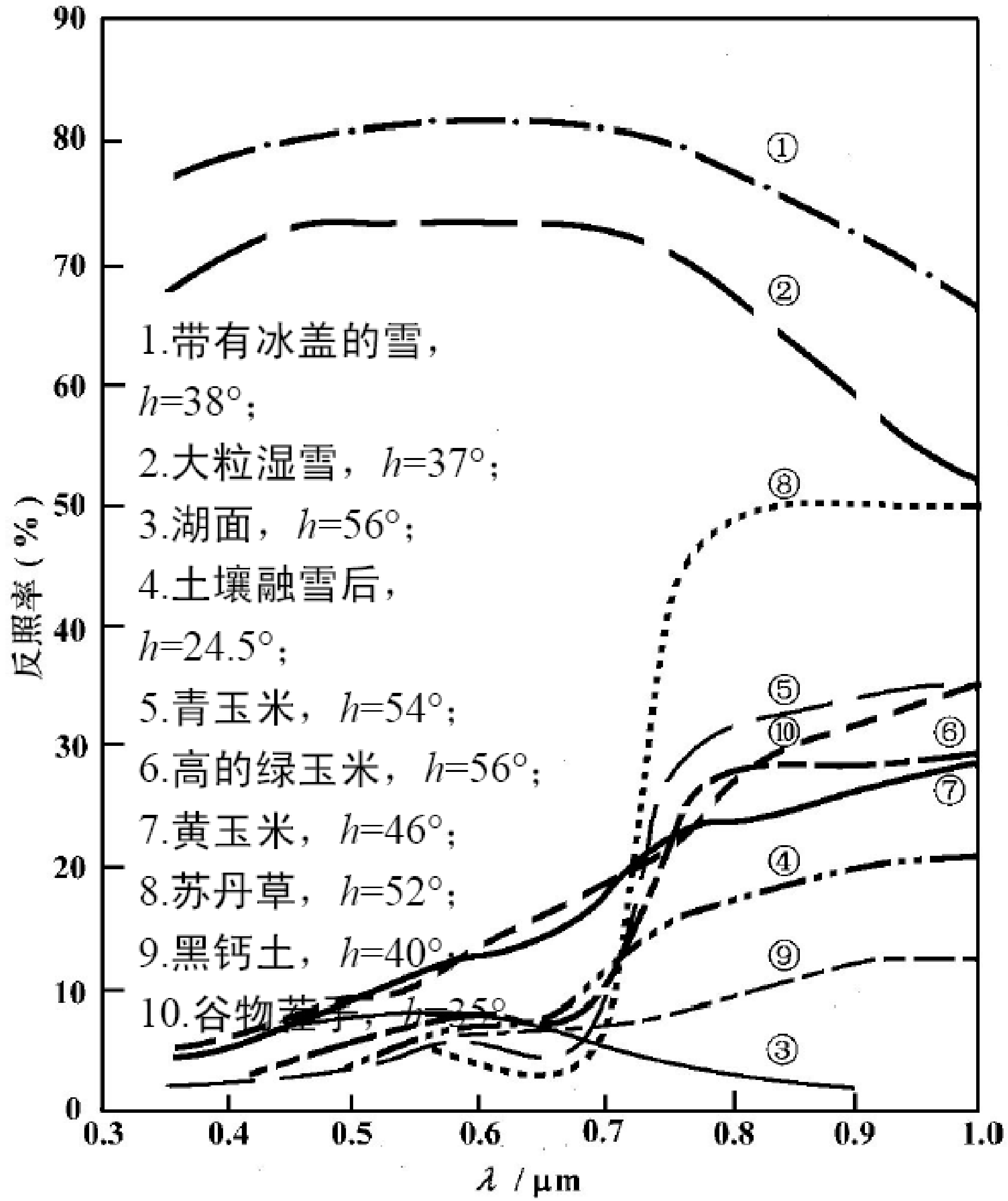
F_{kj}和F_{jk}是第k层向上和向下的一次散射辐射通量密度

$$F_{kj} = R_k S_{t\lambda} \mu_0 \exp(-\tau_j / \mu_0)$$

$$F_{jk} = T_k S_{t\lambda} \mu_0 \exp(-\tau_j / \mu_0)$$

上下边界条件：$D_0 = 0$ 和 $U_n = \alpha[D_n + S_{t\lambda}\mu_0 \exp(-\tau_n/\mu_0)]$，即模式顶没有入射的散射辐射，地面向上的反射辐射是地面反照率乘以总辐射。地面反照率α随地面覆盖物、相对湿度和波长变化。

地面反照率

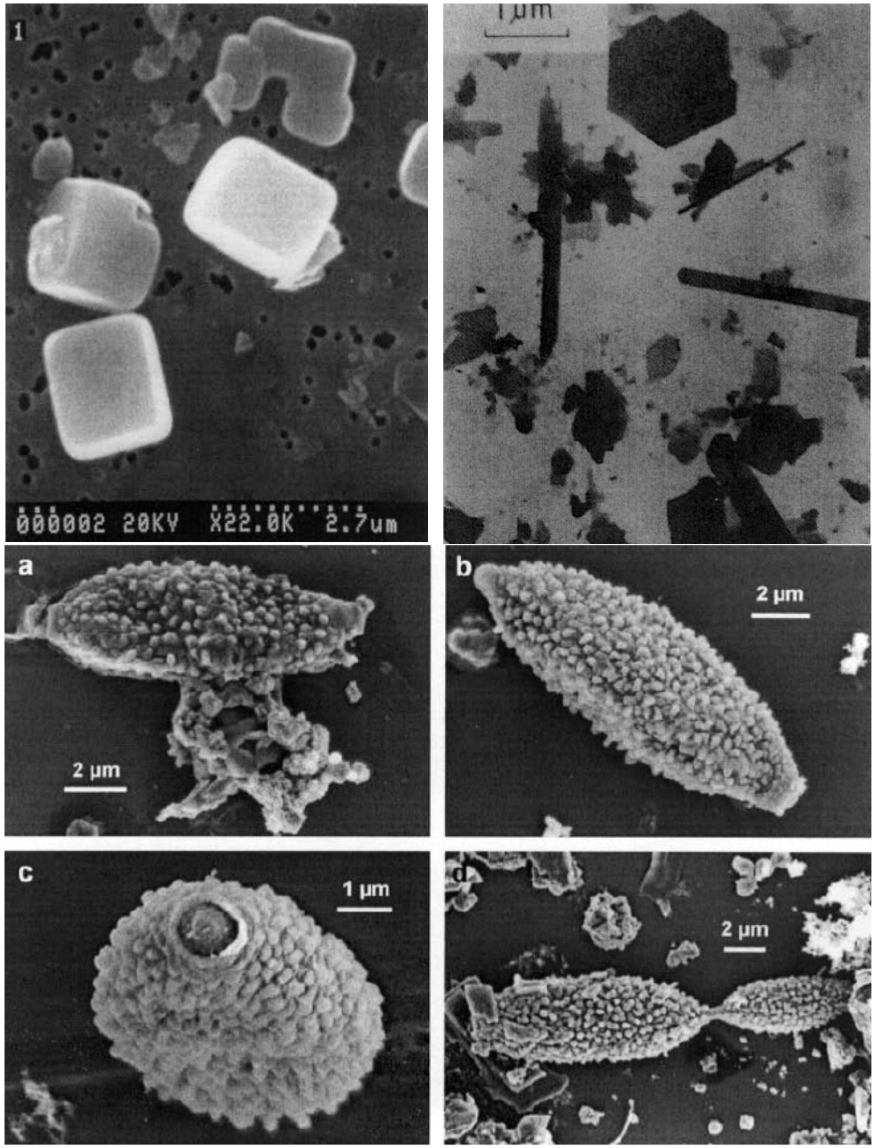


90
80
70
60
50
40
30
20
10
0
反照率（%）
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
λ / μm
①
②
③
④
⑤
⑥
⑦
⑧
⑨
⑩
1.带有冰盖的雪，
h=38°；
2.大粒湿雪，h=37°；
3.湖面，h=56°；
4.土壤融雪后，
h=24.5°；
5.青玉米，h=54°；
6.高的绿玉米，h=56°；
7.黄玉米，h=46°；
8.苏丹草，h=52°；
9.黑钙土，h=40°；

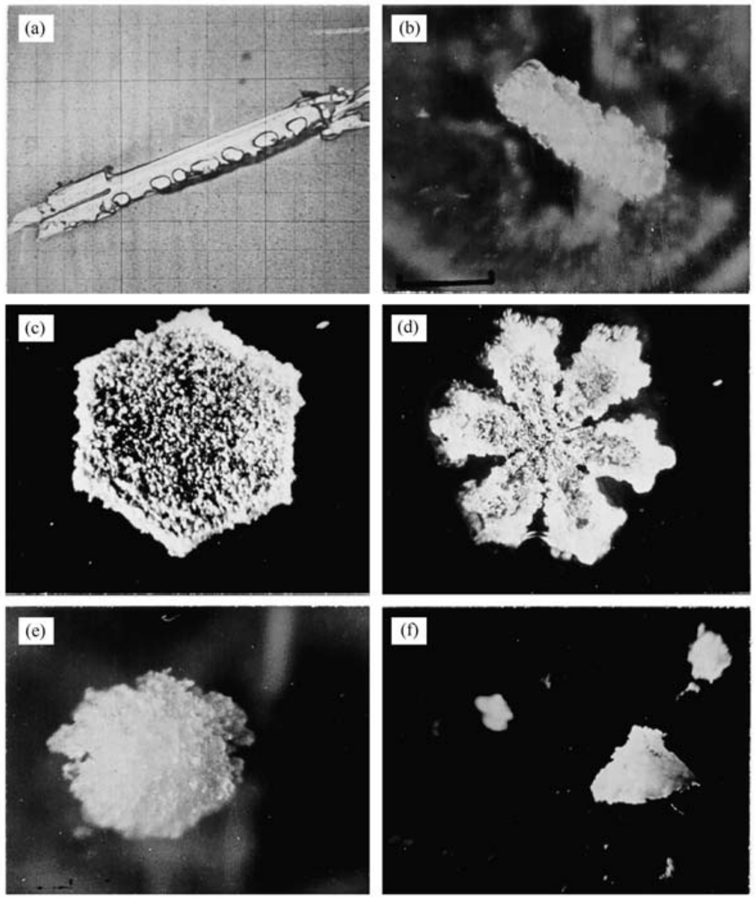
气溶胶光学性质

大气气溶胶

形状和大小？

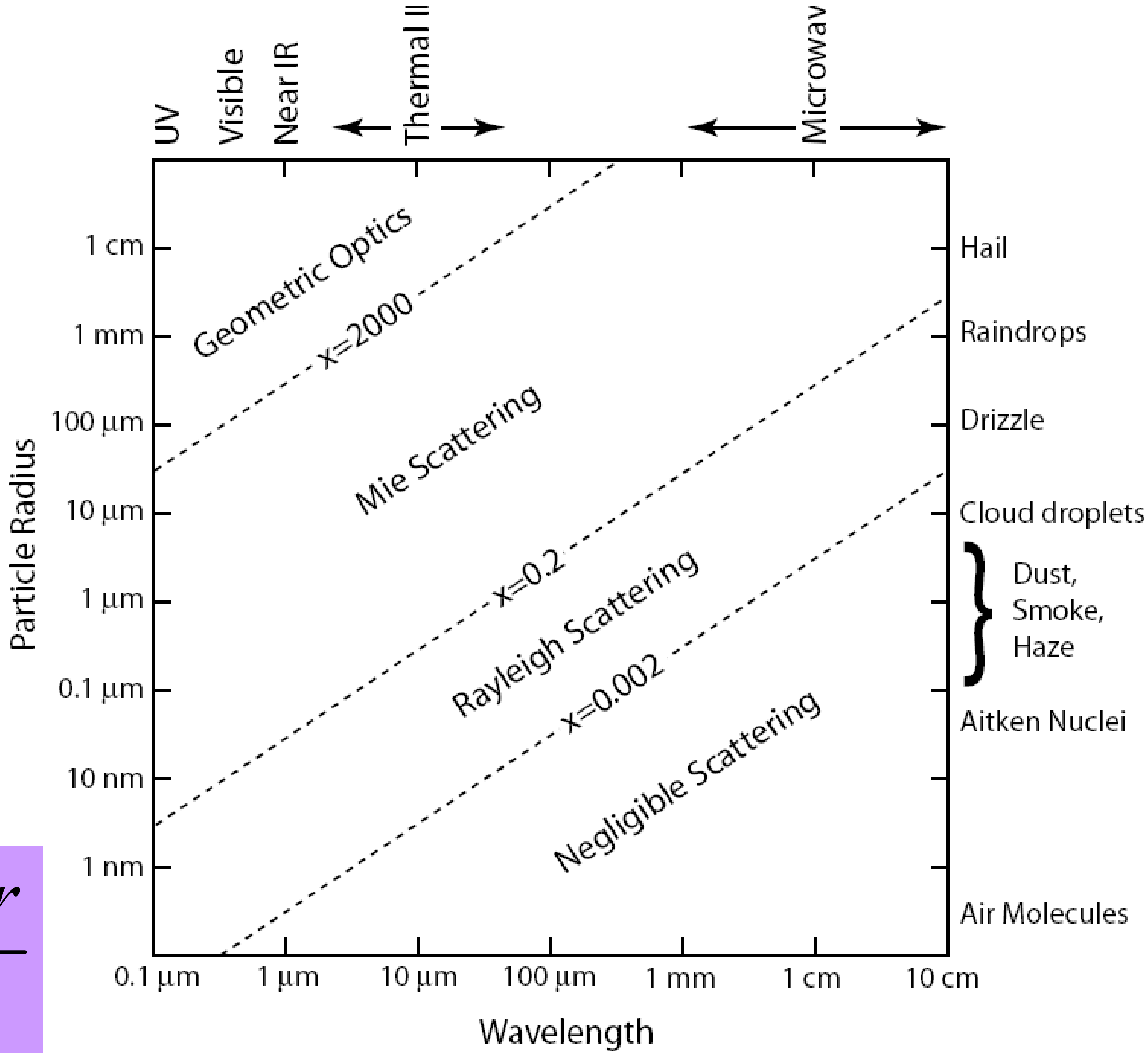


Kokhanovsky, 2008



Wallace and Hobbs, 2006

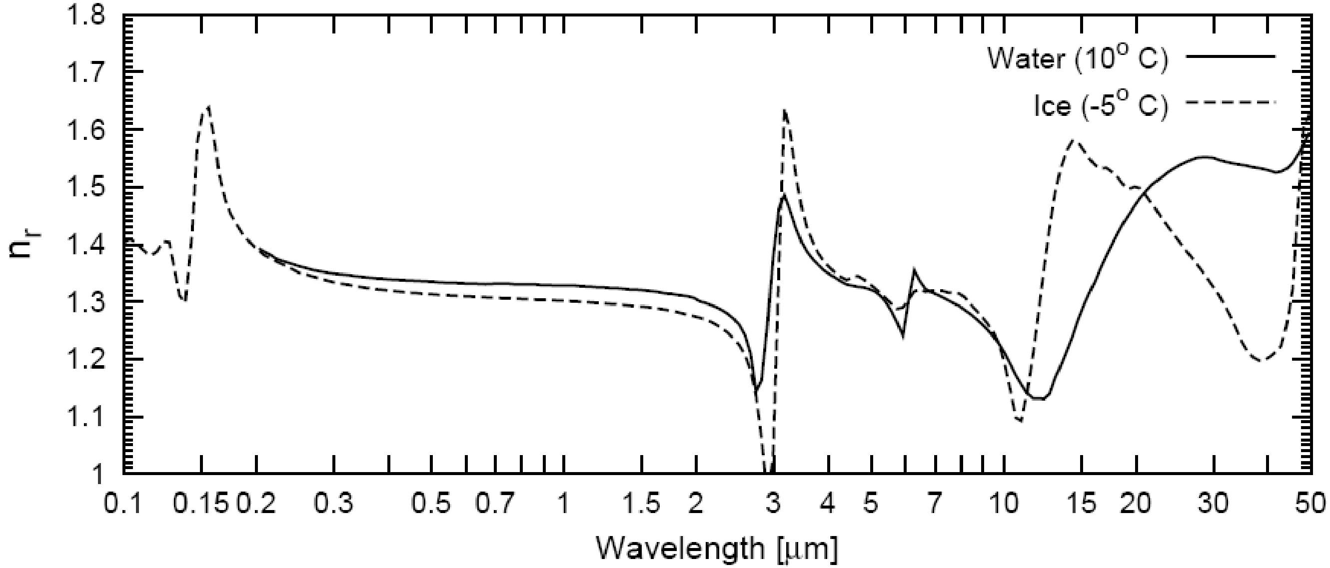
散射的分类—尺度参数



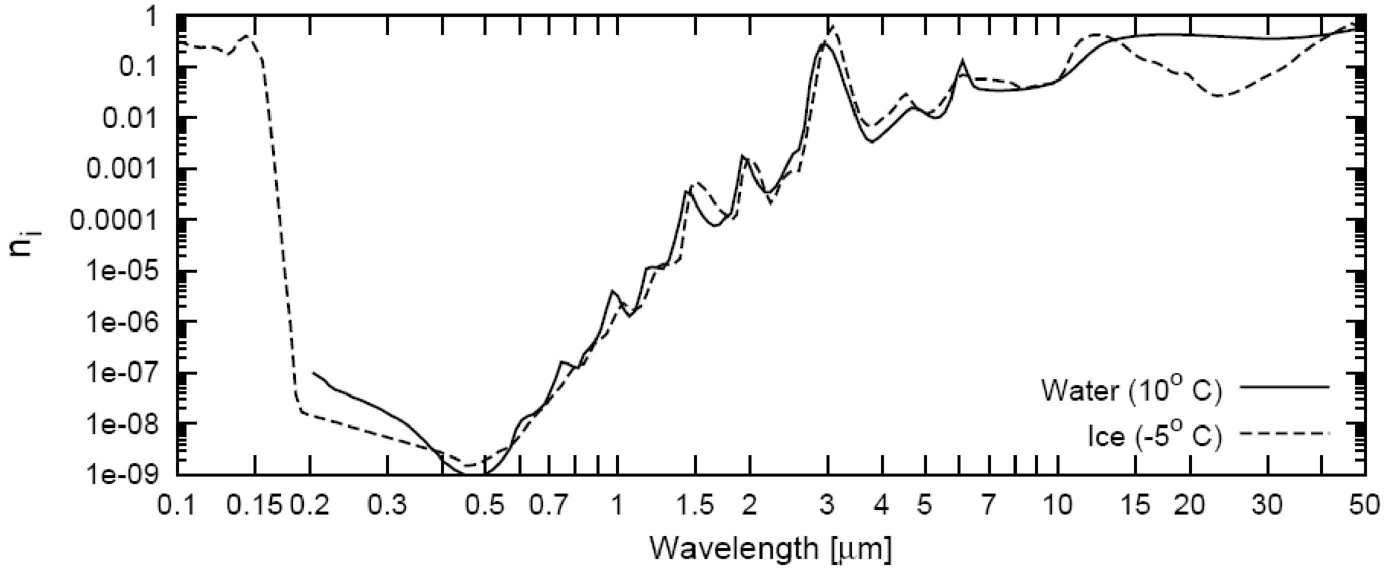
$$x = \frac{2\pi r}{\lambda}$$

Mie散射

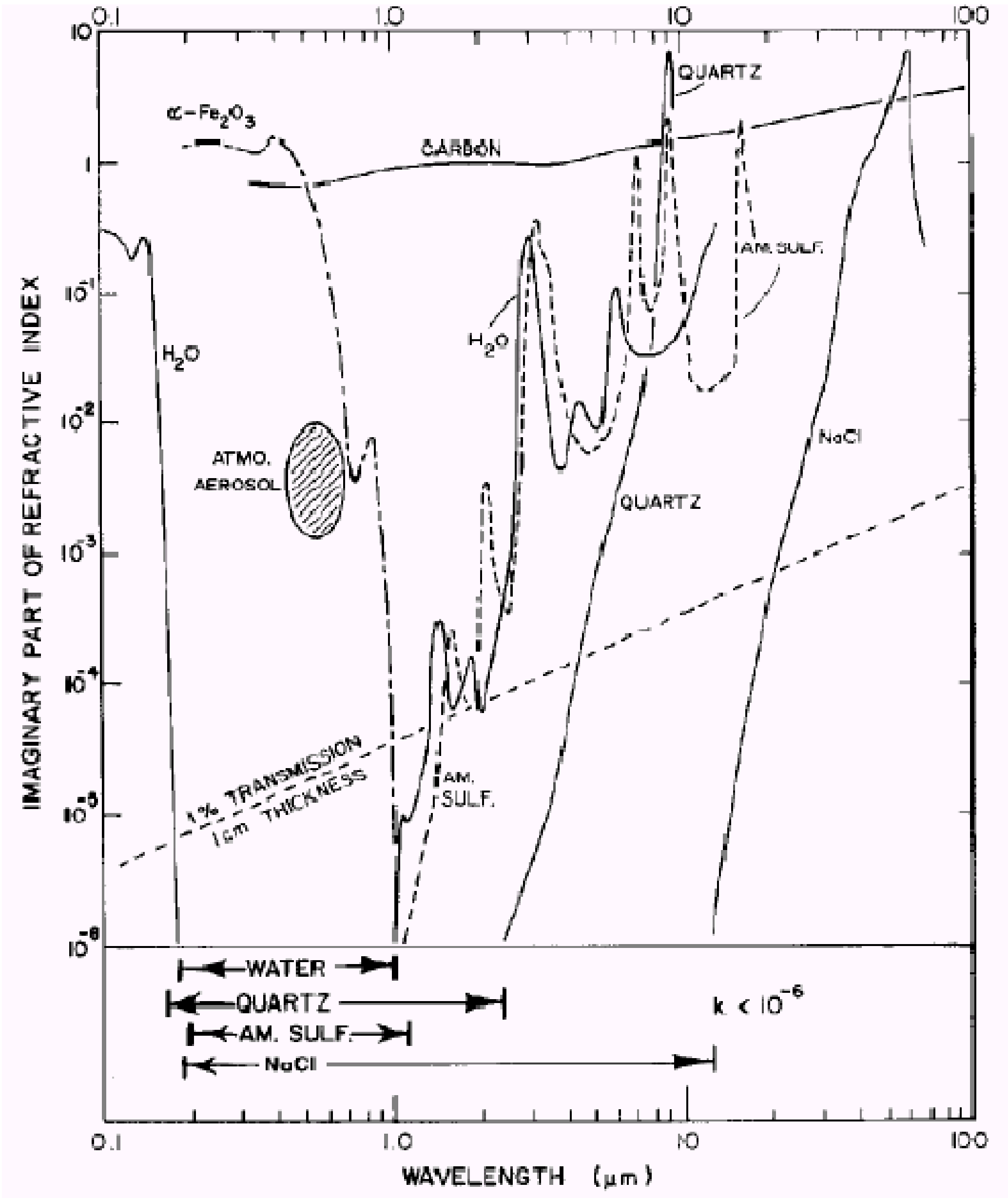
(a) Index of Refraction of Water and Ice (Real Part)



(b) Index of Refraction of Water and Ice (Imag. Part)



Mie散射

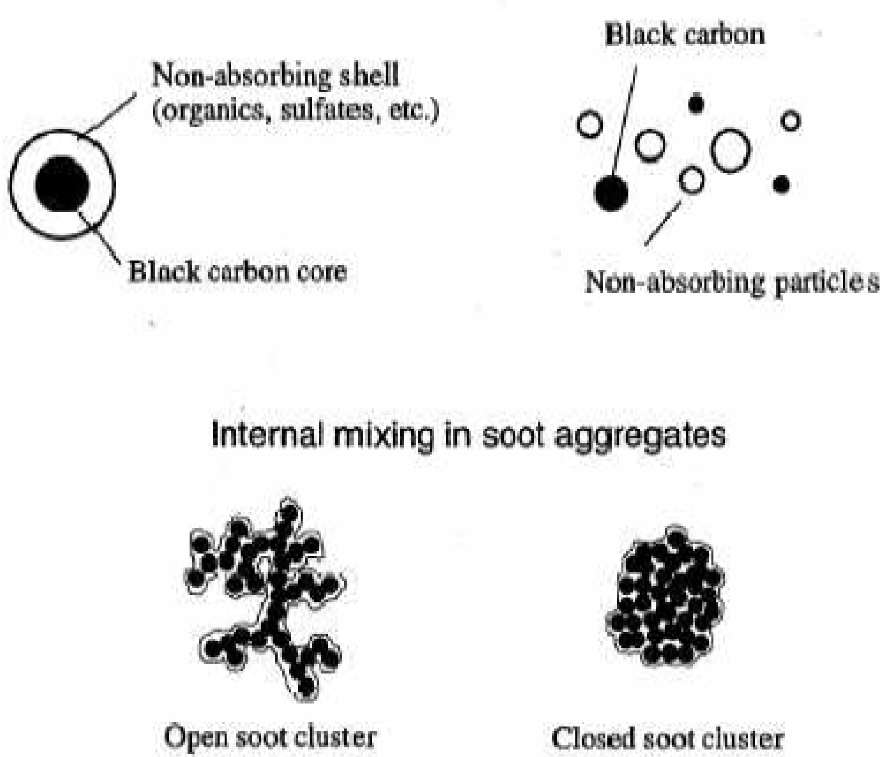


Imaginary part of the refractive indexes of some aerosol materials

Note: Main absorbing species in the SW are black carbon (Soot) and Hematite (dust)

折射指数—混合方式

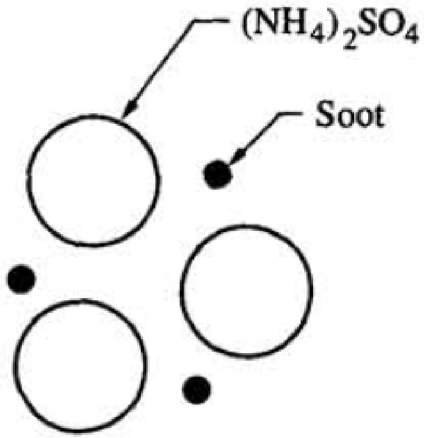
Aerosol Mixture

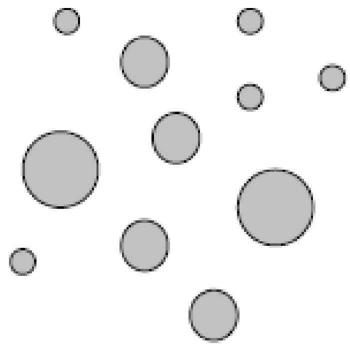


Martins et al., JGR, 1998

External mixing

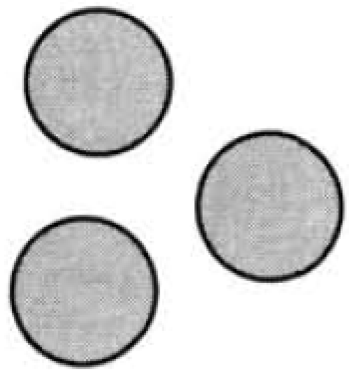
each particle consists of just one chemical component





Internal mixing

each particle consists of a mixture of chemical components



单个粒子米散射参数

消光效率、散射效率和吸收效率（亦称为效率因子）及不对称因子（无量纲）

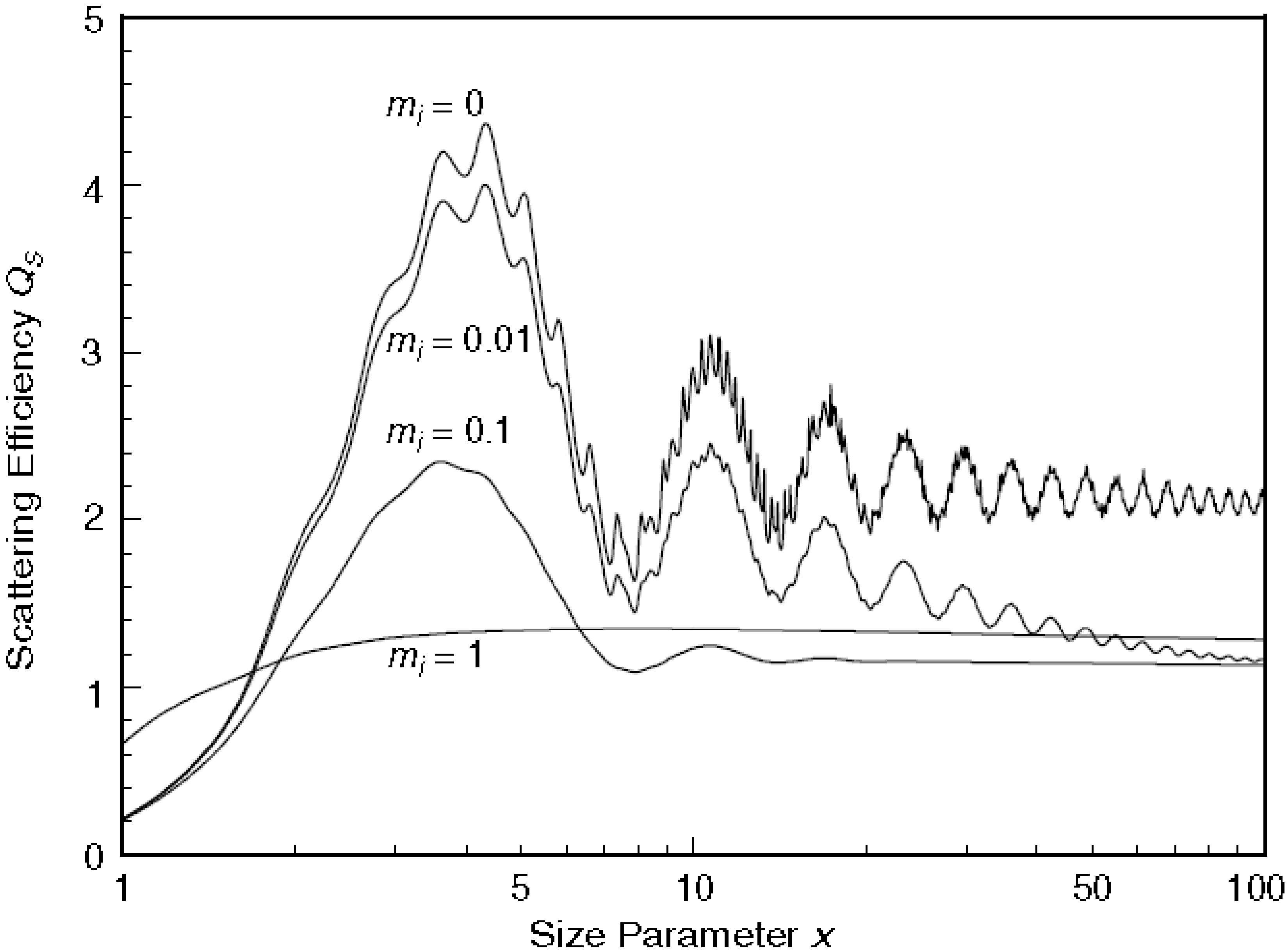
$$Q_e = \frac{\sigma_e}{\pi a^2} = \frac{2}{x^2}\sum_{n=1}^{\infty}(2n+1)\mathrm{Re}[a_n + b_n]$$

$$Q_s = \frac{\sigma_s}{\pi a^2} = \frac{2}{x^2}\sum_{n=1}^{\infty}(2n+1)\left(a_n a_n^* + b_n b_n^*\right)$$

$$Q_a = Q_e - Q_s$$

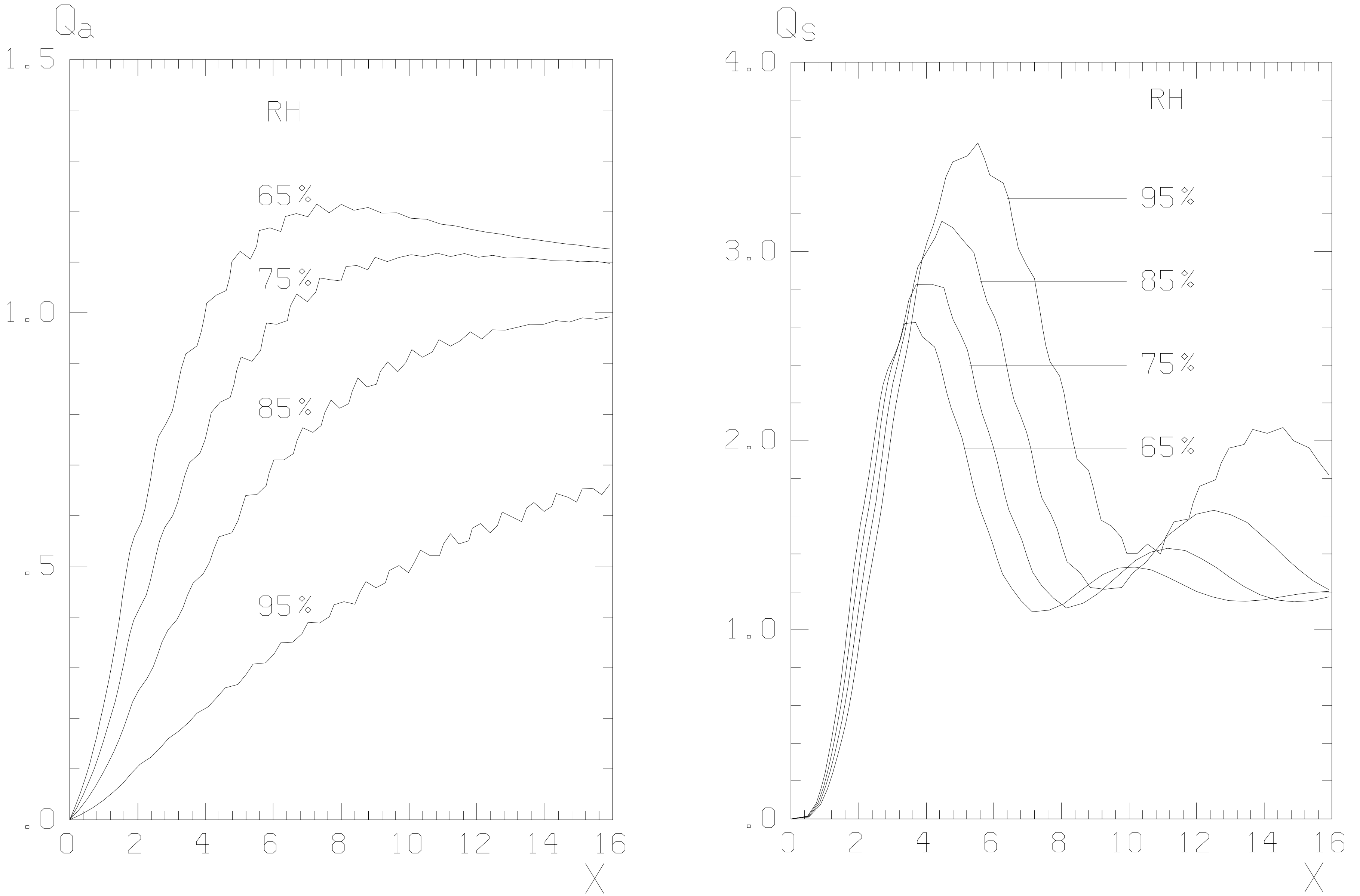
$$g = \frac{4}{x^2 Q_s}\sum_{n=1}^{\infty}\left[\frac{n(n+2)}{n+1}\mathrm{Re}\left(a_n a_{n+1}^* + b_n b_{n+1}^*\right) + \frac{2n+1}{n(n+1)}\mathrm{Re}\left(a_n b_n^*\right)\right]$$

单个粒子米散射参数



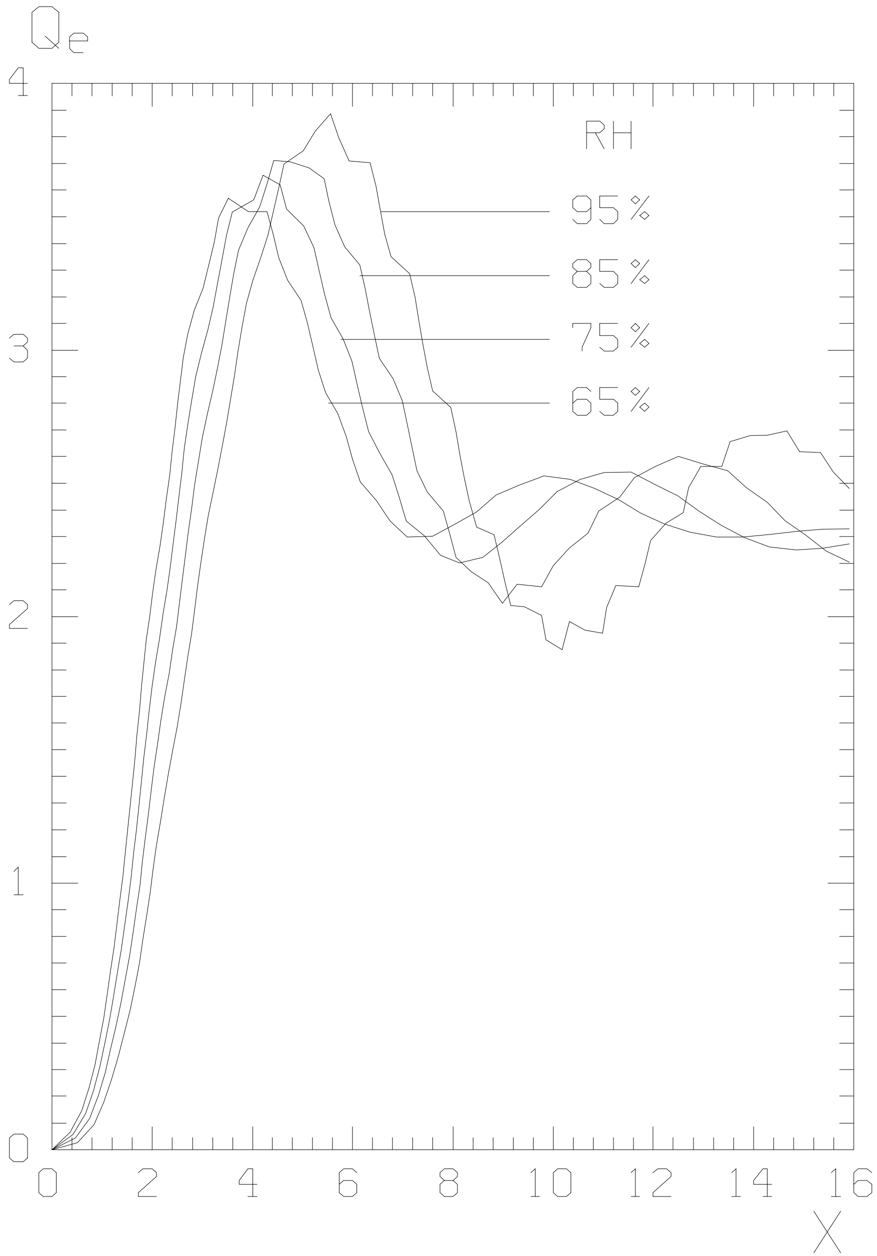
$m_i = 0$
$m_i = 0.01$
$m_i = 0.1$
$m_i = 1$
Scattering Efficiency Q_s
Size Parameter x
0
1
2
3
4
5
1
5
10
50
100

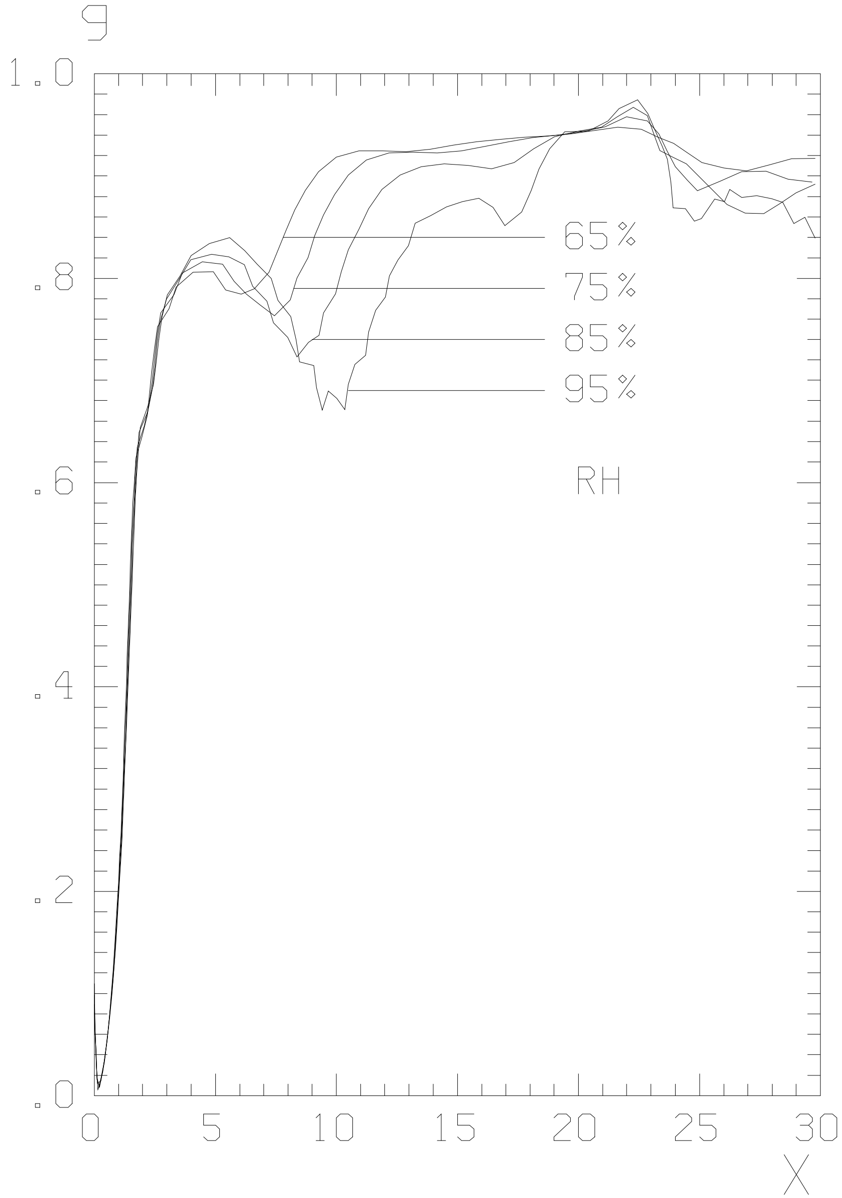
单个粒子米散射参数



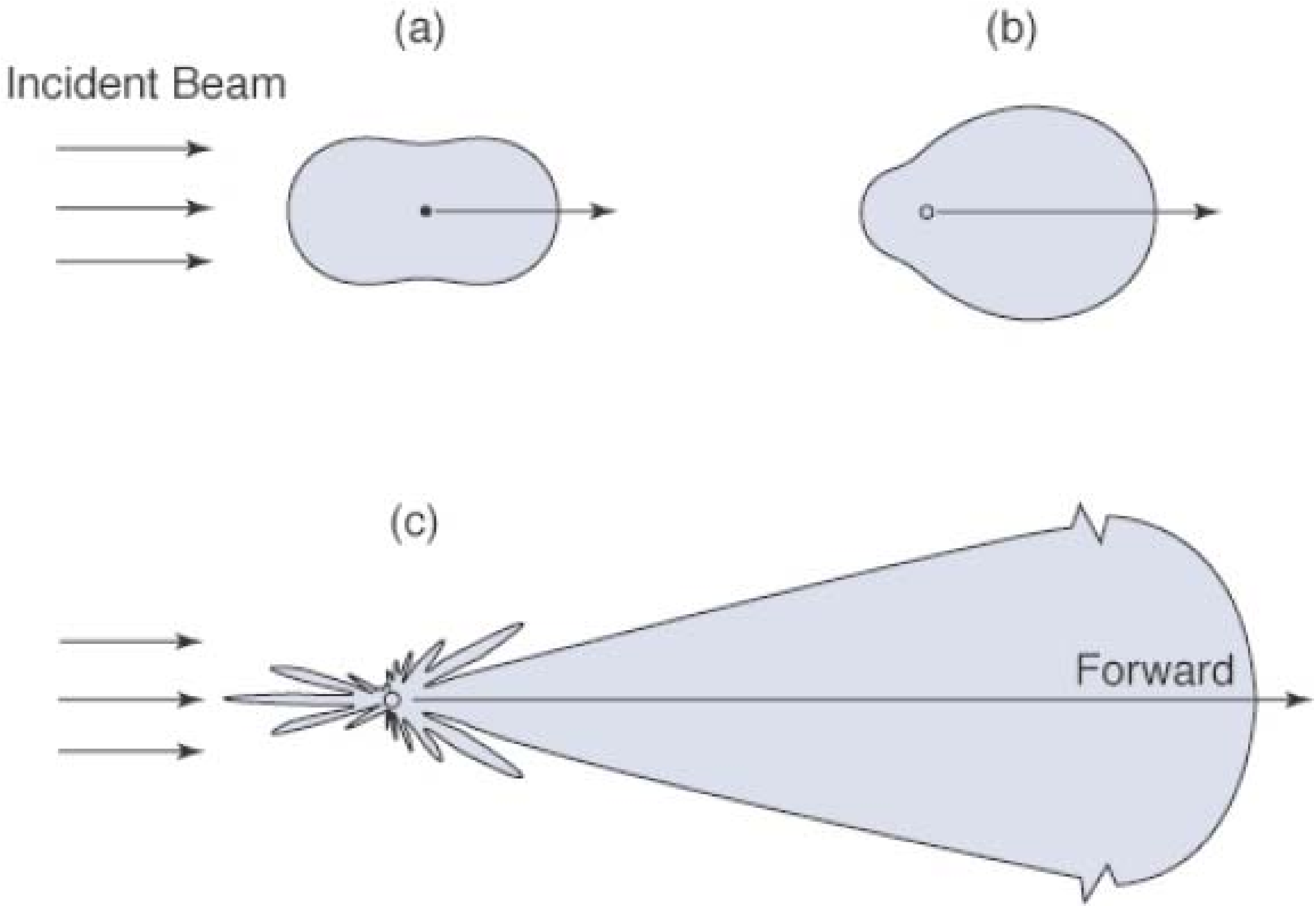
Qa
1.5
1.0
.5
.0
RH
65%
75%
85%
95%
0
2
4
6
8
10
12
14
16
X
Qs
4.0
3.0
2.0
1.0
.0
RH
95%
85%
75%
65%
0
2
4
6
8
10
12
14
16
X

单个粒子米散射参数


Qe
RH
95%
85%
75%
65%
0
1
2
3
4
0 2 4 6 8 10 12 14 16
X


g
1.0
.8
.6
.4
.2
.0
65%
75%
85%
95%
RH
0 5 10 15 20 25 30
X

单个粒子米散射参数



单个粒子米散射参数

- The **scattering phase function P(cosΘ)** is defined as a non-dimensional parameter to describe the angular distribution of the scattered radiation as

$$\frac{1}{4\pi}\int_{\Omega} P(\cos\Theta)\,d\Omega = 1$$ [1

where Θ is called the **scattering angle** between the direction of incidence and observation.

单个粒子米散射参数

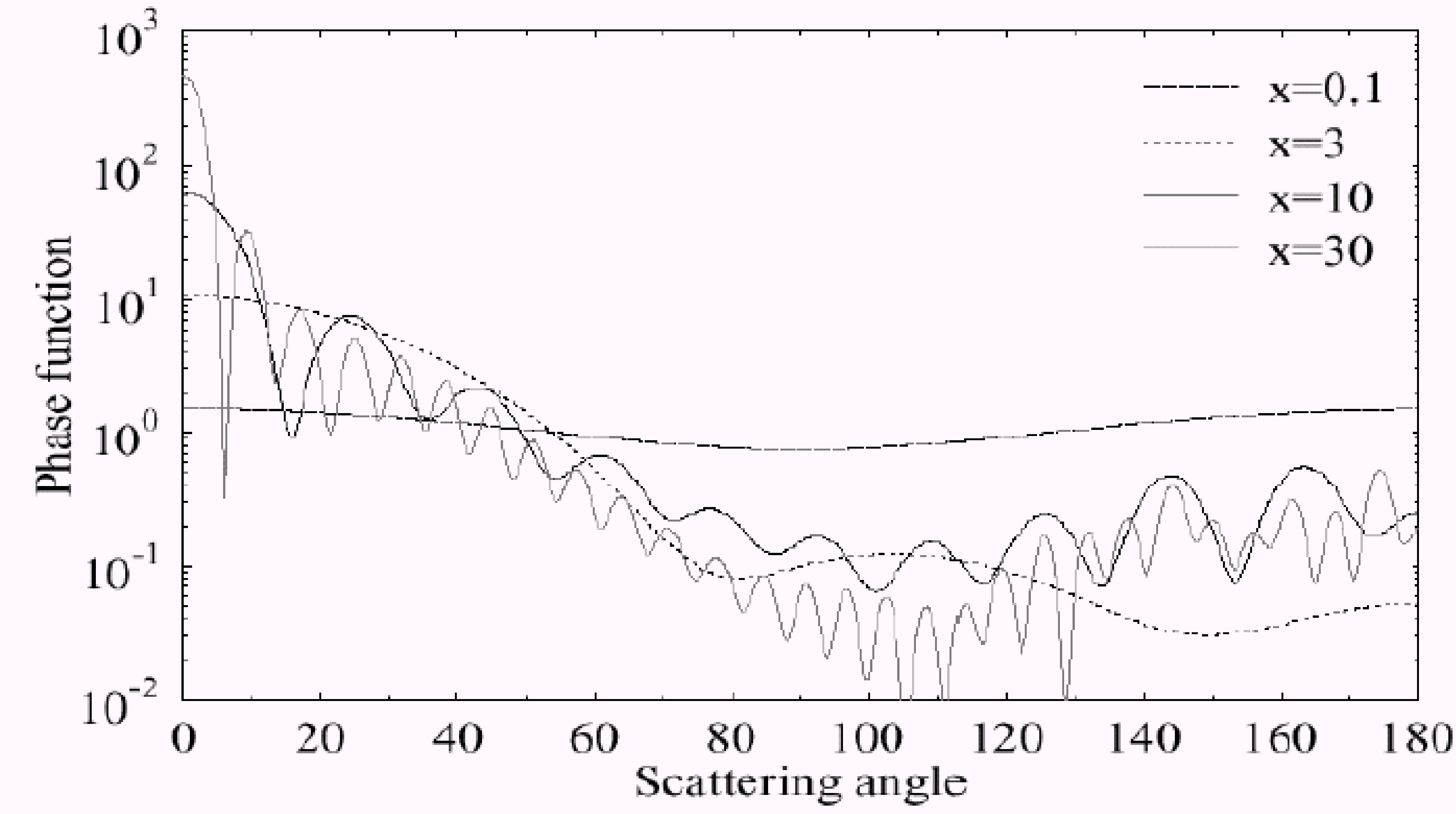
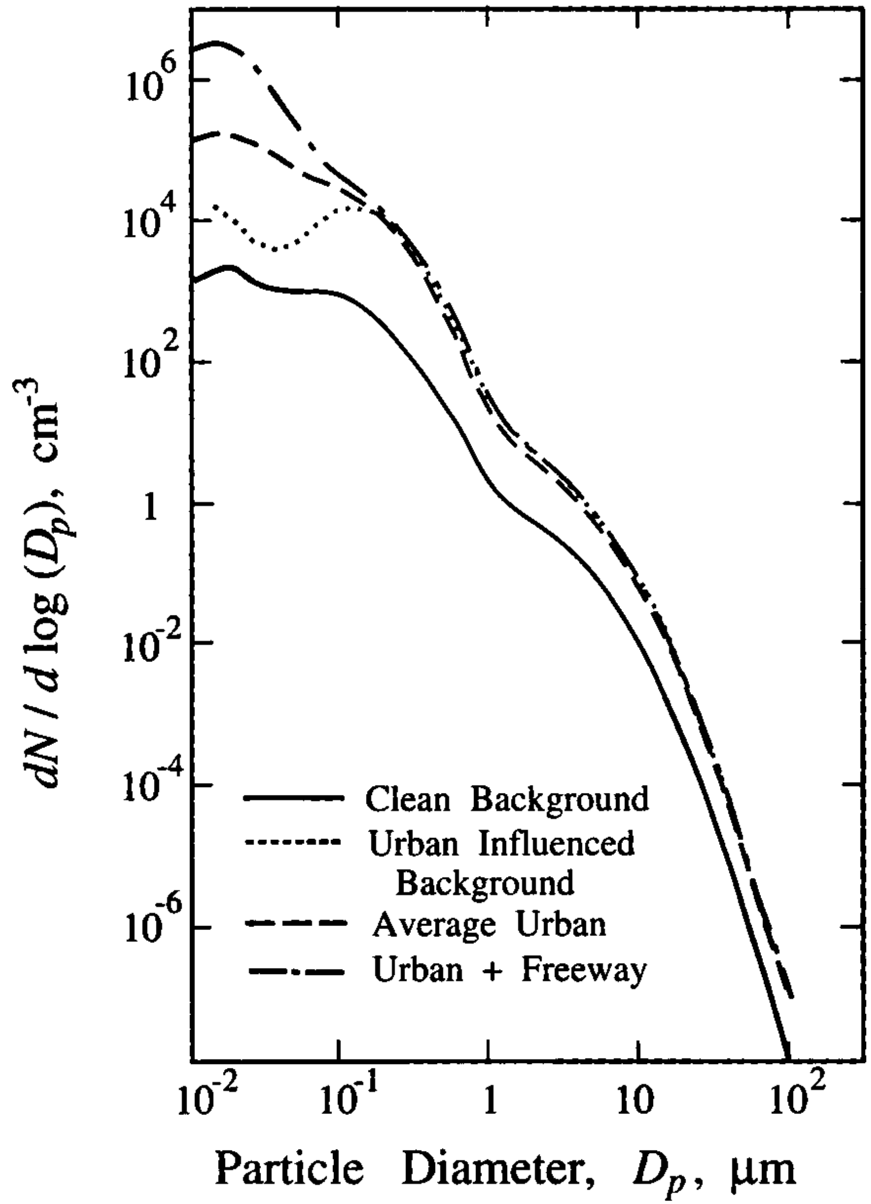


Figure 14.5 Examples of scattering phase functions calculated with Mie theory for several size parameter for nonabsorbing spheres (more in Lab 7).

（尺度）谱分布



10^6
10^4
10^2
1
10^{-2}
10^{-4}
10^{-6}
$dN / d\log(D_p)$, cm^{-3}
Clean Background
Urban Influenced Background
Average Urban
Urban + Freeway
10^{-2}
10^{-1}
1
10
10^2
Particle Diameter, D_p, μm

粒子群的积分光学特性

体积消光系数、体积散射系数、体积吸收系数（单位：μm²cm⁻³=10⁻⁶ m⁻¹）

$$\begin{cases} \beta_e = \int_{r_1}^{r_2} \sigma_e n(r)\,\mathrm{d}r = \pi \int_{r_1}^{r_2} r^2 Q_e \dfrac{\mathrm{d}N(r)}{\mathrm{d}r}\mathrm{d}r \\ \beta_s = \int_{r_1}^{r_2} \sigma_s n(r)\,\mathrm{d}r = \pi \int_{r_1}^{r_2} r^2 Q_s \dfrac{\mathrm{d}N(r)}{\mathrm{d}r}\mathrm{d}r \\ \beta_a = \beta_e - \beta_s \end{cases}$$

粒子群的积分光学特性

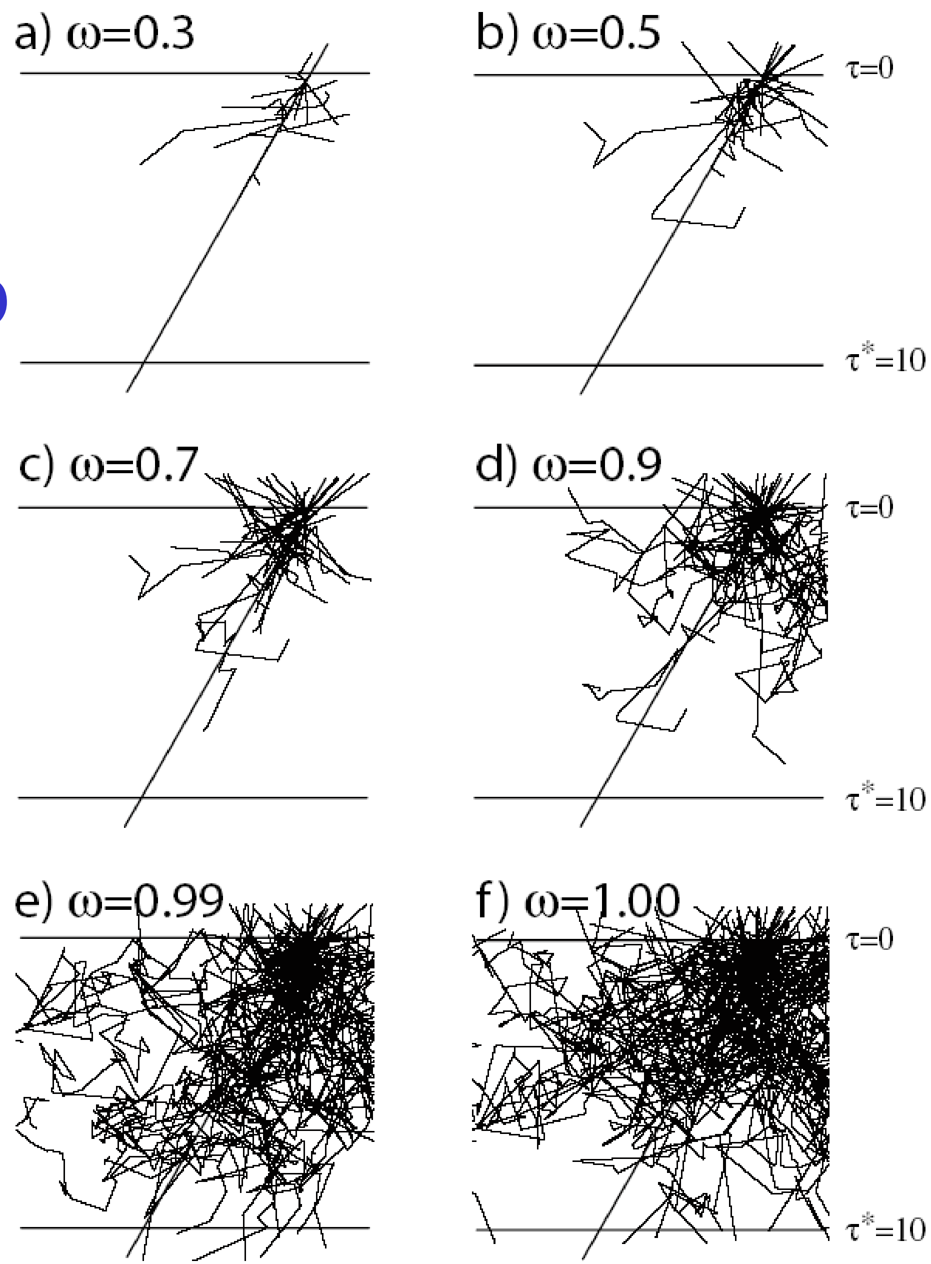
散射比

单次散射反照率

single scattering albedo

散射占消光的比例

$$\omega = \frac{\beta_s}{\beta_e}$$

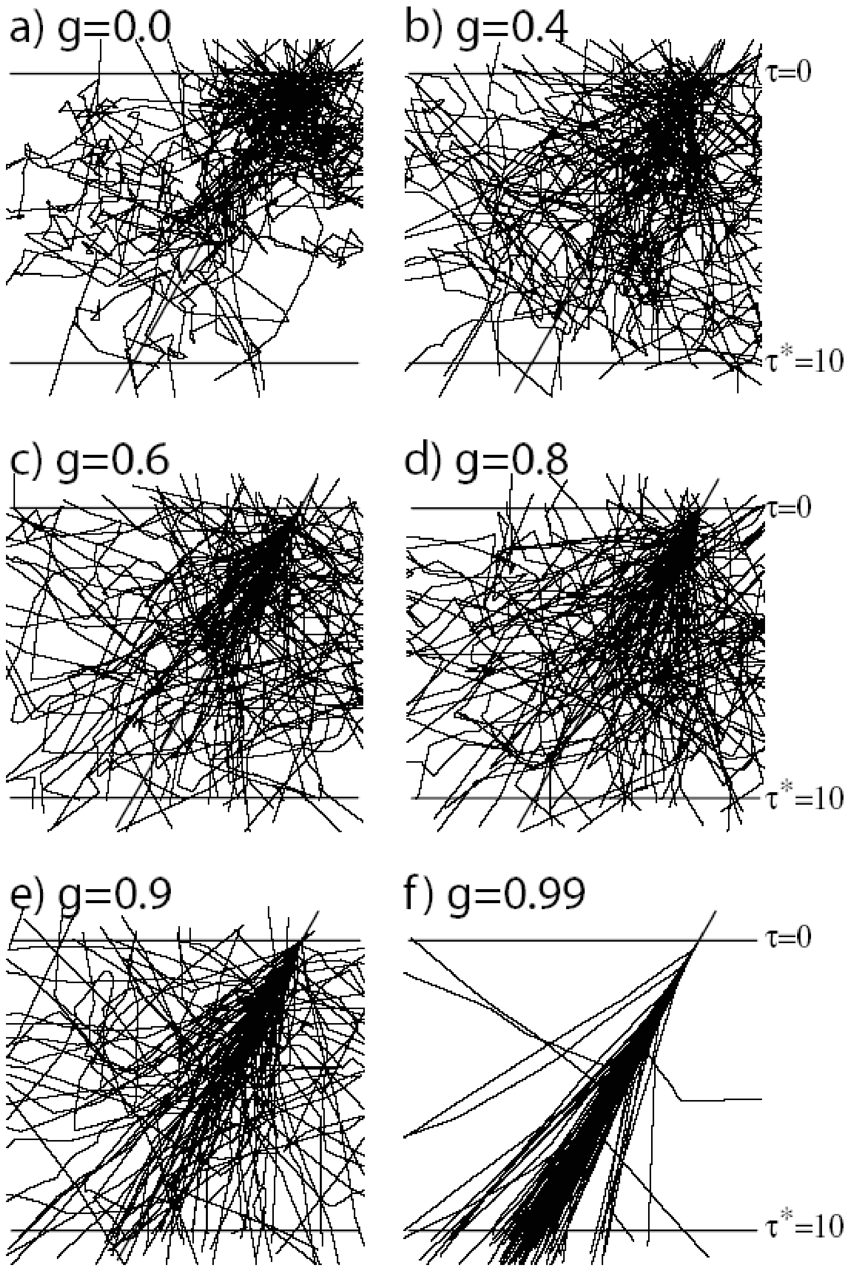


粒子群的积分光学特性

不对称因子

绝对值越大，表示大气中含有大粒子较多

$$g = \frac{\int_{r_1}^{r_2} r^2 Q_s g \frac{\mathrm{d}n(r)}{\mathrm{d}r} \mathrm{d}r}{\int_{r_1}^{r_2} r^2 Q_s \frac{\mathrm{d}n(r)}{\mathrm{d}r} \mathrm{d}r}$$



粒子群光学厚度

$$\tau = \int_{z_1}^{z_2} \beta \mathrm{d}z = \int_{z_1}^{z_2} (\beta_s + \beta_a) \mathrm{d}z$$

对于Junge分布

$$n(r,z) = \frac{\mathrm{d}N(r,z)}{\mathrm{d}r} = C(z) r^{-(\nu+1)}$$

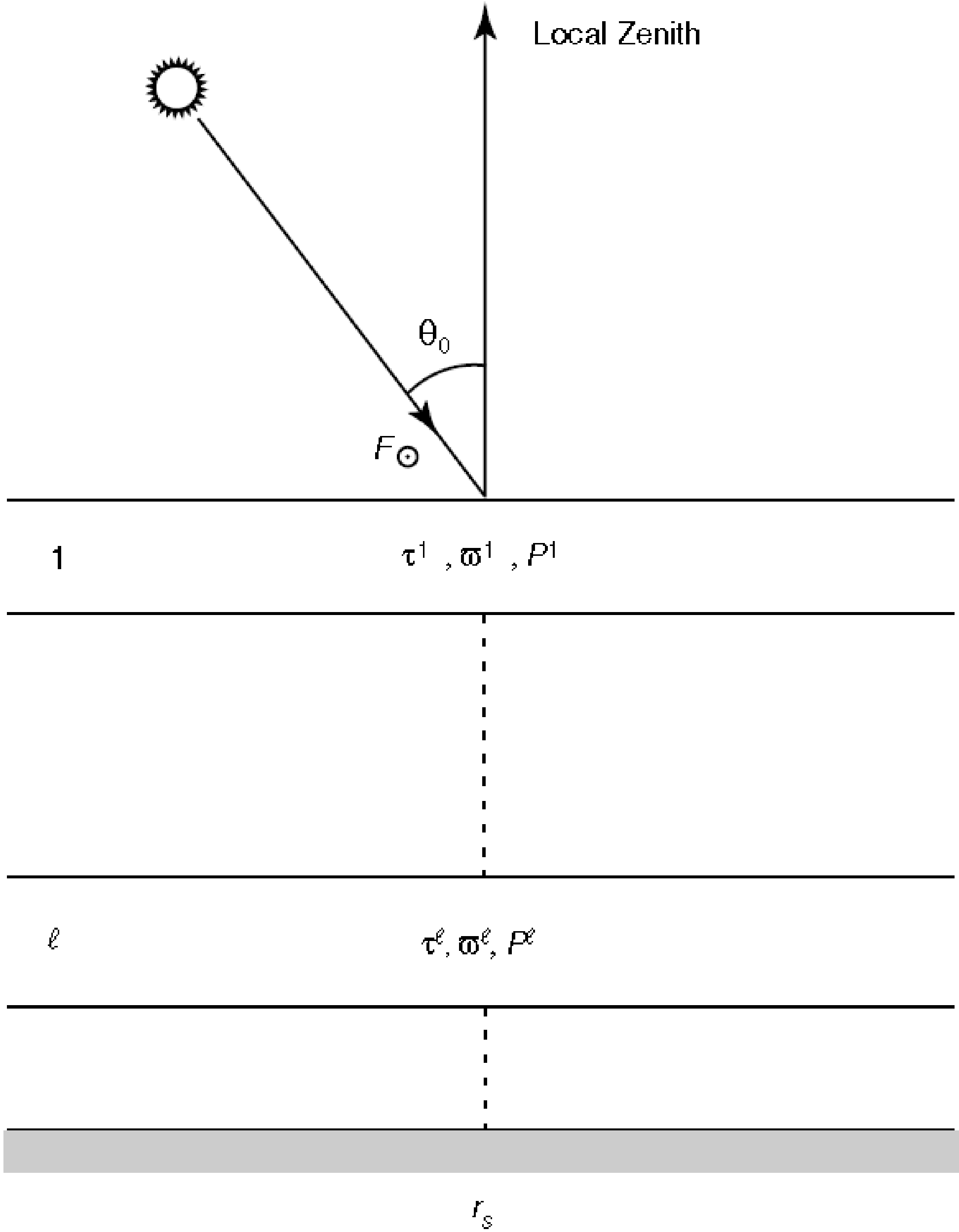
可导出：

$$\tau = k\lambda^{-b} = k\lambda^{-\nu+2}$$

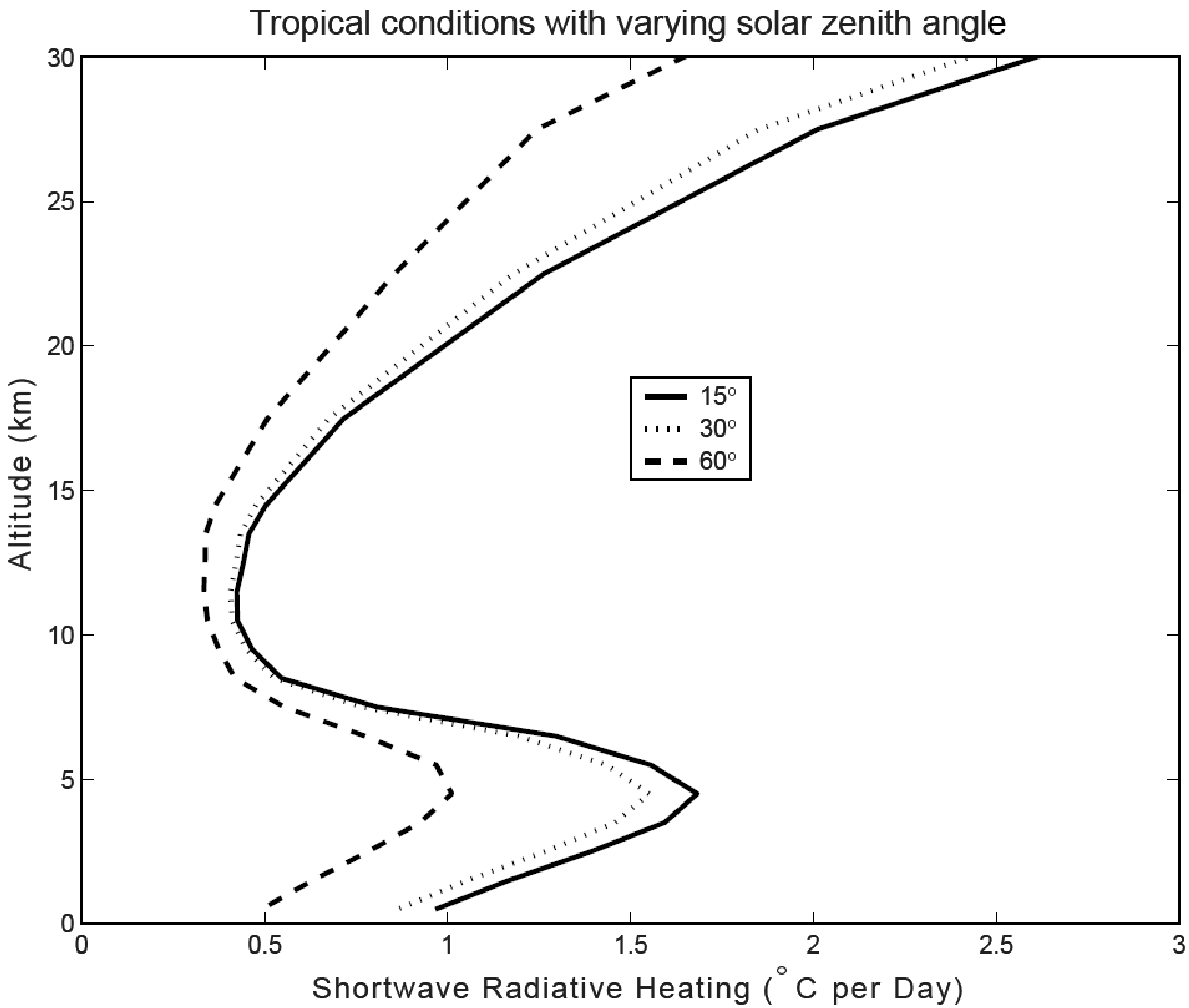
ν为Junge分布中的谱形常数

当ν =3.3时，*k*被称为Ångström浑浊度系数（Ångström *turbidity coefficient*）

大气光学性质


Local Zenith
θ_0
$F_\odot$
1
τ^1 , ϖ^1 , P^1
ℓ
τ^ℓ, ϖ^ℓ, P^ℓ
r_s

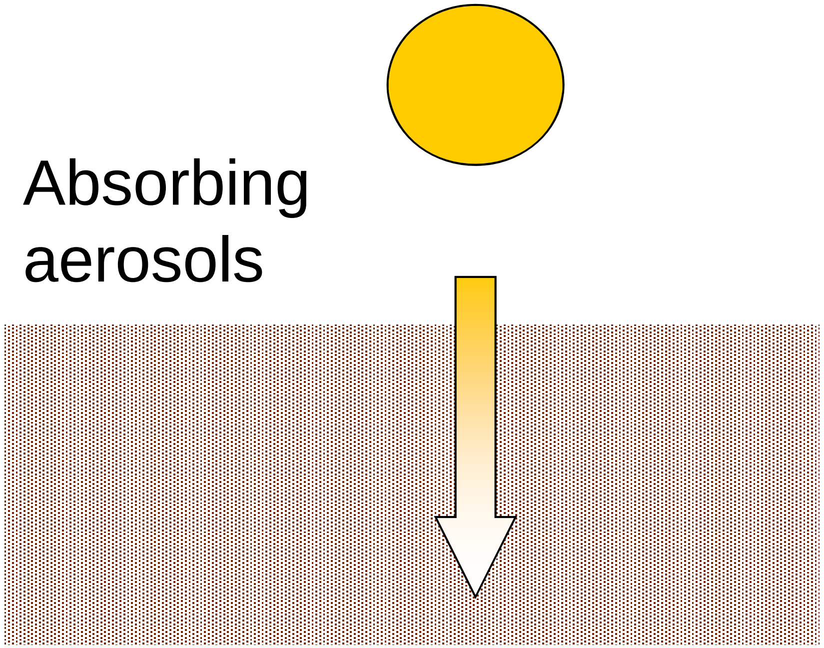
短波辐射增温率



Tropical conditions with varying solar zenith angle
Altitude (km)
Shortwave Radiative Heating (°C per Day)
15°
30°
60°
0
5
10
15
20
25
30
0
0.5
1
1.5
2
2.5
3

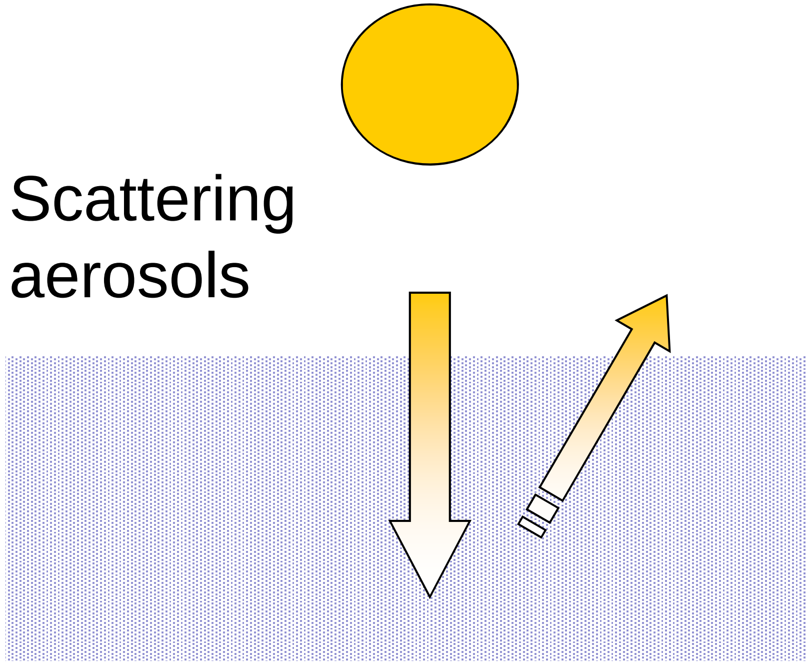
气溶胶的辐射效应

Direct effect



Solar radiation absorbed (Warming)

e.g. Black carbon, mineral dust

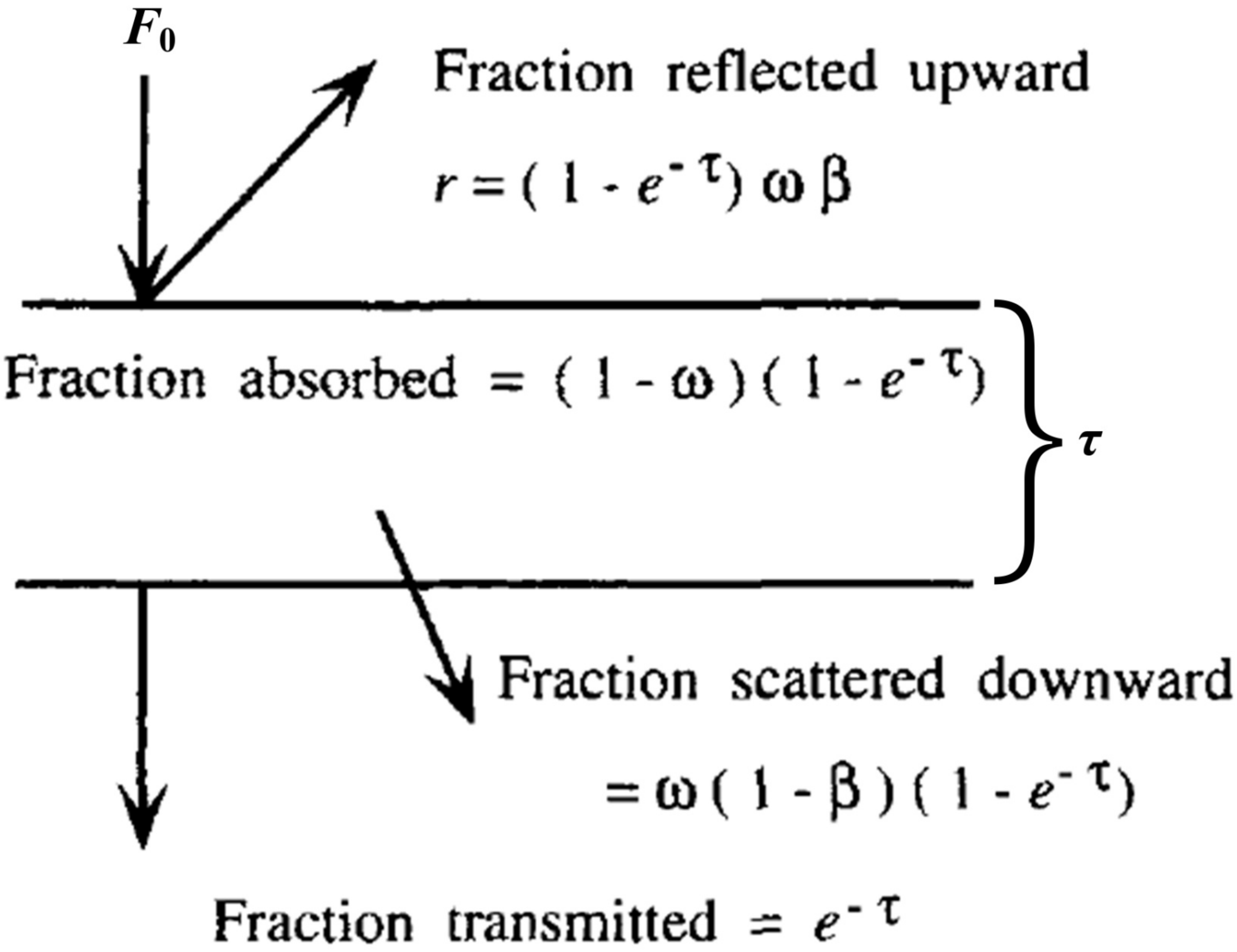


Solar radiation scattered to space (Cooling)

e.g. Sulphates, nitrates, organics

Most aerosols both absorb and scatter!

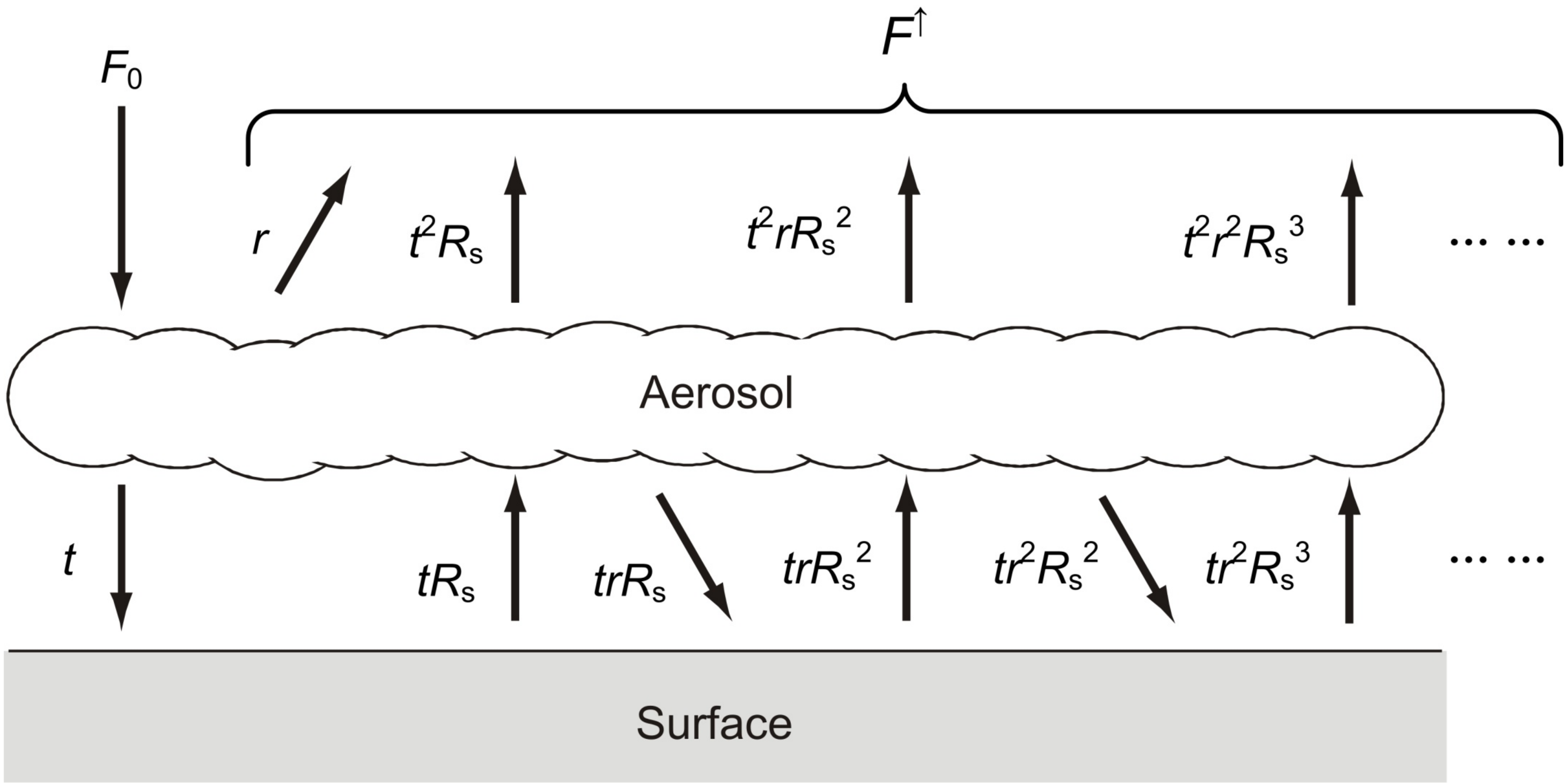
直接效应



总透过率：

$$t = e^{-\tau} + \omega(1-\beta)\left(1-e^{-\tau}\right)$$

直接效应



$$F^{\uparrow} = \left(r + t^2 R_s + t^2 r R_s^{\,2} + t^2 r^2 R_s^{\,3} + \cdots \right) F_0$$

直接效应

$$F^{\uparrow} = \left(r + t^2 R_s + t^2 r R_s^{\ 2} + t^2 r^2 R_s^{\ 3} + \cdots\right) F_0$$

$$= \left[r + t^2 R_s \left(1 + r R_s + r^2 R_s^{\ 2} + r^3 R_s^{\ 3} + \cdots\right)\right] F_0$$

$$= \left[r + \frac{t^2 R_s}{1 - r R_s}\right] F_0 \qquad \left(r < 1;\ R_s < 1\right)$$

气溶胶层与地面的总反射率：

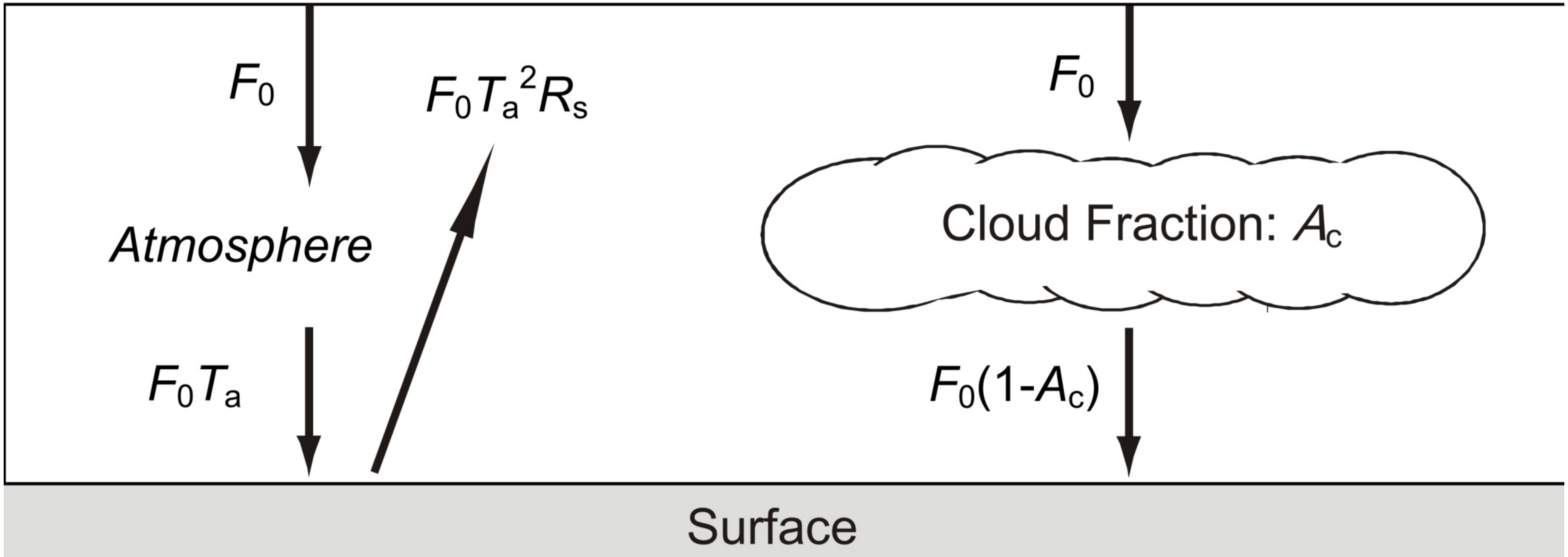
$$R_{as} = \frac{F^{\uparrow}}{F_0} = \left[r + \frac{t^2 R_s}{1 - r R_s}\right]$$

气溶胶层引起的反射率变化：

$$\Delta R_p = R_{as} - R_s = \left(r + \frac{t^2 R_s}{1 - r R_s}\right) - R_s$$

直接效应

气溶胶、大气、云的共同作用



$$\Delta F = F_0 \Delta R_p = F_0 (1 - A_c) T_a^2 \left[\left(r + \frac{t^2 R_s}{1 - r R_s} \right) - R_s \right]$$

直接效应

辐射强迫(Radiative Forcing)

$$\left(F^{\downarrow}-F^{\uparrow}\right)=-\Delta F=-F_0\left(1-A_c\right)T_a^2\left[\left(r+\frac{t^2R_s}{1-rR_s}\right)-R_s\right]$$

$$r=\omega\beta\left(1-e^{-\tau}\right);\ t=e^{-\tau}+\omega\left(1-\beta\right)\left(1-e^{-\tau}\right)$$

影响因子：

- F_0: incident solar flux ($W \cdot m^{-2}$)
- A_c: fraction of the surface covered by clouds
- T_a: fractional transmittance of the atmosphere
- R_s: albedo of the underlying Earth surface

- ω: single-scattering albedo of the aerosol
- β: upscatter fraction of the aerosol
- τ: aerosol optical depth

常用辐射传输软件

Atmospheric radiative transfer codes

http://en.wikipedia.org/wiki/Atmospheric_radiative_transfer_codes

Atmospheric radiation transfer for PV applications

http://www.appropedia.org/Atmospheric_radiation_transfer_for_PV_applications

同学练习

http://172.16.21.121/faculty/jyang/classes/atmosrad/topics.htm

DISORT、SBDART

SHDOM

LBLRTM

LinePak

MODTRAN

MOSART

libRadtran

SCIATRAN

谢谢！