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Preprint ISSN 2198-5855

Accelerated rogue solitons triggered by background radiation

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submitted: June 10, 2015

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No. 2121
Berlin 2015

2010 *Physics and Astronomy Classification Scheme.* 42.65.Re, 42.65.Tg, 42.81.Dp.

Key words and phrases. Rogue waves, Pulse compression, Temporal solitons, Optical event horizons.

We gratefully acknowledge support by The Einstein Center for Mathematics Berlin under project D-OT2 and the Collaborative Research Center 123 PlanOS..

Edited by
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The first observation of extreme events in soliton-fission induced supercontinuum generation in nonlinear fibers initiated an ever growing number of publications on optical rogue waves, forming a research topic of its own [1]. In fact, extreme event dynamics seems to be much wider spread than originally thought, with similar behavior being observed or suggested in a number of completely different physical phenomena, including various types of water waves and matter waves. Compared to the scarce reports of their ocean counterparts, extreme optical waves are readily observed. Conditions identified for rogue-wave supporting systems include generic dispersive and nonlinear contributions to the wave velocity, as described by perturbative contributions to the nonlinear Schrödinger equation (NSE), e.g., third-order dispersion. Therefore closed solutions of the NSE given by solitons or Akhmediev-breathers are regarded as building blocks for the generation of rogue events. These events appear due to the inherent modulation instability, which manifests itself in the anomalous dispersion regime of a nonlinear optical fiber. Depending on the propagation dynamics during supercontinuum generation, high-amplitude structures may occasionally be observed at the end of the fiber, with prototypical statistics of rogue waves. Fundamental solitons represent robust solutions of the NSE and extreme events are attributed to extraordinary solitons which have extracted energy within the highly complex propagation dynamics from the system. Collisions between solitons are regarded one of the main mechanisms for the emergence of such a ‘champion soliton’. In this scenario, two questions immediately arise: (1) Are there other possible mechanisms leading to the emergence of champion solitons? (2) As soliton dynamics is deterministic and therefore predictable, how can such solitons appear in the unpredictable fashion that is attributed to rogue waves?

In our investigations, we focus on an interaction phenomenon that has originally been discussed in fluid dynamics as wave blocking between opposing currents [10]. In the optical analogy, a blocking horizon is established by a refractive index barrier by means of the familiar cross-phase modulation (XPM) between two group-velocity matched optical pulses. This kind of interaction builds the basis for the optical push broom effect [2], the soliton trapping phenomenon [7], and the optical event horizon [8, 3, 4]. In a fiber with one zero-dispersion wavelength, group-velocity matching [Fig. 1(a)] can always be realized between a dispersive wave in the normal dispersion regime and a soliton in the anomalous dispersion regime [9]. The basic idea behind this interaction process is creation of a propagating front in the vicinity of an intense soliton traveling in a nonlinear optical fiber. At this front, the propagation velocity of the dispersive waves also changes abruptly. When a co-propagating dispersive wave with nearly identical group velocity approaches that front, this wave cannot pass the soliton front, but is actually thrown back, i.e., a process that has been referred to as reflection of the dispersive wave. An exemplary reflection process at the leading edge of the soliton is shown in Fig. 1(b)-(d). In supercontinuum generation by soliton fission, preconditions for such a reflection process are naturally granted between the ejected solitons and the accompanying generated resonant radiation [3, 9, 6]. A typical example of supercontinuum generation in the time domain is shown in Fig. 2. The dynamics are described by the nonlinear Schrödinger equation, including the higher-order dispersion as a perturbation. The interaction of the background radiation, relating to phased-matched radiation generated at the fission process, with the first ejected soliton results in a reflection process, as the one shown in Fig. 1. It is important that dispersive radiation as well as the solitons are strongly affected in this interaction process. Both pulses experience a mutual frequency shift,

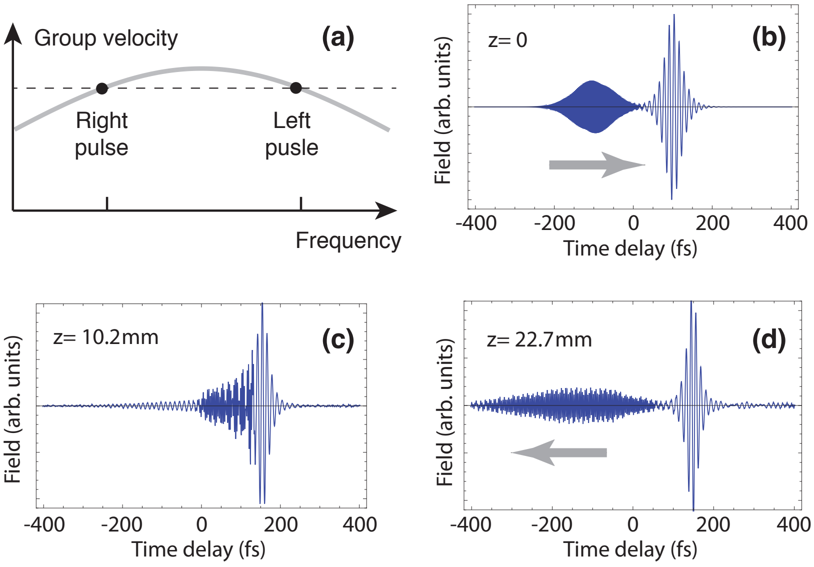

Figure 1: (a) Exemplary group-velocity matching between a soliton (right pulse) and a dispersive wave (left pulse). (b)-(d) Reflection process between the two pulses for a set-up where the dispersive wave approaches the soliton at the leading edge. (b)The soliton is in this case initially slightly faster than the dispersive wave. (c) The dispersive wave cannot penetrate the refraction index barrier (d) After the collision the dispersive wave is faster than the soliton.

which manifests itself in the temporal evolution as a change of the group-velocity. In the shown example, the soliton is shifted toward higher frequencies. Any such frequency shift results in adiabatic soliton re-shaping due to a change of the underlying dispersion value. A shift along the dispersion profile towards lower values of the group-velocity dispersion leads to a strong increase of its peak intensity for the soliton. As long as the soliton is accelerated, its intensity continuously increases (red arrow in Fig. 2). In turn, a strong increase of its peak intensity is induced, which is eventually followed by pulse collapse. This collapse is ultimately unavoidable, given the main preconditions imposed by soliton-fission induced supercontinuum generation, namely the separation of an anomalous and normal dispersion dispersion regime. When the soliton spectrum overlaps with the normal dispersion regime, the soliton quickly loses energy to resonant radiation. The faster and stronger the peak intensity increases, the faster a collapse will result. The peak intensity of the giant soliton may achieve intensities more than ten times higher than the solitons that do not interact with the background. In this sense, an accelerated soliton with an extreme intensity fulfills the unpredictability criterion as ‘appearing from nowhere and disappearing without any trace’. Compiling the statistics from a total of 4000 realizations of supercontinua using different noise seeds, a heavy-tailed figure-L distribution emerges, as it is characteristic for rare but extreme events. These extreme events therefore exhibit all signatures of rogue waves [3].

In order to investigate the difference to other nonlinear interaction types and energy transferring scenarios given by the optical fiber supercontinuum, the influence of higher-order effects, including the Raman effect, has been studied as well as different possible supercontinuum generation processes [4]. It has been verified that the interaction of a soliton with background radiation may lead to giant solitons, without any soliton-soliton or other interaction mechanism. Finally, in Ref. [5], yet another possibility to generate rogue waves by interaction with background radiation is presented. Here an attracting force between two solitons is realized by the interaction with dispersive waves, leading to a fusion of the solitons.

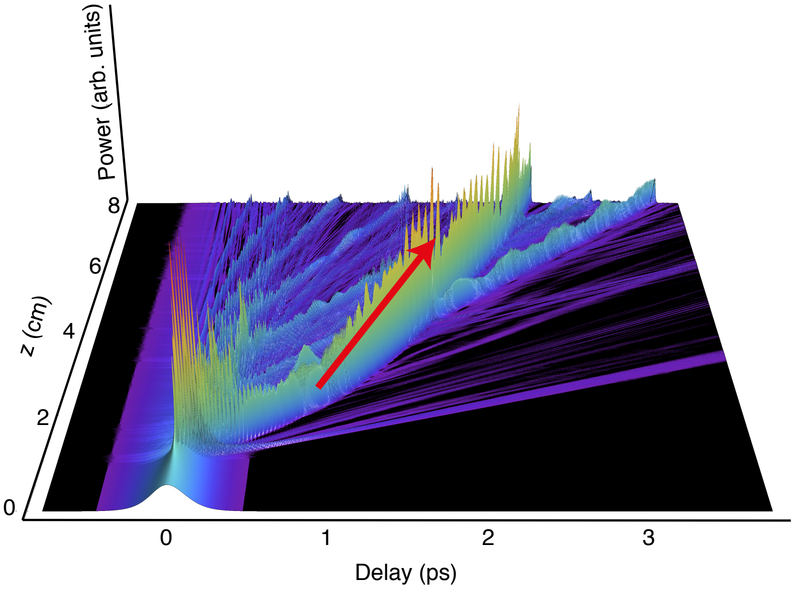

Figure 2: Temporal evolution of supercontinuum generation by soliton fission exhibiting the emergence of an accelerated rogue soliton indicated by an arrow.

Accelerated rogue solitons triggered by background radiation fulfill all generally accepted criteria for rogue waves. In particular, the interaction with the background radiation represents a further mechanism to create a ‘champion soliton’ in the highly complex supercontinuum generation. The underlying main mechanism given by wave blocking and the event horizon concept directly links the presented mechanism to other fields in physics, where analogue systems have been discussed, such as, filamentation matter waves, or hydrodynamics.

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