Although previous studies suggest that carbonaceous bodies would probably have released their energy too high in the atmosphere to have been responsible for Tunguska, our work, because of the more realistic, lower drag coefficient and the less severe calculated heating loads, indicates that a given meteor would airburst at a significantly lower altitude than previously believed[1,2]. As a result, carbonaceous chondrites 50–100 m in diameter are found to airburst in the 6–10-km range characteristic of the Tunguska object. Because these are the most common type of meteor to enter the Earth's atmosphere, they must be considered the most probable cause of the Tunguska event.

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Tuned directionality in cricket ears

SIR – Crickets (*Gryllus bimaculatus*) listening to the 4.5-kHz calling song have excellent directional hearing: the tympanal vibrations vary much with the direction of sound incidence[1,2], but the amplitude of sound pressure at the ears is almost constant[3]. The reasons for this apparent paradox are that sound reaches both the outer surface of the tympanum and the inner surface (through tracheal tubes from the ipsi- and contralateral thoracic spiracles, respectively; see Fig. 1*a*), and that the relative phases of the three sounds depend on the angle of sound incidence.

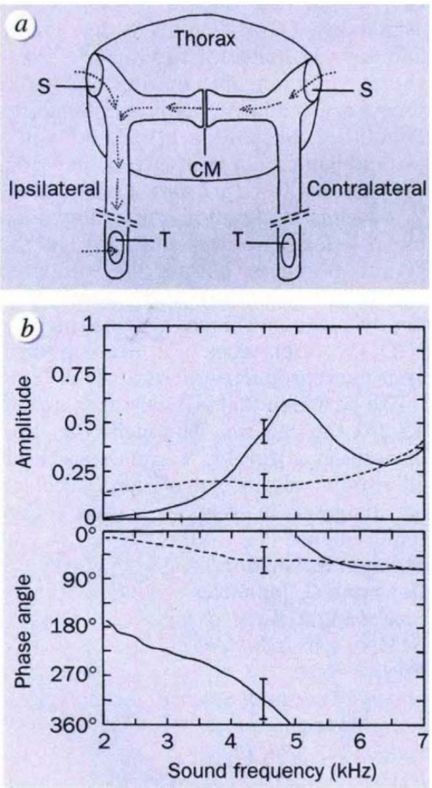

FIG. 1 *a*, The cricket hearing organ. CM, central membrane; S, spiracle (opening on thorax); T, tympanum (in front leg). Dotted arrows, sound paths. *b*, Amplitude and phase of sound arriving at the inner surface of a tympanum from the contralateral spiracle. Solid line, intact; broken line, perforated central membrane. The sound at the spiracle is set to an amplitude of 1 and a phase of 0°. Standard deviations indicated at 4.5 kHz ($n = 5$).

The transmission of sound from a spiracle to the tympanum can be studied by using the tympanal vibrations (recorded with laser vibrometry) for measuring the sound at the inner surface[3]. Sound from the contralateral spiracle is delayed by no less than 313° at 4.5 kHz when it reaches the tympanum (Fig. 1*b*, solid line). This is exactly right for the sound to be almost in phase with the (vectorial) sum of the other two sounds when the sound direction is ipsilateral, and almost out of phase for contralateral sound[3]. The result is the directional diagram in Fig. 2*a* (solid line).

The physical distance from the contralateral spiracle to the tympanum is much too small to account for the 313° delay, so some other factor must be responsible for the large delay. A central membrane (Fig. 1*a*) in the transverse trachea is involved. Holes of 10–25% of its area (made with the tip of a human hair) cause the phase at 4.5 kHz to drop to 54°, and a change is also seen in the amplitude of the transmitted sound (Fig. 1*b*, broken line). The result is a dramatic decrease in the directionality (broken line in Fig. 2*a*), previously observed using electrophysiological techniques[4]. Especially important for crickets walking towards singers is the disappearance of the gradient of auditory sensitivity in the forward direction (Fig. 2*b*, where 30° and 330° are typical extreme positions during phonotactic meandering).

In the intact animal, the change of phase varies much with frequency (Fig. 1*b*). A proper phase, which is a prerequisite for the high directionality of the ear, only exists within a narrow band around the calling song frequency (Fig. 2*b*). The mechanical phase shifting thus tunes the directionality of the ear.

Small animals living on the ground have a frequency band of only a few kilohertz available for long-distance communication. They are too small to emit low-frequency sounds, and high-frequency sounds suffer much attenuation and scattering[5]. They are thus forced to communicate at relatively low frequencies, at which directional hearing is difficult.

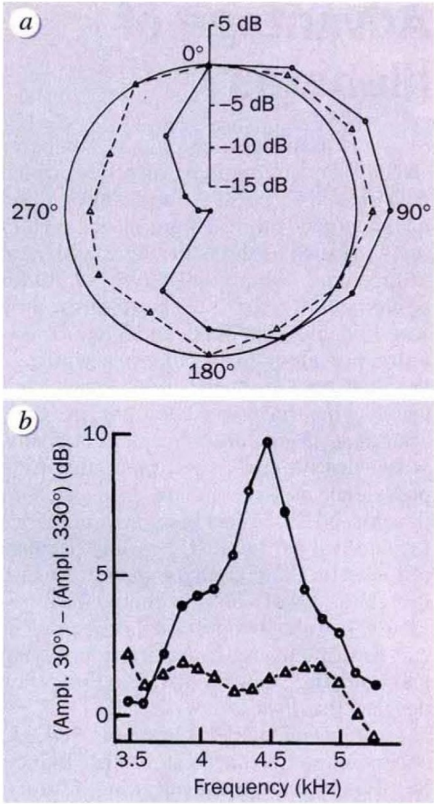

FIG. 2 *a*, Directional dependence of tympanal vibration at 4.5 kHz in a cricket with intact (solid line) and perforated central membrane (broken line). 0°, forward; 90°, ipsilateral sound direction. *b*, Difference between the tympanal vibrations at 30° and 330°. Solid and broken lines as in *a*.

Small grasshoppers with a pressure-difference hearing mechanism similar to that of crickets do not have a mechanical phase shifter in their interaural tracheal air sacs, and their directional hearing around 5 kHz is not very impressive[6]. Calculations show, however, that a much more useful directionality would exist if the sound arriving at the inner surface from the other ear had been more delayed.

The cricket thus stands out as an animal that has solved a major problem in auditory biophysics. It is tempting to speculate that the pure tone calling songs of crickets may have evolved as a consequence of the excellent directional hearing made possible within a very narrow frequency range by the mechanical phase shifter.

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