Experiments with the sunbird

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Abstract

A theoretical description of the sunbird — drinking bird without any external liquid — is compared with experiment. Our sunbird has a black painted body which is illuminated by a light bulb. The transient times and the oscillation periods given by a simulation of the dynamics agree with the measured ones.

1 Introduction

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

The drinking bird is a thermal engine since it produces work from a thermal difference. Instead of using the evaporation of an external liquid as cooling mechanism, a similar thermal gradient may also be induced by heating the body, if the head is kept at room temperature. In fact, monitoring this system is somehow simpler since 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] — it heats up. Then, the vapor pressure of the internal liquid (usually methylene chloride) increases in the body, forcing the liquid to rise up 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 scheme and a photo of our sunbird, whose data are given in Tab. 2 of I.

In Sec. 2 we present a model for the sunbird's period and relate it to the sunbird and light bulb characteristics, and the distance to the light source. In Sec. 3, we describe

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a set of experiments we performed with a sunbird to verify the model, which are very different from the experiments described in I for the drinking bird. In Sec. 4 we apply the dynamical equations of I. The conclusions are in Sec. 5.

2 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, $I\mathcal{V}$, provided by the source so we may write:

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

where ε is a factor which 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 separation d which is peculiar to the lamp [its explicit form is given below, in eqs. (7) and (8)]. Finally, $\alpha < 1$ is a phenomenological parameter describing power losses: it indicates the fraction of electrical power supplied to the light bulb which 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 and the liquid rises in the tube. The result is an oscillation like that described in I (and references therein) for the drinking bird. When eventually the internal liquid reaches a certain height, the bird tips completely forward: we call this a dip, as in the case of the drinking bird, although there is no external liquid. During the dip the liquid which had entered in the head drains back to the body so that the bird goes back to its upright position. A steady periodic motion is then established.

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

$$\mathrm{d}T = \frac{\rho_{\mathrm{I}}\, g\, \mathrm{d}z}{B}\,, \tag{2}$$

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

According to our observations, the bird takes typically a few minutes to dip for the first time, and then starts the periodic motion with a period which is about five times smaller. 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 fall down to room temperature after the dip, but remains higher. When the lamp is switched on, the height z rises to $z_{\max} = \Delta z_0 + \Delta z$, with $\Delta z_0 = L - \Delta l$ ($\Delta l \ll L$), as shown in Fig. 2 (a), which shows the results of a simulation whose details will be presented in Sec. 4. Let us denote by ΔT_0 the temperature difference between the room temperature, T_{R}, and the lowest temperature in the cycle (ΔT_0 corresponds to Δz_0) and by ΔT the temperature variation in a cycle (ΔT corresponds to Δz). When the bird starts to be heated, the temperature rises $\Delta T_0 + \Delta T_0$ and, when the system is in the steady regime, the body temperature oscillates between $T_{\mathrm{R}} + \Delta T_0$ and $T_{\mathrm{R}} + \Delta T_0 + \Delta T$, as shown in Fig. 2 (b).

During a time interval dt, the temperature inside the body increases by

$$\mathrm{d}T = \frac{\dot{U}\,\mathrm{d}t}{C} = \varepsilon A \frac{\alpha I \mathcal{V}}{C f(d)} \mathrm{d}t\,, \tag{3}$$

where C is an effective heat capacity given by

$$C = m_{\mathrm{I}} c_{\mathrm{I}} + m_g^{\mathrm{B}} c_g + m_t c_g\,. \tag{4}$$

Here c_{I} and c_g are the specific heats of the internal liquid and glass respectively, while m_{I}, m_g^{B} and m_t are, respectively, the masses of the internal liquid, body glass, and tube. Equations (2) and (3) also holds for a finite time interval. Combining eqs. (2) and (3) the time elapsed until the first dip occurs (see Fig. 2) is

$$\tau_0 = \frac{\rho_{\mathrm{I}}\, g\, C\, f(d)}{A\, B\, \varepsilon \alpha\, I\, \mathcal{V}} z_{\max}\,. \tag{5}$$

After the fist dip the bird starts a periodic motion, whose period τ is a fraction of τ_0, i.e.

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

where $\beta < 1$, since the internal liquid has only to rise $\Delta z < z_{\max}$. This parameter β, which may be determined phenomenologically for a given bird and lamp, does not depend on the distance d.

Equations (5) and (6) now replace Eq. (6) of I. They have some similaties which it is worth to point out. In both cases the period is proportional to some heat capacity an the temperature variation in one cycle [to see explicitly this dependence in the sunbird one should insert Eq. (2) in Eq. (eq:th08b]. On the other hand, the Eq. (6) of depends on the evaporation rate and on the latent heat of the external liquid, hereas for the sunbird the period depends on the power supplied by the lamp, n the distance between the lamp and the bird and on intrinsic characteristics of he bird such as ϵ, α, A.

3 Experiments

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

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

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

and

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

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. Since the periods of the initial oscillatory motion varied slightly, we had to keep the sunbird working for some time until the periods stabilized. To start a new set of measurements at a new distance, we had to wait about one hour before the temperature of the body 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 $f_{\rm S}$ and $f_{\rm C}$, 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 relashionship assumed in our analysis is supported by the data. From the least-square fits, one obtains $\beta = 0.20$ for the spherical lamp and $\beta = 0.23$ for the conical one.

4 Simulation

In this section, we apply to the sunbird, with the necessary modifications, the dynamical model for the drinking bird which we have introduced in I.

Illumination of the sunbird during dt leads to a temperature increment dT given by Eq. (3). According to (2) this heating forces the liquid to rise dz = d$P/\rho_{\rm I} g$ in the tube [see Eq. (4) in I], where $\mathrm{d}P = B\,\mathrm{d}T$ [see Eq. (2) in I]. The resulting $\mathrm{d}z$ is [compare with Eq. (5)]

$$\mathrm{d}z = \frac{A\,B\,\varepsilon\alpha\,I\,\mathcal{V}}{\rho_{\mathrm{I}}\,g\,C\,f(d)}\mathrm{d}t\,. \tag{9}$$

For a given distance, d, the height z evolves linearly in time, starting with $z(0) = 0$. In Sec. 4 of I we explained how the angular position θ (angle between the tube and the vertical direction) and the angular velocity $\omega = \dot{\theta}$ of the bird evolve 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 from the head to the body, so that, in the simulation, the angular velocity is set to zero and z to $\Delta z_0 = L - \Delta l$, with the experimental value $\Delta l \approx 0.1$ cm (irrespective of the lamp). From (2), the initial temperature increment with respect to T_{R} is then $\Delta T_0 = 0.40$ °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 $\beta = 0.20$, obtained in Sec. 3, and $\varepsilon\alpha = 0.60$, which fit the periods better in the whole range of d [see Fig. 4 (a)]. Figure 4 also shows the simulation results. One gets $\Delta T_0 + \Delta T = 0.53$ °C so that $\Delta T = 0.13$ °C.

Figure 5 (b) shows the time dependence of θ for the sunbird illuminated by the conical lamp at $d = 85$ cm. For this simulation we used the value of the parameter β indicated at the end of Sec. 3 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. One concludes 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 is better for the spherical lamp. The same conclusion may be drawn from Table 1 where we present the slopes of the linear fits to the data of the linear fits to the simulation points, $\tau = m\,f$. The larger discrepancies found for the conical lamp are probably due to some inaccuracy in f_{C} as given by Eq. (8).

		m (fit) / s cm^{-1}	m (simulation) / s cm^{-1}
spherical	τ_0	0.0157	0.0162
	τ	0.0032	0.0035
conical	τ_0	0.0534	0.0447
	τ	0.0123	0.0106

Table 1: Slopes of the linear fits to the periods versus f for the data points and for the simulation points (see Fig. 4)

5 Conclusions

We have discussed the sunbird, which involves, besides liquid-vapor equilibrium, the inverse square law dependence of thermal radiation propagation. We have studied the effect of illumination at different distances, measuring and simulating 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, also in contrast with the drinking bird, there is a noticeable transient time before the steady regime establishes.

We have seen, for both a spherical and a conical lamp, that only a fraction of the electrical power supplied to the lamp 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 of them.

The body heating mechanism works well for birds of various sizes. This fact is interesting since one may control the dynamics of a big sunbird for classroom demonstrations or science centers 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 (Fig. 6) for demonstrations to large audiences.

References

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[2] R. Mentzer, *The drinking bird – The little heat engine that could*, The Physics Teacher **31**, 126-127 (1993).

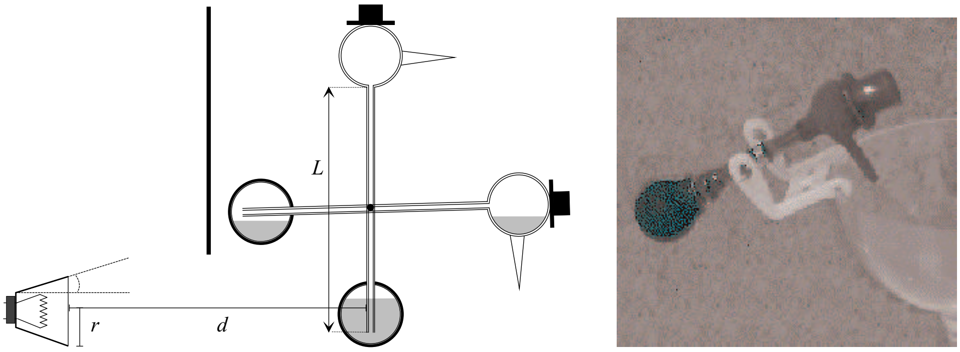

Figure 1: Scheme and photo of our sunbird (drinking bird with a black-painted body) and conical light bulb. A screen prevents the head from being illuminated. The glass is empty. Compare with Fig. 1 of I.

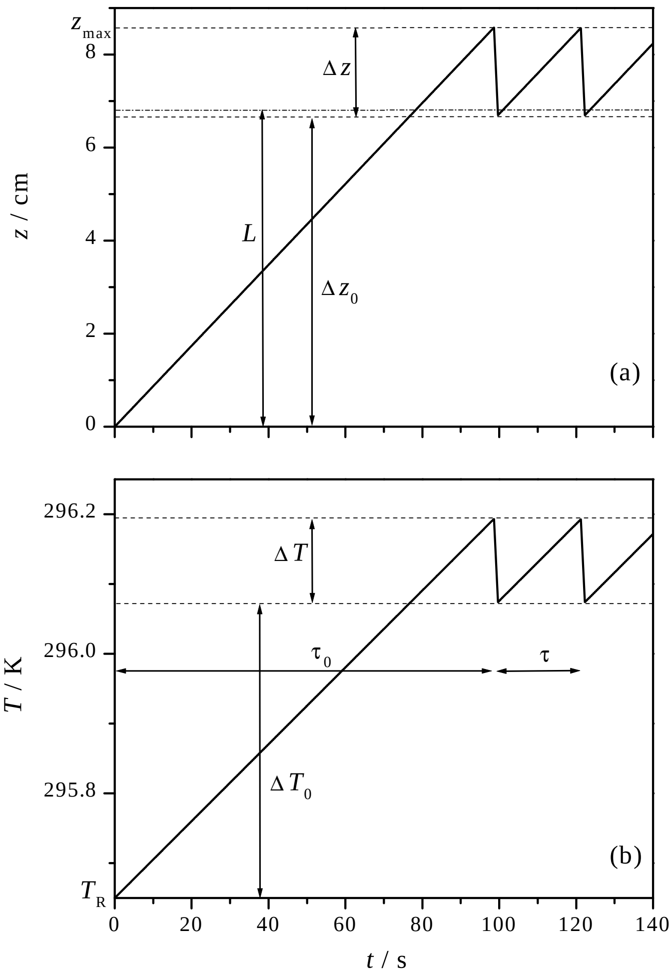

Figure 2: Evolution with time (a) of the internal liquid height of the sunbird, z, and (b) temperature inside the bird's body, T. These results were obtained in the simulation described in Sec. 4, in the conditions indicated in Fig. 5 (a). Compare this figure with Fig. 2 of I, noticing that in I it is the head temperature that is represented instead of the body temperature.

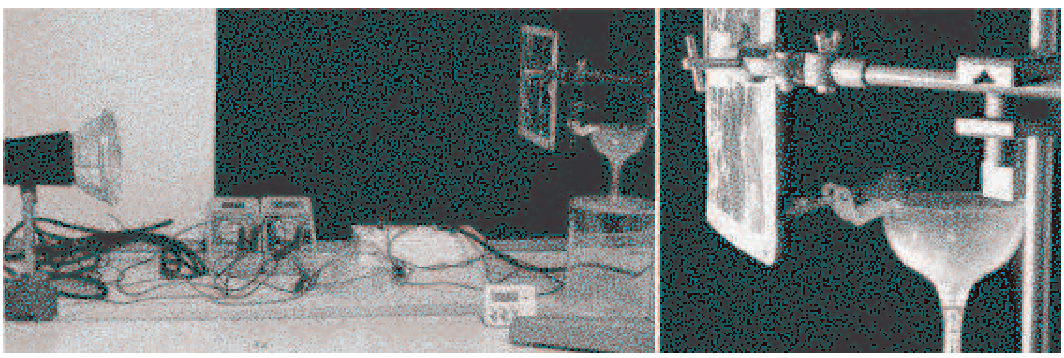

Figure 3: On the left: Sunbird setup consisting of a conical light bulb, a digital watch, an ammeter, a voltmeter, and a ruler. On the right: zoom of the sunbird.

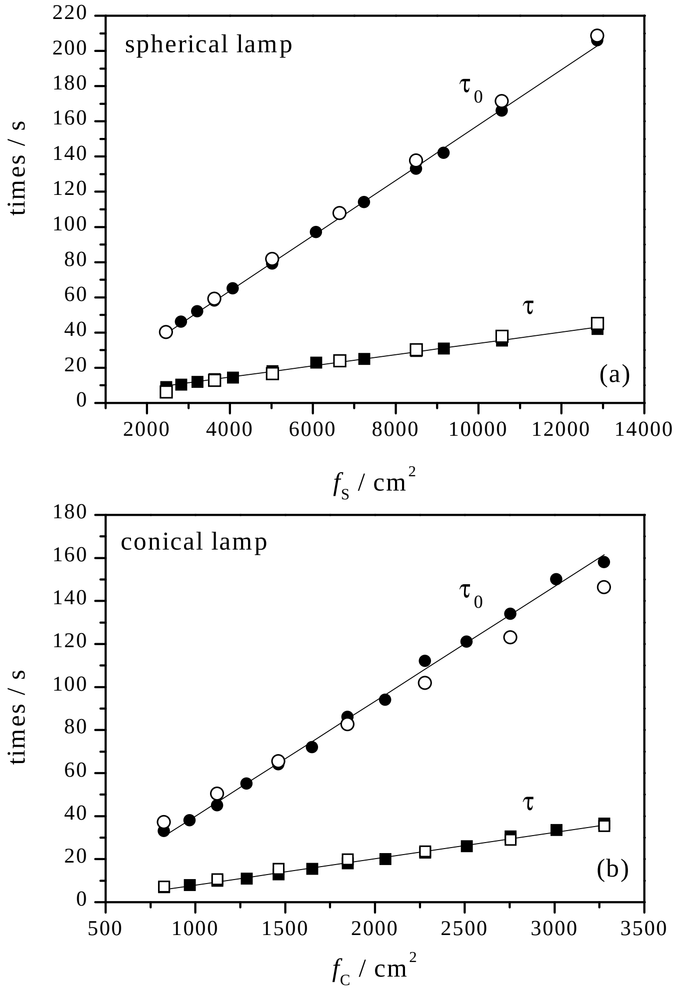

Figure 4: Initial times τ_0 (black circles) and periods τ (black squares) of the sunbird, for the two lamps [(a) spherical and (b) conical] used in our experiments as a function of, respectively, $f_S(d) = 4\pi d^2$ and $f_C(d) = \pi\,(r + \mathrm{tg}\Phi\, d)^2$ (note the different horizontal scales in the upper and lower panels). The straight lines are linear fits to the data: $\tau_0 = 0.86 + 0.0157\, f_S$ (s) and $\tau = 1.88 + 0.0032\, f_S$ (s), for the spherical lamp; and $\tau_0 = -13.45 + 0.0534\, f_C$ (s) and $\tau = -4.46 + 0.0123\, f_C$ (s), for the conic lamp. The open circles and squares correspond to the simulation described in Sec. 4.

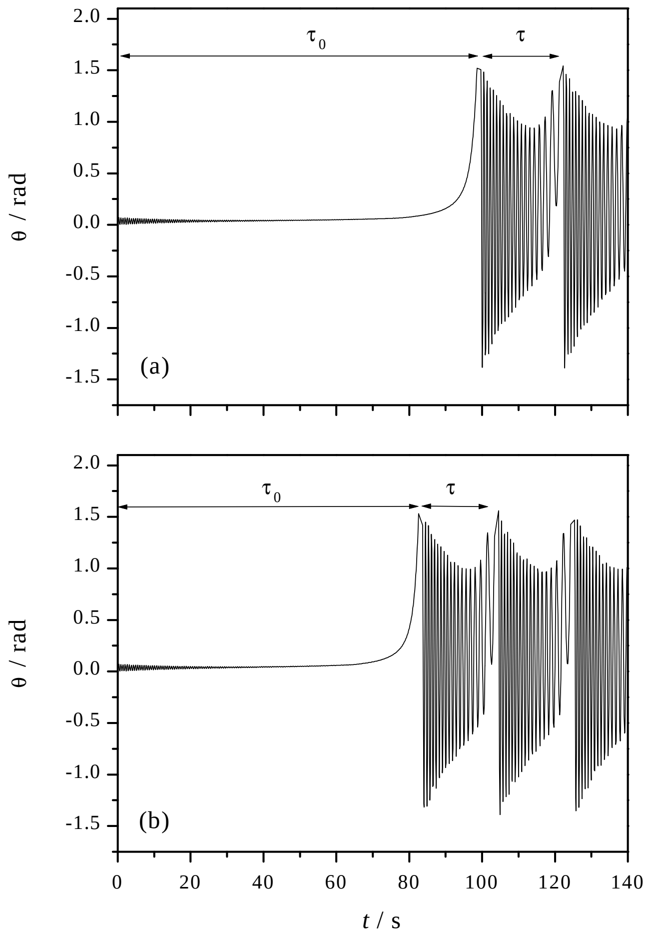

Figure 5: Angle θ as a function of time for the sunbird illuminated with (a) the spherical lamp at the distance $d = 22$ cm and (b) the conical lamp at the distance $d = 85$ cm. In both cases the initial conditions are $\theta(0) = 0.1$ rad and $\omega(0) = 0.0$ rad/s. In (a), the time before the first dip and the period are $\tau_0 = 107.8$ s and $\tau = 23.9$ s (the experimental values are, respectively, $\tau_0 = 105.2$ 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).

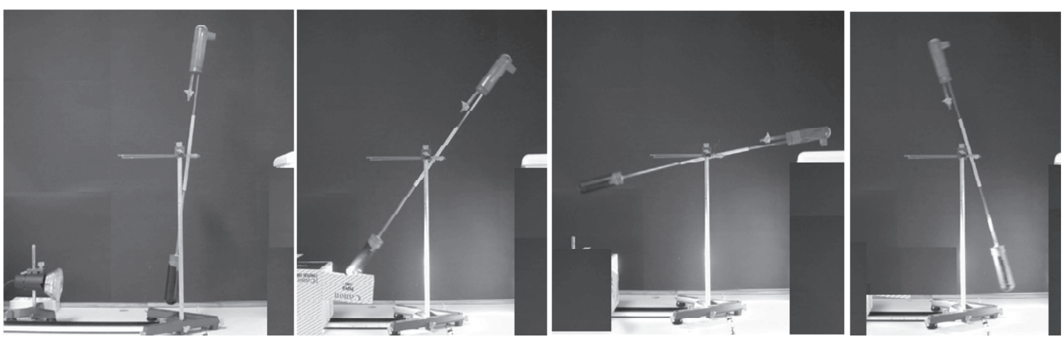

Figure 6: Big sunbird to be used in demonstrations. We have built this 1 m high model.