Spacelike Parallels and Evolutes in Minkowski pseudo-spheres

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Abstract

We consider extrinsic differential geometry on spacelike hypersurfaces in Minkowski pseudo-spheres (hyperbolic space, de Sitter space and the lightcone). In the previous paper [18] we have shown a basic Legendrian duality theorem between pseudo-spheres. We define the spacelike parallels by using the basic Legendrian duality theorem. This definition unifies the notions of parallels of spacelike hypersurfaces in pseudo-spheres. We also define the evolute as the locus of singularities of the spacelike parallels. These notions are investigated as applications of Lagrangian or Legendrian singularity theory. We consider geometric properties of non-singular spacelike hypersurfaces corresponding to singularities of spacelike parallels or evolutes.

1 Introduction

In this paper we describe some results of the project constructing the extrinsic differential geometry on submanifolds of Minkowski pseudo-spheres (cf. [12, 13, 14, 15, 16, 17, 18]). In [18] we have shown a basic Legendrian duality theorem between pseudo-spheres in Minkowski space in order to develop an extrinsic differential geometry for spacelike hypersurfaces in pseudo-spheres. Especially, we have stuck to spacelike hypersurfaces in the lightcone motivated by the results of Asperti and Dajczer [3] on conformally flat Riemannian manifolds. For a spacelike hypersurface in the lightcone, we cannot define the normal vector because the metric is degenerate. However, we have defined the lightlike Gauss image of a spacelike hypersurface in the lightcone as a direct application of the basic duality theorem. The derivative of the lightcone Gauss image can be interpreted as a linear transformation on the tangent space of the spacelike hypersurface which is called the lightcone Weingarten map. Therefore we have the lightlike principal curvatures as the eigenvalues of the lightcone Weingarten map. It follows

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that we have the lightcone Gauss-Kronecker curvature of the hypersurface as the product of the lightlike principal curvatures. We can also apply the Legendrian duality theorem to spacelike hypersurfaces in hyperbolic space or de Sitter space. For hypersurfaces in hyperbolic space, we have reconstructed the hyperbolic Gauss-Kronecker curvature in [18] by using the basic Legendrian duality theorem which was originally introduced in [12].

On the other hand, the notions of parallels and evolutes (focal sets) play important roles in the classical differential geometry for hypersurfaces in Euclidean space. Basic properties of such singular hypersurfaces were investigated by many people [2, 4, 23]. As a consequence, we can interpret that these results on evolutes describe the contact of hypersurfaces with hyperspheres (i.e., totally umbilic hypersurfaces with non-zero Gauss curvatures). It is called the “spherical (or, round) geometry” of hypersurfaces in Euclidean space.

In [13, 14] we have studied the evolutes of hypersurfaces in hyperbolic space and discovered some examples of hypersurfaces that the evolutes are split out of hyperbolic space. Some parts of the evolutes of such examples are located in de Sitter space. Therefore we have defined the notion of hyperbolic evolutes and de Sitter evolutes of hypersurfaces in hyperbolic space. In the Euclidean space, it has been known that the evolute of a hypersurface is the locus of singularities of the parallels of the original hypersurfaces. This means that the corresponding notion of the parallels for hypersurfaces in hyperbolic space might be also split out of hyperbolic space. Under such observation, we introduce the notion of spacelike parallels and evolutes in Minkowski pseudo-spheres. Here, Minkowski pseudo-spheres are hyperbolic space, de Sitter space or the lightcone (cf. §2). In §12 of [18] we remarked that the corresponding notion of parallels and evolutes of spacelike hypersurfaces in the lightcone have quite different properties from the parallels and the evolutes in Euclidean space. Especially if we consider a spacelike hypersurface in the lightcone, the parallels of the spacelike hypersurfaces are never located in the lightcone. Of course the evolute of the hypersurface are also in the same situation. This fact is quite different from the other hypersurfaces theories. Minkowski space is originally from the relativity theory in Physics (i.e., Lorentzian geometry in Mathematics). We refer to the book [22] for general properties of Minkowski space and Lorentzian geometry.

In §2 we give a brief review on the previous results on spacelike hypersurfaces in Minkowski pseudo-spheres. Especially, the basic Legendrian duality theorem in [18] is stated. We also review classification results on totally umbilic spacelike hypersurfaces in pseudo-spheres. We consider such totally umbilic spacelike hypersurfaces as “model hypersurfaces”. Spacelike parallels and caustics are defined in §3 as an application of the basic Legednrian duality theorem. By definition we can show that the caustics is the locus of singularities of spacelike parallels. According to the classification results of the totally umbilic spacelike hypersurfaces in pseudo-spheres, the evolutes is defined in §4. In order to study parallels and evolutes, we introduce timelike height functions and spacelike height functions in §5. By the direct calculation, we can show that the above notions of caustics and evolutes are the same. In §6 and §7 we study parallels and caustics from the view point of Lagrangian or Legendrian singularity theory. In §8 we study the geometric meaning of both the singularities of parallels and evolute from the view point of the contact with families of model hypersurfaces (totally umbilic hypersurfaces). We study generic properties in §9. In §10 we apply the classification results in [10, 27] to the case for n = 3 and draw some pictures.

We shall assume throughout the whole paper that all the maps and manifolds are $C^\infty$ unless the contrary is explicitly stated.
2 Basic concepts and notations

In this section we prepare basic notions on Minkowski space and contact geometry. Let \( \mathbb{R}^{n+1} = \{(x_0, x_1, \ldots, x_n) | x_i \in \mathbb{R}, i = 0, 1, \ldots, n\} \) be an \((n+1)\)-dimensional vector space. For any vectors \( \mathbf{x} = (x_0, \ldots, x_n), \mathbf{y} = (y_0, \ldots, y_n) \) in \( \mathbb{R}^{n+1} \), the pseudo scalar product of \( \mathbf{x} \) and \( \mathbf{y} \) is defined by \( \langle \mathbf{x}, \mathbf{y} \rangle = -x_0y_0 + \sum_{i=1}^{n} x_iy_i \). The space \( (\mathbb{R}^{n+1}, \langle \cdot, \cdot \rangle) \) is called Minkowski \((n+1)\)-space and denoted by \( \mathbb{R}_1^{n+1} \).

We say that a vector \( \mathbf{x} \) in \( \mathbb{R}^{n+1} \setminus \{0\} \) is spacelike, lightlike or timelike if \( \langle \mathbf{x}, \mathbf{x} \rangle > 0, = 0 \) or \(< 0 \) respectively. The norm of the vector \( \mathbf{x} \in \mathbb{R}^{n+1} \) is defined by \( \|\mathbf{x}\| = \sqrt{\langle \mathbf{x}, \mathbf{x} \rangle} \). Given a vector \( \mathbf{n} \in \mathbb{R}_1^{n+1} \) and a real number \( c \), the hyperplane with pseudo normal \( \mathbf{n} \) is given by \( HP(\mathbf{n}, c) = \{\mathbf{x} \in \mathbb{R}_1^{n+1} | \langle \mathbf{x}, \mathbf{n} \rangle = c\} \).

We say that \( HP(\mathbf{n}, c) \) is a spacelike, timelike or lightlike hyperplane if \( \mathbf{n} \) is timelike, spacelike or lightlike respectively.

We have the following three kinds of pseudo-spheres in \( \mathbb{R}_1^{n+1} \): The hyperbolic \( n \)-space is defined by \( H^n(-1) = \{\mathbf{x} \in \mathbb{R}_1^{n+1} | \langle \mathbf{x}, \mathbf{x} \rangle = -1\} \), the de Sitter \( n \)-space by \( S^n_1 = \{\mathbf{x} \in \mathbb{R}_1^{n+1} | \langle \mathbf{x}, \mathbf{x} \rangle = 1\} \) and the (open) lightcone by \( LC^* = \{\mathbf{x} \in \mathbb{R}_1^{n+1} \setminus \{0\} | \langle \mathbf{x}, \mathbf{x} \rangle = 0\} \).

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 \( \phi : N \rightarrow N' \) 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 \( \phi : N \rightarrow N' \). 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 \( \pi : E \rightarrow M \) is called a Legendrian fibration if its total space \( E \) is furnished with a contact structure and its fibers are Legendrian submanifolds. Let \( \pi : E \rightarrow M \) be a Legendrian fibration. For a Legendrian submanifold \( i : L \subset E, \pi \circ i : L \rightarrow M \) 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. [1], 20.3).
In [18] we have shown the basic duality theorem which is the fundamental tool for the study of spacelike hypersurfaces in Minkowski pseudo-spheres. We now consider the following four double fibrations:

(1) (a) $H^n(-1) \times S^n_1 \supset \Delta_1 = \{ (v, w) \mid \langle v, w \rangle = 0 \}$,
(b) $\pi_{11} : \Delta_1 \longrightarrow H^n(-1), \pi_{12} : \Delta_1 \longrightarrow S^n_1$,
(c) $\theta_{11} = \langle dv, w \rangle|_{\Delta_1}, \theta_{12} = \langle v, dw \rangle|_{\Delta_1}$.

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

(3) (a) $LC^* \times S^n_1 \supset \Delta_3 = \{ (v, w) \mid \langle v, w \rangle = 1 \}$,
(b) $\pi_{31} : \Delta_3 \longrightarrow LC^*, \pi_{32} : \Delta_3 \longrightarrow S^n_1$,
(c) $\theta_{31} = \langle dv, w \rangle|_{\Delta_3}, \theta_{32} = \langle v, dw \rangle|_{\Delta_3}$.

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

Here, $\pi_{ij}(v, w) = v$, $\pi_{12}(v, w) = w$, $\langle dv, w \rangle = -w_0 dv_0 + \sum_{i=1}^n w_i dv_i$ and $\langle v, dw \rangle = -w_0 dv_0 + \sum_{i=1}^n v_i dw_i$.

We remark that $\theta^{-1}_{11}(0)$ and $\theta^{-1}_{22}(0)$ define the same tangent hyperplane field over $\Delta_i$ which is denoted by $K_i$. The basic duality theorem is the following theorem:

**Theorem 2.1** 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.

We do not give the proof of the theorem here. However we need the canonical contact diffeomorphism between $\Delta_1$ and $\Delta_4$. We define a smooth mapping

$$\Phi_{14} : \mathbb{R}_1^{n+1} \times \mathbb{R}_1^{n+1} \longrightarrow \mathbb{R}_1^{n+1} \times \mathbb{R}_1^{n+1}$$

by $\Phi_{14}(v, w) = (v + w, v - w)$. The converse mapping is given by

$$\Phi_{41}(v, w) = \left(\frac{v + w}{2}, \frac{v - w}{2}\right).$$

We can also check that $\Phi_{14}(\Delta_1) = \Delta_4$ and $\Phi_{41}(\Delta_4) = \Delta_1$, so that $\Phi_{14}|\Delta_1$ and $\Phi_{41}|\Delta_4$ are diffeomorphism. We can easily check that $\Phi_{14}$ and $\Phi_{41}$ are contact diffeomorphisms.

We now consider differential geometry of hypersurfaces in pseudo-spheres as applications of the basic theorem. Let

$$L_1 : U \longrightarrow \Delta_1$$

be a Legendrian embedding and denote that $L_1(u) = (x^h(u), x^d(u))$. By using the above contact diffeomorphism, we have a Legendrian embedding

$$L_4 : U \longrightarrow \Delta_4.$$
defined by \( \mathcal{L}_4(u) = \Phi_1 \circ \mathcal{L}_3(u) \). We denote that \( \mathcal{L}_4(u) = (x^t_+(u), x^t_-(u)) \), so that we have the following relations:

\[
x^h(u) = \frac{x^t_+(u) + x^t_-(u)}{2}, \quad x^d(u) = \frac{x^t_+(u) - x^t_-(u)}{2}.
\]

We now distinguish three cases as follows:

**Case 1)** We assume that \( x^h : U \longrightarrow H^n(-1) \) is an embedding. In this case \( x^h \) are the hyperbolic Gauss indicatrices of \( x^h \) which are defined in [12]. Nevertheless, we call these the *lightcone Gauss image*. Here, we consider the following model hypersurfaces in hyperbolic space. We consider the eigenvectors of \( x^d \) and \( x^h \) at \( u_0 \) can be considered as linear transformations on the tangent space of \( M = x^h(U) \) at \( p = x^h(u_0) \). We respectively call \( S^d(p) = -dx^d(u_0) \) and \( S^d(p) = -dx^d(u_0) \) the lightcone shape and the *de Sitter shape* operator of \( M = x^h(U) \) at \( p = x^h(u_0) \). We denote the eigenvalue of \( S^d(p) \) by \( \kappa^d(p) \) and the eigenvalue of \( S^d(p) \) by \( \kappa^d(p) \). By the relation \( x^h \pm x^d = x^h \), we have a relation \( S^d(p) = id_{T_pM} \), under the identification of \( U \) and \( M \) through \( x^h \). Therefore, \( S^d(p) \) and \( S^d(p) \) have same eigenvectors and we have a relation that \( \kappa^d(p) = -1 \pm \kappa^d(p) \).

We now define the notion of Gauss-Kronecker curvatures of \( M = x^h(U) \) at \( p = x^h(u_0) \) as follows:

\[
K^\pm(u_0) = \det S^d(p) ; \quad \text{The lightcone Gauss-Kronecker curvature},
\]

\[
K^d(u_0) = \det S^d(p) ; \quad \text{The de Sitter Gauss-Kronecker curvature}.
\]

We remark that \( K^\pm(u_0) \) is called the hyperbolic Gauss-Kronecker curvature in [12]. We say that a point \( u_0 \in U \) or \( p = x^h(u_0) \) is an umbilic point if \( S^d(p) = \kappa^d(p) id_{T_pM} \). Since the eigenvectors of \( S^d(p) \) are the same, the above condition is equivalent to the condition \( S^d(p) = \kappa^d(p) id_{T_pM} \). We say that \( M = x^h(U) \) is *totally umbilic* if all points on \( M \) are umbilic. Here, we consider the following model hypersurfaces in hyperbolic space. We consider the intersection of \( H^n(-1) \) with a hyperplane in \( \mathbb{R}^{n+1} \):

\[
HH(n, c) = HP(n, c) \cap H^n(-1).
\]

We say that \( HH(n, c) \) is a hypersphere if \( n \) is timelike, an *equidistant hypersurface* if \( n \) is spacelike, and a hyperhorospher 

<table>
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<tr>
<th>Proposition 2.2</th>
<th>Suppose that ( M = x^h(U) \subset H^n(-1) ) is totally umbilic. Then ( \kappa^d(p) ) is constant ( \kappa^d ). Under this condition, we have the following classification:</th>
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<tr>
<td>1) Suppose that ( (\kappa^d)^2 + 2\kappa^d \neq 0 ).</td>
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<tr>
<td>a) If ( (\kappa^d)^2 + 2\kappa^d &gt; 0 ), then then ( M ) is a part of hypersphere</td>
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| \[
HH \left( c, \frac{-\kappa^d - 1}{\sqrt{(\kappa^d)^2 + 2\kappa^d}} \right),
\]
| where |
| \[
c = \frac{1}{\sqrt{(\kappa^d)^2 + 2\kappa^d}} x^h(u) + x^h(u) \in H^n(-1)
\] |
is a constant timelike vector.

b) If \((\kappa^c_\pm)^2 + 2\kappa^c_\pm < 0\), then \(M\) is a part of an equidistant hypersurface

\[
HH\left(c, \frac{-\kappa^c_\pm -1}{\sqrt{-(\kappa^c_\pm)^2 - 2\kappa^c_\pm}}\right),
\]

where

\[
c = \frac{1}{\sqrt{-(\kappa^c_\pm)^2 - 2\kappa^c_\pm}}(\kappa^c_\pm x^h(u) + x^c_\pm(u)) \in S^m_1
\]

is a constant spacelike vector. In particular, if \(\kappa^c_\pm = -1\), then \(M\) is a part of hyperplane \(HH(c, 0)\), where \(c = x^d(u)\) is a constant spacelike vector.

2) If \((\kappa^c_\pm)^2 + 2\kappa^c_\pm = 0\), then \(M\) is a part of a hyperborsphere \(HH(c, -\kappa^c_\pm -1)\), where \(c = \kappa^c_\pm x^h(u) + x^c_\pm(u)\) is a constant lightlike vector.

**Case 2)** We assume that \(x^d: U \rightarrow S^m_1\) is an embedding. Since \(L_1\) is a Legendrian embedding, \(x^d\) is a spacelike embedding. (i.e., an embedding and \(x^d_{u_i}\), \((i = 1, \ldots, n - 1)\) are spacelike vectors). We also call \(x^d\) the lightcone Gauss image and \(x^h\) the hyperbolic Gauss image of \(x^d\). By exactly the same calculation as the case 1), we can show that the derivatives of \(x^d_\pm\) and \(x^h\) at \(u_0\) can be considered as linear transformations on the tangent space of \(M = x^d(U)\) at \(p = x^d(u_0)\).

We respectively call \(S^d_\pm(p) = -dx^d_\pm(u_0)\) and \(S^h(p) = -dx^d(u_0)\) the lightcone shape operator and the hyperbolic shape operator of \(M = x^d(U)\) at \(p = x^d(u_0)\). We denote the eigenvalue of \(S^d_\pm(p)\) by \(\kappa^d_\pm(p)\) and the eigenvalue of \(S^h(p)\) by \(\kappa^h(p)\). By the relation \(S^d_\pm(p) = S^h(p) \pm id_{T_p(M)}\), \(S^d_\pm(p)\) and \(S^h(p)\) have same eigenvectors and we have a relation that \(\kappa^d_\pm(p) = \kappa^h(p) \pm 1\).

We now define the notion of Gauss-Kronecker curvatures of \(M = x^d(U)\) at \(p = x(u_0)\) as follows:

\[
K^\pm_\ell(u_0) = \det S^d_\ell(p) ; \quad \text{The lightcone Gauss-Kronecker curvature},
\]

\[
K^h(u_0) = \det S^h_p ; \quad \text{The hyperbolic Gauss-Kronecker curvature},
\]

We say that a point \(u_0 \in U\) or \(p = x^d(u_0)\) is an umbilic point if \(S^d_\pm(p) = \kappa^d_\pm(p)id_{T_p(M)}\). Since the eigenvectors of \(S^d_\pm(p)\) and \(S^h(p)\) are the same, the above condition is equivalent to the condition \(S^h(p) = \kappa^h(p)id_{T_p(M)}\). We say that \(M = x^d(U)\) is totally umbilic if all points on \(M\) are umbilic. Here, we consider the following model hypersurfaces in de Sitter space. We consider the intersection of \(S^m_1\) with a hyperplane in \(\mathbb{R}^{n+1}_1\):

\[
HS(n, c) = HP(n, c) \cap S^m_1.
\]

We say that \(HS(n, c)\) is a hyperbolic hyperquadric if \(n\) is spacelike, a parabolic hyperquadric if \(n\) is lightlike and an elliptic hyperquadric if \(n\) is timelike. We can show the following classification of totally umbilic hypersurfaces in \(S^m_1\) by using exactly the same method as the proof of Proposition 2.2.

**Proposition 2.3** Suppose that \(M = x^d(U) \subset S^m_1\) is totally umbilic. Then \(\kappa^d_\pm(p)\) is constant \(\kappa^d_\pm\). Under this condition, we have the following classification.

(1) Suppose that \((\kappa^c_\pm)^2 + 2\kappa^c_\pm \neq 0\).
(a) If \((\kappa^c) + 2\kappa^c > 0\), then \(M\) is a part of hyperbolic hyperquadric

\[
HS \left( c, \frac{\kappa^c \pm 1}{\sqrt{(\kappa^c)^2 + 2\kappa^c}} \right),
\]

where

\[
c = \frac{1}{\sqrt{(\kappa^c)^2 + 2\kappa^c}}(\kappa^c \mathbf{x}^d(u) + \mathbf{x}^c(u)) \in S^n_1
\]
is a constant spacelike vector.

(b) If \((\kappa^c) + 2\kappa^c < 0\), then \(M\) is a part of elliptic hyperquadric

\[
HS \left( c, \frac{\kappa^c \pm 1}{\sqrt{-(\kappa^c)^2 + 2\kappa^c}} \right),
\]

where

\[
c = \frac{1}{\sqrt{-(\kappa^c)^2 + 2\kappa^c}}(\kappa^c \mathbf{x}^d(u) + \mathbf{x}^c(u)) \in H^n(-1)
\]
is a constant timelike vector.

(2) If \((\kappa^c) + 2\kappa^c = 0\), then \(M\) is a part of parabolic hyperquadric \(HS(c, \kappa^c \pm 1)\), where

\[
c = \kappa^c \mathbf{x}^d(u) + \mathbf{x}^c(u) \in LC^*\] is a constant lightlike vector.

**Case 3** We assume that \(\mathbf{x}^c : U \rightarrow LC^*\) is a spacelike embedding (i.e., an embedding and \((\mathbf{x}^c)_{u_i}, (i = 1, \ldots, n - 1)\) are spacelike vectors). We call \(\mathbf{x}^h(u_0)\) the hyperbolic normal vector to \(M = \mathbf{x}^c(U)\) at \(p = \mathbf{x}^c(u_0)\) and \(\mathbf{x}^d(u_0)\) the de Sitter normal vector to \(M = \mathbf{x}^c(U)\) at \(p = \mathbf{x}^c(u_0)\). We call a mapping \(\mathbf{x}^c : U \rightarrow LC^*\) the lightcone Gauss image of \(M = \mathbf{x}^c(U)\). We also respectively call \(\mathbf{x}^h : U \rightarrow H^n(-1)\) the hyperbolic Gauss image and \(\mathbf{x}^d : U \rightarrow S^n_1\) the de Sitter Gauss image of \(M = \mathbf{x}^c(U)\). We investigated the extrinsic differential geometry of \(M = \mathbf{x}^c(U)\) by using \(\mathbf{x}^c, \mathbf{x}^h, \mathbf{x}^d\) like as the Gauss map of a hypersurface in Euclidean space, in [18]. For the purpose, we have shown that the derivatives \(d\mathbf{x}^c(u_0), d\mathbf{x}^h(u_0), d\mathbf{x}^d(u_0)\) can be considered as linear transformations on the tangent space \(T_pM\) where \(p = \mathbf{x}^c(u_0)\). We respectively call the linear transformations \(S^c(p) = -d\mathbf{x}^c(u_0) : T_pM \rightarrow T_pM\) the lightcone shape operator, \(S^h(p) = -d\mathbf{x}^h(u_0) : T_pM \rightarrow T_pM\) the hyperbolic shape operator and \(S^d(p) = -d\mathbf{x}^d(u_0) : T_pM \rightarrow T_pM\) the de Sitter shape operator. We respectively denote the eigenvalues of \(S^c(p)\) by \(\kappa^c(p)\), \(\kappa^h(p)\) by \(\kappa^h(p)\) and \(\kappa^d(p)\) by \(\kappa^d(p)\), which are respectively called the lightcone principal curvature, the hyperbolic principal curvature and the de Sitter principal curvature of \(M\) at \(p\). We might consider that \(d\mathbf{x}^c(u_0)\) is the identity mapping on \(T_pM\) under the identification between \(U\) and \(M\) through \(\mathbf{x}^c\). By the relations among \(\mathbf{x}^c, \mathbf{x}^h, \mathbf{x}^d\), the principal directions of \(S^c(p), S^h(p), S^d(p)\) are the common and we have the following relations between the corresponding principal curvatures:

\[
\kappa^h(p) = \frac{\kappa^c(p) - 1}{2} \quad \text{and} \quad \kappa^d(p) = \frac{-\kappa^c(p) - 1}{2}.
\]

We now define the notion of curvatures of \(M = \mathbf{x}^c(U)\) at \(p = \mathbf{x}^c(u_0)\) as follows:

- \(K_c(u_0) = \det S^c(p)\) : The lightcone Gauss-Kronecker curvature,
- \(K_h(u_0) = \det S^h(p)\) : The hyperbolic Gauss-Kronecker curvature,
- \(K_d(u_0) = \det S^d(p)\) : The de Sitter Gauss-Kronecker curvature.
We can define the notion of umbilicity like as the case of hypersurfaces in Euclidean space. We say that a point \( p = x_+^\ell(u_0) \) (or \( u_0 \)) is an umbilic point if \( S^\ell(p) = \kappa^\ell(p)id_{T_pM} \). Since the eigenvectors of \( S^\ell(p) \) and \( S^d(p) \) are the same, the above condition is equivalent to both the conditions \( S^h(p) = \kappa^\ell(p)id_{T_pM} \) and \( S^d(p) = \kappa^\ell(p)id_{T_pM} \). We say that \( M = x_+^\ell(U) \) is totally umbilic if all points on \( M \) are umbilic. We now consider what is the totally umbilic hypersurfaces in the lightcone \( LC^* \). We consider the intersection of \( LC^* \) with a hyperplane in \( \mathbb{R}^{n+1}_1 \):

\[
HL(n, c) = HP(n, c) \cap LC^*.
\]

We say that \( HL(n, c) \) is a hyperbolic hyperquadric if \( n \) is spacelike, a parabolic hyperquadric if \( n \) is lightlike and a elliptic hyperquadric if \( n \) is timelike. In [18] we showed the following classification of totally umbilic hypersurfaces in \( LC^* \).

**Proposition 2.4** Suppose that \( M = x_+^\ell(U) \) is totally umbilic. Then \( \kappa^\ell(p) \) is constant \( \kappa^\ell \).

Under this condition, we have the following classification.

1. If \( \kappa^\ell < 0 \), then \( M \) is a part of hyperbolic hyperquadric \( HL(c, 1/\sqrt{-\kappa^\ell}) \), where

\[
c = \frac{-1}{2\sqrt{-\kappa^\ell}}(\kappa^\ell x_+^\ell(u) + x_-^\ell(u)) \in S^n_1
\]

is a constant spacelike vector.

2. If \( \kappa^\ell = 0 \), then \( M \) is a part of parabolic hyperquadric \( HL(c, -2) \), where \( c = x_+^\ell(u) \in LC^* \) is a constant lightlike vector.

3. If \( \kappa^\ell > 0 \), then \( M \) is a part of elliptic hyperquadric \( HL(c, -1/\sqrt{\kappa^\ell}) \), where

\[
c = \frac{1}{2\sqrt{\kappa^\ell}}(\kappa^\ell x_+^\ell(u) + x_-^\ell(u)) \in H^n(-1)
\]

is a constant timelike vector.

By the above proposition, we can classify the umbilic point as follows. Let \( p = x_+^\ell(u_0) \in M = x_+^\ell(U) \) be an umbilic point; we say that \( p \) is a timelike umbilic point if \( \kappa^\ell < 0 \), a lightlike umbilic point (or, lightcone flat point) if \( \kappa^\ell = 0 \), or a spacelike umbilic point if \( \kappa^\ell > 0 \).

In [18] we have shown the lightcone Weingarten formula. Since \( (x_+^\ell)_{u_i} \) (\( i = 1, \ldots n - 1 \)) are spacelike vectors, we induce the Riemannian metric (the lightcone first fundamental form) \( ds^2 = \sum_{i=1}^{n-1} g_{ij}^\ell du_i du_j \) on \( M = x_+^\ell(U) \), where \( g_{ij}^\ell(u) = \langle (x_+^\ell)_{u_i}(u), (x_+^\ell)_{u_j}(u) \rangle \) for any \( u \in U \). We also define the lightcone second fundamental invariant by \( h_{ij}^\ell(u) = \langle -(x_-^\ell)_{u_i}(u), (x_+^\ell)_{u_j}(u) \rangle \) for any \( u \in U \).

**Proposition 2.5** Under the above notations, we have the following lightcone Weingarten formula:

\[
(x_+^\ell)_{u_i} = -\sum_{j=1}^{n-1} (h_+^\ell)^j_{i} (x_+^\ell)_{u_j},
\]

where \((h_+^\ell)^j_{i} = (h_+^\ell)_{ik} (g^\ell_k)^j \) and \((g^\ell_k)^j = (g^\ell_k)_{ij}^{-1} \).

As a corollary of the above proposition, we have an explicit expression of the lightcone Gauss-Kronecker curvature by using Riemannian metric and the lightcone second fundamental invariant.
Corollary 2.6 Under the same notations as in the above proposition, the lightcone Gauss-Kronecker curvature is given by

\[ K_\ell = \frac{\det (h_{ij})}{\det (g_{\alpha\beta})}. \]

We say that a point \( p = x(u) \) is a lightcone parabolic point if \( K_\ell(u) = 0 \), which is equivalent to the condition that \( \det (h_{ij})(u) = 0 \).

3 Spacelike parallels and caustics in Minkowski pseudo-spheres

In this section we introduce the unified notion of parallels of a spacelike hypersurface in Minkowski pseudo-sphere. For any fixed real number \( \phi \in \mathbb{R} \), we define a mapping \( L_1^\phi : U \rightarrow \Delta_1 \) by

\[
L_1^\phi(u) = \left( \frac{\exp(\phi)}{2} x_+^\ell(u) + \frac{\exp(-\phi)}{2} x_-^\ell(u), \frac{\exp(\phi)}{2} x_+^\ell(u) - \frac{\exp(-\phi)}{2} x_-^\ell(u) \right).
\]

We respectively call the images of mappings \( \pi_{11} \circ L_1^\phi(u) = \frac{\exp(\phi)}{2} x_+^\ell(u) + \frac{\exp(-\phi)}{2} x_-^\ell(u) \) the hyperbolic parallel and \( \pi_{12} \circ L_1^\phi(u) = \frac{\exp(\phi)}{2} x_+^\ell(u) - \frac{\exp(-\phi)}{2} x_-^\ell(u) \) the de Sitter parallel.

We now explain why we call these images parallels. If \( \phi = 0 \), \( \pi_{11} \circ L_1^0(u) = x^h(u) \) and \( \pi_{12} \circ L_1^0(u) = x^d(u) \). Since we have the relations

\[ x_+^\ell(u) = x^h(u) + x^d(u), \quad x_-^\ell(u) = x^h(u) - x^d(u), \]

we can translate the hyperbolic parallels and the de Sitter parallels into

\[ \pi_{11} \circ L_1^\phi(u) = \cosh \phi x^h(u) + \sinh \phi x^d(u) \]

and

\[ \pi_{12} \circ L_1^\phi(u) = \sinh \phi x^h(u) + \cosh \phi x^d(u). \]

The above formula means that \( \pi_{11} \circ L_1^\phi(u) \) is the point on the geodesic started from \( x^h(u) \) directed by \( x^d(u) \). Therefore the image of \( \pi_{11} \circ L_1^\phi \) is the locus of the points on the geodesics from \( x^h(U) \) directed by the unit normals \( x^d \) with a constant length. The second formula also means that the geodesics starts from \( x^d(U) \) directed by the unit normals \( x^h \) with a constant length. Therefore we might call these parallels.

We also consider extra properties of \( L_1^\phi : U \rightarrow \Delta_1 \) from the view point of the contact geometry. For positive real numbers \( \lambda, \mu \) with \( \lambda \cdot \mu = 1 \), we define a diffeomorphism

\[ \Psi_{(\lambda,\mu)} : \mathbb{R}_1^{n+1} \times \mathbb{R}_1^{n+1} \rightarrow \mathbb{R}_1^{n+1} \times \mathbb{R}_1^{n+1} \]
by
\[ \Psi(\lambda, \mu)(v, w) = \left( \frac{\lambda v + \mu w}{2}, \frac{\lambda v - \mu w}{2} \right). \]
Since \( \lambda \cdot \mu = 1 \), we have \( \Psi(\Delta_4) = \Delta_4 \). We also have
\[ \Psi'(\lambda, \mu)\theta_{12} = \left( \frac{\lambda v + \mu w}{2}, d\left( \frac{\lambda v - \mu w}{2} \right) \right) = -\frac{1}{2} \theta_{12}, \]
so that \( \Psi(\lambda, \mu)|\Delta_4 \) is a contact diffeomorphism. By definition, we have \( \Psi(\exp(\phi), \exp(-\phi)) \circ \mathcal{L}_4 = \mathcal{L}_1^\phi \). Since \( \mathcal{L}_4 \) is a Legendrian embedding, \( \mathcal{L}_1^\phi \) is a Legendrian embedding.

**Proposition 3.1** The hyperbolic parallel (respectively, de Sitter parallel) is the wave front set of the Legendrian mapping \( \pi_{11} \circ \mathcal{L}_1^\phi \) (respectively, \( \pi_{12} \circ \mathcal{L}_1 \)).

We call \( \mathcal{L}_1^\phi \) a Legendrian parallel.

In the classical Euclidean case, if the distance of the parallels varies, the locus of the singularities of parallels forms a caustics of a certain Lagrangian manifold.

We now review some properties of symplectic manifolds and Lagrangian submanifolds. Let \( N \) be a \( 2n \)-dimensional smooth manifold and \( \omega \) be a 2-form on \( N \). The 2-form \( \omega \) is non-degenerate if \( (\omega)^n \neq 0 \) at any point of \( N \). We say that \( (N, \omega) \) is a symplectic manifold if \( \omega \) is a closed non-degenerate 2-form. In this case \( \omega \) is called a symplectic structure or a symplectic form. Let \( \phi : N \to N' \) be a diffeomorphism between symplectic manifolds \( (N, \omega) \) and \( (N', \omega') \). We say that \( \phi \) is a symplectic diffeomorphism if \( \phi^* \omega' = \omega \). Two symplectic manifolds \( (N, \omega) \) and \( (N', \omega') \) are symplectic diffeomorphic if there exists a symplectic diffeomorphism \( \phi : N \to N' \). A submanifold \( i : L \subset N \) of a symplectic manifold \( (N, \omega) \) is said to be Lagrangian if \( \dim L = n \) and \( i^* \omega = 0 \). We say that a smooth fiber bundle \( \pi : E \to M \) is called a Lagrangian fibration if its total space \( E \) is furnished with a symplectic structure and its fibers are Lagrangian submanifolds. Let \( \pi : E \to M \) be a Lagrangian fibration. For a Lagrangian submanifold \( i : L \subset E, \pi \circ i : L \to M \) is called a Lagrangian map. The critical value set of the Lagrangian map \( \pi \circ i \) is called the caustics of \( i \) which is denoted by \( C_L \). For any \( p \in E \), it is known that there is a local coordinate system \( (x_1, \ldots, x_m, p_1, \ldots, p_m) \) around \( p \) such that
\[ \pi(x_1, \ldots, x_m, p_1, \ldots, p_m) = (x_1, \ldots, x_m) \]
and the symplectic form is given by
\[ \omega = \sum_{i=1}^{m} dp_i \wedge dx_i \]
(cf. [1], 20.3).

We now consider what is the corresponding caustics for spacelike parallels in Minkowski pseudo-spheres. We consider the symplectification \( (\Delta_1 \times \mathbb{R}_+, -d(\eta \theta_{12})) = (\Delta_1 \times \mathbb{R}_+, d(\eta \theta_{11})) \) of the contact manifold \( \Delta_1 \), where \( (v, w), \eta \in \Delta_1 \times \mathbb{R}_+ \). Here \( \mathbb{R}_+ \) is a set of the positive real numbers. Define a mapping
\[ \tilde{\mathcal{L}}_1 : U \times \mathbb{R} \to \Delta_1 \times \mathbb{R}_+ \]
by
\[ \tilde{\mathcal{L}}_1(u, \phi) = (\mathcal{L}_1^\phi(u), \exp(-\phi)). \]
Since $\mathcal{L}_1^\phi$ is an embedding for any fixed $\phi$, $\tilde{\mathcal{L}}_1$ is also an embedding. By a direct calculation, we have $(\tilde{\mathcal{L}}_1^\phi)(\eta \theta_{12}) = -\exp(-\phi) d\phi$, so that $d(\tilde{\mathcal{L}}_1^\phi) = -d \exp(-\phi) \wedge d\phi = 0$. This means that $\tilde{\mathcal{L}}_1$ is a Lagrangian embedding. Let $\pi_{11} : \Delta_1 \times \mathbb{R}_+ \to H^n(-1)$ and $\pi_{12} : \Delta_1 \times \mathbb{R}_+ \to S^n_1$ be the canonical projections, then both the projections are Lagrangian fibrations. Therefore, we have two Lagrangian mappings:

$$
\pi_{11} \circ \tilde{\mathcal{L}}_1 : U \times \mathbb{R} \to H^n(-1); \quad \pi_{11} \circ \tilde{\mathcal{L}}_1(u, \phi) = \pi_{11} \circ \mathcal{L}_1^\phi(u)
$$

$$
\pi_{12} \circ \tilde{\mathcal{L}}_1 : U \times \mathbb{R} \to S^n_1; \quad \pi_{12} \circ \tilde{\mathcal{L}}_1(u, \phi) = \pi_{12} \circ \mathcal{L}_1^\phi(u)
$$

By definition, we have

$$
\frac{\partial (\pi_{11} \circ \tilde{\mathcal{L}}_1)}{\partial u_i}(u, \phi) = \frac{\partial (\pi_{11} \circ \mathcal{L}_1^\phi)}{\partial u_i}(u), \quad \frac{\partial (\pi_{11} \circ \tilde{\mathcal{L}}_1)}{\partial \phi}(u, \phi) = \frac{\partial (\pi_{11} \circ \mathcal{L}_1^\phi)}{\partial \phi}(u),
$$

$$
\frac{\partial (\pi_{12} \circ \tilde{\mathcal{L}}_1)}{\partial u_i}(u, \phi) = \frac{\partial (\pi_{12} \circ \mathcal{L}_1^\phi)}{\partial u_i}(u), \quad \frac{\partial (\pi_{12} \circ \tilde{\mathcal{L}}_1)}{\partial \phi}(u, \phi) = \frac{\partial (\pi_{12} \circ \mathcal{L}_1^\phi)}{\partial \phi}(u)
$$

for $i = 1, \ldots, n - 1$. Since $\mathcal{L}_1$ is a Legendrian embedding, we have $((\pi_{11} \circ \mathcal{L}_1^\phi)_u(u), (\pi_{12} \circ \mathcal{L}_1^\phi)_u(u)) = 0$. It follows that $(\pi_{11} \circ \mathcal{L}_1^\phi)_u(u), \ldots, (\pi_{11} \circ \mathcal{L}_1^\phi)_{u_{n-1}}(u)$ is linearly independent if and only if $(\pi_{11} \circ \tilde{\mathcal{L}}_1)_{u_1}(u, \phi), \ldots, (\pi_{11} \circ \tilde{\mathcal{L}}_1)_{u_{n-1}}(u, \phi), (\pi_{12} \circ \tilde{\mathcal{L}}_1)(u, \phi)$ is linearly independent. Therefore, $(u, \phi) \in U \times \mathbb{R}$ is a singular point of $\pi_{11} \circ \tilde{\mathcal{L}}_1$ if and only if $u$ is a singular point of $\pi_{11} \circ \mathcal{L}_1^\phi$. The same assertion holds for $\pi_{12} \circ \tilde{\mathcal{L}}_1$. We denote the critical value sets of $\pi_{11} \circ \tilde{\mathcal{L}}_1$ by $C_h(\tilde{\mathcal{L}}_1)$ and call the hyperbolic caustics of $\mathcal{L}_1$. We also denote the critical value sets of $\pi_{12} \circ \tilde{\mathcal{L}}_1$ by $C_d(\tilde{\mathcal{L}}_1)$ and call the de Sitter caustics of $\tilde{\mathcal{L}}_1$. The above arguments show the following proposition.

**Proposition 3.2** The hyperbolic caustics $C_h(\tilde{\mathcal{L}}_1)$ (respectively, de Sitter caustics $C_d(\tilde{\mathcal{L}}_1)$) is the locus of singularities of the hyperbolic parallels (respectively, de Sitter parallels).

### 4 Caustics and evolutes of spacelike hypersurfaces in Minkowski pseudo-spheres

We now introduce the notion of evolutes of spacelike hypersurfaces in the lightcone. For a spacelike embedding $\mathbf{x}_+^\ell : U \to LC^*$, we define the total evolute of $M = \mathbf{x}_+^\ell(U)$ by

$$
TE_M = \left\{ \frac{\kappa^\ell(u)}{2\sqrt{|\kappa^\ell(u)|}} \left( \mathbf{x}_+^\ell(u) + \frac{1}{\kappa^\ell(u)} \mathbf{x}_+^\ell(u) \right) \mid \kappa^\ell(u) \text{ is a lightcone principal curvature at } p = \mathbf{x}_+^\ell(u), \ u \in U \right\}.
$$

For a spacelike hypersurface as the above, we have the following decomposition of the total evolute:

$$
TE_M(u) = HE_M \cup DE_M,
$$

where

$$
HE_M = \left\{ \frac{1}{2\sqrt{|\kappa^\ell(u)|}} (\kappa^\ell(u) \mathbf{x}_+^\ell(u) + \mathbf{x}_+^\ell(u)) \mid \kappa^\ell(u) \text{ is a lightcone principal curvature with } \kappa^\ell(u) > 0 \text{ at } p = \mathbf{x}_+^\ell(u), \ u \in U \right\}.
$$
and

\[ DE_M = \left\{ \frac{-1}{2\sqrt{-\kappa^f(u)}}(\kappa^f(u)\mathbf{x}_+^f(u) + \mathbf{x}_-^f(u)) \mid \kappa^f(u) \right\} \text{is a lightcone principal curvature with } \kappa^f(u) < 0 \text{ at } p = \mathbf{x}_+^f(u), \; u \in U. \]

We can show that \( HE_M \subset H^n(-1) \) and \( DE_M \subset S^n_1 \). Therefore we call \( HE_M \) (respectively, \( DE_M \)) the hyperbolic evolute (respectively, de Sitter evolute) of \( M = \mathbf{x}_+^f(U) \).

For any fixed lightcone principal curvature \( \kappa^f \), we define a smooth mapping \( HE_M^f : U_+ \rightarrow H^n(-1) \) by

\[ HE_M^f(u) = \frac{1}{2\sqrt{\kappa^f(u)}}(\kappa^f(u)\mathbf{x}_+^f(u) + \mathbf{x}_-^f(u)), \]

where \( U_+ = \{ u \in U \mid \kappa^f(u) > 0 \} \). We can also define a smooth mapping \( SE_M^f : U_- \rightarrow S^n_1 \) by the similar way for \( U_- = \{ u \in U \mid \kappa^f(u) < 0 \} \). The above mappings give local parametrizations of the evolutes. We have the following proposition:

**Proposition 4.1** Let \( M = \mathbf{x}_+^f(U) \) be a spacelike hypersurface in \( LC^* \) without lightcone parabolic points and lightcone flat points.

(A) The following are equivalent:

1. \( M \) is totally umbilic with \( \kappa^f > 0 \).
2. \( HE_M \) is a point in \( H^n_1(-1) \).
3. \( M \) is a part of an elliptic hyperquadric.

(B) The following are equivalent:

1. \( M \) is totally umbilic with \( \kappa^f < 0 \).
2. \( DE_M \) is a point in \( S^n_1 \).
3. \( M \) is a part of an hyperbolic hyperquadric.

**Proof.** (A) By Proposition 2.4, (1) and (3) are equivalent.

We assume that the condition (1) holds, then the lightcone principal curvature \( \kappa^f(u) = \kappa_u^f \) is constant and \( \kappa^f > 0 \). Therefore we have

\[ \frac{\partial HE_M^f}{\partial u_i}(u) = \frac{1}{2\sqrt{\kappa^f(u)}}(\kappa^f(u)(\mathbf{x}_+^f(u)_{u_i}(u) + (\mathbf{x}_-^f(u)_{u_i}(u)) \right\} \text{for any } u \in U. \]

By the definition of the lightcone principal curvature, \( -(\mathbf{x}_+^f)_{u_i} = \kappa_u^f(\mathbf{x}_+^f(u)_{u_i}(u) \right\} \text{for } i = 1, \ldots, n - 1. \) It follows that \( \partial(HE_M^f/\partial u_i)(u) = 0 \) for \( i = 1, \ldots, n - 1. \) It concludes that \( HE_M^f(u) \) is a point.

On the other hand, we calculate that

\[ \frac{\partial HE_M^f}{\partial u_i}(u) = \frac{1}{2} \left\{ \kappa_u^f(u) \left( \frac{\kappa^f(u)}{\kappa^f(u)}(\mathbf{x}_+^f(u)_{u_i}(u) - \frac{1}{\kappa^f(u)}(\mathbf{x}_-^f(u)_{u_i}(u)) + \sqrt{\kappa^f(u)}(\mathbf{x}_+^f(u)_{u_i}(u) + \frac{1}{\kappa^f(u)}(\mathbf{x}_-^f(u)_{u_i}(u)) \right\} \right. \]

By the lightcone Weingarten formula (Proposition 2.5), we have

\[ \frac{\partial HE_M^f}{\partial u_i}(u) = \frac{1}{2} \left\{ \kappa_u^f(u) \left( \frac{\kappa^f(u)}{\kappa^f(u)}(\mathbf{x}_+^f(u)_{u_i}(u) - \frac{1}{\kappa^f(u)}(\mathbf{x}_-^f(u)_{u_i}(u)) + \sqrt{\kappa^f(u)}\left( \sum_{j=1}^{n-1} \left( \delta_{ij} - \frac{1}{\kappa^f(u)}(h^f)^j_i \right) (\mathbf{x}_+^f(u)_{u_j}(u) \right\} \right. \right. \]
Since \( \{x^\ell_+, x^\ell_+, (x^\ell_+)_{u_1}, \ldots, (x^\ell_+)_{u_{n-1}} \} \) is linearly independent, \( (\partial H E^\ell_M/\partial u_i)(u) = 0 \) if and only if \( M \) is umbilic at \( p = x^\ell_+(u) \) and \( \kappa^\ell_{u_i}(u) = 0 \) for \( i = 1, \ldots, n-1 \). It follows that (1) and (2) are equivalent. This completes the proof of (A).

The assertion (B) also follows from straightforward calculations like as those for the proof of (A). \( \square \)

In [14] we have defined the notion of evolutes of hypersurfaces in \( H^n(-1) \) as follows: For an embedding \( x^h : U \longrightarrow H^n(-1) \), we define the total evolute of \( M = x^h(U) \) by

\[
TE^\ell_M = \left\{ \pm \frac{k^d(u)}{\sqrt{|(k^d)^2(u) - 1|}} \left( x^h(u) + \frac{1}{k^d(u)} x^d(u) \right) \mid k^d(u) \text{ is a de Sitter principal curvature at } p = x^h(u), \, u \in U \right\}.
\]

By the relations \( x^\ell_+ = x^h + x^d \) and \( \kappa^\ell_+(u) = -1 \pm k^d(u) \), the above definition of the total evolute for an embedding \( x^h : U \longrightarrow H^n(-1) \) is the same as the definition of the total evolute for \( x^\ell_+ \).

We can also define the total evolute for a spacelike embedding \( x^d : U \longrightarrow S^n_1 \). It also coincides with the definition of the total evolute for \( x^\ell_+ \). Therefore we omit the detail here.

## 5 Timelike and spacelike height functions

In this section we consider two kinds of families of height functions on a spacelike hypersurface in the lightcone in order to describe the hyperbolic evolute and the de Sitter evolute of the spacelike hypersurface.

For the purpose, we need some concepts and results in the theory of unfoldings of function germs. We shall give a brief review of the theory in Appendices A, B.

We now define two families of functions

\[
H^T : U \times H^n(-1) \longrightarrow \mathbb{R}
\]

by \( H^T(u, v) = \langle x^\ell_+(u), v \rangle \) and

\[
H^S : U \times S^n_1 \longrightarrow \mathbb{R}
\]

by \( H^S(u, v) = \langle x^\ell_+(u), v \rangle \). We call \( H^T \) (respectively, \( H^S \)) a timelike height function (respectively, a spacelike height function) on \( x^\ell_+ : U \longrightarrow LC^* \). We denote that \( h^T_v(u) = H^T(u, v) \) (respectively, \( h^S_v(u) = H^S(u, v) \)).

**Proposition 5.1** Let \( x^\ell_+ : U \longrightarrow LC^* \) be a spacelike embedding. Then

1. \( (\partial H^T_v/\partial u_i)(u) = 0 \) \( (i = 1, \ldots, n-1) \) if and only if there exists a non-zero real number \( \lambda \) such that \( v = \lambda x^\ell_+(u) + (1/4\lambda) x^\ell_+(u) \).
2. \( (\partial H^S_v/\partial u_i)(u) = 0 \) \( (i = 1, \ldots, n-1) \) if and only if there exists a non-zero real number \( \lambda \) such that \( v = \lambda x^\ell_+(u) - (1/4\lambda) x^\ell_+(u) \).

**Proof.** (1) There exist real numbers \( \lambda, \mu, \xi_i \) \( (i = 1, \ldots, n-1) \) such that \( v = \lambda x^\ell_+ + \mu x^\ell_- + \sum_{i=1}^{n-1} \xi_i (x^\ell_+)^{u_i} \). Since \( (\partial H/\partial u_i)(u) = \langle (x^\ell_+)^{u_i}, v \rangle \), we have \( 0 = \langle (x^\ell_+)^{u_i}, v \rangle = \sum_{j=1}^{n-1} \xi_j g^\ell_{ij}(u) \). Since \( g^\ell_{ij} \) is positive definite, we have \( \xi_j = 0 \) \( (j = 1, \ldots, n-1) \). We also have \( -1 = \langle v, v \rangle = 2\lambda \mu \langle x^\ell_+, x^\ell_- \rangle = -4\lambda \mu \). This completes the proof for the assertion (1). The proof for the assertion (2) is given by the almost same calculations as those for the assertion (1), so that we omit the detail. \( \square \)
By Proposition 5.1, we can detect both of the catastrophe sets (cf. Appendix A) of $H^T$ and $H^S$ as follows:

$$C(H^T) = \left\{ (u, v) \in U \times H^n(-1) \big| v = \lambda x_+^\ell(u) + \frac{1}{4\lambda} x_-^\ell(u) \right\},$$

$$C(H^S) = \left\{ (u, v) \in U \times S^n_1 \big| v = \lambda x_+^\ell(u) - \frac{1}{4\lambda} x_-^\ell(u) \right\}.$$ 

Here, we have the following decompositions:

$$C(H^T) = C_+(H^T) \cup C_-(H^T) \text{ and } C(H^S) = C_+(H^S) \cup C_-(H^S),$$

where $C_+(H^T) = \{(u, v) \mid v = \lambda x_+^\ell(u) + (1/4\lambda)x_-^\ell(u), \lambda > 0\}$, $C_-(H^T) = \{(u, v) \mid v = \lambda x_+^\ell(u) + (1/4\lambda)x_-^\ell(u), \lambda < 0\}$ and the definitions of $C_+(H^S)$ and $C_-(H^S)$ are given by the similar way. We also calculate that

$$\frac{\partial^2 H^T}{\partial u_i \partial u_j}(u, v) = \langle (x_+^\ell)_u(u, u_j)(u), v \rangle = -\lambda g_{ij}^\ell + \frac{1}{4\lambda} h_{ij}^\ell$$

on $C(H^T)$ and

$$\frac{\partial^2 H^S}{\partial u_i \partial u_j}(u, v) = \langle (x_+^\ell)_u(u, u_j)(u), v \rangle = -\lambda g_{ij}^\ell - \frac{1}{4\lambda} h_{ij}^\ell$$

on $C(H^S)$.

Therefore, $\det(H(h^T_{u}(u))) = \det(\partial^2 H^T/\partial u_i \partial u_j)(u, v) = 0$ (respectively, $\det(H(h^S_{u}(u))) = 0$) if and only if $\kappa^\ell(u) = 4\lambda^2$ (respectively, $\kappa^\ell(u) = -4\lambda^2$) is a lightcone principal curvature. Since $v \in H^n(-1)$ (respectively, $v \in S^n_1$) and $\kappa^\ell(u) = 4\lambda^2$ (respectively, $\kappa^\ell(u) = -4\lambda^2$) is a lightcone principal curvature with $\kappa^\ell(u) > 0$ (respectively, $\kappa^\ell(u) < 0$), we have

$$\mathcal{B}_H^T = H E_M \cup (-H E_M) \text{ (respectively, } \mathcal{B}_H^S = D E_M \cup (-D E_M)),
$$

where $(-H E_M) = \{-v \mid v \in H E_M\}$ (respectively, $(-D E_M) = \{-v \mid v \in D E_M\}$

**Proposition 5.2** We assume that $p = x_+^\ell(u_0)$ is not a lightcone flat point of $M = x_+^\ell(U)$, then we have the following assertions:

1. $p$ is an umbilic point with $\kappa^\ell(p) > 0$ if and only if there exists $v_0 \in H^n(-1)$ such that $u_0$ is a singular point of $h^T_{v_0}$ and rank $\mathcal{H}(h^T_{v_0}(u_0)) = 0$.
2. $p$ is an umbilic point with $\kappa^\ell(p) < 0$ if and only if there exists $v_0 \in S^n_1$ such that $u_0$ is a singular point of $h^S_{v_0}$ and rank $\mathcal{H}(h^S_{v_0}(u_0)) = 0$.

**Proof.** (1) Since $p$ is an umbilic point, $S^\ell_p = \kappa^\ell(p)id_{T_p M}$. There exists an orthogonal matrix $Q$ such that $iQ((h^\ell)^{ij}_p)Q = \kappa^\ell(p)I$. Hence, we may consider the case $(h^\ell)^{ij}_p = \kappa^\ell(p)I$, so that $(h^T_{ij}) = \kappa^\ell(p)(g^T_{ij})$. Then we put $v_0 = \lambda x_+^\ell(u_0) + \mu x_-^\ell(u_0) \in H^n(-1)$, where $\lambda = \pm(\kappa^\ell(p)/2\sqrt{\kappa^\ell(p)}), \mu = \pm(1/2\sqrt{\kappa^\ell(p)})$. In this case the Hessian matrix $\mathcal{H}(h^T_{v_0}(u_0)) = (-\lambda g_{ij}^\ell + \mu h_{ij}^\ell) = (-\lambda + \mu \kappa^\ell(p))(g^T_{ij}) = 0$.

On the other hand, if $-\lambda g_{ij}^\ell + \mu h_{ij}^\ell = 0$ for all $i, j$, then $(h^T_{ij}) = \kappa^\ell(p)(g^T_{ij}) (\kappa^\ell(p) = \lambda/\mu)$.

This is equivalent to the condition $((-h^\ell)^{ij}_p) = \kappa_p I$.

The proof of (2) is also given by direct calculations like as those of (1). \qed
We say that $u_0$ is a timelike ridge point (respectively, spacelike ridge point) if $h^T_\ell$ (respectively, $h^S_\ell$) has the $A_{k\geq 3}$-type singular point at $u_0$, where $\mathbf{v} \in B_{H^T}$ (respectively, $\mathbf{v} \in B_{H^S}$).

For a function germ $f : (\mathbb{R}^{n-1}, \vec{u}_0) \rightarrow \mathbb{R}$, $f$ has $A_k$-type singular point at $\vec{u}_0$ if $f$ is $\mathcal{R}^+$-equivalent to the germ $\pm u_1^{k+1} \pm u_2^2 \pm \cdots \pm u_{n-1}^2$. We say that two function germs $f_i : (\mathbb{R}^{n-1}, \vec{u}_i) \rightarrow \mathbb{R}$ ($i = 1, 2$) are $\mathcal{R}^+$-equivalent if there exists a diffeomorphism germ $\Phi : (\mathbb{R}^{n-1}, \vec{u}_1) \rightarrow (\mathbb{R}^{n-1}, \vec{u}_2)$ and a real number $c$ such that $f_2 \circ \Phi(u) = f_2(u) + c$.

We now consider the geometric meaning of ridge points. Let $F : LC^* \rightarrow \mathbb{R}$ be a function and $x_\ell^c : U \rightarrow LC^*$ be a spacelike hypersurface. We say that $x_\ell^c$ and $F^{-1}(0)$ have a corank $r$ contact at $p_0 = x(u_0)$ if the Hessian of the function $g(u) = F \circ x_\ell^c(u)$ has corank $r$ at $u_0$. We also say that $x_\ell^c$ and $F^{-1}(0)$ have an $A_k$-type contact at $p_0 = x(u_0)$ if the function $g(u) = F \circ x(u)$ has the $A_k$-type singularity at $u_0$. By definition, if $x_\ell^c$ and $F^{-1}(0)$ have an $A_k$-type contact at $p_0 = x(u_0)$, then these have a corank 1 contact. For any $r \in \mathbb{R}$ and $a_0 \in H^n_+(-1)$ (respectively, $a_0 \in S^n_1$), we consider a function $F : H^n_+(-1) \rightarrow \mathbb{R}$ defined by $F(u) = \langle u, a_0 \rangle - r$. We denote that $HL(a_0, r) = F^{-1}(0) = \{u \in LC^* | \langle u, a_0 \rangle = r \}$. Then $HL(a_0, r)$ is an elliptic hyperquadric (respectively, a hyperbolic hyperquadric) with center $a_0$ if $a_0$ is in $H^n_+(-1)$ (respectively, $S^n_1$). We put $a_0 = HE^c_M(u_0)$ (respectively $a_0 = DE^c_M(u_0)$) and $r_0 = - (\sqrt{|\kappa^f(u_0)|/\kappa^f(u_0)})$, where we fix a lightcone principal curvature $\kappa^f(u)$ on $U$ around $u_0$, then we have the following simple proposition:

**Proposition 5.3** Under the above notations, there exists an integer $k$ with $1 \leq k \leq n-1$ such that $M = x_\ell^c(U)$ and $HL(a_0, r_0)$ have corank $k$ contact at $u_0$.

In the above proposition, $HL(a_0, r_0)$ is called an osculating elliptic hyperquadric (respectively, osculating hyperbolic hyperquadric) of $M = x_\ell^c(U)$ if $a_0 \in H^n_+(-1)$ (respectively, $a_0 \in S^n_1$). We also call $a_0$ the center of the lightcone principal curvature $\kappa^f(u_0)$. By Proposition 5.2, $M = x_\ell^c(U)$ and the osculating elliptic hyperquadric (respectively, hyperbolic hyperquadric) have corank $n-1$ contact at an umbilic point. Therefore the hyperbolic (respectively, de Sitter) ridge point is not an umbilic point.

By the general theory of unfoldings of function germs, the bifurcation set $\mathcal{B}_F$ is non-singular at the origin if and only if the function $f = F|\mathbb{R}^n \times \{0\}$ has the $A_2$-type singularity (i.e., the fold type singularity). Therefore we have the following proposition:

**Proposition 5.4** Under the same notations as in the previous proposition, the total evolute $TE_M$ is non-singular at $a_0 = TE^c_M(u_0)$ if and only if $M = x_\ell^c(U)$ and $HL(a_0, r_0)$ have $A_2$-type contact at $u_0$. Here, $TE^c_M(u_0) = HE^c_M(u_0)$ if $a_0 \in H^n_+(-1)$ and $TE^c_M(u_0) = DE^c_M(u_0)$ if $a_0 \in S^n_1$.

## 6 Evolutes as caustics

In this section we naturally interpret the hyperbolic evolute and the de Sitter evolute of spacelike hypersurface in the lightcone as the caustics given in §3.

For a spacelike embedding $x_\ell^c : U \rightarrow LC^*$, we consider the timelike height function $H^T$ and the spacelike height function $H^S$ (cf. §5). We have the following proposition:

**Proposition 6.1** Both the timelike height function $H^T : U \times H^n_+(-1) \rightarrow \mathbb{R}$ and the spacelike height function $H^S : U \times S^n_1 \rightarrow \mathbb{R}$ on $x_\ell^c$ are Morse families of functions.
Proof. First we consider the timelike height function.

For any \( \mathbf{v} = (v_0, v_1, \ldots, v_n) \in H^n(-1) \), we have

\[
H^T(u, \mathbf{v}) = \mp x_0(u) \sqrt{v_1^2 + \cdots + v_n^2 + 1 + x_1(u) v_1 + \cdots + x_n(u) v_n},
\]

where \( \mathbf{x}_+(u) = (x_0(u), \ldots, x_n(u)) \). We will prove that the mapping

\[
\Delta H^T = \left( \frac{\partial H^T}{\partial u_1}, \ldots, \frac{\partial H^T}{\partial u_{n-1}} \right)
\]

is non-singular at any point. The Jacobian matrix of \( \Delta H^T \) is given as follows:

\[
\begin{bmatrix}
\langle (\mathbf{x}_+)_{u_1}, \mathbf{v} \rangle & \cdots & \langle (\mathbf{x}_+)_{u_1 u_{n-1}}, \mathbf{v} \rangle \\
\vdots & \ddots & \vdots \\
\langle (\mathbf{x}_+)_{u_{n-1} u_1}, \mathbf{v} \rangle & \cdots & \langle (\mathbf{x}_+)_{u_{n-1} u_{n-1}}, \mathbf{v} \rangle
\end{bmatrix}
\]

where \( (\mathbf{x}_+)_{u_i} = \partial^2 \mathbf{x}_+ / \partial u_i \partial u_j \). We will show that the rank of the matrix

\[
X = \begin{pmatrix}
-x_0 v_1 v_0^{-1} + x_{1u_1} & \cdots & -x_0 v_n v_0^{-1} + x_{nu_1} \\
\vdots & \ddots & \vdots \\
-x_0 v_1 v_0^{-1} + x_{1u_{n-1}} & \cdots & -x_0 v_n v_0^{-1} + x_{nu_{n-1}}
\end{pmatrix}
\]

is \( n - 1 \) at \( (u, \mathbf{v}) \in C(H^T) \). It is enough to show that the rank of the matrix

\[
A = \begin{pmatrix}
-x_0 v_1 v_0^{-1} + x_1 & \cdots & -x_0 v_n v_0^{-1} + x_n \\
-x_0 v_1 v_0^{-1} + x_{1u_1} & \cdots & -x_0 v_n v_0^{-1} + x_{nu_1} \\
\vdots & \ddots & \vdots \\
-x_0 v_1 v_0^{-1} + x_{1u_{n-1}} & \cdots & -x_0 v_n v_0^{-1} + x_{nu_{n-1}}
\end{pmatrix}
\]

is \( n \) at \( (u, \mathbf{v}) \in C(H^T) \). We denote that \( \mathbf{a}_i = \begin{pmatrix} x_i \\ x_{1u_1} \\ \vdots \\ x_{1u_{n-1}} \end{pmatrix} \) for \( i = 0, \ldots, n \).

Then we have

\[
A = \begin{pmatrix}
-x_0 v_1 v_0^{-1} + a_1, \ldots, -x_0 v_n v_0^{-1} + a_n
\end{pmatrix}
\]

and

\[
\det A = \frac{v_0}{v_0} \cdot \det(\mathbf{a}_1, \ldots, \mathbf{a}_n) - \frac{v_1}{v_0} \cdot \det(\mathbf{a}_0, \mathbf{a}_2, \ldots, \mathbf{a}_n) - \cdots - \frac{v_n}{v_0} \cdot \det(\mathbf{a}_1, \ldots, \mathbf{a}_{n-1}, \mathbf{a}_0).
\]

On the other hand, we have

\[
\mathbf{x}_+ \wedge (\mathbf{x}_+)_{u_1} \wedge \cdots \wedge (\mathbf{x}_+)_{u_{n-1}} = (-1)^n \det(\mathbf{a}_0, \ldots, \mathbf{a}_{n-1}).
\]

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Since $x^f_+$ is lightlike, there exists non-zero real number $\xi$ such that $\xi \cdot x^f_+(u) = (x^f_+ \wedge (x^f_+)_u \wedge \cdots \wedge (x^f_+)_u^{-1})(u)$ (cf. Lemma 2.1 in [18]).

Therefore we have

$$\det A = \left( \frac{v_0}{v_0^2}, \ldots, \frac{v_n}{v_0^2} \right), x^f_+ \wedge (x^f_+)_u \wedge \cdots \wedge (x^f_+)_u^{-1} \right) = \frac{1}{v_0} \langle \lambda x^f_+ + \frac{1}{4\lambda} x^f_+, \xi x^f_+ \rangle$$

for $(u, v) \in C(H^T)$.

Next we consider the spacelike height function. The proof is also given by direct calculations but a bit more carefully than in the previous case. We use the same notations as those of the previous case (e.g., $x^f_+$ and $a_i$ etc.).

For any $v \in S^1_+$, we have $-v_0^2 + v_1^2 + \cdots + v_n^2 = 1$. Without loss of the generality, we might assume that $v_n \neq 0$. We have $v_n = \pm \sqrt{1 + v_0^2 - v_1^2 - \cdots - v_{n-1}^2}$. We also prove that the mapping

$$H^S(u, v) = -x_0(u)v_0 + x_1(u)v_1 + \cdots + x_{n-1}(u)v_{n-1} \pm x_n(u)\sqrt{1 + v_0^2 - v_1^2 - \cdots - v_{n-1}^2}.$$ We also prove that the mapping

$$\Delta H^S = \left( \frac{\partial H^S}{\partial u_1}, \ldots, \frac{\partial H^S}{\partial u_n} \right)$$

is non-singular at any point. The Jacobian matrix of $\Delta H^S$ is given as follows:

$$\begin{pmatrix}
\langle (x^f_+)_{u_1 u_1}, v \rangle & \cdots & \langle (x^f_+)_{u_1 u_{n-1}}, v \rangle & -x_0 u_1 + x_{n u_1} \frac{v_0}{v_n} & \cdots & x_{n-1} u_1 - x_{n u_1} \frac{v_{n-1}}{v_n} \\
\vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\
\langle (x^f_+)_{u_{n-1} u_1}, v \rangle & \cdots & \langle (x^f_+)_{u_{n-1} u_{n-1}}, v \rangle & -x_0 u_{n-1} + x_{n u_{n-1}} \frac{v_0}{v_n} & \cdots & x_{n-1} u_{n-1} - x_{n u_{n-1}} \frac{v_{n-1}}{v_n}
\end{pmatrix}.$$ We will also show that the rank of the matrix

$$\tilde{X} = \begin{pmatrix}
-x_0 u_1 + x_{n u_1} \frac{v_0}{v_n} & x_{1 u_1} - x_{n u_1} \frac{v_1}{v_n} & \cdots & x_{n-1} u_1 - x_{n u_1} \frac{v_{n-1}}{v_n} \\
\vdots & \vdots & \ddots & \vdots \\
-x_0 u_{n-1} + x_{n u_{n-1}} \frac{v_0}{v_n} & x_{1 u_{n-1}} - x_{n u_{n-1}} \frac{v_1}{v_n} & \cdots & x_{n-1} u_{n-1} - x_{n u_{n-1}} \frac{v_{n-1}}{v_n}
\end{pmatrix}$$

is $n - 1$ at $(u, v) \in C(H^S)$. It should be proven that the rank of the matrix

$$\tilde{A} = \begin{pmatrix}
-a_0 + a_n \frac{v_0}{v_n}, a_1 - a_n \frac{v_1}{v_n}, \ldots, a_{n-1} - a_n \frac{v_{n-1}}{v_n}
\end{pmatrix}$$

is $n$ at $(u, v) \in C(H^S)$.

Therefore we have
\[
\det \tilde{A} = (-1)^{n-1} \left\{ \frac{v_0}{v_n} \cdot \det(a_1, \ldots, a_n) - \frac{v_1}{v_n} \cdot \det(a_0, a_2, \ldots, a_n) \\
+ \cdots + (-1)^n \frac{v_n}{v_n} \cdot \det(a_0, \ldots, a_{n-1}) \right\} \\
= (-1)^{n-1} \left\{ \left( \frac{v_0}{v_n}, \ldots, \frac{v_n}{v_n} \right), x^e_+ \wedge (x^e_+)_{u_1} \cdots \wedge (x^e_+)_{u_{n-1}} \right\} \\
= (-1)^{n-1} \langle \lambda x^e_+ - \frac{1}{4\lambda} x^e_-, x^e_+ \wedge (x^e_+)_{u_1} \cdots \wedge (x^e_+)_{u_{n-1}} \rangle \\
= (-1)^{n-1} \langle \lambda x^e_+ - \frac{1}{4\lambda} x^e_-, \xi x^e_+ \rangle = \frac{(-1)^{n-1} \xi}{2v_n \lambda} \neq 0
\]
for \((u, v) \in C(H^S)\). This completes the proof of proposition. \(\square\)

By the method for constructing the Lagrangian immersion germ from Morse family (cf. Appendix A), we can define a Lagrangian immersion germ whose generating family is the timelike height function or the spacelike height function of \(M = x(U)\) as follows: For a spacelike hypersurface \(x^i_+: U \rightarrow LC^e\), we denote that \(x^i_+(u) = (x_0(u), \ldots, x_n(u))\). Define a smooth mapping

\[
L(H^T): C(H^T) \rightarrow T^*H^n(-1)
\]
by

\[
L(H^T)(u, v) = \left( v, -x_0(u)\frac{v_1}{v_0} + x_1(u), \ldots, -x_0(u)\frac{v_n}{v_0} + x_n(u) \right)
\]
where \(v = (v_0, \ldots, v_n) \in H^n(-1)\) and \(v_0 = \pm \sqrt{v_1^2 + \cdots + v_n^2} + 1\). Therefore we have the local coordinate \((v_1, \ldots, v_n)\). Here we have used the triviality of the cotangent bundle \(T^*H^n(-1)\).

For the de Sitter space \(S^n_t\), we consider the local coordinate \(U_i = \{ v = (v_0, \ldots, v_n) \in S^n_t \mid v_i \neq 0 \}\). Since \(T^*S^n_t\mid U_i\) is a trivial bundle, we define a map

\[
L_i(H^S): C(H^S) \rightarrow T^*S^n_t\mid U_i (i = 0, 1, \ldots, n)
\]
by

\[
L_i(H^S)(u, v) = \left( v, -x_0(u) + x_1(u)\frac{v_0}{v_1}, x_1(u) - x_0(u)\frac{v_1}{v_1}, \ldots, x_i(u) - x_0(u)\frac{v_i}{v_i}, \ldots, x_n(u) - x_i(u)\frac{v_n}{v_i} \right),
\]
where \(v = (v_0, \ldots, v_n) \in S^n_t\) and we denote \((x_0, \ldots, \tilde{x}_i, \ldots, x_n)\) as a point in \(n\)-dimensional space such that the \(i\)-th component \(\tilde{x}_i\) is removed. We can show that if \(U_i \cap U_j \neq \emptyset\) for \(i \neq j\), then \(L_i(H^S)\) and \(L_j(H^S)\) are Lagrangian equivalent which are given by the local coordinate change of \(S^n_t\) and Lagrangian lift of it. Indeed, we denote that the local coordinate change of \(S^n_t\) for \(i < j\); \(\varphi_{ij}: U_i \rightarrow U_j\), defined by

\[
\varphi_{ij}(v_0, \ldots, \tilde{v}_i, \ldots, v_n) = \left( v_0, \ldots, v_i = \sqrt{1 + v_0^2 - v_1^2 - \cdots - v_i^2 - \cdots - v_n^2}, \tilde{v}_i, \ldots, v_n \right).
\]
and \(\tilde{\varphi}_{ij}: T^*S^n_t \rightarrow T^*S^n_t\) are Lagrangian lift of \(\varphi_{ij}\) which defined by \(\tilde{\varphi}_{ij}(\xi) = (\varphi_{ij}^{-1})^*\xi\). Then \(\tilde{\varphi}_{ij}\) are symplectic diffeomorphism germs (cf. [1]). Also we define diffeomorphism germs \(\sigma_{ij}: U \times U_i \rightarrow U \times U_j\) by \(\sigma_{ij}(u, v) = (u, \varphi_{ij}(v))\) and \(\tilde{\sigma}_{ij} = \sigma_{ij}|_{C(H^S)}\), then \(\tilde{\varphi}_{ij} \circ L_i(H^S) = L_j(H^S) \circ \tilde{\sigma}_{ij}\) and \(\varphi_{ij} \circ \pi = \pi \circ \tilde{\varphi}_{ij}\). Therefore we can define a global Lagrangian immersion, \(L(H^S): C(H^S) \rightarrow T^*S^n_t\).

By definition, we have the following corollary of the above proposition:
Corollary 6.2 Under the above notations, \( L(H^T) \) (respectively, \( L(H^S) \)) is a Lagrangian immersion such that the timelike height function \( H^T: U \times H^n_+(-1) \rightarrow \mathbb{R} \) (respectively, spacelike height function \( H^S: U \times S^n_1 \rightarrow \mathbb{R} \)) of \( x^\ell_+ \) is a generating family of \( L(H^T) \) (respectively, \( L(H^S) \)).

Therefore, we have the Lagrangian immersion \( L(H^T) \) (respectively, \( L(H^S) \)) whose caustics is the hyperbolic evolute (respectively, de Sitter evolute) of \( x^\ell_+ \). We call \( L(H^T) \) (respectively, \( L(H^S) \)) the Lagrangian lift of the hyperbolic evolute (respectively, de Sitter evolute) of \( x^\ell_+ \).

On the other hand, we define a mapping

\[
\Psi^T: \Delta_1 \times \mathbb{R}_+ \rightarrow T^*H^n(-1)
\]

by

\[
\Psi^T(v, w, \eta) = \left( v, \eta \left( -(v_0 + w_0)\frac{v_1}{v_0} + (v_1 + w_1), \ldots, -(v_0 + w_0)\frac{v_n}{v_0} + (v_n + w_n) \right) \right),
\]

where \( v = (v_0, v_1, \ldots, v_n) \), \( w = (w_0, w_1, \ldots, w_n) \). Let \( \alpha \) be the canonical one-form on \( T^*H^n(-1) \). Then we have

\[
\begin{align*}
(\Psi^T)^*\alpha &= \sum_{i=1}^{n} \eta \left( -(v_0 + w_0)\frac{v_i}{v_0} + (v_i + w_i) \right) dv_i \\
&= \eta \left( -w_0 \sum_{i=1}^{n} \frac{v_i}{v_0} dv_i + \sum_{i=1}^{n} w_idv_i \right) \\
&= \eta(\mathbf{d}\mathbf{v}, \mathbf{w})|_{\Delta_1} = \eta\theta_{11} = -\eta\theta_{12}
\end{align*}
\]

Therefore \( \Psi^T \) is a symplectic diffeomorphism. By direct calculations, we have

\[
\Psi^T \circ \tilde{L}_1(u, \phi) = L(H^T) \left( u, \frac{\exp(\phi)}{2} x^\ell_+(u) + \frac{\exp(-\phi)}{2} x^\ell_-(u) \right).
\]

By the similar arguments as the above, we have the following theorem.

Theorem 6.3 For any spacelike hypersurface \( x^\delta_: U \rightarrow LC^*, \) both the timelike height function \( H^T: U \times H^n(-1) \rightarrow \mathbb{R} \) and the spacelike height function \( H^S: U \times S^n_1 \rightarrow \mathbb{R} \) are generating families of the Lagrangian embedding \( \tilde{L}_1: U \rightarrow \Delta_1 \times \mathbb{R}_+ \).

Since \( \mathcal{B}_{H^T} = HE_M \cup (-HE_M) \) (respectively, \( \mathcal{B}_{H^S} = DE_M \cup (-DE_M) \)), \( C_8(\tilde{L}_1) = HE_M \cup (-HE_M) \) (respectively, \( C_8(\tilde{L}_1) = DE_M \cup (-DE_M) \)). This means that the hyperbolic caustics (respectively, de Sitter caustics) might be identified with the hyperbolic evolute (respectively, de Sitter evolute) of \( M \).

7 Big fronts

In this section we consider a contact manifold \( (\Delta_1 \times \mathbb{R}_+ \times \mathbb{R}, d\zeta + \eta\theta_{12}) \), where \( ((\mathbf{v}, \mathbf{w}), \eta, \zeta) \in \Delta_1 \times \mathbb{R}_+ \times \mathbb{R} \). For a spacelike hypersurface \( x^\ell_+: U \rightarrow LC^* \), we have a mapping

\[
\tilde{L}_1: U \times \mathbb{R} \rightarrow \Delta_1 \times \mathbb{R}_+ \times \mathbb{R}
\]
defined by
\[ \mathcal{Z}_1(u, \phi) = (\mathcal{L}_1(u, \phi), \exp(-\phi)). \]
Since \( \mathcal{L}_1 \) is an embedding, \( \mathcal{Z}_1 \) is also an embedding. Moreover, we have
\[ (\mathcal{Z}_1)^*(d\zeta + \eta \theta_{12}) = d\exp(-\phi) - (\mathcal{L}_1)^*(\eta \theta_{12}) = d\exp(-\phi) - d\exp(-\phi) = 0, \]
so that \( \mathcal{Z}_1 \) is a Legendrian embedding. We call it the \textit{big Legendrian embedding} associated to the Legendrian family \( \mathcal{L}^\theta \).

Let \( \pi_{1i} : \Delta_1 \times \mathbb{R}_+ \times \mathbb{R} \rightarrow H^n(-1) \times \mathbb{R}, \pi_{12} : \Delta_1 \times \mathbb{R}_+ \times \mathbb{R} \rightarrow S^n_1 \times \mathbb{R} \) be the canonical projections. Since \( \theta_{11} = -\theta_{12} \), we have \( d\zeta + \eta \theta_{12} = d\zeta - \eta \theta_{11} \), so that \( \pi_{11} \) and \( \pi_{12} \) are the projections of Legendrian fibrations. Moreover we have the canonical projections \( \pi_{h1} : H^n(-1) \times \mathbb{R} \rightarrow H^n(-1), \pi_{h2} : H^n(-1) \times \mathbb{R} \rightarrow \mathbb{R}, \pi_{dl} : S^n_1 \times \mathbb{R} \rightarrow S^n_1 \) and \( \pi_{d2} : S^n_1 \times \mathbb{R} \rightarrow \mathbb{R} \). Since both of \( \pi_{h1} \circ \pi_{11} \circ \mathcal{Z}_1 \) and \( \pi_{d2} \circ \pi_{12} \circ \mathcal{Z}_1 \) are submersions, \( \mathcal{Z}_1 \) is a graphlike Legendrian unfoldings with respect to both the Legendrian fibrations \( \pi_{1i}, i = 1, 2 \).

For definitions and basic properties of graphlike Legendrian unfoldings, see Appendix C.

We define two families of functions
\[ \overline{H}^T : U \times H^n(-1) \times \mathbb{R} \rightarrow \mathbb{R} \]
by \( \overline{H}^T(u, v, r) = \langle x^T_+(u), v \rangle - r = H^T(u, v) - r \) and
\[ \overline{H}^S : U \times S^n_1 \times \mathbb{R} \rightarrow \mathbb{R} \]
by \( \overline{H}^S(u, v, r) = \langle x^T_+(u), v \rangle - r = H^S(u, v) - r \). We call \( \overline{H}^T \) (respectively, \( \overline{H}^S \)) an \textit{extended timelike height function} (respectively, \textit{extended spacelike height function}). We consider the mapping
\[ \overline{\Psi}^T : \Delta_1 \times \mathbb{R}_+ \times \mathbb{R} \rightarrow T^*H^n(-1) \times \mathbb{R} \]
defined by \( \overline{\Psi}^T(v, w, \eta, \zeta) = (\Psi^T(v, w, \eta), \zeta) \). We might identify \( T^*H^n(-1) \times \mathbb{R} \) with 1-jet space \( J^1(H^n(-1), \mathbb{R}) \) whose contact structure is given by \( dy - \alpha \), where \( \alpha \) is the canonical one-form on \( T^*H^n(-1) \) and \( y \) is the coordinate of \( \mathbb{R} \). By the previous calculation, we have
\[ (\overline{\Psi}^T)^*(dy - \alpha) = d\zeta + \eta \theta_{12}, \]
so that \( \overline{\Psi}^T \) is a contact diffeomorphism. By Proposition 6.1, we have the following proposition.

\textbf{Proposition 7.1} Both the extended timelike height function \( \overline{H}^T : U \times H^n(-1) \times \mathbb{R} \rightarrow \mathbb{R} \) and the extended spacelike height function \( \overline{H}^S : U \times S^n_1 \times \mathbb{R} \rightarrow \mathbb{R} \) are graphlike Morse families of hypersurfaces.

It follows from the above proposition that we have the following theorem.

\textbf{Theorem 7.2} For any spacelike hypersurface \( x^T_+ : U \rightarrow LC^* \), both the extended timelike height function \( \overline{H}^T : U \times H^n(-1) \times \mathbb{R} \rightarrow \mathbb{R} \) and the extended spacelike height function \( \overline{H}^S : U \times S^n_1 \times \mathbb{R} \rightarrow \mathbb{R} \) are generating families of the graphlike Legendrian unfolding \( \mathcal{L}_1 \).
8 Contact with families of hyperquadrics

In [18] we have studied the contact of spacelike hypersurfaces in $\mathcal{L}C^*$ with parabolic hyperquadrics as applications of theory of contact due to Montaldi[20] and the theory of Legendrian singularities. Briefly speaking, we can completely characterize the contact of spacelike hypersurfaces with parabolic hyperquadrics in terms of the Lightcone Gauss images in generic. If we consider the spacelike parallels and the evolutes instead of the Lightcone Gauss maps, we might consider the problem what kind of geometric information we can get from the singularity of the spacelike parallels or the evolutes. We now start to give a brief review of the theory of contact due to Montaldi[20].

Let $X_i, Y_i (i = 1, 2)$ be submanifolds of $\mathbb{R}^n$ with $\dim X_1 = \dim X_2$ and $\dim Y_1 = \dim Y_2$. We say that the contact of $X_1$ and $Y_1$ at $y_1$ is the same type as the contact of $X_2$ and $Y_2$ at $y_2$ if there is a diffeomorphism germ $\Phi : (\mathbb{R}^n, y_1) \to (\mathbb{R}^n, y_2)$ such that $\Phi(X_1) = X_2$ and $\Phi(Y_1) = Y_2$. In this case we write $K(X_1, Y_1; y_1) = K(X_2, Y_2; y_2)$. It is clear that in the definition $\mathbb{R}^n$ could be replaced by any manifold. In his paper [20], Montaldi gives a characterization of the notion of contact by using the terminology of singularity theory.

**Theorem 8.1** Let $X_i, Y_i (i = 1, 2)$ be submanifolds of $\mathbb{R}^n$ with $\dim X_1 = \dim X_2$ and $\dim Y_1 = \dim Y_2$. Let $g_i : (X_i, x_i) \to (\mathbb{R}^n, y_i)$ be immersion germs and $f_i : (\mathbb{R}^n, y_i) \to (\mathbb{R}, 0)$ be submersion germs with $(y_i, y_i) = (f_i^{-1}(0), y_i)$. Then $K(X_1, Y_1; y_1) = K(X_2, Y_2; y_2)$ if and only if $f_1 \circ g_1$ and $f_2 \circ g_2$ are $K$-equivalent. For the definition of $K$-equivalence, see [19].

For our purpose this theorem is not sufficient. We need the theory of contact of submanifold with families of hypersurfaces. We have two kinds of theories which describe the contact with families of hypersurfaces.

Firstly we consider the one-parameter families of hypersurfaces. Let $X_i (i = 1, 2)$ be submanifolds in $\mathbb{R}^n$ with $\dim X_1 = \dim X_2$ and $f_i : (\mathbb{R}^n \times \mathbb{R}, (y_i, t_i)) \to (\mathbb{R}, 0)$ be function germs such that $f_{i,t}(y) = f_i(y, t)$. We have hypersurface germs $(\mathbb{R}^n \times \mathbb{R}, (y_i, t_i)) \supset \mathcal{Y}(f_i) = f_i^{-1}(0)$. We say that the parametrized contact of $X_1$ and $\mathcal{Y}_1$ at $(y_1, t)$ is the same type as the parametrized contact of $X_2$ and $\mathcal{Y}_2$ at $(y_2, t)$ if there is a diffeomorphism germ $\Phi : (\mathbb{R}^n \times \mathbb{R}, (y_1, t_1)) \to (\mathbb{R}^n \times \mathbb{R}, (y_2, t_2))$ with the from $\Phi(y, t) = (\phi(y, t), t + (t_2 - t_1))$ such that $\Phi(X_1 \times \mathbb{R}) = X_2 \times \mathbb{R}$ and $\Phi(\mathcal{Y}_1) = \mathcal{Y}_2$. In this case we write

$$PK(X_1, \mathcal{Y}_1; (y_1, t_1)) = PK(X_2, \mathcal{Y}_2; (y_2, t_2)).$$

We can show the following parametric version of Montaldi’s theorem just along the line of the proof of the original theorem of Montaldi[20].

**Theorem 8.2** With the above notations, $PK(X_1, \mathcal{Y}_1; (y_1, t_1)) = PK(X_2, \mathcal{Y}_2; (y_2, t_2))$ if and only if $f_1 \circ (g_1 \times \text{id}_\mathbb{R})$ and $f_2 \circ (g_2 \times \text{id}_\mathbb{R})$ are S.P-$K$-equivalent. For the definition of S.P-$K$-equivalence, see Appendix B.

Secondly we consider the codimension 1 foliation germs. Let $X_i (i = 1, 2)$ be submanifolds of $\mathbb{R}^n$ with $\dim X_1 = \dim X_2$, $g_i : (X_i, x_i) \to (\mathbb{R}^n, \bar{y}_i)$ be immersion germs and $f_i : (\mathbb{R}^n, \bar{y}_i) \to (\mathbb{R}, 0)$ be submersion germs. For a submersion germ $f : (\mathbb{R}^n, 0) \to (\mathbb{R}, 0)$, we denote that $\mathcal{F}_f$ be the regular foliation defined by $f$; i.e., $\mathcal{F}_f = \{f^{-1}(c) | c \in (\mathbb{R}, 0)\}$. We say that the contact of $X_1$ with the regular foliation $\mathcal{F}_{f_1}$ at $\bar{y}_1$ is the same type as the contact of $X_2$ with the regular foliation $\mathcal{F}_{f_2}$ at $\bar{y}_2$ if there is a diffeomorphism germ $\Phi : (\mathbb{R}^n, \bar{y}_1) \to (\mathbb{R}^n, \bar{y}_2)$ such that $\Phi(X_1) = X_2$ and $\Phi(Y_1(c)) = Y_2(c)$, where $Y_1(c) = f_1^{-1}(c)$ for each $c \in (\mathbb{R}, 0)$. In this case we write $K(X_1, \mathcal{F}_{f_1}; \bar{y}_1) = K(X_2, \mathcal{F}_{f_2}; \bar{y}_2)$. We apply the method of Goryunov [7] to the case for $\mathcal{R}^+\text{-equivalences}$ among function germs, so that we have the following:
Proposition 8.3 ([7, Appendix]) Let $X_i$ $(i = 1, 2)$ be submanifolds of $\mathbb{R}^n$ with $\dim X_1 = \dim X_2 = n - 1$ (i.e., hypersurfaces), $g_i : (X_i, \bar{x}_i) \rightarrow (\mathbb{R}^n, \bar{y}_i)$ be immersion germs and $f_i : (\mathbb{R}^n, \bar{y}_i) \rightarrow (\mathbb{R}, 0)$ be submersion germs. We assume that $\bar{x}_i$ are singularities of function germs $f_i \circ g_i : (X_i, \bar{x}_i) \rightarrow (\mathbb{R}, 0)$. Then $K(X_1, \mathcal{F}_{g_1}; \bar{y}_1) = K(X_2, \mathcal{F}_{g_2}; \bar{y}_2)$ if and only if $f_1 \circ g_1$ and $f_2 \circ g_2$ are $\mathcal{R}^+$-equivalent. For the definition of $\mathcal{R}^+$-equivalence, see [19].

On the other hand, Golubitsky and Guillemin [6] have given an algebraic characterization for the $\mathcal{R}^+$-equivalence among function germs. We denote $C_0^\infty(X)$ is the set of function germs $(X, 0) \rightarrow \mathbb{R}$. Let $J_f$ be the Jacobian ideal in $C_0^\infty(X)$ (i.e., $J_f = (\partial f/\partial x_1, \ldots, \partial f/\partial x_n)_{e_\infty(X)}$). Let $\mathcal{R}_k(f) = C_0^\infty(X)/J_f^k$ and $[f]$ be the image of $f$ in this local ring. We say that $f$ satisfies the Milnor condition if $\dim \mathcal{R}_1(f) < \infty$.

Proposition 8.4 ([6, Proposition 4.1]) Let $f$ and $g$ be germs of functions at $0$ in $X$ satisfying the Milnor condition with $df(0) = dg(0) = 0$. Then $f$ and $g$ are $\mathcal{R}^+$-equivalent if

1. The rank and signature of the Hessians $\mathcal{H}(f)(0)$ and $\mathcal{H}(g)(0)$ are equal, and
2. There is an isomorphism $\gamma : \mathcal{R}_2(f) \rightarrow \mathcal{R}_2(g)$ such that $\gamma([f]) = [g]$.

We now consider two families of functions $\tilde{\mathcal{S}}^T : LC^* \times H^n(-1) \rightarrow \mathbb{R}$ defined by $\tilde{\mathcal{S}}^T(x, v) = \langle x, v \rangle$ and $\tilde{\mathcal{S}}^S : LC^* \times S^*_1 \rightarrow \mathbb{R}$ defined by $\tilde{\mathcal{S}}^S(x, v) = \langle x, v \rangle$. For any $v_0 \in H^n(-1)$, we define $\mathcal{H}_{v_0}^T(x) = \tilde{\mathcal{S}}^T(x, v_0)$ and we have an elliptic hyperquadric $$(\mathcal{H}_{v_0}^T)^{-1}(c) = HP(v_0, c) \cap LC^* = HL(v_0, c).$$

By definition, $\mathcal{H}_{v_0}^T$ is a submersion. Let $x^\perp : U \rightarrow LC^*$ be a spacelike hypersurface. For any $u_0 \in U$, we have a timelike vector $v_0 = (-1/2c)x^\perp(u_0) + (-c/2)x^\perp(u_0) \in H^n(-1)$, then we have $$\mathcal{H}_{v_0}^T \circ x^\perp(u_0) = \tilde{\mathcal{S}}^T \circ ((x^\perp \times id_{H^n(-1)})(u_0, v_0)) = H^T(u_0, v_0) = c$$ and $$\frac{\partial(\mathcal{H}_{v_0}^T \circ x^\perp)}{\partial u_i}(u_0) = \frac{\partial H^T}{\partial u_i}(u_0, v_0) = 0,$$ for $i = 1, \ldots, n - 1$. This means that $(\mathcal{H}_{v_0}^T)^{-1}(c) = HL(v_0, c)$ is tangent to $M = x^\perp(U)$ at $p = x^\perp(u_0)$. In this case we call $HL(v_0, c)$ a tangent elliptic hyperquadric of $M = x^\perp(U)$ at $p = x^\perp(u_0)$ with the center $v_0$. We denote it $EHL(v_0, c)$. However, there are infinitely many tangent elliptic hyperquadrics at a general point $p = x^\perp(u_0)$ depending on the real number $c$. If the point $v_0$ is a point of the hyperbolic evolute of $M = x^\perp(U)$, the tangent elliptic hyperquadric with the center $v_0$ is called the osculating elliptic hyperquadric (or, focal elliptic hyperquadric). Since $\mathcal{H}_{v_0}^T$ is a submersion, we define a parallel family of elliptic hyperquadrics $$E\mathcal{H}L(v_0) = (\mathcal{H}_{v_0}^T)^{-1}(0),$$
where \( \overline{h}^T_{i} : (LC^* \times \mathbb{R}, (v_0, 0)) \rightarrow (\mathbb{R}, 0) \) is defined by \( \overline{h}^T_{i}(x, t) = h^T_{i}(x) - t \). If \( v_0 = HE^T_M(u_0) \), then \( \mathcal{E}H\mathcal{L}(v_0) \) is the parallel family of elliptic hyperquadrics such that the hyperquadric through \( (v_0, 0) \) is the osculating elliptic hyperquadric of \( M = x_+^T(U) \) with the center \( v_0 \). We can also define the regular foliation

\[
\mathcal{F}_{h^T_{i}} = \{(h^T_{i}(c))^{-1} | c \in (\mathbb{R}, 0)\}
\]

whose leaves are elliptic hyperquadrics such that \( (h^T_{i})^{-1}(0) \) is the osculating elliptic hyperquadric with the center \( v_0 \). In this case \( ((x^T_{i}))^{-1}(\mathcal{F}_{h^T_{i}}), u_0) \) is a singular foliation germ at \( u_0 \) which is called an osculating elliptic hyperquadrical foliation of \( M = x_+^T(U) \) at \( p = x_+^T(u_0) \). We denote it by \( \mathcal{O}\mathcal{F}^T(M, u_0). \)

Let \( (x^T_{i})_i : (U, u_i) \rightarrow LC^* \) be spacelike hypersurface germs. We consider timelike height functions \( H^T_{i} : (U \times H^T_n(-1), (u_i, v_i)) \rightarrow \mathbb{R} \) of \( (x^T_{i})_i \), where \( v_i = HE^T_M(u_i) \). We denote that \( h^T_{i,v_i}(u) = H^T_{i}(u, v_i) \), then we have \( h^T_{i,v_i}(u) = h^T_{v_i}
(\alpha^T_{i})(u) \). As an application of Appendices B and C, we have the following theorem:

**Theorem 8.5** Let \( (x^T_{i})_i : (U, u_i) \rightarrow LC^* \) be spacelike hypersurface germs such that the corresponding graphlike Legendrian unfolding germs

\[
\mathcal{L}^T_{H^T} : (C(H^T_1), (u_i, v_i)) \rightarrow J^1(H^T_n(-1), \mathbb{R})
\]

are S.P\(^{+}\)-Legendrian stable, where \( v_i = HE^T_M(u_i) \). Then the following conditions are equivalent:

1. \( PK\left((x^T_{\alpha})(U), \mathcal{E}H\mathcal{L}(v_\alpha); (x^T_{\beta})(u_\beta)\right) = PK\left((x^T_{\beta})(U), \mathcal{E}H\mathcal{L}(v_\beta); (x^T_{\beta})(u_\beta)\right) \).
2. \( \overline{h}^T_{\alpha,v_\beta} \) and \( \overline{h}^T_{\beta,v_\alpha} \) are S.P-\( K \)-equivalent.
3. \( H^T_{\alpha} \) and \( H^T_{\beta} \) are S.P\(^{+}\)-\( K \)-equivalent.
4. \( \mathcal{L}^T_{H^T_{\alpha}} \) and \( \mathcal{L}^T_{H^T_{\beta}} \) are S.P\(^{+}\)-Legendrian equivalent.
5. The graphlike unfoldings of wave fronts \( W(\mathcal{L}^T_{H^T_{\alpha}}) \) and \( W(\mathcal{L}^T_{H^T_{\beta}}) \) are S.P\(^{+}\)-diffeomorphic.

**Proof.** By Proposition 8.2, the condition (1) is equivalent to the condition (2). Since both of \( \mathcal{L}^T_{H^T_{\alpha}} \) are S.P\(^{+}\)-Legendrian stable, both of \( H^T_{\alpha} \) are S.P\(^{+}\)-\( K \)-versal deformations of \( \overline{h}^T_{\alpha} \) respectively (cf. Theorem B.6). By Proposition B.5, the condition (2) implies the condition (3). It always holds that the condition (3) implies the condition (2). By Theorem B.6 (1), the condition (3) is equivalent to the condition (4). Since both of \( \mathcal{L}^T_{H^T_{\alpha}} \) are S.P\(^{+}\)-Legendrian stable, the assumption of Proposition B.8 is satisfied for \( \mathcal{L}^T_{H^T_{\alpha}} \). It follows that the conditions (4) and (5) are equivalent. This completes the proof.

We also have the following theorem as an application of Appendix A.

**Theorem 8.6** Let \( (x^T_{i})_i : (U, u_i) \rightarrow LC^* \) be spacelike hypersurface germs such that the corresponding Lagrangian submanifold germs

\[
L(H^T_1) : (C(H^T_1), (u_i, v_i)) \rightarrow T^*H^T_n(-1)
\]

are diffeomorphic.
are Lagrangian stable, where \( v_i = H E^\varepsilon_{M_i}(u_i) \). Then the following conditions are equivalent:

1. \( K((x^\varepsilon_+)_\alpha(U), \mathcal{F}_{h_\alpha}; (x^\varepsilon_+)_\alpha(u_\alpha)) = K((x^\varepsilon_+)_\beta(U), \mathcal{F}_{h_\beta}; (x^\varepsilon_+)_\beta(u_\beta)) \).
2. \( h^T_{\alpha,v_\alpha} \) and \( h^T_{\beta,v_\beta} \) are \( \mathcal{R}^+ \)-equivalent.
3. \( H^T_\alpha \) and \( H^T_\beta \) are \( \mathcal{P}-\mathcal{R}^+ \)-equivalent.
4. \( L(H^T_\alpha) \) and \( L(H^T_\beta) \) are Lagrangian equivalent.
5. (a) The rank and signature of the \( \mathcal{H}(h^T_{\alpha,v_\alpha}) \) and \( \mathcal{H}(h^T_{\beta,v_\beta}) \) are equal.
   (b) There is an isomorphism \( \gamma : \mathcal{R}_2(h^T_{\alpha,v_\alpha}) \rightarrow \mathcal{R}_2(h^T_{\beta,v_\beta}) \) such that \( \gamma([h^T_{\alpha,v_\alpha}]) = [h^T_{\beta,v_\beta}] \).

**Proof.** By Proposition 8.3, the condition (1) is equivalent to the condition (2). Since both of \( L(H^T_\alpha) \) are Lagrangian stable, both of \( H^T_\alpha \) are \( \mathcal{R}^+ \)-versal unfoldings of \( h^T_{\alpha,v_\alpha} \) respectively. By the uniqueness theorem on the \( \mathcal{R}^+ \)-versal unfolding of a function germ, the condition (2) is equivalent to the condition (3). By Proposition A.2, the condition (3) is equivalent to the condition (4). It also follows from Proposition A.2 that both of \( h^T_\alpha \) satisfy the Milnor condition. Therefore we can apply Proposition 8.4 to our situation, so that the condition (2) is equivalent to the condition (5). This completes the proof. \( \square \)

We remark that if \( L(H^T_\alpha) \) and \( L(H^T_\beta) \) are Lagrangian equivalent, then the corresponding hyperbolic evolutes are diffeomorphic. Since the hyperbolic evolute of a hypersurface \( M = x^\varepsilon_+(U) \) is considered to be the caustic of \( L(H^T) \), the above theorem gives a symplectic interpretation for the contact of hypersurfaces with family of hyperspheres (cf. Appendix A).

On the other hand, we have the following proposition.

**Proposition 8.7** If \( L(H^T_\alpha) \) and \( L(H^T_\beta) \) are Lagrangian equivalent, then the graphlike unfoldings of wave fronts \( W(\Sigma_{H^T_\alpha}) \) and \( W(\Sigma_{H^T_\beta}) \) are \( S.P^+ \)-diffeomorphic.

**Proof.** Since the \( S.P^+ \)-Legendrian equivalence implies the \( S.P^+ \)-diffeomorphism, the assertion directly follows from Proposition C.2. \( \square \)

By Proposition C.3, if \( \Sigma_{HT} \) is \( S.P^+ \)-Legendrian stable, then \( L(H^T) \) is Lagrangian stable. Therefore, we have the following corollary of Theorem 8.6 and Proposition 8.7.

**Corollary 8.8** Let \( (x^\varepsilon_+)_i : (U, u_i) \rightarrow LC^* \) \( (i = \alpha, \beta) \) be spacelike hypersurface germs such that the corresponding graphlike Legendrian unfolding germs

\[ \Sigma_{HT} : (C(H^T_\alpha), (u_i, v_i)) \rightarrow J^1(H^n(-1), \mathbb{R}) \]

are \( S.P^+ \)-Legendrian stable, where \( v_i = H E^\varepsilon_{M_\alpha}(u_i) \).

If \( K((x^\varepsilon_+)_\alpha(U), \mathcal{F}_{h^T_\alpha}; (x^\varepsilon_+)_\alpha(u_\alpha)) = K((x^\varepsilon_+)_\beta(U), \mathcal{F}_{h^T_\beta}; (x^\varepsilon_+)_\beta(u_\beta)) \), then the graphlike unfoldings of wave fronts \( W(\Sigma_{H^T_\alpha}) \) and \( W(\Sigma_{H^T_\beta}) \) are \( S.P^+ \)-diffeomorphic.

**Proof.** By Theorem 8.6, if \( K((x^\varepsilon_+)_\alpha(U), \mathcal{F}_{h^T_\alpha}; (x^\varepsilon_+)_\alpha(u_\alpha)) = K((x^\varepsilon_+)_\beta(U), \mathcal{F}_{h^T_\beta}; (x^\varepsilon_+)_\beta(u_\beta)) \), then \( L(H^T_\alpha) \) and \( L(H^T_\beta) \) are Lagrangian equivalent, so that \( \Sigma_{H^T_\alpha} \) and \( \Sigma_{H^T_\beta} \) are \( S.P^+ \)-Legendrian equivalent by Proposition 8.7. \( \square \)
Corollary 8.9 Under the same assumptions as those of Theorem 8.6, we have the following:
If one of the conditions of Theorem 8.6 is satisfied then
(1) The hyperbolic evolutes $HE_{M^\alpha}$ and $HE_{M^\beta}$ are diffeomorphic as germs.
(2) The osculating elliptic hyperquadrical foliation germs $\mathcal{O}^T(M_\alpha, u_\alpha)$ and $\mathcal{O}^T(M_\beta, u_\beta)$ are diffeomorphic as germs.

Similarly we can construct the osculating hyperbolic hyperquadric (or, focal hyperbolic hyperquadric) of a spacelike hypersurface $x_+^\alpha : U \rightarrow LC^*$ by using a function $\mathcal{F}^S_{\alpha} : LC^* \times S^1_1 \rightarrow \mathbb{R}$. For any $v_0 \in S^1_1$, we also denote that $h^S_{v_0} (x) = \mathcal{F}^S_{\alpha} (x, v_0)$ and we have $h^S_{v_0} (u) = h^S_{v_0} \circ x_+^\alpha (u)$. We can show that $(h^S_{v_0})^{-1} (c) = HL (v_0, c)$ is tangent to $M = x_+^\alpha (U)$ at $p = x_+^\alpha (u_0)$. In this case we call $HL (v_0, c)$ a tangent hyperbolic hyperquadric of $M = x_+^\alpha (U)$ at $p = x_+^\alpha (u_0)$ with the center $v_0$, we denote it $HHL (v_0, c)$. However, there are infinitely many tangent hyperbolic hypersurfaces at a general point $p = x_+^\alpha (u_0)$ depending on the real number $c$. If the point $v_0$ is a point of the de Sitter evolute of $M = x_+^\alpha (U)$, the tangent hyperbolic hyperquadric with the center $v_0$ is called the osculating hyperbolic hyperquadric (or, focal hyperbolic hyperquadric). Since $h^S_{v_0}$ is a submersion, we define a parallel family of hyperbolic hyperquadrics

$$\mathcal{H}^S h_0^S (v_0) = (h^S_{v_0})^{-1} (0),$$

where $h^S_{v_0} : (LC^* \times \mathbb{R}, (v_0, 0)) \rightarrow (\mathbb{R}, 0)$ is defined by $h^S_{v_0} (x, t) = h^S_{v_0} (x) - t$. If $v_0 = DE^{e}_{M} (u_0)$, then $\mathcal{H}^S h_0^S (v_0)$ is the parallel family of hyperbolic hyperquadrics such that the hyperquadric through $(v_0, 0)$ is the osculating hyperbolic hyperquadric of $M = x_+^\alpha (U)$ with the center $v_0$. We can also define the regular foliation

$$\mathcal{F}^S_{h_0^S} = \{(h^S_{v_0})^{-1} (c) \mid c \in (\mathbb{R}, 0)\}$$

whose leaves are hyperbolic hyperquadrics such that $(h^S_{v_0})^{-1} (0)$ is the osculating hyperbolic hyperquadric with the center $v_0$. In this case $((x_+^\alpha)_{-1}(-1) (\mathcal{F}^S_{h_0^S}), u_0)$ is a singular foliation germ at $u_0$ which is called an osculating hyperbolic hyperquadrical foliation of $M = x_+^\alpha (U)$ at $p = x_+^\alpha (u_0)$. We denote it by $\mathcal{O}^S (M, u_0)$. Then we have the following theorems:

Theorem 8.10 Let $(x_+^\alpha)_{i} : (U, u_i) \rightarrow LC^*$ ($i = \alpha, \beta$) be spacelike hypersurface germs such that the corresponding graphlike Legendrian unfolding germs

$$\mathcal{L}^S_{H^S_i} : (C(H^S_i), (u_i, v_i)) \rightarrow J^1 (S^1_1, \mathbb{R})$$

are S.P$^+$-Legendrian stable, where $v_i = DE^{e}_{M} (u_i)$. Then the following conditions are equivalent:

1. $PK((x_+^\alpha)_{\alpha} (U), \mathcal{H}^S h_0^S (v_0); (x_+^\alpha)_{\alpha} (u_\alpha)) = PK((x_+^\alpha)_{\beta} (U), \mathcal{H}^S h_0^S (v_0); (x_+^\beta)_{\beta} (u_\beta))$.
2. $h^S_{\alpha, v_1}$ and $h^S_{\beta, v_2}$ are S.P-K-equivalent.
3. $H^S_{\alpha}$ and $H^S_{\beta}$ are $v$-S.P$^+$-K-equivalent.
4. $\mathcal{L}^S_{H^S_{\alpha}}$ and $\mathcal{L}^S_{H^S_{\beta}}$ are S.P$^+$-Legendrian equivalent.
5. The graphlike unfoldings of wave fronts $W(\mathcal{L}^S_{H^S_{\alpha}})$ and $W(\mathcal{L}^S_{H^S_{\beta}})$ are S.P$^+$-diffeomorphic.
Theorem 8.11 Let \((x^i_{\alpha})_i : (U, u_i) \rightarrow LC^* (i = \alpha, \beta)\) be spacelike hypersurface germs such that the corresponding Lagrangian submanifold germs

\[ L(H^S_{\alpha}) : (C(H^S_{\alpha}), (u_i, v_i)) \rightarrow T^* S^n_1 \]

are Lagrangian stable, where \(v_i = DE_{M_i}^\varepsilon (u_i)\). Then the following conditions are equivalent:

1. \(K((x^i_{\alpha})_\alpha(U), F_{h^S_{\alpha}} ; (x^i_{\alpha})_\alpha(u_\alpha)) = K((x^i_{\beta})_\beta(U), F_{h^S_{\beta}} ; (x^i_{\beta})_\beta(u_\beta))\).
2. \(h^S_{\alpha,v_\alpha} \hspace{1em} \text{and} \hspace{1em} h^S_{\beta,v_\beta} \) are \(\mathcal{R}^+\)-equivalent.
3. \(H^S_{\alpha} \hspace{1em} \text{and} \hspace{1em} H^S_{\beta} \) are \(P, \mathcal{R}^+\)-equivalent.
4. \(L(H^S_{\alpha}) \hspace{1em} \text{and} \hspace{1em} L(H^S_{\beta}) \) are Lagrangian equivalent.
5. (a) The rank and signature of the \(\mathcal{H}(h^S_{\alpha,v_\alpha})(u_\alpha) \hspace{1em} \text{and} \hspace{1em} \mathcal{H}(h^S_{\beta,v_\beta})(u_\beta) \) are equal,
   (b) There is an isomorphism \(\gamma : \mathcal{R}_2(h^S_{\alpha,v_\alpha}) \rightarrow \mathcal{R}_2(h^S_{\beta,v_\beta}) \) such that \(\gamma([h^S_{\alpha,v_\alpha}]) = [h^S_{\beta,v_\beta}]\).

The proofs of the above theorems are direct analogy of the corresponding proofs of Theorems 8.5 and 8.6, so that we omit the proofs.

We also have the following proposition. Since the proofs are also direct analogy of the proofs of Proposition 8.7 and Corollary 8.8, we omit it.

Proposition 8.12 If \(L(H^S_{\alpha})\) and \(L(H^S_{\beta})\) are Lagrangian equivalent, then the graphlike unfoldings of wave fronts \(W(\mathcal{L}^S_{H^S_{\alpha}})\) and \(W(\mathcal{L}^S_{H^S_{\beta}})\) are \(S.P^+-\)diffeomorphic.

By Proposition C.3, if \(\mathcal{L}^S_{H^S}\) is \(S.P^+-\)Legendrian stable, then \(L(H^S)\) is Lagrangian stable. Therefore, we also have the following corollary.

Corollary 8.13 Let \((x^i_{\alpha})_i : (U, u_i) \rightarrow LC^* (i = \alpha, \beta)\) be spacelike hypersurface germs such that the corresponding graphlike Legendrian unfolding germs

\[ \mathcal{L}^S_{H^S_i} : (C(H^S_{\alpha}), (u_i, v_i)) \rightarrow J^1(S^n_1, \mathbb{R}) \]

are \(S.P^+-\)Legendrian stable, where \(v_i = DE_{M_i}^\varepsilon (u_i)\).

If \(K((x^i_{\alpha})_\alpha(U), F_{b^S_{\alpha}} ; (x^i_{\alpha})_\alpha(u_\alpha)) = K((x^i_{\beta})_\beta(U), F_{b^S_{\beta}} ; (x^i_{\beta})_\beta(u_\beta))\), then the graphlike unfoldings of wave fronts \(W(\mathcal{L}^S_{H^S_{\alpha}})\) and \(W(\mathcal{L}^S_{H^S_{\beta}})\) are \(S.P^+-\)diffeomorphic.

Corollary 8.14 Under the same assumptions as those of Theorem 8.11, we have the following:

1. The de Sitter evolutes \(DE_{M^\alpha}\) and \(DE_{M^\beta}\) are diffeomorphic as germs.
2. The osculating hyperbolic hyperquadrical foliation germs \(\mathcal{O}F^S(M^\alpha, u_\alpha)\) and \(\mathcal{O}F^S(M^\beta, u_\beta)\) are diffeomorphic as germs.

Remarks If we assume that \(x^h : U \rightarrow H^n(-1)\) is an embedding, we can get the information of the contact with families of hyperspheres or equidistant hypersurfaces in \(H^n(-1)\). Analogous assertion to Theorem 8.6 was given as Theorem 5.3 in \cite{14}. Moreover, if we consider a spacelike embedding \(x^d : U \rightarrow S^n_1\), we also get the information of the contact with families of hyperbolic hyperquadrics or elliptic hyperquadrics in \(S^n_1\). However the arguments are almost the same as the previous case, we omit the details.
9 Generic properties

In this section we consider generic properties of spacelike hypersurfaces in pseudo-spheres. The main tool is a kind of transversality theorems. We consider the space of spacelike embeddings $\text{Emb}_s(U,LC^n)$ with Whitney $C^\infty$-topology. We also consider the functions $\tilde{\mathcal{S}}^T: LC^* \times H^n(-1) \to \mathbb{R}$ and $\tilde{\mathcal{S}}^S: LC^* \times S^n_1 \to \mathbb{R}$ which have been defined in §8. We claim that $\mathfrak{h}_T^x$ (respectively, $\mathfrak{h}_S^x$) is a submersion for any $v \in H^n(-1)$ (respectively, $v \in S^n_1$). For any $x^i_+ \in \text{Emb}_s(U,LC^n)$, we have $F^T = \tilde{\mathcal{S}}^T \circ (x^i_+ \times \text{id}_{H^n(-1)})$ (respectively, $F^S = \tilde{\mathcal{S}}^S \circ (x^i_+ \times \text{id}_{S^n_1})$).

We also have the $r$-jet extension of $F^T$ (respectively, $F^S$):

$$j^r_T : U \times H^n(-1) \times \mathbb{R} \to J^r(U \times \mathbb{R}, \mathbb{R})$$

defined by $j^r_T(u,v,t) = j^r_y(u,v,t)$ (respectively, $j^r_T(u,v,t) = j^r_h(u,v,t)$). We consider the trivialization $J^r(U \times \mathbb{R}, \mathbb{R}) = (U \times \mathbb{R}) \times \mathbb{R} \times J^r((n-1) + 1,1)$. For any submanifold $Q \subset J^r((n-1) + 1,1)$, we denote that $\tilde{Q} = (U \times \mathbb{R}) \times \{0\} \times Q$. Then we have the following proposition as a corollary of Lemma 6 in Wassermann [25]. (See also Montaldi [21]).

**Proposition 9.1** Let $Q$ be a submanifold of $J^r((n-1) + 1,1)$. Then the set

$$T^X_Q = \{ x^i_+ \in \text{Emb}_s(U,LC^n) | j^r_T \text{ is transversal to } \tilde{Q} \}$$

is a residual subset of $\text{Emb}_s(U,LC^n)$, where $X = T, S$. If $Q$ is a closed subset, then $T^X_Q$ is open.

For $n \leq 4$, we have a finite list of a generic classification of function germs $f : (\mathbb{R}^k \times \mathbb{R}, 0) \to (\mathbb{R}, 0)$ by the $S.P^-K$-equivalence (cf. Zakalyukin [27] or Izumiya [10, Theorem 4.2]). By the above proposition and Proposition B.7, we have the following theorem.

**Theorem 9.2** Assume that $n \leq 4$ and $X = T, S$. There exists an open dense subset $O \subset \text{Emb}_s(U,LC^n)$ such that for any $x^i_+ \in O$, the germ of the graphlike Legendrian unfolding $\Sigma_{H^x}$ at each point is $S.P^+ -$Legendrian stable.

**Remarks** If we consider the space of embeddings into hyperbolic space $\text{Emb}(U, H^n(-1))$ or the space of spacelike embeddings into de Sitter space $\text{Emb}_s(U, S^n_1)$, we have the similar results as the above assertions. Moreover, we have the universal definitions of spacelike parallels and evolutes in pseudo-spheres, so that the generic classifications are the same as those of the above case.

10 The cases $n = 3$

In this section we consider the case $n = 3$. By Theorem 9.2, there exists an open dense subset $O \subset \text{Emb}_s(U,LC^n)$ such that for any $x^i_+ \in O$, the germ of the graphlike Legendrian unfolding $\Sigma_{H^x}$ at each point is $S.P^+ -$Legendrian stable, where $X = T, S$. By the local classification theorem on graphlike Legendrian unfoldings by the $S.P^+ -$Legendrian equivalence[10, 27], the corresponding graphlike Legendrian unfolding germ $\Sigma_{H^x}$ $(X = T, S)$ at any point is $S.P^+ -$Legendrian equivalent to a graphlike Legendrian unfoldings whose graphlike generating family is stably $x-S.P^+K$-equivalent to one of the following germs:
We remark that the germs of types $B_2, B_3, C_3, B_4, C_4, F_4$ appeared in the classification of big fronts in [27]. However, these germs cannot be realized as graphlike generating families.

On the other hand, by Proposition C.3, the corresponding Lagrangian submanifold germ $L(H^X)(C(H^X))$ at any point is Lagrangian stable for any $x^+ \in \mathcal{O}$. By definition (cf. Appendix C), $S.P^+$-Legendrian equivalence among graphlike Legendrian unfoldings preserve both the caustics and the perestroikas of wavefronts up to local diffeomorphism. This equivalence relation clarifies the “local differential topology” of both the caustics and the perestroikas of wavefront. On the other hand, by Proposition C.2, the Lagrangian equivalence among Lagrangian submanifold germs is stronger equivalence relation than the $S.P^+$-Legendrian equivalence among corresponding graphlike Legendrian unfoldings. Therefore, it is enough to consider the Lagrangian equivalence for low dimensional case such as the case $n = 3$. By the classification theorem of stable Lagrangian submanifold (cf., [1], Page 330, Corollary 2), the corresponding Lagrangian submanifold germ $L(H^X)(C(H^X))$ at any point is Lagrangian equivalent a Lagrangian submanifold germ whose generating family is stably $P-\mathcal{R}^+$-equivalent to one of the following germs:

$$A_2 : q_1^3 + x_1 q_1 + x_2 + x_3 + t,$$
$$A_3^\pm : q_1^3 + x_1 q_1^2 + x_2 q_1 + x_3 \pm t,$$
$$A_4 : q_1^5 + x_1 q_1^3 + x_2 q_1^2 + x_3 q_1 + t,$$
$$D_4^\pm : q_2^2 q_1 \pm q_1^3 + x_1 q_1^2 + x_2 q_1 + x_3 q_2 + t.$$

Since the total evolute is the caustics of the Lagrangian submanifold $L_1(U)$ in $\Delta_1 \times \mathbb{R}_+$ whose generating families are $H^T$ and $H^S$, we have the following theorem as an application of the above classification and Corollaries 8.9, 8.14.

**Theorem 10.1** For any $x^+ \in \mathcal{O}$ and any point $(u_0, v_0) \in U \times H^3(-1)$ (respectively, $(u_0, v_0) \in U \times S^3$), we have the following assertions:

1. The hyperbolic evolute germ $(HE_1, v_0)$ (respectively, de Sitter evolute germ $(DE_1, v_0)$) is diffeomorphic to the fold $(A_2)$, the cuspidal edge $(A_3^\pm)$, the swallowtail $(A_4)$, the pyramid $(D_4^\pm)$ or the purse $(D_4^\pm)$.

2. The osculating elliptic (respectively, hyperbolic) hyperquadrical foliation germ $\mathcal{O}F^T(M, u_0)$ (respectively, $\mathcal{O}F^S(M, u_0)$) is diffeomorphic to the foliation germs $(F_f, 0)$ with $f(q_1, q_2) = F(q_1, q_2, 0)$, where $F(q_1, q_2, x_1, x_2, x_3)$ is one of the germs of type $A_2, A_3^\pm, A_4, D_4^\pm$.

Here, the pictures of the cuspidal edge, the swallowtail, the pyramid and the purse are given in Figure 1.
We can also draw the pictures of the foliation germs $F_f$ in Theorem 10.1, see Figure 2.

Appendix A  The theory of Lagrangian singularities

In this section we give a brief review on the theory of Lagrangian singularities due to [1]. We consider the cotangent bundle $\pi : T^*\mathbb{R}^n \longrightarrow \mathbb{R}^n$ over $\mathbb{R}^n$. Let $(x, p) = (x_1, \ldots, x_n, p_1, \ldots, p_n)$ be the canonical coordinate on $T^*\mathbb{R}^n$. Then the canonical symplectic structure on $T^*\mathbb{R}^n$ is given by the canonical two form $\omega = \sum_{i=1}^{n} dp_i \wedge dx_i$. Let $i : L \longrightarrow T^*\mathbb{R}^n$ be an immersion. We say that $i$ is a Lagrangian immersion if $\dim L = n$ and $i^* \omega = 0$. In this case the critical value of $\pi \circ i$ is called the caustic of $i : L \longrightarrow T^*\mathbb{R}^n$ and it is denoted by $C_L$. The main result in the theory of Lagrangian singularities is to describe Lagrangian immersion germs by using families of function germs. Let $F : (\mathbb{R}^k \times \mathbb{R}^n, 0)) \longrightarrow (\mathbb{R}, 0)$ be an $n$-parameter unfolding of function
germs. We call
\[ C(F) = \left\{ (q, x) \in (\mathbb{R}^k \times \mathbb{R}^n, 0) \mid \frac{\partial F}{\partial q_1}(q, x) = \cdots = \frac{\partial F}{\partial q_k}(q, x) = 0 \right\}, \]
the catastrophe set of \( F \) and
\[ \mathcal{B}_F = \left\{ x \in (\mathbb{R}^n, 0) \mid \exists (q, x) \in C(F) \text{ such that } \text{rank} \left( \frac{\partial^2 F}{\partial q_i \partial q_j}(q, x) \right) < k \right\} \]
the bifurcation set of \( F \).

Let \( \pi_n : (\mathbb{R}^k \times \mathbb{R}^n, 0) \rightarrow (\mathbb{R}^n, 0) \) be the canonical projection, then we can easily show that the bifurcation set of \( F \) is the critical value set of \( \pi_n|_{C(F)} \). We say that \( F \) is a Morse family of functions if the map germ
\[ \Delta F = \left( \frac{\partial F}{\partial q_1}, \ldots, \frac{\partial F}{\partial q_k} \right) : (\mathbb{R}^k \times \mathbb{R}^n, 0) \rightarrow (\mathbb{R}^k, 0) \]
is a non-singular, where \((q, x) = (q_1, \ldots, q_k, x_1, \ldots, x_n) \in (\mathbb{R}^k \times \mathbb{R}^n, 0)\). In this case we have a smooth submanifold germ \( C(F) \subset (\mathbb{R}^k \times \mathbb{R}^n, 0) \) and a map germ \( L(F) : (C(F), 0) \rightarrow T^*\mathbb{R}^n \) defined by
\[ L(F)(q, x) = \left( x, \frac{\partial F}{\partial x_1}(q, x), \ldots, \frac{\partial F}{\partial x_n}(q, x) \right). \]
We can show that \( L(F) \) is a Lagrangian immersion. Then we have the following fundamental theorem ([1], page 300).

**Proposition A.1** All Lagrangian submanifold germs in \( T^*\mathbb{R}^n \) are constructed by the above method.

Under the above notation, we call \( F \) a generating family of \( L(F) \).

We define an equivalence relation among Lagrangian immersion germs. Let \( i : (L, x) \rightarrow (T^*\mathbb{R}^n, p) \) and \( i' : (L', x') \rightarrow (T^*\mathbb{R}^n, p') \) be Lagrangian immersion germs. Then we say that \( i \) and \( i' \) are Lagrangian equivalent if there exist a diffeomorphism germ \( \sigma : (L, x) \rightarrow (L', x') \), a symplectic diffeomorphism germ \( \tau : (T^*\mathbb{R}^n, p) \rightarrow (T^*\mathbb{R}^n, p') \) and a diffeomorphism germ \( \tilde{\tau} : (\mathbb{R}^n, \pi(p)) \rightarrow (\mathbb{R}^n, \pi(p')) \) such that \( \tau \circ i = i' \circ \sigma \) and \( \pi \circ \tau = \tilde{\tau} \circ \pi \), where \( \pi : (T^*\mathbb{R}^n, p) \rightarrow (\mathbb{R}^n, \pi(p)) \) is the canonical projection and a symplectic diffeomorphism germ is a diffeomorphism germ which preserves symplectic structure on \( T^*\mathbb{R}^n \). In this case the caustic \( C_L \) is diffeomorphic to the caustic \( C_{L'} \) by the diffeomorphism germ \( \tilde{\tau} \).

A Lagrangian immersion germ into \( T^*\mathbb{R}^n \) at a point is said to be Lagrangian stable if for every map with the given germ there is a neighborhood in the space of Lagrangian immersions (in the Whitney \( C^\infty \)-topology) and a neighborhood of the original point such that each Lagrangian immersion belonging to the first neighborhood has in the second neighborhood a point at which its germ is Lagrangian equivalent to the original germ.

We can interpret the Lagrangian equivalence by using the notion of generating families. Let \( \mathcal{E}_x \) be the ring of function germs of \( x = (x_1, \ldots, x_n) \) variables at the origin and \( \mathfrak{M}_x = \{ h \in \mathcal{E}_x \mid h(0) = 0 \} \) be the unique maximal ideal. Let \( F, G : (\mathbb{R}^k \times \mathbb{R}^n, 0) \rightarrow (\mathbb{R}, 0) \) be function germs. We say that \( F \) and \( G \) are \( P-\mathcal{R}^+ \)-equivalent if there exists a diffeomorphism germ \( \Phi : (\mathbb{R}^k \times \mathbb{R}^n, 0) \rightarrow (\mathbb{R}^k \times \mathbb{R}^n, 0) \) of the form \( \Phi(q, x) = (\Phi_1(q, x), \phi(x)) \) and a function germ \( h : (\mathbb{R}^n, 0) \rightarrow \mathbb{R} \) such that \( G(q, x) = F(\Phi(q, x)) + h(x) \). For any \( F_1 : (\mathbb{R}^k \times \mathbb{R}^n, 0) \rightarrow (\mathbb{R}, 0) \)}
and \( F_2 : (\mathbb{R}^k \times \mathbb{R}^n, 0) \rightarrow (\mathbb{R}, 0) \), \( F_1 \) and \( F_2 \) are said to be stably \( P-\mathcal{R}^+ \)-equivalent if they become \( P-\mathcal{R}^+ \)-equivalent after the addition to the arguments to \( q_i \) of new arguments \( q_i' \) and to the functions \( F_i \) of nondegenerate quadratic forms \( Q_i \) in the new arguments (i.e., \( F_1 + Q_1 \) and \( F_2 + Q_2 \) are \( P-\mathcal{R}^+ \)-equivalent).

Let \( F : (\mathbb{R}^k \times \mathbb{R}^n, 0) \rightarrow (\mathbb{R}, 0) \) be a function germ. We say that \( F \) is an \( \mathcal{R}^+ \)-versal deformation of \( f = F|_{\mathbb{R}^k \times \{0\}} \) if

\[
\mathcal{E}_q = J_f + \left( \frac{\partial F}{\partial x_1}\mathbb{R}^k \times \{0\}, \ldots, \frac{\partial F}{\partial x_n}\mathbb{R}^k \times \{0\} \right)_R + (1)_R,
\]

where

\[
J_f = \left( \frac{\partial f}{\partial q_1}(q), \ldots, \frac{\partial f}{\partial q_k}(q) \right)_{\mathcal{E}_q}.
\]

**Theorem A.2** Let \( F : (\mathbb{R}^k \times \mathbb{R}^n, 0) \rightarrow (\mathbb{R}, 0) \) and \( G : (\mathbb{R}^k' \times \mathbb{R}^n, 0) \rightarrow (\mathbb{R}, 0) \) be Morse families of functions. Then we have the following:

1. \( L(F) \) and \( L(G) \) are Lagrangian equivalent if and only if \( F \) and \( G \) are stably \( P-\mathcal{R}^+ \)-equivalent.
2. \( L(F) \) is a Lagrangian stable if and only if \( F \) is a \( \mathcal{R}^+ \)-versal deformation of \( F|_{\mathbb{R}^k \times \{0\}} \).

For the proof of the above theorem, see ([1], page 304 and 325). The following proposition describes the well-known relationship between bifurcation sets and equivalence among unfoldings of function germs:

**Proposition A.3** Let \( F, G : (\mathbb{R}^k \times \mathbb{R}^n, 0) \rightarrow (\mathbb{R}, 0) \) be function germs. If \( F \) and \( G \) are \( P-\mathcal{R}^+ \)-equivalent then there exist a diffeomorphism germ \( \phi : (\mathbb{R}^n, 0) \rightarrow (\mathbb{R}^n, 0) \) such that \( \phi(\mathcal{B}_F) = \mathcal{B}_G \).

**Appendix B  Families of wave fronts and discriminant**

In this appendix we give a brief review of the classification theory of both the families of wave fronts and the discriminants. Almost all results are given by Zakalyukin[27]. However, we give some detailed information here which might be new. Moreover some equivalence relations presented here have been independently introduced by the first named author[10] for different purposes from those of Zakalyukin[27].

We consider the projective cotangent bundle \( \pi : PT^*(\mathbb{R}^n \times \mathbb{R}) \rightarrow \mathbb{R}^n \times \mathbb{R} \) over \( \mathbb{R}^n \times \mathbb{R} \). Let \( \Pi : TPT^*(\mathbb{R}^n \times \mathbb{R}) \rightarrow PT^*(\mathbb{R}^n \times \mathbb{R}) \) be the tangent bundle over \( PT^*(\mathbb{R}^n \times \mathbb{R}) \) and \( d\pi : TPT^*(\mathbb{R}^n \times \mathbb{R}) \rightarrow T(\mathbb{R}^n \times \mathbb{R}) \) the differential map of \( \pi \).

For any \( X \in TPT^*(\mathbb{R}^n \times \mathbb{R}) \), there exists an element \( \alpha \in T_{(x,y)}^*(\mathbb{R}^n \times \mathbb{R}) \) such that \( \Pi(X) = [\alpha] \). For an element \( V \in T_{(x,y)}(\mathbb{R}^n \times \mathbb{R}) \), 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 \( PT^*(\mathbb{R}^n \times \mathbb{R}) \) by

\[
K = \{ X \in TPT^*(\mathbb{R}^n \times \mathbb{R}) | \Pi(X)(d\pi(X)) = 0 \}.
\]

Because of the trivialization \( PT^*(\mathbb{R}^n \times \mathbb{R}) \cong (\mathbb{R}^n \times \mathbb{R}) \times P(\mathbb{R}^n \times \mathbb{R})^* \), we call

\[
((x_1, \ldots, x_n, t), [\xi_1 : \ldots : \xi_n : \tau])
\]

a homogeneous coordinate, where \( [\xi_1 : \ldots : \xi_n : \tau] \) is the homogeneous coordinate of the dual projective space \( P(\mathbb{R}^n \times \mathbb{R})^* \). It is easy to show that \( X \in K_{((x,y),[\xi:\tau])} \) if and only if \( \sum_{i=1}^n \mu_i \xi_i + \lambda \tau = 0 \), where \( d\pi(X) = \sum_{i=1}^n \mu_i \frac{\partial}{\partial x_i} + \lambda \frac{\partial}{\partial t} \).
We remark that $PT^* (\mathbb{R}^n \times \mathbb{R})$ is a fibrewise compactification of the 1-jet space $J^1 (\mathbb{R}^n, \mathbb{R})$ as follows: We consider an affine open subset $U_\tau = \{((x, t), [\xi : \tau]) | \tau \neq 0\}$ of $PT^* (\mathbb{R}^n \times \mathbb{R})$. For any $((x, t), [\xi : \tau]) \in U_\tau$, we have

$$((x_1, \ldots, x_n, t), [\xi_1 : \cdots : \xi_n : \tau]) = ((x_1, \ldots, x_n, t), [-\frac{\xi_1}{\tau} : \cdots : -\frac{\xi_n}{\tau} : -1]),$$

so that we may adopt the corresponding affine coordinates $((x_1, \ldots, x_n, t), (p_1, \ldots, p_n))$, where $p_i = -\xi_i / \tau$. On $U_\tau$ we can easily show that $\theta^{-1} (0) = K|U_\tau$, where $\theta = dt - \sum_{i=1}^n p_i dx_i$. This means that $U_\tau$ may be identified with the 1-jet space $J^1 (\mathbb{R}^n, \mathbb{R})$. We call the above coordinate a system of canonical coordinates. Throughout the remainder of this paper, we use this identification so that we have $J^1 (\mathbb{R}^n, \mathbb{R}) \subset PT^* (\mathbb{R}^n \times \mathbb{R})$.

A submanifold $i : L \subset PT^* (\mathbb{R}^n \times \mathbb{R})$ is a Legendrian submanifold if $\dim L = n$ and $d\pi_p (T_p L) \subset K_i (p)$ for any $p \in L$. We say that a point $p \in L$ is a Legendrian singular point if $\mathrm{rank} d(\pi \circ i)_p < n$. We also say that a point $p \in L$ is a space-singular point if $\mathrm{rank} d(\pi_1 \circ \pi \circ i)_p < n$, where $\pi_1 : \mathbb{R}^n \times \mathbb{R} \to \mathbb{R}^n$ is the canonical projection. By definition, if a point $p \in L$ is a Legendrian singular point, then it is a space-singular point. If $i : L \subset J^1 (\mathbb{R}^n, \mathbb{R})$, the converse assertion also holds as the following lemma shows:

**Lemma B.1** Let $i : L \subset PT^* (\mathbb{R}^n \times \mathbb{R})$ be a Legendrian submanifold with $L \subset J^1 (\mathbb{R}^n, \mathbb{R})$. Then a point $p \in L$ is a Legendrian singular point if and only if it is a space-singular point.

**Proof.** Let $p \in L$ be a space-singular point. Then there exists a non-zero tangent vector $v \in T_p L$ such that $d(\pi_1 \circ \pi \circ i)_p (v) = 0$. Under the canonical coordinate of $J^1 (\mathbb{R}^n, \mathbb{R})$, we have

$$i (v) = \sum_{i=1}^n \alpha_i \frac{\partial}{\partial x_i} + \beta \frac{\partial}{\partial t} + \sum_{j=1}^n \gamma_j \frac{\partial}{\partial p_j}$$

for some real numbers $\alpha_i, \beta, \gamma_j$. By the assumption, we have $\alpha_i = 0$ ($i = 1, \ldots, n$). Since $i$ is a Legendrian immersion, we have $0 = \theta (i (v)) = \beta - \sum_{i=1}^n \gamma_i \alpha_i = \beta$. It follows that

$$d\pi \circ i (v) = \sum_{i=1}^n \alpha_i \frac{\partial}{\partial x_i} + \beta \frac{\partial}{\partial t} = 0.$$ 

Therefore, $p \in L$ is a Legendrian singular point. □

We also say that a point $p \in L$ is a *time-singular point* if $\mathrm{rank} d(\pi_2 \circ \pi \circ i)_p < 1$, where $\pi_2 : \mathbb{R}^n \times \mathbb{R} \to \mathbb{R}$ is the canonical projection. Then we have the following lemma.

**Lemma B.2** Let $i : L \subset PT^* (\mathbb{R}^n \times \mathbb{R})$ be a Legendrian submanifold without Legendrian singular points. If $p \in L$ is a space-singular point, then $p$ is not a time-singular point (i.e., $\pi_2 \circ \pi \circ i$ is a submersion at $p$). Moreover, under the same assumption, $i((\pi_2 \circ \pi \circ i)^{-1} (c))$ is an $(n-1)$-dimensional isotropic immersion at $p$, where $c = \pi_2 \circ \pi \circ i (p)$ such that $\mathrm{rank} d(\pi \circ i)((\pi_2 \circ \pi \circ i)^{-1} (c))_p = n-1$ (i.e., $\pi \circ i|((\pi_2 \circ \pi \circ i)^{-1} (c))$ is an immersion at $p$).

**Proof.** By the assumption, $\pi \circ i$ is an immersion. For any $v \in T_p L$, there exist $X_v \in T_{\pi\circ i (p)} (\mathbb{R}^n \times \{0\})$ and $Y_v \in T_{\pi\circ i (p)} (\{0\} \times \mathbb{R})$ such that $d(\pi \circ i)_p (v) = X_v + Y_v$. If $\mathrm{rank} d(\pi_2 \circ \pi \circ i)_p = 0$, then $d(\pi \circ i)_p (v) = X_v$ for any $v \in T_p L$. Since $p$ is a space-singular point, there exists a non-zero
tangent vector \( v \in T_pL \) such that \( X_v = 0 \), so that \( d(\pi \circ i)_p(v) = 0 \). This contradicts to the fact that \( \pi \circ i \) is an immersion.

Since \( i \) is a Legendrian immersion such that \( \pi \circ i \) is an immersion, \( i((\pi_2 \circ \pi \circ i)^{-1}(c)) \) is an \((n-1)\)-dimensional isotropic immersion at \( p \) and \( \pi \circ i((\pi_2 \circ \pi \circ i)^{-1}(c)) \) is also an immersion at \( p \).

For a Legendrian submanifold \( i : L \subset PT^* (\mathbb{R}^n \times \mathbb{R}) \), \( \pi \circ i(L) = W(L) \) is called a big wave front. We have a family of small fronts:

\[
W_i(L) = \pi_1(\pi_2^{-1}(t) \cap W(L)) \quad (t \in \mathbb{R}).
\]

In this sense we call \( L \) a big Legendrian submanifold. The discriminant of the family \( W_i(L) \) is defined as the image of singular points of \( \pi_1|W(L) \). In the general case, the discriminant consists of three components: the caustics \( C_L \), the projection of the set of singular points of \( W(L) \), the Maxwell stratum \( M_L \), the projection of self intersection points of \( W(L) \); and also of the envelope of the family of small fronts \( \Delta \). By definition, \( C_L \cup \Delta \) is the projection of space-singular points. By Lemma B.1, if \( i : L \subset J^1(\mathbb{R}^n, \mathbb{R}) \), then the discriminant is \( C_L \cup M_L \). Moreover, by Lemma B.2, if \( i : L \subset PT^* (\mathbb{R}^n \times \mathbb{R}) \) is not Legendrian singular at any point, then the discriminant is \( M_L \cup \Delta \).

We now consider equivalence relations among Legendrian submanifolds which preserve both of qualitative pictures of bifurcations of families of small fronts and discriminants.

Let \( i : (L, p_0) \subset (PT^*(\mathbb{R}^n \times \mathbb{R}), p_0) \) and \( i' : (L', p'_0) \subset (PT^*(\mathbb{R}^n \times \mathbb{R}), p'_0) \) be Legendrian submanifold germs. We say that \( i \) and \( i' \) are space-time Legendrian equivalent if there exist diffeomorphism germs \( \Phi : (\mathbb{R}^n \times \mathbb{R}, \pi(p_0)) \to (\mathbb{R}^n \times \mathbb{R}, \pi(p'_0)) \) of the form \( \Phi(x, t) = (\phi_1(x), \phi_2(t)) \) and \( \Psi : (L, p_0) \to (L', p'_0) \) such that \( \Phi \circ i = i \circ \Psi \), where \( \Phi : (PT^*(\mathbb{R}^n \times \mathbb{R}), p_0) \to (PT^*(\mathbb{R}^n \times \mathbb{R}), p'') \) is the unique contact diffeomorphism germ with \( \pi \circ \Phi = \Phi \circ \pi \).

This equivalence relation is the most natural equivalence relation among Legendrian immersion germs for our purpose. It might be, however, quite hard to study because it leads the equivalence relation among divergent diagrams \( \mathbb{R}^n \leftarrow \mathbb{R}^n \times \mathbb{R} \to \mathbb{R} \). In order to avoid the difficulty, we introduce rather a strong equivalence relation as follows: We say that \( i \) and \( i' \) are strictly parametrized Legendrian equivalent (or, briefly \( S.P^-\)Legendrian equivalent) if there exist diffeomorphism germs \( \Phi : (\mathbb{R}^n \times \mathbb{R}, \pi(p_0)) \to (\mathbb{R}^n \times \mathbb{R}, \pi(p'_0)) \) of the form \( \Phi(x, t) = (\phi_1(x), t) \) and \( \Psi : (L, p_0) \to (L', p'_0) \) such that \( \Phi \circ i = i \circ \Psi \). Although this equivalence relation is rather easier to handle, functional modulus in the generic classification might appear even in low dimensional case. Therefore, we introduce another equivalence relation which ignores the function moduli as follows: We say that \( i \) and \( i' \) are strictly parametrized Legendrian equivalent (or, briefly \( S.P^+\)Legendrian equivalent) if there exist diffeomorphism germs \( \Phi : (\mathbb{R}^n \times \mathbb{R}, \pi(p_0)) \to (\mathbb{R}^n \times \mathbb{R}, \pi(p'_0)) \) of the form \( \Phi(x, t) = (\phi_1(x), t + \alpha(x)) \) and \( \Psi : (L, p_0) \to (L', p'_0) \) such that \( \Phi \circ i = i \circ \Psi \).

The \( S.P^+\)-Legendrian equivalence has been introduced in [10, 11, 24] for the study of completely integrable holonomic systems of first order partial differential equations. It has also been independently studied by Zakalyukin [27] called the strongly space-equivalence. We remark that the above equivalence relation among big Legendrian submanifold germs preserve both the diffeomorphism types of bifurcations for families of small fronts and caustics.

We study the \( S.P^+\)-Legendrian equivalence by using the notion of generating families of Legendrian submanifold germs.

For any Legendrian submanifold germ \( i : (L, p_0) \subset (PT^*(\mathbb{R}^n \times \mathbb{R}), p_0) \), there exists a gener-
ating family of \(i\) by the Arnol’d-Zakalyukin’s theory [1]. Let \(F : (\mathbb{R}^k \times (\mathbb{R}^n \times \mathbb{R}), 0) \longrightarrow (\mathbb{R}, 0)\) be a function germ such that \((F, d_2 F) : (\mathbb{R}^k \times \mathbb{R}^n \times \mathbb{R}, 0) \longrightarrow (\mathbb{R} \times \mathbb{R}^k, 0)\) is non-singular, where

\[
d_2 F(q, x, t) = \left( \frac{\partial F}{\partial q_1}(q, x, t), \ldots, \frac{\partial F}{\partial q_k}(q, x, t) \right).
\]

In this case we call \(F\) a big Morse family of hypersurfaces. Then \(\Sigma_\ast(F) = (F, d_2 F)^{-1}(0)\) is a smooth \(n\)-manifold germ. Define

\[
\mathcal{L}_F : (\Sigma_\ast(F), 0) \longrightarrow PT^\ast(\mathbb{R}^n \times \mathbb{R})
\]

by

\[
\mathcal{L}_F(q, x, t) = \left( x, t, \left[ \frac{\partial F}{\partial x}(q, x, t) : \frac{\partial F}{\partial t}(q, x, t) \right] \right),
\]

where

\[
\left[ \frac{\partial F}{\partial x}(q, x, t) : \frac{\partial F}{\partial t}(q, x, t) \right] = \left[ \frac{\partial F}{\partial x_1}(q, x, t) : \cdots : \frac{\partial F}{\partial x_n}(q, x, t) : \frac{\partial F}{\partial t}(q, x, t) \right].
\]

It is easy to show that \(\mathcal{L}_F(\Sigma_\ast(F))\) is a Legendrian submanifold germ. By the main theorem of Arnol’d-Zakalyukin [1], we can show the following proposition:

**Proposition B.3** All big Legendrian submanifold germs are constructed by the above method.

Let \(F : (\mathbb{R}^k \times (\mathbb{R}^n \times \mathbb{R}), 0) \longrightarrow (\mathbb{R}, 0)\) be a big Morse family of hypersurfaces. We call \(F\) a generating family of \(\mathcal{L}_F\). We now consider ambiguity of the choice of generating families. Let \(F, G : (\mathbb{R}^k \times (\mathbb{R}^n \times \mathbb{R}), 0) \longrightarrow (\mathbb{R}, 0)\) be big Morse families. We say that \(F\) and \(G\) are strictly \(R\)-equivalent if there exists a diffeomorphism germ \(\Phi : (\mathbb{R}^k \times (\mathbb{R}^n \times \mathbb{R}), 0) \longrightarrow (\mathbb{R}^k \times (\mathbb{R}^n \times \mathbb{R}), 0)\) of the form \(\Phi(q, x, t) = (\phi(q, x, t), x, t)\) such that \(F \circ \Phi = G\). If we carefully read proofs of Lemmas 1 and 2 in ([1], page 307), we can understand the following assertion.

**Proposition B.4** Let \(F, G : (\mathbb{R}^k \times (\mathbb{R}^n \times \mathbb{R}), 0) \longrightarrow (\mathbb{R}, 0)\) be big Morse families of hypersurfaces such that

\[
\text{Image } \mathcal{L}_F = \text{Image } \mathcal{L}_G \quad \text{and} \quad \text{rank } \mathcal{H}(F|\mathbb{R}^k \times \{0\})(0) = \text{rank } \mathcal{H}(G|\mathbb{R}^k \times \{0\})(0) = 0,
\]

where \(\mathcal{H}(f)\) is the Hessian matrix of \(f\). Then \(F\) and \(G\) are strictly \(R\)-equivalent.

Let \(f, g : (\mathbb{R}^k \times \mathbb{R}, 0) \longrightarrow (\mathbb{R}, 0)\) be function germs. We say that \(f\) and \(g\) are \(S.P.\mathcal{K}\)-equivalent (or, strictly \(P-K\)-equivalent) if there exists a diffeomorphism germ \(\Phi : (\mathbb{R}^k \times \mathbb{R}, 0) \longrightarrow (\mathbb{R} \times \mathbb{R}^k, 0)\) of the form \(\Phi(q, t) = (\phi(q, t), t)\) such that \(\langle f \circ \Phi \rangle_{\varepsilon(q,t)} = \langle g \rangle_{\varepsilon(q,t)}\).

Let \(F, G : (\mathbb{R}^k \times (\mathbb{R}^n \times \mathbb{R}), 0) \longrightarrow (\mathbb{R}, 0)\) be function germs. We say that \(F\) and \(G\) are \(x\)-\(S.P^+\mathcal{K}\)-equivalent if there exists a diffeomorphism germ \(\Phi : (\mathbb{R}^k \times (\mathbb{R}^n \times \mathbb{R}), 0) \longrightarrow (\mathbb{R}^k \times (\mathbb{R}^n \times \mathbb{R}), 0)\) of the form \(\Phi(q, x, t) = (\phi(q, x, t), \phi_2(x), t + \alpha(x))\) such that \(\langle F \circ \Phi \rangle_{\varepsilon(q,x,t)} = \langle G \rangle_{\varepsilon(q,x,t)}\), where \(x = (x_1, \ldots, x_n)\) is the canonical coordinate of \((\mathbb{R}^n, 0)\).

The notion of \(S.P^+\mathcal{K}\)-versal deformation plays an important role for our purpose. We define the extended tangent space of \(f : (\mathbb{R}^k \times \mathbb{R}, 0) \longrightarrow (\mathbb{R}, 0)\) relative to \(S.P^+\mathcal{K}\) by

\[
T_e(S.P^+\mathcal{K})(f) = \langle \frac{\partial f}{\partial q_1}, \ldots, \frac{\partial f}{\partial q_k}, f \rangle_{\varepsilon(q,t)} + \langle \frac{\partial f}{\partial t} \rangle_{\mathbb{R}}.
\]
Then we say that a deformation $F$ of $f = F|_{\mathbb{R}^k \times \{0\} \times \mathbb{R}}$ is *infinitesimally $S.P^+\mathcal{K}$-versal* if it satisfies

$$\mathcal{E}_{(q,t)} = T_c(S.P^+\mathcal{K})(f) + \langle \frac{\partial F}{\partial x_1}[\mathbb{R}^k \times \{0\} \times \mathbb{R}, \ldots, \frac{\partial F}{\partial x_n}[\mathbb{R}^k \times \{0\} \times \mathbb{R}] \rangle_{\mathbb{R}}.$$

We simply say that $F$ is a *$S.P^+\mathcal{K}$-versal deformation* of $f$ if it is infinitesimally $S.P^+\mathcal{K}$-versal.

We remark that $F$ is $S.P^+\mathcal{K}$-versal, then $n$ is upper bound for

$$\dim \mathcal{E}_{(q,t)}/T_c(S.P^+\mathcal{K})(f).$$

Moreover, we have the following very important property as a consequence of the versality theorem[5].

**Proposition B.5** 1) Suppose that $F, G$ be $n$-parameter $S.P^+\mathcal{K}$-versal deformations of $f$. Then $F$ and $G$ are $x$-$S.P^+\mathcal{K}$-equivalent.

2) Let $\xi_1(q,t), \ldots, \xi_n(q,t)$ be generators of the $\mathbb{R}$-vector space $\mathcal{E}_{(q,t)}/T_c(S.P^+\mathcal{K})(f)$, then any $n$-parameter $S.P^+\mathcal{K}$-versal deformations are $x$-$S.P^+\mathcal{K}$-equivalent to

$$F(q,x,t) = f(q,t) + \sum_{i=1}^{n} x_i \xi_i(q,t).$$

**Theorem B.6** Let $F : (\mathbb{R}^k \times (\mathbb{R}^n \times \mathbb{R}), 0) \longrightarrow (\mathbb{R}, 0)$ and $G : (\mathbb{R}^{k'} \times (\mathbb{R}^n \times \mathbb{R}), 0) \longrightarrow (\mathbb{R}, 0)$ be big Morse families of hypersurfaces. Then

1) $\mathcal{L}_F$ and $\mathcal{L}_G$ are $S.P^+$-Legendrian equivalent if and only if $F$ and $G$ are stably $x$-$S.P^+$-Legendrian equivalent.

2) $\mathcal{L}_F$ is a $S.P^+$-Legendrian stable if and only if $F$ is a $S.P^+$-$\mathcal{K}$-versal deformation of $f = F|_{\mathbb{R}^k \times \{0\} \times \mathbb{R}}$.

Here, $F$ and $G$ are said to be stably $x$-$S.P^+$-$\mathcal{K}$-equivalent if they become $x$-$S.P^+$-$\mathcal{K}$-equivalent after the addition of non-degenerate quadratic forms in additional variables $q$.

We have another characterization of the $S.P^+$-versality for families of function germs. For any function germ $F : (\mathbb{R}^k \times (\mathbb{R}^n \times \mathbb{R}), 0) \longrightarrow (\mathbb{R}, 0)$, we have the $r$-jet extension

$$j^r_1F : (\mathbb{R}^k \times (\mathbb{R}^n \times \mathbb{R}), 0) \longrightarrow J^r(\mathbb{R}^k \times \mathbb{R}, \mathbb{R})$$

defined by $j^r_1F(q,x,t) = j^rF_x(q,t)$, where $F_x(q,t) = F(q,x,t)$. On the other hand, we have $(S.P-K)^r$-orbits in $J^r(k+1,1)$, where we have the canonical decomposition $J^r(\mathbb{R}^k \times \mathbb{R}, \mathbb{R}) = (\mathbb{R}^k \times \mathbb{R}) \times J^r(k+1,1)$. For any $z = j^r f(0) \in J^r(k+1,1)$, we define that

$$(S.P-K)^r(z) = (\mathbb{R}^k \times \mathbb{R}) \times \{0\} \times (S.P-K)^r(z),$$

where $(S.P-K)^r(z)$ is the $(S.P-K)^r$-orbit through $z$.

**Proposition B.7** Suppose that $f = F|_{\mathbb{R}^k \times \{0\} \times \mathbb{R}}$ is $r$-determined relative to $S.P-K$ (for the definition, see [8]). The following conditions are equivalent:

1) $F$ is a $S.P^+\mathcal{K}$-versal deformation of $f$.

2) $j^r_1F$ is transverse to $(S.P-K)^r(z)$, where $z = j^r f(0)$.
Since the big Legendrian submanifold germ $i : (L, p_0) \subset (PT^*(\mathbb{R}^n \times \mathbb{R}), p_0)$ is uniquely determined on the regular part of the big wave front $W(L)$, we have the following simple but significant property of Legendrian submanifold germs:

**Proposition B.8** Let $i : (L, p_0) \subset (PT^*(\mathbb{R}^n \times \mathbb{R}), p_0)$ and $i' : (L', p_0) \subset (PT^*(\mathbb{R}^n \times \mathbb{R}), p_0)$ be big Legendrian submanifold germs such that regular sets of $\pi \circ i, \pi \circ i'$ are dense respectively. Then $(L, p_0) = (L', p_0)$ if and only if $(W(L), \pi(p_0)) = (W(L'), \pi(p_0))$.

This result has been firstly pointed out by Zakalyukin [26]. The assumption in the above proposition is a generic condition for $i, i'$. Specially, if $i$ and $i'$ are $S.P^+$-Legendrian stable, then these satisfy the assumption. Concerning the discriminant and the bifurcation of small fronts, we define the following equivalence relation among big wave front germs. Let $i : (L, p_0) \subset (PT^*(\mathbb{R}^n \times \mathbb{R}), p_0)$ and $i' : (L', p_0) \subset (PT^*(\mathbb{R}^n \times \mathbb{R}), p_0)$ be Legendrian submanifold germs. We say that $W(L)$ and $W(L')$ are $S.P^+$-**diffeomorphic** if there exists diffeomorphism germ $\Phi : (\mathbb{R}^n \times \mathbb{R}, \pi(p_0)) \rightarrow (\mathbb{R}^n \times \mathbb{R}, \pi(p'_0))$ of the form $\Phi(x, t) = (\phi_1(x), t + \alpha(x))$ such that $\Phi(W(L)) = W(L')$. By Proposition B.8, we have the following proposition.

**Proposition B.9** Let $i : (L, p_0) \subset (PT^*(\mathbb{R}^n \times \mathbb{R}), p_0)$ and $i' : (L', p_0') \subset (PT^*(\mathbb{R}^n \times \mathbb{R}), p_0')$ be big Legendrian submanifold germs such that regular sets of $\pi \circ i, \pi \circ i'$ are dense respectively. Then $i$ and $i'$ are $S.P^+$-Legendrian equivalent if and only if $(W(L), \pi(p_0))$ and $(W(L'), \pi(p'_0))$ are $S.P^+$-**diffeomorphic**.

## Appendix C  Graphlike Legendrian unfoldings

In this appendix, we consider a special class of Legendrian submanifolds in $J^1(\mathbb{R}^n, \mathbb{R}) \subset PT^*(\mathbb{R}^n \times \mathbb{R})$. We say that a Legendrian submanifold $i : L \subset J^1(\mathbb{R}^n, \mathbb{R})$ is a **graphlike Legendrian unfolding** if $\pi_2 \circ \pi \circ i$ is a submersion (i.e., time-nonsingular) at any point $p \in L$. The notion of graphlike legendrian unfoldings has been introduced by the first named author [9] in order to describe the perestroikas of wave fronts given as the level surfaces of the solution for the eikonal equation given by a general Hamiltonian function. Since $L$ is a Legendrian submanifold in $J^1(\mathbb{R}^n, \mathbb{R})$, it has a big generating family at least locally. In this case it has a special form as follows: Let $\mathcal{F} : (\mathbb{R}^k \times (\mathbb{R}^n \times \mathbb{R}), 0) \rightarrow (\mathbb{R}, 0)$ be a big Morse family of hypersurfaces. We say that $\mathcal{F}$ is a graphlike Morse family of hypersurfaces if $(\partial \mathcal{F}/\partial t)(0) \neq 0$. It is easy to show that the corresponding big Legendrian submanifold germ is a graphlike Legendrian unfolding. Of course all graphlike Legendrian unfolding germs can be constructed by the above way. In this case we say that $\mathcal{F}$ is a **graphlike generating family** of $\mathcal{L}_\mathcal{F}(\Sigma_*(\mathcal{F}))$. However, we can reduce more strict form of graphlike generating families. Let $\mathcal{F}$ be a graphlike Morse family of hypersurfaces. By the implicit function theorem, there exists a Morse family of functions $F : (\mathbb{R}^k \times \mathbb{R}^n, 0) \rightarrow (\mathbb{R}, 0)$ such that $(\mathcal{F}(q, x, t))_{(q, x, t)} = (F(q, x) - t)_{(q, x, t)}$. Therefore $F(q, x) - t$ is a graphlike generating family of $\mathcal{L}_\mathcal{F}(\Sigma_*(\mathcal{F}))$. In this case

$$\Sigma_*(\mathcal{F}) = \{(q, x, F(q, x)) \in (\mathbb{R}^k \times (\mathbb{R}^n \times \mathbb{R}), 0) \mid (q, x) \in C(F)\}$$

and

$$\mathcal{L}_\mathcal{F}(q, x, F(q, x)) = (L(F)(q, x), F(q, x)) \in J^1(\mathbb{R}^n, \mathbb{R}) \equiv T^*\mathbb{R}^n \times \mathbb{R}.$$  

Define a map $\mathcal{L}_\mathcal{F} : C(F) \rightarrow J^1(\mathbb{R}^n, \mathbb{R})$ by $\mathcal{L}_\mathcal{F}(q, x) = (q, x, F(q, x), (\partial F/\partial x)(q, x))$, then we have $\mathcal{L}_\mathcal{F}(C(F)) = \mathcal{L}_\mathcal{F}(\Sigma_*(\mathcal{F}))$. We call $W(\mathcal{L}_\mathcal{F}) = \pi(\mathcal{L}_\mathcal{F}(C(F)))$ the **wave fronts** of graphlike
Legendrian unfolding $\mathcal{L}_F$. We simply call $F$ a generating family of the graphlike Legendrian unfolding $\mathcal{L}_F$. For any Morse family of function $F$, we denote that $\mathcal{F}(q, x, t) = F(q, x) - t$. Since $\mathcal{F}(q, x, t)$ is a big Morse family, we can use all the definitions of equivalence relations given in Appendix B. Moreover we can translate the propositions and theorems into corresponding assertions in terms of graphlike Legendrian unfoldings. We denote that $\mathcal{F}(q, t) = f(q) - t$ for any $f \in \mathcal{M}_k$. Then we can represent the extended tangent space of $\mathcal{F} : (\mathbb{R}^k \times \mathbb{R}^n, 0) \rightarrow (\mathbb{R}, 0)$ relative to $S.P^+ - \mathcal{K}$ by

$$T_e(S.P^+ - \mathcal{K})(\mathcal{F}) = \left\{ \frac{\partial f}{\partial q_1}(q), \ldots, \frac{\partial f}{\partial q_k}(q), f(q) - t \right\}_{\mathcal{E}(q,t)} + \langle 1 \rangle_\mathbb{R}.$$

For a deformation $F : (\mathbb{R}^k \times \mathbb{R}^n, 0) \rightarrow (\mathbb{R}, 0)$ of $f$, $\mathcal{F}$ is $S.P^+ - \mathcal{K}$-versal deformation of $\mathcal{F}$ if and only if

$$\mathcal{E}(q,t) = T_e(S.P^+ - \mathcal{K})(\mathcal{F}) + \left\{ \frac{\partial F}{\partial x_1}|\mathbb{R}^k \times \{0\}, \ldots, \frac{\partial F}{\partial x_n}|\mathbb{R}^k \times \{0\} \right\}_{\mathbb{R}}.$$

Moreover, we have the following very important property as a consequence of the versality theorem[5].

**Theorem C.1** Let $F : (\mathbb{R}^k \times \mathbb{R}^n, 0) \rightarrow (\mathbb{R}, 0)$ and $G : (\mathbb{R}^{k'} \times \mathbb{R}^n, 0) \rightarrow (\mathbb{R}, 0)$ be Morse families of functions. Then

1. $\mathcal{L}_F$ and $\mathcal{L}_G$ are $S.P^+ - \text{Legendrian}$ equivalent if and only if $\mathcal{F}$ and $\mathcal{G}$ are stably $x$-$S.P^+ - \mathcal{K}$-equivalent.
2. $\mathcal{L}_F$ is $S.P^+ - \text{Legendrian}$ stable if and only if $\mathcal{F}$ is an $S.P^+ - \mathcal{K}$-versal deformation of $f = F|\mathbb{R}^k \times \{0\}$.

By Proposition A.1, any Lagrangian submanifold germ in $T^*\mathbb{R}^n$ is given by $L(F)(C(F))$ for a Morse family of functions $F$. Let $F, G$ be Morse families of functions, then $L(F)(C(F))$ and $L(G)(C(G))$ are Lagrangian equivalent if and only if $F$ and $G$ are stably $P-\mathcal{R}^+$-equivalent (cf. Theorem A.2). By definition, if $F$ and $G$ are stably $P-\mathcal{R}^+$-equivalent, then $\mathcal{F}$ and $\mathcal{G}$ are stably $x$-$S.P^+ - \mathcal{K}$-equivalent. Therefore we have the following proposition.

**Proposition C.2** If $L(F)(C(F))$ and $L(G)(C(G))$ are Lagrangian equivalent, then $\mathcal{L}_F(C(F))$ and $\mathcal{L}_G(C(G))$ are $S.P^+ - \text{Legendrian}$ equivalent.

**Remarks** The above proposition asserts that the Lagrangian equivalence is stronger equivalence relation than the $S.P^+ - \text{Legendrian}$ equivalence. The $S.P^+ - \text{Legendrian}$ equivalence relation among graphlike Legendrian unfoldings preserves both the diffeomorphism types of bifurcations for families of small fronts and caustics. On the other hand, if we observe the real caustics of rays, we cannot observe the structure of wave front propagations. In this sense, there are hidden structure behind the picture of real caustics (cf. Appendix B). By the above proposition, the Lagrangian equivalence preserve not only the diffeomorphism type of caustics but also the hidden geometric structure of wave front propagations.

Moreover, suppose that $\mathcal{F}$ is a $S.P^+ - \mathcal{K}$-versal deformation of $\mathcal{F}$. By definition, we have

$$\mathcal{E}(q,t) = T_e(S.P^+ - \mathcal{K})(\mathcal{F}) + \left\{ \frac{\partial F}{\partial x_1}|\mathbb{R}^k \times \{0\}, \ldots, \frac{\partial F}{\partial x_n}|\mathbb{R}^k \times \{0\} \right\}_{\mathbb{R}}.$$
Let \(i: (\mathbb{R}^k, 0) \longrightarrow (\mathbb{R}^k \times \mathbb{R}, 0)\) be the canonical inclusion (i.e., \(i(q) = (q, 0)\)). Then we have the canonical projection
\[
i^*: \mathcal{E}_{(q,t)} \longrightarrow \mathcal{E}_q; \quad i^*(h) = h \circ i.
\]
It is easy to show that
\[
i^*(T_c(S.P^+.-\mathcal{K})(\overline{f})) = J_f + \langle 1 \rangle_{\mathbb{R}},
\]
so that we have
\[
\mathcal{E}_q = J_f + \left\langle \frac{\partial F}{\partial x_1}|\mathbb{R}^k \times \{0\}, \ldots, \frac{\partial F}{\partial x_n}|\mathbb{R}^k \times \{0\} \right\rangle_{\mathbb{R}} + \langle 1 \rangle_{\mathbb{R}}.
\]
By Theorems A.2 and C.1, we have the following proposition.

**Proposition C.3** Let \(F: (\mathbb{R}^k \times \mathbb{R}^n, 0) \longrightarrow (\mathbb{R}, 0)\) be a Morse family of functions. If \(L_F\) is \(S.P^+.-\text{Legendrian stable}\), then \(L(F)\) is Lagrangian stable.

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