輻射性衝撃波の構造

Radiative Shocks


目次

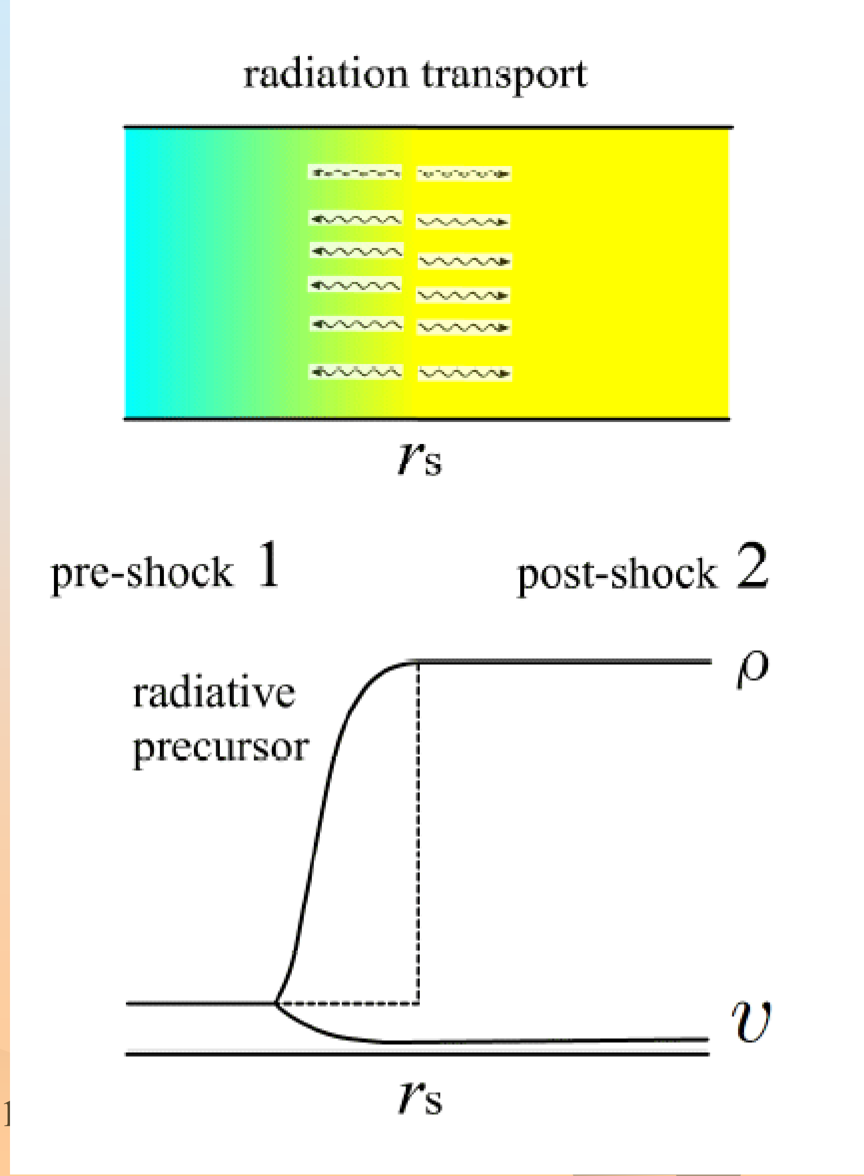

概要

- 構造
  - 前駆領域 precursor
  - 緩和領域 relaxation

今回

- 分類(光学的厚み)
  - thick-thick
  - thin-thin
  - thin-thick
  - thick-thin △

今回



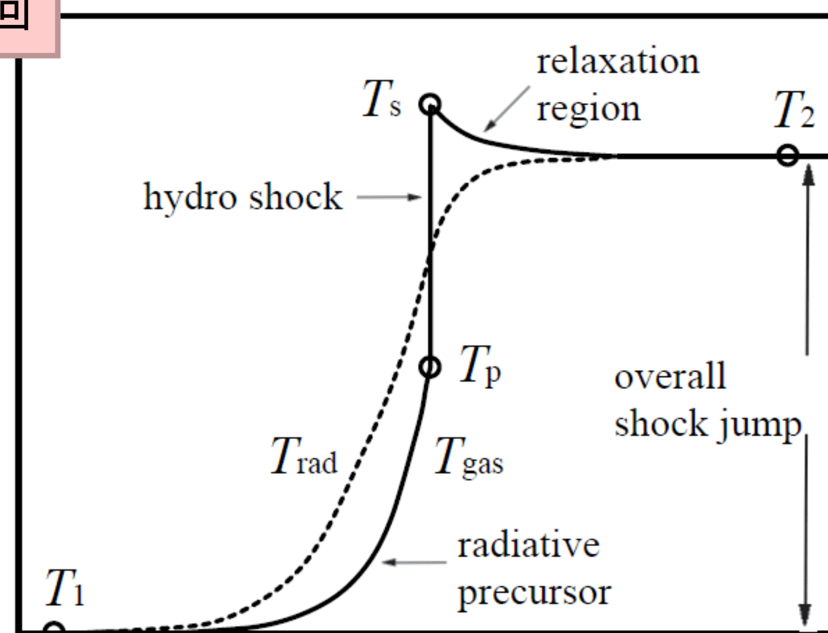
概要

- 分類(ガス輻射平衡)
  - strong equilibrium limit
    (1流体近似)有効比熱比Γ
  - equilibrium diffusion app.
    ($T_{rad}=T_{gas}$)
  - nonequilibrium diffusion
    (T_{rad}<>T_{gas})

$$\Gamma \equiv \frac{\beta+(\gamma-1)(4-3\beta)}{\beta+3(\gamma-1)(1-\beta)}.$$

今回

- 分類(M1, 温度分布)
  - subcritical ($T_p<T_2$)
  - critical ($T_p=T_2$)
  - supercritical ($T_p=T_2$)



平衡拡散近似

- 構造方程式

  衝撃波上流　2、無印

  衝撃波下流　1

- 衝撃波座標　x

- 密度　ρ
- 相対速度　u
- ガス圧、輻射圧　p, P
- 内部E　e, E
- 温度、輻射流束　T, F

$$\rho u = \rho_1 u_1 = j, \tag{23.73}$$

$$\rho u^2 + p + P = \rho_1 u_1^2 + p_1 + P_1, \tag{23.74}$$

$$u\left(\frac{1}{2}\rho u^2 + e + p + E + P\right) + F = u_1\left(\frac{1}{2}\rho_1 u_1^2 + e_1 + p_1 + E_1 + P_1\right), \tag{23.75}$$

$$F = -\frac{c}{\kappa\rho}\frac{dP}{dx} = -\frac{4acT^3}{3\kappa\rho}\frac{dT}{dx}, \tag{23.76}$$

平衡拡散近似

- 跳び条件→
- RH関係↓

$$\rho_2 u_2 = \rho_1 u_1 = j,$$

$$\rho_2 u_2^2 + p_2 + P_2 = \rho_1 u_1^2 + p_1 + P_1,$$

$$\frac{1}{2}u_2^2 + \frac{\gamma}{\gamma-1}\frac{p_2}{\rho_2} + \frac{4P_2}{\rho_2} = \frac{1}{2}u_1^2 + \frac{\gamma}{\gamma-1}\frac{p_1}{\rho_1} + \frac{4P_1}{\rho_1},$$

$$\frac{\gamma}{\gamma-1}\frac{p_2}{\rho_2} + \frac{4P_2}{\rho_2} - \left(\frac{\gamma}{\gamma-1}\frac{p_1}{\rho_1} + \frac{4P_1}{\rho_1}\right) - \frac{1}{2}\left[p_2 + P_2 - (p_1 + P_1)\right]\left(\frac{1}{\rho_1} + \frac{1}{\rho_2}\right) = 0, \qquad (23.80)$$

$$\frac{p_2 + P_2 - (p_1 + P_1)}{\rho_2 - \rho_1} = \frac{\rho_1}{\rho_2}a_1^2 \mathcal{M}_1^2 = \frac{1}{\rho_2}\gamma p_1 \mathcal{M}_1^2, \qquad (23.81)$$

where a_1 ($\equiv \sqrt{\gamma p_1/\rho_1}$) is the sound speed in the upstream region, and $\mathcal{M}_1$ ($\equiv u_1/a_1$) the Mach number of the upstream flow.

温度に関する9次方程式→ガス圧優勢 or 輻射圧優勢

平衡拡散近似

- 前駆領域（衝撃波座標 x）

$$\frac{4acT^3}{3\kappa\rho}\frac{dT}{dx} = \left(\frac{1}{2}\rho u^2 + \frac{\gamma}{\gamma-1}p + 4P\right)u - \left(\frac{1}{2}\rho_1 u_1^2 + \frac{\gamma}{\gamma-1}p_1 + 4P_1\right)u_1. \qquad (23.82)$$

Eliminating u $(=\rho_1 u_1/\rho)$, and again introducing the Mach number $\mathcal{M}_1$ $(= u_1/a_1)$ in the upstream region, we can arrange the above equation as

$$\frac{4acT^3}{3\kappa\rho}\frac{dT}{dx} = \left\{\frac{1}{2}\frac{\gamma p_1}{\rho_1}\mathcal{M}_1^2\left[\left(\frac{\rho_1}{\rho}\right)^2 - 1\right] + \frac{\gamma}{\gamma-1}\left(\frac{p}{\rho} - \frac{p_1}{\rho_1}\right) + \frac{4P}{\rho} - \frac{4P_1}{\rho_1}\right\}\rho_1 u_1. \qquad (23.83)$$

Similarly, the momentum conservation (23.74) is rearranged as

$$p - p_1 = \rho_1 a_1^2 \mathcal{M}_1^2\left(1 - \frac{\rho_1}{\rho}\right) - (P - P_1). \qquad (23.84)$$

平衡拡散近似

- 前駆領域(つづき)

Substituting equations of state $p = (\mathcal{R}/\mu)\rho T$ and $P = aT^4/3$ into equations (23.83) and (23.84), we have two equations on the two variables (ρ and T):

$$\frac{4acT^3}{3\kappa\rho}\frac{dT}{dx} = \left\{\frac{1}{2}\gamma\frac{\mathcal{R}}{\mu}T_1\mathcal{M}_1^2\left[\left(\frac{\rho_1}{\rho}\right)^2 - 1\right] + \frac{\gamma}{\gamma-1}\frac{\mathcal{R}}{\mu}T_1\left(\frac{T}{T_1} - 1\right) + \frac{1}{\rho_1}\frac{4}{3}aT_1^4\left[\frac{\rho_1}{\rho}\left(\frac{T}{T_1}\right)^4 - 1\right]\right\}\rho_1 u_1, \quad (23.85)$$

$$\frac{\mathcal{R}}{\mu}\rho_1 T_1\left(\frac{\rho}{\rho_1}\frac{T}{T_1} - 1\right) = \gamma\frac{\mathcal{R}}{\mu}\rho_1 T_1\mathcal{M}_1^2\left(1 - \frac{\rho_1}{\rho}\right) - \frac{a}{3}T_1^4\left[\left(\frac{T}{T_1}\right)^4 - 1\right]. \quad (23.86)$$

平衡拡散近似

- 前駆領域(つづき)

Introducing the nondimensional quantities, $\tilde{\rho}$ ($\equiv \rho/\rho_1$), $\tilde{T}$ ($\equiv T/T_1$) and $\tilde{x}$ ($\equiv x/\ell_1$, ℓ_1 being a typical length scale), we can finally express equations (23.85) and (23.86), respectively, as

$$\frac{4\alpha_1}{\beta_1\tau_1}\frac{\tilde{T}^3}{\tilde{\rho}}\frac{d\tilde{T}}{d\tilde{x}} = \frac{\gamma}{2}\mathcal{M}_1^2\left(\frac{1}{\tilde{\rho}^2}-1\right) + \frac{\gamma}{\gamma-1}\left(\tilde{T}-1\right) + 4\alpha_1\left(\frac{\tilde{T}^4}{\tilde{\rho}}-1\right) \quad (23.87)$$

$$\tilde{\rho} = \frac{1+\gamma\mathcal{M}_1^2-\alpha_1(\tilde{T}^4-1)-\sqrt{[1+\gamma\mathcal{M}_1^2-\alpha_1(\tilde{T}^4-1)]^2-4\gamma\mathcal{M}_1^2\tilde{T}}}{2\tilde{T}}, \quad (23.88)$$

where α_1 ($\equiv P_1/p_1$), β_1 ($\equiv u_1/c$), and τ_1 ($\equiv \kappa\rho_1\ell_1$). From the physical viewpoints, we here separate several parameters, although β_1 and τ_1 can be renormalized in the coordinate scale. In addition, the root for $\tilde{\rho}$ was chosen so as to $\tilde{\rho}(\tilde{T}_1) = 1$.

平衡拡散近似
ガス圧優勢

- 跳び条件と前駆領域の構造方程式

$$\tilde{\rho}_2 \equiv \frac{\rho_2}{\rho_1} = \frac{(\gamma+1)\mathcal{M}_1^2}{(\gamma-1)\mathcal{M}_1^2+2}, \qquad (23.89)$$

$$\tilde{p}_2 \equiv \frac{p_2}{p_1} = \frac{2\gamma\mathcal{M}_1^2-(\gamma-1)}{\gamma+1}, \qquad (23.90)$$

$$\tilde{T}_2 \equiv \frac{T_2}{T_1} = \frac{[2\gamma\mathcal{M}_1^2-(\gamma-1)][(\gamma-1)\mathcal{M}_1^2+2]}{(\gamma+1)^2\mathcal{M}_1^2}. \qquad (23.91)$$

$$\frac{4\alpha_1}{\beta_1\tau_1}\frac{\tilde{T}^3}{\tilde{\rho}}\frac{d\tilde{T}}{d\tilde{x}} = \frac{\gamma}{2}\mathcal{M}_1^2\left(\frac{1}{\tilde{\rho}^2}-1\right)+\frac{\gamma}{\gamma-1}\left(\tilde{T}-1\right), \qquad (23.92)$$

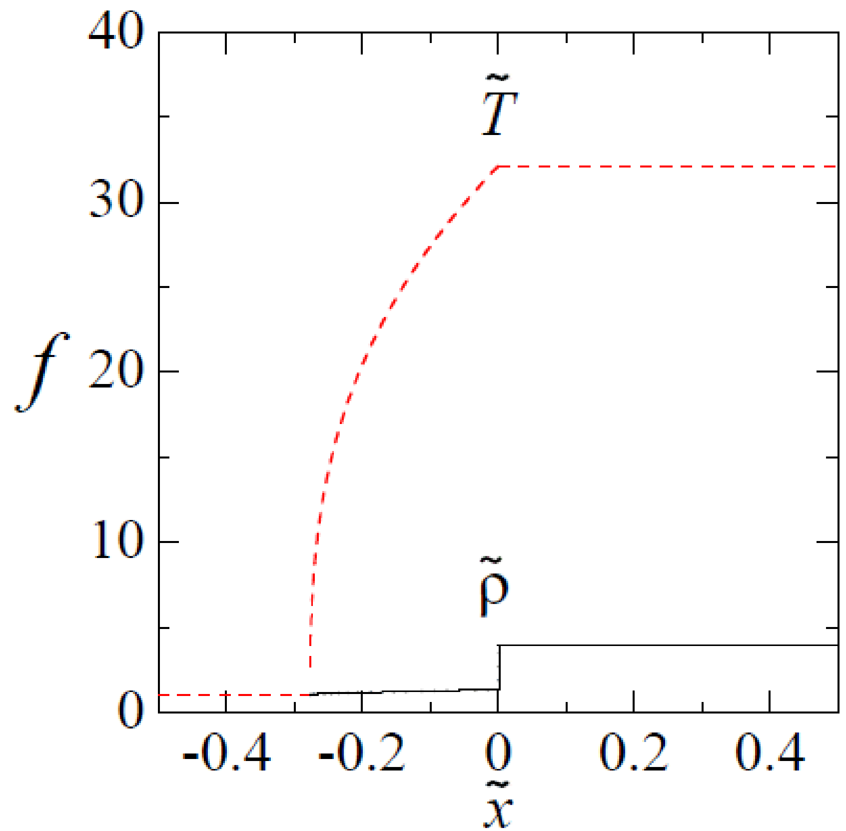
$$\tilde{\rho} = \frac{1+\gamma\mathcal{M}_1^2-\sqrt{(1+\gamma\mathcal{M}_1^2)^2-4\gamma\mathcal{M}_1^2\tilde{T}}}{2\tilde{T}}, \qquad (23.93)$$

平衡拡散近似
ガス圧優勢

- 密度構造は不連続
- 温度構造は連続
- →isothermal shock

- 輻射性衝撃波では輻射エネルギーが上流へ貫入し、前駆領域の温度を上昇させる。ガス圧優勢の場合、衝撃波が強くなると、上流の温度は急激に上昇し、下流の温度に達する。下流の温度より高くはなれないので、その後は、前駆領域を押し広げていく。

- $\gamma=5/3$; $\alpha_1/\beta_1\tau_1=0.00001$; $M_1=10$



平衡拡散近似
輻射圧優勢

- 跳び条件と前駆領域の構造方程式

$$\frac{4P_2}{\rho_2} - \frac{4P_1}{\rho_1} - \frac{1}{2}(P_2 - P_1)\left(\frac{1}{\rho_1} + \frac{1}{\rho_2}\right) = 0, \tag{23.98}$$

$$\frac{P_2 - P_1}{\rho_2 - \rho_1} = \frac{\rho_1}{\rho_2} a_1^2 \mathcal{M}_1^2 = \frac{P_1}{\rho_1}\frac{\gamma}{\alpha_1}\mathcal{M}_1^2, \tag{23.99}$$

which are easily solve to yield

$$\tilde{\rho}_2 \equiv \frac{\rho_2}{\rho_1} = \frac{7\gamma\mathcal{M}_1^2/\alpha_1}{\gamma\mathcal{M}_1^2/\alpha_1 + 8}, \tag{23.100}$$

$$\tilde{P}_2 \equiv \frac{P_2}{P_1} = \frac{6\gamma\mathcal{M}_1^2/\alpha_1 - 1}{7}. \tag{23.101}$$

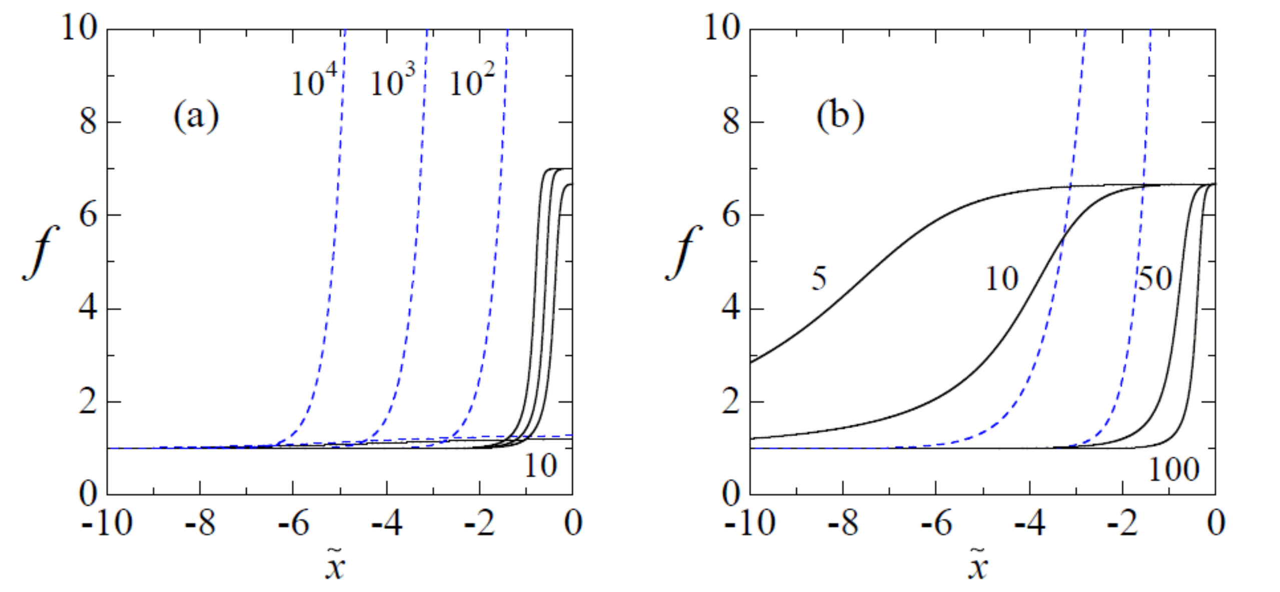
$$\frac{1}{\beta_1\tau_1}\frac{1}{\tilde{\rho}}\frac{d\tilde{P}}{d\tilde{x}} = \frac{1}{2}\frac{\gamma}{\alpha_1}\mathcal{M}_1^2\left(\frac{1}{\tilde{\rho}^2} - 1\right) + 4\left(\frac{\tilde{P}}{\tilde{\rho}} - 1\right), \tag{23.102}$$

$$\frac{1}{\tilde{\rho}} = 1 + \frac{1 - \tilde{P}}{\gamma\mathcal{M}_1^2/\alpha_1}. \tag{23.103}$$

平衡拡散近似
輻射圧優勢

- 密度構造が連続
- →continuous shock
- 輻射圧優勢の場合、衝撃波が強くなっても、上流の温度はそれほど上昇しないが、密度構造は連続的に変化。
- 圧縮率は
- 最大7倍

- $\gamma=5/3\,;\alpha_1=100\,;\beta_1=0.01$
- (a) $\tau_1=100\,;M_1=10^{1\text{-}4}$
- (b) $M_1=100\,;\tau_1=5\text{-}100$
- 実線　ρ、破線　P



相対論的輻射性衝撃波

Fukue 2019b

福江　純@大阪教育大学

相対論的輻射性衝撃波
ガス圧優勢

- 跳び条件
- Γ=5/3

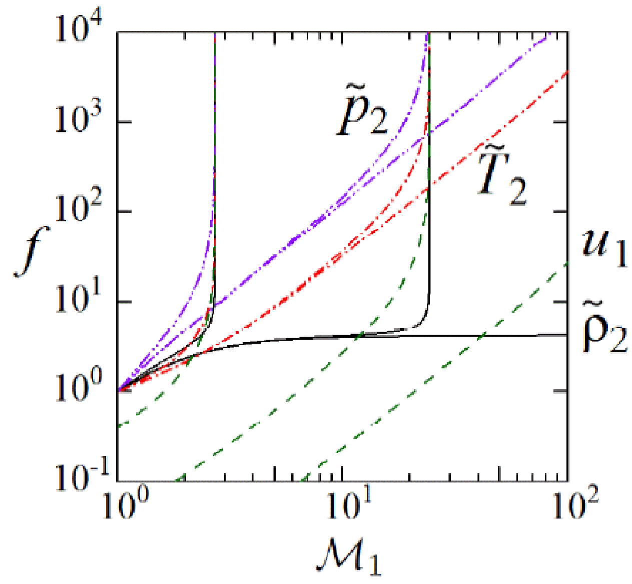


Fig. 25.2 Post-shock quantities as a function of $\mathcal{M}_1$ in the gas-pressure dominated case ($\Gamma = 5/3$). Solid curves represent $\tilde{\rho}_2$, where $\nu_1 = 0.00001, 0.001, 0.1$ from right to left. Chain-dotted ones mean $\tilde{T}_2$, where $\nu_1 = 0.00001, 0.001, 0.1$ from right to left, while two-dot chain ones are $\tilde{p}_2$, where $\nu_1 = 0.00001, 0.001, 0.1$ from right to left. Finally, dashed ones denote the pre-shock u_1, where $\nu_1 = 0.00001, 0.001, 0.1$ from bottom to top.

相対論的輻射性衝撃波
ガス圧優勢

- 前駆領域
- Γ=5/3

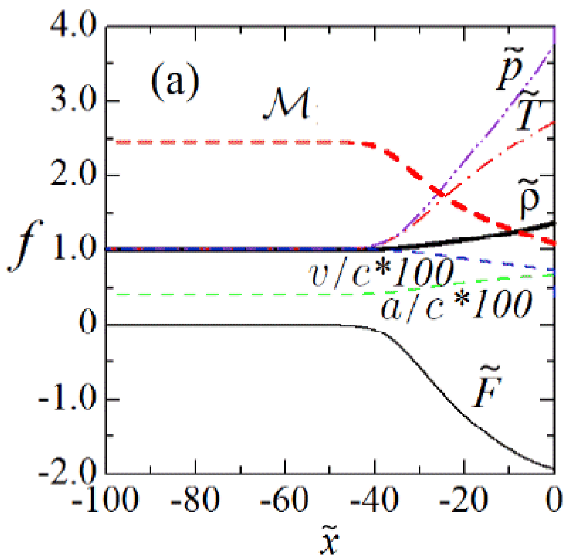


Fig. 25.4 Typical solutions for the radiative precursor region of the relativistic radiative shocks in the gas-pressure dominated case as a function of the normalized coordinate. Thick solid curves represent $\tilde{\rho}$, thin chain-dotted ones $\tilde{T}$, thin two-dot chain ones $\tilde{p}$, thin dashed ones v/c (upper) and a/c, thick dashed ones $\mathcal{M}$, and thin solid ones $\tilde{F}$. The parameters are $\Gamma = 5/3$ and (a) $\nu_1 = 0.00001$ and $\mathcal{M}_1 = 2.46$ ($\tilde{p}_2 = 7.3$, $\beta_1 = 0.01$), and (b) $\nu_1 = 0.1$ and $\mathcal{M}_1 = 2.20$ ($\tilde{p}_2 = 9.3$, $\beta_1 = 0.74$). The density distribution is discontinuous, while the temperature one is continuous.

相対論的輻射性衝撃波
輻射圧優勢

- 跳び条件
- Γ=5/3

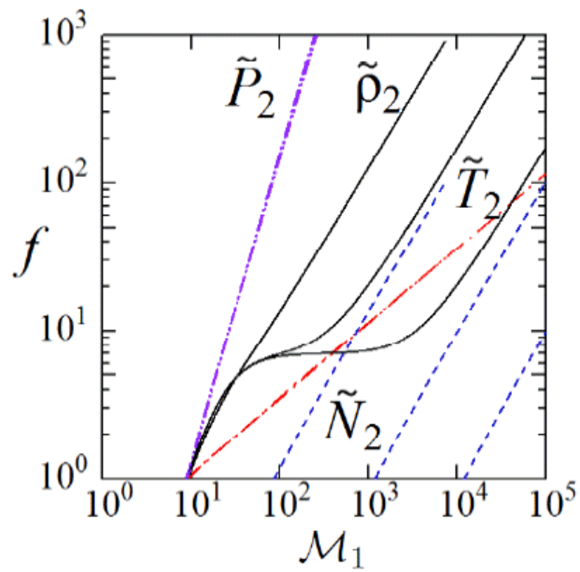


Fig. 25.6 Post-shock quantities as a function of $\mathcal{M}_1$ in the radiation-pressure dominated case. Solid curves represent $\tilde{\rho}_2$, where $\nu_1 = 0.00001, 0.001, 0.1$ from right to left. Chain-dotted ones mean $\tilde{T}_2$, while two-dot chain ones are $\tilde{P}_2$; both do not depend on N_2. Finally, dashed ones denote N_2, where $N_1 = 0.00001, 0.001, 0.1$ from right to left. The parameters are $\Gamma = 5/3$ and $\alpha_1 = 100$.

相対論的輻射性衝撃波
輻射圧優勢

- 前駆領域
- Γ=5/3

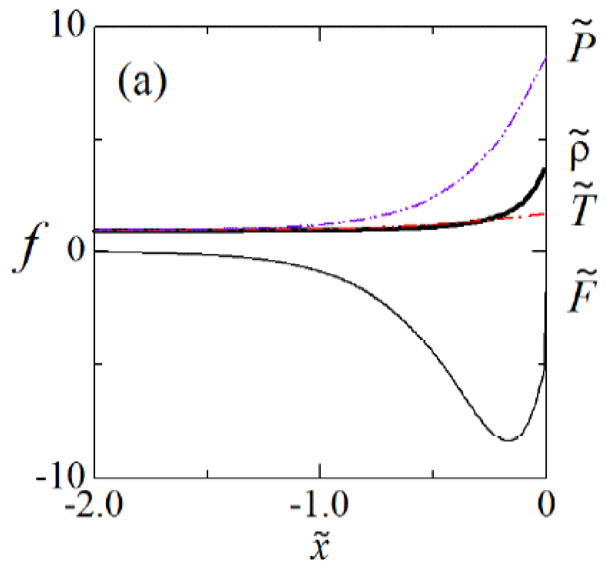


Fig. 25.8 Typical solutions for the radiative precursor region of the relativistic radiative shocks in the radiation-pressure dominated case as a function of the normalized coordinate. Thick solid curves represent $\tilde{\rho}$, thin chain-dotted ones $\tilde{T}$, thin two-dot chain ones $\tilde{P}$, and thin solid ones $\tilde{F}$. The parameters are $\Gamma = 5/3$ and $\alpha_1 = 100$ (a) $N_1 = 0.00001$ and $\mathcal{M}_1 = 24.8$ ($N_2 = 0.000022$, $\beta_1 = 0.01$), and (b) $N_1 = 0.1$ and $\mathcal{M}_1 = 52.85$ ($N_2 = 0.55$, $\beta_1 = 0.91$). The temperature distribution is continuous.

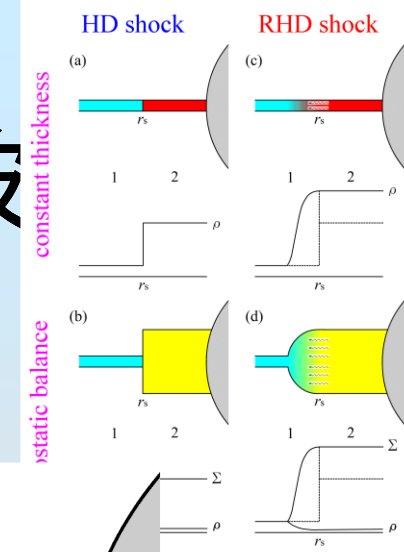

円盤降着流における輻射性衝撃波の構造

Fukue 2019a

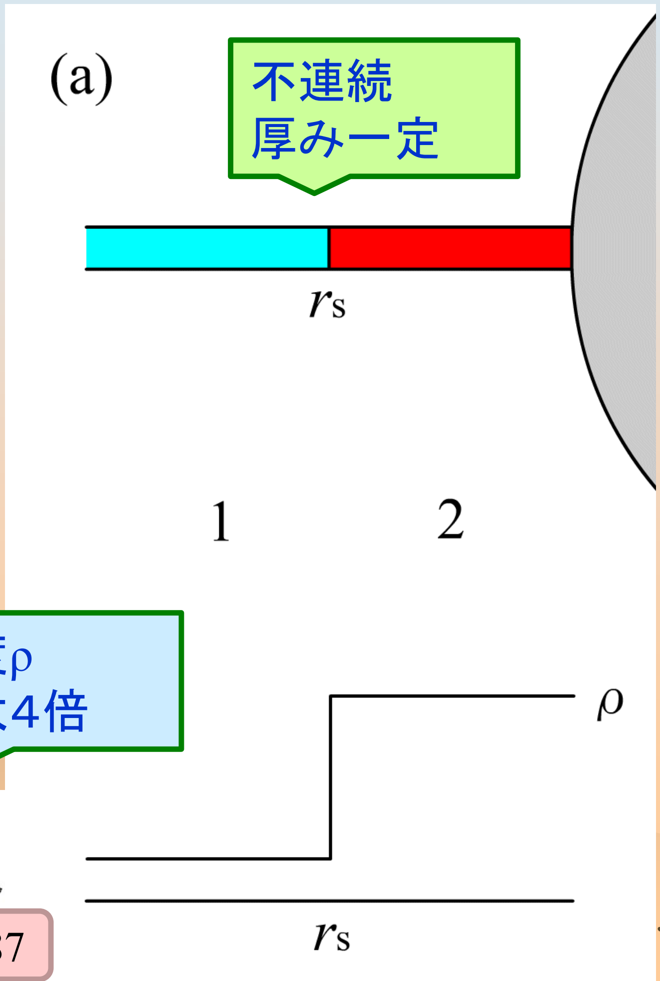
Radiative Shocks in Disk Accretion

福江　純＠大阪教育大学

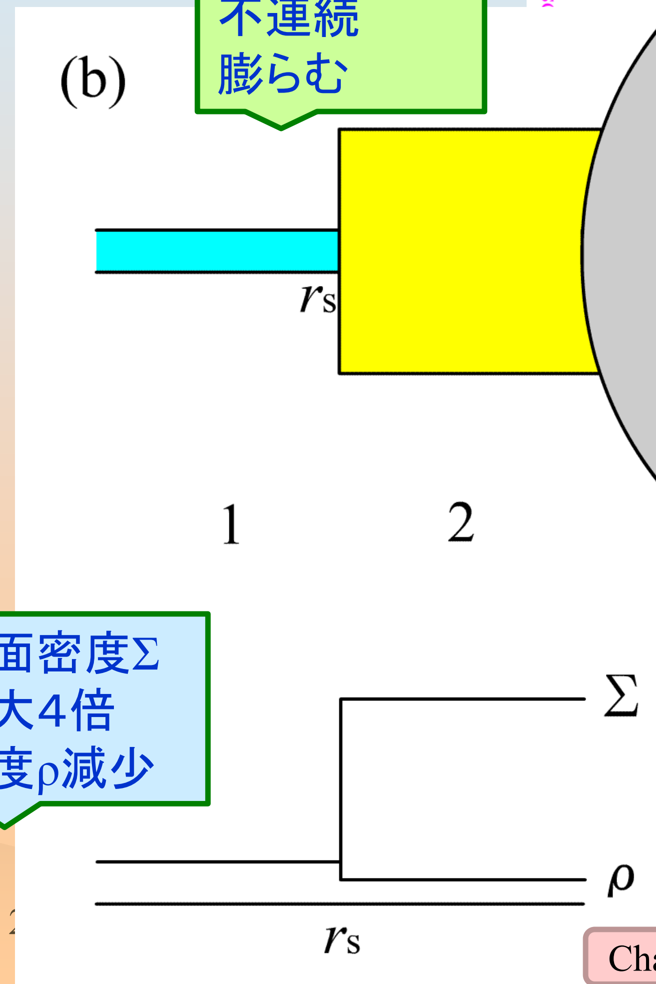

1　円盤降着と輻射性衝撃波

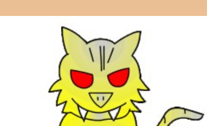


- HD：1D hydro shocks



- HD：vertical

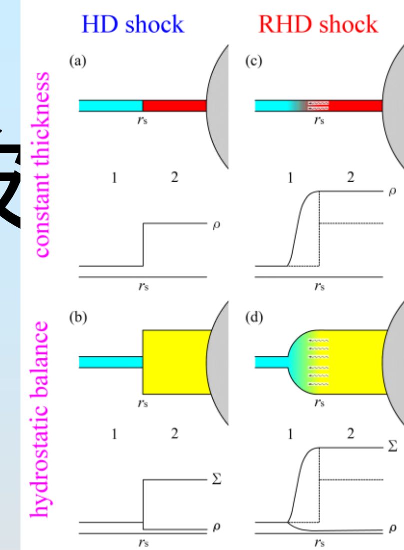




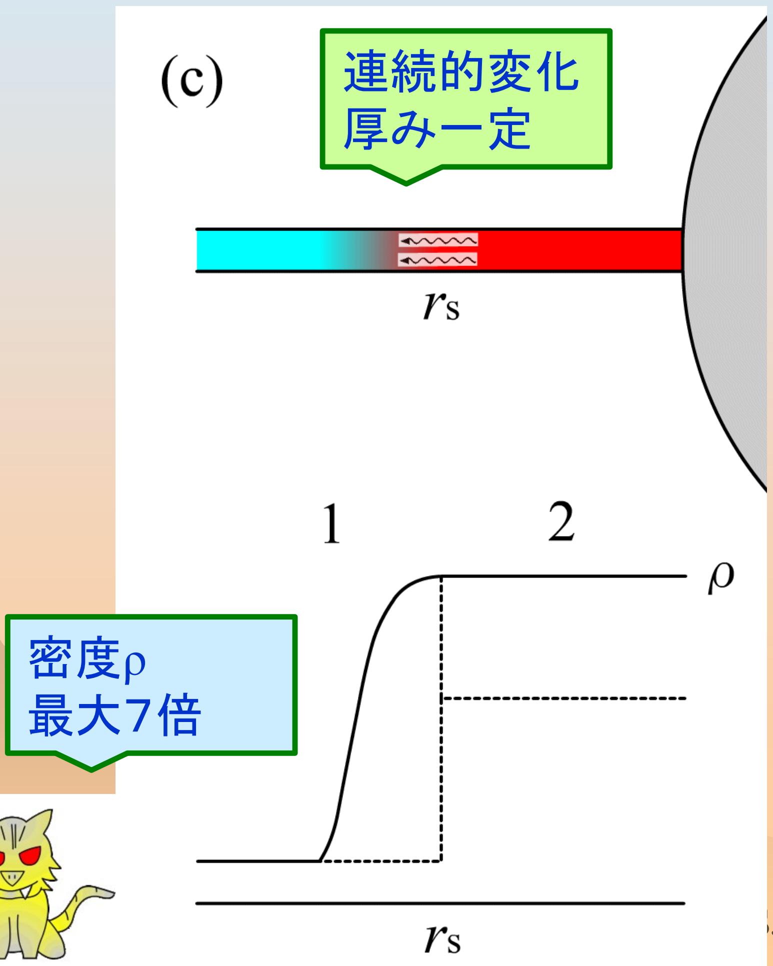
Fukue 1987

Chakurabarti 1989

1　円盤降着と輻射性衝撃波



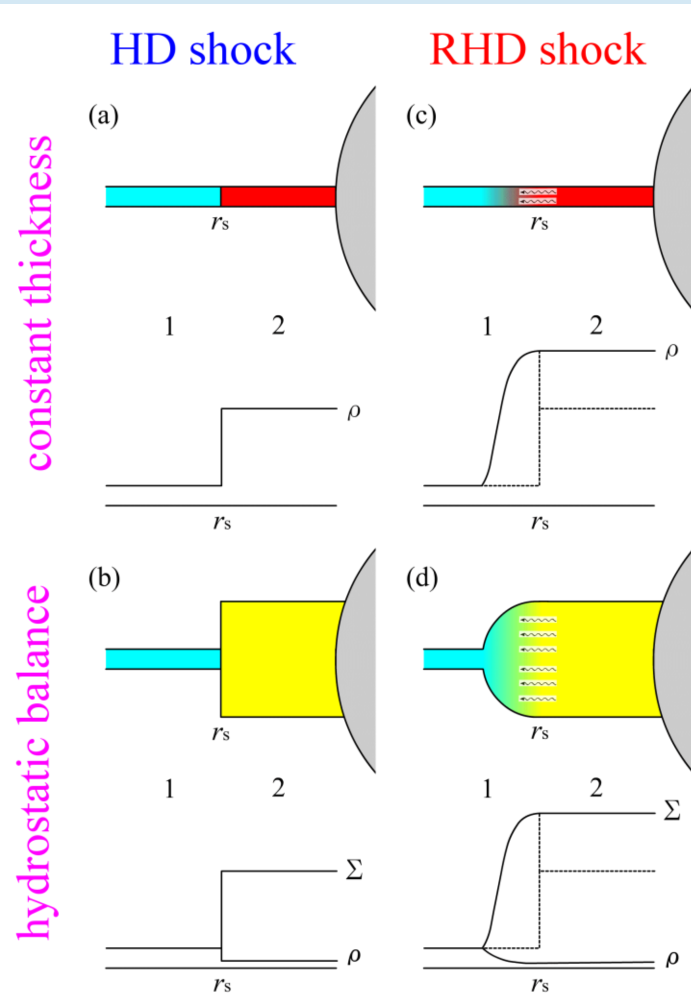
- RHD : 1D radiative shocks



- （光学的に厚い）
- 輻射拡散の効果

Zel'dovich 1957
Raizer 1957
Zel'dovich+Raizer 1966
Mihalas+Mihalas 1984
Lacey 1988
Bouquet+ 2000
Drake 2005, 2007
Lowrie+ 1999
Lowrie+Rauenzahn 2007
Lowrie+Edwards 2008
Tolstov+ 2015
Ferguson+ 2017

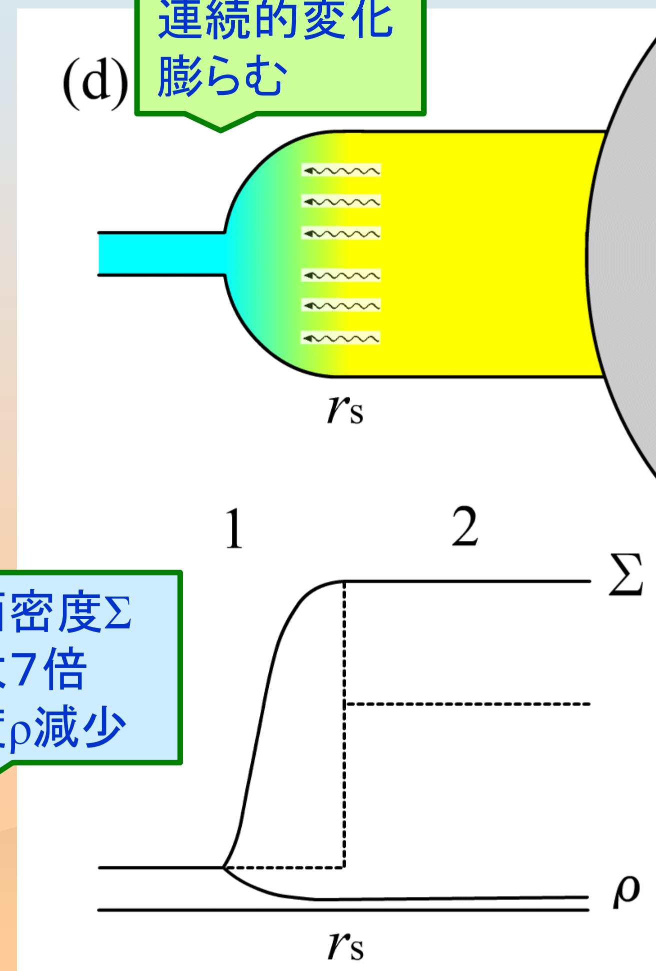
1　円盤降着と輻射性衝撃波＋＋



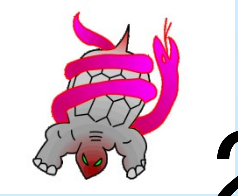
- RHD: radiative/vertical

連続的変化
膨らむ

輻射拡散
静水圧平衡



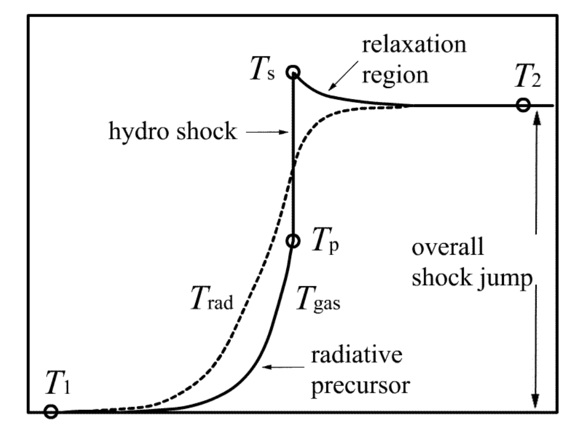
表面密度Σ
最大7倍
密度ρ減少

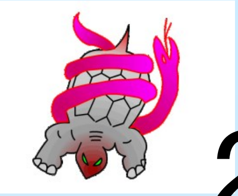


２　基礎方程式:平衡拡散近似

- 半径方向の降着流
- 光学的に厚い
- 平衡拡散近似
- エディントン近似
- 鉛直方向静水圧平衡
- 重力場・角運動量無視

- Strong Equilibrium
  - 有効比熱比
- Equilibrium Diffusion Approximation
  - $T_{\mathrm{rad}}=T_{\mathrm{gas}}$
  - 輻射拡散
- Nonequilibrium Diff.
  - T_{rad}<>T_{gas}
  - ゼルドヴィッチスパイク





2　基礎方程式:平衡拡散近似

- mass flux
- momentum flux
- energy flux

$$h\rho u = h_1\rho_1 u_1 = j \ (\mathrm{constant}),$$

$$h(\rho u^2 + p + P) = h_1(\rho_1 u_1^2 + p_1 + P_1)$$

$$h\rho u\left(\frac{1}{2}u^2 + \frac{\gamma}{\gamma-1}\frac{p}{\rho} + \frac{4P}{\rho}\right) + hF =$$

$$h_1\rho_1 u_1\left(\frac{1}{2}u_1^2 + \frac{\gamma}{\gamma-1}\frac{p_1}{\rho_1} + \frac{4P_1}{\rho_1}\right),$$

- radiative diffusion

$$F = -\frac{c}{\kappa\rho}\frac{dP}{dx} = -\frac{4acT^3}{3\kappa\rho}\frac{dT}{dx},$$

- vertical hydrostatic

$$\frac{GM}{r^3}h^2 = \frac{p+P}{\rho},$$

$$\frac{GM}{r_1^3}h_1^2 = \frac{p_1+P_1}{\rho_1},$$

or combined into the form:

$$h^2\frac{\rho}{p+P} = h_1^2\frac{\rho_1}{p_1+P_1},$$

２　基礎方程式:平衡拡散近似

- overall jump conditions
- 拡散項は落とす

- 密度 ρ
- 速度 u
- ガス圧 p, 輻射圧 P
- 厚み h

$$h_2\rho_2 u_2 = h_1\rho_1 u_1 = j,$$

$$h_2(\rho_2 u_2^2 + p_2 + P_2) = h_1(\rho_1 u_1^2 + p_1 + P_1),$$

$$\frac{1}{2}u_2^2 + \frac{\gamma}{\gamma-1}\frac{p_2}{\rho_2} + \frac{4P_2}{\rho_2} = \frac{1}{2}u_1^2 + \frac{\gamma}{\gamma-1}\frac{p_1}{\rho_1} + \frac{4P_1}{\rho_1},$$

$$\frac{h_2^2}{h_1^2} = \frac{\rho_1}{\rho_2}\frac{p_2+P_2}{p_1+P_1}$$

2　基礎方程式：平衡拡散近似

- Rankine-Hugoniot relation

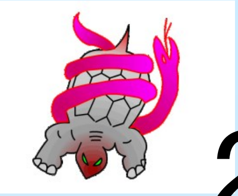
$$\frac{\gamma}{\gamma-1}\frac{p_2}{\rho_2}+\frac{4P_2}{\rho_2}-\left(\frac{\gamma}{\gamma-1}\frac{p_1}{\rho_1}+\frac{4P_1}{\rho_1}\right)$$

$$+\frac{1}{2}\frac{\frac{h_2}{h_1}(p_2+P_2)-(p_1+P_1)}{\frac{h_2}{h_1}\rho_2-\rho_1}\left(\frac{\rho_1}{\rho_2}\frac{h_1}{h_2}-\frac{\rho_2}{\rho_1}\frac{h_2}{h_1}\right)=0, \qquad (12)$$

$$\left[\frac{h_2}{h_1}(p_2+P_2)-(p_1+P_1)\right]\frac{\frac{h_2}{h_1}\rho_2}{\frac{h_2}{h_1}\rho_2-\rho_1}=\gamma p_1 \mathcal{M}_1^2, \qquad (13)$$

where $\mathcal{M}_1$ ($\equiv u_1/a_1$) the Mach number of the upstream flow,

$$\left(\frac{h_2}{h_1}\right)^2=\frac{\rho_1}{\rho_2}\frac{p_2+P_2}{p_1+P_1}.$$



2　基礎方程式:平衡拡散近似

- Radiative Precursor
- 温度 T: 衝撃波座標 x

$$
\begin{aligned}
h\frac{c}{\kappa\rho}\frac{dP}{dx} = h\frac{4acT^3}{3\kappa\rho}\frac{dT}{dx}
&= \left(\frac{1}{2}u^2 + \frac{\gamma}{\gamma-1}\frac{p}{\rho} + \frac{4P}{\rho}\right)h\rho u \\
&\quad - \left(\frac{1}{2}u_1^2 + \frac{\gamma}{\gamma-1}\frac{p_1}{\rho_1} + \frac{4P_1}{\rho_1}\right)h_1\rho_1 u_1. \qquad (15)
\end{aligned}
$$

$$
\begin{aligned}
\frac{h}{h_1}\frac{\rho_1}{\rho}\frac{\alpha_1}{\tau_1\beta_1}\frac{d}{d\tilde{x}}\frac{P}{P_1} &= \frac{1}{2}\gamma\mathcal{M}_1^2\left[\left(\frac{\rho_1}{\rho}\right)^2\left(\frac{h_1}{h}\right)^2 - 1\right] \\
&\quad + \frac{\gamma}{\gamma-1}\left(\frac{p}{p_1}\frac{\rho_1}{\rho} - 1\right) + 4\alpha_1\left(\frac{P}{P_1}\frac{\rho_1}{\rho} - 1\right) \qquad (16)
\end{aligned}
$$

$$
\frac{h}{h_1}p - p_1 + \frac{h}{h_1}P - P_1 = P_1\frac{\gamma}{\alpha_1}\mathcal{M}_1^2\left(1 - \frac{h_1}{h}\frac{\rho_1}{\rho}\right). \qquad (17)
$$

３　輻射圧優勢の場合

- Overall jump conditions
- 輻射圧 P

$$\frac{4P_2}{\rho_2}-\frac{4P_1}{\rho_1}+\frac{1}{2}\frac{\frac{h_2}{h_1}P_2-P_1}{\frac{h_2}{h_1}\rho_2-\rho_1}\left(\frac{\rho_1}{\rho_2}\frac{h_1}{h_2}-\frac{\rho_2}{\rho_1}\frac{h_2}{h_1}\right)=0,$$

$$\frac{h_2^2}{h_1^2}=\frac{\rho_1}{\rho_2}\frac{P_2}{P_1},$$

- 表面密度 $\Sigma=h\rho$

$$7\frac{P_2}{\Sigma_2}h_2-7+\frac{1}{\Sigma_2}-h_2P_2=0,$$

$$\Sigma_2 h_2=P_2,$$

and finally solved as

$$\Sigma_2=\frac{1}{14}\left[1-P_2^2+\sqrt{(1-P_2^2)^2+196P_2^2}\right].$$

３　輻射圧優勢の場合

- Overall jump conditions
- P
- $\Sigma = h\rho$

$$\left(\tilde{h}_2 \tilde{P}_2 - 1\right) \frac{\tilde{h}_2 \tilde{\rho}_2}{\tilde{h}_2 \tilde{\rho}_2 - 1} = \frac{\gamma}{\alpha_1} \mathcal{M}_1^2,$$

where $\alpha_1 = P_1 / p_1$.

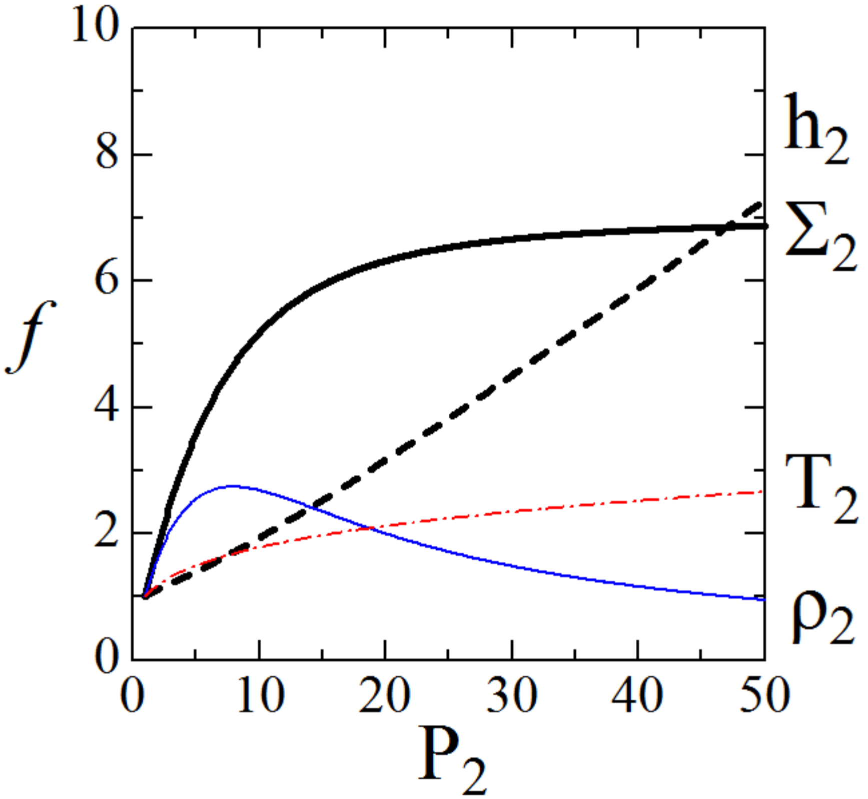
$$\frac{P_2^2 - \Sigma_2}{\Sigma_2 - 1} = \frac{\gamma}{\alpha_1} \mathcal{M}_1^2.$$

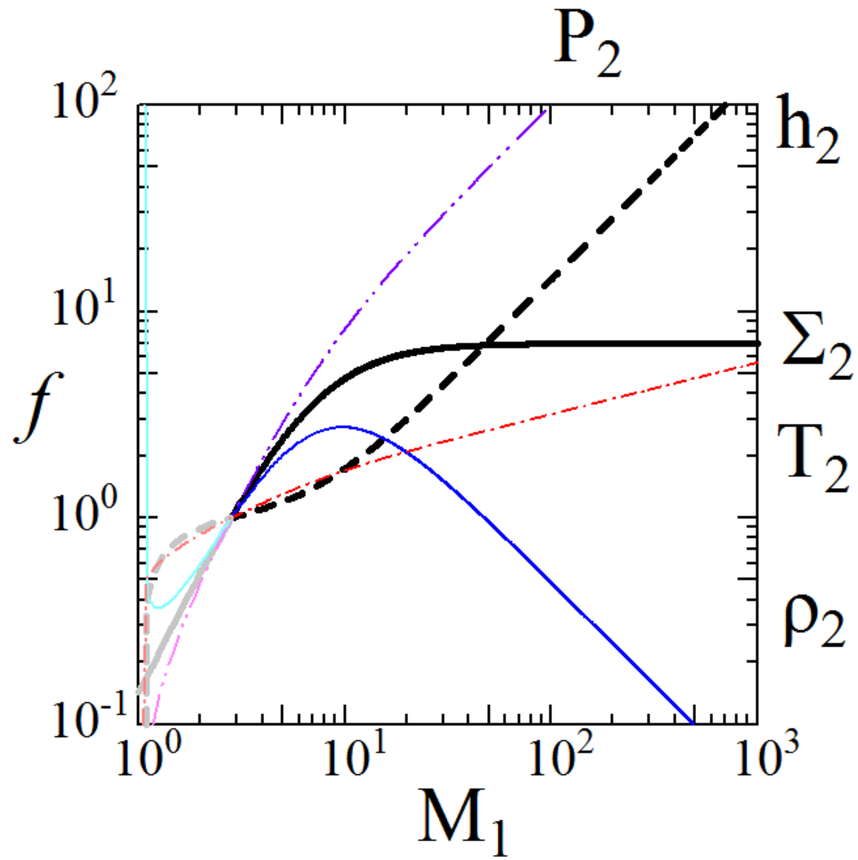
$$\Sigma_2 = \frac{7(\gamma/\alpha_1)\mathcal{M}_1^2}{(\gamma/\alpha_1)\mathcal{M}_1^2 + 8},$$

$$P_2^2 = \frac{[6(\gamma/\alpha_1)\mathcal{M}_1^2 - 1](\gamma/\alpha_1)\mathcal{M}_1^2}{(\gamma/\alpha_1)\mathcal{M}_1^2 + 8},$$

３　輻射圧優勢の場合

- P_2
- M_1





３　輻射圧優勢の場合

- Radiative Precursor
- 輻射圧 P

$$\frac{1}{\tau_1\beta_1}\frac{\tilde{h}}{\tilde{\rho}}\frac{d\tilde{P}}{d\tilde{x}} = \frac{1}{2}\frac{\gamma}{\alpha_1}\mathcal{M}_1^2\left(\frac{1}{\tilde{h}^2\tilde{\rho}^2}-1\right)+4\left(\frac{\tilde{P}}{\tilde{\rho}}-1\right),$$

$$\tilde{h}\tilde{P}-1 = \frac{\gamma}{\alpha_1}\mathcal{M}_1^2\left(1-\frac{1}{\tilde{h}\tilde{\rho}}\right),$$

$$\tilde{h}^2 = \frac{\tilde{P}}{\tilde{\rho}}.$$

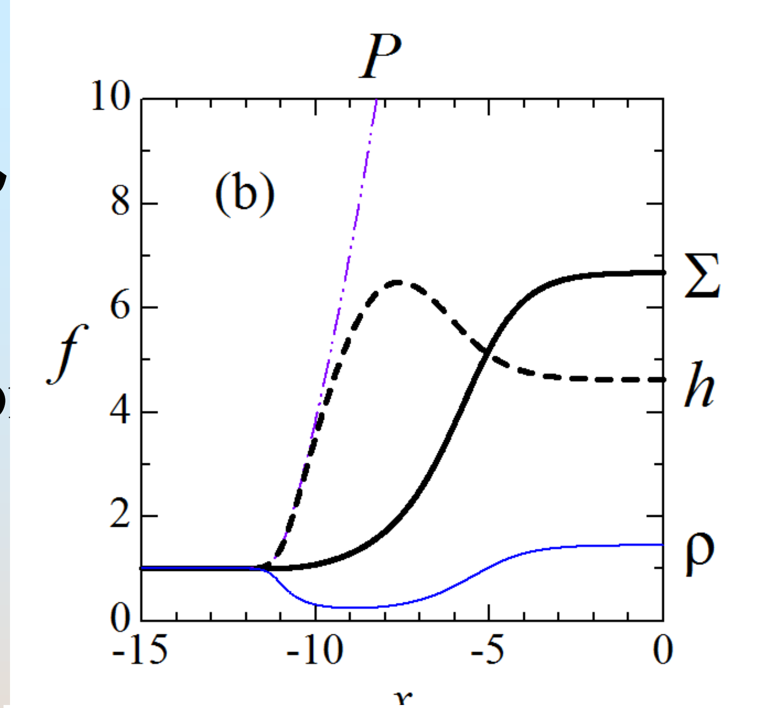
Again, introducing the surface density Σ ($\equiv h\rho$), and e
nating h, we can obtain the following equations:

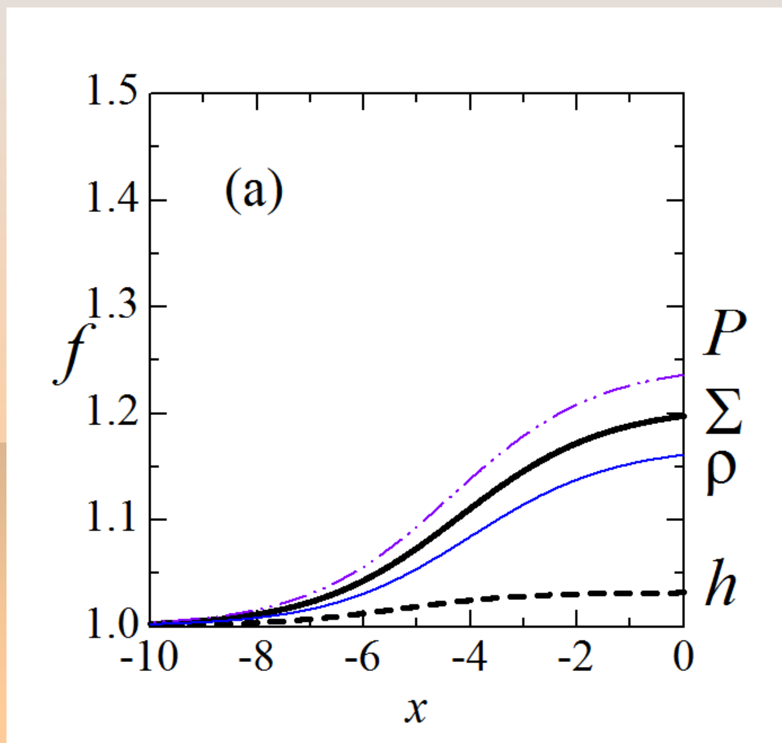
$$\frac{1}{\tau_1\beta_1}\frac{P^2}{\Sigma^3}\frac{dP}{dx} = \frac{1}{2}\frac{\gamma}{\alpha_1}\mathcal{M}_1^2\left(\frac{1}{\Sigma^2}-1\right)+4\left(\frac{P^2}{\Sigma^2}-1\right),$$

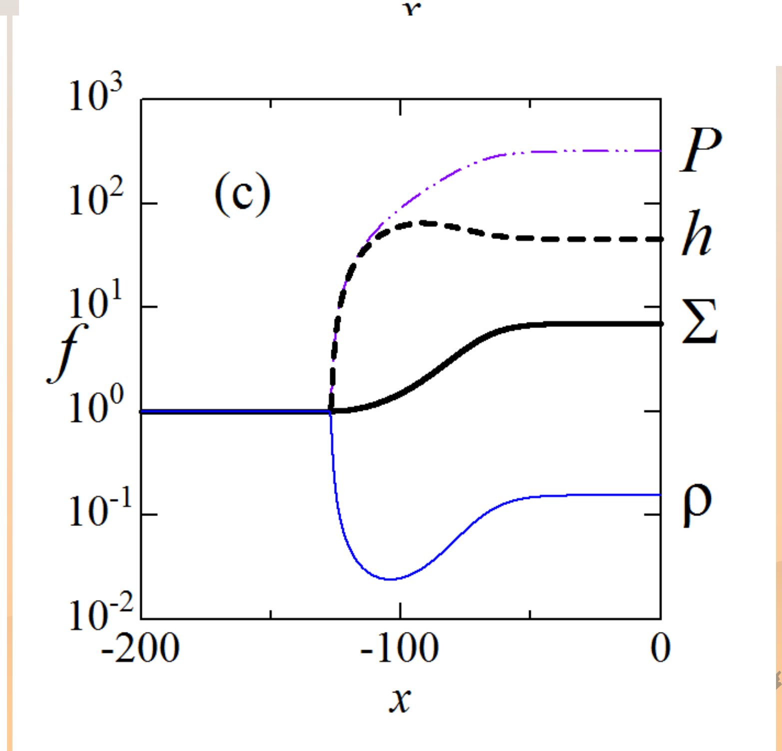
$$\Sigma = \frac{P^2+(\gamma/\alpha_1)\mathcal{M}_1^2}{1+(\gamma/\alpha_1)\mathcal{M}_1^2}.$$

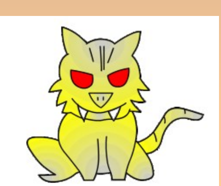
3　輻射圧優勢

- Radiative Precursor
- Co
- Continuous Shock
- $\gamma=5/3$, $\alpha_1=P_1/p_1=100$
- $M_1=$
- 10,
- 100,
- 1000



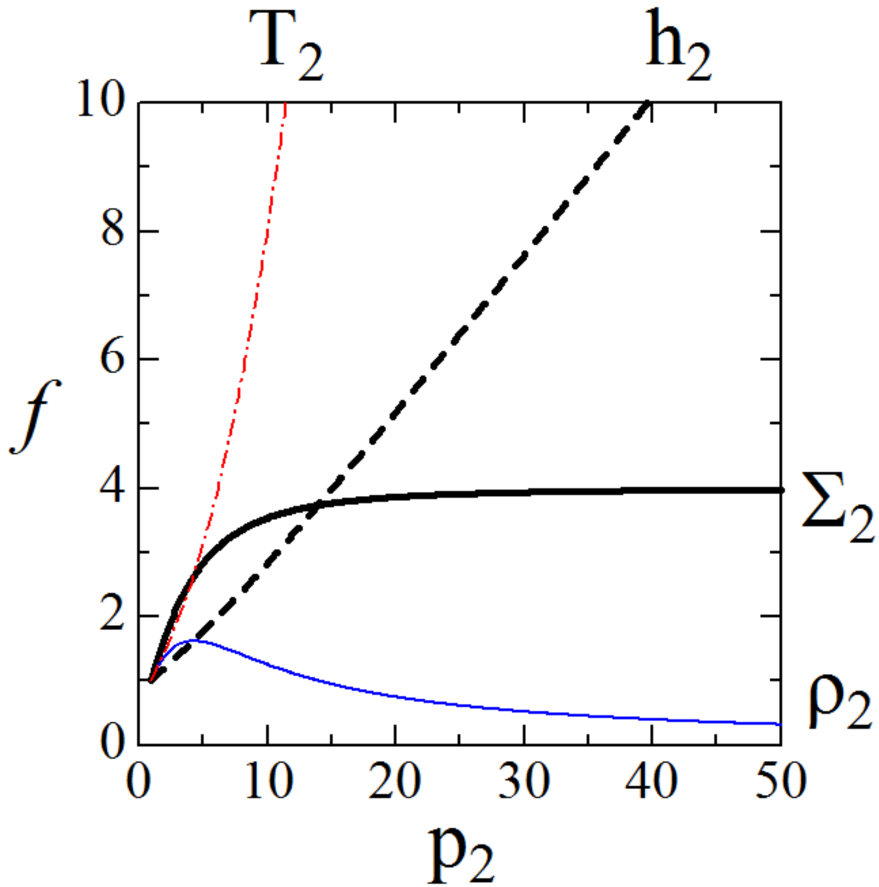




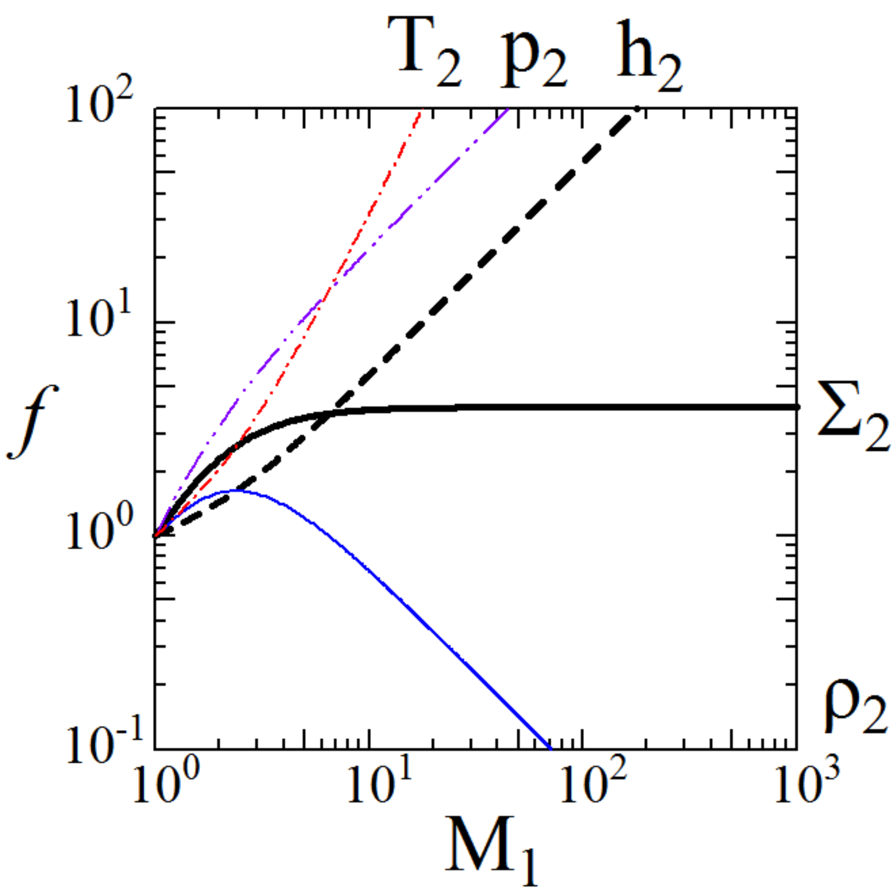


4　ガス圧優勢の場合

- p_2

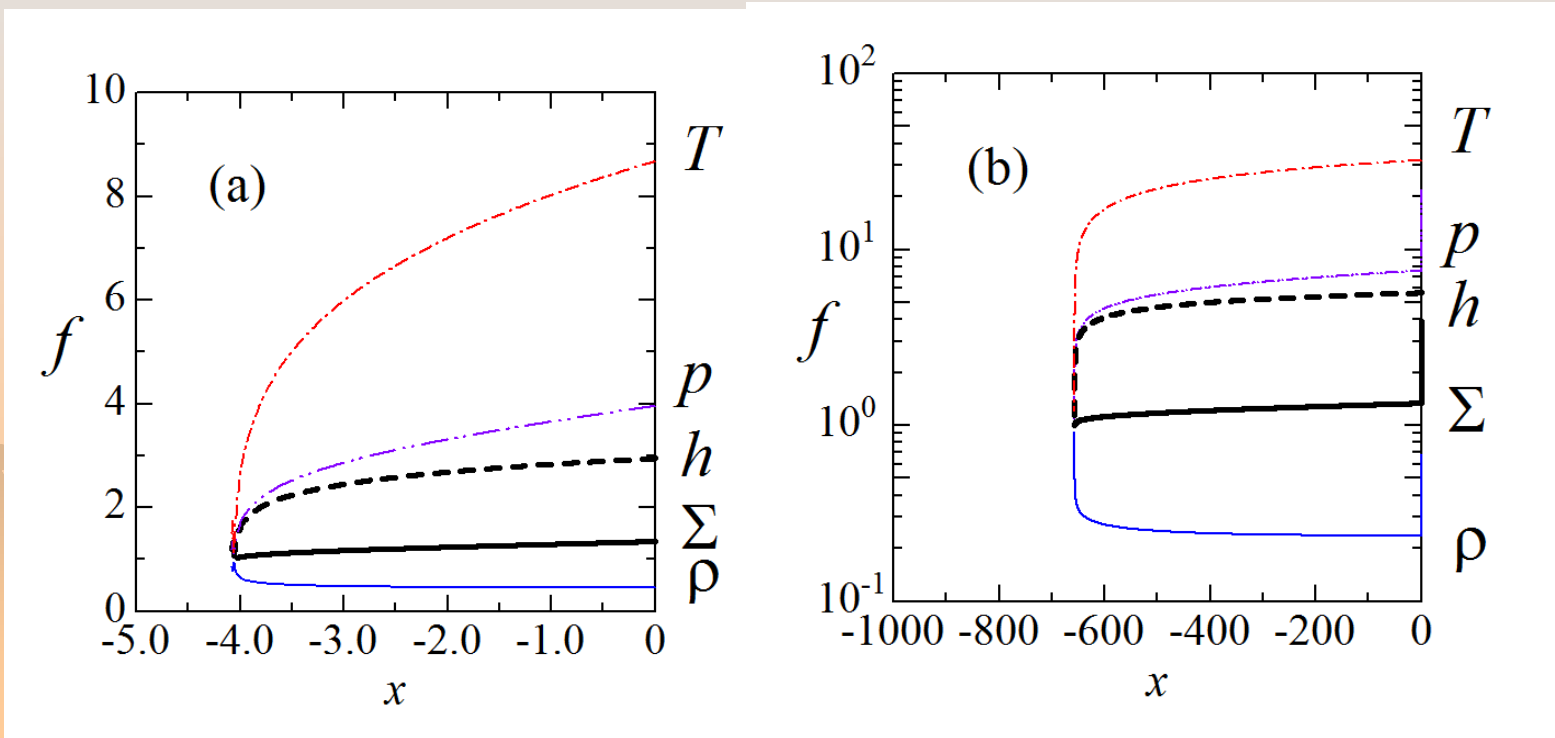


- M_1



4　ガス圧優勢の場合

- Radiative Precursor
- Isothermal Shock
- $\gamma=5/3$, $\alpha_1=0.00001$
- $M_1=$
- 5
- 10



課題

- magnetic field
- gas+radiation pre.
- rigorous EoS
- 重力場、曲率変化
  - Fukue 2019d
- 遷音速解とつなげる
- wave
- stability
- multi-components
  - dust
  - pair plasma

今後の課題

- 平衡拡散近似(1-T)
  - 非平衡拡散(2-T)
  - 輻射輸送方程式
- 降着流への組み込み
  - Okuda+ 2004
  - 重力場の変化、角運動量保存
- 相対論的輻射性衝撃波
  - cf. Cissoko 1997; Farris+ 2008; Budnik+ 2010; Takahashi+ 2013; Sadowski+ 2013; Tolstov+ 2015; Beloborodov 2017; Fukue 2018c


参考文献

輻射性衝撃波

Bouquet, S. et al. 2000, ApJS, 127, 245

Budnik, R. et al. 2010, ApJ, 725, 63

Drake, R.P. 2005, Ap&SS, 298, 49

Drake, R.P. 2007, Phys. Plasma, 14, 043301

Ferguson, J.M. et al. 2017, JQSpRT

Fukue, J. 2019a, PASJ, 71, 38 (radiative shocks in disk)

Fukue, J. 2019d, PASJ, in press (gravitational field, curvature, spherical)

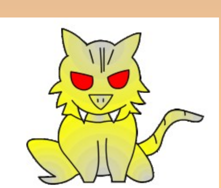
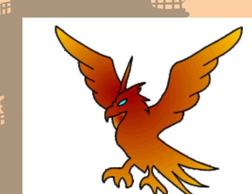
Lacey, C.G. 1988, ApJ, 326, 769

Lowrie, R.B., Edwards, J.D. 2008, Shock Waves, 18, 129

Lowrie, R.B. et al. 1999, ApJ, 521, 432

Lowrie, R.B. et al. 2007, Shock Waves, 16, 445

Zeldovich, Y.B., Raizer, Y.P. 1966, Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena

参考文献

相対論的輻射性衝撃波

Belobolodov, A.M. 2017, ApJ, 838, 125

Cissoko, M. 1997, Phys. Rev. D., 55, 4555

Farris, B.D. et al. 2008, Phys. Rev. D., 78, 024023

Fukue, J. 2019b, MNRAS, 483, 2538 (relativistic radiative shocks)

Fukue, J. 2019c, MNRAS, 483, 3839 (relativistic radiative shocks in disk)

Sadowski, A. et al. 2013, MNRAS, 429, 3533

Takahashi, H.R. et al. 2013, ApJ, 764, 122

Tolsov, A. et al. 2015, ApJ, 811, 47