Experiments with a sunbird

J. Güémez[a)] and R. Valiente[b)]
Departamento de Física Aplicada, Universidad de Cantabria, E-39005 Santander, Spain

C. Fiolhais[c)] and M. Fiolhais[d)]
Departamento de Física and Centro de Física Computacional, Universidade de Coimbra, P-3004-516 Coimbra, Portugal

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A theoretical description of the sunbird, a drinking bird without any external liquid, is compared with experiment. The transient times and the periods of oscillation given by a simulation of the dynamics agree with the measured values.
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I. INTRODUCTION

In the well-known drinking bird, water or another external liquid evaporates from the head of a toy bird, establishing a thermal gradient between the bird's head and the body. In Ref. 1, hereafter referred to as paper I, we studied the dynamics of that system.

The drinking bird is a thermal engine because it produces work from a thermal difference. Instead of using the evaporation of an external liquid as a cooling mechanism of the head, a similar thermal gradient may be induced by heating the body, with the head kept at room temperature. In fact, monitoring this system is simpler because illumination is easier to control than the evaporation of an external liquid.

When the black painted body of a drinking bird is illuminated either by a light bulb or by the sun, hence the name "sunbird,"[2] its temperature increases. As a result, the vapor pressure of the internal liquid (usually methylene chloride) increases in the body, forcing the liquid to rise in the tube. The bird undergoes a cycle similar to that of the drinking bird: the same type of motion may therefore be produced without any external liquid. Figure 1 shows a schematic and a photo of our sunbird, whose characteristics are given in Table I of paper I.

In Sec. II we present a model for the sunbird's period and relate it to the properties of the sunbird and light bulb and the distance to the light source. In Sec. III, we describe a set of experiments to verify the model. In Sec. IV we apply the dynamical equations of paper I. Our conclusions are given in Sec. V.

II. SUNBIRD PERIOD

For a bird illuminated by a light bulb with current I and voltage $\mathcal{V}$, the power absorbed by its illuminated surface is a fraction of the power provided by the source so that we may write:

$$\dot{U}=\varepsilon A\frac{\alpha I\mathcal{V}}{f(d)}, \tag{1}$$

where ε is a factor that takes into account the absorption properties of the body ($\varepsilon\approx 1$ for a dull black surface), A is the projected area of the bird's body, and $f(d)$ is a function of the distance d from the lamp to the bird. The explicit form of f—which is peculiar to the lamp and accounts for the inverse square law—is given in Eqs. (7) and (8). The phenomenological parameter, $\alpha<1$, describes power losses; its value indicates the fraction of electrical power supplied to the light bulb that is converted into thermal radiation.

While the body is illuminated, the temperature of the internal liquid increases and according to the Clausius–Clapeyron equation, the vapor pressure also increases. Thus, the pressure in the body exceeds that in the head, forcing the liquid to rise in the tube. The result is an oscillation such as that described in paper I and references therein for the drinking bird. When the internal liquid reaches a certain height, the bird tips completely forward. We call this motion a dip, as for the drinking bird, although there is now no external liquid. During the dip the liquid, which had entered in the head, drains back to the body so that the bird returns to its initial upright position. A steady periodic motion is then established.

The temperature variation is related to the corresponding variation in z (the height of the internal liquid top level with respect to the surface level in the body) by an equation similar to Eq. (5) of paper I, namely

$$dT=\frac{\rho_I g\,dz}{B}, \tag{2}$$

where ρ_I is the density of the internal liquid and B is a constant characteristic of the bird. $B=(2.07\pm 0.01)\times 10^3\ \mathrm{Pa\,K^{-1}}$ is the value corresponding to our drinking bird, which is the same as in paper I; see paper I for details.

According to our observations, the bird typically takes a few minutes to dip for the first time, and then starts a periodic motion with a period that is about five times smaller than the transient time. We denote the initial time by τ_0 and the period by τ. At the beginning of each cycle the upper level of the liquid is close to the head, meaning that the body temperature does not decrease to room temperature after the dip, but remains higher. When the lamp is switched on, the height z rises to $z_{\max}=z'+\Delta z$, with $z'=L-\Delta l$ ($\Delta l\ll L$), as shown in Fig. 2(a), which represents the results of a simulation whose details will be presented in Sec. IV. We denote by $\Delta T'$ the temperature difference between the room temperature, T_R, and the lowest temperature in the cycle ($\Delta T'$ is the temperature difference corresponding to z') and by ΔT the temperature variation in a cycle (ΔT corresponds to Δz). When we initially heat the bird, the temperature rises by $\Delta T'+\Delta T$ and, when the system is in its steady state, the body temperature oscillates between $T_R+\Delta T'$ and $T_R+\Delta T'+\Delta T$, as shown in Fig. 2(b). The rate of the temperature variation inside the body is

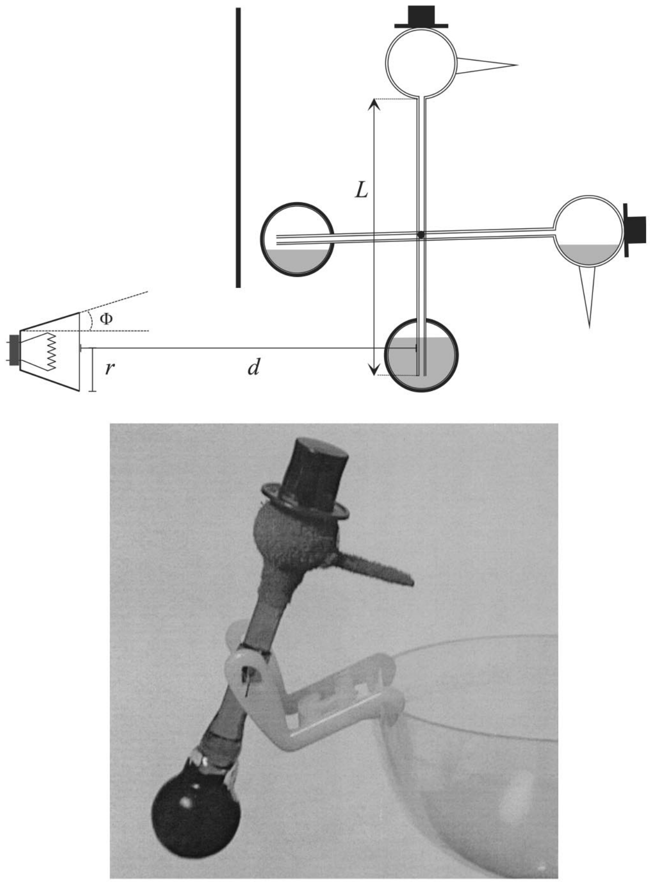

Fig. 1. Schematic and photo of our sunbird (drinking bird with a black-painted body) illuminated by a conical light bulb. A screen prevents the head from being illuminated. The glass is empty. Compare with Fig. 1 of paper I.

$$\frac{dT}{dt}=\frac{\dot{U}}{C}=\varepsilon A\frac{\alpha I\mathcal{V}}{Cf(d)}, \tag{3}$$

where C is an effective heat capacity given by

$$C=m_I c_I+m_g^B c_g+m_t c_g. \tag{4}$$

Here c_I and c_g are the specific heats of the internal liquid and glass, respectively, and m_I, m_g^B, and m_t are the masses of the internal liquid, body glass, and tube, respectively. We combine Eqs. (2) and (3) to find the time elapsed before the first dip (see Fig. 2):

$$\tau_0=\frac{\rho_I g C f(d)}{AB\varepsilon\alpha I\mathcal{V}}z_{\max}. \tag{5}$$

Afterward the bird starts a periodic motion with a period τ that is a fraction of τ_0, that is,

$$\tau=\beta\tau_0, \tag{6}$$

where $\beta<1$, because the internal liquid rises an amount $\Delta z<z_{\max}$. The phenomenological parameter β, which may be determined for a given bird and lamp, does not depend on the distance d.

Equations (5) and (6) replace Eq. (6) of paper I, but there are some similarities that should be mentioned. In both cases the period is proportional to a heat capacity and the temperature variation in one cycle. [To see explicitly this dependence for the sunbird, substitute Eq. (2) in Eq. (5).] The period of the drinking bird depends on the evaporation rate and on the latent heat of the external liquid [Eq. (6) of paper I], whereas for the sunbird the period depends on the power supplied by the lamp, on the distance between the lamp and the bird, and on certain intrinsic characteristics of the bird such as ε, α, and A.

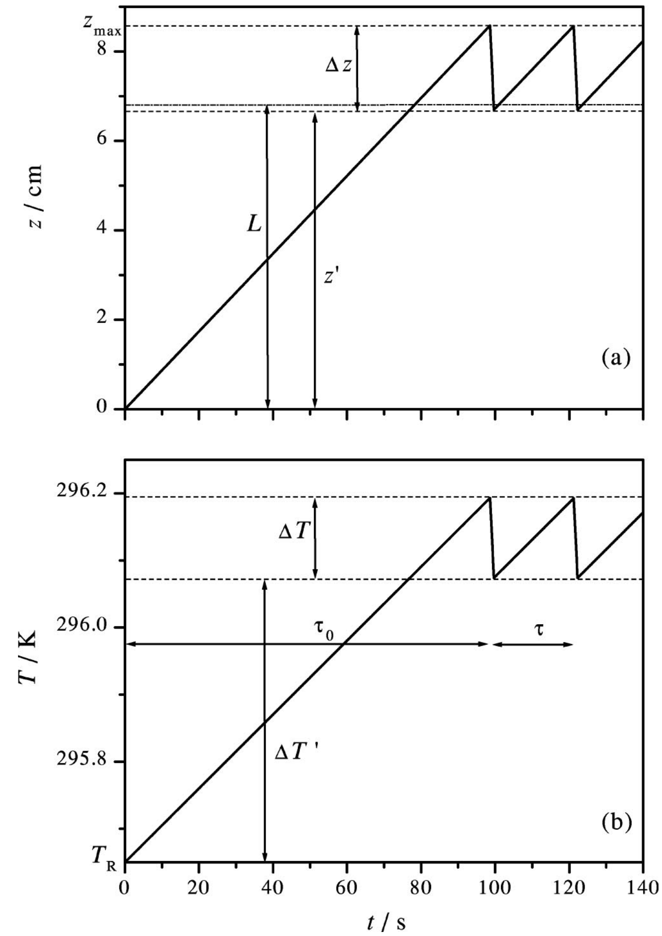

Fig. 2. Evolution (a) of the internal liquid height of the sunbird, z, and (b) the temperature inside the bird's body, T. These results were obtained in the simulation described in Sec. IV, under the conditions indicated in Fig. 5(a). Compare this result with Fig. 2 of paper I, recalling that in paper I it is the head temperature which is represented instead of the body temperature.

III. EXPERIMENTS

For our bird, the mass of the internal liquid, the mass of the glass in the body, and the mass of the tube are $m_I=2.658$ g, $m_g^B=0.642$ g, and $m_t=1.900$ g, respectively. With these values and the specific heats of the glass and the internal liquid given in Table I of paper I, we find $C=6.25$ J °C^{-1}. The projected area (area of a circle) of Eq. (1) is $A=2.51$ cm^2.

We placed the bird at different distances from the light bulb (Fig. 3). We used a Philips 240–250 V, 200 W spherical lamp, with current $I=0.74$ A and voltage $\mathcal{V}=220$ V, and a 230 V, 120 W Philips Spotone PAR38 30° conical Flood lamp, operating with a current $I=0.52$ A and voltage $\mathcal{V}=220$ V. The function $f(d)$ in Eq. (1) is given by

$$f_S(d)=4\pi d^2 \qquad \text{(spherical light bulb)} \tag{7}$$

and

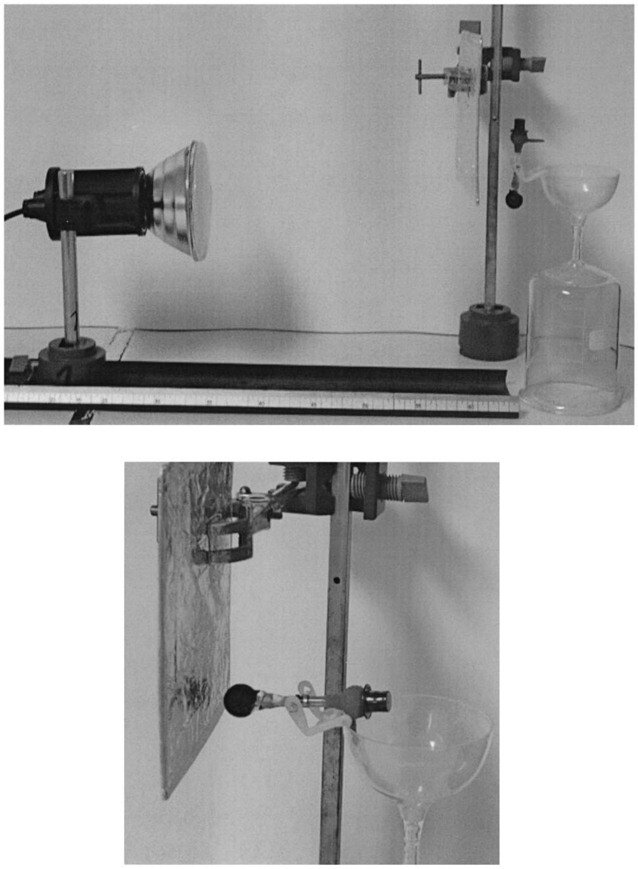

Fig. 3. Top: sunbird setup consisting of a conical light bulb, a digital watch, an ammeter, a voltmeter, and a ruler. Bottom: close-up of the sunbird.

$$f_C(d)=\pi(r+tg\Phi d)^2 \qquad \text{(conical light bulb)}, \tag{8}$$

where r is the emitting surface radius of the conical lamp and Φ its characteristic angle (Fig. 1). For our lamp $r=5.5$ cm and $\Phi=15°$.

With the bird initially at room temperature, we switched on the lamp and measured τ_0. Because the period of the initial oscillatory motion varied slightly, we had to keep the sunbird working for some time until the motion stabilized. To start a new set of measurements at a new distance, we had to wait about 1 h before the body's temperature returned to room temperature.

In Fig. 4 we show our results for the initial time τ_0 and the period τ as a function of f_S and f_C for the spherical and conical lamps, respectively. The results are consistent with Eqs. (5) and (6); τ is indeed proportional to τ_0. In particular, the inverse square relationship assumed in our analysis is supported by the data. From the least-square fits, we obtain $\beta=0.20$ for the spherical lamp and $\beta=0.23$ for the conical one.

IV. SIMULATION

We modified the model which we described in paper I to describe the dynamics of the sunbird. The illumination of the sunbird during the time dt leads to a temperature increment dT given by Eq. (3). According to Eq. (2), this temperature increase forces the liquid to rise $dz=dP/\rho_I g$ in the tube [see Eq. (4) in paper I], where $dP=BdT$ [see Eq. (2) in paper I]. The resulting dz is [compare with Eq. (5)]

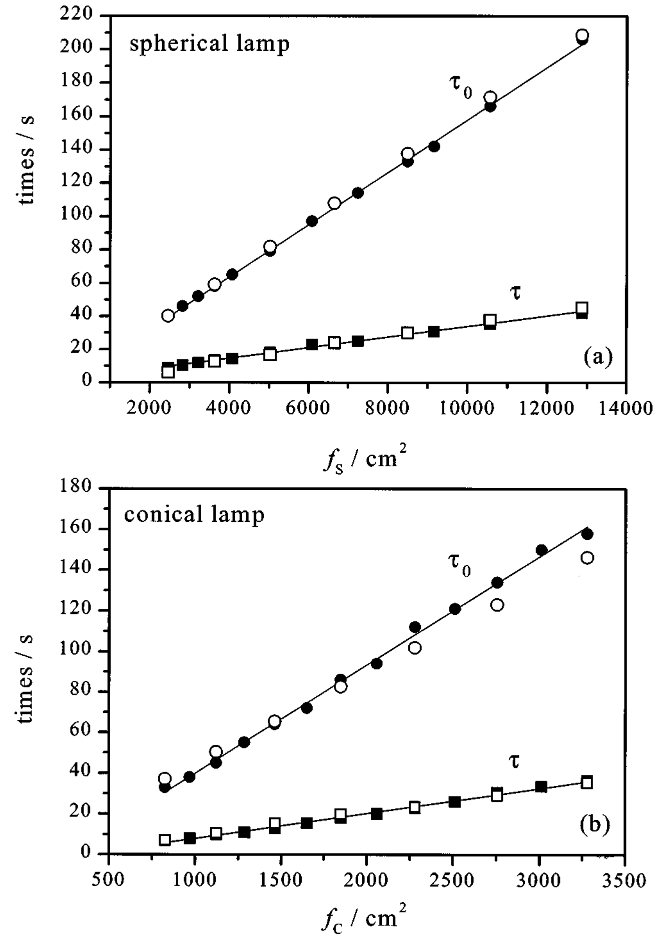

Fig. 4. Initial times τ_0 (closed circles) and periods τ (closed squares) of the sunbird for the (a) spherical and (b) conical lamps used in our experiments as a function of, respectively, $f_S(d)=4\pi d^2$ and $f_C(d)=\pi(r+tg\Phi d)^2$. (Note the different horizontal scales in the upper and lower panels.) The straight lines are linear fits to the data. The open circles and squares correspond to the simulation described in Sec. IV.

$$dz=\frac{AB\varepsilon\alpha I\mathcal{V}}{\rho_I gCf(d)}dt. \tag{9}$$

For a given distance, d, the height z evolves linearly in time, starting at $z(0)=0$. In Sec. IV of paper I we explained how the angular position θ (the angle between the tube and the vertical direction) and the angular velocity $\omega=\dot{\theta}$ of the bird change in time. The derivations of the momentum of inertia and torque of the bird are given there.

When $\theta=90°$ (bird's dip), part of the internal liquid returns to the body, so that, in the simulation, the angular velocity is set to zero and z is set to $z'=L-\Delta l$, with the experimental value $\Delta l\approx 0.1$ cm (independent of the lamp). From Eq. (2), the initial temperature change is $\Delta T'=0.40\,°\mathrm{C}$.

In Fig. 5(a) we show the angle θ as a function of time for the spherical lamp at $d=22$ cm. For this simulation we used $\beta=0.20$ and $\varepsilon\alpha=0.60$, which fit the periods better in the

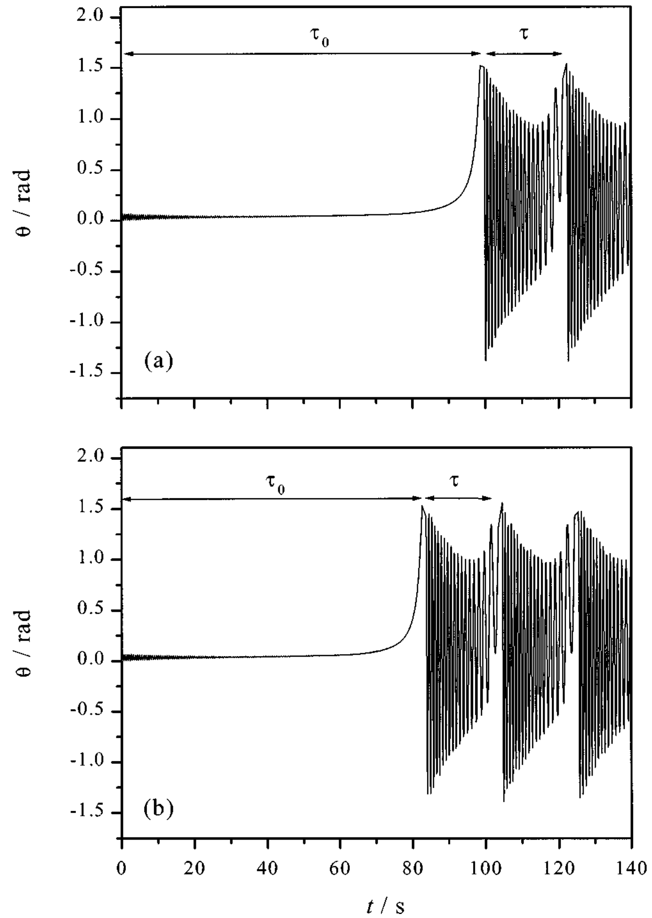

Fig. 5. The angle θ as a function of time for the sunbird illuminated with (a) a spherical lamp at the distance $d = 22$ cm and (b) a conical lamp at the distance $d = 85$ cm. In both cases the initial conditions are $\theta(0) = 0.1$ rad and $\omega(0) = 0.0$ rad/s. In (a) the time before the first dip and the period obtained in the simulation are $\tau_0 = 107.8$ s and $\tau = 23.9$ s. (The experimental values are $\tau_0 = 105.2$ s and $\tau = 23.0$ s.) In (b), these quantities are $\tau_0 = 82.6$ s and $\tau = 19.8$ s. (The experimental values are now $\tau_0 = 82.5$ s and $\tau = 18.3$ s.)

entire range of d [see Fig. 4(a)]. Figure 4 also shows the simulation results. We obtain $\Delta T' + \Delta T = 0.53\,°\mathrm{C}$, so that $\Delta T = 0.13\,°\mathrm{C}$.

Figure 5(b) shows the time dependence of θ for the sunbird illuminated by the conical lamp at $d = 85$ cm. We used the value $\beta = 0.23$ and $\varepsilon\alpha = 0.31$. As for the spherical lamp, the latter value arises from fitting the periods in the whole range of d [see Fig. 4(b)]. Figure 4 also shows the simulation results in this case. We conclude from Fig. 5 that the transient times for the sunbird (τ_0) are larger than for the drinking bird.

We note from Fig. 4 that the agreement between the data and the simulation results is better for the spherical lamp. The same conclusion may also be drawn from Table I where we present the slopes of the linear fits to the data and to the simulation values, $\tau = mf$. The larger discrepancies found for the conical lamp are probably due to an inaccuracy in f_C as given by Eq. (8).

Table I. The slopes of the linear fits to the period vs f for the data points and for the simulation points (see Fig. 4). The units of the slope are s/cm.

	m (fit)	m (simulation)
Spherical τ_0	0.0157	0.0162
τ	0.0032	0.0035
Conical τ_0	0.0534	0.0447
τ	0.0123	0.0106

V. CONCLUSIONS

We have discussed the sunbird, which involves, besides liquid–vapor equilibrium, the inverse square law dependence of thermal radiation. We studied the effect of placing the lamp at different distances, and measured and simulated the time for the first dip and the subsequent times between consecutive dips. In contrast to the drinking bird, the temperature of the body increases above room temperature. And in contrast to the drinking bird, there is a noticeable transient time before the steady state regime establishes.

Only a fraction of the electrical power supplied to the spherical and conical lamps is converted into thermal radiation. Although this fraction is different for each lamp, we observed that the fraction of internal liquid that had to be re-heated after the first dip is similar for both.

The body heating mechanism works well for birds with various sizes. This fact is interesting because we may control the dynamics of a big sunbird for classroom demonstrations or science center exhibitions in contrast to the usual drinking bird, which depends on the humidity and whose height is limited by the natural cooling mechanism. We have constructed such a big sunbird for demonstrations to large audiences.

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[a]Electronic mail: guemezj@unican.es
[b]Electronic mail: valientr@unican.es
[c]Electronic mail: tcarlos@teor.fis.uc.pt
[d]Electronic mail: tmanuel@teor.fis.uc.pt

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