

高能天体物理笔记

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第一章 高能辐射机制简述

1.1 辐射传播相关物理量的定义

$I_\nu(\theta, \phi)$: specific intensity (brightness, 亮度), 单位面积, 单位时间, 单位频率, 法线方向单位立体角穿过的能量,

$$I_\nu(\theta, \phi) = \frac{dE}{dA dt d\nu d\Omega}. \quad (1.1)$$

若法线方向沿 z 轴正方向, 且不要求法线方向穿过,

$$I_\nu(\theta, \phi) = \frac{dE}{(dA \cos \theta) dt d\nu d\Omega}. \quad (1.2)$$

J_ν : 平均强度,

$$J_\nu = \frac{1}{4\pi} \int I_\nu(\theta, \phi) d\Omega. \quad (1.3)$$

在自由空间, 沿视线方向, 辐射强度不变.

F_ν : monochromatic energy flux (单色能流量): 单位面积, 单位时间, 在单位频率间隔穿过的能量,

$$F_\nu = \int I_\nu(\theta, \phi) \cos \theta d\Omega. \quad (1.4)$$

\mathcal{F} : energy fluence (能流): 单位面积穿过的能量,

$$\mathcal{F} = \int F_\nu dt d\nu. \quad (1.5)$$

$u_\nu(\theta, \phi)$: radiative energy density 辐射能量密度,

$$u_\nu(\theta, \phi) = \frac{dE}{(dA c dt) d\nu d\Omega}, \quad (1.6)$$

$$u_\nu(\theta, \phi) = \frac{1}{c} I_\nu(\theta, \phi). \quad (1.7)$$

$$u_\nu = \frac{4\pi}{c} J_\nu. \quad (1.8)$$

整理: specific intensity / brightness

$$dE_\nu(\Omega) = I_\nu(\Omega) dA_\perp(\Omega) dt d\Omega d\nu, \quad (1.9)$$

net flux

$$dE_\nu = F_\nu dA dt d\nu \quad (1.10)$$

$$= \int_\Omega I_\nu(\Omega) dA_\perp(\Omega) dt d\Omega d\nu \quad (1.11)$$

$$= \int_\Omega I_\nu(\Omega) dA \cos \theta dt d\Omega d\nu \quad (1.12)$$

$$= \left(\int_\Omega I_\nu(\Omega) \cos \theta d\Omega \right) dA dt d\nu, \quad (1.13)$$

momentum flux

$$dP_{\perp\nu}(\Omega) = dp_{\perp\nu}(\Omega) dA dt d\nu, \quad (1.14)$$

$$dP_{\perp\nu}(\Omega) = dP_\nu(\Omega) \cos \theta \quad (1.15)$$

$$= (dE_\nu(\Omega)/c) \cos \theta \quad (1.16)$$

$$= (I_\nu(\Omega)/c) \cos^2 \theta d\Omega dA dt d\nu, \quad (1.17)$$

energy density

$$dE_\nu(\Omega) = u_\nu(\Omega) dV_\perp(\Omega) d\Omega d\nu \quad (1.18)$$

$$= u_\nu(\Omega) dA_\perp(\Omega) c dt d\Omega d\nu, \quad (1.19)$$

$$dE_\nu(\Omega) = I_\nu(\Omega) dA_\perp(\Omega) dt d\Omega d\nu, \quad (1.20)$$

$$J_\nu = \frac{\int I_\nu(\Omega) d\Omega}{\int d\Omega} \quad (1.21)$$

$$= \int (I_\nu(\Omega)/4\pi) d\Omega. \quad (1.22)$$

$$I_{\nu 1}(\Omega) dA_{\perp 1}(\Omega) dt d\Omega_1 d\nu = I_{\nu 2}(\Omega) dA_{\perp 2}(\Omega) dt d\Omega_2 d\nu, \quad (1.23)$$

$$d\Omega_1 = dA_{\perp 2}(\Omega)/r^2, \quad d\Omega_2 = dA_{\perp 1}(\Omega)/r^2, \quad (1.24)$$

$$I_{\nu 1}(\Omega) = I_{\nu 2}(\Omega). \quad (1.25)$$

1.2 辐射转移

$$ddE_\nu(\Omega) = \epsilon_\nu(\Omega) dV_\perp(\Omega) dt d\Omega d\nu \quad (1.26)$$

$$= \epsilon_\nu(\Omega) dA_\perp(\Omega) ds dt d\Omega d\nu \quad (1.27)$$

$$= dI_\nu(\Omega) dA_\perp(\Omega) dt d\Omega d\nu \quad (1.28)$$

$$dI_\nu(\Omega) = \epsilon_\nu(\Omega) ds, \quad (1.29)$$

$$dS_\perp(\Omega) = \sigma_\nu dN_\perp(\Omega) \quad (1.30)$$

$$= \sigma_\nu n dV_\perp(\Omega) \quad (1.31)$$

$$= \sigma_\nu n dA_\perp(\Omega) ds, \quad (1.32)$$

$$ddE_\nu(\Omega) = -I_\nu(\Omega) dS_\perp(\Omega) dt d\Omega d\nu \quad (1.33)$$

$$= -I_\nu(\Omega) \sigma_\nu n dA_\perp(\Omega) ds dt d\Omega d\nu \quad (1.34)$$

$$= -I_\nu(\Omega) \alpha_\nu dA_\perp(\Omega) ds dt d\Omega d\nu \quad (1.35)$$

$$= dI_\nu(\Omega) dA_\perp(\Omega) dt d\Omega d\nu \quad (1.36)$$

$$dI_\nu(\Omega) = -I_\nu(\Omega) \alpha_\nu ds, \quad (1.37)$$

1.3 辐射机制

1.3.1 黑体辐射

热平衡: 宏观无热量交换. 热辐射: 辐射源热平衡. 黑体辐射: 辐射源热平衡 + 辐射全被辐射源吸收 \Rightarrow 辐射热平衡.

$$\hbar\omega/kT \ll 1, \propto \omega^2 \quad \hbar\omega/kT \gg 1, \propto e^{-\hbar\omega/kT}. \quad \hbar\omega_W/kT \approx 2.82.$$

1.3.2 加速带电粒子的电磁辐射

$$\vec{A}(t, \vec{r}) = \frac{\mu_0}{4\pi} \int \frac{\vec{j}(t - |\vec{r} - \vec{r}'|, \vec{r}')}{|\vec{r} - \vec{r}'|} dV' \quad (1.38)$$

$$\vec{r}_e(t), \vec{j}(t, \vec{r}') = q\delta(\vec{r}' - \vec{r}_e)\vec{v}_e, K = 1 - \frac{\vec{r} - \vec{r}_e}{|\vec{r} - \vec{r}_e|} \vec{v}_e, \\ \vec{A}(t, \vec{r}) = \left[\frac{q\vec{v}_e}{K|\vec{r} - \vec{r}_e|} \right] \Big|_{t=t-|\vec{r}-\vec{r}_e|} \quad (1.39)$$

电场中单电子的辐射

$$I_{\parallel}/I_{\perp} \approx 1/\gamma^2, \omega \approx \gamma v/b.$$

热韧致辐射 $\tau \gg 1, \propto \omega^2, \tau \ll 1 \wedge \hbar\omega/kT \ll 1, \approx \text{const}, \hbar\omega/kT \gg 1,$
 $\propto e^{-\hbar\omega/kT}.$

非热韧致辐射

1.3.3 磁场中单电子的辐射

$$evB = \gamma m \omega^2 r = \gamma m \omega v, \omega_g = eB/\gamma m = \omega_{\text{cycle}}/\gamma.$$

回旋辐射

同步辐射 周期 $2\pi/\omega_g$, 宽度 $\approx 1/\gamma^3\omega_g$.

$$\omega/\omega_c \ll 1, \propto \omega^{1/3}, \omega/\omega_c \gg 1, \propto e^{-\omega/\omega_c}. \omega_c = 3\gamma^2 eB/2m = (3/2)\gamma^3\omega_g. \\ \tau \gg 1, I(\omega) \propto \omega^{5/2}, \tau \ll 1, N(E) \propto E^{-p}, I(\omega) \propto \omega^{-(p-1)/2}.$$

1.3.4 光子散射

Thomson 散射

$$m_e c^2 = \frac{e^2}{4\pi\epsilon_0 r_e} \\ \frac{d\sigma_T}{d\Omega} := \frac{\frac{dE_{\text{out}}}{dt d\Omega}}{S_{\text{in}}} = \frac{\frac{dE_{\text{out}}}{dt d\Omega}}{\frac{dE_{\text{in}}}{dt dA}}, \quad S_{\text{in}} \sigma_T = \frac{dE_{\text{out}}}{dt} \quad (1.40)$$

Compton 散射

$$\hbar\omega/m_e c^2 \ll 1, \sigma \approx \sigma_T, \hbar\omega/m_e c^2 \gg 1, \sigma \propto \omega^{-1}.$$

逆 Compton 散射

$$\omega \leq 4\gamma^2\omega_0. \omega \ll 4\gamma^2\omega_0, \propto \omega$$

第二章 银河系内

2.1 星际介质

$$x/D = \theta, (1-x)/D = \alpha, \alpha = [x/(1-x)]\theta, \theta_{\text{sca}} = \theta + \alpha = [x/(1-x) + 1]\theta = 1/(1-x) \theta, \theta = (1-x)\theta_{\text{sca}}.$$

$$\sqrt{1+\delta^2} \approx 1 + \frac{1}{2}\delta^2, xD(1 + \frac{1}{2}\theta^2) + (1-x)D(1 + \frac{1}{2}\alpha^2), \frac{1}{2}xD\theta^2 + \frac{1}{2}(1-x)D\alpha^2 = \frac{1}{2}xD\theta^2 + \frac{1}{2}(1-x)D[x^2/(1-x)^2]\theta^2 = \frac{1}{2}xD\theta^2 + \frac{1}{2}D[x^2/(1-x)]\theta^2, \frac{1}{2}x + \frac{1}{2}[x^2/(1-x)] = \frac{1}{2}x/(1-x)$$

2.2 XB

第三章 银河系外

3.1 一般星系

^{26}Al 衰变, 1.089 MeV 谱线.

色色图: 较软能段硬度比 $\frac{M-S}{H+M+S}$ -较硬能段硬度比 $\frac{H-M}{H+M+S}$.

3.2 AG

多波段, 强度高.

3.2.1 AG 分类

3.2.2 AGN 统一模型

3.2.3 射电宁静 AGN

区域: AGN 核心区域, 靠近 BH, 吸积盘内侧.

3.2.4 宽线, 窄线, 反响映射

3.2.5 射电噪 AGN

视超光速

Doppler 增亮

3.3 GRB