Heat Equation on Vector Bundles

Junrong Yan

1 Basic Settings

Let (M,g) be a closed Riemannian manifolds with Levi-Civita connection ∇^{LC}, $E\to M$ be a hermitian bundle with hermitian metric h. Let ∇^E a unitary connection on E, then the connection Laplacian $\Delta^E:\Gamma(E)\to\Gamma(E)$ is defined as

$$\Delta^E := -\sum_i \nabla^E_{e_i}\nabla^E_{e_i} + \nabla^E_{\nabla^{LC}_{e_i}e_i},$$

where $\{e_i\}$ is a local orthonormal frame.

Let s be a smooth section of $E\to M$, denote $|s|^2 = h(s,s)$. Let Δ^{LC} be the Laplace–Beltrami operator on (M,g), then

Theorem 1.1 (Bochner formula)**.**

$$\Delta^{LC}|s|^2 = 2h(\Delta^E s, s) - 2\sum_i h(\nabla^E_{e_i}s, \nabla^E_{e_i}s)$$

By Bochner Formula, one has

Theorem 1.2 (Maximal Principle)**.** *Let $\Omega\subset M$ be a connected domain in M with smooth boundary. Assume that $s\in\Gamma(E)$ solves*

$$\begin{cases}\Delta^E s = 0 \ \textit{in}\ \Omega\\ s=0\ \textit{on}\ \partial\Omega.\end{cases}$$

Then $\sup_{p\in\Omega}|s|^2(p) = \sup_{p\in\partial\Omega}|s|^2(p)$.

2 Heat Equation

It follows from Bochner Formula again that

Theorem 2.1 (Maximal Principle)**.** *Let $s(t)$ be a time dependent section solves*

$$\begin{cases}(\partial_t+\Delta^E)s(t) = 0\ \textit{in}\ M\times[0,\infty)\\ s(0)=s_0\\ \lim_{t\to\infty} s(t) = 0.\end{cases} \tag{1}$$

for some $s_0\in\Gamma(E)$. Then $\sup_{(p,t)\in M\times[0,\infty)}|s|^2 = \sup_{p\in M}|s_0|^2$.

Set $p_i : M \times M \to M$, $(p_1, p_2) \to p_i$, $i = 1, 2$, and let $E^* \to M$ be the dual bundle of $E \to M$, then heat kernel $K(t, x, y)$ with respect to Δ^E is a time-dependent section of $p_1^* E \otimes p_2^* E^*$, such that

$$s(t,x) := \int_M (K(t,x,y), s_0(y))\, dy$$

solves (1), where $(\cdot, \cdot)$ is the nature pairing of E^* and E.

Proposition 2.2. *1. $K(t, x, y)$ solves*

$$\begin{cases} (\partial_t - \Delta_y^E) K(t,x,y) = 0, \\ \lim_{t\to 0} K(t,x,y) = \delta_x(y) \sum_i e_i(x) \otimes \widetilde{e}_j(y), \end{cases}$$

where $\{e_i\}, \{\widetilde{e}_j\}$ are orthonormal basis of E and E^* near x and y respectively.

2. $K(t, x, y) = K(t, y, x)^*$.

3. $K(t+s, x, y) = \int_M (K(s, x, z), K(s, z, y))\, dz$. Hence, $K(2t, x, x) = \int_M (K(s, x, y), K(s, x, y)^*)\, dy$.

Theorem 2.3. *Let $k(t, x, y)$ be the heat kernel with respect to Δ^{LC}, then $|K(t, x, y)|^2 = h(K(t, x, y), K(t, x, y)) \le nk(t, x, y)$, where h is the metric on $p_1^* E \otimes p_2^* E^*$ induced by h on $E \to M$, $n = \mathrm{rank}(E)$.*

Proof. By Bochner formula,

$$\begin{cases} (\partial_t - \Delta_y^{LC}) \left(|K(t,x,y)|^2 - nk(t,x,y)\right) \le 0, \\ \lim_{t\to 0} \left(|K(t,x,y)|^2 - nk(t,x,y)\right) = 0. \end{cases}$$

By classical maximal principle, the result follows. □

3 Heat equation for Hodge Laplacian

Let Δ^H be the Hodge Laplacian, Δ^C be the connection laplacian on $\Lambda^*(T^*M) \to M$, then one has Bochner-Lichnerowicz-Weitzenbock formula

$$\Delta^H = \Delta^C + \sum_{e_i, e_j} c(e_i) c(e_j) R(e_i, e_j),$$

where $\{e_i\}$ is a local orthonormal frame, $\{e^i\}$ is its dual frame, $c(e_i) = e^i \wedge -\iota_{e_i}$, R is the curvature operator.

Theorem 3.1. *Let $K^H(t, x, y)$ be the heat kernel with respect to Δ^H, then there exists $C = C(n, R) > 0$, such that*

$$|K^H(t,x,y)|^2 \le e^{Ct} 2^n k(t,x,y),$$

where $n = \dim(M)$.

Proof. By Bochner formula and Bochner-Lichnerowicz-Weitzenbock formula, there exists $C = C(n, R) > 0$, such that

$$\begin{cases} (\partial_t - \Delta_y^{LC}) \left(e^{-Ct}|K(t,x,y)|^2 - nk(t,x,y)\right) \leq 0, \\ \lim_{t\to 0} \left(e^{-Ct}|K(t,x,y)|^2 - nk(t,x,y)\right) = 0. \end{cases}$$

By classical maximal principle, the result follows. □

Corollary 3.2. *There exists $C(n, R) > 0$, such that for all $t \in (0, 1)$,*

$$\int_M |K(t,x,y)|^2 dy \leq C(n,R).$$

Proof. This is because

$$\int_M k(t,x,y) dy = 1.$$

□

4 Hear equation for Witten Laplacian on $\mathbb{R}$

Let f be a smooth function on $\mathbb{R}$, $d_{Tf} := d + Tdf \wedge (T > 0)$ be the Witten deformation of d, then Witten Laplacian $\Delta_{Tf} := d_{Tf}d_{Tf}^* + d_{Tf}^* d_{Tf}$, where d_{Tf}^* is the formal adjoint of d_{Tf}.

Let $K_{Tf}(t, x, y)$ be the heat kernel of Δ_{Tf}.

Theorem 4.1. *Assume that $f'' \geq -C_1$ for some $C_1 > 0$, then there exist $C_2 = C_2(n, R)$, such that*

$$|K_{Tf}(t,x,y)|^2 \leq e^{tTC_1} e^{-Tf} 2^n k(t,x,y).$$

Proof. The proof proceeds along the same lines as the proof of Theorem 2.3. □