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A mandala of Legendrian dualities for pseudo-spheres in semi-Euclidean space

Liang Chen and Shyuichi Izumiya

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Abstract

We show six Legendrian dualities between pseudo-spheres in semi-Euclidean space which are basic tools for the study of extrinsic differential geometry of submanifolds in these pseudo-spheres.

1 Introduction

A theorem of Legendrian dualities for pseudo-spheres in Minkowski space has been shown by the second author in [8] which is now a fundamental tool for the study of extrinsic differential geometry on submanifolds in these pseudo-spheres from the view point of Singularity theory (cf., [8, 11, 12]). In this paper we consider similar Legendrian dualities between pseudo-spheres in general semi-Euclidean space. The main results (cf., Theorems 3.1 and 3.2) are simple generalizations of the previous results in [8, 10]. However, there are some new applications and information.

The Lorentzian space form with negative sectional curvature is called Anti de Sitter space which is given as a pseudo-sphere with a negative radius in semi-Euclidean space with index 2. This space is a very important subject in Physics (the theory of general relativity, the string theory and the brane world scenario etc [19, 20, 21]). We can apply the Legendrian duality theorem to this space and obtain some new geometric properties of submanifolds. The detailed arguments on this application will be appeared in elsewhere.

Recently there appeared several results on submanifolds in hyperbolic space and de Sitter space which are pseudo-spheres in Minkowski space ([1, 6, 7, 17, 18]). We give an interesting interpretation on the set of Legendrian dualities from a new point of view (i.e, a mandala of Legendrian dualities in Fig 1.1). We can add some new information on the above results from this point of view.

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2 Basic notions

In this section we prepare basic notions on semi-Euclidean space. Let \( \mathbb{R}^{n+1} = \{(x_1, \ldots, x_{n+1}) \mid x_i \in \mathbb{R}, i = 1, \ldots, n+1\} \) be an \((n+1)\)-dimensional vector space. For any vectors \( \mathbf{x} = (x_1, \ldots, x_{n+1}), \mathbf{y} = (y_1, \ldots, y_{n+1}) \) in \( \mathbb{R}^{n+1} \), the pseudo scalar product of \( \mathbf{x} \) and \( \mathbf{y} \) is defined by \( \langle \mathbf{x}, \mathbf{y} \rangle = -\sum_{i=1}^{r} x_i y_i + \sum_{i=r+1}^{n+1} x_i y_i \). The space \( \langle \mathbb{R}^{n+1}, \langle \cdot, \cdot \rangle \rangle \) is called semi-Euclidean \((n+1)\)-space with index \( r \) and denoted by \( \mathbb{R}^{n+1}_r \). We say that a vector \( \mathbf{x} \) in \( \mathbb{R}^{n+1}_r \setminus \{0\} \) is spacelike, null or timelike if \( \langle \mathbf{x}, \mathbf{x} \rangle > 0, = 0 \) or \( < 0 \) respectively. The norm of the vector \( \mathbf{x} \in \mathbb{R}^{n+1}_r \) is defined by \( \| \mathbf{x} \|=\sqrt{|\langle \mathbf{x}, \mathbf{x} \rangle|} \). We have the following three kinds of pseudo-spheres in \( \mathbb{R}^{n+1}_r \): The pseudohyperbolic \( n \)-space with index \( r - 1 \) is defined by

\[ H^n_{r-1} = \{ \mathbf{x} \in \mathbb{R}^{n+1}_r \mid \langle \mathbf{x}, \mathbf{x} \rangle = -1 \}, \]

the pseudo \( n \)-sphere with index \( r \) by

\[ S^n_r = \{ \mathbf{x} \in \mathbb{R}^{n+1}_r \mid \langle \mathbf{x}, \mathbf{x} \rangle = 1 \} \]

and the (open) nullcone by

\[ \Lambda^n = \{ \mathbf{x} \in \mathbb{R}^{n+1}_r \setminus \{0\} \mid \langle \mathbf{x}, \mathbf{x} \rangle = 0 \} \].

In relativity theory \( \mathbb{R}^{n+1}_1 \) is called Minkowski \((n+1)\)-space, \( S^n_1 \) de Sitter \( n \)-space and \( H^n_1 \) is Anti de Sitter \( n \)-space which is denoted by \( \text{AdS}^n \). These are the Lorentzian space forms. Moreover, \( H^n_0 \) is called hyperbolic \( n \)-space and \( S^n_0 \) is the Euclidean unit sphere which are the Riemannian space forms.

3 Legendrian dualities

We now review some properties of contact manifolds and Legendrian submanifolds. Let \( N \) be a \((2n+1)\)-dimensional smooth manifold and \( K \) be a tangent hyperplane field on \( N \). Locally such a field is defined as the field of zeros of a 1-form \( \alpha \). The tangent hyperplane field \( K \) is non-degenerate if \( \alpha \wedge (d\alpha)^n \neq 0 \) at any point of \( N \). We say that \((N, K)\) is a contact manifold if \( K \) is a non-degenerate hyperplane field. In this case \( K \) is called a contact structure and \( \alpha \) is a contact form. Let \( \phi : N \to N' \) be a diffeomorphism between contact manifolds \((N, K)\) and \((N', K')\). We say that \( \phi \) is a contact diffeomorphism if \( d\phi(K) = K' \). Two contact manifolds \((N, K)\) and \((N', K')\) are contact diffeomorphic if there exists a contact diffeomorphism \( \phi : N \to N' \). A submanifold \( i : L \subset N \) of a contact manifold \((N, K)\) is said to be Legendrian if \( \dim L = n \) and \( dt_x(T_xL) \subset K_{i(x)} \) at any \( x \in L \). We say that a smooth fiber bundle \( \pi : E \to M \) is called a Legendrian fibration if its total space \( E \) is furnished with a contact structure and its fibers are Legendrian submanifolds. Let \( \pi : E \to M \) be a Legendrian fibration. For a Legendrian submanifold \( i : L \subset E, \pi \circ i : L \to M \) is called a Legendrian map. The image of the Legendrian map \( \pi \circ i \) is called a wavefront set of \( i \) which is denoted by \( W(L) \). For any \( p \in E \), it is known that there is a local coordinate system \((x_1, \ldots, x_m, p_1, \ldots, p_m, z)\) around \( p \) such that

\[ \pi(x_1, \ldots, x_m, p_1, \ldots, p_m, z) = (x_1, \ldots, x_m, z) \]

and the contact structure is given by the 1-form

\[ \alpha = dz - \sum_{i=1}^{m} p_i dx_i \]
(cf. [2], 20.3).

In [8] we have shown the basic duality theorem which is the fundamental tool for the study of spacelike hypersurfaces in Minkowski pseudo-spheres. In this paper we consider the similar dualities in semi-Euclidean space. We now consider the following four double fibrations:

(1) (a) \( H^{n-1}_{r-1} \times S^n_r \supset \Delta_1 = \{ (v, w) \mid \langle v, w \rangle = 0 \} \),
    (b) \( \pi_{11} : \Delta_1 \longrightarrow H^{n-1}_{r-1}, \pi_{12} : \Delta_1 \longrightarrow S^n_r \),
    (c) \( \theta_{11} = \langle dv, w \rangle|\Delta_1, \theta_{12} = \langle v, dw \rangle|\Delta_1 \).

(2) (a) \( H^{n-1}_{r-1} \times \Lambda^n \supset \Delta_2 = \{ (v, w) \mid \langle v, w \rangle = -1 \} \),
    (b) \( \pi_{21} : \Delta_2 \longrightarrow H^{n-1}_{r-1}, \pi_{22} : \Delta_2 \longrightarrow \Lambda^n \),
    (c) \( \theta_{21} = \langle dv, w \rangle|\Delta_2, \theta_{22} = \langle v, dw \rangle|\Delta_2 \).

(3) (a) \( \Lambda^n \times S^n_r \supset \Delta_3 = \{ (v, w) \mid \langle v, w \rangle = 1 \} \),
    (b) \( \pi_{31} : \Delta_3 \longrightarrow \Lambda^n, \pi_{32} : \Delta_3 \longrightarrow S^n_r \),
    (c) \( \theta_{31} = \langle dv, w \rangle|\Delta_3, \theta_{32} = \langle v, dw \rangle|\Delta_3 \).

(4) (a) \( \Lambda^n \times \Lambda^n \supset \Delta_4 = \{ (v, w) \mid \langle v, w \rangle = -2 \} \),
    (b) \( \pi_{41} : \Delta_4 \longrightarrow \Lambda^n, \pi_{42} : \Delta_4 \longrightarrow \Lambda^n \),
    (c) \( \theta_{41} = \langle dv, w \rangle|\Delta_4, \theta_{42} = \langle v, dw \rangle|\Delta_4 \).

Here, \( \pi_{ij}(v, w) = v, \pi_{ij}(v, w) = w, \langle dv, w \rangle = -w_0dw_0 + \sum_{i=1}^n w_idv_i \) and \( \langle v, dw \rangle = -v_0dw_0 + \sum_{i=1}^n v_idw_i \) are one-forms on \( \mathbb{R}^{n+1}_r \times \mathbb{R}^{n+1}_r \).

We remark that \( \theta_{ij}^{-1}(0) \) and \( \theta_{ij}^{-1}(0) \) define the same tangent hyperplane field over \( \Delta_i \) which is denoted by \( K_i \). The basic duality theorem is the following theorem:

**Theorem 3.1** Under the same notations as the previous paragraph, each \((\Delta_i, K_i) (i = 1, 2, 3, 4)\) is a contact manifold and both of \(\pi_{ij} (j = 1, 2)\) are Legendrian fibrations. Moreover those contact manifolds are contact diffeomorphic each other.

Before we give the proof, we include here a quick review on the canonical contact structure on the projective cotangent bundle over a manifold. Let \( \pi : PT^*(M) \rightarrow M \) be the projective cotangent bundle over an \( n \)-dimensional manifold \( M \). This fibration can be considered as a Legendrian fibration with the canonical contact structure \( K \) on \( PT^*(M) \). We now review geometric properties of this space. Consider the tangent bundle \( \tau : TPT^*(M) \rightarrow PT^*(M) \) and the differential map \( d\tau : TPT^*(M) \rightarrow N \) of \( \pi \). For any \( X \in TPT^*(M) \), there exists an element \( \alpha \in T^*(M) \) such that \( \tau(X) = [\alpha] \). For an element \( V \in T_x(M) \), the property \( \alpha(V) = 0 \) does not depend on the choice of representative of the class \([\alpha]\). Thus we can define the canonical contact structure on \( PT^*(M) \) by

\[
K = \{ X \in TPT^*(M) | \tau(X)(d\pi(X)) = 0 \}.
\]

For a local coordinate neighborhood \((U, (x_1, \ldots, x_n)) \) on \( M \), we have a trivialization \( PT^*(U) \cong U \times P(\mathbb{R}^{n-1})^* \) and we call \( \{(x_1, \ldots, x_n), [\xi_1 : \ldots : \xi_n]\) homogeneous coordinates, where \([\xi_1 : \ldots : \xi_n]\) are homogeneous coordinates of the dual projective space \( P(\mathbb{R}^{n-1})^* \). It is easy to show that \( X \in K(x, [\xi]) \) if and only if \( \sum_{i=1}^n \mu_i \xi_i = 0 \), where \( d\tilde{\pi}(X) = \sum_{i=1}^n \mu_i \xi_i \). This means that the contact form \( \alpha \) on the affine coordinates \( U_j = \{ (x, [\xi]) | \xi_j \neq 0 \} \subset PT^*(U) \) is given by \( \alpha = \sum_{i=1}^n (\xi_i/\xi_j)dx_i \).

**Proof.** By definition we can easily show that each \( \Delta_i \) \((i = 1, 2, 3, 4)\) is a smooth submanifold in \( \mathbb{R}^{n+1}_r \times \mathbb{R}^{n+1}_r \) and each \( \pi_{ij} \) \((i = 1, 2, 3, 4; j = 1, 2)\) is a smooth fibration. It also follows from the definition of \( \theta_{ij} \) that each fibre of \( \pi_{ij} \) is an integral submanifold of \( K_i \) \((i = 1, 2, 3, 4)\).
Finally, we show that \((\Delta_1, K_1)\) is a contact manifold. For any \(v = (v_1, \cdots, v_{n+1}) \in H_{r-1}^n\), we have \(\sum_{i=1}^r v_i^2 \neq 0\). Therefore \((v_1, \cdots, v_r) \neq (0, \ldots, 0)\). We consider a coordinate neighborhood \(V_1^+ = \{v = (v_1, \ldots, v_{n+1}) \in H_{r-1}^n | v_i > 0\}\) on which we have \(v_1 = \sqrt{-\sum_{i=2}^r v_i^2 - \sum_{i=r+1}^{n+1} v_i^2 + 1}\). Therefore, we regard that \((v_2, \cdots, v_{n+1})\) is the local coordinates on \(V_1^+\).

For any \(w = (w_1, \ldots, w_{n+1}) \in S_r^n\), we have \(\sum_{i=1}^{n+1} w_i^2 \neq 0\), so that \((w_{r+1}, \ldots, w_{n+1}) \neq (0, \ldots, 0)\). We also consider a coordinate neighborhood \(W_{r+1}^+ = \{w \in S_r^n | w_{r+1} > 0\}\). Then \(V_1^+ \times W_{r+1}^+\) is one of the local coordinate of \(H_{r-1}^n \times S_r^n\). We now define a mapping

\[
\Phi : \Delta_1 \cap (V_1^+ \times W_{r+1}^+) \longrightarrow PT^n H_{r-1}^n | V_1^+ \n\]

by

\[
\Phi(v, w) = (v, [(w_1 v_2 - w_2 v_1) : \cdots : (w_1 v_r - w_r v_1) : (-w_1 v_{r+1} + w_{r+1} v_1) : \cdots : (-w_1 v_{n+1} + w_{n+1} v_1)])
\]

Let \((v_2, \ldots, v_{n+1}, [\xi_2 : \cdots : \xi_{n+1}])\) be homogeneous coordinates of \(PT^n H_{r-1}^n | V_1^+ \subseteq V_1^+ \times P(\mathbb{R}^{n-1})^*\). We have the canonical contact form \(\alpha = \sum_{i=2}^{n+1} (\xi_i / \xi_j) dv_i\) on \(PT^n H_{r-1}^n\) over \(V_1^+ \times U_j\), where \(U_j = \{[\xi] | \xi_j \neq 0\}\). It follows that

\[
\Phi^* \alpha = \frac{\pm v_1}{w_j v_1 - w_j v_j} \left( -\sum_{i=1}^r w_i dv_i + \sum_{i=r+1}^{n+1} w_i dv_i \right)
\]

\[
= \frac{\pm v_1}{w_j v_1 - w_j v_j} \langle dv, w \rangle |_{\Delta_1} = \frac{\pm v_1}{w_j v_1 - w_j v_j} \theta_{11},
\]

where \(\pm\) depends on \(j\) of \(\Phi^{-1}(V_1^+ \times U_j)\). Since

\[
\Delta_1 \cap (V_1^+ \times W_{r+1}^+) = \bigcup_{j=2}^{n+1} \Phi^{-1}(V_1^+ \times U_j),
\]

\(\theta_{11}\) is a contact form on \(\Delta_1 \cap (V_1^+ \times W_{r+1}^+)\) such that \(\Phi\) is a contact morphism. We also have the similar calculation as the above on the other coordinate neighborhoods. Thus \(\Delta_1, (\theta_1|_0)\) is a contact manifold. For the other \(\Delta_i\) \((i = 2, 3, 4)\) we define smooth mappings \(\Psi_i : \Delta_i \longrightarrow \Delta_i\) by

\[
\Psi_{12}(v, w) = (v, v + w),
\]

\[
\Psi_{13}(v, w) = (v - w, -w),
\]

\[
\Psi_{14}(v, w) = (v - w, v + w).
\]

We can construct the converse mappings defined by

\[
\Psi_{21}(v, w) = (v, w - v),
\]

\[
\Psi_{31}(v, w) = (v - w, -w)
\]

\[
\Psi_{41}(v, w) = \left(\frac{v + w}{2}, \frac{w - v}{2}\right).
\]

Therefore, \(\Psi_{1i}\) are diffeomorphisms. Moreover, we have

\[
\Psi_{12} \theta_{21} = \langle dv, v + w \rangle |_{\Delta_1} = \langle dv, v \rangle |_{\Delta_1} + \langle dv, w \rangle |_{\Delta_1}
\]

\[
= \langle dv, w \rangle |_{\Delta_1} = \theta_{11}.
\]
We now explain the situation by a “mandala of Legendrian dualities” as the following commutative diagram:

\[ H^n_{r-1} \times S^n_r \]

\[ \Delta_1 \]

\[ \Delta_2 \quad \Delta_3 \]

\[ \Lambda^n \times \Lambda^n \]

\[ H^n_{r-1} \times \Lambda^n \]

\[ \Lambda^n \times S^n_r \]

Fig. 1. The Mandala of Legendrian Dualities

We can also give contact diffeomorphisms \( \Psi_{ij} : \Delta_i \longrightarrow \Delta_j \) for other pairs \((i, j)\) as follows:

\[ \Psi_{23}(v, w) = (2v - w, v - w), \]
\[ \Psi_{32}(v, w) = (v - w, v - 2w), \]
\[ \Psi_{24}(v, w) = (2v - w, w), \]
\[ \Psi_{42}(v, w) = \left( \frac{v + w}{2}, w \right), \]
\[ \Psi_{34}(v, w) = (v, v - 2w), \]
\[ \Psi_{43}(v, w) = \left( v, \frac{v - w}{2} \right). \]

We can also consider the following two extra double fibrations:

\( (a) S^n_r \times S^n_r \supset \Delta_5 = \{ (v, w) \mid \langle v, w \rangle = 0 \}, \)
\( (b) \pi_{51} : \Delta_5 \longrightarrow S^n_r, \pi_{52} : \Delta_5 \longrightarrow S^n_r, \)
\( (c) \theta_{51} = (dv, w)|\Delta_5, \theta_{52} = (v, dw)|\Delta_5. \)

\( (a) H^n_{r-1} \times H^n_{r-1} \supset \Delta_6 = \{ (v, w) \mid \langle v, w \rangle = 0 \}, \)
\( (b) \pi_{61} : \Delta_6 \longrightarrow H^n_{r-1}, \pi_{62} : \Delta_6 \longrightarrow H^n_{r-1}, \)
\( (c) \theta_{61} = (dv, w)|\Delta_6, \theta_{62} = (v, dw)|\Delta_6. \)

We have the following theorem.
Theorem 3.2 Under the same notations as the above, each $(\Delta_i, K_i)$ $(i = 5, 6)$ is a contact manifold and both of $\pi_{ij}$ $(j = 1, 2)$ are Legendrian fibrations.

The proof of the theorem is almost the same as that for $(\Delta_1, K_1)$ in Theorem 3.1. We can show that $(\Delta_5, K_5)$ (respectively, $(\Delta_6, K_6)$) is locally diffeomorphic to the projective cotangent bundle $\pi: PT^*H_{r-1} \rightarrow H_{r-1}$ (respectively, $\pi: PT^*S^n \rightarrow S^n$) which sends $K_i$ to the canonical contact structure. We remark that these contact manifolds $(\Delta_j, K_j)$ $(j = 5, 6)$ are not canonically contact diffeomorphic to $(\Delta_i, K_i)$ $(i = 1, 2, 3, 4)$. Therefore we cannot add these contact manifolds to the mandala of Legendrian dualities. By definition, $S^n$ is a unit sphere in Euclidean space $\mathbb{R}^{n+1}_0$, so that $(\Delta_5, K_5)$ is the well known classical spherical duality in this case. Finally we remark that $\Delta_6 = \emptyset$ in $H_6^0 \times H_6^0$.

4 Applications

In this section we consider differential geometry of hypersurfaces in pseudo-spheres as an application of the Legendrian dualities theorems.

4.1 Pseudo-spheres in $\mathbb{R}^{n+1}_{1}$

We consider hypersurfaces in pseudo-spheres in Minkowski space. In [7] it has been studied a local extrinsic differential geometry on hypersurfaces in hyperbolic space $H^0_n$ as an application of Legendrian singularity theory. We give a brief review on the theory. Let $X: U \rightarrow H^0_n$ be a regular hypersurface (i.e., an embedding), where $U \subset \mathbb{R}^{n-1}$ is an open subset. We denote that $M = x(U)$ and identify $M$ with $U$ through the embedding $X$. Since $(X, X) \equiv -1$, we have $(X_u, X) \equiv 0$ $(i = 1, \ldots, n - 1)$, where $u = (u_1, \ldots, u_{n-1}) \in U$. This means that $X$ is a timelike unit normal vector field to $M$ in $\mathbb{R}^{n+1}_1$. We can construct a spacelike unit normal $e(u)$ of $M$ in $H^0_n$ at $p = X(u)$ with the properties $(e, X_u) \equiv (e, X) \equiv 0, (e, e) \equiv 1$. Therefore the vector $X \pm e$ is lightlike. We define maps $E: U \rightarrow S^n$ and $L^\pm: U \rightarrow LC^*$ by $E(u) = e(u)$ and $L^\pm(u) = X(u) \pm e(u)$ which are called the de Sitter Gauss image and the lightcone Gauss image of $M$. In order to define curvatures for $M$, we can use both of the de Sitter Gauss image $E$ and the lightcone Gauss image $L^\pm$ like as the Gauss map of a hypersurface in Euclidean space. We can interpret that $dE(u)$ is a linear transformation on $T_pM$ for $p = X(u)$. Since the derivative $dX(u)$ can be identified with the identity mapping $1_{T_pM}$ on the tangent space $T_pM$ under the identification of $U$ and $M$ via the embedding $X$, we have

$$dL^\pm(u) = 1_{T_pM} \pm dE(u),$$

so that $dL^\pm(u)$ can be also interpreted as a linear transformation on $T_pM$. We call the linear transformation $A_p = -dE(u)$ the de Sitter shape operator and $S^\pm_p = -dL^\pm(u): T_pM \rightarrow T_pM$ the lightcone shape operator of $M$ at $p = X(u)$ at $p = X(u)$. The de Sitter Gauss-Kronecker curvature of $M$ at $p = X(u)$ is defined to be $K_{d}(u) = \det A_p$ and the lightcone Gauss-Kronecker curvature of $M$ at $p = X(u)$ is $K_{l}^\pm(u) = \det S^\pm_p$.

In [7] we have investigated the geometric meanings of the lightcone Gauss-Kronecker curvature from the contact viewpoint. One of the consequences of the results is that the lightcone Gauss-Kronecker curvature estimates the contact of hypersurfaces with hyperhorospheres. It has been also shown that the Gauss-Bonnet type theorem holds on the (normalized) lightcone Gauss-Kronecker curvature [9]. We emphasize that we discovered a new geometry in hyperbolic.
space through these research [3, 7, 9, 13] which is called “Horospherical Geometry”. We can interpret the above construction by using the Legendrian duality theorem. For any regular hypersurface $X : U \longrightarrow H^n(-1)$, we have $\langle X(u), \mathbb{E}(u) \rangle = 0$. Therefore, we can define a pair of embeddings

$$L_1 : U \longrightarrow \Delta_1$$

by $L_1(u) = (X(u), \mathbb{E}(u))$. By definition, $L_1$ is a Legendrian embedding if and only if $\mathbb{E}$ is a spacelike unit normal vector field along $M$. Therefore we have the wave front $\mathbb{F}(U) = \pi_{12} \circ L_1(U)$ of $L_1(U)$ through the Legendrian fibration $\pi_{12}$. On the other hand, by the mandala of Legendrian dualities, $L_2 = \Psi_{12} \circ L_1$ is a Legendrian embedding into $(\Delta_2, K_2)$, so that we have $L_2(u) = (X(u), L^+(u))$. If we consider another normal direction $\mathbb{E}(u) = -e(u)$, then we have $L_3(u) = (X(u), L^-(u))$. Moreover, the mandala of the Legendrian dualities gives more information. We have $L_3 = \Psi_{13} \circ L_1$ and $L_4 = \Psi_{14} \circ L_1$ which are Legendrian embeddings into $(\Delta_3, K_3)$ and $(\Delta_4, K_4)$ respectively. Especially $L_4$ is useful for the study of spacelike hypersurfaces in the nullcone (lightcone). Since the induced metric on the nullcone is degenerate, we cannot apply ordinary submanifold theory of semi-Riemannian geometry. In [8] the Legendrian embedding $L_4$ has been used for the construction of the extrinsic differential geometry on spacelike hypersurfaces in the nullcone. In [17] Kasedou constructed the extrinsic differential geometry on spacelike hypersurfaces in $S^n$ analogous to the theory in [7]. For a spacelike embedding $X : U \longrightarrow S^n_1$, he defined a hyperbolic Gauss image $\mathbb{E} : U \longrightarrow H^n_0$ and a lightcone Gauss image $\mathbb{L}^\pm : U \longrightarrow \Lambda^n$ exactly the same way as those in [7]. Of course, some geometric properties are different from those of hypersurfaces in $H^n_0$. We can also interpret his construction by the mandala of Legendrian dualities similar way as the case for hypersurfaces in $H^n_0$. However, we have some more information by the mandala of Legendrian dualities. We can start any Legendrian embedding $L_i : U \longrightarrow \Delta_i$ ($i = 1, 2, 3, 4$). Here we start $i = 1$. Then we write $L_1(u) = (X^h(u), X^d(u))$, $M^h = X^h(U)$ and $M^d = X^d(U)$. Since $L_1$ is a Legendrian embedding, $X^h$ and $X^d$ can be considered as unit normal vector fields each other. If $X^h, X^d$ are immersive, these are exactly unit normal vector fields each other in the ordinary sense, so that we can define the principal curvatures on these hypersurfaces each other. Suppose that both of $X^h$ and $X^d$ are immersive, we denote $\kappa^h(u)$ (respectively, $\kappa^d(u)$) one of the principal curvatures of $M^h$ (respectively, $M^d$) with the Gauss image $X^d$ (respectively, $X^h$) at $u \in U$. Under the identification of $U$ with $M^h$ (respectively, $M^d$) through $X^h$ (respectively, $X^d$), $dX^d$ is the inverse mapping of $dX^h$ vice versa. Therefore we have the following proposition.

**Proposition 4.1** Under the above notation, suppose that both of $X^h$ and $X^d$ are immersive. Then we have the relation $\kappa^d(u)\kappa^h(u) = 1$.

By the above proposition, we have nice dual relations between special surfaces in $H^3_0$ and $S^3_1$. For example the dual surface of a Linear Weingarten surface in $H^3_0$ is also a Linear Weingarten surface in $S^3_1$ vice versa. There appeared several results on such surfaces recently [1, 6, 18]. Moreover, in [14, 16] it has been classified the generic singularities of exceptional Linear Weingarten surfaces in $H^3_0$ and $S^3_1$ which are corresponding by the Legendrian duality. There are very beautiful dual relations between these singularities.

### 4.2 Anti de Sitter space in $\mathbb{R}^{n+1}_2$

In [4, 5, 15] extrinsic differential geometry on submanifolds in Anti de Sitter space are investigated. In these papers, it has been only considered the case when $n \leq 4$. The detailed
singularities of Lagrangian submanifold which is the lift of the Anti de Sitter map is a Lagrangian map such that the Legendrian embedding null Gauss-Kronecker curvature. We may consider that an embedding from an open subset or the swallowtail. The singularities of the singular set of by

\[ \pm (u) = (X(u), e(u)) \text{ and } \mathcal{L}_2^\pm (u) = (X(u), N^\pm (u)). \]

The Legendrian embedding \( \mathcal{L}_2 \) is the most interesting one. Analogous to the previous subsection, we can define the principal curvatures by using the Legendrian duality and study geometric properties of these curvatures as an application of the theory of Legendrian singularities (cf., [5] for \( n = 3 \)). We denote the product of the principal curvatures \( K_{AdS^n}(u) \) corresponding to the Legendrian embedding \( \mathcal{L}_2 \) and call it the \( AdS \)-null Gauss-Kronecker curvature of \( M \). In this case, we have the following construction: We define the following set

\[ S^1_t \times S^{n-2}_s = \{ x = (x_1, \cdots, x_{n+1}) \in \Lambda^n \mid x_1^2 + x_2^2 = 1 \}. \]

For any \( x = (x_1, \cdots, x_{n+1}) \in \Lambda^n \), we have

\[ \bar{x} = \frac{1}{\sqrt{x_1^2 + x_2^2}} x \in S^1_t \times S^{n-2}_s. \]

We may consider that \( S^1_t \times S^{n-2}_s \) is the ideal boundary (i.e., the end) of \( H^n_t \) which has a conformally flat Lorentzian structure. We can define the \( \text{Anti de Sitter } S^1_t \times S^{n-2}_s \)-Gauss map

\[ \mathbb{NG}^\pm : U \longrightarrow S^1_t \times S^{n-2}_s \]

by \( \mathbb{NG}^\pm (u) = \overline{N^\pm (u)} \). We define the corresponding Gauss-Kronecker curvature by differentiating the \( \text{Anti de Sitter } S^1_t \times S^{n-2}_s \)-Gauss map. We denote it \( \mathbb{K}_{AdS^n}(u) \) and call the \( \text{normalized } AdS \)-null Gauss-Kronecker curvature of \( M \). We can show that the \( \text{Anti de Sitter } S^1_t \times S^{n-2}_s \)-Gauss map is a Lagrangian map such that the Legendrian embedding \( \mathcal{L}_2(U) \) is a covering over the Lagrangian submanifold which is the lift of the \( \text{Anti de Sitter } S^1_t \times S^{n-2}_s \)-Gauss map. Since singularities of \( N^\pm \) (respectively, \( \mathbb{NG}^\pm \)) are the zero points set of \( K_{AdS^n} \) (respectively, \( \mathbb{K}_{AdS^n} \)), the singular set of \( N^\pm \) and \( \mathbb{NG}^\pm \) are the same. Moreover, in [5] we have classified the generic singularities of \( N^\pm \). The result is that generic singularities of \( N^\pm \) are the only the cuspidal edge or the swallowtail. The \( \text{cuspidal edge} \) is parametrized by \( C = \{ (x_1, x_2, x_3) \mid x_1 = 3u^4 + u^2v, x_2 = 4u^3 + 2uv, x_3 = v \} \) (cf., Fig.2).

![Cuspidal edge](image)

![Swallowtail](image)

**Fig. 2.**
By a general result of the theory of Legendrian/Lagrangian singularities, the cuspidal edge (respectively, the swallowtail) of $\mathbb{N}^\pm$ is the fold point (respectively, the cusp point) of $\mathbb{N}G^\pm$ (cf., [2], Part III).

Finally we remark that there is a conjecture in Physics that the classical gravitation theory on $AdS^n$ is equivalent to the conformal field theory on the ideal boundary of $AdS^n$ proposed by Maldacena [19]. It is called the $AdS/CFT$-correspondence or the holographic principle [21]. If the conjecture is true, extrinsic geometric properties on submanifolds in $AdS^n$ have corresponding Gage theoretic geometric properties in the ideal boundary $S^1_t \times S^{n-2}_s$. Here, we might say that the Anti de Sitter $S^1_t \times S^{n-2}_s$-Gauss map is one of the analogous notions belonging to the $AdS/CFT$-correspondence in Mathematics.

References


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