引力波天文学笔记

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目录

第一章　引力波

1.1 Linearized Gravity

[4]. 流形 $\mathbb{R}^4$. 任意坐标系 $\{x^\mu\}$, $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} = \eta_{\mu\nu} + \gamma_{\mu\nu} s + \mathrm{O}(s^2)$, 得

$$R_{\mu\nu\lambda\sigma} = \partial_\sigma \partial_{[\mu} h_{\lambda]\nu} - \partial_\nu \partial_{[\mu} h_{\lambda]\sigma} + \mathrm{O}(s^2). \tag{1.1}$$

$\bar{h}_{\mu\nu} := h_{\mu\nu} - \frac{1}{2}\eta_{\mu\nu}\eta^{\lambda\sigma}h_{\lambda\sigma} = h_{\mu\nu} - \frac{1}{2}\eta_{\mu\nu}h$.

$$-\frac{1}{2}\partial^\lambda \partial_\lambda \bar{h}_{\mu\nu} + \partial^\lambda \partial_{(\mu}\bar{h}_{\nu)\lambda} - \frac{1}{2}\eta_{\mu\nu}\partial^\lambda\partial^\sigma \bar{h}_{\lambda\sigma} + \mathrm{O}(s^2) = 8\pi T_{\mu\nu}. \tag{1.2}$$

存在 $\{x^\mu\}$, 使得 $\partial^\nu \bar{h}_{\mu\nu} + \mathrm{O}(s^2) = 0$ (Lorentz gauge). 令 $\{x^\mu\}$ 满足 $\partial^\nu \bar{h}_{\mu\nu} + \mathrm{O}(s^2) = 0$, 则

$$\partial^\lambda \partial_\lambda \bar{h}_{\mu\nu} + \mathrm{O}(s^2) = -16\pi T_{\mu\nu}. \tag{1.3}$$

略去 $\mathrm{O}(s^2)$ 条件: $h_{\mu\nu}$, $\partial_\lambda h_{\mu\nu}$...小.

1.2 Radiation Gauge

[4]. 存在 $\{x^\mu\}$, 使得 $h + \mathrm{O}(s^2) = 0$ (TT gauge [5]) 且 $h_{0\mu} + \mathrm{O}(s^2) = 0$.

1.3 Quadrupole Approximation

[4]. 下略 $\mathrm{O}(s^2)$. 由(1.3)得

$$\bar{h}_{\mu\nu}(t, \vec{r}) = 4\int \frac{T_{\mu\nu}(t - |\vec{r} - \vec{r}'|, \vec{r}')}{|\vec{r} - \vec{r}'|}\,\mathrm{d}V'. \tag{1.4}$$

$$\hat{\bar{h}}_{\mu\nu}(\omega,\vec{r}) := \frac{1}{\sqrt{2\pi}}\int \bar{h}_{\mu\nu}(t,\vec{r})e^{i\omega t}\mathrm{d}t \tag{1.5}$$

$$= 4\int \frac{\hat{T}_{\mu\nu}(\omega,\vec{r}')}{|\vec{r}-\vec{r}'|}e^{i\omega|\vec{r}-\vec{r}'|}\,\mathrm{d}V'. \tag{1.6}$$

由 $\partial^\nu \bar{h}_{\mu\nu} = 0$,

$$-i\omega\hat{\bar{h}}_{0\mu} = \sum_i \frac{\partial\hat{\bar{h}}_{i\mu}}{\partial x^i}. \tag{1.7}$$

$|\vec{r}| \gg |\vec{r}'|$ 且 $\omega \ll 1/|\vec{r}'|$,

$$\hat{\bar{h}}_{ij}(\omega,\vec{r}) = 4\frac{e^{i\omega|\vec{r}|}}{|\vec{r}|}\int \hat{T}_{ij}(\omega,\vec{r}')\,\mathrm{d}V'. \tag{1.8}$$

$$\int \hat{T}_{ij}\,\mathrm{d}V' = \int\sum_k(\hat{T}_{kj}\frac{\partial x'^i}{\partial x'^k})\,\mathrm{d}V' \tag{1.9}$$

$$= \sum_k\left[\int\frac{\partial}{\partial x'^k}(\hat{T}_{kj}x'^i)\,\mathrm{d}V' - \int\frac{\partial\hat{T}_{kj}}{\partial x'^k}x'^i\,\mathrm{d}V'\right] \tag{1.10}$$

$$= \sum_k\int\partial'_k\,(\hat{T}_{kj}x'^i)\,\mathrm{d}V' - \sum_k\int\frac{\partial\hat{T}_{kj}}{\partial x'^k}x'^i\,\mathrm{d}V' \tag{1.11}$$

$$= \int\hat{T}_{kj}x'^i\,\mathrm{d}S' - \sum_k\int\frac{\partial\hat{T}_{kj}}{\partial x'^k}x'^i\,\mathrm{d}V' \tag{1.12}$$

$$= -\sum_k\int\frac{\partial\hat{T}_{kj}}{\partial x'^k}x'^i\,\mathrm{d}V' \tag{1.13}$$

$$= -\int(\sum_k\partial'_k\hat{T}_{kj})x'^i\,\mathrm{d}V' \tag{1.14}$$

$$= -\int(\partial_0\hat{T}_{0j})x'^i\,\mathrm{d}V' \tag{1.15}$$

$$= -i\omega\int\hat{T}_{0j}x'^i\,\mathrm{d}V' \tag{1.16}$$

$$= \int\hat{T}_{(ij)}\,\mathrm{d}V' \tag{1.17}$$

$$= -i\omega\int\hat{T}_{0(j}x'^{i)}\,\mathrm{d}V' \tag{1.18}$$

$$= -\frac{i\omega}{2}\int(\hat{T}_{0j}x'^i + \hat{T}_{0i}x'^j)\,\mathrm{d}V', \tag{1.19}$$

$$\tag{1.20}$$

$$-\frac{i\omega}{2}\int(\hat{T}_{0j}x'^i+\hat{T}_{0i}x'^j)\,\mathrm{d}V'=-\frac{i\omega}{2}\int\sum_k(\hat{T}_{0k}x'^i\frac{\partial x'^j}{\partial x'^k}+\hat{T}_{0k}\frac{\partial x'^i}{\partial x'^k}x'^j)\,\mathrm{d}V' \tag{1.21}$$

$$=-\frac{i\omega}{2}\sum_k\left[\int\frac{\partial}{\partial x'^k}(\hat{T}_{0k}x'^ix'^j)\,\mathrm{d}V'-\int\frac{\partial\hat{T}_{0k}}{\partial x'^k}x'^ix'^j\,\mathrm{d}V'\right] \tag{1.22}$$

$$=-\frac{i\omega}{2}\sum_k\int\partial'_k\,(\hat{T}_{0k}x'^ix'^j)\,\mathrm{d}V'+\frac{i\omega}{2}\sum_k\int\frac{\partial\hat{T}_{0k}}{\partial x'^k}x'^ix'^j\,\mathrm{d}V' \tag{1.23}$$

$$=-\frac{i\omega}{2}\sum_k\int\hat{T}_{0k}x'^ix'^j\,\mathrm{d}S'+\frac{i\omega}{2}\sum_k\int\frac{\partial\hat{T}_{0k}}{\partial x'^k}x'^ix'^j\,\mathrm{d}V' \tag{1.24}$$

$$=\frac{i\omega}{2}\sum_k\int\frac{\partial\hat{T}_{0k}}{\partial x'^k}x'^ix'^j\,\mathrm{d}V' \tag{1.25}$$

$$=\frac{i\omega}{2}\int(\sum_k\partial'_k\hat{T}_{0k})x'^ix'^j\,\mathrm{d}V' \tag{1.26}$$

$$=\frac{i\omega}{2}\int(\partial_0\hat{T}_{00})x'^ix'^j\,\mathrm{d}V' \tag{1.27}$$

$$=-\frac{\omega^2}{2}\int\hat{T}_{00}\,x'^ix'^j\,\mathrm{d}V'. \tag{1.28}$$

$$q_{ij}(t):=\int T_{00}\,x'^ix'^j\,\mathrm{d}V', \tag{1.29}$$

$$\hat{\bar{h}}_{ij}(\omega,\vec{r})=-2\omega^2\frac{e^{i\omega|\vec{r}|}}{|\vec{r}|}\hat{q}_{ij}(\omega), \tag{1.30}$$

$$\bar{h}_{ij}(t,\vec{r})=\frac{2}{|\vec{r}|}\frac{\mathrm{d}^2}{\mathrm{d}t^2}q_{ij}(t-|\vec{r}|). \tag{1.31}$$

1.4 + Mode and × Mode

寻新标架 $(e'^1)_a=(e^+)_a$, $(e'^2)_a=(e^\times)_a$, $(e'^3)_a=(e^r)_a$, $\bar{h}_{ij}(e^i)_a(e^j)_b=\bar{h}'_{ij}(e'^i)_a(e'^j)_b$, 取 x, y 分量后去迹, $h_+=\frac{1}{2}(\bar{h}'_{11}-\bar{h}'_{22})$, $h_\times=\bar{h}'_{12}=\bar{h}'_{21}$? [3]

[1], $\vec{n}:=\frac{\vec{r}}{|\vec{r}|}$,

$$h_{ij}^{\mathrm{TT}}=\frac{2}{|\vec{r}|}\mathcal{P}_{ijkm}\frac{\mathrm{d}^2}{\mathrm{d}t^2}Q^{km}(t-|\vec{r}|), \tag{1.32}$$

$$\mathcal{P}_{ijkm} := (\delta_{ik} - \vec{n}_i\vec{n}_k)(\delta_{jm} - \vec{n}_j\vec{n}_m) - \frac{1}{2}(\delta_{ij} - \vec{n}_i\vec{n}_j)(\delta_{km} - \vec{n}_k\vec{n}_m), \tag{1.33}$$

$$Q^{km}(t) := \int T_{00}\left(x'^k x'^m - \frac{1}{3}\delta^{km}\sum_n x'^n x'^n\right)\mathrm{d}V' \tag{1.34}$$

1.5 电磁—引力对比

$$A_\mu(t,\vec{r}) = \frac{\mu_0}{4\pi}\int \frac{J_\mu(t-|\vec{r}-\vec{r}'|,\vec{r}')}{|\vec{r}-\vec{r}'|}\mathrm{d}V' \tag{1.35}$$

$$\bar{h}_{\mu\nu}(t,\vec{r}) = 4G\int \frac{T_{\mu\nu}(t-|\vec{r}-\vec{r}'|,\vec{r}')}{|\vec{r}-\vec{r}'|}\mathrm{d}V' \tag{1.36}$$

$$A_\mu(t,\vec{r}) = \frac{1}{\sqrt{2\pi}}\int \hat{A}_\mu(\omega,\vec{r})e^{-i\omega t}\mathrm{d}t \tag{1.37}$$

$$\bar{h}_{\mu\nu}(t,\vec{r}) = \frac{1}{\sqrt{2\pi}}\int \hat{\bar{h}}_{\mu\nu}(\omega,\vec{r})e^{-i\omega t}\mathrm{d}t \tag{1.38}$$

$$\hat{A}_\mu(\omega,\vec{r}) = \frac{\mu_0}{4\pi}\int \frac{\hat{J}_\mu(\omega,\vec{r}')}{|\vec{r}-\vec{r}'|}e^{i\omega|\vec{r}-\vec{r}'|}\mathrm{d}V' \tag{1.39}$$

$$\hat{\bar{h}}_{\mu\nu}(\omega,\vec{r}) = 4G\int \frac{\hat{T}_{\mu\nu}(\omega,\vec{r}')}{|\vec{r}-\vec{r}'|}e^{i\omega|\vec{r}-\vec{r}'|}\mathrm{d}V' \tag{1.40}$$

$$\hat{A}_\mu(\omega,\vec{r}) = \frac{\mu_0}{4\pi}\frac{e^{i\omega|\vec{r}|}}{|\vec{r}|}\int \hat{J}_\mu(\omega,\vec{r}')e^{-i\omega(\frac{\vec{r}}{|\vec{r}|}\cdot\vec{r}')}\mathrm{d}V' \tag{1.41}$$

$$\hat{\bar{h}}_{\mu\nu}(\omega,\vec{r}) = 4G\frac{e^{i\omega|\vec{r}|}}{|\vec{r}|}\int \hat{T}_{\mu\nu}(\omega,\vec{r}')e^{-i\omega(\frac{\vec{r}}{|\vec{r}|}\cdot\vec{r}')}\mathrm{d}V' \tag{1.42}$$

$$\hat{A}_\mu(\omega,\vec{r}) = \frac{\mu_0}{4\pi}\frac{e^{i\omega|\vec{r}|}}{|\vec{r}|}\int \hat{J}_\mu(\omega,\vec{r}')\left[1 - i\omega(\frac{\vec{r}}{|\vec{r}|}\cdot\vec{r}') - \dots\right]\mathrm{d}V' \tag{1.43}$$

$$\hat{\bar{h}}_{\mu\nu}(\omega,\vec{r}) = 4G\frac{e^{i\omega|\vec{r}|}}{|\vec{r}|}\int \hat{T}_{\mu\nu}(\omega,\vec{r}')\left[1 - i\omega(\frac{\vec{r}}{|\vec{r}|}\cdot\vec{r}') - \dots\right]\mathrm{d}V' \tag{1.44}$$

1.5.1 电偶极—引力对比

$$\hat{A}_i = \frac{\mu_0}{4\pi}\frac{e^{i\omega|\vec{r}|}}{|\vec{r}|}\int \hat{J}_i \,\mathrm{d}V' \tag{1.45}$$

$$\hat{\bar{h}}_{ij} = 4G\frac{e^{i\omega|\vec{r}|}}{|\vec{r}|}\int \hat{T}_{ij}\,\mathrm{d}V' \tag{1.46}$$

$$\int \hat{J}_i \,\mathrm{d}V' = -i\omega\int \hat{J}_0 x'^i \,\mathrm{d}V' \tag{1.47}$$

$$\int \hat{T}_{ij}\,\mathrm{d}V' = -\frac{\omega^2}{2}\int \hat{T}_{00}\, x'^i x'^j \,\mathrm{d}V' \tag{1.48}$$

$$p_i = \int \hat{J}_0 x'^i \,\mathrm{d}V' \tag{1.49}$$

$$q_{ij} = \int \hat{T}_{00}\, x'^i x'^j \,\mathrm{d}V' \tag{1.50}$$

$$\hat{A}_i = \frac{\mu_0}{4\pi}\frac{e^{i\omega|\vec{r}|}}{|\vec{r}|}(-i\omega p_i) \tag{1.51}$$

$$\hat{\bar{h}}_{ij} = 4G\frac{e^{i\omega|\vec{r}|}}{|\vec{r}|}(-\frac{\omega^2}{2}q_{ij}) \tag{1.52}$$

$$A_i = \frac{\mu_0}{4\pi}\frac{1}{|\vec{r}|}\frac{\mathrm{d}}{\mathrm{d}t}p_i(t-|\vec{r}|) \tag{1.53}$$

$$\bar{h}_{ij} = 4G\frac{1}{|\vec{r}|}\frac{1}{2}\frac{\mathrm{d}^2}{\mathrm{d}t^2}q_{ij}(t-|\vec{r}|) \tag{1.54}$$

1.5.2 电四极—引力对比

$$\hat{A}_i(\omega,\vec{r}) = \frac{\mu_0}{4\pi}\frac{e^{i\omega|\vec{r}|}}{|\vec{r}|}\ \ (-i\omega)\int \hat{J}_i(\omega,\vec{r}')(\frac{\vec{r}}{|\vec{r}|}\cdot\vec{r}')\,\mathrm{d}V' \tag{1.55}$$

$$\hat{A}_i = \frac{\mu_0}{4\pi}\frac{e^{i\omega|\vec{r}|}}{|\vec{r}|}(-i\omega)\int \hat{J}'_i n^j x'_j \,\mathrm{d}V' \tag{1.56}$$

$$\hat{A}_i = \frac{\mu_0}{4\pi}\frac{e^{i\omega|\vec{r}|}}{|\vec{r}|}(-i\omega)\int n^j x'_j \hat{J}'_i \,\mathrm{d}V' \tag{1.57}$$

$$\hat{A}_i = \frac{\mu_0}{4\pi}\frac{e^{i\omega|\vec{r}|}}{|\vec{r}|}(-i\omega)n^j\left[\int x'_{(j}\hat{J}'_{i)}\,\mathrm{d}V'\right] \tag{1.58}$$

$$\begin{aligned}
\int x'_{(j}\hat{J}'_{i)}\,\mathrm{d}V' &= \frac{1}{2}\int(\hat{J}'_j x'_i + \hat{J}'_i x'_j)\,\mathrm{d}V' && (1.59)\\
&= \frac{1}{2}\int\sum_k(\hat{J}'_k x'^i\frac{\partial x'^j}{\partial x'^k} + \hat{J}'_k\frac{\partial x'^i}{\partial x'^k}x'^j)\,\mathrm{d}V' && (1.60)\\
&= \frac{1}{2}\sum_k\left[\int\frac{\partial}{\partial x'^k}(\hat{J}'_k x'^i x'^j)\,\mathrm{d}V' - \int\frac{\partial\hat{J}'_k}{\partial x'^k}x'^i x'^j\,\mathrm{d}V'\right] && (1.61)\\
&= \frac{1}{2}\sum_k\int\partial'_k\,(\hat{J}'_k x'^i x'^j)\,\mathrm{d}V' - \frac{1}{2}\sum_k\int\frac{\partial\hat{J}'_k}{\partial x'^k}x'^i x'^j\,\mathrm{d}V' && (1.62)\\
&= \frac{1}{2}\sum_k\int\hat{J}'_k x'^i x'^j\,\mathrm{d}S' - \frac{1}{2}\sum_k\int\frac{\partial\hat{J}'_k}{\partial x'^k}x'^i x'^j\,\mathrm{d}V' && (1.63)\\
&= -\frac{1}{2}\sum_k\int\frac{\partial\hat{J}'_k}{\partial x'^k}x'^i x'^j\,\mathrm{d}V' && (1.64)\\
&= -\frac{1}{2}\int(\sum_k\partial'_k\hat{J}'_k)x'^i x'^j\,\mathrm{d}V' && (1.65)\\
&= -\frac{1}{2}\int(\partial_0\hat{J}'_0)x'^i x'^j\,\mathrm{d}V' && (1.66)\\
&= -\frac{i\omega}{2}\int\hat{J}'_0 x'^i x'^j\,\mathrm{d}V' && (1.67)
\end{aligned}$$

$$D_{ij} = \int\hat{J}'_0\,x'^i x'^j\,\mathrm{d}V' \tag{1.68}$$

$$\hat{A}_i = \frac{\mu_0}{4\pi}\frac{e^{i\omega|\vec{r}|}}{|\vec{r}|}(-\frac{\omega^2}{2}n^j D_{ij}) \tag{1.69}$$

$$A_i = \frac{\mu_0}{4\pi}\frac{1}{|\vec{r}|}n^j\frac{1}{2}\frac{\mathrm{d}^2}{\mathrm{d}t^2}D_{ij}(t-|\vec{r}|) \tag{1.70}$$

第二章　电磁引力

[2].

2.1　时空张量转化为空间张量

$$h_{ab} := g_{ab} + Z_a Z_b. \tag{2.1}$$

$$h_a{}^b = \delta_a{}^b + Z_a Z^b. \tag{2.2}$$

$$Z^a h_{ab} = 0. \tag{2.3}$$

$$V_{\langle a\rangle} := h_a{}^b V_b. \tag{2.4}$$

$$Z^a V_{\langle a\rangle} = 0. \tag{2.5}$$

$$T_{\langle ab\rangle} := h_{(a}{}^c h_{b)}{}^d T_{cd} - \frac{1}{3} h_{cd} T^{cd} h_{ab}. \tag{2.6}$$

$$Z^a (h_a{}^c h_b{}^d T_{cd}) = 0. \tag{2.7}$$

$$Z^a (h_b{}^c h_a{}^d T_{cd}) = 0. \tag{2.8}$$

$$Z^a (h_{(a}{}^c h_{b)}{}^d T_{cd}) = 0. \tag{2.9}$$

$$Z^a (h_{cd} T^{cd} h_{ab}) = 0. \tag{2.10}$$

$$Z^a T_{\langle ab\rangle} = 0. \tag{2.11}$$

$$T_{(\langle ab\rangle)} = T_{\langle ab\rangle}. \tag{2.12}$$

$$h^{ab} T_{\langle ab\rangle} = 0. \tag{2.13}$$

$$\varepsilon_{abc} := \varepsilon_{abcd} Z^d. \tag{2.14}$$

$$\varepsilon_{0123} := -\sqrt{|g|}. \tag{2.15}$$

$$T_a := \frac{1}{2}\varepsilon_{abc} T^{[bc]}. \tag{2.16}$$

$$[U,V]_a := \varepsilon_{abc} U^b V^c. \tag{2.17}$$

$$[S,T]_a := \varepsilon_{abc} g_{de} S^{bd} T^{ce}. \tag{2.18}$$

$$\mathrm{D}_t T^{a\ldots}{}_{b\ldots} := Z^c \nabla_c T^{a\ldots}{}_{b\ldots}. \tag{2.19}$$

$${}^3\nabla_a T^{b\ldots}{}_{c\ldots} := h_a{}^p h^b{}_q \ldots h_c{}^r \ldots \nabla_p T^{q\ldots}{}_{r\ldots}. \tag{2.20}$$

$$(\operatorname{div} V) := {}^3\nabla^a V_a. \tag{2.21}$$

$$(\operatorname{curl} V)_a := \varepsilon_{bca} {}^3\nabla^b V^c. \tag{2.22}$$

$$(\operatorname{div} T)_a := {}^3\nabla^b T_{ab}. \tag{2.23}$$

$$(\operatorname{curl} T)_{ab} := \varepsilon_{cd(a} {}^3\nabla^c g_{b)e} T^{ed}. \tag{2.24}$$

2.2 电磁空间矢量

$${}^*F_{ab} := \frac{1}{2}\varepsilon_{abcd} F^{cd} \tag{2.25}$$

$$E_a := F_{ab} Z^b = E_{\langle a\rangle}. \tag{2.26}$$

$$B_a := {}^*F_{ab} Z^b = B_{\langle a\rangle}. \tag{2.27}$$

$$\rho = -Z^a J_a. \tag{2.28}$$

$$j_a = h_a{}^b J_b. \tag{2.29}$$

$$\nabla_{[a} F_{bc]} = 0. \tag{2.30}$$

$$\nabla^a F_{ab} = \mu J_b. \tag{2.31}$$

$$(\operatorname{div} E) = \mu\rho - \dots. \tag{2.32}$$

$$(\operatorname{div} B) = + \dots. \tag{2.33}$$

$$(\operatorname{curl} E)_a + \dots = -\mathrm{D}_t B_{\langle a\rangle} - \dots. \tag{2.34}$$

$$(\operatorname{curl} B)_a + \dots = \mu j_a + \mathrm{D}_t E_{\langle a\rangle} + \dots. \tag{2.35}$$

2.3 引力空间张量

$$^{*}C_{abcd} := \frac{1}{2}\varepsilon_{abef}C^{ef}{}_{cd}. \tag{2.36}$$

$$E_{ab} := C_{acbd}Z^cZ^d = E_{\langle ab\rangle}. \tag{2.37}$$

$$B_{ab} := {}^{*}C_{acbd}Z^cZ^d = B_{\langle ab\rangle}. \tag{2.38}$$

$$(\operatorname{div} E)_a = \kappa\frac{1}{3}{}^{3}\nabla_a\rho - \dots. \tag{2.39}$$

$$(\operatorname{div} B)_a = \kappa(\rho + p)\omega_a + \dots. \tag{2.40}$$

$$(\operatorname{curl} E)_{ab} + \dots = -\mathrm{D}_t B_{\langle ab\rangle} - \dots. \tag{2.41}$$

$$(\operatorname{curl} B)_{ab} + \dots = \kappa\frac{1}{2}(\rho + p)\sigma_{ab} + \mathrm{D}_t E_{\langle ab\rangle} + \dots. \tag{2.42}$$

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