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PROSPECTS FOR FINDING THE MOST VALUABLE POTENTIAL RESOURCE OF THE MOON: WATER P. M. Muller Jet Propulsion Laboratory
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If free water can be found and extracted easily in quantity on the moon, the resulting supply of cheap rocket fuel makes an immense difference in the practicality of large scale lunar operations and colonization. Unfortunately, petrological analyses and most resulting models of lunar interior evolution appear to contraindicate the presence of water in the moon. It is suggested that these and other observations are not yet able to finally disprove the presence of water-ice trapped below the surface. On the other side of the question, compelling evidence that the sinuous rilles are positive water indicators is reviewed. There is also the possibility of a definitive experimental test. The Radar Sounder Experiment results from 15mhz observations reported at this conference show unexpectedly strong echoes at depths between roughly 200m - 1km in the *margins* of Serenitatis and Crisium. It is a suggestive observation, because even a small amount of water, under the trapped ice for example, is consistent with this data and the fact that the experiment radar fails to see anything more *below* these areas. The locations agree with the distribution of sinuous rilles, and in depth with the earlier suggestion that the moon acts as a water-ice trap between depths of about 100m and the 0°C isotherm for any internal outgassing or impactive (*e.g.* cometary) deposition of ice. On a more speculative level, the presence of transient events, cinder cones, eroded craters, ghost craters, sinuous rille deltas, and mare shoreline benches/beaches, is at least consistent with the early presence of water even on the *surface* for short durations. In view of the critical role of water to lunar industrialization, we must be conservative, and view the question of water trapped below the surface as at least scientifically *open*. It is also essential to note that *if* the water-ice is present, we do know where to look, and can expect to find it at a feasible depth for recovery. It is concluded that further studies of the water situation scientifically, and eventual direct search for water in likely lunar areas, should receive very high priority in any lunar resources program.

The basic key to practical use of the moon as a manufacturing base for space exploration, is the availability of materials suitable for refueling rockets. This follows from the tyranny of Celestial Mechanics (in the required Δv for space flight), and the practical limitations of chemical rocket fuels. This is well known, but an example is pertinent. It is cheaper to operate a rocket from the surface of the moon to low earth orbit ($\Delta v \simeq$ 6km/s), than to reach low earth orbit from the earth's surface ($\Delta v \simeq$ 7km/s plus atmospheric drag loss and fighting the 1g environment). The moon-to-orbit

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shuttle need not be aerodynamic, nor capable of high accelerations (>1g) to operate efficiently. Operating from *lunar* orbit, refueling the lunar orbit station from the lunar surface, it is possible to operate a *round* trip, one stage, moon-orbit to earth-orbit to moon-orbit shuttle ($\Delta v \simeq 8$km/s) with substantial payloads. This profile is orders of magnitude cheaper than an operation mounted from the earth's surface, and surely makes the difference between viable, and prohibitively expensive, earth-moon industrialization.

The best, and perhaps the only *practical* form for this resource is water directly obtained as H_2O. Dissociation to liquid H_2 and O_2 should be economic with solar power because of the absence of a significant lunar atmosphere (*e.g.* aluminum foil reflectors in excavations or craters etc). Alternatives such as removing the very small amounts of hydrogen found in the lunar soils[1], coupled with extracting the abundant but tightly bonded oxygen, are probably orders of magnitude more costly. It would therefore be very fortuitous indeed if free water in useable quantities could be found and exploited in a manner similar to earth's petroleum.

Unfortunately, in the view of most scientists, there is no free water on the moon[2]: "Water is effectively absent from the moon." Petrologists and others have looked almost in vain for evidnece of water from the samples, and even the so-called *rusty* rocks[3] are more likely to have arisen from volcanic, fumarolic, or contaminatory processes. In fact, the consensus of petrologists is that the lunar material did not even *arise* under conditions including water, contrary to the earth (and probably Mars) where it is generally accepted that the atmosphere and hydrosphere were baked out of the interior of the planet. Despite this strong argument, we have learned from the History of Science that it is very difficult to disprove a plausible hypothesis by the process of eliminating all possibilities. It is not difficult to conceive of possible alternatives: (a) moon formed cold, water only near surface or driven up as the moon heated, not involved in fractionating, but trapped, and giving rise to sinuous rilles where released; (b) moon formed fractionated except for mare lavas which formed deep in water free environment, leaving water trapped in the crust which the mascons show has remained cold. It would be very unconservative to view all possibilities as presently disproven.

On the other side of the question, sinuous rilles stand as the strongest indicator of where to look for trapped water. This was first suggested[4], but other non-erosion explanations including lava tubes (drainage channels)[5] and ash flows[6] have been advanced. These seem difficult to support[7], and [7] makes a strong case for sinuous rilles as the result of a very special kind of erosion. This can take place without the need to invoke a significant lunar atmosphere, and the water can be held to pressure under an overburden of ice[8], or as subsurface flow under soil and ice etc. There was, and remains some criticism of this model[9], but this can be answered[10], and the erosion explanation stands as plausible, and in my view, the most likely. Sinuous rilles generally begin in craters, and they are distributed around the

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circular maria[7]. We therefore know where to look.

As to the origin of water initially, comets[11] and trapped outgassing[12] have been suggested. This latter argument particularly, convinces me that the probability of finding trapped water-ice is too substantial to ignore. The near-surface lunar temperature is below 0°C, and 100m of lunar soil overburden will preserve ice on the airless moon for geological time[12]. The moon therefore acts as a water-trap, and a substantial fraction of emplaced or outgassed water (if it was ever present), *must* be trapped between the 0°C isotherm and 100m below the overburden. If the ice is present, it is within a practical recovery depth.

Other than sample analysis, only one Apollo experiment gives us the chance to identify deposits of ice, and this is the Radar Sounder. The data calibration has been very demanding and the experimenter's quick look results are only now becoming available in this conference [13]. The 15mhz results show surprisingly bright returns, which come up from deep below the maria Serenitatis and Crisium, to within 200m - 1km of the surface at the shores, sometimes appearing also below the higher surrounding territory. Ice itself is not easy to see compared with the expected rock (dielectrics near 3 for ice, 4 for regolith), but even a very small amount of water below the ice, would give rise to precisely the observed result. It is particularly significant that the radar fails to see anything *below* this final bright return level, as though its dielectric was very high: water≈ 80. This observation agrees in location with the distribution of sinuous rilles, and in depth with the ice-trap argument, and further study is warranted.

On a more speculative level, we have indication of transient events[14], and photographic evidence of apparently volcanic cinder cones, eroded craters, ghost craters, sinuous rille deltas, and mare shoreline benches/beaches[15]. While there are other explanations for these phenomena, it is curious that the presence of active water (probably under an ice overburden) on the surface for a short time in the absence of significant precipitation, could explain all of these photographic observations simultaneously. There are great difficulties with trying to place water on the surface, but there may be ways of satisfying all constraints[16].

The point of this paper is not to attempt a demonstration that trapped water on the moon is likely, though I personally believe that it is probable. The argument of this paper is that: (a) water is probably the most valuable natural resource we could find on the moon to support large scale lunar industrialization; (b) the arguments against water in the moon are strong, but not yet definitively able to rule out its presence; (c) there *is* provocative evidence on the positive side of this question; (d) therefore, *conservatism* of science demands that we treat the question of trapped water-ice as *open*, and; (e) pursue with vigor the further study of the question, and undertake an adequate search, as a very high priority part of any lunar resources program.

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REFERENCES:

(1) Chang, S. *et al.* 1974 Abst. L. S. C. V, p. 106-9; Gibson, E. K. *et al.* 1975 Abst. L.S.C. VI, p. 290-292.

(2) Taylor, S. R. 1975 *Lunar Science: A Post-Apollo View* Pergamon p. 228.

(3) Ref. 1 p. 230.

(4) Pickering, W. H. 1903 *The Moon* Doubleday.

(5) Kuiper, G. P. *et al.*1966 *JPL Tech. Rep.* 32-800.

(6) Cameron, W. S. 1964 *JGR* 69,2423.

(7) Peale, S. J. *et al.* 1968 Nature 5173, 1222 .

(8) Lingenfelter, R. E. *et al* 1968 *Science* 161, 266.

(9) Schumm, S. A.; Simons, D. B. 1969 *Science* 165, 201.

(10) Lingenfelter, R. E. *et al.* 1969 *Science* 165, 202.

(11) Urey, H. C. 1967 *Nature* 216, 1094.

(12) Gold, T. 1966 in *The Nautre of the Lunar Surface* Johns Hopkins.

(13) Brown, W. E., Jr. 1976 *In Press* Proc. L. S. C. VII.

(14) Middlehurst, B. M. 1967 *Rev. Geophys.* 5, 173.

(15) Muller, P. M. 1976 *In Prep:* Photographic Evidence Consistent with the Pristine Presence of Lunar Oceans; or Watson, Gilvarry, Kopal, cited in Ward, S. H. 1969 *IEEE Trans* GE7 # 1 p. 19.

(16) Urey, H. C. 1969 *Bul. Atom Sci* XXV.