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一类动态黑洞的非热辐射*

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研究了一类动态黑洞视界附近的粒子能级交错. 给出了交错能级最大值的表达式. 所得结果覆盖了所有已知的动态黑洞的结果. 对于动态非球对称黑洞, 其非热辐射的频率范围不仅依赖于时间,而且依赖于角度,这是新的结果.

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1 引 言

Damour 和 Deruelle[1] 研究了弯曲时空中的 Hamilton-Jacobi 方程, 根据此方程, 人们已对稳态黑洞的非热辐射进行了研究[2]。近年来, 对动态黑洞物理特征的研究引起了人们的广泛兴趣[3—9]。动态黑洞的非热辐射也是一个值得研究的课题。我们采用推广的 Tortoise 坐标变换,找到了导出粒子能级表达式的新方法, 有效地研究了一类动态黑洞的非热辐射。

2 计 算 结 果

一般而言,动态时空线元可以表示为

$$ds^2 = g_{\mu\nu}dx^\mu dx^\nu. \tag{1}$$

采用球坐标 ($x^0 = v, x^1 = r, x^2 = \theta, x^3 = \phi$), 并利用零曲面条件

$$g^{\mu\nu}\frac{\partial F}{\partial x^\mu}\frac{\partial F}{\partial x^\nu} = 0, \tag{2}$$

得出黑洞视界面方程为

$$g^{00}\left(\frac{\partial r}{\partial v}\right)^2 - 2g^{01}\left(\frac{\partial r}{\partial v}\right) + 2g^{02}\left(\frac{\partial r}{\partial v}\right)\left(\frac{\partial r}{\partial \theta}\right) + 2g^{03}\left(\frac{\partial r}{\partial v}\right)\left(\frac{\partial r}{\partial \phi}\right) + g^{11}$$

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$$-2g^{12}\left(\frac{\partial r}{\partial\theta}\right)-2g^{13}\left(\frac{\partial r}{\partial\phi}\right)+g^{22}\left(\frac{\partial r}{\partial\theta}\right)^2+2g^{23}\left(\frac{\partial r}{\partial\theta}\right)\left(\frac{\partial r}{\partial\phi}\right)+g^{33}\left(\frac{\partial r}{\partial\phi}\right)^2=0. \tag{3}$$

满足此方程的 r_H 就是局部事件视界[10]。

在(1)式表述的动态时空中，粒子的运动方程为

$$g^{\mu\nu}\left(\frac{\partial S}{\partial x^\mu}-\beta A_\mu\right)\left(\frac{\partial S}{\partial x^\nu}-\beta A_\nu\right)-\mu^2=0, \tag{4}$$

即

$$\begin{aligned}&g^{00}\left(\frac{\partial S}{\partial v}-\beta A_0\right)^2+2g^{01}\left(\frac{\partial S}{\partial v}-\beta A_0\right)\left(\frac{\partial S}{\partial r}-\beta A_1\right)+2g^{02}\left(\frac{\partial S}{\partial v}-\beta A_0\right)\\&\times\left(\frac{\partial S}{\partial\theta}-\beta A_2\right)+2g^{03}\left(\frac{\partial S}{\partial v}-\beta A_0\right)\left(\frac{\partial S}{\partial\phi}-\beta A_3\right)+g^{11}\left(\frac{\partial S}{\partial r}-\beta A_1\right)^2\\&+2g^{12}\left(\frac{\partial S}{\partial r}-\beta A_1\right)\left(\frac{\partial S}{\partial\theta}-\beta A_2\right)+2g^{13}\left(\frac{\partial S}{\partial r}-\beta A_1\right)\\&\times\left(\frac{\partial S}{\partial\phi}-\beta A_3\right)+g^{22}\left(\frac{\partial S}{\partial\theta}-\beta A_2\right)^2+2g^{23}\left(\frac{\partial S}{\partial\theta}-\beta A_2\right)\\&\times\left(\frac{\partial S}{\partial\phi}-\beta A_3\right)+g^{33}\left(\frac{\partial S}{\partial\phi}-\beta A_3\right)^2-\mu^2=0,\end{aligned} \tag{5}$$

式中 A_μ 是物质场的广义规范势，β 是相应于 A_μ 的“荷”。当 A_μ 是电磁四矢时，β 是粒子电荷。

为了研究黑洞视界附近的非热辐射，对(5)式作推广的 Tortoise 坐标变换[9,10]

$$\begin{aligned}&r_*=r+\frac{1}{2\kappa}\ln[r-r_H(v,\theta,\phi)],\quad \theta_*=\theta-\theta_0,\\&v_*=v-v_0,\qquad\qquad \phi_*=\phi-\phi_0.\end{aligned} \tag{6}$$

由此可得部分关系式

$$\begin{aligned}&\frac{\partial}{\partial r}=\frac{2\kappa(r-r_H)+1}{2\kappa(r-r_H)}\frac{\partial}{\partial r_*},\quad \frac{\partial}{\partial v}=\frac{\partial}{\partial v_*}-\frac{\left(\frac{\partial r_H}{\partial v}\right)}{2\kappa(r-r_H)}\frac{\partial}{\partial r_*},\\&\frac{\partial}{\partial\theta}=\frac{\partial}{\partial\theta_*}-\frac{\left(\frac{\partial r_H}{\partial\theta}\right)}{2\kappa(r-r_H)}\frac{\partial}{\partial r_*},\quad \frac{\partial}{\partial\phi}=\frac{\partial}{\partial\phi_*}-\frac{\left(\frac{\partial r_H}{\partial\phi}\right)}{2\kappa(r-r_H)}\frac{\partial}{\partial r_*}.\end{aligned} \tag{7}$$

把(7)式代入方程(5)中，得到方程(5)在推广的 Tortoise 坐标下的形式，经过一定的计算可得

$$\frac{\partial S}{\partial r_*}=\frac{2\kappa(r-r_H)[-\tilde{B}\pm(\tilde{B}^2-\tilde{A}\tilde{C})^{1/2}]}{\tilde{A}}, \tag{8}$$

式中

$$\tilde{A}=g^{00}\left(\frac{\partial r_H}{\partial v}\right)^2-2g^{01}\left(\frac{\partial r_H}{\partial v}\right)[2\kappa(r-r_H)+1]+2g^{02}\left(\frac{\partial r_H}{\partial v}\right)\left(\frac{\partial r_H}{\partial\theta}\right)$$

$$+ 2g^{03}\left(\frac{\partial r_H}{\partial v}\right)\left(\frac{\partial r_H}{\partial \phi}\right) + g^{11}[2\kappa(r - r_H) + 1]^2 - 2g^{12}\left(\frac{\partial r_H}{\partial \theta}\right)$$

$$\times [2\kappa(r - r_H) + 1] - 2g^{13}\left(\frac{\partial r_H}{\partial \phi}\right)[2\kappa(r - r_H) + 1]$$

$$+ g^{33}\left(\frac{\partial r_H}{\partial \phi}\right)^2 + g^{22}\left(\frac{\partial r_H}{\partial \theta}\right)^2 + 2g^{23}\left(\frac{\partial r_H}{\partial \theta}\right)\left(\frac{\partial r_H}{\partial \phi}\right), \tag{9}$$

$$\tilde{B} = -g^{00}\left(\frac{\partial S}{\partial v_*}\right)\left(\frac{\partial r_H}{\partial v}\right) + g^{00}\beta A_0\left(\frac{\partial r_H}{\partial v}\right) + g^{01}\left(\frac{\partial S}{\partial v_*}\right)[2\kappa(r - r_H) + 1]$$

$$+ g^{01}\beta A_1\left(\frac{\partial r_H}{\partial v}\right) - g^{01}\beta A_0[2\kappa(r - r_H) + 1]$$

$$- g^{02}\left(\frac{\partial r_H}{\partial v}\right)\left(\frac{\partial S}{\partial \theta_*}\right) - g^{02}\left(\frac{\partial r_H}{\partial \theta}\right)\left(\frac{\partial S}{\partial v_*}\right) + g^{02}\beta A_2\left(\frac{\partial r_H}{\partial v}\right)$$

$$+ g^{02}\beta A_0\left(\frac{\partial r_H}{\partial \theta}\right) - g^{03}\left(\frac{\partial r_H}{\partial \phi}\right)\left(\frac{\partial S}{\partial v_*}\right) - g^{03}\left(\frac{\partial r_H}{\partial v}\right)\left(\frac{\partial S}{\partial \phi_*}\right)$$

$$+ g^{03}\beta A_3\left(\frac{\partial r_H}{\partial v}\right) + g^{03}\beta A_0\left(\frac{\partial r_H}{\partial \phi}\right) - g^{11}\beta A_1[2\kappa(r - r_H) + 1]$$

$$+ g^{12}\left(\frac{\partial S}{\partial \theta_*}\right)[2\kappa(r - r_H) + 1] - g^{12}\beta A_2[2\kappa(r - r_H) + 1]$$

$$+ g^{13}[2\kappa(r - r_H) + 1]\left(\frac{\partial S}{\partial \phi_*}\right) + g^{12}\beta A_1\left(\frac{\partial r_H}{\partial \theta}\right)$$

$$- g^{13}\beta A_3[2\kappa(r - r_H) + 1] - g^{13}\beta A_1\left(\frac{\partial r_H}{\partial \phi}\right) - g^{22}\left(\frac{\partial r_H}{\partial \theta}\right)\left(\frac{\partial S}{\partial \theta_*}\right)$$

$$+ g^{22}\beta A_2\left(\frac{\partial r_H}{\partial \theta}\right) - g^{23}\left(\frac{\partial r_H}{\partial \phi}\right)\left(\frac{\partial S}{\partial \theta_*}\right) - g^{23}\left(\frac{\partial r_H}{\partial \theta}\right)\left(\frac{\partial S}{\partial \phi_*}\right)$$

$$+ g^{23}\beta A_3\left(\frac{\partial r_H}{\partial \theta}\right) + g^{23}\beta A_2\left(\frac{\partial r_H}{\partial \phi}\right) + g^{33}\beta A_3\left(\frac{\partial r_H}{\partial \phi}\right)$$

$$- g^{33}\left(\frac{\partial r_H}{\partial \phi}\right)\left(\frac{\partial S}{\partial \phi_*}\right), \tag{10}$$

$$\tilde{C} = g^{00}\left(\frac{\partial S}{\partial v_*}\right)^2 - 2g^{00}\beta A_0\left(\frac{\partial S}{\partial v_*}\right) + g^{00}\beta^2 A_0^2 - 2g^{01}\beta A_1\left(\frac{\partial S}{\partial v_*}\right)$$

$$+ 2g^{01}\beta^2 A_0 A_1 + 2g^{02}\left(\frac{\partial S}{\partial v_*}\right)\left(\frac{\partial S}{\partial \theta_*}\right) - 2g^{02}\beta A_2\left(\frac{\partial S}{\partial v_*}\right)$$

$$- 2g^{02}\beta A_0\left(\frac{\partial S}{\partial \theta_*}\right) + 2g^{03}\left(\frac{\partial S}{\partial v_*}\right)\left(\frac{\partial S}{\partial \phi_*}\right) - 2g^{03}\beta A_3\left(\frac{\partial S}{\partial v_*}\right)$$

$$- 2g^{03}\beta A_0\left(\frac{\partial S}{\partial \phi_*}\right) + g^{11}\beta^2 A_1^2 - 2g^{12}\beta A_1\left(\frac{\partial S}{\partial \theta_*}\right) + 2g^{12}\beta^2 A_1 A_2$$

$$- 2g^{13}\beta A_1\left(\frac{\partial S}{\partial \phi_*}\right) + g^{13}\beta^2 A_1 A_3 + g^{22}\left(\frac{\partial S}{\partial \theta_*}\right)^2 - 2g^{22}\beta A_2\left(\frac{\partial S}{\partial \theta_*}\right)$$

$$+ g^{22}\beta A_2^2 + 2g^{23}\beta^2 A_2 A_3 + 2g^{23}\left(\frac{\partial S}{\partial \theta_*}\right)\left(\frac{\partial S}{\partial \phi_*}\right) - 2g^{23}\beta A_3\left(\frac{\partial S}{\partial \theta_*}\right)$$

$$+ g^{33}\left(\frac{\partial S}{\partial \phi_*}\right) - 2g^{23}\beta A_2\left(\frac{\partial S}{\partial \phi_*}\right) - 2g^{33}\beta A_3\left(\frac{\partial S}{\partial \phi_*}\right)$$

$$+ g^{33}\beta^2 A_3^2 + 2g^{02}\beta^2 A_0 A_2 + 2g^{03}\beta^2 A_0 A_3 - \mu^2, \tag{11}$$

式中 S 是 Hamilton 主函数，$\frac{\partial S}{\partial r_*}$ 应为实数. 因此，由(8)式得到

$$\tilde{B}^2 - \tilde{A}\tilde{C} \geqslant 0, \tag{12}$$

式中 $\tilde{B}$ 和 $\tilde{C}$ 均与 $\partial S/\partial v_*$ 有关，而 $\partial S/\partial v_*$ 又与粒子能量有关，所以，(12)式就是粒子能量所满足的关系式，只有满足此式的粒子能级才存在。定义

$$\frac{\partial S}{\partial v_*} = -\omega; \quad \frac{\partial S}{\partial \theta_*} = p_2; \quad \frac{\partial S}{\partial \phi_*} = p_3. \tag{13}$$

把(13)，(11)，(10)和(9)式代入(12)式，得

$$\omega^2\left\{-g^{00}\left(\frac{\partial r_H}{\partial v}\right) + g^{01}[2\kappa(r - r_H) + 1] - g^{02}\left(\frac{\partial r_H}{\partial \theta}\right) - g^{03}\left(\frac{\partial r_H}{\partial \phi}\right)\right\}^2$$

$$- 2\omega\tilde{b}\left\{-g^{00}\left(\frac{\partial r_H}{\partial v}\right) + g^{01}[2\kappa(r - r_H) + 1] - g^{02}\left(\frac{\partial r_H}{\partial \theta}\right)\right.$$

$$\left.- g^{03}\left(\frac{\partial r_H}{\partial \phi}\right)\right\} + \tilde{b}^2 - \omega^2\tilde{A}g^{00} + \tilde{A}\omega(-2g^{00}\beta A_0 - 2g^{01}\beta A_1 + 2g^{02}p_2$$

$$- 2g^{02}\beta A_2 + 2g^{03}p_3 - 2g^{03}\beta A_3) - \tilde{A}\tilde{C}' \geqslant 0. \tag{14}$$

取上式等号解之得

$$\omega^{\pm} = \frac{H\tilde{b} - \tilde{A}(-\beta g^{0\mu}A_\mu + g^{02}p_2 + g^{03}p_3)}{H^2 - \tilde{A}g^{00}} \pm D, \tag{15}$$

式中

$$D = \frac{1}{H^2 - \tilde{A}g^{00}}\{\tilde{A}^2[(-\beta g^{0\mu}A_\mu + g^{02}p_2 + g^{03}p_3)^2 - g^{00}\tilde{C}'] - \tilde{A}H$$

$$\times [2\tilde{b}(-\beta g^{0\mu}A_\mu + g^{02}p_2 + g^{03}p_3)H\tilde{C}'] - \tilde{A}g^{00}\tilde{b}^2\}^{1/2}, \tag{16}$$

$$H = -g^{00}\left(\frac{\partial r_H}{\partial v}\right) + g^{01}[2\kappa(r - r_H) + 1] - g^{02}\left(\frac{\partial r_H}{\partial \theta}\right) - g^{03}\left(\frac{\partial r_H}{\partial \phi}\right), \tag{17}$$

$$\tilde{b} = g^{00}\beta A_0\left(\frac{\partial r_H}{\partial v}\right) + g^{01}\beta A_1\left(\frac{\partial r_H}{\partial v}\right) - g^{01}\beta A_0[2\kappa(r - r_H) + 1]$$

$$- g^{02}p_2\left(\frac{\partial r_H}{\partial v}\right) + g^{02}\beta A_2\left(\frac{\partial r_H}{\partial v}\right) + g^{02}\beta A_0\left(\frac{\partial r_H}{\partial \theta}\right) - g^{03}p_3\left(\frac{\partial r_H}{\partial v}\right)$$

$$+ g^{03}\beta A_3\left(\frac{\partial r_H}{\partial v}\right) + g^{03}\beta A_0\left(\frac{\partial r_H}{\partial \phi}\right) - g^{11}\beta A_1[2\kappa(r - r_H) + 1]$$

$$+ g^{12}p_2[2\kappa(r - r_H) + 1] - g^{12}\beta A_2[2\kappa(r - r_H) + 1]$$

$$+ g^{12}\beta A_1\left(\frac{\partial r_H}{\partial \theta}\right) - g^{13}p_3[2\kappa(r - r_H) + 1] - g^{13}\beta A_3[2\kappa(r - r_H) + 1]$$

$$+ g^{13}\beta A_1\left(\frac{\partial r_H}{\partial\phi}\right) - g^{22}p_2\left(\frac{\partial r_H}{\partial\theta}\right) - g^{23}p_2\left(\frac{\partial r_H}{\partial\phi}\right) + g^{22}\beta A_2\left(\frac{\partial r_H}{\partial\theta}\right)$$
$$- g^{23}p_3\left(\frac{\partial r_H}{\partial\theta}\right) + g^{23}\beta A_3\left(\frac{\partial r_H}{\partial\theta}\right) + g^{23}\beta A_2\left(\frac{\partial r_H}{\partial\phi}\right)$$
$$- g^{33}p_3\left(\frac{\partial r_H}{\partial\phi}\right) + g^{33}\beta A_3\left(\frac{\partial r_H}{\partial\phi}\right), \tag{18}$$

$$\begin{aligned}\widetilde{C}' = {} & g^{00}\beta^2A_0^2 + 2g^{01}\beta^2A_0A_1 - 2g^{02}\beta A_0p_2 - 2g^{03}\beta A_0p_3 + g^{11}\beta^2A_1^2 - 2g^{12}\beta A_1p_2 \\ & + 2g^{12}\beta^2A_1A_2 - 2g^{13}\beta A_3p_3 + 2g^{13}\beta^2A_1A_3 + g^{22}p_2^2 - 2g^{22}\beta A_2p_2 \\ & + g^{22}\beta^2A_2^2 + 2g^{23}\beta^2A_2A_3 + 2g^{23}p_2p_3 - 2g^{23}\beta A_3p_2 - 2g^{23}\beta A_2p_3 \\ & + g^{33}p_3^2 - 2g^{33}\beta A_3p_3 + g^{33}\beta^2A_3^2 + 2g^{02}\beta^2A_0A_2 + 2g^{03}\beta^2A_0A_3 - \mu^2.\end{aligned} \tag{19}$$

由(14)和(15)式可知，粒子能级分布为

$$\omega \geqslant \omega^+;\ \omega \leqslant \omega^-. \tag{20}$$

粒子能量处于 $\omega^- < \omega < \omega^+$ 的状态是禁戒的，禁区的宽度为

$$\Delta\omega = 2D. \tag{21}$$

在以上导出粒子能级分布的过程中，未取 r 的特殊值，因此，计算所得的结论在黑洞视界附近及远处都适合。下面研究黑洞视界附近的能级分布情形。

当 $r \to r_H$ 时，得到

$$\begin{aligned}\widetilde{A}|_{r\to r_H} = {} & g^{00}\left(\frac{\partial r_H}{\partial v}\right)^2 - 2g^{01}\left(\frac{\partial r_H}{\partial v}\right) + 2g^{02}\left(\frac{\partial r_H}{\partial v}\right)\left(\frac{\partial r_H}{\partial\theta}\right) \\ & + 2g^{03}\left(\frac{\partial r_H}{\partial v}\right)\left(\frac{\partial r_H}{\partial\phi}\right) + g^{11} - 2g^{12}\left(\frac{\partial r_H}{\partial\theta}\right) \\ & - 2g^{13}\left(\frac{\partial r_H}{\partial\phi}\right) + g^{33}\left(\frac{\partial r_H}{\partial\phi}\right)^2 + 2g^{23}\left(\frac{\partial r_H}{\partial\theta}\right)\left(\frac{\partial r_H}{\partial\phi}\right) \\ & + g^{22}\left(\frac{\partial r_H}{\partial\theta}\right)^2 = 0.\end{aligned} \tag{22}$$

此式与方程(3)一致，是局部事件视界 r_H 所满足的方程。

由(22)，(21)和(15)—(19)式可得

$$\Delta\omega|_{r\to r_H} = 0, \tag{23}$$

$$\begin{aligned}\omega^+|_{r\to r_H} = \omega^-|_{r\to r_H} = \omega_0 = {} & \frac{\tilde{b}}{H}\Big|_{r\to r_H} \\ = {} & \frac{\beta A_\mu\left[g^{\mu j}\left(\frac{\partial r_H}{\partial x^j}\right) - g^{\mu 1}\right]}{g^{01} - g^{00}\left(\frac{\partial r_H}{\partial v}\right) - g^{02}\left(\frac{\partial r_H}{\partial\theta}\right) - g^{03}\left(\frac{\partial r_H}{\partial\phi}\right)}\Bigg|_{r\to r_H} \\ & + \frac{p_2\left[g^{12} - g^{j2}\left(\frac{\partial r_H}{\partial x^j}\right)\right] - p_3\left[g^{13} + g^{j3}\left(\frac{\partial r_H}{\partial x^j}\right)\right]}{g^{01} - g^{00}\left(\frac{\partial r_H}{\partial v}\right) - g^{02}\left(\frac{\partial r_H}{\partial\theta}\right) - g^{03}\left(\frac{\partial r_H}{\partial\phi}\right)}\Bigg|_{r\to r_H},\end{aligned} \tag{24}$$

式中 $j = 0,2,3;\ \mu = 0,1,2,3$.

(23)和(24)式表明，在一类动态黑洞视界附近，出现了粒子正负能级交错现象，在能级的交错区，禁区的宽度为零，处于负能态而能量高于最低正能态的粒子，将通过量子隧道效应穿过禁区成为出射正能粒子，这是与黑洞温度无关的自发辐射过程．ω_0 是交错能级的最大值，由(24)式表述．显然，ω_0 由两项组成，第一项取决于物质场的广义规范势，第二项主要由广义动量 p_2 和 p_3 决定．只要广义规范势 A_μ 不为零或黑洞有加速度，就会在黑洞视界附近出现正负能级交错，导致自发辐射的产生，这是对费密子而言．对于玻色子，除了自发辐射过程外，还会发生受激辐射．自发辐射和受激辐射都属于与黑洞温度无关的非热辐射，其辐射频率的最大值由(24)式决定．

3 结果与讨论

根据上面的计算结果，对特殊情况进行讨论．

3.1 Vaidya-Bonner 黑洞

Vaidya-Bonner 黑洞是球对称带电蒸发黑洞，时空线元为

$$ds^2 = -\left[1 - \frac{2M(v)}{r} + \frac{Q^2(v)}{r^2}\right] dv^2 + 2dvdr + r^2 d\Omega^2. \tag{25}$$

由(24)和(25)式可得

$$\omega_0 = eQ/r_H, \tag{26}$$

根据(25)和(15)式得出

$$\omega^{\pm}|_{r\to\infty} \to \pm\mu, \tag{27}$$

(26)，(27)式与已知结论完全一致．对于 Vaidya-Bonner 黑洞，辐射粒子的频率范围是

$$\mu < \omega \leqslant eQ/r_H. \tag{28}$$

辐射频率的最大值与角度无关，这是特殊情况．

3.2 动态 Kinnersley 黑洞

变加速直线运动的 Kinnersley 黑洞，时空线元为

$$\begin{aligned} ds^2 = &(1 - 2ar\cos\theta - r^2 f - 2Mr^{-1})dv^2 - 2dvdr \\ &+ 2r^2 f dv d\theta - r^2 d\theta^2 - r^2 \sin^2\theta d\phi^2. \end{aligned} \tag{29}$$

由(29)和(24)式得到

$$\begin{aligned} \omega_0 = &p_2\left[f - \frac{1}{r_H^2}\left(\frac{\partial r_H}{\partial\theta}\right)\right] - \beta\left\{A_0 + A_1\left[\left(\frac{\partial r_H}{\partial v}\right) + \left(\frac{\partial r_H}{\partial\theta}\right)\right]\right. \\ &\left.\cdot\left[f - \frac{1}{r_H^2}\left(\frac{\partial r_H}{\partial\theta}\right)\right]\right\} + A_2\left[f - \frac{1}{r_H^2}\left(\frac{\partial r_H}{\partial\theta}\right)\right]\Big\}. \end{aligned} \tag{30}$$

这是变加速直线运动黑洞非热辐射频率的最大值，与文献 [11] 的结论一致．对于动态 Kinnersley 黑洞而言，非热辐射的频率范围不仅与时间有关，而且还与角度有关．

4 结　论

(24)式具有一定的综合性，包括了一类动态黑洞的情形，对于不同的特殊情况，非热

辐射频率的最大值不同. 应该强调的是,对于动态非球对称黑洞,交错能级最大值 ω_0 不仅随时间变化,而且与角度有关. 因此,非热辐射的频率范围不仅依赖于时间,而且与角度有关,这是具有重要意义的结论.

[1] T. Damour, N. Deruelle, in Proceedings of the First Marcel Grossmann Meeting on General Relativity, by R. Ruffini (North-Holland Publishing Company, Amsterdam, 1975), p.476.
[2] 赵峥,物理学报,**32**(1983),1233.
[3] S. W. Kim, *Phys. Lett.* **A41**(1989), 238.
[4] R. Balbinot, *Phys. Rev.*, **D33**(1986), 1611.
[5] W.A. Hiscock, *Phys. Rev.*, **D23** (1981), 2813.
[6] J.W. York, Jr., *Phys. Rev.*, **D33**(1986), 2092.
[7] R. Balbinot, A. Barletta, *Class. Quantum Grav.*, **6**(1989), 195.
[8] Zhao Zheng, Dai Xian-xin, *Modern Phys. Lett.*, **A7** (1992), 1771.
[9] 赵峥,中国科学,**23**(1993),178.
[10] 罗志强、赵峥,物理学报,**42**(1993),506.
[11] 杨树政、肖兴国、赵峥,科学通报,**38**(1993),1371.

NON-THERMAL RADIATIONS OF A TYPE OF NON-STATIONARY BLACK HOLE

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ABSTRACT

The crossing of the particle energy levels near the event horizons of a type of non-stationary black hole is studied. The representative of the maximum value of the crossing energy levels is shown. The conclusion given covers all known results for non-stationary black holes. A new interesting result of this paper is that the frequency distribution of the non-thermal radiation, from a non-spherically symmetric and non-stationary black hole, depends on not only the time, but also the angle.

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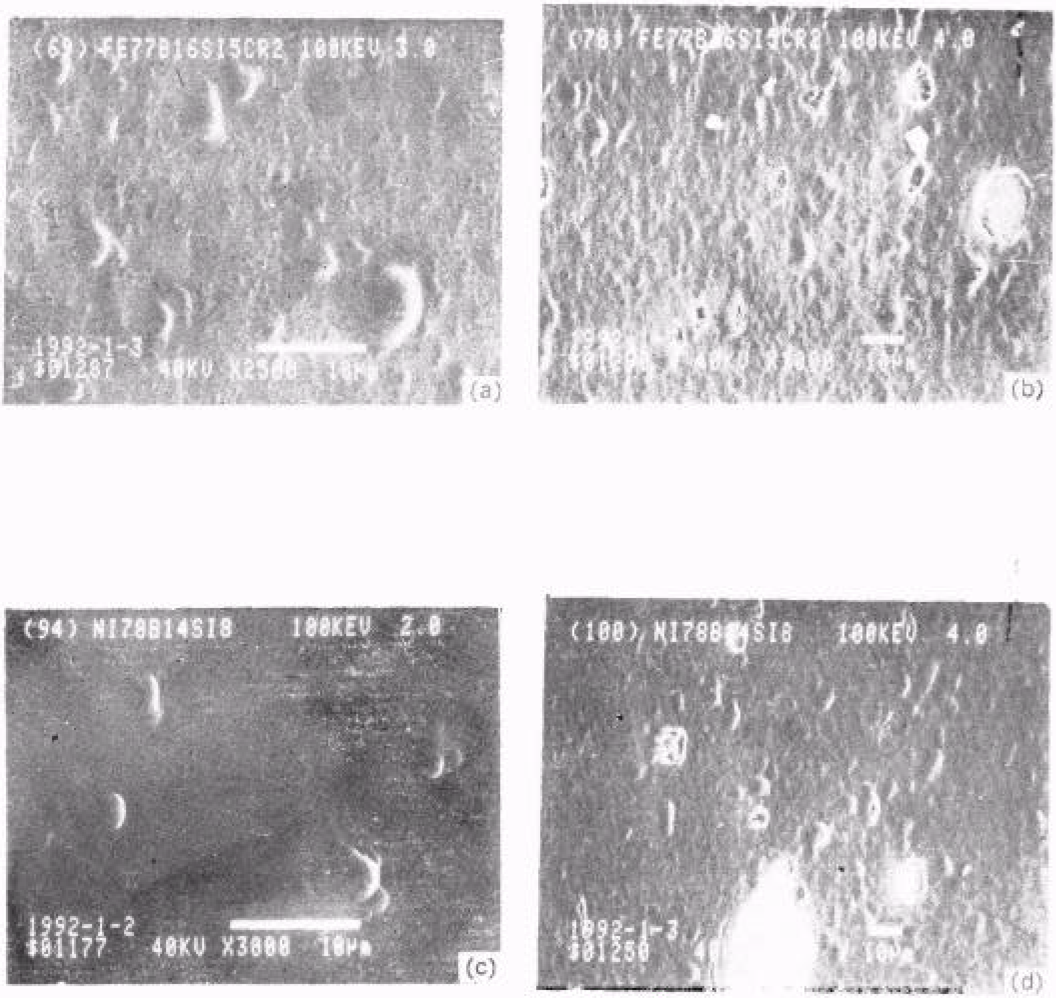

图 1　100keV He^+ 辐照非晶态合金 $Fe_{77}B_{16}Si_5Cr_2$ 和 $Ni_{78}B_{14}Si_8$ 的 SEM 图
图上方分别给出样品号、材料、辐照能量和剂量（$\times 10^{18} He/cm^2$）

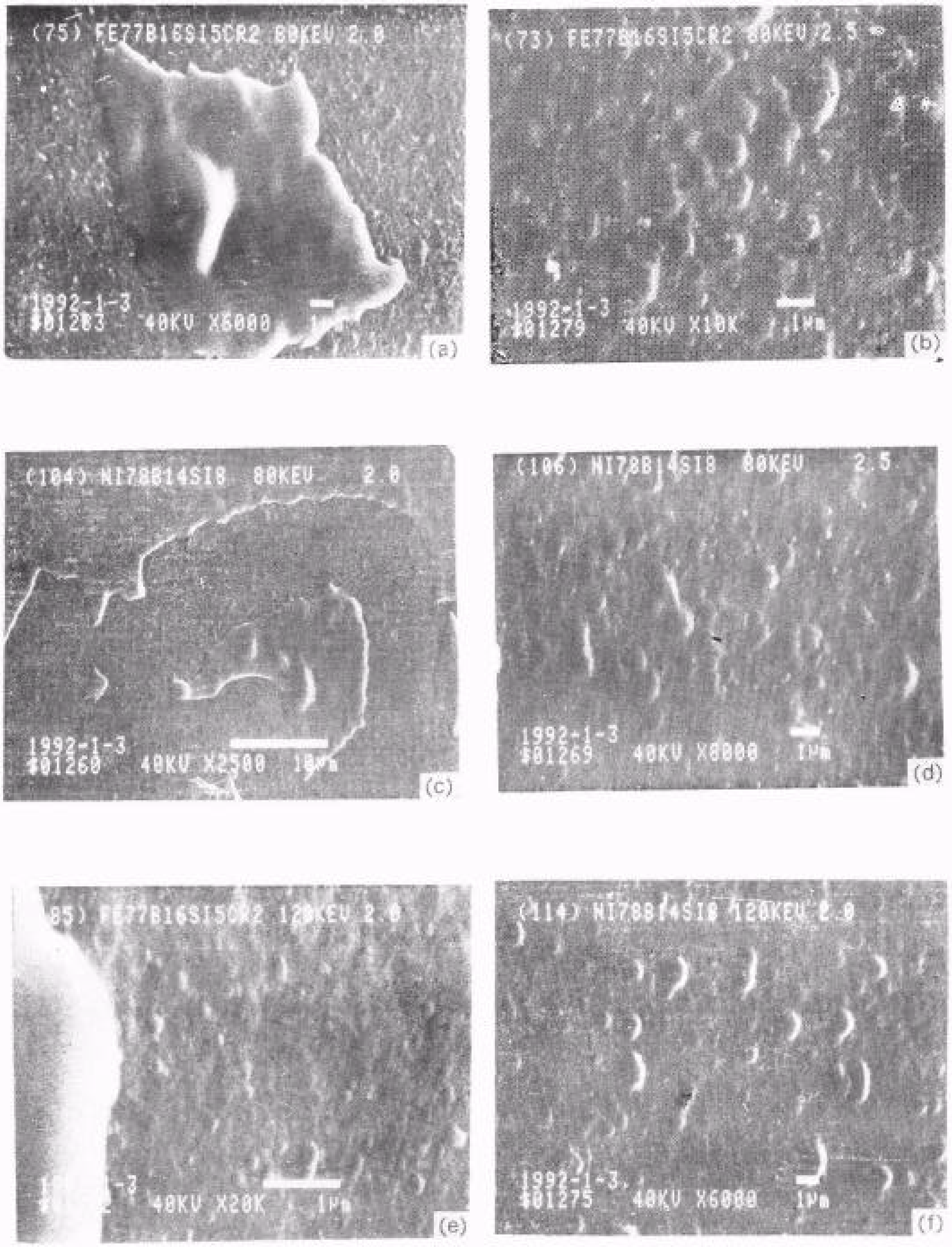

图3 80keV 和 120keV He^{+} 辐照 $Fe_{77}B_{16}Si_{5}Cr_{2}$ 和 $Ni_{78}B_{14}Si_{8}$ 的 SEM 图
图上方分别给出样品号、材料、辐照能量和剂量（$\times 10^{18} He/cm^{2}$）