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Bioenergetics and stellar luminosities

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Research Article

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Abstract

We draw attention to a curious coincidence wherein the most (steadily emitting) luminous objects in the Universe from stellar X-ray sources to ultra-luminous quasars and Ultra Luminous Infrared Galaxies, steadily emit a power per unit mass, which is just the same value as the maximal metabolic rate in (warm-blooded) bio-organisms.

There has been much discussion (West *et al.* 1997; Banavar *et al.* 1999; McNab 2003) of universal relationships between the basal metabolic rate of warm-blooded animals and their corresponding mass M. In particular, we have Kleiber's law, where the metabolic rate B is related to mass M by the relation:

$$B = aM^{3/4}, \tag{1}$$

where a is a constant. If B is in kilocalories, M is in kilograms, then a is about 90 kcal/kg$^{3/4}$. This law is roughly found to be valid for a very wide range of organism masses (ranging from elephants weighing a few tons to rodents weighing a few grams). Equation (1) implies, for example, that an average human being at rest has a power requirement of about a 100 kcal (420 kilojoules) per hour, equivalent to a power output of a little over a 100 watts. A detailed discussion of Kleiber's law and possible theoretical derivations appears in Sivaram & Sastry (2004). The power per unit mass radiated by the human body is $\sim 10^4$ ergs/s/g. For the Sun this is 2 ergs/s/g. So mass for mass we are at least 5000 times more luminous than the Sun. Of course all radiation we emit is in the far infrared (IR) corresponding to a body temperature of about 37°C. Kleiber's law implies that the smallest warm-blooded creatures (shrews, etc.) emit $\sim 10^5$ ergs/s/g. This is about the upper limit of the radiant flux ('luminosity') emitted per unit mass by bio-organisms on Earth.

We wish to point out a very curious coincidence. Now in astrophysics, generally speaking, the maximal luminosity which can be emitted by any stellar object of mass M is given by the so-called Eddington luminosity, at which the radiation pressure of the luminous flux of the star balances the gravitational force (matter would be dispersed away from the star above this luminosity). This maximal luminosity $L_{\max}$ (or Eddington luminosity) for a celestial object of mass M is given by:

$$L_{\max} = \frac{4\pi GMm_{\mathrm{p}}c}{\sigma_{\mathrm{T}}}, \tag{2}$$

where σ_{T} is the Thompson cross-section, m_{p} is the proton mass, G is the gravitational constant and c is velocity of light.

$$\sigma_{\mathrm{T}} = \frac{8\pi}{3}\left(\frac{e^2}{m_{\mathrm{e}}c^2}\right)^2, \tag{3}$$

e and m_{e} are the electron charge and mass, respectively (for relevant equations refer Sivaram, 1982; Shapiro & Teukolsky, 1983).

From equations (2) and (3), we obtain the maximal stellar luminosity per unit mass as:

$$\frac{L_{\max}}{M} = \frac{4\pi Gm_{\mathrm{p}}c}{\sigma_{\mathrm{T}}} = 10^5 \text{ ergs/g/s}. \tag{4}$$

This is a constant (independent of M). A star of solar mass at this maximal luminosity would emit $\sim 2 \times 10^{38}$ ergs/s (2×10^{38} W). The most luminous objects in the Universe from stellar X-ray sources to ultra-luminous quasars, including Ultra Luminous Infrared Galaxies, etc. steadily emit at a power per unit mass of $(L/M) = 10^5$ ergs/g/s, as given by equation (4) (Sivaram 1982). This has a curious coincidence with the maximal metabolic rate (per unit mass) in bio-organisms, which has the same value. So the most luminous celestial objects

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and most 'luminous' bio-organisms steadily emit the same total radiant flux per unit mass (albeit at different wavelengths and the physics of course is quite different).

Again the theoretical maximum luminosity allowed from physical considerations, arises in general relativity (GR). We have here the so-called Gunn luminosity given by (Sivaram 1982):

$$L_{\max(\mathrm{GR})} = \frac{c^5}{G} = 2 \times 10^{59} \mathrm{ergs/s}. \tag{5}$$

If the total luminosity emitted by all objects in the Universe is assumed to be this theoretical upper limit (fixed by GR) and we divide this by the total baryonic mass in the Universe (3×10^{54}g) we again end up with the same value of L/M as given by equation (4). Thus, even cosmologically speaking, the upper theoretical limit of the luminosity to mass ratio of the baryonic mass is again of the same value (present in the Universe).

We can perhaps understand the coincidence between the upper limits as follows. For stars, the maximal luminosity per unit mass is well explained by the physics involved as we have described above. Now, warm-blooded organisms (like humans) have to maintain a fixed body temperature (around 37°C or 310 K). The human body for instance has a surface area of around a square metre. We radiate at all wavelengths (like a black body) with a peak wavelength in the far IR (corresponding to the above temperature). So for an area of 1 m^2 (from black-body radiation) power is $\sim 10^9$ ergs/s ergs/s or 100 W, which is what we actually emit. This corresponds to an emission of about 2×10^4 ergs/g/s (for a 60 kg person).

Smaller creatures have a larger relative area. The heat is lost through the surface, but generated over the volume. So surface to volume scales as $1/L$ (L is the typical length scale), and L scales as $M^{1/3}$. The smallest warm-blooded creatures (like a shrew) would have a mass 1000 times less. So relative surface area is ten times more. Thus, the power emitted per unit mass is now some ten times larger (scaling as $M^{-1/3}$). To maintain their body temperatures, their power generated per unit mass is then 2×10^5 ergs/g/s (ten times that for a human), which is indeed what we get for stars ($L_{\max}/M$, equation (4)).

In the case of stars, the luminosity–mass relation is well explained by the laws of physics. For bio-organisms, it is more complex (West & Brown 2004). An understanding of Kleiber's law (equation (1)) is given in the reference: Sivaram & Sastry (2004, pp. 126–129). We briefly sketch the argument here. The work done in stretching muscle of elasticity e and cross-section A is:

$$W \propto eA \frac{\mathrm{d}x}{\mathrm{d}t}. \tag{6}$$

The rate at which the tendon is stretched, ($\mathrm{d}x/\mathrm{d}t$), and elasticity e, is more or less material independent. Hence, $W \propto A$, i.e. $W \propto d^2$, d is the bone diameter. Mass M scales as $d^2\, h$, h being the height. For a wide range of creatures, $h \propto d^{2/3}$. Thus, $M \propto d^{8/3} \propto A^{4/3}$. So $A \propto M^{3/4}$, implying $W \propto M^{3/4}$, which is Kleiber's law.

As this derivation does not seemingly involve the acceleration due to gravity, or other characteristics of the host planet, we can wonder whether similar law holds for warm-blooded organisms on other exoplanets. Will extraterrestrial life have a similar scaling law which seems universal on Earth? This is a point to ponder.

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