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A separated vortex ring underlies the flight of the dandelion

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Supplementary Discussion

Observation of the SVR

Seeds held fixed in the wind tunnel

There is a rich literature on the flow around bluff bodies, such as disks and spheres[?] [?]. In the case of disks, the nature of the wake of the disk depends on its Reynolds number. At low *Re*, the flow past a solid disk forms an axisymmetric recirculation bubble in its wake[?]. As *Re* increases, the flow in the wake region undergoes a series of bifurcations leading to a loss in symmetry and the breakdown in stability[?]. The same depth of analysis has not been carried out for the flow past a porous disk at these Reynolds numbers, so it is unclear how these bifurcations are affected by porosity. Our experiments revealed that the qualitative changes in the wake of porous bodies is fundamentally different than for solid bodies, and we have discovered that a new vortical structure, previously thought to be unphysical[?] emerges – the SVR.

Extended Data Fig. 1 depicts our flow visualization of the SVR generated by ten dandelion seeds fixed in the wind tunnel. The visualization was carried out following the procedure outlined in M1. The pappus of the dandelion prevents air from flowing through it, creating an SVR. This vortex was previously thought to be too unstable; yet, a stable SVR is generated by each biological sample. The discovery of this vortical structure prompts many further inquiries into the bifurcational structure of the wake region. We know that the SVR loses axisymmetry as *Re* increases (see Extended Data Fig. 3), but the precise value of the *Re* at which this happens is not known. At higher *Re*, the wake may maintain reflectional symmetry, but it is not clear if this is the case. Such studies are analogues of those undertaken for impervious disks in the literature, and a parametric study should recover the results for impervious disks as the porosity tends to zero. However, there are additional phenomena related specifically to the porous nature of the disk. Our numerical modelling suggests that as the porosity increases, the recirculation bubble will shrink until, at some critical porosity, the SVR will disappear entirely[?]. This critical value of porosity represents a step-change in the function of a structure. This is of fundamental importance to our understanding of how evolution has adapted bristly structures for functions such as particle capture and locomotion.

Seeds freely flying in the wind tunnel

Fixing our samples in the wind tunnel is a very effective way to visualize the structure of the SVR, but the full problem of seed flight requires the study of all six degrees of freedom of the pappuses motion. In order to see if the SVR is present in freely flying seeds, we need to unlock these degrees of freedom by visualizing the flow around freely flying seeds.

In Extended Data Fig. 1, we showed that the air around fixed dandelion pappuses forms into an SVR around each sample. We verified this for a range of flow speeds, including the dandelions' terminal velocities. To identify if freely flying dandelions also have an SVR, we visualized the flow around the same ten dandelion samples freely flying in the wind tunnel in Extended Data Fig. 2, confirming that the SVR is indeed present in freely flying seeds.

Symmetry breaking of the SVR

The recirculation bubble behind a disk loses its axisymmetry at some critical *Re*, attaining reflectional symmetry. We wanted to know if the SVR also exhibited symmetry breaking. Extended Data Fig. 3 shows the flow visualization around a dandelion sample in the wind tunnel at two different Reynolds numbers. At low Re, the SVR is axisymmetric (a and b), but it loses this symmetry at higher *Re* (c and d), as for impervious disks[?].

As mentioned before, we do not know what is the critical Reynolds number for the loss in axisymmetry. Indeed, further studies should elucidate the nature of the bifurcation(s). This is of interest not only to the fluid dynamics community, but to biologists too. In the case where the reflectional symmetry is preserved, there is likely to be a lift force in the lateral direction tending to pull the seed in a certain direction. This preferred direction may also persist when the flow becomes unsteady, as is the case for a sphere[?]. It would be particularly enlightening to find out if such a directional preference is in other plumed seeds.

The microfabrication of the porous disks

The importance of the wall effect depends on the interaction of the boundary layers of nearby bodies[?] . For very low *Re*, the boundary layers are so thick that even relatively large changes in separation, do not significantly alter the permeability of the composite structure. In the case of the dandelion, the filament-based *Re* is indeed low, but not so low that separation does not matter. We anticipate that wall effect in the dandelion's pappus is highly sensitive to the nature of porosity.[?] Hence, we have kept the design as close to the biological sample as possible – a linear increase in porosity in the radial direction. There could be other porous designs that are more effective at stabilizing the seed with high drag. It would be particularly interesting to know what porous structure maximizes the drag under the constraint of wake stability.

The flow past impervious versus porous disks and the pappus

The breakdown in stability of the recirculation bubble in the wake of impervious disks is well understood: the breakdown leads to the three-dimensional flow with periodic shedding of hairpin-shaped vortex structures[?] . In Extended Data Fig. 5, we show snapshots from the visualization of the steady flow past an impervious disk, a porous disk, and a dandelion pappus (Column 1). In each case, a vortex remains steadily in the wake of the body. Columns 2, 3, and 4 of Extended Data Fig. 5 indicate snapshots of flow visualization at different stages of vortex shedding in the wake of the same impervious disk, porous disk, and dandelion pappus as in Column 1.

One of the key features of the dandelion's flight is that its porosity is tuned to stabilize the SVR at the *Re* corresponding to its terminal velocity. At higher *Re*, the SVR breaks down into vortex shedding. We have calculated the point at which this bifurcation occurs, but we have not yet classified the bifurcation; nor have we examined in detail the vortical structures that are shed once this bifurcation is reached. Furthermore, it is of interest to consider the shedding frequency of porous disks, and how it compares with that of impervious disks at the same *Re*.

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