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ON LUNAR "TEMPERATURES"

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ABSTRACT

A lunar surface of part "rock" and part "dirt" is suggested by Luna IX and Surveyor I pictures. It is shown that the lunar night and eclipse temperatures are correctly predicted from the amount of rock observed in pictures if that rock is bare. The nature of the detectors used is an essential part of the calculation. In this model, eclipse "hot spots" are due to mean rock densities about five times the lunar surface average. The radio emission temperature measurements are not useful in distinguishing between this model and the conventional homogeneous surface models, at least with the signal/noise available at present. The failure to observe in the radio emission the temperature dependence of dielectic loss is commented on.

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THE INFLUENCE OF SURVEYOR I AND LUNAR IX PICTURES ON THE APPARENT CHARACTER OF THE LUNAR SURFACE

Pictures taken by Luna IX and Surveyor I both show a lunar landscape which might be characterized as covered by a more or less uniform blanket of "dirt," with occasional "rocks." The boulders appear to be covered by at most a thin layer of "dirt," and may be bare.

Infrared studies of the temperature of the lunar surface during a lunation cycle and during eclipses have normally been interpreted (ref. 1, 2, 3, 4) using a model in which the lunar surface has not horizontal variations (though vertical layering is sometimes allowed). The most recent work at radio wavelengths is given by Troitskii (ref. 2). A recent summary of all temperature results and models is presented by Aarons (ref. 3), and the newest conventional model is described by Linsky (ref. 4). On the basis of such models cooling curves can be calculated. Such calculations are in good qualitative (and fair quantitative) agreement with infrared temperature measurements if the lunar surface is characterized by $(K\rho C)^{-1/2} \approx 1000$, where K is the thermal conductivity, ρ the density, and C the specific heat of the lunar surface material.

Infrared measurements of surface temperature describe a temperature only if the surface has a single temperature over the region being examined. If different parts of the surface have different temperatures, the infrared studies no longer describe a temperature. The interpretation of experimental results as single temperature can then be totally misleading, for the resultant number is strongly influenced by the temperature distribution and by the spectral window of the infrared detector.

Let us suppose that the majority (say better than 80%) of the Moon is covered by a homogeneous dirt, and that some small fraction (in the 0-20% range) is covered by bare rocks of various sizes. Such a model is compatible with Surveyor pictures, and the cumulative distribution of rock sizes is given in the Surveyor I Preliminary Report (ref. 5). This model is also compatible with all optical albedo and polarization studies, for the rock occupies only a small fraction of the total surface area. In the infrared measurements during the lunar night, however, this rock can be very important.

At lunar noon, the majority of the lunar surface material (the "dirt") has the same temperature, near 375°K. The rock will be somewhat cooler, and almost any properly calibrated infrared temperature measuring device will report for the Moon a temperature near 375°K. For convenience, let us define the noon temperature observed as 375°K, and the noon detector response as unity.

A narrow-band infrared detector whose band pass is at energy E will have a response law for a surface temperature T

$$R = \frac{e^{E/n \cdot 375} - 1}{e^{E/nT} - 1} \qquad (1)$$

where K is Baltzman's constant. E/K will be defined as T_D, the detector characteristic temperature. Such a response is plotted in Figure 1 for a detector having its band-pass at 12μ (i.e., E = .103 eV, T_D1 1200°K).

The works of Pettit and Nicholson, Pettit, Sinton, and Sinton and Strong (see references of reference 1) have been based on detectors whose characteristic fell off as fast or faster than the one of Figure 1. The position of the transmission windows in the Earth's atmosphere also allow the use of the 20μ window but it has not been used in any of the complete lunation studies to date.

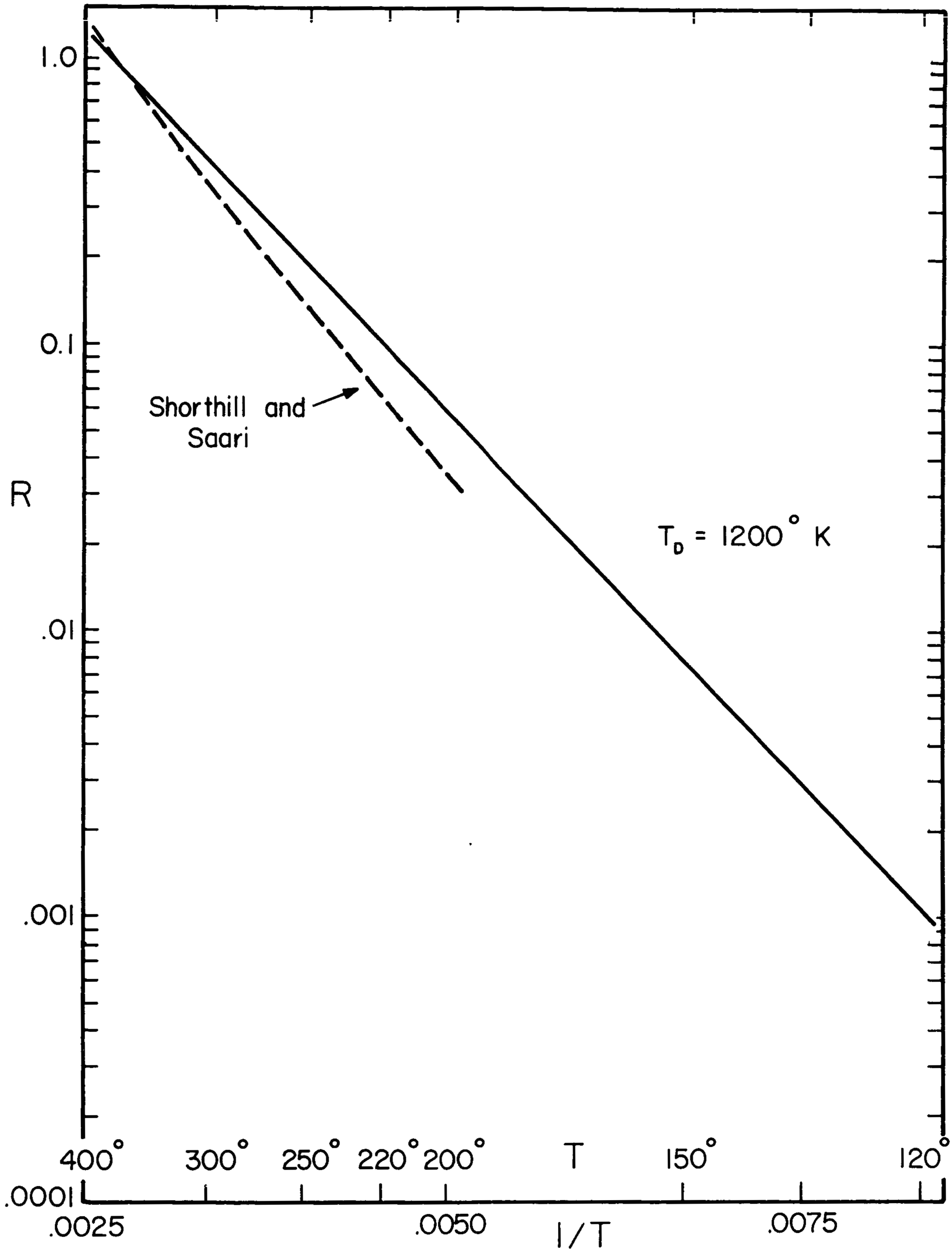

Figure 1 The response R of a detector having a characteristic temperature T_D = 1200° K (solid line) and of Shorthill and Saari's detector (dashed line).

The midnight temperature "observed" is $120^{o}K$. Let us calculate what might be expected for an observed midnight temperature based on bare rocks. Bare rock has a $(K\rho c)^{+1/2}$ of about .05. Thermal waves of a lunation period T = 28 days = 2.4×10^{6} seconds. The penetration depth for such a temperature wave is $\ell = (K\rho c)^{1/2} \left(\frac{\tau}{2\pi}\right)^{1/2}$ = 30 cm for bare rock. A rock of size smaller than about twice this (allowing for cooling from both sides) will follow the lunation period well enough to be ignored, while rocks larger than 60 cm can be expected to display the thermal behavior of a rock surface. From the Surveyor I Preliminary Report (ref. 5) one finds that 1 - 1 1/2% of the lunar surface area is covered by rocks bigger than 60 cm in size and will have the characteristic emission of materials of rock-like $K\rho c$. Bare rock at lunar midnight will have a temperature of $220^{o}K$. A lunar surface consisting entirely of rock should produce a signal R of 0.105 (see Fig. 1), so a surface of 1% rock will return a signal from the rock of 0.00105. If the rest of the lunar surface (the "dirt") has dropped below $100^{o}K$, the entire signal will result from the rock, and the signal of .00105 will be interpreted as an apparent temperature of $120^{o}K$. The midnight temperature observed by Sinton and by Pettit and Nicholson are 120 - $125^{o}K$! In fact, the entire lunation temperature curve agrees about as well with the simple model of 1% rock surface, $(K\rho c)^{1/2} \approx .05$ (a dirt surface having a negligible $K\rho c$) as it does with any other model, as shown in Figure 2.

Recently Low (ref. 6) has re-measured the night-time temperature of the Moon, and has found, using a detector characteristic temperature of approximately $700^{o}K$, that the lunar surface "temperature" drops to $90^{o}K$ just before dawn (with a wide variation between different locations). On the basis of this lower detector temperature, a midnight "temperature" of 75^{o} and a dawn temperature of about 70^{o} would have been expected to be recorded.

The agreement is not precise, nor should it be with such a radically simplified theory completely neglecting $K\rho c$ for the dirt. No theory based

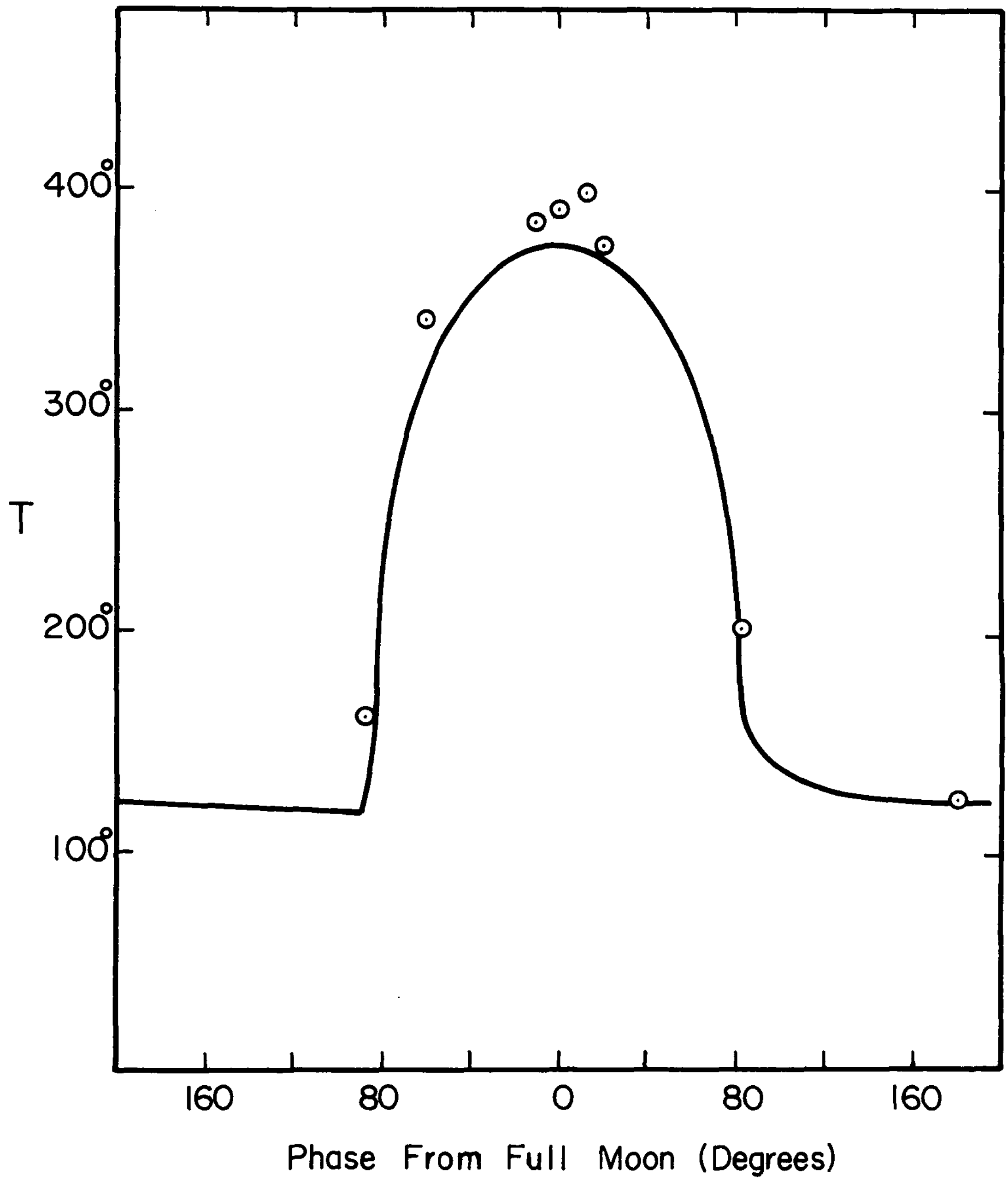

Figure 2 The calculated apparent lunation curve for a rock and dirt model. The experimental points shown are from Sinton. Temperature is in degrees Kelvin. Almost all the systematic difference between theory and experiment would be removed by a slightly different choice of noon temperature.

on a homogeneous surface, however, produces any reason for a discrepancy between the older measurements using a high T_D and the recent low T_D results, while the present oversimplified model, predicts such an apparent discrepancy.

Infrared temperature measurements during an eclipse provide an alternative method of evaluating models of the surface thermal properties of the Moon. While in principle the experiment is similar to the lunation cycle analysis, the different time scale ($\sim$ 2 hours instead of 28 days) provide a check on agreement between theory and experiments. The simplest homogeneous models have not proved capable of quantitatively explaining with the same $K\rho c$ both eclipse and lunation experiments (ref. 1, 3, 4), although reasonable qualitative agreement can be obtained. Additional parameters introduced by reasonable physical models (layering or a temperature dependent thermal conductivity) appreciably improve the quantitative fit.

The model of a few per cent bare rock plus a lunar dirt of very small $K\rho c$ again provides a good qualitative description of the eclipse temperature cycle. An eclipse lasting 2 hours has a thermal penetration depth of about 1/8 of the penetration depth during the lunation cycle, and rocks as small as 8 cm would therefore be seen as "bare rock" during such an eclipse. If 1% of the lunar surface is covered by rocks bigger than 60 cm in size, then, from the Surveyor I distribution, the per cent of area covered by rocks of linear dimension greater than X centimeters is approximately

$$\% = \ln_e \left(\frac{164}{X}\right) \qquad (2)$$

and about 3% of the lunar surface would be effectively "rock" for the eclipse cooling experiment. This rock, according to usual cooling curves, will reach a temperature of 345°K an hour after totality has begun. 3% of such rock will return a signal (see Fig. 1) of .03 x 0.77 = .123, which is interpreted by the instrument as a temperature, of 172°K. The measured "temperature" at the sub-earth point is ~200°K at this time during the eclipse. A measured temperature of 200° would be equivalent to ~ 6% of the surface covered by rocks bigger than 8 cm in diameter.

Shorthill and Saari (ref. 7, 8) have investigated the cooling behavior of detailed areas of the Moon with a detector whose calibration is given by the dashed line of Fig. 1. In a typical eclipse cooling anomoly, they find an infrared hot spot (e.g. the crater of Kepler Copernicus) cools to ~220°K while its environs cool to ~200°K. These numbers would require about 8% and 4% of surface covered by rocks bigger than 8 cm.

More recently, using a narrow band detector with T_D close to 1200°K, Saari and Shorthill have at high resolution found typical eclipse temperatures of 180°K, with local hot-spots as warm as 230°K. These figures would correspond to ~ 4% and 15% coverage by rocks greater than 8 cm in diameter. "Hot spots" demanding 15% coverage are many in number but small in total area, and seem to be unambiguously associated with craters. Large concentrations of rocks in Surveyor pictures are clearly associated with craters.

The model we have been discussing is badly oversimplified, for it neglects completely the $K\rho c$ of the dirt, and very crudely approximates the effect of the distribution of rock sizes. If, however, the rocks observed in the Surveyor photographs are bare and have a $K\rho c$ similar to earth rock, the rocks are the major source of infrared signal during lunar darkness. This basic premise of the model can be easily checked by making temperature measurements during lunation and eclipse using several different T_D and examining the consistency of the resulting measurements.

THERMAL MEASUREMENTS AT RADIO WAVELENGTHS

Measurements have been made of the lunar temperature at wavelengths from 1 mm to several centimeters by using radio techniques (ref. 2, 3). The measurements under consideration have all been made at wavelengths sufficiently long that a particular portion of the Moon produces a radio signal proportional to the temperature and area of the portion. As a result, the exponential favoring of hot surfaces present in infrared studies does not occur in radio studies. A few percent of rocks have no appreciable effect on the radio emission and the radio emission studies the temperature of the "dirt."

The penetration depths of a thermal wave (first harmonic) during a lunation cycle in material of $(K\rho c)^{1/2} = .001$ is 7 millimeters and during an eclipse about 1.0 millimeters. The depth of penetration of the radio wave (absorption length) is believed to be several wavelengths, so for all available radio data except the 1 millimeter lunation data, the depth of radio wave penetration is large compared to the thermal wave. Let T(x) be the temperature of the lunar surface as a function of depth x, and $\alpha_\lambda(x, T)$ be the absorption coefficient for depth x at wavelength λ and temperature T. The observed microwave temperature of this surface at normal incidence is:

$$T_M = \int_0^\infty \alpha_\lambda(x, T)\, T(x)\, e^{\int_0^x \alpha(y)dy}\, dx \qquad (3)$$

If α is constant (the usual supposition) and the radio penetration depth great compared to the thermal wave penetration depth, one finds

$$T_M = \overline{T} + \int_0^\infty \Delta T(x)\, dx \qquad (4)$$

where $\overline{T}$ is asymptotic the interior temperature and $\Delta T = T(x) - \overline{T}$.

If in addition the specific heat is independent of temperature, then one can write

$$\frac{dT_M}{dt} = \alpha \frac{1}{c\rho} s(t) \tag{5}$$

where c is the specific heat, ρ the density, and s(t) is the net heat flux through the surface at time t. T_M can be calculated from a knowledge of the solar radiation incident and the temperature of the "dirt" surface. The constant of integration can be determined from (4). As a result of this simple expression (4) or (5), all radio eclipse data tends to look like all other eclipse data (except for the factor α which will in general be wavelength dependent) and all radio lunation data again will have a single form except for the factor α.

The complete insensitivity of the microwave temperature fits to surface models can be seen from the following

1) s(t) depends only weekly on $K\rho c$ in form, while the amplitude of s(t) varies much more strongly with $K\rho c$.

2) Even if the rocks were to produce a signal 5 times that of the dirt during lunar night, this would result in an error of only 20° in the dirt temperature, and a factor of 2 reduction in $(K\rho c)^{1/2}$ would suffice to correct this.

3) α multiplies the fluctuating part of the microwave temperature T_M. Thus any model which fits the infrared temperature measurements can also be made to fit the microwave measurements with about the same precision as any other model by properly choosing α. Linsky (ref. 4) came to a similar discouraging conclusion.

CONCLUSION

There are, in principle, checks which can be made to improve the situation by examining the radio data for internal consistency in comparison to infrared data. For example, during lunar night or eclipse s(t) is determined by the temperature of lunar dirt. Eclipse and lunation data on radio emission at the same wavelength can then be used to check at microwave frequencies the surface temperature ratio measured in the infrared. In this ratio α and ρc disappear. A temperature dependence of thermal conductivity would not influence the result. A wavelength of 3 millimeters seems the most likely candidate for such a comparison, but eclipse studies at 3 millimeters have not yet been published.

Emission studies have shown that the tan δ (δ is the loss angle) is approximately independent of wavelength, a good engineering approximation in most earth minerals and dielectrics. Therefore, most loss mechanisms in such materials involve thermal activation, and the temperature dependence of tan δ should be

$$\tan \delta \sim Ae^{-B/T}$$

as is indeed generally observed. B is of the order of 10,000°Kelvin or so in typical materials. As a result, tan δ is strongly temperature dependent, changing by an order of magnitude in 30° (when near room temperature) ! The absorption coefficient is proportional to tan δ, so should be by far the parameter of the lunar surface which varies most markedly with temperature. Under the circumstances, it seems amazing that no explicit effects of this strong temperature dependence stand out in the radio emission data. Either the lunar surface material is unlike almost all Earth rocks and dielectrics in this respect, or the current interpretation of radio emission variations during lunation and eclipse needs drastic revision.

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