mation of a crater with dimensions comparable to or greater than those of the projectile. Although a fraction of each crater volume undoubtedly represents inelastic compression of the target, examination of crater morphologies suggests that this fraction is small and that, throughout the velocity range studied, erosion was more effective than accretion. Thus, there is no disagreement between our results for hydrated silicates and those of Gault *et al.* (*6*) for basalt. However, there is a striking difference between the accretionary behavior of silicates and that of metals (*4*).

The silicate data pose no major problems for current accretionary theories (*1*, *2*). Indeed, this conclusion has already been reached by Hartmann (*15*), on the basis of an analysis of the data of Gault *et al.* (*6*). Silicate accretion took place only between particles whose orbits were similar. However, over at least part of the velocity range in which silicate accretion was efficient, metal particles would have rebounded without accreting. This finding suggests that, if both metal and silicate were present during accretion, fractionation of one with respect to the other would have occurred. In particular, at the low velocities which must have prevailed during most of the accretionary process, silicates would have been preferentially accreted. Similarly, if some regions of the solar system were characterized by higher interparticle velocities, bodies enriched in metal may have been produced. In this respect it may be significant that among the terrestrial planets there is a rough tendency for density, and therefore assumed metal content, to increase with orbital velocity.

These conclusions clearly apply only within the framework of conventional accretionary theories. Alternative theories, such as that of Urey (*16*) in which planetary growth is thought to have occurred by gravitational collapse of local regions of gas and dust, are by no means excluded. In addition, the presence of volatile coatings on grains or the existence of an appreciable gaseous nebula during accretion would undoubtedly have had significant effects on the accretion efficiency.

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References and Notes

1. See, for example: G. P. Kuiper, in *Astrophysics*, J. A. Hynek, Ed. (McGraw-Hill, New York, 1951), p. 369; H. Alfvén and G. Arrhenius, *Astrophys. Space Sci.* **8**, 338 (1970).
2. W. K. Hartmann, *Astrophys. J.* **152**, 81 (1968).
3. S. Auer, E. Grün, P. Rauser, V. Rudolph, K. Sitte, in *Space Research*, A. P. Mitra, L. G. Jacchia, W. S. Newman, Eds. (North-Holland, Amsterdam, 1968), vol. 8, p. 606; V. Rudolph, *Z. Naturforsch. A* **24**, 326 (1969); H. Dietzel, G. Neukum, P. Rauser, *J. Geophys. Res.*, in press.
4. G. Neukum, thesis, University of Heidelberg (1968).
5. H. C. Urey, *The Planets, Their Origin and Development* (Yale Univ. Press, New Haven, 1952).
6. D. E. Gault, E. M. Shoemaker, H. J. Moore, *Nat. Aeronaut. Space Admin. Tech. Note D-1767* (1963).
7. J. F. Vedder, *Earth Planet. Sci. Lett.* **11**, 291 (1971).
8. ———, *Rev. Sci. Instrum.* **34**, 1175 (1963).
9. H. Shelton, C. D. Hendricks, Jr., R. F. Wuerker, *J. Appl. Phys.* **31**, 1243 (1960).
10. Kaolinite was obtained from the Particle Information Service, Los Altos, California. For an illustration of this material, see R. E. Grim, *Clay Mineralogy* (McGraw-Hill, New York, 1953), p. 111.
11. Type I carbonaceous meteorites are commonly considered primitive because they exhibit less elemental fractionation with respect to solar abundances than any other material [see H. C. Urey, in *Nuclear Processes in Geologic Settings* (National Academy of Sciences–National Research Council, Washington, D.C., 1953), p. 49; E. Anders, *Geochim. Cosmochim. Acta* **35**, 516 (1971)]. The primitive chemistry of the bulk meteorite is probably dominated by the ill-defined phyllosilicate which makes up approximately 60 to 70 percent of such a meteorite [see J. F. Kerridge, in *Mantles of the Earth and Terrestrial Planets*, S. K. Runcorn, Ed. (Wiley, London, 1967), p. 35; *Nature Phys. Sci.* **230**, 66 (1971)].
12. The sample, from Salt River Valley, Arizona, was supplied by J. Sinkankas.
13. W. A. Deer, R. A. Howie, J. Zussman, *Rock-Forming Minerals* (Wiley, New York, 1962), vol. 3.
14. The distribution of projectile material inside the impact crater was irregular and unknown. Consequently, it was not possible to use conventional methods of correcting x-ray intensities for absorption and other geometrical effects, nor was it possible to convert x-ray intensity values into absolute mass units.
15. Hartmann (*2*) has shown that, with a 100 percent sticking efficiency and a reasonable value for the spatial density of accretable material, the asteroids could have accreted within 10^8 years if interparticle velocities fell in the range 0.04 to 0.2 km/sec.
16. H. C. Urey, *Mon. Not. Roy. Astron. Soc.* **131**, 199 (1966).
17. We thank G. Arrhenius for suggesting the study of low-density silicates. We thank D. Avant, K. Bozeman, J. Erlichman, R. Garrard, H. Lem, L. Vedder, and W. Wallace for assistance. We thank D. C. Black, W. L. Quaide, and R. T. Reynolds for critical comments. One of us (J.F.K.) was supported by a National Aeronautics and Space Administration–National Research Council postdoctoral associateship.
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Telecommunications with Muon Beams

Abstract. *The properties of well-collimated beams of muons with energies in the range of 10^9 electron volts may be suited to some specialized needs in telecommunications. A demonstration of muon telecommunications has been carried out at Argonne National Laboratory.*

The unique penetrating power of high-energy muons compared to that of other particles results from their lack of strong (nuclear) interactions and from their large mass compared to the electron mass, which reduces their electromagnetic energy losses in matter. Thus, except for light and neutrinos, muons form the bulk of the cosmic radiation fluxes at the bottom of the atmosphere. Muons from cosmic rays have been used in "x-raying" pyramids (*1*). For the same reasons, terrestrial point-to-point communications could be carried out by sufficiently energetic collimated beams of muons, which can penetrate the thickness of the earth's atmosphere. I discuss, first, short-range (about 20 km) communication systems, then long-range (1000 km or more) systems.

Angular divergences of a few milliradians or less are easily obtained in presently available secondary beams from high-energy accelerators. This means that for a path length of 10 km, a square detector 10 m on a side can pick up a large fraction of the beam. Such large detectors could be either scintillator counter-telescopes or large, inexpensive Cerenkov counters with a medium of air.

Scattering in the air over such a path can be reduced to a few milliradians if the beam energy is above 3 Gev. These beams can penetrate metal or other dense or conducting substances, the thickness of penetration being roughly proportional to the beam energy. (For each 10^9 electron volts of energy, muons can pass through about 0.5 m of steel.) They provide, therefore, an alternative to microwave communications for point-to-point systems if physical barriers intervene.

The flux required would increase linearly with the information bandwidth and vary inversely with the cross section of the beam. Present-day accelerators are quite adequate for supplying the necessary muon fluxes, through pi-meson decays, from secondary beams.

It is necessary to estimate the required flux, however, in order to determine the possible radiation hazard to the environment.

Under ideal conditions, the timing of individual muon departures could be used for coding, that is, pulse position modulation. This could be accomplished for secondary beams by using high-power microwave cavities, as used in radio-frequency beam separators, or by modulating the targeting of the primary proton beam. A timing accuracy of 10^{-9} second, probably a lower limit with present detector technology, would yield a maximum practical capacity for a wide-band telecommunication channel of 1000 megabits per second, if an average beam intensity of 10^9 muons per second were allowable. With a typical cross section of 100 cm^2 for a research accelerator secondary beam and a channel rate of 1 megabit per second, a flux of 10 muons per second per square centimeter would be present in the beam. This would be greater by about a factor of 10 than the flux in cosmic-ray background radiation. (Since the latter contains predominantly particles with lower energies, it can be discriminated against to improve the signal-to-noise ratio by energetic and directional means.) If the beam area were expanded to 100 m^2 before any contact with the environment, the flux for such a channel could be as low as the natural background flux. Of course, for narrower-bandwidth systems (such as teletype or voice systems) of 10^4 bits per second, there would be no problem with flux.

The energy required for line-of-sight muon beam communication is primarily dependent on the (Lorentz dilated) muon lifetime. The muon range in air is not a limiting factor. A decay path length of 35 km is achieved with a muon energy of 5 Gev.

For long-distance communication systems, the bending of the orbits of charged particles in the earth's magnetic field can be utilized. In an optimum case, an orbit for 50-Gev muons passing along the magnetic equator just outside the atmosphere would have a radius of curvature approximately equal to that of the earth. This would allow signal propagation as far as the muon decay length, which would be about 500 km for this energy. If a factor of 10 were allowed in signal loss, a range of 1000 km could be achieved; the beam would reenter the atmosphere and penetrate to ground level. Since fluctuations in the geomagnetic field are small and scattering in the atmosphere is negligible at this energy, the beam could remain relatively well collimated even over such a large distance, although large detectors (many meters in diameter) would be necessary for good efficiency.

Even longer (global) communication paths could be achieved in principle if the (stable) electrons resulting from muon decays could be detected, for example, by means of the showers of high-energy photons they might produce in the upper atmosphere upon reentry. The collimation of these decay products would be almost as good as that of the primary muon beam.

In economic terms, even with present accelerator construction techniques, long-range wide-band telecommunication with muon beams might compete with the relatively expensive microwave or satellite communications. (With microwave relay towers the costs are about \$10 million per 1000 km and with satellites, including ground stations, about \$18 million.) In some cases, as when rugged terrain or sea paths are involved, satellites are the only competitors. It is expected that simpler and more economical construction techniques would be devised if muon communicators were to be designed specifically, rather than general-purpose research accelerators. The use of superconductor technology, for example, could help to reduce the costs of proton synchrotrons to about \$10 million for 100-Gev protons (*2*), which are adequate to produce a beam of 50-Gev muons. There is an increasing economic need for such wide-band long-range telecommunications in connection with data transmission between computer facilities.

Using a secondary beam from the 12-Gev Zero Gradient (proton) Synchrotron at Argonne National Laboratory, I carried out a simple demonstration of information transmission via muon beam in April 1972. A portion of a beam of 6-Gev negative pi-mesons was allowed to decay into muons, which passed through 1.5 m of concrete shielding and other fairly massive obstacles. The muons then traveled approximately 150 m until they were intercepted by two scintillation counters (30 cm square) in coincidence, connected to a paper strip-chart recorder. The beam intensity was modulated by mechanically inserting a block of brass about 7.5 cm long into the beam. This caused an energy loss of a few percent, which was sufficient to defocus the beam trajectories in the quadrupole and bending magnets. Morse code characters were then communicated by using a switch to actuate the solenoids that moved the brass block into the beam. The system could be used, with improved collimation and increased muon intensity, to communicate over several kilometers, if desired.

Designing and developing muon communication systems should provide experience that will be valuable in designing similar systems with neutrino beams. The latter could penetrate any amount of earth and provide direct line-of-sight communications between any two points, and they would not require any intensity limitations for safe fluxes. The collimation of high-energy neutrino beams is nearly as good as that of muon beams, and no multiple scattering divergences occur. Such systems await the development of sufficiently massive detectors and sufficiently intense or energetic (or both) accelerator beams for pi-meson production. However, even with present technology, the reception of a few neutrino events per hour may be possible at global distances, for example, between the National Accelerator Laboratory (Batavia, Illinois) and Australia.

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References and Notes

1. L. W. Alvarez, J. A. Anderson, F. El Bedwei, J. Burkhard, A. Fakhry, A. Girgis, A. Goneid, F. Hassan, D. Iverson, G. Lynch, Z. Miligy, A. H. Moussa, M.-Sharkawi, L. Yazolino, *Science* **167**, 832 (1970).
2. M. A. Green, Report UCRL-20299, Lawrence Radiation Laboratory, Berkeley, California (1971). This information is contained in "Advanced accelerator concepts and technology," a report to the High Energy Physics Advisory Panel of the Atomic Energy Commission by the Subpanel on Advanced Accelerator Technology (chairman, B. Cork, Argonne National Laboratory, Argonne, Illinois), September 1971.
3. I would like to acknowledge invaluable assistance from many of the Argonne staff in preparing the demonstration; in particular, I thank J. Steinhoff for a great deal of assistance and A. Yokosawa and his collaborators for a loan of equipment and for assistance. D. D. Jovanovic provided the suggestion of energy-loss modulation, and the design and fabrication of the modulator was carried out by J. Dawson and his group. Conversations with T. M. Knasel of the University of Chicago provided some of the ideas for long-distance schemes. U. E. Kruse of the University of Illinois was also of assistance in the demonstration. The work was performed under the auspices of the Atomic Energy Commission.

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