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# Last but not least

## Mach bands change asymmetrically during solar eclipses

**Abstract.** Observations made during two partial eclipses of the Sun show that the Mach bands on shadows cast by the Sun disappear and reappear asymmetrically as an eclipse progresses. These changes can be explained as due to changes in the shape of the penumbras of shadows as the visible portion of the Sun forms crescents of different orientation.

### 1 Introduction

Shadows cast by objects in full sunlight exhibit Mach bands—strips of light and dark not physically present in the shadows but visible at their edges. This is because the Sun as seen from the surface of the Earth is not a point source but a disc subtending 30 min of arc. Shadows made by the Sun do not have sharp, step-function edges; they have penumbras approximately ramp-shaped (trapezoidal), and such shapes produce Mach bands, for reasons not yet fully agreed upon (Mach 1865; Ratliff 1965; Morrone et al 1986; Ross et al 1989; Pessoa 1996). Here we report that shadows lose some of their Mach bands during eclipses, but do so asymmetrically.

### 2 Methods

We made observations of shadows cast by the Sun while a partial eclipse was in progress in Perth, Western Australia, on the afternoon of 16 February 1999. Observations were confirmed on both coasts of Australia during a subsequent eclipse on 4 December 2002, visible both in Eastern and Western Australia. Shadows were subsequently modeled by convolving silhouettes of a square and a circle with others representing the full and partially eclipsed Sun.

### 3 Results and discussion

Observations showed that as the eclipse on 16 February 1999 progressed and the Sun formed a crescent with the prongs pointing to the left (see figure 1) bright Mach bands disappeared on the left side of our shadows, but not on the right (see figure 2). Later, as it formed a crescent with the prongs pointing downward, bright Mach bands returned briefly on both sides. As the eclipse progressed further to form a crescent Sun with the prongs pointing to the right, bright Mach bands disappeared on the right side but were visible on the left. Finally, as the Sun became more circular, bright Mach bands were, as usual, visible on both sides of shadows. Changes in dark Mach bands were less conspicuous and were not recorded. The observations made on 16 February 1999 were confirmed during a subsequent eclipse on 4 December 2002.

As the Moon 'swallows the sun' it breaks down the Sun's symmetry, leaving crescents (figure 1) that are mirror-symmetric about a single axis. The forms of shadows cast by the Sun at each stage of an eclipse may be calculated by the convolution of different crescent patterns with the silhouettes of objects. Figure 2 shows the calculated shadow of a square when the Sun is full, and the shadows of a square and a circle when it is a right-handed crescent (prongs pointing to the left). Careful observation of these images, when displayed on a high-resolution, gamma-corrected display, shows that light and dark bands are visible all around the shadow of the square when the Sun is full. When it is a right-handed crescent, bright and dark bands are visible on the top and bottom, a bright band but not a dark band on the right side, and no bands on the left. The shadow of the circle shows the full range of penumbra types a crescent Sun can form.

**Figure 1.** A photomontage showing the progress of an eclipse as seen from Perth, Western Australia, on Tuesday, 16 February 1999. The eclipse was at maximum shortly after 3.30 pm.

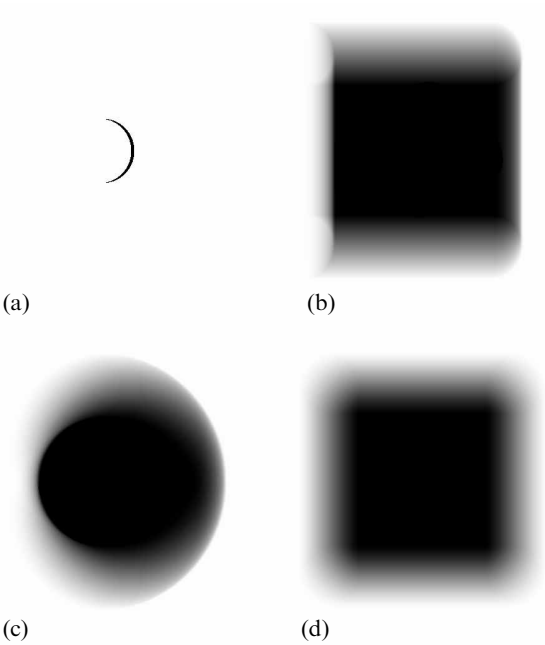


**Figure 2.** Shadows computed by convolving Sun shapes with silhouettes of objects. (a) The shape of the crescent Sun. (b) The shadow of a square cast by the crescent Sun. (c) The shadow of a circular disc cast by the crescent Sun. (d) The shadow of a square cast by a full Sun.

A range of penumbra types is also observable on the computed shadow in figure 4, and, as in figure 2, bright Mach bands are prominent on one side and absent on the other.

A more detailed analysis of the penumbras of a square with the Sun a right-handed crescent (figure 2b) is provided in figure 3. A vertical slice through the shadow of the square shows the luminance profiles of the penumbras to be symmetrical and approximately trapezoidal. A horizontal slice shows an asymmetry, the right penumbra profile being concave as viewed from within the shadow, the left convex.

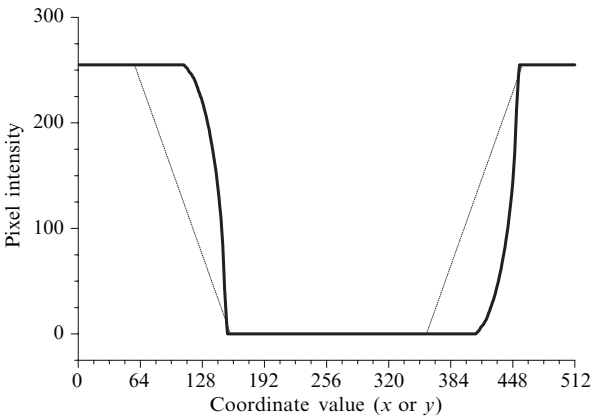


**Figure 3.** Horizontal (thick line) and vertical (thin line) slices through the shadow of a square cast by the crescent Sun (figure 2a) showing intensity profiles.

Solar eclipses occur because of the happy accident that the Sun and the Moon are both spheres and both subtend to a viewer on Earth almost the same visual angle, 0.5 deg. That size enables the Sun to throw shadows of our own bodies on which we can see Mach bands. If it were much smaller or more distant we could not, since the penumbras of our own shadows would subtend too small an angle at our eyes. Mach bands are not visible on very narrow ramps (Fiorentini 1972; Ross et al 1981, 1989). We could, of course, see them on other objects since penumbra size depends upon the distance of a shadow from the object that casts it, and, in any case, the angular size of a penumbra can be altered by changing viewing distance. But this is not possible for our own shadows: if we move closer to a surface, the penumbra of our own shadow shrinks. Shakespeare's Richard III (figure 4) said he had

**Figure 4.** A shadow computed by convolving the silhouette of Laurence Olivier portraying Richard III with the shape of a crescent sun.

"No delight to pass away the time
Unless to spy my shadow in the sun
And descant on mine own deformity".

Future watchers of eclipses will now have something new to delight them, the changing play of their shadows and the Mach bands on them.

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