Expansion of Co-Compact Convex Spacelike Hypersurfaces in Minkowski Space by Their Curvature

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Abstract. We consider the expansion of co-compact convex hypersurfaces in Minkowski space by functions of their curvatures, and prove under quite general conditions that solutions are asymptotic to the self-similar expanding hyperboloid. In particular this implies a convergence result for a class of special solution of the cross-curvature flow of negatively curved Riemannian metrics on three-manifolds.

1. Introduction

There is a great deal of literature concerning the evolution of hypersurfaces by geometric heat equations in Euclidean space, particularly concerning evolution by mean curvature [Hu1, Hu2, W2, W3, HS1, HS2, HS3, SW, A7, CM, W1] but also including many other evolution equations in which the speed is a nonlinear function of the principal curvatures [T, C, Ge1, U, A1, A3, A4, HI, A5, AMZ, ALM]. There is an analogous situation for spacelike hypersurfaces in Minkowski space, and in particular the evolution of spacelike hypersurfaces by mean curvature flow has received considerable attention (see for example [E1, E2, E3]). See also [Ge2, Ge3, Ge4] where spacelike hypersurfaces are deformed by inverse mean curvature flows in more general Lorenzian background spaces.

In this paper we are interested in the evolution of convex spacelike hypersurfaces by nonlinear functions of the principal curvatures. We restrict our attention to the situation of co-compact hypersurfaces, where the hypersurface is invariant under a discrete group of ambient isometries, and the quotient with respect to this group is compact. This is a rather special situation, which excludes many difficult cases studied in previous work on the mean curvature flow (see [E3] for example). In particular such hypersurfaces are always comparable to a hyperboloid at infinity. Our motivation to understand this case arises in part from an interesting relation between these evolution equations for hypersurfaces and the cross-curvature flow, which is a fully nonlinear parabolic evolution equation for negatively curved metrics on compact three-manifolds introduced by Chow and Hamilton [CH]. Our results on evolving spacelike hypersurfaces (specifically, where the hypersurface is of dimension three and the speed in the direction of the unit normal vector ν is equal to the Gauss curvature K) amount to analysis of an interesting class of special solutions for the cross-curvature flow. Rather little is known about solutions of the cross curvature flow in general (see [B, MC, KY, DKY, Gl, CNSC, CSC]). We discuss the relation between Gauss curvature flow and cross curvature flow in Section 11.

The flows we consider are as follows: Denote the first fundamental form of an embedding X by g, and the second fundamental form by h. We consider functions F(h, g) of the form

Key words and phrases. Spacelike hypersurface, Curvature flow, Cross curvature flow.

The research of the first and fourth authors was partly supported by Discovery Projects grant DP120100097 of the Australian Research Council. The research of the second author was partly supported by National Natural Science Foundation of China under grants 11271132, 11071212 and 11131007. The authors are grateful for the hospitality of the Mathematical Sciences Center of Tsinghua University where some of the research was carried out.
$F = f(\kappa_1, \ldots, \kappa_n)$, where $\kappa_i$ is the $i$th principal curvature (that is, the $i$th eigenvalue of $h$ with respect to $g$), and $F$ is a smooth symmetric function defined on the positive cone $\Gamma_+ = \{(x_1, \ldots, x_n) : \min_i x_i > 0\}$, which is increasing in each argument and homogeneous of degree one. We define the ‘dual’ function $F_*$ by $F_*(A, g) = F(g, A)^{-1}$ for $A$ positive definite, which means that $F_*(\tau, \tilde{g}) = f_*(\tau_1, \ldots, \tau_n)$ where $\tau_1, \ldots, \tau_n$ are the eigenvalues of the matrix $\tau$ with respect to the inner product $\tilde{g}$, and $f_*(x_1, \ldots, x_n) = f(x_1^{-1}, \ldots, x_n^{-1})^{-1}$.

Our primary result is the following:

**Theorem 1.** Let $S = F(h, g)^{\alpha}$ where $F = f(\kappa_1, \ldots, \kappa_n) = \frac{1}{f_*(\kappa_1, \ldots, \kappa_n)}$, and suppose that either

1. $0 < \alpha \leq 1$, $f$ is concave, and $f = 0$ on the boundary of $\Gamma_+$;
2. $0 < \alpha \leq 1$ and both $f$ and $f_*$ are concave;
3. $0 < \alpha \leq 1$, $f_*$ is concave and $f_* = 0$ on the boundary of $\Gamma_+$;
4. $0 < \alpha \leq 1$ and $n = 2$; or
5. $\alpha > 1$, $f_*$ is concave and zero on the boundary of the positive cone, and $\kappa_i > \kappa_j$ implies $\frac{\partial f_*}{\partial \kappa_i} \geq \frac{\partial f_*}{\partial \kappa_j}$.

Then for any co-compact spacelike uniformly locally convex initial embedding $X_0 : \tilde{M} \to \mathbb{R}^{n,1}$, there exists a unique co-compact solution $X : \tilde{M} \times [0, \infty) \to \mathbb{R}^{n,1}$ of the flow

$$\frac{\partial X}{\partial t} = S
\nu.$$  
(1)

The rescaled embeddings given by $\tilde{X}(p, t) = \frac{X(p, t)}{(1 + t)^{\frac{1}{n-1}}}$ converge in $C^\infty$ to a limiting embedding with image equal to the future timelike hyperboloid $\mathbb{H}^n$.

The condition in case 5 is unusual, but includes several cases of interest, including $f = E_k^\frac{1}{n}$ for $k = 1, \ldots, n$ (see section 10 for details). In particular the application to the cross curvature flow involves the Gauss curvature flow, which is contained in case 5 with $\alpha = n$ and $f = E_1^{1/n}$, in which case $f_*\tau_i = f_1\tau_j$ for all $i$ and $j$.

Theorem 1 is in some regards less difficult to prove than the corresponding results for Euclidean hypersurfaces (see for example [AMZ]), although each case requires slightly different treatment, and the estimation of principal curvatures in cases 2, 3 and especially 5 is very delicate. The results are somewhat stronger than those known in the Euclidean setting: For example, speeds given by powers of ratios of elementary symmetric functions of principal curvatures $S = (E_k/E_l)^{\alpha/(k-\ell)}$, $0 \leq \ell < k \leq n$, are contained in case 2 for $\alpha \leq 1$ and in case 5 for $\alpha > 1$ if $\ell = 0$. In the Euclidean setting, it was shown in [AMZ] that such flows are definitely not well-behaved in the Euclidean setting (in the sense that smooth solutions can develop curvature singularities before they shrink to a point) unless either $\alpha = 1$ or $\ell = 0$, and the results for $\ell = 0$ are established only for $\alpha = 1$ except in a few special cases. The examples given in [AMZ] can be modified to show that the assumptions of Theorem 1 are close to optimal: For example, the condition that $F_*$ must be zero on the boundary of the positive cone for $\alpha > 1$ is essentially necessary, and for $\alpha \leq 1$ at least the restriction of $F$ to a boundary face of the positive cone must be inverse-concave. It is not clear whether the extra condition in case 5 can be removed, but an inspection of the proof shows that it can certainly be weakened.

One reason for the comparative simplicity of the evolution of spacelike hypersurfaces is the fact that the self-similar expanding hyperboloids become comparable to each other for large times, in contrast to the situation for contracting Euclidean spheres.

We have not included in Theorem 1 some cases which are somewhat more general but require considerable work to prove, such as cases where $f_*$ may not be concave, but the restriction of $f$ to a boundary face of $\Gamma_+$ is inverse-concave. The proofs and statements of these cases are analogous to those in the Euclidean case proved in [AMZ] Theorems 4–7].
2. Spacelike Hypersurfaces

We consider the Minkowski space $\mathbb{R}^{n,1}$, which is the vector space $\mathbb{R}^{n+1}$ equipped with the Minkowski inner product $x \cdot y = -x_0y_0 + \sum_{i=1}^{n} x_iy_i$. A vector $v$ in $\mathbb{R}^{n,1}$ is called spacelike, timelike or null if the 'length' $v \cdot v$ is positive, negative or zero. A timelike vector is called future timelike if it has positive first component, and past timelike if the first component is negative.

The hyperbolic space $\mathbb{H}^n$ embeds naturally into $\mathbb{R}^{n,1}$ as the future timelike unit sphere, i.e. $\mathbb{H}^n = \{ x : x \cdot x = -1, \ x_0 > 0 \}$.

2.1. Computations on the hypersurface. We consider complete hypersurfaces described by embeddings $X : \mathbb{M} \rightarrow \mathbb{R}^{n,1}$. The embedding is assumed to be spacelike, so the induced inner product $g(u,v) = X_*(u) \cdot X_*(v)$ is positive definite at each point. In this case we can associate to each point $x \in \mathbb{M}$ a unique future timelike normal vector $\nu \in \mathbb{H}$.

We briefly describe the local differential geometry of spacelike hypersurfaces, indicating in particular where differences occur with the Euclidean setting. We define the second fundamental form $h \in \text{Sym}_2(TM)$ by the following formula: For any tangent vector fields $U$ and $V$ on $\mathbb{M}$,

$$U(X,V) = h(U,V)\nu + X_*(\nabla_U V).$$

Here as in the Euclidean case $\nabla$ is the Levi-Civita connection of the metric $g$. Similarly we define the Weingarten map as the derivative of the normal: Since $\nu \cdot \nu = -1$, we have $\nu \cdot X_*(U) = 0$ for any vector $U$, so that $\nu_*(U)$ is entirely tangential to $X(\mathbb{M})$ and we can write

$$\nu_*(U) = X_*(A(U))$$

where $A \in \text{End}(TM)$ is the Weingarten map. Differentiating the identity $X_*(U) \cdot \nu = 0$ yields a relation between $A$ and $h$ (the Weingarten relation):

$$0 = V(X_*(U)) \cdot \nu + X_*(U) \cdot \nu_*(V) = -h(U,V) + X_*(U) \cdot X_*(-A(V)) = -h(U,V) + g(U,A(V)).$$

The second fundamental form satisfies the Codazzi identity $\nabla_ih_{jk} = \nabla_jh_{ik}$ as in the Euclidean case. However a crucial difference arises in the Gauss equations relating the intrinsic curvature of the metric $g$ to the second fundamental form: We have

$$R_{ijkl} = h_{jk}h_{il} - h_{ik}h_{jl},$$

which differs from the Euclidean Gauss equation in the sign of the right hand side.

2.2. Computation using support functions. The support function machinery for convex bodies is very convenient for dealing with evolution of convex hypersurfaces in Euclidean space. Similarly there is a support function formalism for spacelike convex hypersurfaces in Minkowski space, which we now describe: Given a convex hypersurface $X(\mathbb{M})$ the support function $u : \mathbb{H}^n \rightarrow \mathbb{R}$ is defined by $u(z) = \inf \{ -z \cdot p : p \in X(\mathbb{M}) \}$. In particular for a co-compact uniformly convex hypersurface (see section 3 below), $z$ is well-defined on all of $\mathbb{H}^n$, and the hypersurface can be reconstructed from $u$ by the following embedding:

$$\tilde{X} = uz - z_*(\nabla u),$$

where $\nabla$ is the Levi-Civita connection of the standard (induced hyperbolic) metric on $\mathbb{H}^n$. The principal curvatures $\kappa_1, \ldots, \kappa_n$ of $X(\mathbb{M})$ (defined as the eigenvalues of the second fundamental form $h$ with respect to the induced metric $g$) can then be computed as the reciprocals of the eigenvalues $r_1, \ldots, r_n$ of the positive definite bilinear form $\tau_{ij} = u\delta_{ij} - \nabla_i \nabla_j u$ (since the map $X$ is the inverse of the Weingarten map and we have $\partial_i X = \tau_{ik} \delta^{kl} \partial_l z$). We accordingly refer to $r_1, \ldots, r_n$ as the principal radii of curvature. As in the Euclidean case the matrix $\tau$ satisfies a Codazzi-type identity: $\nabla_i \tau_{jk} = \nabla_j \tau_{ik}$. 

3. Cocompactness

We will further assume that there is a subgroup $G$ of the group $\text{Isom}_+(\mathbb{R}^{n,1})$ of future-preserving isometries of $\mathbb{R}^{n,1}$ such that for each $T \in G$, $T(X(M)) = X(M)$, and $G$ acts properly discontinuously on $\tilde{M}$. $G$ is then the fundamental group of the quotient $M = \tilde{M}/G$, and acts by isometries on $M$ with the induced metric $g$. We assume that the quotient $M$ is compact.

The tensors $g$, $h$ and $A$ are well-defined on $M$: If $T \in G$ then $T_\ast$ is an isometry from $T_\ast \tilde{M}$ to $T_{T(x)}M$, and $\nu_{T_\ast} = T_\ast(\nu_x)$ for any $x \in \tilde{M}$. It follows that $h_{T_\ast}(T,U,T,V) = h(U,V)$ and $T_\ast(A_2(U)) = A_2(T_\ast(U))$.

3.1. The linear representation. The future-preserving isometries $\text{Isom}_+(\mathbb{R}^{n,1})$ of $\mathbb{R}^{n,1}$ have the form $z \mapsto Lz + b$, where $b \in \mathbb{R}^{n,1}$ and $L$ is a linear transformation in $O_+(n,1)$, the space of future-preserving linear transformations preserving the Lorentzian inner product. Thus the inclusion of $G$ in $\text{Isom}_+(\mathbb{R}^{n,1})$ can be written in the form

$$g(z) = L(g)z + b(g),$$

and we have

$$L(g_2g_1)z + b(g_2g_1) = g_2g_1(L(g_2)(g_1z)) + b(g_2) + L(g_2)L(g_1)z + L(g_2)b(g_1) + b(g_2)$$

for all $z \in \mathbb{R}^{n,1}$ and $g_1, g_2 \in G$. In particular the linear part of this inequality implies that the map $L : G \to O_+(n,1)$ is itself a representation. We call this the linear representation of $G$.

3.2. The support function and standard cocompact hypersurfaces. If $\tilde{M}$ is such that the inclusion of $G$ in $\text{Isom}_+(\mathbb{R}^{n,1})$ is contained in the linear part $O_+(n,1)$ for some choice of origin — that is, $b(g) = 0$ for all $g \in G$ in equation (7) — we say that the hypersurface is standard. The standard hypersurfaces are somewhat easier to work with: In particular the support function $u$ is then well defined on the quotient $H/L(G)$, since in this case we have

$$u(L(g)z) = \inf\{-L(g)z \cdot p : p \in X(\tilde{M})\} = \inf\{-L(g)z \cdot L(g)p : p \in X(\tilde{M})\} = \inf\{-z \cdot p : p \in X(\tilde{M})\} = u(z),$$

for each $g \in G$, since $L(g)p$ ranges over $X(\tilde{M})$ when $p$ does. In the non-standard case the support function is defined on $\tilde{M}$ but not on $M$: The support function is $O_+(n,1)$ invariant but not $\text{Isom}_+(\mathbb{R}^{n,1})$ invariant. In particular, maximum principle arguments involving the support function in the general case must take into account the behaviour at infinity.

4. Evolution equations

4.1. Evolution equations on the hypersurface. We follow the notational conventions of [AMZ], in particular using the following expressions for the speed $S$: We write $S(h,g) = S(A) = F(A)^0$, where $F$ is homogeneous of degree 1, smooth, invariant under change of basis and strictly increasing on the positive cone: $\frac{\partial}{\partial s} F(A + sB) > 0$ whenever $B$ is nonzero and positive semidefinite. We denote by $F^{ij}$ the derivative of $F$ with respect to the components of $A$, so that $\frac{\partial}{\partial s} F(A + sB) = F^{ij} B_{ij}$. $F$ can be expressed in the form $F = f(\kappa_1, \ldots, \kappa_n)$ where $f$ is a smooth symmetric function on $\mathbb{R}^n$ which is increasing in each argument and homogeneous of degree one. We denote $\hat{f}^i = \frac{\partial f}{\partial \kappa_i}$. In an orthonormal frame of eigenvectors for $A$, the matrix $\hat{F}$ is also diagonal, with diagonal entries equal to $\hat{f}^i$ (see [AS, Theorem 5.1]). Similarly we denote by $\hat{F}$ the second derivatives of $F$ with respect to components of $A$, and by $\hat{f}$ the second derivatives of $f$ with respect to the principal curvatures.
Evolution equations for geometric quantities on the hypersurface can be deduced following the corresponding arguments from the Euclidean case: The evolution of the induced metric $g$ is computed as follows:

$$
\frac{\partial}{\partial t} g_{ij} = \frac{\partial}{\partial t} \left( \frac{\partial X}{\partial x^i} \cdot \frac{\partial X}{\partial x^j} \right) = \frac{\partial}{\partial x^k} (S\nu) \cdot \frac{\partial X}{\partial x^i} + \frac{\partial X}{\partial x^k} \cdot \frac{\partial}{\partial x^i} (S\nu) = SA^k g_{kj} + Sg_{ik} A^k_j = 2S h_{ij}.
$$

(8)

The evolution of the unit normal is as follows: We have $0 = \frac{\partial \nu}{\partial t} \cdot \nu$, and

$$
\left( \frac{\partial}{\partial t} \nu \right) \cdot \frac{\partial X}{\partial x^i} = \frac{\partial}{\partial t} \left( \nu \cdot \frac{\partial X}{\partial x^i} \right) = -\nu \cdot \frac{\partial S}{\partial x^i} + SA^j_i \frac{\partial X}{\partial x^j} = \frac{\partial S}{\partial x^i}.\]

(9)

The evolution of the second fundamental form is as follows:

$$
\frac{\partial}{\partial t} h_{ij} = \frac{\partial}{\partial t} \left( \frac{\partial \nu}{\partial x^i} \cdot \frac{\partial X}{\partial x^j} \right) = \frac{\partial}{\partial x^k} \left( \frac{\partial S}{\partial x^i} \frac{\partial X}{\partial x^j} \right) \cdot \frac{\partial X}{\partial x^k} + \frac{\partial \nu}{\partial x^i} \cdot \frac{\partial S}{\partial x^j} = \nabla_i \nabla_j S + SA^p_i A^q_j g_{pq}.
$$

(10)

Introducing the canonical spacetime connection (as in [AH, Section 6.3] or [AB, Section 2.3]) by setting $\nabla_t \partial_i = Sh^p_i \partial_p$, this then becomes

$$
\nabla_t h_{ij} = \partial_t h_{ij} - h(\nabla_t \partial_i, \partial_j) - h(\partial_i, \nabla_t \partial_j) = \nabla_i \nabla_j S - Sh^p_i h_{pj}.
$$

(11)

An evolution equation for the speed follows: Since $\nabla_t g_{ij} = 0$,

$$
\frac{\partial}{\partial t} S(h, g) = \dot{S}^{ij} \nabla_i \nabla_j S - \dot{S} S(h^2).
$$

(12)

Equation (11) may be converted to the form of a parabolic equation using a version of Simons’ identity obtained by applying the Codazzi and Gauss identities:

$$
\nabla_i \nabla_j h_{kl} = \nabla_i \nabla_k h_{jl} = \nabla_k \nabla_l h_{ij} + R_{ikl}^p h_{pl} + R_{ik}^p h_{lp} + \nabla_k \nabla_l h_{ij} + h_{jk} h^p_i h_{pl} - h_{ij} h^p_k h_{lp} + h_{kl} h^p_i h_{jp} - h_{il} h^p_k h_{jp}.
$$

Symmetrising in $(i,j)$ and in $(k,l)$ gives the required identity:

$$
\nabla_i \nabla_j h_{kl} = \nabla_k \nabla_l \nabla_{ij} h_{kl} = \nabla_k \nabla_l \nabla_{ij} h_{kl} = \nabla_{ij} \nabla_k \nabla_l h_{kl} = \nabla_{ij} \nabla_k \nabla_l h_{kl} + \nabla_k \nabla_l h_{ij} h_{kl} + h_{kj} h^p_i h_{lp} + h_{kj} h^p_l h_{ip}.
$$

(13)
This is very similar to the corresponding Euclidean identity, but with the signs of the curvature terms reversed. Substituting this in the evolution equation \(10\) gives the following:

\[
\nabla_t h_{ij} = \dot{S}^{ij} \nabla_i \nabla_j h_{kl} + \ddot{S}(\nabla_i h, \nabla_j h) - Sh_i^h h_{pj} \\
= \dot{S}^{ij} (\nabla_k \nabla_i h_{ij} - h_i^h h_{kp} + h_k h_i^h h_{j}p) + \ddot{S}(\nabla_i h, \nabla_j h) - Sh_i^h h_{pj}
\]

(14)

This may also be written in the following form since \(S = F^\alpha\):

\[
\nabla_t h_{ij} = \alpha F^{\alpha-1} \dot{F}^{kl} \nabla_k \nabla_i h_{ij} + \alpha F^{\alpha-1} \ddot{F}(\nabla_i h, \nabla_j h) + \alpha(\alpha - 1) F^{\alpha-2} \nabla_i F \nabla_j F
\]

(15)

\(\alpha(\alpha - 1) F^{\alpha-2} \ddot{F}(A^2) h_{ij}\),

In this case \(12\) takes the following form:

\[
\frac{\partial}{\partial t} F^{\alpha} = \alpha F^{\alpha-1} \dot{F}^{kl} \nabla_k \nabla_j F^{\alpha} - \alpha F^{2\alpha-1} \ddot{F}(h^2).
\]

The evolution equations \(15\) and \(16\) are identical to the Euclidean counterparts (see \(A\) \(M\) \(Z\) Lemma 9), except that all of the curvature terms have their sign reversed. Since \(h\) and \(g\) are well-defined on \(M\), equations \(14\)–\(16\) hold on \(M\) and not just on \(\bar{M}\).

### 4.2. Evolution equations in the Gauss map parametrisation

The evolution equation \(11\) yields an evolution equation for the support function \(u\) on \(\bar{M}\): Since \(u(z, t) = -X \circ \nu^{-1}(z) \cdot z\),

\[
\frac{\partial u}{\partial t} = \left( -\frac{\partial X}{\partial \nu^{-1}(z)} - X_s \left( \frac{\partial}{\partial t} \nu^{-1}(z) \right) \right) \cdot z = S|_{\nu^{-1}(z)} = s \left( \frac{1}{r_1}, \ldots, \frac{1}{r_n} \right).
\]

Here \(S = F_s(\tau)^{-\alpha}\), where \(F_s\) is the dual function of \(F\), defined by \(F_s(A) = F(A^{-1})^{-1}\). Equation \(17\) implies evolution equations for the speed and for the matrix \(r\):

\[
\frac{\partial}{\partial t} F^{-\alpha} = -\alpha F^{-(1+\alpha)} \dot{F}^{kl} \frac{\partial u}{\partial kl} - \nabla_k \nabla_l \frac{\partial u}{\partial kl}
\]

(18)

\(\alpha F^{-(1+\alpha)} \dot{F}^{kl} \nabla_k \nabla_l F^{-\alpha} - \alpha F^{-(1+2\alpha)} \dot{F}_{s}(g)\).

The evolution equation for \(r\) can be computed as follows: From the definition of \(r\),

\[
\frac{\partial}{\partial t} r_{ij} = \frac{\partial}{\partial t} \bar{g}_{ij} - \nabla_i \nabla_j \frac{\partial u}{\partial t}
\]

\(\alpha \nabla_i \left( F^{-(1+\alpha)} \nabla_j F_s \right) + F^{-(1+\alpha)} \bar{g}_{ij}
\]

\(\alpha F^{-(1+\alpha)} \nabla_i \nabla_j \frac{\partial u}{\partial kl} + \alpha F^{-(1+\alpha)} \dot{F}^{kl} \nabla_i \nabla_j \frac{\partial u}{\partial kl} - \alpha(1 + \alpha) F^{-(2+\alpha)} \nabla_i \nabla_j F_s + F^{-(1+\alpha)} \dot{F}_{s}(g_{ij})
\]

\(= \alpha F^{-(1+\alpha)} \nabla_i \nabla_j \frac{\partial u}{\partial kl} + \alpha F^{-(1+\alpha)} \dot{F}^{kl} \nabla_i \nabla_j \frac{\partial u}{\partial kl} - \alpha(1 + \alpha) F^{-(2+\alpha)} \nabla_i \nabla_j F_s + F^{-(1+\alpha)} \dot{F}_{s}(g_{ij})
\]

A Simons-like identity holds:

\[
\nabla_i \nabla_j \tau_{kl} = \nabla_i \nabla_k \tau_{jl} = \nabla_k \nabla_i \tau_{jl} = \nabla_k \nabla_i \tau_{jl} \frac{\partial u}{\partial kl} + \bar{R}_{ikj} \frac{\partial u}{\partial kl} + \bar{R}_{ikl} \frac{\partial u}{\partial kl}
\]

On symmetrisation this becomes

\[
\nabla_i \nabla_j \tau_{kl} = \nabla_i \nabla_j \tau_{kl} \frac{\partial u}{\partial kl} + \bar{R}_{ikj} \frac{\partial u}{\partial kl} + \bar{R}_{ikl} \frac{\partial u}{\partial kl}
\]

(19)
This gives the following (noting that $\dot{F}(\tau) = F$):
\[
\frac{\partial}{\partial \tau} \tau_{ij} = \alpha F_*^{-1(\alpha + 1)} F_*^{kl} \nabla_h \nabla_i \tau_{kl} + \alpha F_*^{-1(\alpha + 1)} F_*^{kl,mn} \nabla_r \tau_{kl} \nabla_j \tau_{mn} \\
- \alpha (1 + \alpha) F_*^{-2(\alpha + 1)} \nabla_i F_* \nabla_j F_* + (1 - \alpha) F_*^{-\alpha} \dot{g}_{ij} + \alpha F_*^{-1(\alpha + 1)} F_* (\dot{g}) \tau_{ij}.
\]
Again these are the same as in the Euclidean case (see [AMZ, Lemma 10]), but with the signs of the curvature terms reversed.

In general, equation (17) holds on $\mathbb{H}^n$, but not on the quotient $\mathbb{H}^n/L(G)$ except in the standard case. However, equations (18)–(20) hold on the quotient since $\tau$ is invariant under isometries.

5. SHORT TIME EXISTENCE OF SOLUTIONS

Although the map $X$ is defined on the spatially non-compact space $\tilde{M} \times [0, T)$, we can use the co-compactness to produce a co-compact solution for a short time relatively easily (that is, without concern for the behaviour at infinity).

We will show that the evolving hypersurfaces can be written for a short time as normal graphs over the initial hypersurface, and that the graph function is defined on $M$ rather than $\tilde{M}$. Precisely, we will construct a solution $X : \tilde{M} \times [0, \delta) \rightarrow \mathbb{R}^{n+1}$ of the form
\[
X(\varphi(x, t), t) = X(x, 0) + u(\pi(x), t)v(x, t),
\]
for some $\delta > 0$, where $\pi : \tilde{M} \rightarrow M$ is the projection, $\varphi(\cdot, t)$ is a diffeomorphism of $\tilde{M}$ for each $t$ (commuting with the deck transformations on $\tilde{M}$ corresponding to the covering map $\pi$) and $u : M \times [0, \delta) \rightarrow \mathbb{R}$ is a smooth function. We will produce $u$ as the solution of a scalar parabolic equation on the compact manifold $M$.

The geometric invariants of a hypersurface given as a normal graph of the form (21) can be computed directly as follows: Writing $X_0 = X(\cdot, 0)$ for the initial embedding and $\partial^I_t = \frac{\partial}{\partial x^i} X_0$ for the initial coordinate tangent vectors in some local coordinates for $\tilde{M}$, the coordinate tangent vectors of the embedding $X^I(x) = X(\varphi(x, t), t)$ are given by
\[
\partial^I_t : = \frac{\partial}{\partial x^i} (X_0 + \tilde{u} \nu_0) \\
= (\delta^p_i + \tilde{u} (h^0)_{ij}^p) \partial^0_p + \nabla_i \tilde{u} \nu_0,
\]
where $h^0$ is the second fundamental form of $X_0$ and $\nu_0$ is the unit normal of $X_0$, and $\tilde{u} = u \circ \pi$.

From this the following expression for the unit normal $\nu^I$ of $X^I$ follows:
\[
\nu^I = \sigma^{-1} (\nu^0 + [(g^0 + \tilde{u} h^0)^{-1}]^{kl} \nabla_i \tilde{u} \partial^0_k),
\]
where
\[
\sigma = \sqrt{1 + g^0_{ip} [(I + \tilde{u} h^0)^{-1}]^{kl} [((I + \tilde{u} h^0)^{-1}]^{kl}_q [I + \tilde{u} h^0]^{kl}_q} \nabla_k \tilde{u} \nabla_i \tilde{u}.
\]

The induced metric is computed from (22):
\[
g^{IJ} = \partial^I \cdot \partial^J = (\delta^p_i + \tilde{u} (h^0)^p_i) (\delta^q_j + \tilde{u} (h^0)^q_j) g^{0}_{pq} - \nabla_i \tilde{u} \nabla_j \tilde{u}.
\]
The second fundamental form is given as follows:
\[
h^{IJ} = \nu^I \cdot \nabla^J \nu^0 \\
= \sigma^{-1} \{ \nabla^0_i \nabla_j \tilde{u} + \tilde{u} (h^0)^p_i (h^0)^p_j + (h^0)^{ij} \}
\[
- [(g^0 + \tilde{u} (h^0)^{-1}]^{lp} \nabla_r \tilde{u} \left( \nabla_i \tilde{u} h^0_{ip} + \nabla_i \tilde{u} h^0_{jp} + u \nabla^0_i h^0_{ij} \right) \}.
Differentiating equation (21) with respect to $t$ and taking the inner product with $\nu^0$, we obtain the following expression for the time derivative of $\tilde{u}$ if $X$ evolves according to (1):

$$\frac{\partial \tilde{u}}{\partial t} = \frac{\partial X}{\partial t} \cdot \nu^0 = \sigma S \langle h^1, g^1 \rangle,$$

where $g^1$ and $h^1$ are given in terms of $\tilde{u}$ by equations (25) and (26). In particular this has the form $\frac{\partial \tilde{u}}{\partial t} = S[\nabla^0 \nabla \tilde{u}, \nabla u, u, x]$, where $S$ is smooth and strictly monotone in the first argument, so this is a scalar fully nonlinear parabolic equation for $\tilde{u}$. Furthermore, the equation is invariant under the deck transformations on $\tilde{M}$, and so is well-defined as an equation on $M$. We define $\tilde{u}(x, t) = u(\pi(x), t)$, where $u$ is the solution of the corresponding equation on the compact manifold $M$. We leave it to the reader to check that one can solve for the diffeomorphisms $\varphi(., t)$ to produce from this a co-compact solution of the original equation (1).

6. Estimates on support function and speed in the standard case

6.1. Upper and lower bounds on the support function. From the evolution equation (17) we have the following: Let $\tilde{u}(t) = \left(u_0^{1+\alpha} + (1 + \alpha)t\right)^{\frac{1}{1+\alpha}}$. Then $\frac{\partial}{\partial t} \tilde{u}(t) = \tilde{u}(t)^{-\alpha}$, so we can write

$$\frac{\partial}{\partial t} (u - \tilde{u}) = F_*\left(t\right)^{-\alpha} - \tilde{u}^{-\alpha} = F_*\left(t\right)^{-\alpha} - F_*\left(\tilde{u}g\right)^{-\alpha} = a^{kl} \left(\nabla_k \nabla_l (u - \tilde{u}) - \bar{g}_{kl}(u - \tilde{u})\right),$$

where $a^{kl} = \int_0^1 F_*^{-(1+\alpha)} \hat{F}^{kl}\left(\alpha s + \tilde{u}g\right) ds$ is positive definite since $F_*$ is increasing. It follows by the maximum principles that positivity or negativity of $u - \tilde{u}$ are preserved. If $u_- \leq u(x, 0) \leq u_+$ for all $x \in M$ then

$$\left(u_0^{1+\alpha} + (1 + \alpha)t\right)^{\frac{1}{1+\alpha}} \leq u(x, t) \leq \left(u_0^{1+\alpha} + (1 + \alpha)t\right)^{\frac{1}{1+\alpha}}.$$

In particular this implies that $u((1 + \alpha)t)^{\frac{1}{1+\alpha}}$ converges uniformly to 1 as $t \to \infty$ (if the solution exists for all time).

6.2. Upper and lower bounds on the speed. In this situation there are upper and lower bounds on the speed which hold in great generality. It is useful to first rewrite the evolution for $u$ as follows:

$$\frac{\partial}{\partial t} u = \alpha F_*^{-(1+\alpha)} \hat{F}_*^{kl} \nabla_k \nabla_l u - \alpha F_*^{-(1+\alpha)} \hat{F}_*\left(\bar{g}\right)u + (1 + \alpha)F_*^{-\alpha}.$$

The latter equation together with equation (18) yield an evolution equation for $uF^\alpha$:

$$\frac{\partial}{\partial t} (uF^\alpha) = \alpha F_*^{-(1+\alpha)} \hat{F}_*^{kl} \nabla_k \nabla_l (uF^\alpha) - 2\alpha^2 F_*^{-(2+\alpha)} \hat{F}_*^{kl} \nabla_k \nabla_l (uF^\alpha) + (1 + \alpha).$$

Thus upper and lower bounds on $uF^\alpha - (1 + \alpha)t$ are preserved. Let $c_- = \inf_{M \times \{0\}} (uF^\alpha)$ and $c_+ = \sup_{M \times \{0\}} (uF^\alpha)$. Then for any $t > 0$ in the interval of existence,

$$c_- + (1 + \alpha)t \leq uF^\alpha(x, t) \leq c_+ + (1 + \alpha)t,$$

for all $x \in M$. When combined with (28), this gives strong upper and lower bounds on $F_*$, which imply in particular that $F_*(1 + \alpha)t^{\frac{1}{1+\alpha}}$ converges uniformly to 1 as $t \to \infty$ (again assuming long time existence).
Lemma 2. There exist \( r > 0 \) and \( R > 0 \) such that for any \( z_0 \in \mathbb{H}^n \), there exist \( p_-(z_0) \) and \( p_+(z_0) \) such that for every \( z \in \mathbb{H}^n \),

\[
-p_-(z_0) \cdot z + R \leq u(z,0) \leq -p_+(z_0) \cdot z + r,
\]

with equality holding throughout when \( z = z_0 \).

Proof. By compactness of \( M \), there exist \( 0 < r \leq R \) such that \( \frac{|v|^2}{R} \leq h(v,v) \leq \frac{|v|^2}{r} \) for all \( v \neq 0 \) in \( TM \) (equivalently \( r \bar{g}(v,v) \leq g(v,v) \leq r \bar{g}(v,v) \) for all \( v \in TM \)). Given \( z_0 \in \mathbb{H}^n \), choose \( p_+(z_0) = \bar{X}(z_0,0) - rz_0 \) and \( p_-(z_0) = \bar{X}(z_0,0) - Rz_0 \). Let \( u_+(z) = u(z,0) + p_+(z_0) \cdot z - r \) and \( u_-(z) = u(z,0) + p_-(z_0) \cdot z - R \). Then

\[
u_+(z) = \bar{X}(z,0) \cdot z + (\bar{X}(z_0,0) - rz_0) \cdot z - r = (\bar{X}(z_0,0) - \bar{X}(z_0,0) + r(z-z_0)) \cdot z.
\]

In particular \( u_+(z_0) = 0 \) and \( \partial_t u_+|_{z_0} = 0 \), and \( \tau_{ij}[u_+] = \tau_{ij}[u] - r \bar{g}_{ij} \geq 0 \). Thus along any geodesic \( \gamma \) from \( z_0 \) in \( \mathbb{H}^n \),

\[
\frac{d}{ds} \left( \cosh^2 s \frac{d}{ds} \left( \frac{u}{\cosh(s)} \right) \right) = -\frac{u}{r} \gamma', \gamma' \cosh(s) \leq 0,
\]

from which it follows that \( u_+ \leq 0 \) everywhere. Similarly \( u_- \geq 0 \), as required.

Corollary 3. With \( r, R, p_-(z_0), \) and \( p_+(z_0) \) as in Lemma 2, for every \( z \in \mathbb{H}^n \) and every \( t \in [0,T) \)

\[
-p_-(z_0) \cdot z + (R^{1+\alpha} + (1 + \alpha)t) \frac{1}{r} \leq u(z,t) \leq -p_+(z_0) \cdot z + (R^{1+\alpha} + (1 + \alpha)t) \frac{1}{r}.
\]

Proof. The proof uses the maximum principle, but some care is required to control the behaviour near infinity. For any \( \varepsilon > 0 \) and fixed \( z_0 \in \mathbb{H}^n \), let \( v_\varepsilon(z,t) = u(z,t) + p_-(z_0) \cdot z - \varepsilon z \cdot z_0 \). Then \( v_\varepsilon(z,0) \geq R \) for all \( z \) and \( v_\varepsilon(z,0) \geq -\varepsilon z \cdot z_0 \rightarrow \infty \) as \( z \rightarrow \infty \) in \( \mathbb{H}^n \). Also, for each \( \varepsilon > 0 \),

\[
\frac{\partial}{\partial t} v_\varepsilon = F_* (\varepsilon |v_\varepsilon|)^{-\alpha}.
\]

In particular while the solution remains smooth, \( \frac{\partial}{\partial t} v_\varepsilon \) is bounded, and so \( v_\varepsilon(z,t) \rightarrow \infty \) as \( z \rightarrow \infty \) in \( \mathbb{H}^n \) for each \( t \) in the interval of existence. It follows that \( v_\varepsilon(.,t) \) attains an interior minimum, and the maximum principle implies

\[
v_\varepsilon \geq (R^{1+\alpha} + (1 + \alpha)t) \frac{1}{r}.
\]

Taking \( \varepsilon \rightarrow 0 \) gives the desired lower bound on \( u(z,t) \). The proof of the upper bound is similar.

The speed bounds can now be proved using an identity related to one employed for mean curvature flow by Smoczyk [5] (see also [AMZ, Theorem 14]):

Proposition 4. If \( u(z,0) + p : z \geq 0 \) for all \( z \in \mathbb{H}^n \), then \( u(z,t) - (1 + \alpha) F_* (z,t)^{-\alpha} + p : z \geq 0 \) for all \( z \in \mathbb{H}^n \) and \( t \geq 0 \). If \( u(z,0) + p : z \leq 0 \) for all \( z \in \mathbb{H}^n \) then \( u(z,t) - (1 + \alpha) F_* (z,t)^{-\alpha} + p : z \leq 0 \) for all \( z \in \mathbb{H}^n \) and \( t \geq 0 \).

Proof. If \( w = u + p : z - (1 + \alpha) F_*^{-\alpha} \) (for any \( p \)) then

\[
\frac{\partial}{\partial t} w = \alpha F_*^{-(1+\alpha)} F_*^{kt} (\nabla_k \nabla_l w - g_{kl} w).
\]

In the first case of the proposition, \( w(z,0) \geq 0 \) for all \( z \in \mathbb{H}^n \). Choose any fixed \( z_0 \in \mathbb{H}^n \) and let \( w_\varepsilon = w + \varepsilon z_0 \cdot z \) with \( \varepsilon > 0 \), so that \( w_\varepsilon > 0 \) and \( w_\varepsilon(z,0) \rightarrow \infty \) as \( z \rightarrow \infty \) in \( \mathbb{H}^n \). Since \( F_*^{-\alpha} \) is
bounded in the interval of existence (by compactness of \( M \), \( w_z(z, t) \to \infty \) as \( z \to \infty \) in \( \mathbb{H}^n \) for each \( t > 0 \) in the interval of existence. In particular, \( w_z \) attains an interior minumum, and the maximum principle applies to prove that this minimum remains non-negative. Thus \( w_z(z, t) \geq 0 \) for each \( \varepsilon > 0 \), and sending \( \varepsilon \) to zero yields \( w(z, t) \geq 0 \) for all \( z \in \mathbb{H}^n \) and all \( t \geq 0 \) in the interval of existence. The proof of the second case is similar.

\[ \text{Corollary 5. For every } z \in \mathbb{H}^n \text{ and every } t > 0 \text{ in the interval of existence of the solution,} \]

\[ \frac{(R^{1+\alpha} + (1 + \alpha)t)^{\frac{1}{1+\alpha}} - R}{(1 + \alpha)t} \leq F^\alpha_*(z, t) \leq \frac{(r^{1+\alpha} + (1 + \alpha)t)^{\frac{1}{1+\alpha}} + R - r}{(1 + \alpha)t}. \]

Proof. To prove the lower bound, fix \( z_0 \in \mathbb{H}^n \). By Lemma 2, there is a point \( p_+(z_0) \) such that \( u(z, 0) + p_+(z_0) \cdot z \leq \epsilon \) for all \( z \in \mathbb{H}^n \). Let \( p = p_+(z) - r z_0 \). Then \( u(z, 0) + p \cdot z = u(z, 0) + p_+(z_0) \cdot z - r z_0 \cdot z \leq r - r \cdot z_0 \leq 0 \), with equality holding for \( z = z_0 \). Hence Proposition 4 applies to give that \( u(z, t) + p \cdot z - (1 + \alpha)t F^\alpha_*(z, t) \leq 0 \) for each \( z \in \mathbb{H}^n \) and \( t > 0 \) in the interval of existence. Applying this for \( z = z_0 \) gives

\[ F^\alpha_*(z_0, t) \geq \frac{u(z_0, t) - u(z_0, 0)}{(1 + \alpha)t}. \]

Finally, Corollary 3 implies

\[ u(z_0, t) - u(z_0, 0) \geq \left( R^{1+\alpha} + (1 + \alpha)t \right)^{\frac{1}{1+\alpha}} - R. \]

It follows that

\[ F^\alpha_*(z_0, t) \geq \frac{(R^{1+\alpha} + (1 + \alpha)t)^{\frac{1}{1+\alpha}} - R}{(1 + \alpha)t} \]

as claimed.

The proof of the upper bound follows a similar pattern: Fixing \( z_0 \in \mathbb{H}^n \) as before, Lemma 2 implies the existence of \( p_-(z_0) \) such that \( u(z, 0) + p_-(z_0) \cdot z \geq R \), with equality for \( z = z_0 \). Proposition 4 implies that \( u(z, t) + p_-(z_0) \cdot z - (1 + \alpha)t F^\alpha_*(z, t) \geq 0 \) for all \( z \) and \( t \geq 0 \), so that \( F^\alpha_*(z, t) \leq \frac{u(z, 0) + p_-(z_0) \cdot z}{(1 + \alpha)t} \). Corollary 3 then gives \( u(z, t) + p_+(z_0) \cdot z \leq \left( r^{1+\alpha} + (1 + \alpha)t \right)^{\frac{1}{1+\alpha}} \). Also note that from Lemma 2, \( u(z_0, 0) + p_+(z_0) \cdot z_0 = r \) and \( u(z_0, 0) + p_-(z_0) \cdot z_0 = R \), and therefore \( (p_+(z_0) - p_-(z_0)) \cdot z_0 = R - r \). It follows that

\[ u(z_0, t) + p_-(z_0) \cdot z_0 = u(z_0, t) + p_+(z_0) \cdot z_0 + (p_-(z_0) - p_+(z_0)) \cdot z_0 \leq \left( r^{1+\alpha} + (1 + \alpha)t \right)^{\frac{1}{1+\alpha}} + R - r, \]

and hence

\[ F^\alpha_*(z_0, t) \leq \frac{(r^{1+\alpha} + (1 + \alpha)t)^{\frac{1}{1+\alpha}} + R - r}{(1 + \alpha)t}. \]

The upper speed bound provided by Corollary 3 degenerates as \( t \to 0 \). However, since the short time existence result provides an upper bound on the speed for small times, we have bounds on the speed for all times:

\[ F^\alpha_* \leq (C + (1 + \alpha)t)^{-\frac{1}{1+\alpha}}. \]

8. Bounds on principal curvatures

Different arguments are required to establish bounds on principal curvatures for the various classes of flows considered. The following sub-sections treat each case of Theorem 1 in turn:
8.1. Bounds on the principal curvatures: $f$ concave and $f|_{\partial \Gamma^+} = 0$. If $f$ is concave and $0 < \alpha \leq 1$, then equation (15) implies
\begin{equation}
\nabla_{\partial} h_{ij} \leq \alpha F^{\alpha - 1} \hat{F}^k l_k \nabla h_{ij} - (1 - \alpha) F^{\alpha} h_{ij}^2 - \alpha F^{\alpha - 1} \hat{F} (A^2) h_{ij}.
\end{equation}
Combining this with the evolution equation (16) for $F^\alpha$ gives
\begin{equation}
\nabla_{\partial} \left( \frac{h_{ij}}{F^\alpha} \right) \leq \alpha F^{\alpha - 1} \hat{F}^k l_k \nabla i_{ij} \left( \frac{h_{ij}}{F^\alpha} \right) + 2 \alpha^2 F^{\alpha - 2} \hat{F}^k l_k F \nabla j_{ij} \left( \frac{h_{ij}}{F^\alpha} \right) - (1 - \alpha) F^{2\alpha} \left( \frac{h_{ij}}{F^\alpha} \right)^2.
\end{equation}
The speed bounds of Corollary 5 therefore imply that the maximum of $(1 + t)^{\frac{\alpha}{2 - \alpha}} F^{-\alpha} \kappa_{\text{max}}$ does not increase if it is large, and it follows that there exists a constant $C$ such that
\[ \kappa_{\text{max}} \leq C F^\alpha (1 + t)^{-\frac{\alpha}{2 - \alpha}} \leq C (1 + t)^{-\frac{\alpha}{2 - \alpha}}. \]
Therefore $\kappa_{ij}/F \leq \tilde{C}$ where $\tilde{C}$ is a constant independent of $t$. Since $\kappa_{ij}/F$ is homogeneous of degree zero and approaches infinity on the boundary of $\Gamma^+$, there exists $\varepsilon > 0$ such that $\kappa_{\text{min}} \geq \varepsilon \kappa_{\text{max}}$. Therefore $\kappa_{\text{min}} \geq \varepsilon (1 + t)^{-\frac{\alpha}{2 - \alpha}}$ by the lower speed bound. It follows that there exist constants $0 < C_- < C_+$ such that
\begin{equation}
\kappa_i (x, t) \leq C_+ (1 + t)^{-\frac{\alpha}{2 - \alpha}}
\end{equation}
for all $x \in M$ and $t$ in the interval of existence.

8.2. Bounds on the principal curvatures: $F$ and $F_*$ concave. The key step in cases 2 and 4 of Theorem 1 is an estimate on the smallest principal curvature (or largest principal radius), which is closely related to the estimate proved in [AMZ, Lemma 11] in the case $\alpha = 1$ in the Euclidean setting.

We consider the evolution equation for the tensor $G_{ij} = F_*^{-\alpha} \tau_{ij}$, and apply the tensor maximum principle (see [Ha], Theorem 9.1), and particularly the refinement proved in [A5, Theorem 3.2]) to bound the maximum eigenvalue. Equations (20) and (18) yield the following evolution equation for $G_{ij}$:
\begin{equation}
\frac{\partial}{\partial t} G_{ij} = \alpha F_*^{- (1 + \alpha)} \hat{F}^k l_k \nabla F_{ij} - 2 \alpha F_*^{- (1 + \alpha)} \hat{F}^k l_k \nabla F_{ij} + \alpha F_*^{- (1 + 2\alpha)} \hat{F}^k l_k \nabla_{ij} F_{ij} - (1 - \alpha) F_*^{- (2\alpha)} \nabla^2_{ij} F_{ij},
\end{equation}
At a point where a maximum of the largest eigenvalue of $G_{ij}$ occurs, choose an orthonormal basis for $TH^n$ which diagonals $\tau$ (hence also $G$) with eigenvalues in decreasing order, so that the maximum eigenvalue of $G_{ij}$ is $\tau G_{ij}$. Note that $\hat{F}$ is then also diagonal at the maximum point, and the second derivatives $\hat{F}_*$ can be written in terms of the derivatives of $F_*$ using the expression in [A1, Equation 2.23]. The speed bound of Corollary 5 and the result of [A5, Theorem 3.2] imply that there exists $C$ such that the maximum eigenvalue of $G_{ij} - C (1 + t)^{\frac{\alpha}{2 - \alpha}} \tilde{F}_{ij}$ is decreasing, provided the following holds at the maximum point:
\begin{align*}
Q & := \alpha F_*^{- (1 + 2\alpha)} \hat{F}^k l_k \nabla F_{ij} - (1 + \alpha) F_*^{- (2\alpha)} (\nabla F_{ij})^2 - \alpha (1 + \alpha) F_*^{- (1 + 2\alpha)} \nabla F_{ij}^2 \leq 0.
\end{align*}
The optimal choice of \( \Gamma \) is obtained by completing the square, giving

\[
Q = \alpha F_*^{-(1+2\alpha)} \tilde{F}^m_{kk} \nabla_1 r_{kk} \nabla_1 \tau_{mn} - \alpha (1 + \alpha) F_*^{-(2+2\alpha)} \nabla_1 F_*^2 \\
+ 2\alpha \tau_1 F_*^{-1} \sum_k F_*^k (\nabla_k F_*^{-\alpha})^2 + 2\alpha F_*^{-(1+\alpha)} \sum_{k,p} F_*^k (\nabla_k G_{1p})^2/G_{pp} - G_{11}\]

Multiplying through by \( \alpha^{-1} F_*^{1+2\alpha} \) gives the following:

\[
\alpha F_*^{1+2\alpha} Q = \sum_{k,l} F_*^k \nabla_1 r_{kk} \nabla_1 r_{ll} + \sum_{k>\ell} \frac{j_k - j_\ell}{t_k - t_\ell} \nabla_1 r_{kl} - (1 + \alpha) \frac{\nabla_1 F_*^2}{F_*} \\
+ 2\tau_1 \sum_k \frac{j_k}{t_k - t_1} \left( \frac{\nabla_k F_*^{-\alpha}}{F_*^{-\alpha}} \right)^2 + 2\alpha F_*^\alpha \sum_{k,p} j_k (\nabla_k G_{1p})^2.
\]

We note that \( \nabla_k G_{1p} = \nabla_k (F_*^{-\alpha} \tau_{1p}) = F_*^{-\alpha} \nabla_k \tau_{1p} \) for \( p \neq 1 \) at the maximum point, while \( \nabla_k G_{11} = 0 \). This gives the following:

\[
\sum_{k,l} j_k^l \nabla_1 \tau_{1kl} = \sum_{k>\ell} \frac{j_k - j_\ell}{t_k - t_\ell} \left( \nabla_k \tau_{1\ell} \right)^2 + \sum_{k>\ell>1} \frac{j_k}{t_k - t_\ell} \nabla_1 \tau_{1\ell}^2 \\
- \frac{(1 + \alpha) F_*}{\alpha t_1^2} \left( \nabla_1 \tau_{11} \right)^2 + \sum_{k>\ell} \frac{j_k}{t_k - t_\ell} \left( \nabla_k \tau_{1\ell} \right)^2 + 2\sum_{k>p>1} \frac{j_k}{t_p - t_1} \nabla_1 \tau_{1p}^2 \\
- \frac{(1 + \alpha) F_*}{\alpha t_1^2} \left( \nabla_1 \tau_{11} \right)^2 + 2\sum_{k>\ell} \frac{j_k}{t_k - t_1} \left( \nabla_k \tau_{1\ell} \right)^2 + 2\sum_{k,p>1} \frac{j_k}{t_p - t_1} \nabla_1 \tau_{1kp}^2.
\]

The concavity of \( f_* \) implies that the terms on the first line are all non-positive. The remaining terms are all manifestly non-positive except for the fifth term. Consider the terms which involve \( (\nabla_k \tau_{11})^2 \) with \( k > 1 \): These are

\[
2\sum_{k>1} \frac{j_k}{t_k - t_1} \left( \nabla_k \tau_{11} \right)^2 + 2\sum_{k>\ell} \frac{j_\ell}{t_\ell - t_1} \left( \nabla_\ell \tau_{1\ell} \right)^2 + 2\sum_{k>\ell>1} \frac{j_k}{t_k - t_\ell} \left( \nabla_k \tau_{1\ell} \right)^2 \\
= 2\sum_{k>1} j_k \left( \frac{1}{t_k - t_1} + \frac{1}{t_1} \right) \left( \nabla_k \tau_{11} \right)^2 \\
= 2\sum_{k>1} j_k \frac{t_1}{t_k(t_k - t_1)} \left( \nabla_k \tau_{11} \right)^2.
\]

This leaves only the terms involving \( \nabla_1 \tau_{11} \) to consider: These are (omitting those in the \( \hat{f}_* \) term, which are non-positive)

\[
\left( -\frac{1 + \alpha}{\alpha} \frac{f_*}{t_1^2} + 2\frac{j_1}{t_1} \right) \left( \nabla_1 \tau_{11} \right)^2 = \left( -\frac{1 + \alpha}{\alpha} \sum_{k>1} \frac{j_k}{t_k^2} + \frac{\alpha}{\alpha} \frac{j_1}{t_1} \right) \left( \nabla_1 \tau_{11} \right)^2.
\]

In cases 2 and 3 this term is again non-positive since \( \alpha < 1 \). Therefore the maximum principle applies to show that \( \tau_{11} F_*^{-\alpha} \leq C(1 + t)^{-\alpha} \), and hence \( \tau_{11} \leq C(1 + t)^{-\alpha} \).

In case 2 the argument of section 8.2 gives \( \kappa_{\max} \leq C(1 + t)^{-\frac{\alpha}{2}} \). The argument above gives \( \kappa_{\max} \leq C(1 + t)^{-\frac{\alpha}{2}} \), so that \( \kappa_{\min} \geq C(1 + t)^{-\frac{\alpha}{2}} \). Therefore all principal curvatures of the hypersurface are comparable to \( (1 + t)^{-\frac{\alpha}{2}} \), and an estimate of the form (32) holds.
8.3. **Bounds on the principal curvatures:** $F_r$, concave and $F_r |_{\partial \Gamma} = 0$. In case 3, the estimate $\tau_{\text{max}} \leq C(1 + t)^{\frac{3}{2}}$ holds by the argument of the previous section. Since the speed bounds also give $F_r \geq C(1 + t)^{\frac{3}{2}}$, it follows that $\frac{\tau_{\text{max}}}{C} \leq C$. This quantity is scaling invariant and approaches infinity on the boundary of the positive cone, and so defines a properly contained sub-cone of the positive cone. It follows that $\frac{\tau_{\text{max}}}{C} \leq C$ for some $C$, so all principal curvatures are comparable to each other and to $F_r$. In particular an estimate of the form (32) holds.

8.4. **Bounds on the principal curvatures:** $n = 2$. The argument to control principal curvatures in this case is closely related to the main result of [A6]: As in that paper the key step is to compute the evolution equation for $G = \frac{(\kappa_2 - \kappa_1)^2}{(\kappa_2 + \kappa_1)^2}$. The equations are identical, except that the sign is reversed in the ‘reaction’ terms involving curvature alone. Thus the calculation in section 8.2 can again be applied: The argument there shows that the maximum eigenvalue of the principal curvatures of the form (32).

8.5. **Bounds on the principal curvatures:** The case $\alpha > 1$. In case 3, the computation from section 8.2 can again be applied: The argument there shows that the maximum eigenvalue of $F_{r_0} \alpha (1 + t)^{-\frac{3}{2}} \tilde{g}_{ij}$ is non-increasing, provided that we can show that the terms involving $\nabla^2 r_{11}$ are non-negative. The condition $\alpha \leq 1$ was not used in controlling any of the other terms. These terms are given by

$$\left( -\frac{1 + \alpha}{\alpha} \sum_{k=1}^n \frac{f_k r_k}{t_i} + \frac{\alpha - 1}{\alpha} \frac{f_1}{t_1} \right) (\nabla^2 r_{11})^2.$$
so \(f_i^1 \tau_i - f_j^1 \tau_j = f^2(\hat{f}^1 \kappa_i - \hat{f}^1 \kappa_j) \leq 0\). In particular this implies that \(f_i^k \tau_k \geq f_i^1 \tau_1\) for all \(k > 1\).

Substituting this in the terms above gives the following upper bound:

\[
\left( - (n - 1) \frac{1 + \alpha}{\alpha} + \frac{\alpha - 1}{\alpha} \frac{\hat{f}_i^1}{\tau_i} \right) \left( \nabla_i \tau_1 \right)^2.
\]

This is non-positive, so the maximum principle applies to give \(r_{\max} \leq C(1 + t)^{1/\alpha}\). The upper bound on \(\kappa_{\max}\) follows as in case 3 since \(f_*\) is zero on the boundary of the positive cone, and the estimate \(32\) holds as before.

9. Higher regularity and convergence

Bounds on all higher derivatives of the curvature of the evolving hypersurfaces can now be established, as follows: In order to obtain useful estimates we make use of the scaling properties of the equation. Let \(X: \bar{M} \times [0, T) \to \mathbb{R}^n_1\) be a solution of (1). For fixed \(\tau \in [0, T)\), define \(X_{\tau}: \bar{M} \times \left[ -\frac{\tau}{1 + \tau}, \frac{T-\tau}{1 + \tau} \right) \to \mathbb{R}^n_1\) by

\[
X_{\tau}(z, t) = (1 + \tau)^{-\frac{1}{1+\alpha}} X(z, \tau + t(1 + \tau)).
\]

Then \(X_{\tau}\) is again a solution of equation (1), which is co-compact with the inclusion of \(G\) in \(\text{Isom}_+(\mathbb{R}^n_1)\) given as in equation (7) by

\[
g_{\tau}(z) = L(g)z + (1 + \tau)^{-\frac{1}{1+\alpha}} b(g).
\]

The bounds established in the previous sections imply the following bounds for \(X_{\tau}\): The bounds on the support function from Corollary 3 give

\[
- \frac{p_-(z_0) \cdot z}{(1 + \tau)^{1/(1+\alpha)}} + \left( \frac{R^{1+\alpha}}{1 + \tau} - (1 + \alpha) \frac{1}{1 + \tau} \right) \leq u_\tau(z, t)
\]

\[
\leq - \frac{p_+(z_0) \cdot z}{(1 + \tau)^{1/(1+\alpha)}} + \left( \frac{R^{1+\alpha}}{1 + \tau} - (1 + \alpha) \frac{1}{1 + \tau} \right) \leq u_\tau(z, t).
\]

The speed bounds of Corollary 5 give the following for \(t \geq 0\):

\[
\left( C_- (1 + \tau)^{-1/(1+\alpha)} + (1 + \alpha)(1 + t) \right) \leq F_{\tau}(x, t)^\alpha \leq \left( C_+(1 + \tau)^{-1/(1+\alpha)} + (1 + \alpha)(1 + t) \right)
\]

for some \(C_-\) and \(C_+\) independent of \(\tau\) (away from \(\tau = 0\)). In particular, the speed has positive bounds above and below independent of \(\tau\) on \(\bar{M} \times [0, 1]\). Similarly, the principal curvature bound (32) implies that the principal curvatures of \(X_{\tau}\) have positive upper and lower bounds independent of \(\tau\) on \(\bar{M} \times [0, 1]\) (away from \(\tau = 0\)).

Bounds in \(C^{0, \beta}\) on the second fundamental form now follow, by slightly different arguments for each case of Theorem 1. In case 1 \(F^0\) is concave, and the Krylov-Safonov estimates can be applied (for example, to the scalar equation given by describing the evolving hypersurface as a graph). In cases 2, 3, and 5 \(F_{\tau}^{-\alpha}\) is a concave function of the principal radii of curvature, and the Krylov-Safonov estimate can be applied to equation (17). Finally, in case 4 the estimates of \(\text{A2}\) can be applied.

Schauder estimates now imply bounds on all higher derivatives of the curvature, and it follows that the time of existence is infinite (by the same argument as presented in \cite{A2} or \cite{H1}).

Finally, the estimate of Corollary 3 implies that \(X_{\tau}(\cdot, 0)\) converges locally in Hausdorff distance to the unit future hyperboloid. Standard interpolation inequalities imply that the principal curvatures of these hypersurfaces converge locally uniformly to 1, and the co-compactness and higher regularity then imply that the rescaled hypersurfaces converge in \(C^k\) for every \(k\) to the
hyperboloid (an argument similar to that in [Hul] must be used to show that the map \(X_\tau(\cdot, 0)\) converges, as well as the image hypersurface). This completes the proof of Theorem 1.

10. Elementary symmetric functions in case 5

For application of Theorem 1 it is useful to know which of the commonly used examples are covered in the various cases. Many examples satisfying the conditions of cases 1–4 are included in [AMZ]. Here we will establish the most important examples covered by case 5 of the theorem: The flows with speed \(S = E_k^{\alpha/k}\), where \(E_k\) is the \(k\)th elementary symmetric function of the principal curvatures. Note that in this case \(f = E_k^{1/k}\), and \(f_\tau = (E_k^{E_{\alpha/k}})^{1/k}\), which is concave and zero on the boundary of the positive cone. The following proposition therefore shows that these flows satisfy the requirements of case 5 of Theorem 1 for \(\alpha > 1\):

**Proposition 6.** Let \(E_k\) be the \(k\)th elementary symmetric function, defined on the positive cone \(\Gamma_+\). If \(f = E_k^{1/k}\) then \(\dot{f}_\tau \leq \dot{f}_1\) for \(\kappa_i > \kappa_j\).

**Proof.** By definition,

\[
E_k(\kappa_1, \ldots, \kappa_n) = \sum_{A \subseteq \{1, \ldots, n\}} \prod_{i \in A} \kappa_i,
\]

The derivative with respect to \(\kappa_i\) can be computed as follows: \(\dot{E}_k\) is a linear function of \(\kappa_i\), with a factor \(\kappa_i\) appearing in each term in the sum corresponding to a set \(A\) with \(i \in A\):

\[
\dot{E}_k^i = \sum_{A \subseteq \{1, \ldots, n\}} \prod_{j \in A \setminus \{i\}} \kappa_j.
\]

Therefore

\[
\dot{E}_k^i \kappa_i = \sum_{A \subseteq \{1, \ldots, n\}} \prod_{|A| = k, i \in A} \kappa_i.
\]

If \(i \neq j\) then this can be expanded as follows:

\[
\dot{E}_k^i \kappa_i = \sum_{A : |A| = k, i \in A} \prod_{A \subseteq \{1, \ldots, n\}} \kappa_j + \sum_{A : |A| = k, i, j \in A} \prod_{A \subseteq \{1, \ldots, n\}} \kappa_j = \kappa_i \kappa_j \left( \sum_{B : |B| = k - 2} \prod_{B \subseteq \{1, \ldots, n\} \setminus \{i, j\}} \kappa_j \right) + \kappa_i \left( \sum_{C : |C| = k - 1} \prod_{C \subseteq \{1, \ldots, n\} \setminus \{i, j\}} \kappa_j \right).
\]

It follows that

\[
\dot{E}_k^i \kappa_i - \dot{E}_k^j \kappa_j = (\kappa_i - \kappa_j) \left( \sum_{C : |C| = k - 1} \prod_{C \subseteq \{1, \ldots, n\} \setminus \{i, j\}} \kappa_j \right).
\]

In particular, if \(\kappa_i > \kappa_j\) then \(\dot{E}_k^i \kappa_i - \dot{E}_k^j \kappa_j \geq 0\). Finally, if \(f = E_k^{1/k}\) then \(\dot{f}_\tau = \frac{1}{k} E_k^{-k-1} \dot{E}_k^i\) for each \(i\), and the result follows.

The reader may check that the flows defined by \(f = \prod_{k=1}^n E_k^{\alpha_k/k}\) also satisfy the conditions of case 5 of Theorem 1 for any \(\alpha_1, \ldots, \alpha_n \geq 0\) with \(\sum_{k=1}^n \alpha_k = 1\).
11. Application to the cross curvature flow

In [CH], Chow and Hamilton introduced an interesting fully nonlinear heat flow for negatively (or positively) curved metrics on a three dimensional manifold, called the ‘cross curvature flow’ (hereafter abbreviated ‘XCF’). We discuss the formulation of this below. The discussion in [CH] relates principally to the negatively curved case, and the authors give strong indications that the XCF should deform any negatively curved metric on a compact 3-manifold to a hyperbolic metric, modulo scaling. This result is not yet known, and our purpose here is to show that this does indeed hold for metrics which are locally isometrically embeddable in Minkowski space \( \mathbb{R}^{3,1} \).

Chow and Hamilton define the cross curvature tensor as follows: First, the Einstein tensor is defined by

\[
P_{ij} = R_{ij} - \frac{1}{2} R g_{ij},
\]

where \( R \) is the scalar curvature. The cross curvature tensor (which Chow and Hamilton denote by \( h_{ij} \) but we denote \( X_{ij} \) to avoid confusion with the second fundamental form) is defined if \( P \) is invertible by

\[
X_{ij} = (\det P)(P^{-1})_{ij}.
\]

Alternatively, the following expression defines \( X_{ij} \) without the assumption that \( P \) is invertible:

\[
X_{ij} = \frac{1}{2} \mu_{iab} \mu_{jcd} P_{ac} P_{bd}.
\]

In particular, if we work in a frame where \( P \) is diagonal, then so is \( X \):

\[
P = \begin{bmatrix} \lambda & 0 & 0 \\ 0 & \mu & 0 \\ 0 & 0 & \nu \end{bmatrix} \implies X = \begin{bmatrix} \mu \nu & 0 & 0 \\ 0 & \lambda \nu & 0 \\ 0 & 0 & \lambda \mu \end{bmatrix}.
\]

Our interest here is in the case where the metric \( g \) is embeddable (locally) with some second fundamental form \( h_{ij} \), in either Euclidean space \( \mathbb{R}^4 \) or Minkowski space \( \mathbb{R}^{3,1} \). Then the Gauss equations give the following expression for the curvature tensor, where we take \( \gamma = 1 \) for embedding into \( \mathbb{R}^4 \) and \( \gamma = -1 \) for embedding into \( \mathbb{R}^{3,1} \):

\[
R_{abcd} = \gamma (h_{ac} h_{bd} - h_{bc} h_{ad}).
\]

From equation (34) we then have

\[
P_{ij} = \frac{\gamma}{4} \mu_{iab} \mu_{jcd} (h_{ac} h_{bd} - h_{bc} h_{ad})
\]

\[
= \frac{\gamma}{2} \mu_{iab} \mu_{jcd} h_{ac} h_{bd}.
\]

In particular in a frame which diagonalizes \( h \) we also have \( P \) diagonal (hence also \( X \)):

\[
h = \begin{bmatrix} a & 0 & 0 \\ 0 & b & 0 \\ 0 & 0 & c \end{bmatrix} \implies P = \gamma \begin{bmatrix} bc & 0 & 0 \\ 0 & ac & 0 \\ 0 & 0 & ab \end{bmatrix}.
\]

By equation (37) we have (calculating in the same frame)

\[
X = \begin{bmatrix} a^2 bc & 0 & 0 \\ 0 & ab^2 c & 0 \\ 0 & 0 & abc^2 \end{bmatrix} = K h,
\]

where \( K = \det h = abc \).
The cross-curvature flow is defined by
\begin{equation}
\frac{\partial}{\partial t} g_{ij} = -2\gamma X_{ij},
\end{equation}
In particular in the case where the metric is locally embeddable this becomes
\begin{equation}
\frac{\partial}{\partial t} g_{ij} = -2\gamma K h_{ij}.
\end{equation}
Comparison with equation (8) shows that the metric induced by a solution of Gauss curvature flow in Minkowski space satisfies the cross-curvature flow with \( \gamma = -1 \), and Lemma 9 of [AMZ] shows that the induced metric of a solution of Gauss curvature flow in \( \mathbb{R}^4 \) satisfies the cross curvature flow with \( \gamma = 1 \).

Buckland [B] proved that the cross curvature flow with \( \gamma = 1 \) has a unique solution for any positively curved smooth initial metric on a compact 3-manifold, and the cross-curvature flow with \( \gamma = -1 \) has a unique solution for any initial metric with negative sectional curvatures on a compact 3-manifold. It follows that in the locally embeddable case, the solution of XCF with a negatively curved initial metric is precisely the induced metric of the solution of Gauss curvature flow we construct in this paper. In particular we proved that the evolving hypersurfaces under Gauss curvature flow approach the hyperboloid modulo scaling, and therefore the metric approaches a hyperbolic metric modulo scaling.

The corresponding result in the case \( \gamma = 1 \) is not known: It is not known whether convex compact hypersurfaces become spherical under the Gauss curvature flow in \( \mathbb{R}^{n+1} \) for \( n \geq 3 \) (although in the case of antipodally symmetric hypersurfaces this follows from the results of Firey [F] together with the methods of [A4]). See [A3] for the case \( n = 2 \).

References


