Detecting the colours of darkness

Experiments have confirmed predictions about the structure of a white-light vortex

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Every wave field is characterized by two numbers: a local amplitude and a phase. If the amplitude is zero at a certain location, the phase of the field will be indeterminate at that point. Such phase singularities, or vortices, are encountered in many different systems, and the movements of the tides provide a beautiful example.

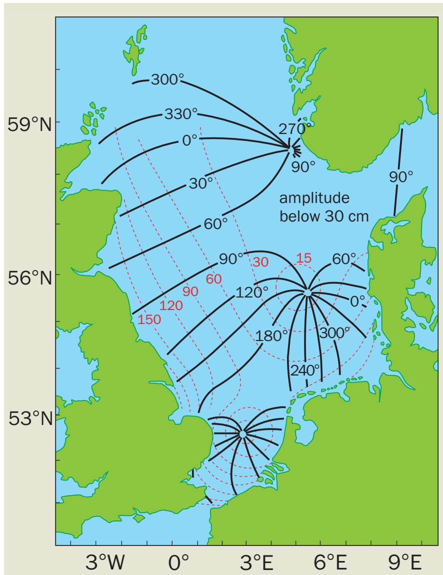
The average level of the sea is determined by tidal waves (which should not to be confused with the wind-driven waves that are superposed on them). Every 12 hours the water level oscillates between high tide and low tide, but the pattern of tidal waves is surprisingly complex. For instance, the high tide in the North Sea occurs at 3 p.m. at all points along the line of equal phase indicated by 0° in figure 1, and at 4 p.m. at points along the 30° line, while the low tide occurs at 3 p.m. along the 180° line and so on. But what about the points where the different lines intersect? Clearly the phase is undefined, or singular, at these points, which means that there are no high or low tides there.

Phase singularities like these are also common in optics, and there has been great interest in the properties of optical vortices in recent years. Now Jonathan Leach and Miles Padgett of Glasgow University have studied the structure of an optical vortex for the first time, and confirmed predictions about its properties (2003 *New J. Phys.* **5** 154).

Phase singularities

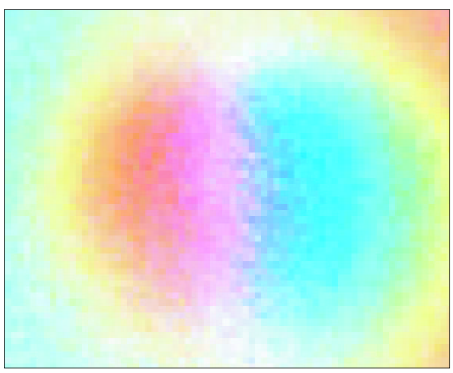
It has been known since the late 1960s that "Airy rings" – regions of zero amplitude that are produced by the diffraction of light through a circular aperture – are actually phase singularities. Only recently, however, have we realized that this could make it possible to manipulate light spectra.

The precise location of the Airy rings depends on the wavelength of the light. If a lens is used to focus polychromatic light, for example, the zeros of the green component will lie closer to the central axis than those of the red component. This causes the spectrum to change dramatically from point to point, and means that a particular frequency is completely suppressed at each position in the focal plane. These phenomena were predicted in 2002 by Greg Gbur of the Free University in Amsterdam, Emil Wolf of the University of Rochester and the present author, and were later observed by Gabriel Popescu and Aristide Dogariu of the University of Central Florida.



J F Nye *et al.* 1988 *Proc. R. Soc.* A **417**

1 Tidal vortices – lines of equal phase (black) and equal amplitude (red) of the tidal movements in the North Sea reveal three phase singularities where the lines of equal phase meet. At these points, which also occur in many optical systems, the tidal amplitude is zero. The time of the high tide also changes from day to day.



2 Researchers have now measured the colour pattern that the eye would see near the centre of a dispersed white-light vortex beam. It consists of a transition from red to blue across the vortex that is separated by a narrow purple region, and, as predicted, the pattern contains no green.

Inspired by these developments, Michael Berry of Bristol University investigated what colour the eye would perceive near such phase singularities (2002 *New J. Phys.* **4** 66 and 74). In contrast to a spectrometer, which measures the intensity of each wavelength, the retina translates the visible spectrum into just three colours – red, green and blue – which are then combined in the brain to produce the perception of a single colour.

But the intensity of light near a phase singularity is extremely faint, which means that the light needs to be amplified if we are to see anything at all. One way to do this would be to increase the amplitude of the red, green and blue stimuli by the same factor until the colour with the largest amplitude is fully saturated. Berry predicted that if we could use such a "chromoscope" to view the colour distribution round a vortex in a beam of white light, the structure that we would see would be universal: in particular, there would always be a transition from red to blue that is separated by a narrow area of purple. Moreover, we would not see any green.

This universal structure is formed, Berry explained, because the spectrum is shifted towards the blue on one side of the singularity and towards the red on the other side. In between, and in the region above and below, the roughly symmetrical mixture of red and blue is strongly desaturated and therefore gives the impression of white rather than green to the human eye.

Viewing vortices

Verifying Berry's predictions is not easy because the field intensity near the vortices is many orders of magnitude smaller than it is elsewhere. But by cleverly manipulating the phase structure of a "white-light vortex beam", the Glasgow team has now succeeded in doing precisely this. Leach and Padgett produced a beam with a phase-singularity line at its centre by sending a broadband plane wave from a tungsten lamp through a computer-generated hologram. The hologram acts as a special type of diffraction grating and adds a helical component to the phase of the beam. This gives the beam a dark core and the amplitude of each frequency component is zero at all points along the axis of the beam.

The researchers then used a trick to separate the vortex lines for each frequency. They inserted a prism in the beam to cause a small amount of dispersion and therefore create a beam in which the zeros of intensity for red and blue no longer coincided. By capturing this light with a CCD camera that mimics the three-colour response of the human eye, Leach and Padgett were able to measure the spatial colour distribution of light in the vicinity of a red and a blue vortex line. Finally, they applied Berry's "chromoscope" to the red–green–blue signal to convert the image into the colours that the human eye would see (see figure 2).

This experiment confirms beautifully the predicted transition from red, through purple, to blue in the vicinity of an optical vortex. Moreover, the colour green is indeed found to be absent. This research clearly shows that there is more to phase singularities than meets the eye.