



**Figure 1** A male *Liophryne schlaginhaufeni* transporting froglets. Eleven froglets are visible (out of 22 in total) on the lateral and dorsal surfaces of the adult. The froglet located on top of the father's head is preparing to jump off.

remote rainforest at 800–1,350 m, where the topography and rainfall (6.4 m per year)<sup>2</sup> are extreme. All microhylid frogs on New Guinea are thought to develop directly from eggs, skipping the aquatic tadpole stage and hatching as miniature versions of the adults<sup>3</sup>.

Among the many (more than 20) microhylid species at this site, I discovered that, in addition to guarding eggs, males of at least two species (*Liophryne schlaginhaufeni* and *Sphenophryne cornuta*) transport the froglets after they have hatched (Fig. 1). I observed 23 froglet-transport events: 9 in *S. cornuta* and 14 in *L. schlaginhaufeni*. In all of the 19 cases for which the sex of the transporting individual was ascertained, froglets were transported by the male.

Five entire transport-clutches (from eggs to independent froglets) were seen in *L. schlaginhaufeni*, with males carrying froglets for three to nine nights (mean  $\pm$  s.d.,  $6.6 \pm 2.6$ ;  $n=5$ ) and travelling 0–17 metres each night ( $7.6 \pm 4.19$ ;  $n=29$ ) through herbaceous vegetation, and seeking refuge under the leaf litter of the forest floor during the day. Total transportation distances ranged from 34 to 55 m ( $44.4 \pm 8.7$  m;  $n=5$ ).

The regular dispersal pattern of froglets has potential benefits. Froglets distributed themselves evenly over time (fewer than seven froglets dispersing per night;  $3.6 \pm 1.7$ ;  $n=49$ ) and space (between 0.4 and 5.5 m;  $3.3 \pm 0.7$  m;  $n=49$ ) by individually jumping off the transporting male. The rewards accrued by the froglets might include less competition for food, a lower chance of predation and a decreased potential for inbreeding because they are widely dispersed.

Male parental care in other frog families includes both attendance and

transport of eggs and tadpoles, but not froglet transport<sup>4</sup>. Froglet transport has only been reported for females in a single species, the Jamaican cave-breeding frog *Eleutherodactylus cundalli*<sup>5</sup>, and has either not been observed in New Guinean frogs<sup>6</sup> or has been only briefly described without identification of the species or sex of the caring adult<sup>7</sup>.

Uniparental male care is extremely rare in terrestrial vertebrates<sup>8</sup>. Even in groups with male care, most species display maternal or biparental care, or no care at all. The microhylid frogs of New Guinea are the only known large group (over 150 species in about 20 genera) of terrestrial vertebrates in which male care predominates. Comparative cost–benefit analyses should provide insights into the evolution of this behaviour and the role of parental care in the radiation of microhylid frogs on New Guinea, adding to our understanding of the environmental and/or historical conditions under which male parental care evolves.

**David Bickford**

University of Miami, PO Box 249118, Coral Gables, Florida 33124-0421, USA, and

Wildlife Conservation Society, Papua New Guinea Program, PO Box 277, Goroka, EHP,

Papua New Guinea

e-mail: bickford@bio.miami.edu

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Cosmology

## Black holes constrain varying constants

There is evidence to suggest that the fine-structure constant,  $\alpha$  — a measure of the strength of the electromagnetic interaction between photons and electrons — is slowly increasing over cosmological timescales<sup>1–4</sup>. As  $\alpha = e^2/\hbar c$  (where  $e$  is the electronic charge,  $\hbar$  is Planck's constant and  $c$  is the speed of light), this would call into question which of these fundamental quantities are truly constant. Here we consider black-hole thermodynamics as a test of which constants might actually be variable, discounting those that could lead to a violation of the generalized second law of thermodynamics.

Observational evidence suggests that there has been a variation of  $\Delta\alpha/\alpha = -0.72 \pm 0.18 \times 10^{-5}$  over the past 6–10 billion years<sup>1</sup>. This result could be interpreted as supporting some non-standard cosmological theories that invoke varying the speed of light<sup>5–7</sup> or the electronic charge<sup>8</sup>. It has been shown<sup>9</sup> that a varying- $c$  cosmology, through changes to standard units, can be rephrased as a varying- $e$  theory, similar to the one proposed earlier<sup>8</sup>. If attention is restricted to electromagnetic phenomena, there is no observational difference between the theories, and either  $c$  or  $e$  could account equally well for the variation in  $\alpha$ . However, there may be fundamental theoretical reasons concerned with gravitation to favour varying  $c$  over varying  $e$ .

One way to introduce gravitation into the discussion is through the theory of black-hole thermodynamics. Entropy is associated with the area of a black hole's event horizon<sup>10,11</sup>, leading to a generalized second law of thermodynamics in which the event horizon's area may only decrease if there is a corresponding increase in the conventional entropy of the black hole's environment<sup>10,11</sup>.

In the case of a non-rotating black hole with electric charge  $Q$  and mass  $M$ , the area of its event horizon,  $A_H$ , is obtained in conventional general-relativity theory from the Reissner–Nordström solution of Einstein's field equations

$$A_H = 4\pi r^2 \quad (1)$$

where

$$r = \frac{G}{c^2} [M + \sqrt{M^2 - Q^2/G}] \quad (2)$$

The entropy of a black hole is given by  $S_H = (kc^3/G\hbar)A_H/4$ , which becomes

$$S_H = \frac{k\pi G}{\hbar c} [M + \sqrt{M^2 - Q^2/G}]^2 \quad (3)$$

where  $k$  is Boltzmann's constant.

An increase in the magnitude of the electric charge,  $Q$ , with  $c$  and  $G$  remaining constant, implies a reduction in the area of the event horizon. By contrast, a decrease in the speed of light,  $c$ , would lead to an increase in event-horizon area. Thus the two contending alternatives for an increase in  $\alpha$  produce opposite outcomes as far as black-hole entropy is concerned.

It could be argued that a reduction in event-horizon area implies a violation of the generalized second law of thermodynamics, and so the fundamental electric charge therefore cannot increase. However, before we can be secure in that interpretation, several conditions must be satisfied. The black hole will radiate heat into its environment through the Hawking process, and, as  $Q$  changes, the temperature will also change. For the second law of thermodynamics to be violated, the black hole must not raise the entropy of the environment by more than its own entropy decreases. This condition is readily satisfied by immersing the black hole in a heat bath of equal temperature and allowing the heat radiation to change isentropically as the charge varies.

Furthermore, equation (3) is based on standard gravitational theory. In a non-standard theory that involves varying  $e$  or  $c$ , the formula for the area of the event horizon might differ<sup>12</sup>. Also, the Hawking process may be modified in a way that alters the relationship between temperature, entropy and event-horizon area. Equation (3) must then be considered as an approximation of the limit of small variation of 'constants'. However, it is unlikely that minor modification of equation (3) will reverse the sign of the relationship between charge and event-horizon area.

Moreover, in the standard theory there is a maximal electric charge, given by  $Q^2 = M^2$ , above which the event horizon disappears and the black hole is replaced by a naked singularity. A modified theory might alter the value of this maximal charge, but there will still be a limit above which any increase in charge will create a naked singularity, violating the cosmic-censorship hypothesis<sup>13</sup>.

Our arguments, although only suggestive, indicate that theories in which  $e$  increases with time are at risk of violating both the second law of thermodynamics and the cosmic-censorship hypothesis. Thus, black-hole thermodynamics may provide a stringent criterion against which contending theories for varying 'constants' should be tested.

**P. C. W. Davies\***, **Tamara M. Davis†**,  
**Charles H. Lineweaver†**

\*Australian Centre for Astrobiology, Macquarie University, Sydney 2109, Australia  
e-mail: pdavies@els.mq.edu.au

†Department of Astrophysics, University of New South Wales, Sydney 2052, Australia

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Kinematics

## Gliding flight in the paradise tree snake

Most vertebrate gliders, such as flying squirrels, use symmetrically paired 'wings' to generate lift during flight, but flying snakes (genus *Chrysopelea*) have no such appendages or other obvious morphological specializations to assist them in their aerial movements<sup>1–6</sup>. Here I describe the three-dimensional kinematics of gliding by the paradise tree snake, *Chrysopelea paradisi*, which indicate that the aerial behaviour of this snake is unlike that of any other glider and that it can exert remarkable control over the direction it takes, despite an apparent lack of control surfaces.

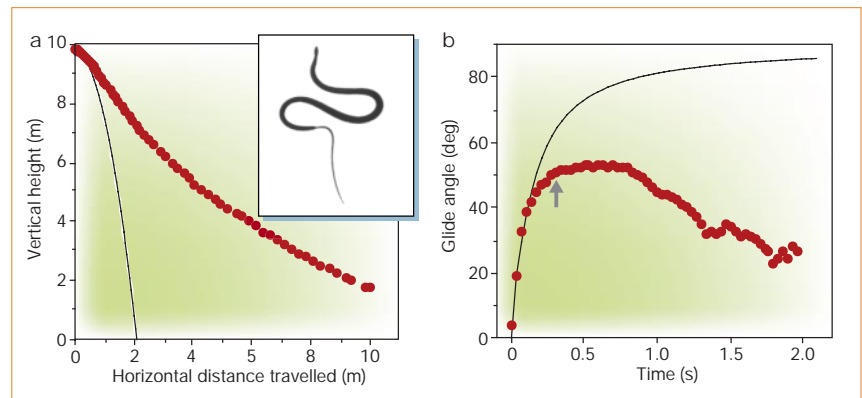
I determined the full three-dimensional gliding trajectory of wild-caught *C. paradisi*, a southeast Asian arboreal colubrid. Snakes were videotaped and photographed jumping from a horizontal branch at the top of a 10-metre-high tower in an open field at the Singapore Zoological Gardens. Two video cameras were positioned to record in stereo, allowing the three-dimensional coordinates

of the head, midpoint and vent of the snake to be monitored throughout its trajectory.

*C. paradisi* prepares for take-off by hanging from a branch, with the anterior body looped into a 'J' shape. The snake jumps by accelerating up and away from the branch, straightening the body and dorsoventrally flattening it from head to vent. Its body width roughly doubles, with the ventral surface acquiring a slightly concave shape. As the snake gains speed while falling, the body pitches downwards and the head and vent are brought towards the midpoint to form an 'S' shape in the horizontal plane. The snake begins to undulate laterally, starting with the anterior body. The flight trajectory shallows (Fig. 1) as lift is generated. Throughout the trajectory, its body posture changes in a characteristic way during each undulatory cycle.

In a typical glide, the snake took off with a maximum upward acceleration of  $14.4 \pm 0.8 \text{ m s}^{-2}$  (mean  $\pm$  s.e.m.) and horizontal velocity of  $1.7 \pm 0.1 \text{ m s}^{-1}$  ( $n=7$  for both) when fully airborne. During mid-glide, the snake undulated at a frequency of  $1.3 \pm 0.1 \text{ Hz}$ , with a wave height (peak to trough) of  $33 \pm 2\%$  snout–vent length ( $n=7$  for both). The airspeed (the speed along its trajectory) and sinking speed were  $8.1 \pm 0.2$  and  $4.7 \pm 0.5 \text{ m s}^{-1}$  ( $n=8$ ), respectively. The glide angle late in the trajectory was  $31 \pm 3^\circ$  ( $n=8$ ), although the glide angle continued to change throughout.

*C. paradisi* is surprisingly adept at aerial manoeuvring. In contrast to many fliers, *C. paradisi* turns without banking. Instead, turns are initiated by movement of the anterior body, and occur only during the half of the undulatory cycle when the head is moving towards the direction of the turn. In one sequence, a snake (snout–vent length, 47 cm;



**Figure 1** Representative glide trajectory of *Chrysopelea paradisi* (snout–vent length, 64 cm; mass, 27 g). **a**, Aerial trajectory, not including take-off sequence. *Chrysopelea* data points (red) are unsmoothed three-dimensional midpoint coordinates, projected in a lateral plane and sampled at 30 Hz. The wing loading, determined from the ventral silhouette of the aerial snake, is  $26 \text{ N m}^{-2}$ . The angle of attack of the anterior body ranges from  $5^\circ$  to  $60^\circ$ . Black curve, theoretical path of a projectile launched with the same initial velocity as the snake. The snake exits from the field of view of the cameras before landing. **b**, Glide angle through time for this same trajectory (red). Glide angle is the angle between the local trajectory and the horizon. The glide angle starts near zero, reflecting the snake's initial horizontal velocity, and then deviates from the theoretical projectile (black) early in the trajectory, roughly where the snake starts undulating (arrow). The glide angle levels off in the ballistic dive at about  $53^\circ$ , then decreases at a rate of  $22^\circ \text{ s}^{-1}$ . Both the glide angle and the airspeed change throughout the trajectory, indicating that equilibrium was not reached in this sequence.

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