Observation of rogue events in non-Markovian light: supplement

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Observation of rogue events in non-Markovian light: supplementary material

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This document provides supplementary information to “Observation of rogue events in non-Markovian light”. The supplementary material includes four sections. The first section presents the intensity probability distributions of the one-dimensional simulated data presented in Fig. 6 of the main text. The second section presents examples of one-dimensional non-Markovian phase masks. The third section presents examples of the one-dimensional simulated intensity patterns that enter the photorefractive crystal, which represent the true Fourier transform of the non-Markovian imprinted beams. The last section presents simulated propagation traces through linear and nonlinear media of a far-field pattern generated by a typical 1D r=7 non-Markovian phase mask.

1. INTENSITY PROBABILITY DISTRIBUTIONS OF THE ONE-DIMENSIONAL SIMULATED DATA

Below we present the intensity probability distributions computed from the 1D simulation, corresponding to Fig. 6 of the main text. Figures S1a-e show the distributions generated by the totally random phase mask, the r=0 mask, the r=4 mask, the r=7 mask, and the r=8 mask, respectively, in semi-log scale. Each sub figure displays the distribution after propagation through a linear (blue squares), positive nonlinear (red diamonds) and negative nonlinear (green circles) medium. The left column displays the intensity probability distributions after propagation through a linear medium only, so that the trend with growing r is clearer (the data is the same as in the right column). As in the 2D simulation, the distribution becomes more elongated as r increases (see left column), and the combination of positive nonlinear propagation and large r values serves to create extremely long-tailed distributions (see right column). Yet when the order is increased further and the phase mask becomes completely ordered, as occurs for r=8 (Fig S1e), the distribution becomes linear just like in the completely random and r=0 cases (Fig S1a and b). This shows that it is the unique state of correlated random variables that gives rise to rogue events.

2. EXAMPLES OF ONE-DIMENSIONAL NON-MARKOVIAN PHASE MASKS

In this section we present examples of typical 1D non-Markovian phase masks, such as those used in the 1D simulation discussed in section 3c of the main text. For clarity, a zoomed-in view of ten sections of nine entrees (i.e. 10x9 entrees, corresponding to ten puzzles of the r=0 phase mask) of the masks are shown, out of approximately 10,000 entrees used in the simulation. The values shown are those assigned out of the numbers 1-9, which are later translated to phase values, φ, according to $\phi = 2\pi \frac{N}{9}$. Fig. S3a shows a random phase mask, while Fig. S3b-d show non-Markovian phase masks corresponding to r=0,4,7 accordingly. Fig. S3e shows a phase mask corresponding to r=8, which is the grating case. We can see that in spite of the increasing correlations between the randomly-assigned entrees, the non-Markovian phase masks (Fig. S3b-d) do not display periodicity. In the r=7 mask a single section of 9 entries might have some
Supplementary Material

Fig. S1. 1D simulation results: The intensity probability distributions for different 1D phase masks, after propagation through a linear (blue squares), positive nonlinear (red diamonds) and negative nonlinear (green circles) medium. The left column displays the intensity probability distributions after propagation through a linear medium only, so that the trend with growing \( r \) is clearer. (a) For a completely random phase mask. (b) For the \( r=0 \) phase mask. (c) For the \( r=4 \) phase mask. (d) For the \( r=7 \) phase mask. (e) For the \( r=8 \) phase mask. The trends follow those of the 2D simulation, showing more elongated distributions for larger \( r \) values. Yet when the mask becomes completely ordered, for \( r=8 \), the distribution becomes linear again, as in the completely random case and \( r=0 \) cases.

3. EXAMPLES OF THE SIMULATED ONE-DIMENSIONAL INTENSITY PATTERNS AT THE CRYSTAL INPUT

Here we present examples of the intensity patterns at the input facet of the photorefractive crystal, for reference. These patterns are similar to those presented in Fig. 6 of the main text, but before they have undergone linear or nonlinear propagation. The input facet of the crystal is the far-field of the SLM and therefore we can examine the exact Fourier transform of the non-Markovian imprinted beams. Fig. S3(a)-(e) show the intensity patterns corresponding to a random phase mask and the \( r=0,4,7,8 \) masks, accordingly. Upon comparison with Fig. 6e of the main text, we see that the \( r=8 \) intensity pattern is a true Dirac comb, since the comb teeth have not been widened by diffraction due to linear propagation. We note that the \( r=7 \) intensity pattern is not related to the \( r=8 \) intensity pattern by any simple mathematical operation.

4. PROPAGATION TRACES OF A ONE-DIMENSIONAL SIMULATED INTENSITY PATTERN

Below we show examples of simulated propagation traces of the one-dimensional far-field pattern generated by a \( r=7 \) phase mask. Propagation traces through negative nonlinear (Fig. S4a), linear (Fig. S4b) and positive nonlinear (Fig. S4c) media are presented. \( z=0 \) represents the input facet of the photorefractive crystal and \( z=1 \) represents the output facet. Several examples of waves whose intensity exceeds two times the SWH are marked with white arrows. Intensities were normalized to the maximum intensity in the pattern at position \( z=0 \). We see that the rogue events generated in all three types of media are transient. The traces in Fig. S4a and S4c follow the typical trends of the nonlinear Schrödinger equation [1–3].

REFERENCES

1. N. Akhmediev, B. Kibler, F. Baronio, M. Belić, W.-P. Zhong, Y. Zhang, W. Chang, J. M. Soto-Crespo, P. Vouzas, P. Grelu et al., “Roadmap on optical rogue waves and extreme events,” J. Opt. 18, 063001 (2016).
2. M. Onorato, S. Residori, U. Bortolozzo, A. Montina, and F. Arecchi, “Rogue waves and their generating mechanisms in different physical contexts,” Phys. Reports 528, 47–89 (2013).
3. J. M. Dudley, F. Dias, M. Erkintalo, and G. Genty, “Instabilities, breathers and rogue waves in optics,” Nat. Photon. 8, 755–764 (2014).
Fig. S2. Examples of 1D non-Markovian phase masks used in the 1D simulation. A zoomed-in view of ten sections of nine entrees (10x9 entrees) of the phase masks, out of approximately 10,000 entrees used in the 1D simulation. The values presented are those assigned out of the numbers 1-9, which are later translated to phase values.

(a) A completely random phase mask. (b)-(d) The phase masks corresponding to $r=0, 4, 7$ accordingly. (e) The phase mask corresponding to $r=8$, a grating with a repeating random pattern. The non-Markovian phase masks (Fig. S2b-d) do not display periodicity, even when examining just ten sections.
Fig. S3. 1D simulation results: Examples of the intensity patterns entering the photorefractive crystal. The intensity patterns at the far-field of the SLM plane, which is the input facet of the photorefractive crystal. (a) For a completely random phase mask. (b) For the r=0 phase mask. (c) For the r=4 phase mask. (d) For the r=7 phase mask. (e) For the r=8 phase mask. The examples of the intensity patterns shown here are similar to those presented in Fig. 6 of the main text, but without additional linear or nonlinear propagation. Accordingly we can see that the r=8 intensity pattern looks like a true Dirac comb, since the comb teeth have not been widened by diffraction as in Fig 6e.
**Fig. S4.** 1D simulation results: Propagation traces of a far-field pattern generated by a typical $r=7$ non-Markovian phase mask. The propagation is shown from the input facet of the photorefractive crystal ($r=0$) to the output facet ($r=1$). (a) Propagation through a negative nonlinear medium. (b) Propagation through a linear medium. (c) Propagation through a positive nonlinear medium. Examples of waves exceeding two times the SWH are marked with white arrows. We note that the generated rogue events for all three media are transient.