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# Solitary wave behavior in sand dunes observed from space

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[1] Although the dynamics of individual barchan dunes are well understood, their interactions are the subject of ongoing scientific interest and debate. Numerical and analog model predictions of shape-preserving binary dune collisions have been hard to test due to the long timescales over which such processes typically occur. This paper documents ten binary dune collisions in a 45-year time sequence of satellite images from the Bodélé Depression in Chad. The observations confirm that when two barchan dunes collide, a transfer of mass occurs so that one dune appears to travel through the other unscathed, like a solitary wave. **Citation:** Vermeesch, P. (2011), Solitary wave behavior in sand dunes observed from space, *Geophys. Res. Lett.*, *38*, L22402, doi:10.1029/2011GL049610.

[2] The world's deserts contain a number of dune types, depending on the availability of sand and the dominant wind regime [*Reffet et al.*, 2010]. Of these different types, the barchan or crescentic dune is perhaps the best understood. Barchans are found in areas with a relatively limited sand supply and a unimodal wind regime [*Bagnold*, 1941]. Under these conditions, they can be easily simulated in wind tunnels and computer models [*Wippermann and Gross*, 1986]. Nevertheless, considerable controversy exists regarding an intriguing prediction of these models, namely that barchan interactions are characterized by solitary wave behavior [*Schwämmle and Herrmann*, 2003; *Endo et al.*, 2004; *Katsuki et al.*, 2005; *Durán et al.*, 2005, 2011]. The proposed mechanism is as follows. Because the velocity of barchan dunes is inversely proportional to their size, small dunes eventually catch up with large ones. Computer models indicate that when this happens, the upwind dune captures the sediment of the downwind dune and starves it of sand. As a result, the upwind dune grows and slows down, while the downwind dune shrinks and speeds up again. Seen from a distance, the small dune appears to traverse right through the large dune.

[3] Although the occurrence of small barchans at the down-wind side of big ones is seen by some as evidence that barchan dunes could behave like solitons [*Besler*, 2002], such 'snap shot' views are equivocal, and could also be interpreted as barchans calved from the dune horns [*Elbelrhiti et al.*, 2005] and blown sideways by short term cross-winds [*Livingstone et al.*, 2005]. The only way to settle the debate is continuous monitoring of the collision process from start to finish [*Ewing and Kocurek*, 2010]. Unfortunately, this is usually very difficult, because most barchan dunes on Earth move too slowly to see dune interactions occurring on time scales of less than a few decades.

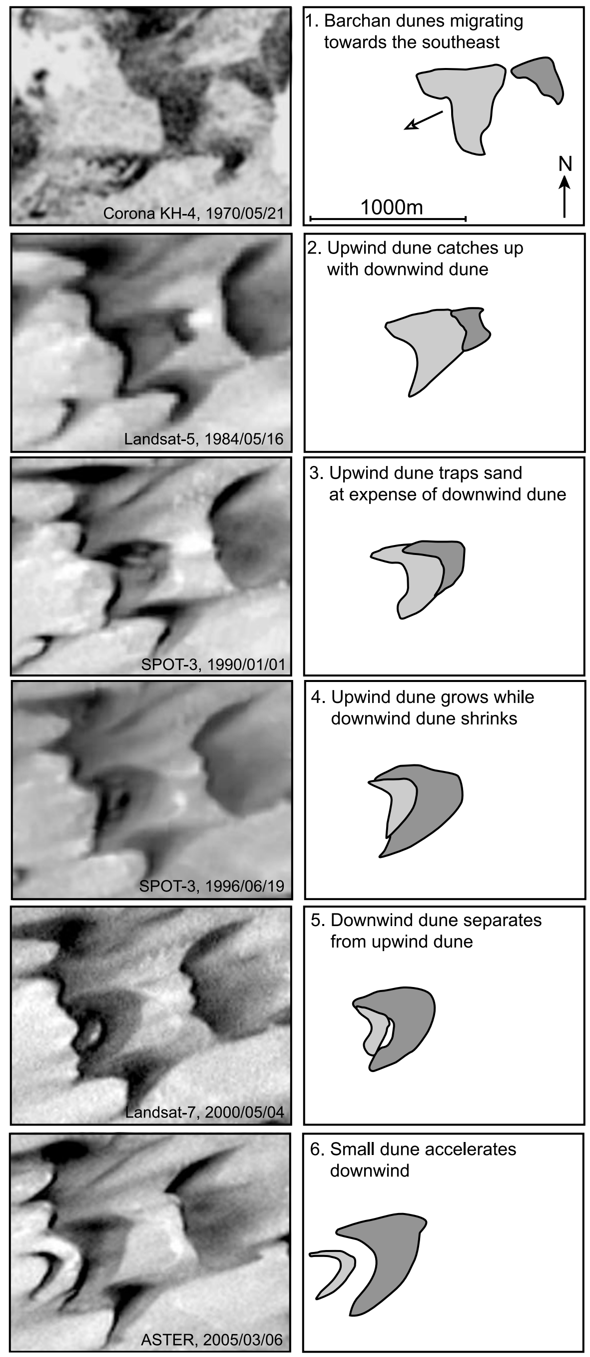


**Figure 1.** Sequence of six (left) high resolution satellite images and (right) interpretive sketches of a 'head-on' collision between two barchan dunes in the Bodélé Depression (N16°54′17″, E17°2′58″) exhibiting solitary wave behavior. An animated version of this and nine other time series can be viewed in the auxiliary material.

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**Table 1.** List of Binary Dune Collisions Documented as Animations in the Auxiliary Material[a]

| Number | Latitude | Longitude | $r_i$ | $\theta_i$ |
|---|---|---|---|---|
| s1 | 16°54′17″ | 17°02′58″ | 0.29 ± 0.10 | 0.25 ± 0.13 |
| s2 | 16°53′46″ | 17°01′35″ | 0.34 ± 0.19 | 0.24 ± 0.21 |
| s3 | 16°44′57″ | 18°05′44″ | 0.54 ± 0.56 | 0.37 ± 0.45 |
| s4 | 16°49′06″ | 18°11′06″ | 0.52 ± 0.30 | 0.09 ± 0.24 |
| s5 | 16°59′33″ | 18°03′33″ | 0.13 ± 0.11 | 0.12 ± 0.25 |
| o1 | 16°48′27″ | 17°18′41″ | 0.16 ± 0.07 | 0.67 ± 0.15 |
| o2 | 16°54′32″ | 17°04′56″ | 0.59 ± 0.29 | 0.52 ± 0.22 |
| o3 | 17°02′33″ | 18°34′10″ | 0.45 ± 0.13 | 0.52 ± 0.12 |
| o4 | 16°55′33″ | 18°29′30″ | 0.70 ± 0.16 | 0.96 ± 0.11 |
| o5 | 16°41′30″ | 17°22′47″ | 0.55 ± 0.28 | 3.25 ± 0.42 |

[a]Labels with pre-fix ‘s’ refer to soliton collisions, those beginning with ‘o’ are off-center collisions. Geographical coordinates refer to the location of the actual collisions. $r_i$ is the initial volume ratio of the two dunes estimated from the ratio of their respective widths ($r_i \equiv (w_1/w_2)^3$ [*Durán et al.*, 2011]). $\theta_i$ is the initial lateral offset between the dune crests ($\theta_i \equiv 2(y_1 - y_2)/w_2$ [*Durán et al.*, 2011]). Uncertainty estimates for $r_i$ and $\theta_i$ assume a 3 pixel uncertainty in the manual selection of dune horn and crest locations. Dunes s1 and o1 are shown in Figures 1 and 2.

One notable exception to this is the Bodélé Depression in northern Chad, which contains some of the world’s largest and fastest moving barchan dunes [*Vermeesch and Drake*, 2008]. This is due to a unique combination of extremely strong winds and the fact that Bodélé dunes are largely made of low density diatomite flakes, which easily break down to form the world’s most important source of eolian dust [*Giles*, 2005]. The Bodélé thus forms a unique natural laboratory where eolian processes are magnified and accelerated. Various Earth observation satellites have monitored northern Chad from space since the mid-1960s. A time series of co-registered Landsat, SPOT, and ASTER scenes, combined with declassified American spy satellite images yields a 45 year record of dune migration in the Bodélé, revealing several clear examples of solitary wave behavior (Figure 1 and Table 1). Five of these solitons are shown as animations in the auxiliary material[1] and at http://ucl.ac.uk/~ucfbpve/solitons.

[4] Much of the confusion and controversy regarding so-called solitary wave behavior in dunes stems from the fact that there is no physical mechanism by which one mass of sand could pass through another [*Livingstone et al.*, 2005], and neither is it possible for one dune to climb across another, as it would be destroyed by the slip face of the latter [*Durán et al.*, 2005]. It is important to reiterate that colliding dunes are not ‘real’ solitons, but only *appear* to behave like solitons, whose shape is preserved not by a transfer of momentum, but by a transfer of mass [*Hersen and Douady*, 2005]. Numerical models indicate that solitary wave behavior only occurs when the initial volume ratio ($r_i$) of the two interacting dunes is greater than ~0.25 [*Durán et al.*, 2005]. Smaller ratios lead to either complete absorption of the small dune, or ‘breeding’ of several little dunes [*Durán et al.*, 2005, 2011]. Unfortunately, visual inspection of the two-dimensional satellite imagery used in the time series analysis did not permit direct measurements of the relative dune volumes. However, using the dune widths raised to the third power as a substitute for volume, as advocated by *Durán et al.* [2011], yields approximate volume ratios of 0.13–0.54, consistent with the model prediction within the (admittedly large) analytical uncertainties (Table 1). A more rigorous and precise quantitative validation of the soliton model would require high resolution digital elevation models. The author is in the process of acquiring these for future research.

[5] ‘head-on’ collision (a.k.a. ‘bedform repulsion’, sensu [*Kocurek et al.*, 2010]) is just one of the ways in which dunes can interact. When the initial lateral offset ($\theta_i$ [*Durán et al.*, 2011]) between two colliding dunes is greater than 0.5

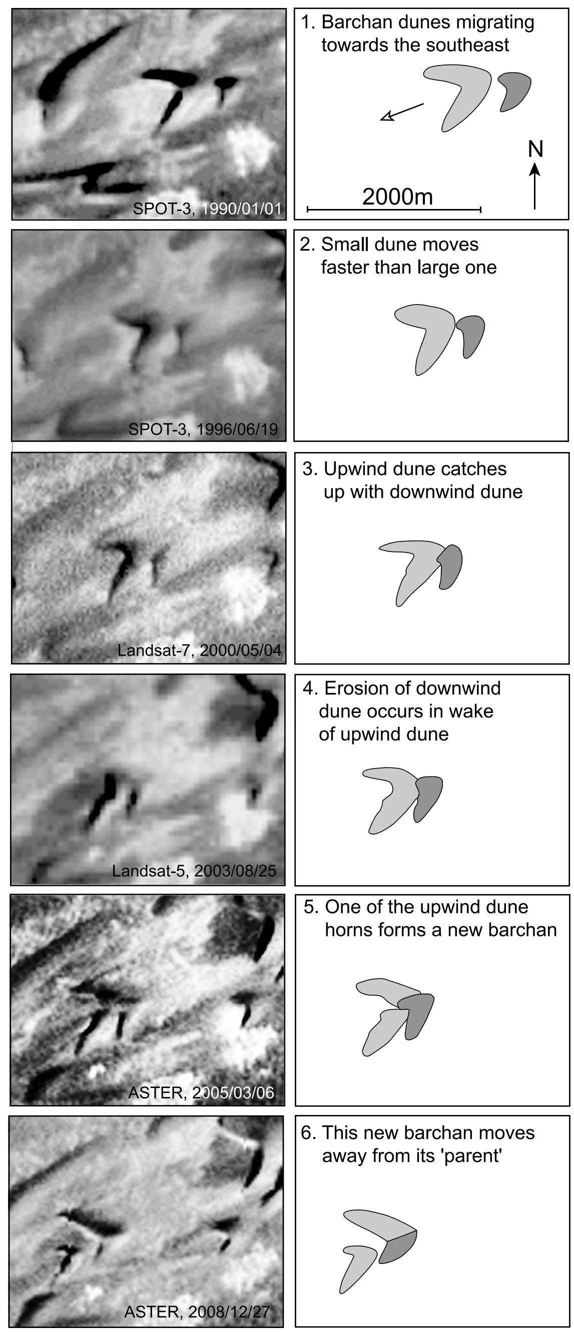


**Figure 2.** Sequence of six (left) high resolution satellite images and (right) interpretive sketches of an off-center collision between two barchan dunes in the Bodélé Depression (N16°48′27″, E17°18′41″). An animated version of this and nine other time series can be viewed in the auxiliary material.

[1]Auxiliary materials are available in the HTML. doi:10.1029/2011GL049610.

a different type of dune interaction arises. The time series of satellite images reveals a number of these 'off-center' collisions (Figure 2 and Table 1). Analog models and analytical calculations have indicated that such dune interactions may be instrumental in maintaining the long-term stability of barchan dune fields [*Hersen et al.*, 2004; *Hersen and Douady*, 2005; *Kocurek et al.*, 2010]. Laboratory experiments in flume tanks show that, when a small and fast barchan collides with one of the horns of a larger and slower downwind dune, it literally 'pushes' away that horn [*Hersen and Douady*, 2005]. This results in the creation of a new barchan and an exchange of mass between the two dunes, similar to that which occurs as a result of the 'head-on' collisions discussed before. Exactly the same kind of behavior is observed in the Bodélé Depression (Figure 2), five further examples of which are shown as animations in the auxiliary material.

[6] Over the past two decades or so, a series of increasingly sophisticated numerical models have been developed in order to explain dune morphology and formation [e.g., *Wippermann and Gross*, 1986; *Zhang et al.*, 2010]. Great strides have been made in our ability to model the saltation of sand and turbulent flow of air [*Livingstone et al.*, 2007]. The strength of scientific models, however, lies not in the description of the natural environment, but in their ability to make testable predictions. The observation of shape-preserving binary dune collisions in the real world confirms the validity of the numerical and analog models that predicted them, lending credibility to other predictions that such models might make.

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## References

Bagnold, R. A. (1941), *The Physics of Blown Sand and Desert Dunes*, Methuen, London.

Besler, H. (2002), Complex barchans in the Libyan desert: Dune traps or overtaking solitons?, *Z. Geomorphol.*, *126*, 59–74.

Durán, O., V. Schwämmle, and H. Herrmann (2005), Breeding and solitary wave behavior of dunes, *Phys. Rev. E*, *72*, 021308.

Durán, O., V. Schwämmle, P. Lind, and H. Herrmann (2011), Size distribution and structure of barchan dune fields, *Nonlinear Processes Geophys.*, *18*, 455–467.

Elbelrhiti, H., P. Claudin, and B. Andreotti (2005), Field evidence for surface-wave-induced instability of sand dunes, *Nature*, *437*, 720–723.

Endo, N., K. Taniguchi, and A. Katsuki (2004), Observation of the whole process of interaction between barchans by flume experiments, *Geophys. Res. Lett.*, *31*, L12503, doi:10.1029/2004GL020168.

Ewing, R., and G. Kocurek (2010), Aeolian dune interactions and dune-field pattern formation: White Sands Dune Field, New Mexico, *Sedimentology*, *57*, 1199–1219.

Giles, J. (2005), The dustiest place on Earth, *Nature*, *434*, 816–819.

Hersen, P., and S. Douady (2005), Collision of barchan dunes as a mechanism of size regulation, *Geophys. Res. Lett.*, *32*, L21403, doi:10.1029/2005GL024179.

Hersen, P., K. H. Andersen, H. Elbelrhiti, B. Andreotti, P. Claudin, and S. Douady (2004), Corridors of barchan dunes: Stability and size selection, *Phys. Rev. E*, *69*, 011304.

Katsuki, A., H. Nishimori, N. Endo, and K. Taniguchi (2005), Collision dynamics of two barchan dunes simulated using a simple model, *J. Phys. Soc. Jpn.*, *74*, 538–541.

Kocurek, G., R. C. Ewing, and D. Mohrig (2010), How do bedform patterns arise? New views on the role of bedform interactions within a set of boundary conditions, *Earth Surf. Processes Landforms*, *35*, 51–63.

Livingstone, I., G. F. S. Wiggs, and M. Baddock (2005), Barchan dunes: Why they cannot be treated as 'solitons' or 'solitary waves', *Earth Surf. Processes Landforms*, *30*, 255–257.

Livingstone, I., G. F. S. Wiggs, and C. M. Weaver (2007), Geomorphology of desert sand dunes: A review of recent progress, *Earth Sci. Rev.*, *80*, 239–257.

Reffet, E., S. C. du Pont, P. Hersen, and S. Douady (2010), Formation and stability of transverse and longitudinal sand dunes, *Geology*, *38*, 491–494.

Schwämmle, V., and H. J. Herrmann (2003), Geomorphology: Solitary wave behaviour of sand dunes, *Nature*, *426*, 619–620.

Vermeesch, P., and N. Drake (2008), Remotely sensed dune celerity and sand flux measurements of the world's fastest barchans (Bodélé, Chad), *Geophys. Res. Lett.*, *35*, L24404, doi:10.1029/2008GL035921.

Wippermann, F. K., and G. Gross (1986), The wind-induced shaping and migration of an isolated dune: A numerical experiment, *Boundary Layer Meteorol.*, *36*, 319–334.

Zhang, D., C. Narteau, and O. Rozier (2010), Morphodynamics of barchan and transverse dunes using a cellular automaton model, *J. Geophys. Res.*, *115*, F03041, doi:10.1029/2009JF001620.

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