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## ON THE GENERALIZED SOLITON SOLUTIONS OF THE MODIFIED KORTEWEG-DE VRIES EQUATION

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In this paper, we discuss the asymptotic property of the generalized soliton solutions of the modified Korteweg-de Vries ( $K-dv$ ) equation

$$(1) \quad v_t + 6v^2v_x + v_{xxx} = 0, \quad -\infty < x, t < \infty$$

where  $v_t$  and  $v_x$  denote partial derivatives of  $v=v(x, t)$  with respect to  $t$  and  $x$  respectively. This equation gives one of the simplest modifications of the  $K-dV$  equation

$$u_t - 6uu_x + u_{xxx} = 0, \quad -\infty < x, t < \infty.$$

Both of the  $K-dV$  equation and the modified  $K-dV$  equation are known to have progressive wave solutions;

$$u(x, t) = -2^{-1}c \operatorname{sech}^2(2^{-1}c^{1/2}(x-ct-\delta)), \quad c > 0$$

for the  $K-dV$  equation,

$$(2) \quad v(x, t) = \pm c^{1/2} \operatorname{sech}(c^{1/2}(x-ct-\delta)), \quad c > 0$$

for the modified  $K-dV$  equation.

Each of such solutions is called a solitary wave solution or a soliton on account of its shape.

On the other hand, Gardner, Greene, Kruskal and Miura [1] have related the solution  $u(t)=u(x, t)$  of the  $K-dV$  equation to the scattering theory of the one dimensional Schrödinger operator with the potential  $u(t)$  and found that discrete eigenvalues are invariants and the reflection coefficient and normalization coefficients vary exponentially with respect to  $t$  (see also Lax [3]). Here a soliton of the  $K-dV$  equation is characterized as the solution with one discrete eigenvalue and the zero reflection coefficient. Furthermore, the reflectionless potential with  $N$  discrete eigenvalues can be written in closed form in terms of exponentials by the method of Kay and Moses [2] for each  $t$ . These potentials are called  $N$ -tuple wave solutions.  $N$ -tuple wave solution

satisfies actually the  $K$ - $dV$  equation and behaves like a superposition of  $N$  solitons for large  $t$  (see Tanaka [7]).

Recently, Tanaka [5], [6] has related the solution of the modified  $K$ - $dV$  equation (1) to the scattering theory of the differential operator

$$(3) \quad L_u = i \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} D - i \begin{bmatrix} 0 & u \\ u^* & 0 \end{bmatrix} \quad D = d/dx$$

where  $u^*$  denote the complex conjugate of  $u$  and, on the basis of this relation, constructed a family of particular solutions which includes solitons (2) as the simplest case (see also Wadati [8]). We call these solutions the generalized soliton solutions.

In this paper, we study the generalized soliton solution with purely imaginary discrete eigenvalues. In this case, the generalized soliton solutions decompose into  $N$  solitons for large  $t$ .

Our result is similar to that of the  $N$ -tuple wave solution of the  $K$ - $dV$  equation. But comparing with the  $N$ -tuple wave solution, the expression of the generalized soliton solution is somewhat complicated.

In section 1, we summarize the general properties of the scattering data of  $L_u$ . In section 2, following [6], we describe the relation between the scattering data of  $L_u$  and a solution of the modified  $K$ - $dV$  equation, and introducing the generalized soliton solutions, we state our main theorem. In section 3, we rewrite the formula of the generalized soliton solution into the form which is more convenient for our consideration. In section 4, we give the proof of our main theorem.

### 1. The scattering data of $L_u$

We summarize the general properties of the scattering data of  $L_u$  from [4], [9]. Consider the eigenvalue problem

$$(4) \quad L_u y = \zeta y \quad y = {}^t(y_1, y_2)$$

on the real axis  $(-\infty, \infty)$ . If  $u(x)$  is integrable, then, for  $\zeta = \xi + i\eta$ ,  $\eta \geq 0$ , there are unique solutions  $\phi_{\pm}$  of (4) (called Jost solutions) which behave as

$$\begin{aligned} \phi_+(x, \zeta) &= {}^t(0, 1) \exp(i\zeta x) + o(1) & x \rightarrow \infty. \\ \phi_-(x, \zeta) &= {}^t(1, 0) \exp(-i\zeta x) + o(1) & x \rightarrow -\infty. \end{aligned}$$

Then  $\phi_{\pm}(x, \zeta)$  are analytic in  $\zeta$ ,  $I_m \zeta > 0$ . Note that if  $y$  is a solution of (4), then

$$y^* = {}^t(y_2^*, -y_1^*)$$

is a solution of (4) where  $\zeta$  is replaced by  $\zeta^*$ . If  $\zeta = \xi$  is a non zero real number,

then  $\phi_+$  and  $\phi_+^*$  are linearly independent solutions of (4). So there are  $a(\xi)$  and  $b(\xi)$  such that

$$(5) \quad \phi_- = a(\xi)\phi_+^* + b(\xi)\phi_+.$$

From (5),  $a(\xi) = \det(\phi_-, \phi_+)$ , so  $a(\xi)$  can be extended to the analytic function  $a(\zeta)$ ,  $I_m \zeta > 0$ .

If  $u(x)$  satisfies an additional condition

$$\int_{-\infty}^{\infty} (1 + |x|) |u(x)| dx < \infty$$

then there is a function  $f \in L^1(0, \infty)$  such that

$$a(\zeta) = 1 + \int_0^{\infty} f(t) \exp(i\zeta t) dt \quad I_m \zeta \geq 0.$$

Moreover, if we assume that  $a(\xi)$  is not equal to zero for  $\xi \in \mathbf{R}$ , then  $a(\zeta)$  has finite number of zeros  $\zeta_1, \zeta_2, \dots, \zeta_N$ ,  $I_m \zeta_k > 0$ . For  $\zeta = \zeta_j$ ,  $\phi_{\pm}(x, \zeta_j)$  are linearly dependent, so there is a non zero constant  $d_j$  such that

$$\phi_-(x, \zeta_j) = d_j \phi_+(x, \zeta_j) \quad (1 \leq j \leq N).$$

By the asymptotic properties of  $\phi_{\pm}$ , they are square integrable *i.e.*  $\zeta_j$  are discrete eigenvalues of  $L_u$ . We have

$$a'(\zeta_j) = -2id_j \int_{-\infty}^{\infty} \phi_{+1}(x, \zeta_j) \phi_{+2}(x, \zeta_j) dx.$$

Now suppose that  $\zeta_j$  are simple zeros. Put

$$c_j = d_j / a'(\zeta_j)$$

(called normalization coefficients of eigenfunctions) and

$$r(\xi) = b(\xi) / a(\xi)$$

under the assumption,  $a(\xi) \neq 0$  for any  $\xi \in \mathbf{R}$  (called the reflection coefficient). The triplet  $S = \{r(\xi), \zeta_j, c_j; 1 \leq j \leq N\}$  is called the scattering data of  $L_u$ . Suppose that  $u = iv$  is purely imaginary, then eigenvalues  $\zeta_j$  are distributed symmetrically in  $I_m \zeta > 0$  with respect to the imaginary axis, *i.e.* let  $M$  be a non negative integer  $2M \leq N$ , and  $\pi$  be a permutation among natural number 1 and  $N$  defined  $\pi(j) = j + 1, j \text{ odd } \leq 2M; \pi(j) = j - 1, j \text{ even } \leq 2M; \pi(j) = j, j > 2M$ , then we have

$$(6) \quad \zeta_{\pi(j)} = -\zeta_j^* \quad c_{\pi(j)} = c_j^*$$

(see Tanaka [5] [6]).

## 2. The generalized soliton solutions

For a smooth real valued function  $v=v(x)$ , put

$$B_v = -4D^3 + 3 \begin{bmatrix} -v^2 & iv_x \\ iv_x & -v^2 \end{bmatrix} D + 3D \begin{bmatrix} -v^2 & iv_x \\ iv_x & -v^2 \end{bmatrix}$$

then the operator  $[B_v, L_{iv}] = B_v L_{iv} - L_{iv} B_v$  is the multiplication by the matrix

$$\begin{bmatrix} 0 & -6v^2 v_x - v_{xxx} \\ 6v^2 v_x + v_{xxx} & 0 \end{bmatrix}.$$

Therefore, for a smooth real valued function  $v(t)=v(x, t)$ , the operator evolution equation

$$(7) \quad \frac{d}{dt} L_{iv(t)} = [B_{v(t)}, L_{iv(t)}]$$

is equivalent to the modified  $K$ - $dV$  equation (1). Now suppose that a smooth real valued function  $v(t)=v(x, t)$  is a solution of the modified  $K$ - $dV$  equation (1) which satisfies the conditions for the existence of the scattering data for each  $t$ . Consider the operator  $L_{iv(t)}$ , then we have the scattering data  $S_t = \{r(\xi, t), \zeta_j(t), c_j(t)\}$  depending on  $t$  as a parameter. Then we have

$$(8) \quad \begin{aligned} \zeta_j(t) &= \zeta_j(0) \\ c_j(t) &= c_j(0) \exp(8i\zeta_j^3 t) \\ r(\xi, t) &= r(\xi, 0) \exp(8i\xi^3 t). \end{aligned}$$

These remarkable facts have been derived from the relation (7) (see Tanaka [5] and Wadati [8]). Conversely to the above, Tanaka [6] has shown the following.

**Theorem** (Tanaka [6]). *Let  $\pi$  be a permutation defined above, and  $\zeta_j$  ( $\zeta_i \neq \zeta_j$ ,  $i \neq j$ ),  $c_j$  ( $1 \leq j \leq N$ ) be complex numbers which satisfy the condition (6). Put*

$$\begin{aligned} c_j(t) &= c_j \exp(8i\zeta_j^3 t) \\ \lambda_j &= \lambda_j(x, t) = c_j(t)^{1/2} \exp(i\zeta_j x). \end{aligned}$$

Let  $\psi_{i,j} = \psi_{i,j}(x, t)$ ,  $i=1, 2, j=1, 2, \dots, N$  be the solution of

$$\begin{aligned} \psi_{1,j} + \sum_{k=1}^N \lambda_j \lambda_k^* (\zeta_j - \zeta_k^*)^{-1} \psi_{2,k}^* &= 0 \\ \sum_{k=1}^N \lambda_k \lambda_k^* (\zeta_k - \zeta_j^*)^{-1} \psi_{1,k} + \psi_{2,j}^* &= \lambda_j^* \quad (1 < j < N) \end{aligned}$$

with non degenerate coefficient matrix, then the function

$$(10) \quad v(x, t) = -2 \sum_{j=1}^N \lambda_j^*(x, t) \psi_{2,j}^*(x, t)$$

is a real valued function and satisfies the modified  $K$ - $dV$  equation (1).

If  $N=1$ , then  $\zeta_1=i\eta$ ,  $\eta>0$  and  $c_1=c$  is non zero real number. Therefore we have solutions

$$v(x, t) = (\text{sign } c) s(x-4\eta^2t-\delta, \eta)$$

where

$$s(x, \eta) = -2 \eta \operatorname{sech} 2\eta x$$

and

$$\delta = \delta(c, \eta) = (2\eta)^{-1} \log (|c|/2\eta).$$

These solutions coincide with solutions (2). So we call the solutions  $v(x, t)$  defined by (10) the generalized soliton solutions.

Now let  $M=0$ , then  $\zeta_j=i\eta_j$  ( $\eta_j>0$ ) and  $c_j=c_j(0)$  are real. We can assume  $0<\eta_1<\eta_2<\dots<\eta_N$  without loss of generality. We can now state our main result.

**Theorem.** *Let  $M=0$ , then the generalized soliton solutions decompose into  $N$  solitons as  $t \rightarrow \pm \infty$ ;*

$$v(x, t) - \sum_{j=1}^N (\text{sign } c_j) s(x-4\eta_j^2t-\delta_j^\pm, \eta_j) \rightarrow 0$$

uniformly in  $x$ , where

$$\begin{aligned} \delta_j^+ &= \delta(c_j, \eta_j) + \eta_j^{-1} \log \prod_{i=j+1}^N (\eta_i - \eta_j) (\eta_i + \eta_j)^{-1} \\ \delta_j^- &= \delta(c_j, \eta_j) + \eta_j^{-1} \log \prod_{i=1}^{j-1} (\eta_j - \eta_i) (\eta_j + \eta_i)^{-1}. \end{aligned}$$

### 3. Rearrangement of the formula (10)

In this section we rewrite the generalized soliton solution  $v(x, t)$  (10) into the form which is more convenient for our purpose.

Put  $\phi_{ij} = \phi_{ij}(x, t) = \lambda_j(x, t) \psi_{ij}(x, t)$  ( $i=1, 2, 1 \leq j \leq N$ ). Then we have

$$v(x, t) = -2 \sum_{j=1}^N \phi_{2j}(x, t).$$

Eliminating  $\phi_{1j}$  from (9), we have a system of  $N$  linear algebraic equations for  $\phi_{2j}$

$$(11) \quad \sum_{l=1}^N \alpha_{jl} \phi_{2l} = 1 \quad (1 \leq j \leq N)$$

where

$$(12) \quad \alpha_{jl} = \alpha_{jl}(x, t) = \sum_{i=1}^N \lambda_i^2 (\eta_j + \eta_i)^{-1} (\eta_i + \eta_l)^{-1} + \lambda_j^{-2} \delta_{jl}$$

( $\delta_{jl}$  being Kronecker's symbol).

Let  $V=V(x, t)$  be the determinant of the coefficient matrix  $(\alpha_{kl}(x, t))$  of (11)

and  $V_j = V_j(x, t)$  be the determinant obtained by replacing the  $j$ -th column of  $V$  by  ${}^t(1, 1, \dots, 1)$ . Then by the Cramer's formula we have

$$\phi_{2j}(x, t) = V_j(x, t) V(x, t)^{-1}.$$

Put

$$\mathbf{n}_j = {}^t((\eta_1 + \eta_j)^{-1}, (\eta_2 + \eta_j)^{-1}, \dots, (\eta_N + \eta_j)^{-1}).$$

$$\mathbf{e}_j = {}^t(0, \dots, 0, \overset{j}{1}, 0, \dots, 0)$$

$$\mathbf{e} = {}^t(1, 1, \dots, 1)$$

$$\mathbf{p}_{i,j} = \mathbf{p}_{i,j}(x, t) = c_j(\eta_i + \eta_j)^{-1} \exp(-2\eta_j z_j) \mathbf{n}_j$$

$$\mathbf{q}_j = \mathbf{q}_j(x, t) = c_j^{-1} \exp(2\eta_j z_j) \mathbf{e}_j$$

where  $z_j = x - 4\eta_j^2 t$ . Put  $\Lambda_j = \{1, 2, \dots, j\}$ ,  $\Lambda^j = \{j, j+1, \dots, N\}$  (we denote  $\Lambda_N$  by  $\Lambda$ ). We use the notations as follows.

For  $J \subset \Lambda$ ,  $\sigma \in I(J)$  means that  $\sigma$  is an injective mapping from  $J$  into  $\Lambda$ , for  $j, k \in \Lambda$ ,  $k \leq j$ ,  $\sigma \in B(k, j)$  means that  $\sigma$  is a bijective mapping from  $\Lambda^k - \{j\}$  onto  $\Lambda^{k+1}$ , and  $\sigma \in S^j$  means that  $\sigma$  is a permutation among natural numbers  $j$  and  $N$ . For  $J, J' \subset \Lambda$ , put

$$(13) \quad e(J, J'; x, t) = \exp(2\sum_{i \in J} \eta_i z_i - 2\sum_{i \in J'} \eta_i z_i).$$

Now, for  $J \subset \Lambda$  and  $\sigma \in I(J^c)$ , let  $V(J, \sigma) = V(J, \sigma; x, t)$  be the determinant of  $N$ -th order whose  $i$ -th column coincides with  $\mathbf{q}_i(x, t)$  if  $i \in J$ , and  $\mathbf{P}_{i\sigma(i)}(x, t)$  if  $i \in J$ . Note that

$${}^t(\alpha_{1j}, \alpha_{2j}, \dots, \alpha_{Nj}) = \sum_{i=1}^N \mathbf{p}_{ji}(x, t) + \mathbf{q}_j(x, t)$$

and  $\mathbf{p}_{1j}, \mathbf{p}_{2j}, \dots, \mathbf{p}_{Nj}$  are linearly dependent for each  $x, t$ . Hence, by the  $N$  linearity, we have

$$V(x, t) = \sum_J \sum_{\sigma} V(J, \sigma; x, t)$$

By the way, we can express  $V(J, \sigma)$  as

$$V(J, \sigma; x, t) = K_{J\sigma} e(J, \sigma(J^c); x, t)$$

( $K_{J\sigma}$  being a constant which can be determined easily). So  $V(x, t)$  is some linear combination of functions (13).

Similarly to the above, for  $j \in \Lambda$ ,  $J \subset \Lambda - \{j\}$ , and  $\sigma \in I((J \cup \{j\})^c)$ , let  $V(j, J, \sigma) = V(j, J, \sigma; x, t)$  be the determinant of  $N$ -th order whose  $i$ -th column coincides with  $\mathbf{q}_i(x, t)$  if  $i \in J$ ,  $\mathbf{p}_{i\sigma(i)}(x, t)$  if  $i \in (J \cup \{j\})^c$  and  $\mathbf{e}$  if  $i=j$ , then we have

$$V_j(x, t) = \sum_J \sum_{\sigma} V(j, J, \sigma; x, t).$$

Now, Theorem (for  $t \rightarrow \infty$ ) reduces to

**Theorem'.** Put, for  $j \in \Lambda$

$$v_j = v_j(x, t) = -2 \sum_{i=j}^N \sum_{\sigma \in B(j, i)} V(i, \Lambda_{j-1}, \sigma; x, t) V(x, t)^{-1}$$

and

$$R = R(x, t) = v(x, t) - \sum_{j=1}^N v_j(x, t)$$

then as  $t \rightarrow \infty$

$$v_j(x, t) - (\text{sign } c_j) s(x - 4\eta_j^2 t - \delta_j^+, \eta_j) \rightarrow 0$$

and

$$R(x, t) \rightarrow 0$$

uniformly in  $x$ .

#### 4. Proof of Theorem '

It is necessary for our purpose to determine the coefficients of  $e(\Lambda_j, \Lambda^{j+1}; x, t)$ ,  $j=0, 1, 2, \dots, N$ , in  $V(x, t)$  (we denote them by  $K_j$ ) and  $e(\Lambda_{j-1}, \Lambda^{j+1}; x, t)$ ,  $j=1, 2, \dots, N$ , in the numerator of the generalized soliton solution (expressed by the Cramer's formula)

$$-2 \sum_{j=1}^N V_j(x, t)$$

(we denote them by  $M_j$ ). Then we have

**Lemma 1.**

$$K_j = \prod_{i=1}^j c_i^{-1} \prod_{i=j+1}^N c_i \det(e_1, \dots, e_j, n_{j+1}, \dots, n_N)^2$$

and

$$M_j = \prod_{i=1}^{j-1} c_i^{-1} \prod_{i=j+1}^N c_i \det(e_1, \dots, e_{j-1}, e, n_{j+1}, \dots, n_N)^2.$$

Proof. One can see immediately that

$$\sum_{\sigma \in S^{j+1}} V(\Lambda_j, \sigma; x, t) = K_j e(\Lambda_j, \Lambda^{j+1}; x, t).$$

Therefore, we have

$$K_j = \prod_{i=1}^j c_i^{-1} \prod_{i=j+1}^N c_i \sum_{\sigma \in S^{j+1}} \prod_{i=j+1}^N (\eta_i + \eta_{\sigma(i)})^{-1} \det(e_1, \dots, e_j, n_{\sigma(j+1)}, \dots, n_{\sigma(N)} \mathbf{n}).$$

By the way, the relations

$$\det(\mathbf{e}_1, \dots, \mathbf{e}_j \mathbf{n}_{\sigma(j+1)}, \dots, \mathbf{n}_{\sigma(N)}) = (\text{sign } \sigma) \det(\mathbf{e}_1, \dots, \mathbf{e}_j, \mathbf{n}_{j+1}, \dots, \mathbf{n}_N)$$

and

$$\sum_{\sigma \in S^{j+1}} (\text{sign } \sigma) \prod_{i=j+1}^N (\eta_i + \eta_{\sigma(i)})^{-1} = \det(\mathbf{e}_1, \dots, \mathbf{e}_j, \mathbf{n}_{j+1}, \dots, \mathbf{n}_N)$$

hold.

Next, note that

$$(14) \quad -2 \sum_{i=j}^N \sum_{\sigma \in B(j,i)} V(i, \Lambda_{j-1} \sigma; x, t) = M_j e(\Lambda_{j-1}, \Lambda^{j+1}; x, t).$$

The calculation for  $M_j$  is completely parallel to the above.

Q.E.D.

Next we have

**Lemma 2.** As  $t \rightarrow \infty$

$$v_j(x, t) - (\text{sign } c_j) s(x - 4\eta_j^2 t - \delta_j^+, \eta_j) \rightarrow 0$$

uniformly in the infinite sector

$$(15) \quad -\varepsilon t \leq z_j = x - 4\eta_j^2 t \leq \varepsilon t, \quad t > 0$$

where  $\varepsilon$  is sufficiently small positive constant e.g.  $0 < \varepsilon < 2 \text{Min}_{1 \leq i \leq N-1} (\eta_{i+1}^2 - \eta_i^2)$ .

Proof. Recall that  $V(x, t)$  is a linear combination of functions (13).

Therefore, it is easy to see that

$$(16) \quad e(\Lambda^{j+1}, \Lambda_{j-1}; x, t) V(x, t) = K_{j-1} \exp(-2\eta_j z_j) (1 + B_{j,1}(x, t)) \\ + K_j \exp(2\eta_j z_j) (1 + B_{j,2}(x, t)) + B_{j,3}(x, t)$$

where  $B_{jk}(x, t)$  ( $k=1, 2, 3$ ) are polynomials of  $\exp(\pm 2\eta_i z_i)$ ,  $\pm i \geq \pm j + 1$  whose constant terms are equal to zero. If  $(x, t)$  is in the sector (15), then we have

$$(17) \quad \exp(\pm 2\eta_i z_i) \leq \exp(\pm 4\eta_i(\eta_j^2 - \eta_j^2)t), \quad (\pm i \geq \pm j + 1).$$

Therefore, for  $t \rightarrow \infty$ ,  $B_{jk}(x, t)$  converge to zero uniformly in the sector (15).

Hence, for large  $t$

$$(e(\Lambda^{j+1}, \Lambda_{j-1}; x, t) V(x, t))^{-1}$$

behaves like

$$(K_{j-1} \exp(-2\eta_j z_j) + K_j \exp(2\eta_j z_j))^{-1}$$

in the sector (15). Recall that (see (14))

$$v_j(x, t) = M_j e(\Lambda_{j-1}, \Lambda^{j+1}; x, t) V(x, t)^{-1}$$

and put

$$u_j = u_j(x, t) = M_j \cdot (K_{j-1} \exp(-2\eta_j z_j) + K_j \exp(2\eta_j z_j))^{-1}.$$

Then, for large  $t$ ,  $v_j(x, t)$  behaves like  $u_j(x, t)$  in the sector (15). One can see that

$$u_j(x, t) = (\text{sign } c_j) s(x - 4\eta_j^2 t - \delta_j^+, \eta_j)$$

by the relations (see Lemma 1)

$$K_{j-1}/M_j = c_j (2\eta_j)^{-2} \prod_{i=j+1}^N (\eta_i + \eta_j)^2 (\eta_i + \eta_j)^{-2}$$

and

$$K_j/M_j = c_j^{-1} \prod_{i=j+1}^N (\eta_i + \eta_j)^2 (\eta_i - \eta_j)^{-2}. \quad \text{Q.E.D.}$$

Next we have

**Lemma 3.**

i)  $(e(\Lambda^{j+1}, \Lambda_{j-1}; x, t) V(x, t))^{-1}$  and  $\exp(\pm 2\eta_j z_j) (e(\Lambda^{j+1}, \Lambda_{j-1}; x, t) V(x, t))^{-1}$  are bounded in the sector (15).

ii)  $(e(\Lambda^{j+1}, \Lambda_j; x, t) V(x, t))^{-1}$  is bounded in the sector

$$(18) \quad (4\eta_j^2 + \varepsilon)t \leq x \leq (4\eta_{j+1}^2 - \varepsilon)t, \quad t > 0.$$

(If  $j=0, N$ , then (18) are the half spaces  $x \leq (4\eta_1^2 - \varepsilon)t$  and  $(4\eta_N^2 + \varepsilon)t \leq x$  respectively.)

Proof. i) is a direct consequences of the fact that a soliton is bounded.

ii) Similarly to Lemma 2, one can show that for large  $t$

$$(e(\Lambda^{j+1}, \Lambda_{j-1}; x, t) V(x, t))^{-1} \quad j = 0, 1, \dots, N$$

behaves like  $1/K_j$  in the sector (18). And  $K_j$  is not equal to zero. Q.E.D.

For  $k \in \Lambda$ ,  $J \subset \Lambda - \{k\}$ , and  $\sigma \in I((J \cap \{k\})^c)$  put

$$(k, J, \sigma)_+ = J - J \cap \sigma(J \cup \{k\})^c$$

and

$$(k, J, \sigma)_- = \sigma(J \cup \{k\})^c - J \cap \sigma(J \cup \{k\})^c$$

then we have

$$(19) \quad V(k, J, \sigma; x, t) V(x, t)^{-1} = K e((k, J, \sigma)_+, (k, J, \sigma)_-; x, t) V(x, t)^{-1}.$$

Next we have

**Lemma 4.** *If*

$$(20) \quad \{(k, J, \sigma)_-^c \cap \Lambda^{j+1}\} \cup \{(k, J, \sigma)_+^c \cap \Lambda_{j-1}\}$$

*is not empty, then  $V(k, J, \sigma) V^{-1}$  converges to zero uniformly in the infinite sector*

$$-\varepsilon t \leq x - 4\eta_j^2 t \leq \varepsilon t.$$

*Proof.* By (19) and Lemma 3, there is  $K > 0$  such that

$|V(k, J, \sigma; x, t) V(x, t)^{-1}| \leq K e((k, J, \sigma)_+^c, (k, J, \sigma)_+^c; x, t) e(\Lambda^{j+1}, \Lambda_{j-1}; x, t)$  where  $(k, J, \sigma)_\pm^c = (k, J, \sigma)_\pm - \{j\}$  if  $j \in (k, J, \sigma)_\pm^c$ . If (20) is not empty, then  $e((k, J, \sigma)_+^c, (k, J, \sigma)_+^c; x, t) e(\Lambda^{j+1}, \Lambda_{j-1}, x, t)$  is a finite product of  $\exp(\pm 2\eta_i z_i)$ ,  $\pm i \geq \pm j + 1$ , and is not constant. Q.E.D.

If (20) is empty, then

$$(k, J, \sigma)_+ \supset \Lambda_{j-1}, \quad (k, J, \sigma)_- \supset \Lambda^{j+1}.$$

Note that

$$(k, J, \sigma)_+ \cap (k, J, \sigma)_- = \phi$$

$$(21) \quad |(k, J, \sigma)_+| + |(k, J, \sigma)_-| \leq N - 1.$$

Therefore we have

$$(k, J, \sigma)_+ = \Lambda_{j-1} \quad (k, J, \sigma)_- = \Lambda^{j+1}.$$

This implies that

$$(22) \quad k \geq j, J = \Lambda_{j-1}, \text{ and } \sigma \in B(j, k).$$

Hence, (20) is empty, if and only if (22) holds.

Therefore, by Lemma 4, as  $t \rightarrow \infty$ ,  $v_i(x, t)$ ,  $i \neq j$ , and  $R(x, t)$  converge to zero uniformly in the sector  $-\varepsilon t \leq x - 4\eta_j^2 t \leq \varepsilon t$ ,  $t > 0$ .

Next we have

**Lemma 5.** *As  $t \rightarrow \infty$ ,  $V(k, J, \sigma; x, t) V(x, t)^{-1}$  converges to zero uniformly in the infinite sector*

$$(4\eta_j^2 + \varepsilon)t \leq x \leq (4\eta_{j+1}^2 - \varepsilon)t, \quad t > 0$$

*for any  $k, j, J$  and  $\sigma$ .*

*Proof.* By Lemma 3, there is  $K > 0$  such that

$$|V(k, J, \sigma; x, t) V(x, t)^{-1}| \leq K e((k, J, \sigma)_+, (k, J, \sigma)_-; x, t) e(\Lambda^{j+1}, \Lambda_{j-1}; x, t)$$

$e((k, J, \sigma)_+, (k, J, \sigma)_-; x, t) e(\Lambda^{j+1}, \Lambda_{j-1}; x, t)$  is a finite product of  $\exp(-2\eta_i z_i)$ ,  $i \leq j$  and  $\exp(2\eta_i z_i)$ ,  $i \geq j + 1$ , and is not constant, because of the relation (21). Similarly to (17), it is easy to see that  $-2\eta_i z_i$ ,  $i \leq j$  and  $2\eta_i z_i$ ,  $j \geq 1$  can be estimated by  $B_i t, B_i < 0$ . Q.E.D.

This complete the proof of Theorem '.

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