Reports

Satellite Elongation into a True "Sky-Hook"

The authors have made a very interesting suggestion in this paper. One referee described the "Sky Hook" as "a delightful idea and a grandiose scheme for a future technology." However, the reviewers were concerned about problems of stability and felt that these might make "Sky Hook" impracticable. The majority recommended that we accept this paper in spite of their reservations.—*Editor.*

Abstract. *The theoretical possibility of self-supporting cables extending into space from earth and from extraterrestrial rotating or revolving bodies is examined. In principle, augmentation (and duplication) of the installation and the launching of masses into orbit or into space could be accomplished with energy derived entirely from the rotation of the central body. In practice, a portion of the total energy requirement would probably be supplied by simple mechanical devices.*

Since a satellite is in balance between centrifugal and gravitational forces, tension will be exerted by any mass extended from a small artificial satellite in a direction radial to its orbit. Thus, masses extended toward the central body about which the satellite revolves will exert tension toward the central body, and masses extended in the opposed sense will produce tension outward. Increasing the radial elongation of a satellite will produce increasing tension, with the maximum tension at the point of balance of gravitational and centrifugal forces (if the radial orientation is maintained).

In the case of an earth satellite a greatly elongated synchronous satellite could, in principle, be extended to the surface of the earth and be attached there. If the elongation of the satellite were then further increased or if a mass were added to its outer termination, a net upward tension at the surface of the earth would result. In practice, this greatly elongated satellite would be a tapered fiber or cable (*1*) and would be self-supporting.

In addition to its self-support, such a cable installed near the equator of a rotating planet or natural satellite (or, in some cases, at the pole of a rapidly revolving body) and extending sufficiently beyond the radius of orbit of a synchronous satellite would have some other interesting and useful properties.

Masses that were moved along the cable from the surface of the central body to the outer terminus of the cable would be launched into space with a release of net energy derived from the kinetic energy of the central body. The mass would require an input of energy in its motion out to the synchronous radius and would release energy for the remainder of its motion along the cable.

The energy requirements of the first portion of the motion of a mass could perhaps be recovered from the terminal portion of a preceding launch, or they could merely be supplied by an independent prime energy source. In either case ordinary mechanical energy suffices, and reaction propulsion is not a requirement.

Since a tapered cable of a strong material could, in principle, support its own mass to any arbitrary length, and if only the mechanical requirement of strength of possible materials is considered, such installations extending from the earth and other bodies of the solar system appear possible (*2*). For the earth, the choice mode of initial installation would appear to be a balanced cable—spinning, in both senses, from a synchronous satellite along with reaction guidance of the positions of the advancing termini. Once a minimum initial installation were in place, it could be increased and strengthened by addition from the surface of the earth. Subsequently very large masses could be slung into space by mechanical hoisting along the cable as described. Also the installation could be duplicated by using its peculiar properties. Two adjacent installations would permit the lifting of masses by alternating vertical motions of the cables imposed at the surface of the earth. Duplicates could be "exported" by ship to other equatorial locations.

In addition to their use for launching materials into space, such installations could support laboratories for observation of conditions in space at high altitudes; they could resupply energy or materials to satellites or spacecraft, collect energy or material from space and the high atmosphere, support very tall structures on the earth's surface, and others. There is no immediate limit to the total mass that could be retained near the 1-day orbit by such a cable.

A treatment of the statics (*2*) of this system for the earth results in the characteristics of the installation and its pay loads (Table 1) for several conceivable construction materials. The "reproduction factor" $[T(a)/gm]$ is the ratio of the tension $[T(a)]$ at the earth's surface to the total mass (gm) of the cable and is an inverse measure of the number of ascents necessary to duplicate the cable. It is also a direct measure of the usefulness in raising pay loads and of the work that can be done at the earth's surface to dissipate any unwanted motions that might result from tidal forces or varying wind drag. For example, tidal forces of about $10^{-6}g$ can be expected to affect the cable. For

Table 1. Parameters for mose favorable materials suitable for a cable for earth conditions.

Material	Theoretical strength* (10^{10} dyne/cm^2)	Fiber† strength (10^{10} dyne/cm^2)	Young's modulus ($\times 10^{-12}$)	Density (g/cm^3)	Reproduction factor‡	Mass‡,§ (metric tons)	Base‡,§ diameter (cm)
Glass in Al‖	10‖	8	1	2.7	0.9×10^{-9}	4.7×10^{7}	2.5×10^{-2}
Alumina	26‖	15§,¶	3.5	3.8	1.8×10^{-8}	1.2×10^{6}	1.36×10^{-3}
Quartz	~ 73	24¶	7.3	2.65	7×10^{-5}	200	8.5×10^{-3}
Graphite	34‖	24‡,¶,#	~10#	2.25	1.8×10^{-4}	76	8.5×10^{-3}
Beryllium	~ 33		3.3	1.85	1×10^{-3}	10	6.2×10^{-3}
Diamond	~100		10.6**	3.51	6×10^{-3}	0.5	2×10^{-3}

* Figure is about 10 percent of Young's modulus unless otherwise noted. For more sophisticated calculations of tensile strength see Cottrell (*3*). † Highest reported experimental values for fibers. ‡ These entries are calculated for cable with strength of fiber in all cases except beryllium and diamond. There the tensile strength is taken to be 10 percent of Young's modulus. § Total mass and base diameter are shown for cables of sufficient strength to withstand wind at 200 km/hr. ‖ See Kelly (*4*). ¶ See Cottrell (*3*, p. 236). # See *5*. ** Calculated from elastic constants of diamond (*6*).

all cables described in Table 1 with reproduction factors *less* than 10^{-6}, tidal accelerations must be dissipated by motion imposed at the earth's surface. All cables probably must be provided with mechanisms for such motion.

If necessary, the lower terminus of the initial cable can be founded on a high-altitude structure, such as a tethered balloon, above the influence of significant atmospheric winds. The initial fiber thus has no theoretical gross lower limit of size. A later, generated cable (if not the initial cable) should be founded at the surface, however, and hence the lower limit of its size is determined by drag forces from atmospheric winds.

As examples, we have calculated the lower terminal diameters and resultant total cable masses, assuming that winds at 200 km/hr on a 1-km length of unfaired cable might develop a drag force equal to the cable tension (that is, to produce a 45° departure from the vertical near the lower cable terminus) (Table 1).

For earth conditions the *mechanical* characteristics of conceivable materials give reproduction factors the order of 1/1000 and modest masses for the minimum surface-founded cable. The "theoretical strengths" (Table 1) are greater by at least two orders of magnitude than those attained in present engineering practice and may never be achievable. In this eventuality the required masses will be greater than those tabulated.

The conditions on some other bodies of the solar system appear to be less demanding of materials than the conditions on earth. From the surface of Mars, the Martian satellites, the backside of the earth's moon, some of the Jovian moons and rapidly rotating asteroids, the system probably would be capable of launching large masses to any point in the solar system without excessive demands on materials.

An analysis of the statics of a system extending from a single rotating body follows.

The mechanics of such a system installed on an isolated rotating body can be treated in terms of the following parameters: r = radial distance from the center of the body (height); $A(r)$ = cross-sectional area of cable at height r; $T(r)$ = tension in cable at height r; Y = yield stress of cable; ρ = density of cable; m = mass attached to top of cable; M = mass of cable; a = radius of planet; ω = angular velocity of planet; g = surface gravity of planet; $\epsilon = a\omega^2/g$ = ellipticity of planet; $\lambda = (g\, a^2\, \omega^{-2})^{1/3}$ = radius of stationary orbit; $\gamma = \rho\, Y^{-1}\, (g\, a^2\, \omega)^{2/3}$; $\psi(s) = (1 - s)^2\, [(\tfrac{1}{2}) + (1/s)]$, where s is any functional variable. For the earth, $\lambda = 4.22 \times 10^9$ cm and $\gamma = \rho\, Y^{-1}\, 9.45 \times 10^{10}$, $\gamma\, \psi\, (a/\lambda) = \rho\, Y^{-1}\, 4.85 \times 10^{11}$ in *cgs* units.

If the cable is stressed to its yield strength everywhere, then

$$A(r) = A(\lambda)e^{-\gamma\psi(r/\lambda)}$$

In particular, $A(\lambda)$ is the maximum value of $A(r)$, and $\ln\,[A(\lambda)/A(a)] =$

$$\frac{\rho}{Y} ga\left(1-\frac{a}{\lambda}\right)^2 \left(1+\frac{a}{2\lambda}\right)$$

For the earth $a/\lambda = 0.151$; then

$$A(\lambda)/A(a) \approx e^{(\rho/Y)ga}$$

Note here that the thickening of the cable from the bottom at $r = a$ to the thickest point at $r = \lambda$ is approximately independent of ω.

The ratio of the mass of the apparatus, $(M + m)$, to the mass of the load it can lift, $T(a)/g$, is

$$\frac{g(M+m)}{T(a)} = \epsilon^{-2/3}\, e^{\gamma\psi(a/\lambda)} \times \left[\frac{\lambda R^2}{R^3-\lambda^3} e^{-\gamma\psi(R/\lambda)} + \gamma \int_{a/\lambda}^{R/\lambda} e^{-\gamma\psi(\sigma)} d_\sigma\right]$$

For a fixed total mass $(M + m)$, this ratio is minimized [and the load $T(a)/g$ maximized] by taking $R = \infty$, $m = 0$. The difference between $R = 3\,\lambda$ and $R = \infty$ is negligible for realistic values of γ. When $R = \infty$ and $m = 0$,

$$gM/T(a) = \gamma\epsilon^{-2/3} e^{\gamma\psi(a/\lambda)} \int_{a/\lambda}^{\infty} e^{-\gamma\psi(s)} ds$$

Then the total mass of material to constitute the inital cable would be:

$$M = \lambda\rho A(a) e^{\gamma\psi(a/\lambda)} \int_{a/\lambda}^{\infty} e^{-\gamma\psi(s)} ds$$

The minimum acceptable value of $A(a)$ is set by practical considerations of wind drag and anchoring force in the cable. (The anchoring force is also, of course, the maximum weight, including acceleration, of a vehicle that climbs the cable.)

The installation from a revolving *and* rotating body is ordinarily subject to two choices of the *modus operandi.* The analysis is much more complex.

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References and Notes

1. The device would be continuously tapered with its maximum diameter at the radius of the synchronous orbit.
2. We have not considered conditions in the ionosphere and in space that might have deleterious effects upon any material employed; we have not estimated the probability of collision with meteoroids or man-made satellites; and we have examined only the obvious linear problems of stability. We are quite aware that the engineering problems inherent in this system could be answered only by a program commensurate with some of the large contemporary projects.
3. A. H. Cottrell, *The Mechanical Properties of Matter* (Wiley, New York, 1964), p. 235.
4. A. Kelly, *Sci. Amer.* **212**, 28 (1965).
5. R. Bacon, in *Growth and Perfection of Crystals*, R. H. Doremus, B. W. Roberts, D. Turnbull, Eds. (Wiley, New York, 1958).
6. American Institute of Physics Handbook (New York, 1963), sec. 2, p. 52.

26 November 1965

Ammonium Micas: Possible Sources of Atmospheric Ammonia and Nitrogen

Abstract. *Ammonium muscovite,* $NH_4Al_2AlSi_3O_{10}(OH)_2$, *and ammonium phlogopite,* $NH_4Mg_3AlSi_3O_{10}(OH)_2$, *have been synthesized hydrothermally at gas pressures of 2 kilobars and temperatures between 550° and 730°C. Both micas are stable only in environments of high ammonia fugacity. Ammonia or nitrogen, or both, are released by thermal decomposition, cation exchange, or oxidation. The ammonia : nitrogen ratio in the gas depends primarily on the hydrogen fugacity and the temperature of the environment. Calculations show that, even in a predifferentiated Earth, nitrogen may have predominated. The total amount of nitrogen present on the surface of Earth could be accounted for by the decomposition of a layer of ammonium muscovite 170 meters thick.*

The origin and the composition of the terrestrial primitive atmosphere have recently been extensively discussed (*1*). Considerable evidence supports the theory that the atmosphere accumulated from degassing of Earth throughout its geologic history. Common constituents during the earliest periods are assumed to be CH_4, NH_3, and H_2O. The primary sources of the ammonia, and hence of the nitrogen in today's atmosphere, were presumably either ammonium silicates or metal nitrides.

The average nitrogen content of igneous and metamorphic rocks and minerals is low (*2*), with micas containing in general the largest amounts. Silicates from unusual environments may be greatly enriched in ammonia.