Bull. Korean Math. Soc. **46** (2009), No. 2, pp. 321–329
DOI 10.4134/BKMS.2009.46.2.321

LINEAR WEINGARTEN HYPERSURFACES IN A UNIT SPHERE

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Abstract. In this paper, we have considered linear Weingarten hypersurfaces in a sphere and obtained some rigidity theorems. The purpose of this paper is to give some extension of the results due to Cheng-Yau [3] and Li [7].

1. Introduction

Let M be a hypersurface in an $(n+1)$-dimensional unit sphere $S^{n+1}(1)$. As is well known to us, there are many rigidity results for hypersurfaces in a unit sphere with constant mean curvature or with constant scalar curvature. Now we want to introduce an well-known theorem due to Cheng-Yau [3] as follows:

Theorem 1.1. *Let M be an n-dimensional compact hypersurface in a unit sphere $S^{n+1}(1)$. If*

(1) *M has nonnegative sectional curvature,*

(2) *the normalized scalar curvature r of M is constant and $r \geq 1$,*

then M is either totally umbilical, or $M = S^{n-k}(a) \times S^k(\sqrt{1-a^2})$, $1 \leq k \leq n-1$.

On the other hand, Li [7] studied some hypersurfaces in a unit sphere with scalar curvature proportional to mean curvature and proved the following theorem.

Theorem 1.2. *Let M be an n-dimensional compact hypersurface in a unit sphere $S^{n+1}(1)$. If*

(1) *M has nonnegative sectional curvature,*

Received May 23, 2008.
2000 *Mathematics Subject Classification.* Primary 53C20; Secondary 53C42.
Key words and phrases. linear Weingarten hypersurfaces, rigidity theorems, Cheng-Yau differential operator.
The first author was partly supported by grant No. 10531090 of NSFC and by Doctoral Program Foundation of the Ministry of Education of China 2006. The second author was supported by grant Proj. No. R17-2008-001-01001-0 from Korea Science & Engineering Foundation.

(2) *the normalized scalar curvature r of M is proportional to mean curvature H of M, that is,*

$$r = aH, \qquad a^2 \geq \frac{4n}{n-1},$$

where a is a constant, then M is either totally umbilical, or $M = S^{n-k}(a) \times S^k(\sqrt{1-a^2})$, $1 \leq k \leq n-1$.

Now let us introduce a notion for linear Weingarten hypersurfaces in an $(n+1)$-dimensional unit sphere $S^{n+1}(1)$ as follows:

Definition 1.1. Let M be a hypersurface in an $(n+1)$-dimensional unit sphere $S^{n+1}(1)$. We call M a *linear Weingarten hypersurface* if $cR+dH+e=0$, where c, d and e are constants such that $c^2+d^2 \neq 0$, R and H respectively denote the scalar curvature and the mean curvature of M.

Remark 1.1. When the constant $d=0$ in Definition 1.1, a linear Weingarten hypersurface M reduces to a hypersurface with constant scalar curvature. When the constant $c=0$ in Definition 1.1, a linear Weingarten hypersurface M reduces to a hypersurface with constant mean curvature. In such a sense, the linear Weingarten hypersurfaces can be regarded as a natural generalization of hypersurfaces with constant scalar curvature or with constant mean curvature.

By investigating Cheng-Yau's operator $\square$ given in [3] and using some new estimations, we want to study linear Weingarten hypersurfaces in a unit sphere as follows:

Theorem 1.3. *Let M be an n-dimensional compact hypersurface in a unit sphere $S^{n+1}(1)$. If*

(1) *M has nonnegative sectional curvature,*

(2) *the normalized scalar curvature r and the mean curvature H of M satisfies the following conditions*: $r = aH + b$, $(n-1)a^2 - 4n + 4nb \geq 0$, *then M is either totally umbilical, or $M = S^{n-k}(a) \times S^k(\sqrt{1-a^2})$, $1 \leq k \leq n-1$.*

Remark 1.2. Since $R = n(n-1)r$, a hypersurface M in Theorem 1.3 satisfying $r = aH + b$ is just a linear Weingarten hypersurface in Definition 1.1.

Remark 1.3. When the constant a in above identically vanishes, our Theorem 1.3 reduces to Theorem 1.1. When the constant b vanishes, our Theorem 1.3 reduces to Theorem 1.2.

In all of theorems mentioned above, we have assumed that M has nonnegative sectional curvature. In the following theorem, we want to study linear Weingarten hypersurfaces in a unit sphere without the assumption of nonnegative sectional curvature. In fact, we prove the following:

Theorem 1.4. *Let M be a hypersurface in $S^{n+1}(1)$. If*

(1) *$r = aH + b$, $(n-1)a^2 - 4n + 4nb \geq 0$,*

(2) *$|B|^2 \leq 2\sqrt{n-1}$,*

then either $|B|^2 = 0$ *and* M *is a totally umbilical hypersurface or* $|B|^2 = 2\sqrt{n-1}$ *and* $M = S^1(c) \times S^{n-1}(\sqrt{1-c^2})$.

2. Preliminaries

There are many studies on compact hypersurfaces in an $(n+1)$-dimensional unit sphere $S^{n+1}(1)$ (see [1], [2], [3], [5]-[12]). In this paper, let us also denote by M a compact hypersurfaces in $S^{n+1}(1)$. We choose a local orthonormal frame $\{e_A\}_{1\le A\le n+1}$ in $S^{n+1}(1)$, with dual coframe $\{\omega_A\}_{1\le A\le n+1}$, such that, at each point of M, $e_1, \dots, e_n$ are tangent to M and e_{n+1} is the positively oriented unit normal vector. We shall make use of the following convention on the ranges of indices:

$$1 \le A, B, C, \dots, \le n+1; \quad 1 \le i, j, k, \dots, \le n.$$

Then the structure equations of $S^{n+1}(1)$ are given by

$$d\omega_A = \sum_{B=1}^{n+1} \omega_{AB} \wedge \omega_B, \quad \omega_{AB} + \omega_{BA} = 0, \tag{2.1}$$

$$d\omega_{AB} = \sum_{C=1}^{n+1} \omega_{AC} \wedge \omega_{CB} - \omega_A \wedge \omega_B. \tag{2.2}$$

When restricted to M, we have $\omega_{n+1} = 0$ and

$$0 = d\omega_{n+1} = \sum_{i=1}^{n} \omega_{n+1i} \wedge \omega_i. \tag{2.3}$$

By Cartan's lemma, there exist functions h_{ij} such that

$$\omega_{n+1i} = \sum_{j=1}^{n} h_{ij}\omega_j, \quad h_{ij} = h_{ji}. \tag{2.4}$$

This gives the second fundamental form of M, $B = \sum_{i,j} h_{ij}\omega_i\omega_j e_{n+1}$. The mean curvature H is defined by $H = \frac{1}{n}\sum_i h_{ii}$. From (2.1)-(2.4) we obtain the structure equations of M

$$d\omega_i = \sum_{j=1}^{n} \omega_{ij} \wedge \omega_j, \quad \omega_{ij} + \omega_{ji} = 0, \tag{2.5}$$

$$d\omega_{ij} = \sum_{k=1}^{n} \omega_{ik} \wedge \omega_{kj} - \frac{1}{2}\sum_{k,l=1}^{n} R_{ijkl}\omega_k \wedge \omega_l \tag{2.6}$$

and the Gauss equation

$$R_{ijkl} = \delta_{ik}\delta_{jl} - \delta_{il}\delta_{jk} + h_{ik}h_{jl} - h_{il}h_{jk}. \tag{2.7}$$

Then it follows that

$$n(n-1)(r-1) = n^2H^2 - |B|^2, \tag{2.8}$$

where R_{ijkl} denotes the components of the Riemannian curvature tensor of M, $n(n-1)r$ is the scalar curvature of M and $|B|^2 = \sum_{i,j=1}^n h_{ij}^2$ is the square norm of the second fundamental form of M.

Let h_{ijk} denote the covariant derivative of h_{ij}. We then have

$$\sum_k h_{ijk}\omega_k = dh_{ij} + \sum_k h_{kj}\omega_{ki} + \sum_k h_{ik}\omega_{kj}. \tag{2.9}$$

Thus, by exterior differentiation of (2.4), we obtain the Codazzi equation

$$h_{ijk} = h_{ikj}. \tag{2.10}$$

The second covariant derivative of h_{ij} is defined by

$$\sum_i h_{ijkl}\omega_l = dh_{ijk} + \sum_m h_{mjk}\omega_{mi} + \sum_m h_{imk}\omega_{mj} + \sum_m h_{ijm}\omega_{mk}. \tag{2.11}$$

By exterior differentiation of (2.9), we can get that the following Ricci identities hold

$$h_{ijkl} - h_{ijlk} = \sum_m h_{mj}R_{mikl} + \sum_m h_{im}R_{mjkl}. \tag{2.12}$$

For a smooth function f defined on M, the gradient, the hessian (f_{ij}) and the Laplacian $\triangle f$ of f are defined by

$$df = \sum_i f_i\omega_i, \quad \sum_j f_{ij}\omega_j = df_i + \sum_j f_j\omega_{ji}, \quad \triangle f = \sum_i f_{ii}. \tag{2.13}$$

Let $\phi = \sum_{i,j} \phi_{ij}\omega_i \otimes \omega_j$ be a symmetric tensor defined on M, where

$$\phi_{ij} = nH\delta_{ij} - h_{ij}. \tag{2.14}$$

Following Cheng-Yau [3], we introduce an operator $\Box$ associated to ϕ acting on any smooth function f by

$$\Box f = \sum_{i,j} \phi_{ij}f_{ij} = \sum_{i,j}(nH\delta_{ij} - h_{ij})f_{ij}. \tag{2.15}$$

Since ϕ_{ij} is divergence-free, it follows that the operator $\Box$ is self-adjoint relative to the L^2 inner product of M, i.e.,

$$\int_M f\Box g dv = \int_M g\Box f dv. \tag{2.16}$$

We choose $e_1, \ldots, e_n$ such that

$$h_{ij} = \lambda_i\delta_{ij}, \tag{2.17}$$

then we have

$$\begin{aligned} \Box(nH) &= nH\triangle(nH) - \textstyle\sum_i \lambda_i(nH)_{,ii} \\ &= \tfrac{1}{2}\triangle(nH)^2 - \textstyle\sum_i (nH)_{,i}^2 - \sum_i \lambda_i(nH)_{,ii} \\ &= \tfrac{1}{2}n(n-1)\triangle r + \tfrac{1}{2}\triangle|B|^2 - n^2|\nabla H|^2 - \textstyle\sum_i \lambda_i(nH)_{,ii}. \end{aligned} \tag{2.18}$$

On the other hand, we can deduce from (2.10) and (2.12) that

$$\frac{1}{2}\triangle|B|^2 = \sum_{i,j,k} h_{ijk}^2 + \sum_i \lambda_i (nH)_{,ii} + \frac{1}{2}\sum_{i,j} R_{ijij}(\lambda_i - \lambda_j)^2. \tag{2.19}$$

Putting (2.19) into (2.18), we obtain

$$\Box(nH) = \frac{1}{2}n(n-1)\triangle r + |\nabla B|^2 - n^2|\nabla H|^2 + \frac{1}{2}\sum_{i,j} R_{ijij}(\lambda_i - \lambda_j)^2. \tag{2.20}$$

From the Gauss equation, we have $R_{ijij} = 1 + \lambda_i\lambda_j$, putting this into (2.20), we get

$$\begin{aligned}\Box(nH) &= \tfrac{1}{2}n(n-1)\triangle r + |\nabla B|^2 - n^2|\nabla H|^2 \\ &\quad + n|B|^2 - n^2H^2 - |B|^4 + nH\textstyle\sum_i \lambda_i^3.\end{aligned} \tag{2.21}$$

Next we introduce the following lemma

Lemma 2.1. *Let M be a hypersurface in $S^{n+1}(1)$. If*

$$r = aH + b \quad \text{and} \quad (n-1)a^2 - 4n + 4nb \geq 0, \tag{2.22}$$

then we have

$$|\nabla B|^2 \geq n^2|\nabla H|^2, \tag{2.23}$$

where $n(n-1)r$ is scalar curvature of M, H denotes the mean curvature of M.

Proof. By the formula (2.7), we have

$$|B|^2 = n^2H^2 + n(n-1)(1-r) = n^2H^2 + n(n-1)(1 - aH - b), \tag{2.24}$$

it follows that

$$2h_{ij}h_{ijk} = 2n^2HH_{,k} - n(n-1)aH_{,k}, \tag{2.25}$$

then we obtain

$$4\sum_k \left(\sum_{i,j} h_{ij}h_{ijk}\right)^2 = [2n^2H - n(n-1)a]^2|\nabla H|^2. \tag{2.26}$$

Hence we deduce that

$$\begin{aligned}4\left(\sum_{i,j} h_{ij}^2\right)\left(\sum_{i,j,k} h_{ijk}^2\right) &\geq 4\sum_k \left(\sum_{i,j} h_{ij}h_{ijk}\right)^2 \\ &= [2n^2H - n(n-1)a]^2|\nabla H|^2,\end{aligned} \tag{2.27}$$

that is,

$$4|B|^2|\nabla B|^2 \geq [2n^2H - n(n-1)a]^2|\nabla H|^2. \tag{2.28}$$

On the other hand,

$$\begin{aligned} &[2n^2H - n(n-1)a]^2 - 4n^2|B|^2 \\ &= 4n^4H^2 + n^2(n-1)^2a^2 - 4n^3(n-1)Ha \\ &\quad - 4n^3[nH^2 + (n-1)(1 - aH - b)] \\ &= n^2(n-1)[(n-1)a^2 - 4n + 4nb] \\ &\geq 0. \end{aligned} \tag{2.29}$$

From this, together with Lemma 2.1, we have

$$4|B|^2|\nabla B|^2 \geq [2n^2H - n(n-1)a]^2|\nabla H|^2 \geq 4n^2|B|^2|\nabla H|^2,$$

then we obtain either $|B|^2 = 0$ and $|\nabla B|^2 = n^2|\nabla H|^2 = 0$ or $|\nabla B|^2 \geq n^2|\nabla H|^2$. This completes the proof of Lemma 2.1. □

Remark 2.1. When the constant a vanishes, our Lemma 2.1 reduce to Lemma 3.2 in [6] due to Li.

In this paper, we also need the following lemma due to Okumura [9].

Lemma 2.2. *Let μ_i, $i = 1, \ldots, n$, be real numbers such that $\sum_i \mu_i = 0$ and $\sum_i \mu_i^2 = \beta^2$, where $\beta =$ constant ≥ 0. Then*

$$-\frac{n-2}{\sqrt{n(n-1)}}\beta^3 \leq \sum_i \mu_i^3 \leq \frac{n-2}{\sqrt{n(n-1)}}\beta^3 \tag{2.30}$$

and the equality holds if and only if at least $(n-1)$ of the μ_i are equal.

3. Proofs of Theorem 1.3 and Theorem 1.4

First in this section, we want to prove Theorem 1.3 as follows:
By (2.20), we can obtain

$$0 = \int_M (|\nabla B|^2 - n^2|\nabla H|^2)dv + \frac{1}{2}\int_M \sum_{i,j} R_{ijij}(\lambda_i - \lambda_j)^2 dv. \tag{3.1}$$

By using of Lemma 2.1, we can deduce that

$$|\nabla B|^2 \geq n^2|\nabla H|^2. \tag{3.2}$$

Since M has nonnegative sectional curvature and (3.1), we know that

$$|\nabla B|^2 = n^2|\nabla H|^2, \quad \sum_{i,j} R_{ijij}(\lambda_i - \lambda_j)^2 = 0, \tag{3.3}$$

that is,

$$|\nabla B|^2 = n^2|\nabla H|^2, \quad R_{ijij} = 0 \ \text{ if } \ \lambda_i \neq \lambda_j. \tag{3.4}$$

Then it follows from the Gauss equation $R_{ijij} = 1 + \lambda_i\lambda_j$ and (3.4) that either M is totally umbilical or M has two distinct constant principal curvatures λ, μ and $1 + \lambda\mu = 0$. This completes the proof of Theorem 1.3. □

Next we want to give the proof of Theorem1.4 as follows:

• Case 1: $n = 2$.

In this case, we obtain from the Gauss equation that

$$2(r-1) = 4H^2 - |B|^2 = 2\lambda_1\lambda_2. \tag{3.5}$$

Combining (2.21) and the Gauss equation (3.5), we obtain

$$\begin{aligned}
\Box(2H) &= \triangle r + |\nabla B|^2 - 4|\nabla H|^2 + 2|B|^2 - 4H^2 - |B|^4 + 2H\sum_{i=1}^{2}\lambda_i^3 \\
&= \triangle r + |\nabla B|^2 - 4|\nabla H|^2 + 2|B|^2 - 4H^2 - |B|^4 \\
&\quad + 2H(\lambda_1+\lambda_2)(\lambda_1^2 - \lambda_1\lambda_2 + \lambda_2^2) \\
&= \triangle r + |\nabla B|^2 - 4|\nabla H|^2 + 2|B|^2 - 4H^2 - |B|^4 \\
&\quad + 4H^2(|B|^2 - (r-1)) \\
&= \triangle r + |\nabla B|^2 - 4|\nabla H|^2 + |B|^2 - 2(r-1) - |B|^4 \\
&\quad + \{|B|^2 + 2(r-1)\}\{|B|^2 - (r-1)\} \\
&= \triangle r + |\nabla B|^2 - 4|\nabla H|^2 + r(|B|^2 + 2 - 2r) \\
&= \triangle r + |\nabla B|^2 - 4|\nabla H|^2 + (4H^2 + 2 - |B|^2)(|B|^2 - 2H^2),
\end{aligned} \tag{3.6}$$

then we get the following integral equality

$$\int_M (|\nabla B|^2 - 4|\nabla H|^2)dv + \int_M (4H^2 + 2 - |B|^2)(|B|^2 - 2H^2)dv = 0. \tag{3.7}$$

Since $|B|^2 \leq 2$, we know that

$$(4H^2 + 2 - |B|^2)(|B|^2 - 2H^2) \geq 0. \tag{3.8}$$

By Lemma 2.1, we have

$$|\nabla B|^2 - 4|\nabla H|^2 \geq 0. \tag{3.9}$$

Combining (3.7), (3.8) and (3.9), we obtain $|\nabla B|^2 - 4|\nabla H|^2 = 0$ and $(4H^2 + 2 - |B|^2)(|B|^2 - 2H^2) = 0$, that is, either $H = 0$ and $|B|^2 = 2$ or $|B|^2 - 2H^2 = 0$. If $H = 0$ and $|B|^2 = 2$, we know that $M = S^1(c) \times S^1(\sqrt{1-c^2})$ from a result of [5]. If $|B|^2 - 2H^2 = 0$, M is totally umbilical.

• Case 2: $n \geq 3$.

Let $\mu_i = \lambda_i - H$ and $|Z|^2 = \sum_i \mu_i^2$, we get

$$\sum_i \mu_i = 0, \quad |Z|^2 = |B|^2 - nH^2, \tag{3.10}$$

$$\sum_i \lambda_i^3 = \sum_i \mu_i^3 + 3H|Z|^2 + nH^3. \tag{3.11}$$

By (3.10) and (3.11), we obtain

$$\begin{aligned}\Box(nH) = & \frac{1}{2}n(n-1)\triangle r + |\nabla B|^2 - n^2|\nabla H|^2 \\ & + |Z|^2(n + nH^2 - |Z|^2) + nH\sum_i \mu_i^3.\end{aligned} \tag{3.12}$$

Combining (3.12) and Lemma 2.2, we get

$$\begin{aligned}\Box(nH) \geq & \tfrac{1}{2}n(n-1)\triangle r + |\nabla B|^2 - n^2|\nabla H|^2 \\ & + |Z|^2\left(n + nH^2 - |Z|^2 - \tfrac{n(n-2)}{\sqrt{n(n-1)}}|H||Z|\right).\end{aligned} \tag{3.13}$$

Hence we have the following:

Lemma 3.1. *Let M be a compact hypersurface in $S^{n+1}(1)$. Then we have*

$$\begin{aligned}0 \geq & \int_M (|\nabla B|^2 - n^2|\nabla H|^2)dv \\ & + \int_M |Z|^2\left(n + nH^2 - |Z|^2 - \frac{n(n-2)}{\sqrt{n(n-1)}}|H||Z|\right)dv.\end{aligned} \tag{3.14}$$

Now, we assume $r = aH + b$ and $(n-1)a^2 - 4n + 4nb \geq 0$. For a real number $d = \frac{n+2\sqrt{n-1}}{n-2}\sqrt{n} > 0$, we have

$$2|H||Z| \leq dH^2 + \frac{1}{d}|Z|^2. \tag{3.15}$$

By Lemma 2.1, Lemma 3.1 and (3.15), we obtain

$$\begin{aligned}&\int_M |Z|^2\Bigg\{n + nH^2\left(2 - \frac{(n-2)d}{2\sqrt{n(n-1)}} + \frac{n(n-2)}{2\sqrt{n(n-1)}d}\right) \\ &- |B|^2\left(1 + \frac{n(n-2)}{2\sqrt{n(n-1)}d}\right)\Bigg\}dv \leq 0,\end{aligned}$$

that is,

$$0 \geq \int_M |Z|^2\left\{n - \frac{n}{2\sqrt{n-1}}|B|^2\right\}dv. \tag{3.16}$$

Noting that $|B|^2 \leq 2\sqrt{n-1}$, we know that the right hand side of (3.16) is nonnegative, it follows that $|\nabla B|^2 = n^2|\nabla H|^2$ and $\int_M |Z|^2\left\{n - \frac{n}{2\sqrt{n-1}}|B|^2\right\}dv = 0$. Then we have either $|Z|^2 = |B|^2 - nH^2 = 0$ and M is totally umbilical or $|B|^2 = 2\sqrt{n-1}$.

If M is not totally umbilical, we can see that

$$|B|^2 = 2\sqrt{n-1}, \tag{3.17}$$

it follows from Lemma 2.2, Lemma 3.1 and (3.17) that

$$\lambda_1 = \cdots = \lambda_{n-1} \neq \lambda_n, \tag{3.18}$$

and $M = S^1(c) \times S^{n-1}(\sqrt{1-c^2})$. This completes the proof of Theorem 1.4. $\square$

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