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of integrable wave equations**

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REPORT No. 4, 2012/2013, spring

ISSN 1103-467X

ISRN IML-R- -4-12/13- -SE+spring

A coupling problem for entire functions and its application to the long-time asymptotics of integrable wave equations

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Abstract. We propose a novel technique for analyzing the long-time asymptotics of integrable wave equations in the case when the underlying isospectral problem has purely discrete spectrum. To this end, we introduce a natural coupling problem for entire functions, which serves as a replacement for the usual Riemann–Hilbert problem, which does not apply in these cases. As a prototypical example, we investigate the long-time asymptotics of the dispersionless Camassa–Holm equation.

1. Introduction

Integrable wave equations play a key role in understanding numerous phenomena in science. In this connection, understanding the long-time asymptotics of solutions is crucial. Roughly speaking, the typical behavior is that any (sufficiently fast) decaying initial profile splits into a number of solitons plus a decaying dispersive part. This has been first observed numerically for the Korteweg–de Vries equation [30]. Corresponding asymptotic formulas were derived and justified with increasing level of rigor over the last thirty years. To date, the most powerful method for deriving such long-time asymptotics is the nonlinear steepest descent method from Deift and Zhou [11], which was inspired by earlier work of Manakov [24] and Its [19]. More on this method and its history can be found in the survey [12]; an expository introduction to this method for the Korteweg–de Vries equation can be found in [17].

Although this method has found to be applicable to a wide range of integrable wave equations, there are still some exceptions. The most notable one is the Camassa–Holm equation, also known as the dispersive shallow water equation,

$$u_t - u_{xxt} + 2\kappa u_x = 2u_x u_{xx} - 3uu_x + uu_{xxx}, \quad x, t \in \mathbb{R}, \quad (1.1)$$

where $u \equiv u(x, t)$ is the fluid velocity in the x direction, $\kappa \geq 0$ is a constant related to the critical shallow water wave speed, and subscripts denote partial derivatives. It was first introduced by Camassa and Holm in [7] and Camassa et al. [8] as a model for shallow water waves, but it actually already appeared earlier in a list by Fuchssteiner and Fokas [16]. Regarding the hydrodynamical relevance of this

2010 *Mathematics Subject Classification.* Primary 37K40, 35Q35; Secondary 30D20, 37K20.

Keywords. Coupling problem, long-time asymptotics, Camassa–Holm equation.

Research supported by the Austrian Science Fund (FWF) under Grant No. Y330 and by the AXA Research Fund under the Mittag-Leffler Fellowship Project.

equation, let us also mention the more recent articles by Johnson [20], Ionescu-Kruse [18] as well as Constantin and Lannes [10].

While in the case $\varkappa > 0$ there is an underlying Riemann–Hilbert problem which can be analyzed using the nonlinear steepest descent method [4], [5], [6], this breaks down in the limiting case $\varkappa = 0$. In this case, the solitons are no longer smooth but have a single peak and hence are also known as peakons. Nevertheless, it was conjectured by McKean [25] (cf. also [26], [27]) that solutions split into a train of peakons, in accordance with earlier numerical observations by Camassa et al. [8]. However, apart from the multi-peakon case [2] (and some low-regularity solutions [22] as well as for a simplified flow [23]), this has been an open problem, resolved only recently by us in [15]. The technical problem here stems from the fact that the underlying isospectral problem has purely discrete spectrum and hence it is no longer possible to set up the usual scattering theory. Our approach in [15] circumvented this shortcoming by a thorough investigation of the associated isospectral problem, which then allowed us to deduce long-time asymptotics. However, this approach has still some drawbacks. For example, it is not possible to obtain long-time asymptotics which hold uniformly in sectors.

The aim of the present article is to propose a novel approach to such kind of problems, which seems to be more natural. In some sense, it can be thought of as an adaptation of the usual Riemann–Hilbert problem approach. More precisely, we will replace the Riemann–Hilbert problem with a certain coupling problem for entire functions. Consequently, we will investigate the asymptotic behavior of solutions to this problem under known behavior of the given data.

As a prototypical example, we will apply our results to derive long-time asymptotics for the dispersionless Camassa–Holm equation. However, we expect that this new technique will also work for other equations, whose underlying isospectral problem exhibits purely discrete spectrum. For example, it can immediately be applied to derive long-time asymptotics for corresponding equations in the whole Camassa–Holm hierarchy. While for the positive members of this hierarchy one gets qualitatively the same asymptotic picture, the situation is somewhat different for the negative ones (including for instance the extended Dym equation). Although solutions of negative members of the Camassa–Holm hierarchy still split into a train of peakons, their speed will be proportional to the modulus of the corresponding eigenvalue. This causes the larger peakons to be the slower ones and the smaller peakons to be the faster ones, creating a qualitatively different picture.

2. Coupling problem

The purpose of this section is to introduce the notion of a *coupling problem* for entire functions. To this end, consider a fixed discrete set $\sigma \subseteq \mathbb{R}$ such that the sum

$$\sum_{\lambda \in \sigma} \frac{1}{|\lambda|} \tag{2.1}$$

is finite. It is well known that under this condition, the infinite product

$$W(z) = \prod_{\lambda \in \sigma} \left(1 - \frac{z}{\lambda}\right), \quad z \in \mathbb{C}, \tag{2.2}$$

converges locally uniformly to an entire function of exponential type zero [3, Lemma 2.10.13], [21, Theorem 5.3]. Furthermore, we introduce the quantities $\eta_\lambda \in \mathbb{R} \cup \{\infty\}$ for each $\lambda \in \sigma$ which are referred to as the *coupling constants*.

Definition 2.1. *A solution of the coupling problem with data $\{\eta_\lambda\}_{\lambda \in \sigma}$ is a pair of entire functions (Φ_-, Φ_+) of exponential type zero such that the following three conditions are satisfied:*

(C) *Coupling condition:*

$$\Phi_+(\lambda) = \eta_\lambda \Phi_-(\lambda), \quad \lambda \in \sigma$$

(G) *Growth and positivity condition:*

$$\operatorname{Im} \left(\frac{z \Phi_-(z) \Phi_+(z)}{W(z)} \right) \geq 0, \quad \operatorname{Im}(z) > 0$$

(N) *Normalization condition:*

$$\Phi_-(0) = \Phi_+(0) = 1$$

In order to be precise, if $\eta_\lambda = \infty$ for some $\lambda \in \sigma$, then the coupling condition (C) in this definition has to be read as $\Phi_-(\lambda) = 0$. The growth and positivity condition (G) means that the meromorphic function

$$\frac{z \Phi_-(z) \Phi_+(z)}{W(z)}, \quad z \in \mathbb{C} \setminus \mathbb{R}, \quad (2.3)$$

is a so-called Herglotz–Nevanlinna function, which satisfy certain growth restrictions (to be seen from their integral representations; [1, Chapter 6], [28, Chapter 5]). Moreover, let us mention that since the residues of such a function are known to be nonpositive, condition (G) also requires the necessary presumption

$$\frac{\lambda \Phi_-(\lambda)^2}{W(\lambda)} \eta_\lambda \leq 0, \quad \lambda \in \sigma, \quad (2.4)$$

on the sign of all coupling constants which are finite. Thus the coupling constants corresponding to the smallest (in modulus) positive and negative element of σ have to be nonnegative. The consecutive coupling constants then have to be alternating nonpositive and nonnegative. Furthermore, the condition (G) also tells us that the zeros of the numerator and the denominator of the function in (2.3) are interlacing (after cancelation) [21, Theorem 27.2.1]. In particular, this guarantees that the sums

$$\sum_{\mu \in \rho_\pm} \frac{1}{|\mu|} \quad (2.5)$$

are finite, where ρ_\pm denote the sets of all (necessarily simple) zeros of the functions Φ_\pm . As a consequence, these functions can be written as the canonical products

$$\Phi_\pm(z) = \prod_{\mu \in \rho_\pm} \left(1 - \frac{z}{\mu} \right), \quad z \in \mathbb{C}, \quad (2.6)$$

bearing in mind the normalization condition (N). Finally, we mention the bounds

$$|\Phi_\pm(z)| \leq \prod_{\lambda \in \sigma} \left(1 + \frac{|z|}{|\lambda|} \right), \quad z \in \mathbb{C}, \quad (2.7)$$

upon roughly estimating (2.6) and employing the interlacing condition once more.

The simplest case of a coupling problem prevails when the set σ consists of only one point. In this case, it is indeed possible to write down the solution explicitly in terms of the one single coupling constant.

Proposition 2.2. *Suppose that $\sigma = \{\lambda_0\}$ for some nonzero $\lambda_0 \in \mathbb{R}$. If the coupling constant $\eta_{\lambda_0} \in \mathbb{R} \cup \{\infty\}$ is not negative, then the coupling problem has a unique solution given by*

$$\Phi_{\pm}(z) = \left(1 - z \frac{1 - \min(1, \eta_{\lambda_0}^{\pm 1})}{\lambda_0}\right), \quad z \in \mathbb{C}. \quad (2.8)$$

Proof. It is readily verified that the given polynomials are indeed a solution of the coupling problem. Conversely, if (Ψ_-, Ψ_+) is another solution, then

$$\Psi_{\pm}(z) = 1 - a_{\pm}z, \quad z \in \mathbb{C},$$

for some $a_{\pm} \in \mathbb{R}$ with $a_- a_+ = 0$. Moreover, we infer that $0 \leq a_{\pm} \lambda_0 \leq 1$ in view of the Herglotz–Nevanlinna property (more precisely, from the interlacing condition of the poles and zeros). Lastly, the coupling condition (C) takes the form

$$1 - a_+ \lambda_0 = \eta_{\lambda_0} (1 - a_- \lambda_0).$$

Now if $\eta_{\lambda_0} \leq 1$, then necessarily $a_- = 0$ since otherwise we get the contradiction

$$1 = \eta_{\lambda_0} (1 - a_- \lambda_0) < 1.$$

Consequently, we may express a_+ in terms of the coupling constant using the coupling condition. In much the same manner, one may obtain the coefficients a_{\pm} if $\eta_{\lambda_0} \geq 1$ and finally end up with

$$a_{\pm} = \frac{1 - \min(1, \eta_{\lambda_0}^{\pm 1})}{\lambda_0}$$

in either case, which finishes the proof. \square

Note that there is no solution of the coupling problem in Proposition 2.2 if the coupling constant is negative, since it would violate the positivity condition (G).

3. Asymptotic analysis

We shall now derive a general result on the asymptotic behavior of solutions to the coupling problem. Therefore, let Δ be a first-countable topological space (that is, every point has a countable neighborhood basis) and fix some $\delta_{\infty} \in \Delta$. Again, we denote with $\sigma \subseteq \mathbb{R}$ a discrete set such that the sum (2.1) is finite and define the entire function W by (2.2). Moreover, for every $\delta \in \Delta$ we consider a set of coupling constants $\eta_{\lambda}(\delta) \in \mathbb{R} \cup \{\infty\}$ indexed by $\lambda \in \sigma$.

Theorem 3.1. *Suppose there is a partition $\sigma_- \cup \{\lambda_0\} \cup \sigma_+$ of σ such that*

$$-\ln |\eta_{\lambda}(\delta)| \rightarrow \pm\infty \quad (3.1)$$

as $\delta \rightarrow \delta_{\infty}$ for each $\lambda \in \sigma_{\pm}$ and define the conjugated coupling constants by

$$\hat{\eta}_{\lambda_0}(\delta) = \eta_{\lambda_0}(\delta) \prod_{\lambda \in \sigma_-} \left(1 - \frac{\lambda_0}{\lambda}\right) \prod_{\lambda \in \sigma_+} \left(1 - \frac{\lambda_0}{\lambda}\right)^{-1}, \quad \delta \in \Delta. \quad (3.2)$$

If the pairs $(\Phi_-(\cdot, \delta), \Phi_+(\cdot, \delta))$ are solutions of the coupling problem with data $\{\eta_\lambda(\delta)\}_{\lambda \in \sigma}$ for every $\delta \in \Delta$, then

$$\frac{\Phi_-(z, \delta)\Phi_+(z, \delta)}{W(z)} = 1 + \frac{z}{\lambda_0 - z} \min(\hat{\eta}_{\lambda_0}(\delta)^{-1}, \hat{\eta}_{\lambda_0}(\delta)) + o(1) \quad (3.3)$$

as $\delta \rightarrow \delta_\infty$, locally uniformly for all $z \in \mathbb{C} \setminus \sigma$.

Proof. First consider a sequence $\delta_k \in \Delta$, $k \in \mathbb{N}$ with $\delta_k \rightarrow \delta_\infty$ as $k \rightarrow \infty$ such that the entire functions $\Phi_\pm(\cdot, \delta_k)$ converge locally uniformly as $k \rightarrow \infty$. The respective limits are entire functions of exponential type zero in view of (2.7) and will be denoted by Ψ_\pm . Due to assumption (3.1) and the coupling condition, we conclude that $\Psi_\pm(\lambda) = 0$ for $\lambda \in \sigma_\pm$ (also observe that the quantities $\Phi_\pm(\lambda, \delta)$ are uniformly bounded in $\delta \in \Delta$). As a consequence, the meromorphic Herglotz–Nevanlinna function

$$\frac{z\Psi_-(z)\Psi_+(z)}{W(z)}, \quad z \in \mathbb{C} \setminus \mathbb{R}, \quad (3.4)$$

has only one pole and thus at most two zeros, which are necessarily simple. Consequently, we may write (keep in mind that these functions are of exponential type zero and that their zeros have genus zero)

$$\Psi_\pm(z) = P_\pm(z) \prod_{\lambda \in \sigma_\pm} \left(1 - \frac{z}{\lambda}\right), \quad z \in \mathbb{C},$$

where P_\pm are polynomials such that P_-P_+ has at most one zero, which is simple. Moreover, the pair (P_-, P_+) satisfies the coupling condition

$$P_+(\lambda_0) = \eta_{\lambda_0, \infty} P_-(\lambda_0),$$

where the constant $\eta_{\lambda_0, \infty} \in \mathbb{R} \cup \{\infty\}$ is given as the limit

$$\eta_{\lambda_0, \infty} = \prod_{\lambda \in \sigma_-} \left(1 - \frac{\lambda_0}{\lambda}\right) \prod_{\lambda \in \sigma_+} \left(1 - \frac{\lambda_0}{\lambda}\right)^{-1} \lim_{k \rightarrow \infty} \Phi_+(\lambda_0, \delta_k) \Phi_-(\lambda_0, \delta_k)^{-1}.$$

Hereby note that the limit is nonnegative because of (2.4). In view of Proposition 2.2 we now may write down the polynomials P_\pm explicitly and conclude that

$$\frac{\Phi_-(z, \delta_k)\Phi_+(z, \delta_k)}{W(z)} \rightarrow 1 + \frac{z}{\lambda_0 - z} \min\left(\eta_{\lambda_0, \infty}^{-1}, \eta_{\lambda_0, \infty}\right)$$

as $k \rightarrow \infty$, locally uniformly in $z \in \mathbb{C} \setminus \sigma$. Finally, from the very definition of the constants $\eta_{\lambda_0, \infty}$ we may also rewrite this as

$$\frac{\Phi_-(z, \delta_k)\Phi_+(z, \delta_k)}{W(z)} = 1 + \frac{z}{\lambda_0 - z} \min(\hat{\eta}_{\lambda_0}(\delta)^{-1}, \hat{\eta}_{\lambda_0}(\delta)) + o(1)$$

as $k \rightarrow \infty$, locally uniformly in $z \in \mathbb{C} \setminus \sigma$.

Finally, if the claim of the theorem was not true, then there would be a compact set $K \subseteq \mathbb{C} \setminus \sigma$ and a subsequence $\delta_k \in \Delta$, $k \in \mathbb{N}$ with $\delta_k \rightarrow \delta_\infty$ as $k \rightarrow \infty$ such that

$$\left| \frac{\Phi_-(z, \delta_k)\Phi_+(z, \delta_k)}{W(z)} - 1 - \frac{z}{\lambda_0 - z} \min(\hat{\eta}_{\lambda_0}(\delta_k)^{-1}, \hat{\eta}_{\lambda_0}(\delta_k)) \right| > \varepsilon \quad (3.5)$$

for all $z \in K$, $k \in \mathbb{N}$ and some $\varepsilon > 0$. However, a compactness argument (recall (2.7) and apply Montel's theorem) shows that there is a subsequence δ_{k_l} such that $\Phi_\pm(\cdot, \delta_{k_l})$ converges locally uniformly as $l \rightarrow \infty$. In view of the first part of the proof, this gives a contradiction to (3.5). \square

The assumptions in Theorem 3.1 allow one of the coupling constants to be arbitrary. This will turn out to be crucial to obtain long-time asymptotics of the Camassa–Holm equation which are valid uniformly in sectors. However, in the case when all of the coupling constants are supposed to converge to zero or infinity, one obtains the following result.

Corollary 3.2. *Suppose that we have $|\ln |\eta_\lambda(\delta)|| \rightarrow \infty$ as $\delta \rightarrow \delta_\infty$ for every $\lambda \in \sigma$. If the pairs $(\Phi_-(\cdot, \delta), \Phi_+(\cdot, \delta))$ are solutions of the coupling problem with data $\{\eta_\lambda(\delta)\}_{\lambda \in \sigma}$ for every $\delta \in \Delta$, then*

$$\frac{\Phi_-(z, \delta)\Phi_+(z, \delta)}{W(z)} \rightarrow 1 \quad (3.6)$$

as $\delta \rightarrow \delta_\infty$, locally uniformly for all $z \in \mathbb{C} \setminus \sigma$.

Proof. Similarly to the first part of the proof of Theorem 3.1, one infers that

$$\frac{\Phi_-(z, \delta_k)\Phi_+(z, \delta_k)}{W(z)} \rightarrow 1$$

as $k \rightarrow \infty$, locally uniformly for all $z \in \mathbb{C} \setminus \sigma$ as long as the functions $\Phi_\pm(\cdot, \delta_k)$ are assumed to converge locally uniformly. In fact, this follows since the function in (3.4) is now known to have no poles at all. Now the claim follows in much the same manner as in the second part of the proof of Theorem 3.1, invoking a compactness argument. \square

4. Applications to the Camassa–Holm equation

As anticipated in the introduction, we will now demonstrate that our results provide a powerful tool to derive long-time asymptotics for the dispersionless Camassa–Holm equation. To this end, let u be a solution of

$$u_t - u_{xxt} = uu_{xxx} - 3uu_x + 2u_xu_{xx} \quad (4.1)$$

with decaying spatial asymptotics. To be precise, we will assume that the quantities

$$\omega(x, t) = u(x, t) - u_{xx}(x, t), \quad x \in \mathbb{R}, \quad (4.2)$$

are finite signed measure for each time $t \geq 0$.

These conditions guarantee (see [15, Theorem 3.1]) that for every time $t \geq 0$ and $z \in \mathbb{C}$, there are unique solutions $\phi_\pm(z, \cdot, t)$ of the differential equation

$$-\phi_\pm''(z, x, t) + \frac{1}{4}\phi_\pm(z, x, t) = z\omega(x, t)\phi_\pm(z, x, t), \quad x \in \mathbb{R}, \quad (4.3)$$

(the prime denotes spatial differentiation) with the spatial asymptotics

$$\phi_\pm(z, x, t) \sim e^{\mp \frac{x}{2}}, \quad \phi_\pm'(z, x, t) \sim \mp \frac{1}{2}e^{\mp \frac{x}{2}}, \quad x \rightarrow \pm\infty. \quad (4.4)$$

In view of [15, Theorem 4.1], it is known that these solutions are real entire and of exponential type zero with respect to the spectral parameter.

Now the importance of the spectral problems (4.3) lies in the well-known fact that their spectra are invariant under the Camassa–Holm flow, that is, they are the same for all times $t \geq 0$ (for example, we refer to [2, Section 2], [7], [9, Section 3],

[14, Theorem 5.1]). For this reason, we may simply denote the spectrum of (4.3) with σ , which is known to be real and purely discrete such that the sum

$$\sum_{\lambda \in \sigma} \frac{1}{|\lambda|} \quad (4.5)$$

is finite, in view of [15, Proposition 3.3]. The Wronskian of our two solutions

$$W(z) = \phi_+(z, x, t)\phi'_-(z, x, t) - \phi'_+(z, x, t)\phi_-(z, x, t), \quad z \in \mathbb{C}, \quad (4.6)$$

turns out to be independent of space $x \in \mathbb{R}$ and time $t \geq 0$. Indeed, this function is the characteristic function of the spectral problem (4.3), that is,

$$W(z) = \prod_{\lambda \in \sigma} \left(1 - \frac{z}{\lambda}\right), \quad z \in \mathbb{C}, \quad (4.7)$$

in view of [15, Corollary 4.2].

In order to point out the connection to the coupling problem for entire functions, one observes that the solutions $\phi_+(\lambda, \cdot, t)$ and $\phi_-(\lambda, \cdot, t)$ are linearly dependent for every eigenvalue $\lambda \in \sigma$ and time $t \geq 0$. Hence there is some nonzero real $c_\lambda(t) \in \mathbb{R}$ such that we may write

$$\phi_+(\lambda, x, t) = c_\lambda(t)\phi_-(\lambda, x, t), \quad x \in \mathbb{R}. \quad (4.8)$$

The time evolution for these quantities is known to be given explicitly by

$$c_\lambda(t) = c_\lambda(0)e^{-\frac{t}{2\lambda}}, \quad t \geq 0, \quad \lambda \in \sigma. \quad (4.9)$$

More precisely, this follows from the well-known time evolution of the associated norming constants (for example, see [2, Section 2], [9, Section 3], [14, Theorem 5.1]) and the identity in [15, Lemma 3.2],

$$-\dot{W}(\lambda) = c_\lambda(t) \int_{\mathbb{R}} \phi_-(\lambda, x, t)^2 d\omega(x, t), \quad t \geq 0, \quad \lambda \in \sigma, \quad (4.10)$$

where the dot denotes differentiation with respect to the spectral parameter.

We have now collected all necessary ingredients to prove the announced long-time asymptotics for the solution u of the Camassa–Holm equation. In fact, the proof of this result is almost immediate from the general results on asymptotic analysis for our coupling problem of entire functions derived in the previous section.

Theorem 4.1. *Let $S \subseteq \mathbb{R} \times (0, \infty)$ be a closed sector which contains at most finitely many of the rays r_λ , $\lambda \in \sigma$ given by $2\lambda x = t$. Then we have*

$$u(x, t) = \sum_{\lambda \in \sigma} \frac{1}{2\lambda} e^{-|x - \frac{t}{2\lambda} + \xi_\lambda|} + o(1) \quad (4.11)$$

for $(x, t) \in S$ as $t \rightarrow \infty$, where the phase shifts ξ_λ for each $\lambda \in \sigma$ are given by

$$\xi_\lambda = \ln |c_\lambda(0)| + \sum_{\kappa \in \sigma \setminus \{\lambda\}} \operatorname{sgn} \left(\frac{1}{\lambda} - \frac{1}{\kappa} \right) \ln \left| 1 - \frac{\lambda}{\kappa} \right|, \quad \lambda \in \sigma. \quad (4.12)$$

Proof. For every $x \in \mathbb{R}$ and $t \geq 0$ we introduce the entire functions

$$\Phi_\pm(z, x, t) = e^{\pm \frac{x}{2}} \phi_\pm(z, x, t), \quad z \in \mathbb{C},$$

which will turn out to be a solution of a particular coupling problem. In fact, one clearly has the coupling condition (C)

$$\Phi_+(\lambda, x, t) = e^{x - \frac{t}{2\lambda}} c_\lambda(0) \Phi_-(\lambda, x, t), \quad \lambda \in \sigma. \quad (4.13)$$

Moreover, due to [13, Proposition 4.4], the function

$$\frac{z \Phi_-(z, x, t) \Phi_+(z, x, t)}{W(z)} = \left(\frac{\phi'_-(z, x, t)}{z \phi_-(z, x, t)} - \frac{\phi'_+(z, x, t)}{z \phi_+(z, x, t)} \right)^{-1}, \quad z \in \mathbb{C} \setminus \mathbb{R},$$

is a Herglotz–Nevanlinna function, ensuring the growth and positive condition (G). In fact, this can also be verified by a direct calculation, using the differential equation (4.3). Finally, the normalization condition (N) is immediate from the definition.

We will first consider the special case when the sector S contains precisely one ray, say r_{λ_0} for some $\lambda_0 \in \sigma$. Upon defining the sets $\sigma_{\pm} \subseteq \sigma$ by

$$\sigma_{\pm} = \{\lambda \in \sigma \mid \pm \lambda_0^{-1} < \pm \lambda^{-1}\},$$

one obtains a partition $\sigma_- \cup \{\lambda_0\} \cup \sigma_+$ of σ such that

$$\mp \left(\frac{x}{t} - \frac{1}{2\lambda} \right) > \varepsilon_{\lambda}, \quad (x, t) \in S, \quad \lambda \in \sigma_{\pm},$$

for some $\varepsilon_{\lambda} > 0$, $\lambda \in \sigma_{\pm}$. Therefore, the coupling constants in (4.13) satisfy

$$-\ln \left| e^{x - \frac{t}{2\lambda}} c_{\lambda}(0) \right| = - \left(\frac{x}{t} - \frac{1}{2\lambda} \right) t - \ln |c_{\lambda}(0)| \rightarrow \pm \infty, \quad \lambda \in \sigma_{\pm},$$

for $(x, t) \in S$ as $t \rightarrow \infty$. In view of Theorem 3.1 and [15, Lemma 3.4] this yields

$$u(x, t) = \frac{1}{2\lambda_0} e^{-\left| x - \frac{t}{2\lambda_0} + \xi_{\lambda_0} \right|} + o(1)$$

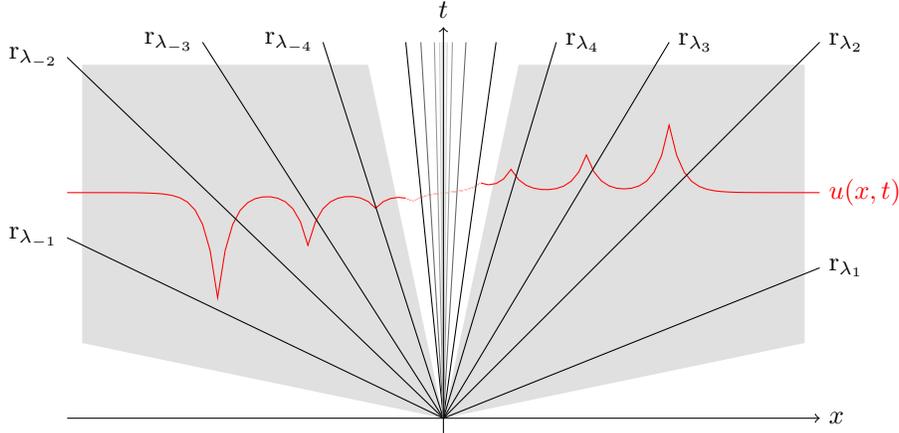
for $(x, t) \in S$ as $t \rightarrow \infty$. But this proves the claim in this special case, since

$$\sum_{\lambda \in \sigma \setminus \{\lambda_0\}} \frac{1}{2\lambda} e^{-\left| x - \frac{t}{2\lambda} + \xi_{\lambda} \right|} = o(1)$$

for $(x, t) \in S$ as $t \rightarrow \infty$, as Lebesgue's dominated convergence theorem shows.

In order to finish the proof in the general case, not that under our assumptions we may cover the sector S with finitely many sectors of the type considered above. \square

The typical long-time behavior of a solution u of the Camassa–Holm equation, derived in Theorem 4.1 can be depicted as follows:



Hereby, the grey areas represent two sectors in which our long-time asymptotics hold uniformly. Each of the rays r_λ , accumulating at the t -axis, corresponds to an eigenvalue $\lambda \in \sigma$ of the underlying isospectral problem. After long time, one can see that the solution u splits into a train of single peakons, each of which travels along one of the rays, with height and speed determined by the corresponding eigenvalue.

Due to the conditions on the sector in Theorem 4.1, we do not obtain long-time asymptotics of solutions, which hold uniformly in sectors around the t -axis (as long as the spectrum is not finite, that is, in the multi-peakon case). However, we are able to derive long-time asymptotics which hold uniformly in strips near the t -axis, that is, as long as x stays bounded (cf. [29, Theorem 1.2]).

Corollary 4.2. *Given some $R > 0$, one has*

$$u(x, t) = \sum_{\lambda \in \sigma} \frac{1}{2\lambda} e^{-|x - \frac{t}{2\lambda} + \xi_\lambda|} + o(1) \quad (4.14)$$

for $|x| \leq R$ as $t \rightarrow \infty$.

Proof. With the notation from the proof of Theorem 4.1 we see that the coupling constants in (4.13) for every $\lambda \in \sigma$ satisfy

$$\left| \ln \left| e^{x - \frac{t}{2\lambda}} c_\lambda(0) \right| \right| = \left| x - \frac{t}{2\lambda} + \ln |c_\lambda(0)| \right| \rightarrow \infty$$

as $t \rightarrow \infty$. Therefore, an application of Corollary 3.2 shows that

$$u(x, t) = o(1)$$

as $t \rightarrow \infty$, in view of [15, Lemma 3.4]. To finish the proof note that the right hand side of (4.14) converges to zero as $t \rightarrow \infty$, as an application of Lebesgue's dominated convergence theorem shows. \square

Acknowledgments. We gratefully acknowledge the kind hospitality of the *Institut Mittag-Leffler* (Djursholm, Sweden) during the scientific program on *Inverse Problems and Applications* in spring 2013, where most of this article was written.

References

- [1] N. I. Akhiezer and I. M. Glazman, *Theory of linear operators in Hilbert space; Two volumes bound as one*, Dover Publications, Inc., New York 1993.
- [2] R. Beals, D. H. Sattinger and J. Szmigielski, *Multipeakons and the classical moment problem*, Adv. Math. **154** (2000), no. 2, 229–257.
- [3] R. P. Boas, *Entire functions*, Academic Press Inc., New York, 1954.
- [4] A. Boutet de Monvel and D. Shepelsky, *Riemann–Hilbert problem in the inverse scattering for the Camassa–Holm equation on the line*, in “Probability, geometry and integrable systems”, 53–75, Math. Sci. Res. Inst. Publ., 55, Cambridge Univ. Press, Cambridge, 2008.
- [5] A. Boutet de Monvel, A. Its, and D. Shepelsky, *Painlevé-type asymptotics for the Camassa–Holm equation*, SIAM J. Math. Anal. **42** (2010), no. 4, 1854–1873.
- [6] A. Boutet de Monvel, A. Kostenko, D. Shepelsky and G. Teschl, *Long-time asymptotics for the Camassa–Holm equation*, SIAM J. Math. Anal. **41** (2009), no. 4, 1559–1588.
- [7] R. Camassa and D. Holm, *An integrable shallow water equation with peaked solitons*, Phys. Rev. Letters **71** (1993), 1661–1664.
- [8] R. Camassa, D. Holm, and J. M. Hyman, *A new integrable shallow water equation*, Adv. Appl. Mech. **31** (1994), 1–33.
- [9] A. Constantin, *On the scattering problem for the Camassa–Holm equation*, R. Soc. Lond. Proc. Ser. A Math. Phys. Eng. Sci. **457** (2001), no. 2008, 953–970.

- [10] A. Constantin and D. Lannes, *The hydrodynamical relevance of the Camassa–Holm and Degasperis–Procesi equations*, Arch. Rational Mech. Anal. **192** (2009), no. 1, 165–186.
- [11] P. Deift and X. Zhou, *A steepest descent method for oscillatory Riemann–Hilbert problems*, Ann. of Math. (2) **137** (1993), 295–368.
- [12] P. A. Deift, A. R. Its, and X. Zhou, *Long-time asymptotics for integrable nonlinear wave equations*, in “Important developments in soliton theory”, 181–204, Springer Ser. Nonlinear Dynam., Springer, Berlin, 1993.
- [13] J. Eckhardt, *Direct and inverse spectral theory of singular left-definite Sturm–Liouville operators*, J. Differential Equations **253** (2012), no. 2, 604–634.
- [14] J. Eckhardt and A. Kostenko, *An isospectral problem for global conservative multi-peakon solutions of the Camassa–Holm equation*, Comm. Math. Phys. (to appear).
- [15] J. Eckhardt and G. Teschl, *On the isospectral problem of the dispersionless Camassa–Holm equation*, Adv. Math. **235** (2013), 469–495.
- [16] B. Fuchssteiner and A. Fokas, *Symplectic structures, their Bäcklund transforms and hereditary symmetries*, Phys. D **4** (1981), 47–66.
- [17] K. Grunert and G. Teschl, *Long-time asymptotics for the Korteweg–de Vries equation via nonlinear steepest descent*, Math. Phys. Anal. Geom. **12** (2009), no. 3, 287–324.
- [18] D. Ionescu-Kruse, *Variational derivation of the Camassa–Holm shallow water equation*, J. Nonlinear Math. Phys. **14** (2007), no. 3, 303–312.
- [19] A. R. Its, *Asymptotic behavior of the solutions to the nonlinear Schrödinger equation, and isomonodromic deformations of systems of linear differential equations*, Soviet. Math. Dokl. **24:3** (1981), 452–456.
- [20] R. S. Johnson, *Camassa–Holm, Korteweg–de Vries and related models for water waves*, J. Fluid Mech. **455** (2002), 63–82.
- [21] B. Ya. Levin, *Lectures on Entire Functions*, Transl. Math. Mon. **150**, Amer. Math. Soc., Providence, RI, 1996.
- [22] L.-C. Li, *Long time behaviour for a class of low-regularity solutions of the Camassa–Holm equation*, Comm. Math. Phys. **285** (2009), no. 1, 265–291.
- [23] E. Loubet, *Genesis of solitons arising from individual flows of the Camassa–Holm hierarchy*, Comm. Pure Appl. Math. **59** (2006), 408–465.
- [24] S. V. Manakov, *Nonlinear Fraunhofer diffraction*, Sov. Phys. JETP **38:4** (1974), 693–696.
- [25] H. P. McKean, *Fredholm determinants and the Camassa–Holm hierarchy*, Comm. Pure Appl. Math. **56** (2003), no. 5, 638–680.
- [26] H. P. McKean, *The Liouville correspondence between the Korteweg–de Vries and the Camassa–Holm hierarchies*, Comm. Pure Appl. Math. **57** (2004), 416–418.
- [27] H. P. McKean, *Breakdown of the Camassa–Holm equation*, Comm. Pure Appl. Math. **56** (2003), 998–1015.
- [28] M. Rosenblum and J. Rovnyak, *Topics in Hardy classes and univalent functions*, Birkhäuser Verlag, Basel, 1994.
- [29] Z. Xin and P. Zhang, *On the weak solutions to a shallow water equation*, Comm. Pure Appl. Math. **53** (2000), no. 11, 1411–1433.
- [30] N. J. Zabusky and M. D. Kruskal, *Interaction of solitons in a collisionless plasma and the recurrence of initial states*, Phys. Rev. Lett. **15** (1965), 240–243.

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