Reports

Temperatures of a Close Earth Satellite Due to Solar and Terrestrial Heating

For a satellite sufficiently high in the earth's atmosphere so that it has any considerable orbit lifetime, practically all heat exchange must be by radiation. Although considerable heat would be received from terrestrial reflection and reradiation, the predominant source will be solar.

The theory of planetary temperatures to be expected according to Stefan's law, $E = \sigma T^4$, has been treated thoroughly by several writers (*1–4*). A direct derivation, used by most writers, of the steady-state temperature of a surface at the earth's distance from a vertical sun utilizes the observed solar constant for E and the known Stefan-Boltzmann constant in the above equation. We will show here only an independent derivation of this temperature as found by utilizing the observed effective color temperature of the sun according to Wien's law as 6150°K, and the observed solar parallax, which implies a linear solar radius of 433,000 miles and a mean distance of 93 million miles. Thus, the radiation from the photosphere would lead to the relation for a black body giving maximum equilibrium temperature $T_{\text{max.}}$ at the earth's distance as:

$$\left(\frac{T_{\text{max.}}}{6150^\circ\text{K}}\right)^4 = \left(\frac{433{,}000}{93{,}000{,}000}\right)^2,$$

giving

$$T_{\text{max.}} = 418^\circ\text{K}.$$

This result is completely independent of pyrheliometric data; the latter yield a temperature some 25° lower. Observational confirmation of the present result is indicated by Pettit and Nicholson's determination (*4*, p. 118) of the central full-moon radiation temperature as 407°K, which, multiplied by the gray body approximation factor $(1+A)^{1/4}$, using their determination of the moon's radiometric albedo $A = 0.093$, gives exactly 417°K as its true subsolar temperature. On a relatively rapidly rotating body such as an artificial satellite, no point except the pole of a spin axis directed toward the sun could satisfy even the geometric conditions, and its small size combined with good heat conductivity preclude any close approach to such a high temperature, even on the skin.

For points on a surface inclined by an angle ϕ to solar radiation, the energy received must be multiplied by cos ϕ. Since on a sphere the mean value of cos ϕ is ½, and only half the surface is sunlit at any moment, the mean incoming energy corresponds to ¼, and the resulting mean absolute temperature of all parts of the satellite to $\frac{1}{2}^{1/2}$ of the maximum found above—that is, $T_1 = 296^\circ\text{K}$ for a black satellite in sunlight 100 percent of the time. Then, also, time spent in the earth's shadow is proportional to a further reduction in incoming energy, so that, in general,

$$T_1 = (296^\circ\text{K})\,(F)^{1/4},$$

where F is the fraction of time the satellite is sunlit, represents the time mean of temperature for all parts of the satellite due to direct solar heating alone. For a likely percentage of time in sunlight of 80 percent—that is, $F = 0.8$—the corresponding mean $T_1 = 281^\circ\text{K} = 8^\circ\text{C}$. Central internal parts of an artificial satellite would remain near 8°C; less protected parts near the surface might vary between 22°C or higher when the satellite is in sunlight, down to −6°C or lower when it is in eclipse. These are black-body temperatures and neglect all energy received from the earth.

The mean effect of terrestrial planetary *radiation* can be shown to be practically negligible, as follows. For a satellite at a height of 10 percent of the earth's radius, the radiation energy would fall off 20 percent, thus reducing the planetary temperature of 296°K by 5 percent to 281°K, which is identical with that due to solar heating, as found above for a satellite sunlit 80 percent of the time.

The effect due to terrestrial *reflection* of sunlight is much more considerable but uncertain, depending as it does on the mean radiometric albedo of the earth. Considering that Pettit and Nicholson (*4*, p. 134) have estimated the moon's radiometric albedo at less than 10 percent and that the lower latitude areas under the satellite may be darker than average, 30 percent seems a safe maximum estimate of the earth's effective radiometric albedo (*5*). Also, the maximum angular diameter of the earth from a satellite at workable orbital height is about 140°, so that it covers only (1 − sin 20°) = 2/3 of a hemisphere, and the mean cosine of reflection angle would be ½. Hence, the maximum estimated energy reflection from the earth to the satellite would be about 10 percent of that received directly from the sun. However, since the earth would be effectively "full" to the satellite only half the time on the average, the mean energy received should be increased by a factor of not more than 1.05 over that assumed for computing temperatures due to solar heating alone. These mean black-body temperatures should thus be increased by a factor of no more than $(1.05)^{1/4} = 1.013$, leading to $T_2 = (300^\circ\text{K})\ (F)^{1/4}$, considering both solar and terrestrial heating. For a black satellite in sunlight 100 percent of the time, $T_2 = 27^\circ\text{C}$; for 80 percent in sunlight, $T_2 = 12^\circ\text{C}$. These are the highest mean temperatures to be expected, provided that the total solar absorptivity and thermal emissivity are equal (that is, the gray-body approximation holds) and that the satellite has no internal source of heat.

For an artificial satellite the total solar radiation absorptivity α and thermal emissivity ε of its surface can be determined experimentally before launching. The surface total reflectivity or radiometric albedo is $(1-\alpha)$. The resultant heating energy would be that of a black body, multiplied by α/ε, so that the actual mean temperature would be $T_3 = (300^\circ\text{K})\ (\alpha F/\varepsilon)^{1/4}$.

A recent report (*6*) gives these data for possible satellite shell materials. For typical aluminum alloys the ratio α/ε varies from less than 1/3 when the surface has been coated with silicone to about 3 when the surface is clean and polished. Since the resulting fourth root factors vary between 0.77 and 1.3, the corresponding range on mean temperature is

$$(231^\circ\text{K})\,(F)^{1/4} < T_3 < (390^\circ\text{K})\,(F)^{1/4}.$$

Evidently the surface characteristics of an artificial satellite could be adjusted to produce any desired mean temperature within this range, say $37^\circ\text{C} = 310^\circ\text{K}$ for $F = 1$. For this temperature $\alpha/\varepsilon = (31/30)^4 = 1.13$ would thus be a satisfactory ratio of absorptivity to emissivity.

Finally, it should be emphasized that

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the relations developed above specify how all these predicted temperatures depend upon the assumed effective temperature of the sun, and, to a much less degree, on the radiometric albedo of the earth. Reversing these relations, an immediate implication of the temperatures telemetered from actual satellites of which heating characteristics are known would thus be improved estimates of the heating characteristics of earth and sun.

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References and Notes

1. H. N. Russell, *Astrophys. J.* 43, 178 (1916).
2. H. N. Russell, R. S. Dugan, J. Q. Stewart, *Astronomy* (Ginn, New York, 1938), p. 541.
3. D. H. Menzel, *Astrophys. J.* 58, 65 (1923).
4. E. Pettit and S. B. Nicholson, *Astrophys. J.* 71, 102 (1930).
5. Visual albedo of 0.39 is given by A. Danjon, *Ann. Observatoire Strasbourg* 3, pt. 3, 168 (1937).
6. G. B. Wilkes, "Total normal emissivities and solar absorptivities of materials," *WADC Technical Rept. 54-42* (1954).

5 March 1958

Difference in Response of Phosphatases in Chick Embryo to Injection of Substrate

Recent studies have shown that the administration of appropriate substrates, both in vivo and in culture, can bring about an increase in the activities of certain enzymes in tissues of the chick embryo (*1*). As part of our work on the functional differentiation of the small intestine (*2, 3*), we examined the influence of an injected phosphate ester on the alkaline phosphomonoesterase activity of the chick embryo duodenum. Obtaining positive results in this attempt, we have extended our investigations to other organs and to acid phosphomonoesterase in order to determine whether the response we obtained is peculiar to one phosphatase in one organ, or is more general. These experiments have led to the discovery that although alkaline phosphatase is always elevated under the conditions we have employed, acid phosphatase is in all cases unaffected or is decreased slightly.

In the tests reported here, 25 mg of disodium phenylphosphate in 0.1 ml of isotonic saline was injected into the chorioallantoic vesicle daily, beginning at 14 days of incubation. At 17 days the eggs were opened, the embryos were weighed, and samples of duodenum, liver, mesonephros, and metanephros were removed. Enzyme assays were run on total homogenates of these tissues, with phenylphosphate being used as substrate (*2*). Individual determinations involved from 0.5 to 1.5 mg of fresh tissue in 3.25 ml of fluid (approximately 2 to 10 μg of nitrogen per milliliter). The alkaline phosphatase was determined at *p*H 9.6 in the presence of 0.01*M* $MgCl_2$, the acid phosphatase at *p*H 5.4.

The results (Table 1) reveal that administration of substrate increases the alkaline phosphatase activity not only in the duodenum, in which the enzyme is normally accumulating rapidly during the test period, but also in the two kidneys, in which it is accumulating at a lower rate, and in the liver, in which it decreases somewhat. The effect on liver is also interesting because the enzyme is not associated with brush borders in this organ, as it is in the intestine and the kidneys. Acid phosphatase is not affected or is even lowered slightly in the same samples in which the alkaline phosphatase is increased. Total nitrogen content is not significantly altered by phosphate injection except in the metanephros, in which the nitrogen content of the experimentals is about 10 percent less than that of the controls.

Since duodenal phosphatase may be elevated in the chick embryo by adrenal stimulation (*4*), the possibility presents itself that the enzyme increases reported in this paper are secondary to a general stress effect resulting from the administration of an abnormal substrate, or from release of phenol from the substrate. This possibility may be eliminated, for three reasons. First, the treated embryos at 17 days are as heavy as the controls and are capable of developing normally beyond the test period; their mesonephric weights also are the same as those of the controls. Second, the administration of phenol and dibasic sodium phosphate in quantities equivalent to those contained in the disodium phenylphosphate used in the principal experiments brought about no change in the alkaline or acid phosphatase content of the duodenum. Third, phenylphosphate (but not phenol) produced a significant increase in the alkaline phosphatase content of isolated duodenal fragments cultured in Earle's saline solution or Eagle's nutrient medium, as compared with fragments cultured without substrate. Thus one may infer that the effects observed in vivo are not dependent on the intermediation of organs other than the affected organ. These experiments will be reported in detail later.

Other experiments now in progress are concerned with the effectiveness of other phosphate esters in inducing increase of alkaline phosphatase. Beta-glycerophosphate (25 mg/day) has thus far given only slight and inconsistent results. Phenolphthalein phosphate (25 mg/day) is ineffective. Beta-naphthyl phosphate (25 mg in 0.5 ml of fluid per day) produces no change after 2 days. Since both the acid and alkaline enzymes have strong affinity for all these substrates, it may be that in embryonic tissues, as in microorganisms (*5*), a suitable substrate is not necessarily an effective inducer. This point is being further examined in in vitro experiments.

The uniformity of the difference of response of acid and alkaline phosphatase in all organs studied suggests that the explanation for the difference is not to be sought in terms of the intracellular associations of the enzymes, which vary considerably among the tissues we have examined, but rather in the nature of the enzymes themselves, or in the enzyme-forming systems. Before this question can be profitably approached, it is necessary to consider whether the positive results we have obtained are due to

Table 1. Phosphatase in tissue of chick embryos injected with disodium phenylphosphate (+ Php) or saline (− Php) between 14 and 17 days of incubation. Phosphatase activity is given in micrograms of phenol liberated per 10 μg of nitrogen in 30 minutes. Each value is the average of 8 to 22 determinations and is followed by the standard error of the mean.

Tissue	Phosphatase activity				
	14 days	17 days			
	− Php	− Php	+ Php	% difference	P
Duodenum					
alkaline	3.3 ± 0.17	8.7 ± 0.42	14.8 ± 0.85	+ 70.1	< 0.01
acid	1.9 ± 0.16	2.6 ± 0.15	2.8 ± 0.10	− 7.7	< 0.3
Liver					
alkaline	5.3 ± 0.36	4.7 ± 0.24	7.9 ± 0.43	+ 68.1	< 0.01
acid	4.9 ± 0.41	6.5 ± 0.32	6.3 ± 0.37	− 3.2	> 0.5
Mesonephros					
alkaline	18.4 ± 1.58	29.4 ± 3.13	48.4 ± 3.13	+ 94.1	< 0.01
acid	8.7 ± 0.32	11.5 ± 0.64	11.3 ± 0.33	− 1.7	> 0.5
Metanephros					
alkaline	9.8 ± 0.71	14.8 ± 1.12	42.5 ± 2.09	+ 187.1	< 0.01
acid	5.3 ± 0.29	7.6 ± 0.21	6.8 ± 0.23	− 10.5	< 0.02