letters

quark binding mechanism, and there are no problems encountered with statistics. The normal nuclear force is assumed to be due mainly to virtual-pion (that is, quark-pair) exchange in the usual way.

It is possible that the highly-ionizing cosmic ray particle with unusual characteristics that was detected recently by a Berkeley-Houston group (see October 1975, page 17) may be one of these highly charged "quarks". When the data for this event are completely calibrated this possibility will be able to be considered in detail. Of course the negative results of searches for monopoles in other cosmic ray experiments render it much more probable that the Berkeley-Houston particle carries electric rather than magnetic charge.

At the present time it is evident that if quarks are highly charged then they must also be quite massive, because otherwise they would surely have been detected already in numerous bubble chamber experiments. This suggests that the recently discovered heavy resonances (J, ψ, χ, upsilon and others) may be the lightest radial excitations of bound quark states.

In any case it seems that the existence of testable alternatives to the fashionable quark model, which at least attempt to satisfy Heisenberg's requirements, could be usefully brought to the attention of experimentalists, including those who will be engaged in particle searches at the new accelerators such as PETRA or ISABELLE. It is hardly necessary to add that searching for highly charged particles (either magnetically or electrically charged) is much easier than searching for fractionally charged particles.

References

1. J. Schwinger, Science 188, 1300 (1975).
2. P. C. M. Yock, Physical Review D13, 1316 (1976).

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More on Mercury's satellite

In his March letter (page 12) Bruce Bushman, quoting Isaac Asimov, offers an explanation of the fact that Mercury has no satellites. In essence, the argument is that outside of Mercury's Roche limit—2.44 times its radius—the gravitational force of the Sun is much greater than is that of Mercury, and hence a satellite in such an orbit cannot be stable. Inside the Roche limit, of course, the satellite would be broken up by the tidal effects of the planet.

Asimov considers the ratio $(M_1/R_1^2)/(M_2/R_2^2)$ of the gravitational forces of a planet (body 1) and the Sun (body 2) to be a measure of which body is the dominant one in the motion of the satellite. Indeed, he expresses surprise that the Moon is stable, since the ratio for that body is 0.46, much less than the value of 30 typical for the other satellites in the solar system.

There is, in fact, no problem with the stability of our own Moon, and Asimov's explanation of Mercury's lack of a satellite cannot be upheld. The reason is that the gravitational acceleration of the Sun on the Moon is very nearly equal at all times to that of the Sun on the Earth. The acceleration of the Moon *relative* to the Earth due to the Sun is therefore a tidal acceleration proportional to M_2R_1/R_2^3. Comparing this with the direct acceleration of the Earth on the Moon, we arrive at the ratio $(M_1/R_1^2)/(M_2R_1/R_2^3) = (M_1/R_1^3)/(M_2/R_2^3)$, which determines which body is dominant. (The near cancellation of the direct accelerations of the Sun is seen very clearly when the full equations of motion are written out, for which consult a standard text such as Brouwer and Clemence.[1])

For the Moon, this ratio is nearly 200, so that the Moon is well within the stable region. Nevertheless, the fact that the Sun's gravitational acceleration on the Moon is so nearly equal to that on the Earth means that the orbits of the two bodies around the Sun are very similar—so similar, in fact, that *the Moon's orbit is always concave towards the Sun,* a fact that is surprising to many at first and certainly in conflict with many illustrations in elementary texts. There are, in particular, no "loops" in the Moon's orbit around the Sun.

For Mercury, the point where the above ratio is unity occurs at a distance of over 3×10^5 km from Mercury, while Mercury's Roche limit is at roughly 6×10^3 km. It is clear that there is a large region where a satellite of Mercury could have a stable orbit.

Reference

1. Dirk Brouwer, G. M. Clemence, *Methods of Celestial Mechanics*, New York: Academic Press, (1961).

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. . . A qualitative measure of the importance of the solar disturbing force on a Mercurian satellite is the size of the sphere of influence or, equally appropriate, the size of the Hill sphere. These imaginary spheres are regions where a particle can be considered to be under the control of Mercury and perturbed by the Sun; outside the spheres the particle is thought to be controlled by the Sun and perturbed by Mercury. A simple calculation shows these spheres to be 60 to 100 Mercurian radii in size. Satellites of Mercury thus have the vast range between the Roche limit and the outer boundary in which they can reside safely without suffering the fates proposed by Asimov; if this were not true, NASA would not even consider a Mercury orbiter.

A more likely explanation for the absence of moons about the innermost planet is the action of solid-body tides as proposed by Burns (*Nature* **242**, (1973), 23–25) and Ward and Reid (*Month Not. Roy. Astron. Soc.* **164** (1973), 21–32). Since Mercury is spinning slowly, having a period of about 58 days, most hypothetical satellites that could orbit it would move more rapidly than the surface. Due to energy dissipation, the tidal response of Mercury lags the position of the satellite, and this produces a transverse drag on the satellite, pulling it inward toward its demise on the surface. All satellites larger than a few kilometers in radius can be shown to be eliminated over the age of the solar system by such a process. Since this mechanism operates on the satellites of any slowly spinning planet, it is interesting to note that neither Venus nor Pluto, the other two planets with long spin records, have satellites.

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... The Roche limit is calculated for a *fluid* body; and a solid moon within the Roche limit could be held together by the cohesive strength of the material composing it. A satellite smaller than several hundred kilometers in diameter will be rigid in the sense that the solid forces can resist gravitational forces; and it could, in principle, orbit Mercury. Such a small satellite would probably be irregular in shape, since the spherical shape of larger bodies is caused by their failure to resist gravity. Thus, Asimov has not shown that Mercury could have no moon, but only that it can't have a big round one!

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THE AUTHOR COMMENTS: My original article on the subject was published some time ago; I discovered the error in my analysis. When the letter appeared in PHYSICS TODAY I wrote to Bruce Bushman promptly and told him I was wrong.

I am also willing to admit to the readers of PHYSICS TODAY that I was wrong. May it be the only time that I am to find myself egregiously wrong, but I strongly suspect it won't be.

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Correction

September, page 5: The material shown in the September cover photograph is Type 304 stainless steel, no Inconel 600 as we reported in the cover note. □