tion" (*11*). The struggling of properly immobilized animals was minimal after the first day, and lesions or tourniquet effects in the extremities were avoided through adequate technique. If this particular form of stress is regarded as mainly emotional, the results support the opinion that emotional factors may under certain circumstances favor the manifestation of congenital defects (*12*).

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12. We wish to thank Dr. Ancel Keys for giving us the opportunity to carry out this study during our stay in the United States.

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Perturbations of the Orbit of the Echo Balloon

Abstract. The motion of the Project Echo communications satellite during its first 12 days clearly confirms previous predictions of the influence of solar radiation pressure. During this time, solar pressure reduced perigee height by 44 km. The approximate value of 1.1×10^{-18} g/cm^3 has been obtained for the average air density at the 1600-km altitude of the satellite.

The successful launching of the Echo I balloon on 12 August 1960 provided the first definitive test of the effect of solar radiation pressure on satellite orbits. The importance of this effect on the orbits of large, lightweight satellites was originally discovered and first demonstrated theoretically in the spring of 1959 by the authors, in collaboration with R. W. Parkinson (*1*).

As reported by the National Aeronautics and Space Administration (NASA), Echo I is an aluminum-coated, half-mil Mylar sphere, 100± 1 feet in diameter. Its weight when launched was 157.00 lb, including 33.34 lb of sublimating powders. Hence its cross-sectional area-to-mass ratio (A/M) was initially 102 cm^2/g. Small holes introduced before launching, and meteoric punctures, will permit gas to escape, reducing the mass at a rate difficult to predict. The acceleration due to solar radiation is $K(I/c)(A/M)$, where I is the solar energy flux (*2*), c is the velocity of light, and K is a constant $(0 \leqq K \leqq 2)$ whose value depends on the reflecting characteristics of the surface. For specular reflection from a perfect sphere, $K = 1$. Small irregularities in the shape or any diffuseness in the reflection of sunlight will tend to increase K. (For a sphere whose reflection is completely diffuse, $K = 1.44$.) In addition, if the balloon surface nearest the sun is at a higher temperature, the emitted infrared radiation will be nonisotropic and will have the effect of increasing K.

At the time of writing of this report, orbit data were available only for the first 12 days. Orbital elements were computed from the data by P. Zadunaisky of the Smithsonian Astrophysical Observatory (*3, 4*). Zadunaisky used only unrefined angular data obtained by the Baker-Nunn cameras. Each computed set of elements was determined from two days of observations, centered about the epoch of the elements. The trial expressions for the mean anomaly, the eccentricity, and the argument of perigee consisted of second order polynomials. However, in the latter two cases, all but the lowest order coefficient were held fixed throughout the computation (*5*). The data obtained each day were well distributed about the orbit, and hence the residuals are rather small; the probable errors of the elements are indicated on the appropriate graphs (see Figs. 1 and 2). Short-period terms appear neither in the elements computed from observations nor in our theoretical results, since these terms are averaged out in both cases.

In Fig. 1, we have plotted the orbit eccentricity (e) versus time through

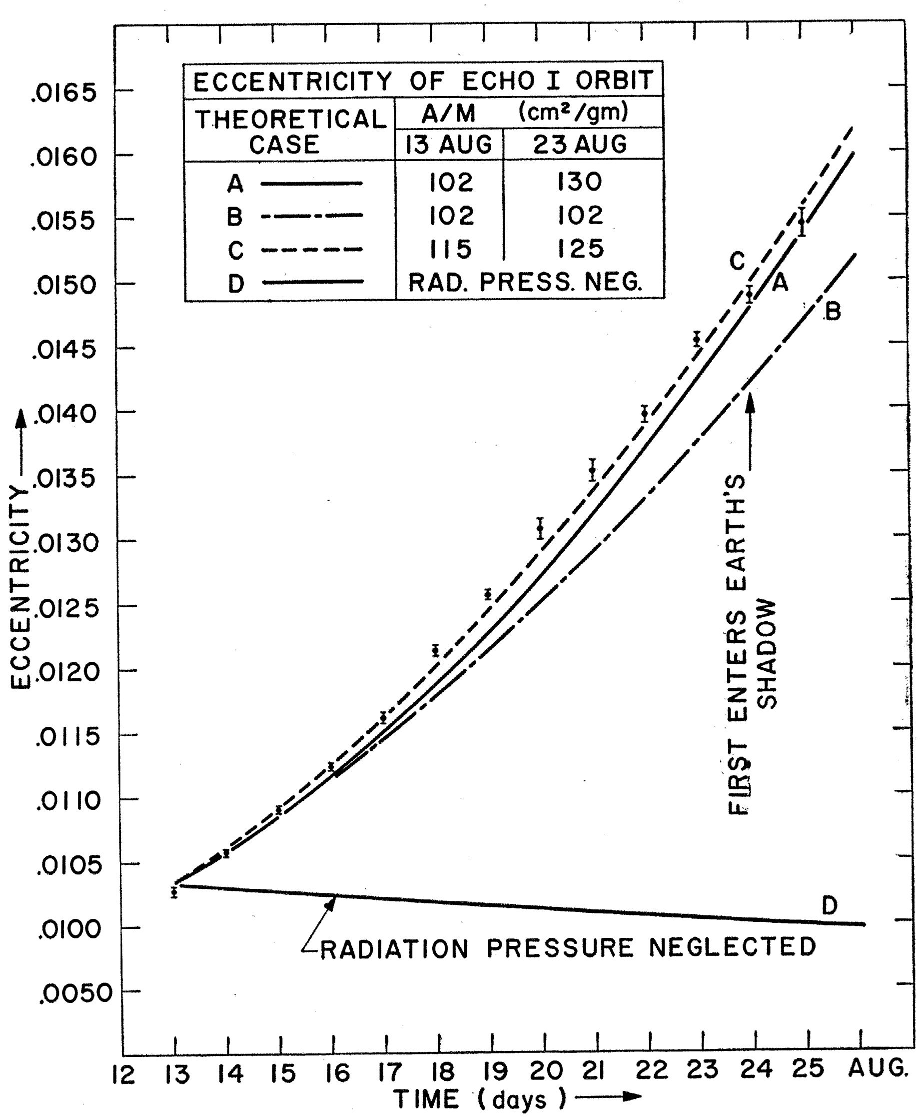

Fig. 1. Time variation of eccentricity.

25 August. It can be seen that the initial increase in eccentricity was about 3×10^{-4} per day, and that this rate increased to about 5.5×10^{-4} per day in 12 days. Similarly the argument of perigee (ω), plotted in Fig. 2, shows a varying rate of increase. The other three elements [semimajor axis (a), longitude of ascending node (Ω), and inclination (i)] are not plotted, because over this short time interval the effects of radiation pressure on these elements are comparable to the probable errors associated with the data. Gravitational and air drag perturbations adequately account for the observed changes in these elements.

The theoretical cases **A**, **B**, **C**, and **D**, also plotted on Figs. 1 and 2, all include the effects of air drag and gravitational perturbations. Case **D** omits the effect of radiation pressure entirely. Note that without radiation pressure e would decrease initially instead of increase, mostly because of the third harmonic of the earth's field, but also because of air drag. The linear increase in ω in case **D** is due primarily to the second harmonic. The wide divergence between case **D** and the experimental points on both figures shows that an important perturbation has been neglected.

Cases **A**, **B**, and **C** include the effects of radiation pressure, but make different assumptions about the "effective" area-to-mass ratio, KA/M. In case **B**, we assume KA/M has the constant value 102 cm²/g. This could correspond to complete specular reflection from a spherical Echo balloon which maintains its initial mass. However, this model cannot account for the experimental change in e, regardless of choice of initial orbital elements. Case **A** assumes an initial KA/M of 102 cm²/g; but this value was increased by about 2 percent per day (*6*) until 23 August, and was then kept constant at 130 cm²/g. Such an increase could, for example, correspond to a loss, from the Echo balloon (with $K = 1$), of 3.2 lb of sublimated powder each day for 10 days. It is clear that Case **A** results in a closer fit to the eccentricity data, without substantially changing the variations in ω.

Better agreement with the data can be obtained by increasing the initial value of KA/M (*7*). For example, case **C** assumed an initial value of 115 cm²/g whose reciprocal was increased by 7×10^{-5} g/cm² per day. One possible realization of this model would be an Echo balloon (with $K = 1.13$) that loses mass at the rate of about 1 lb per day.

In Fig. 2, we find that the slope of the experimental data and of curves for cases **A**, **B**, and **C** are initially quite different from that of case **D**. However, after the first week, the slopes all approach the same value. This fact is easily explained: As the earth-sun line approaches perpendicularity with the line of apsides, radiation pressure tends to displace the orbit in the direction of the latter line, and therefore its effect on the argument of perigee diminishes. On 24 August the earth-sun line is perpendicular to the line of apsides, and the change in ω due to the solar pressure vanishes, leaving only changes due to the other perturbations (which are common to all four cases).

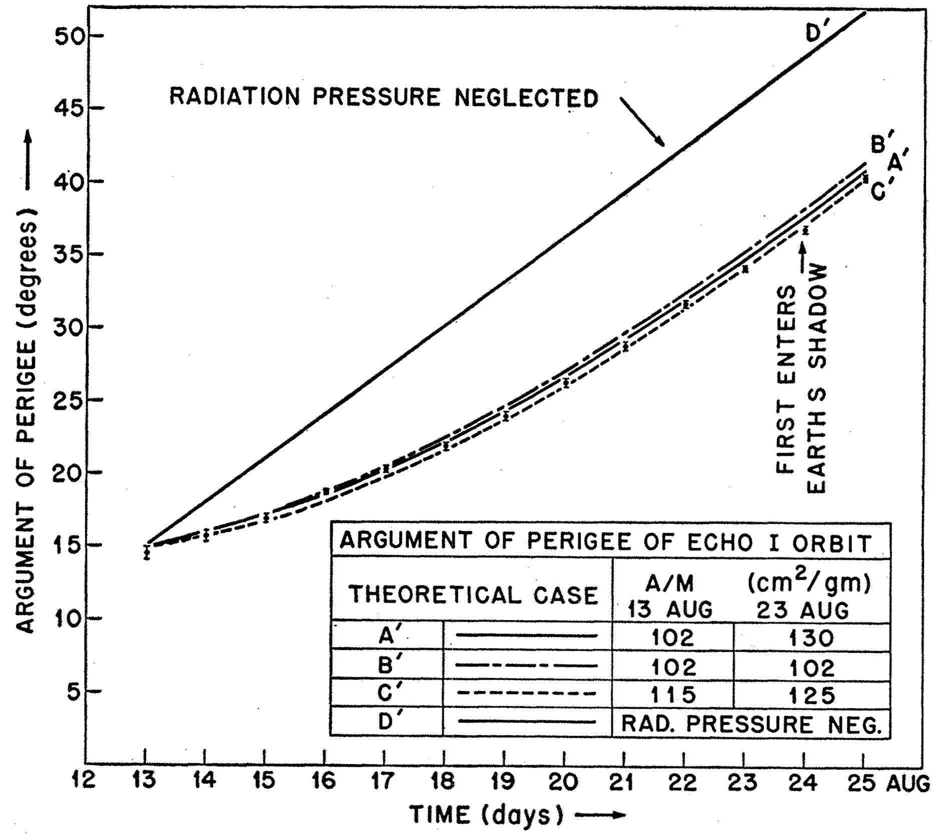

Fig. 2. Time variation of argument of perigee.

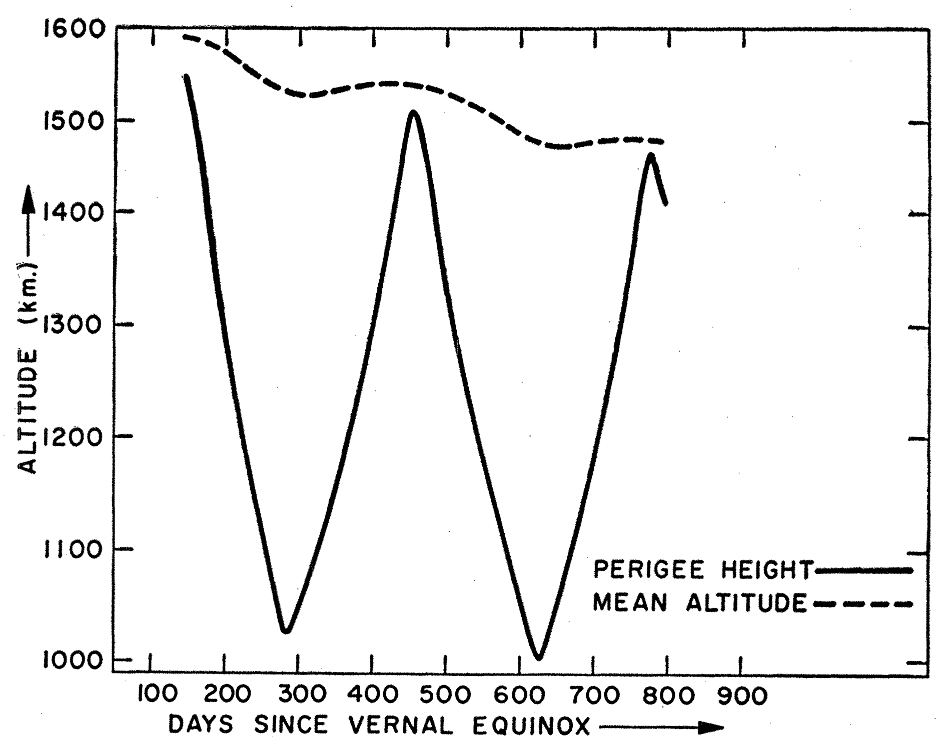

Fig. 3. Time variation of perigee height and mean altitude.

The generally good agreement between the theoretical models and the actual orbit followed by Echo I during its first 12 days indicates that no drastic, permanent change occurred in the shape of the balloon for that period. Polarization and cross section experiments carried out with the M.I.T. Millstone Hill radar also support this conclusion (*8*).

In our analysis we have included many other perturbations which might be of importance in determining the orbit of Echo I. One of these is the effect of solar radiation reflected from the earth. At the present state of knowledge, it is not possible to formulate an accurate model of the earth's reflection characteristics. We are considering a simple model involving an arbitrary but uniform (over the surface) mixture of diffuse and specular reflection. However, only specular reflection is now included in our computer program. Results from this program indicate the effect on e and ω, even assuming a reflection coefficient of unity (a considerable overestimate), is only 1 percent of the effect of direct solar pressure. The perturbations caused in the first 12 days by the third, fourth, and fifth harmonics of the earth's gravitational field, and by the lunar and solar fields, are mostly quite small. (One exception is the change in eccentricity, caused by the third harmonic, which is $\sim -3 \times 10^{-5}$ per day).

The effect on the orbit of a possible charge on the balloon was also investigated. Calculations indicate that even if the potential of the balloon were 100 volts the effect on the orbit due to interaction with the earth's magnetic field would be several orders of magnitude below observational accuracy. Charge drag at this altitude can also be ignored. Other known perturbations which cannot yet be treated quantitatively include variations in the solar flux; effects of corpuscular radiation from the sun; momentum transfer due to micrometeorite impacts; and fluctuations in the value of KA/M due, for example, to changes in thermal conductivity, spin rate, surface conditions, and shape of the balloon.

Calculations indicate that since the balloon did not enter the earth's shadow until about the 140th revolution (*9*), direct radiation pressure caused only a minute change in the inclination and ascending node of the orbit—less than 10^{-4} deg/rev. However, an analysis of the perturbation equations shows that the earth's shadow can play an important part in the changes of these elements. In particular, if the shadow region is asymmetrical with respect to the nodal line, a much greater change in Ω occurs. Similarly, a shadow region which is asymmetrical with respect to the perpendicular to the nodal line will lead to a noticeable change in i. The magnitude of the change is, of course, dependent on many variables. For example, on 29 August, the shadow lies wholly on one side of this perpendicular and extends about 80° in true anomaly. This results in a rate of change in i of $-.003°$ per day.

In Fig. 3, we have plotted the theoretical prediction of perigee height and mean altitude versus time, assuming a KA/M of 102 cm²/g. We see that perigee height oscillates with a period of about 300 days and that the peak-to-peak amplitude is approximately 500 km. The initial rate of decrease of perigee height is about 2.0 km/day; but this rate then increases to its maximum value of 5.3 km/day by 29 August. The slow average decrease in mean altitude is due to the effects of atmospheric drag. The decrease is not monotonic, because solar radiation can cause a net increase (or decrease) in orbital energy per revolution when the balloon passes through the earth's shadow (nonconservative force field). We note that these curves were computed on the basis of the balloon's maintaining a constant $KA/M = 102$ cm²/g. As was indicated above, KA/M is larger for the Echo balloon; this will cause a proportionate increase in the peak-to-peak amplitude of the oscillation in perigee height, but it will have no effect on the period. Since KA/M can be expected to change radically if the balloon loses its spherical shape, large deviations from these curves may be expected. In view of the uncertainties involved and our imprecise knowledge of air density, it is impossible to predict accurately the lifetime of Echo I. The balloon may perish on one of its first descents through the atmosphere, or it may remain in orbit for many years.

The average air density at a 1600-km altitude, during the first five days after the Echo launch, was obtained from the decay of the orbit's semimajor axis. We found a value for this density of $(1.1 \pm .2) \times 10^{-18}$ g/cm³. In the calculation, it was assumed that the scale height is greater than about 130 km (*10*), and that the air drag acceleration is $(A/M)v^2\rho$, where $A/M = 102$ cm²/g, v is the instantaneous satellite velocity, and ρ is the air density.

For orbits which are partly in shadow, it is necessary to consider the gain or loss of energy due to radiation pressure when determining air density. The increases in mean altitude versus time in Fig. 3 show that this effect predominates over air drag for months at a time. In fact, at these altitudes, the change in a due to radiation pressure is almost always more important than the change due to air drag—provided that the orbit is partly in shadow.

We also note that the minimum perigee heights shown in Fig. 3 always occur on the sunlit side of the earth. This is generally true for the minimum perigees of orbits with inclinations between about 40° and 50°, and comparable mean altitudes. Below 40° inclination, at these altitudes, the minimum perigee heights occur on the dark side of the earth. These considerations should be useful in selecting orbits for measuring diurnal variations in air density at high altitudes.

Note added in proof: In a previous report by Parkinson, Jones, and Shapiro [*Science* **131**, 920 (1960)], an error appears in Eq. 1. The first minus sign appearing in the equation should have been omitted. The equation should have read:

$$|\dot{c}(\theta)| \cong P\frac{A}{m}\left[\frac{3(2\pi-\alpha)+\sin\alpha}{4\pi n}\right]\cos\theta \quad (1)$$

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2. For the solar constant we have used the value 2.00 Cal/cm² min, quoted in the American Institute of Physics Handbook with a probable error of 2 percent. Because of the uncertainties in KA/M, it is difficult to obtain from the Echo orbit a more precise value for the solar constant.
3. The use of the computer program employed in this work will be described in a forthcoming special report of the Smithsonian Astrophysical Observatory by P. Zadunaisky. The theoretical development on which the program is based can be found in a paper by G. Veis, *Smithsonian Contrib. Astrophys.* **3**, No. 9 (1960).
4. Preliminary calculations of the National Space Surveillance Control Center confirm the general trend of the orbit computed by Zadunaisky.
5. The trial expression for the eccentricity actually contained an additional time-dependent term whose coefficients were kept constant. This term incorporated the effects of the higher harmonics of the earth's gravitational field.
6. More accurately, the inverse of A/M was decreased at the constant rate of 0.0002 g/cm² per day.
7. Another possibility is to assume that the mass loss is uniformly accelerated (corresponding to a constant pressure and a constant micrometeorite puncture rate).
8. G. H. Pettengill, L. G. Kraft, MIT Lincoln Laboratory, private communication.
9. We considered the earth's shadow to be a right circular cylinder with a radius equal to that of the earth's mean equator.
10. The orbit determination is not yet precise enough to determine a scale height at the 1600-km altitude.

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6 September 1960