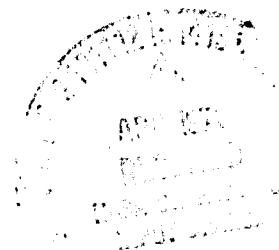SEMI-ANNUAL STATUS REPORT

FOR

INVESTIGATION OF THE DAYTIME LUNAR ATMOSPHERE

FOR

LUNAR SYNTHESIS PROGRAM

COVERING THE PERIOD OF

1 OCTOBER 1974 THROUGH 31 MARCH 1976

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PROGRESS REPORT

Synthesis studies of the daytime lunar atmosphere have been directed toward improved understanding of fundamental lunar atmospheric dynamics and the relationship of the detectable atmosphere to physical processes of the lunar surface and interior. The primary source of data used in this research is the Apollo 17 lunar surface mass spectrometer, which provided excellent measurements of the synodic variation of ^{40}Ar and ^{4}He at the landing site through most of 1973.

Preliminanry results of the argon and helium research have been reported by Hodges (1975) and further progress was presented at the Sixth Lunar Science Conference by Hodges and Hoffman (1975a,b). A more detailed paper on the implications of argon escape on the interior structure of the moon is now in press (Hodges and Hoffman, 1975c). Evidence of moelcular gases in the daytime lunar atmosphere has been given by Hoffman and Hodges (1975).

Concentration of these studies on the argon and helium problems has been fruitful not only because of the availability of good measurements, but also because the temporal variations of each gas give important clues to the nature of certain geochemical and physical properties of the moon. Briefly, the ^{40}Ar is radiogenic and its escape rate from the lunar atmosphere requires release of a significant fraction (about 8%) of the argon produced from the decay of ^{40}K within the moon. Furthermore the process of argon release from the solid moon is time varying and related to seismic activity. Most of the helium on the moon is due to release of implanted solar wind α particles from the regolith.

The remainder of this report is divided into two parts, one on argon and the other on helium. Each discussion is essentially a condensation of results which have originated mainly from research supported by this grant. The material is extracted from recent publications and from papers now in preparation.

Implications of ^{40}Ar Escape on the Lunar Interior

The fact that argon is an important atmospheric species is somewhat puzzling in view of the difficulty involved in transporting an argon atom from its place of formation deep within the solid moon to the surface and then into the atmosphere. This has spurred the development of a succession of progressively more realistic models of the argon atmosphere (cf. Hodges et al.; 1974, Hodges and Hoffman, 1974a, and Hodges 1975), with a view toward accurate determination of the relationship between atmospheric concentration measurements and the argon escape rate. Briefly, the rate of escape of ^{40}Ar from the moon appears to be variable, implying an episodic process of release of this radiogenic gas from the interior of the moon. The average rate of loss of argon from the lunar atmosphere is about 2 x 10^{21} atoms/sec, which is about 8% of the present argon production rate for the entire moon (2.4 x 10^{22} atoms/sec) if the average lunar potassium abundance is about 100 ppm as suggested by Taylor and Jakeš (1974) and by Ganapathy and Anders (1974). To put these rates in planetologic perspective, the present rate of release of ^{40}Ar needed to account for its 1% abundance in the terrestrial atmosphere should be about 1.1 x 10^{24} atoms/sec if the fraction of total production effusing

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into the atmosphere has remained constant over geologic time. For a
lunar equivalent mass of earth this rate amounts to 1.4×10^{22} atoms/sec.

It is surprising that although the rates of effusion of ^{40}Ar
from the moon and earth are comparable, their total atmospheric abundances
differ by more than 15 orders of magnitude. The answer to this puzzle
lies in differing escape processes. On earth the escape of argon ions
is inhibited by the geomagnetic field, so that almost all of the argon
ever released is now present in the atmosphere. However, the lack of
both a lunar magnetic field and an ionosphere allows the solar wind to
impinge directly on the planet, and hence, to accelerate any ions formed
near the moon. As a result the average lifetime for lunar argon is only
about 80 to 100 days. The product of lifetime and loss rate gives the
atmospheric argon content to be only about 10^6gm, most of which resides
on the nighttime surface as a result of adsorption.

Figure 1 shows the temporal variation of the total argon loss
from the moon due to photoionization during 1973. It should be noted that
this rate is proportional to both atmospheric abundance and to escape rate.
Triangles represent the most accurate determinations of the photoionization
rate at sunrises where the concentration is greatest. Each circle gives the
rate found by model extrapolation of a 5° longitudinal average of concen-
tration to an equivalent sunrise concentration. High values of the circles
early in the year are due to a decaying artifact contribution to the low
nighttime concentration. The large variance of the photoionization rate
represented by the circles is indicative of the noise inherent in the night-
time concentration data.

Two important aspects of the ^{40}Ar rate show up clearly in
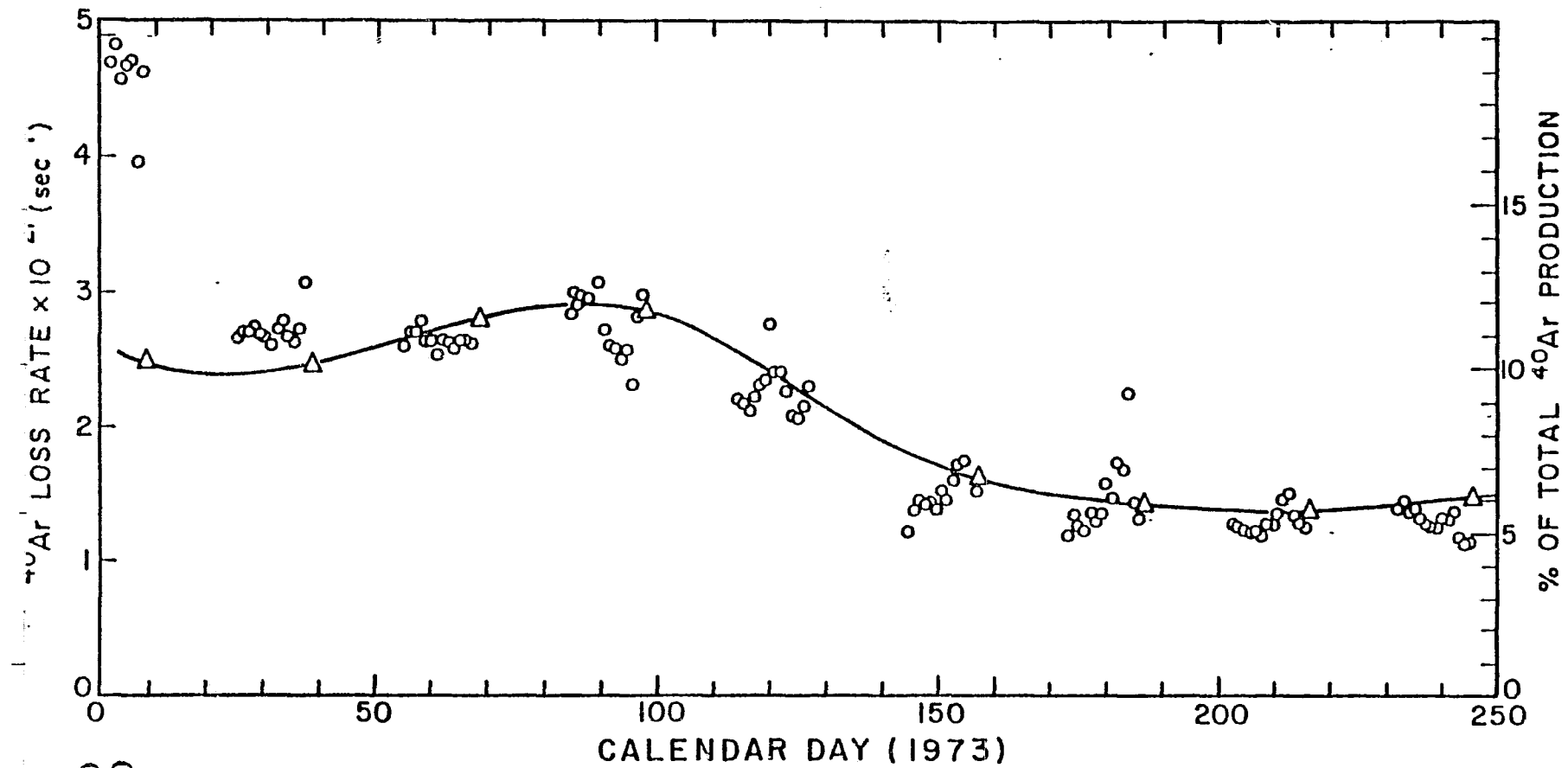Figure 1. First, the time average of the loss rate is roughly

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Figure 1

The rate of loss of ^{40}Ar from the moon deduced from nighttime (circles) and sunrise (triangles) measurements at the Apollo 17 site during 1973.

2×10^{21} atoms/sec, corresponding to about 8% of the total lunar production of ^{40}Ar if the potassium abundance is 100 ppm. If a large fraction of the photoions were to impact the lunar surface and sub-sequently become recycled into the atmosphere, then the actual source of new atoms would be a lesser part of the production rate. However, the second obvious feature of Figure 1, the time variation of the photoionization rate (and hence of argon abundance), argues strongly that there is very little regolith recycling of ^{40}Ar. The clue that argon recycling is unimportant is found in the decay of the photo-ionization rate between about day 100 and day 150, where the decay time constant is roughly equivalent to the average lifetime of argon atoms, i.e. about 100 days.

If ψ_s is used to denote the total rate of supply of atoms, both new and recycled, to the atmosphere and ψ_i is the photoionization rate, then continuity requires

$$\psi_s = \psi_i + \tau \frac{d\psi_i}{dt} \tag{1}$$

where τ is the average atomic lifetime. Figure 2 shows the argon source, ψ_s, required to supply the photoionization rate shown in Figure 1 for three values of the lifetime τ.

An important feature of equation 1, and hence of Figure 2 is that the total argon source must include an essentially constant contribution from recycled atoms, and that temporal variation of ψ_s must arise from internal changes in the moon which affect the rate of release of new argon atoms. Since each contribution to ψ_s is a positive definite quantity, it is obvious that the strength of the regolith source
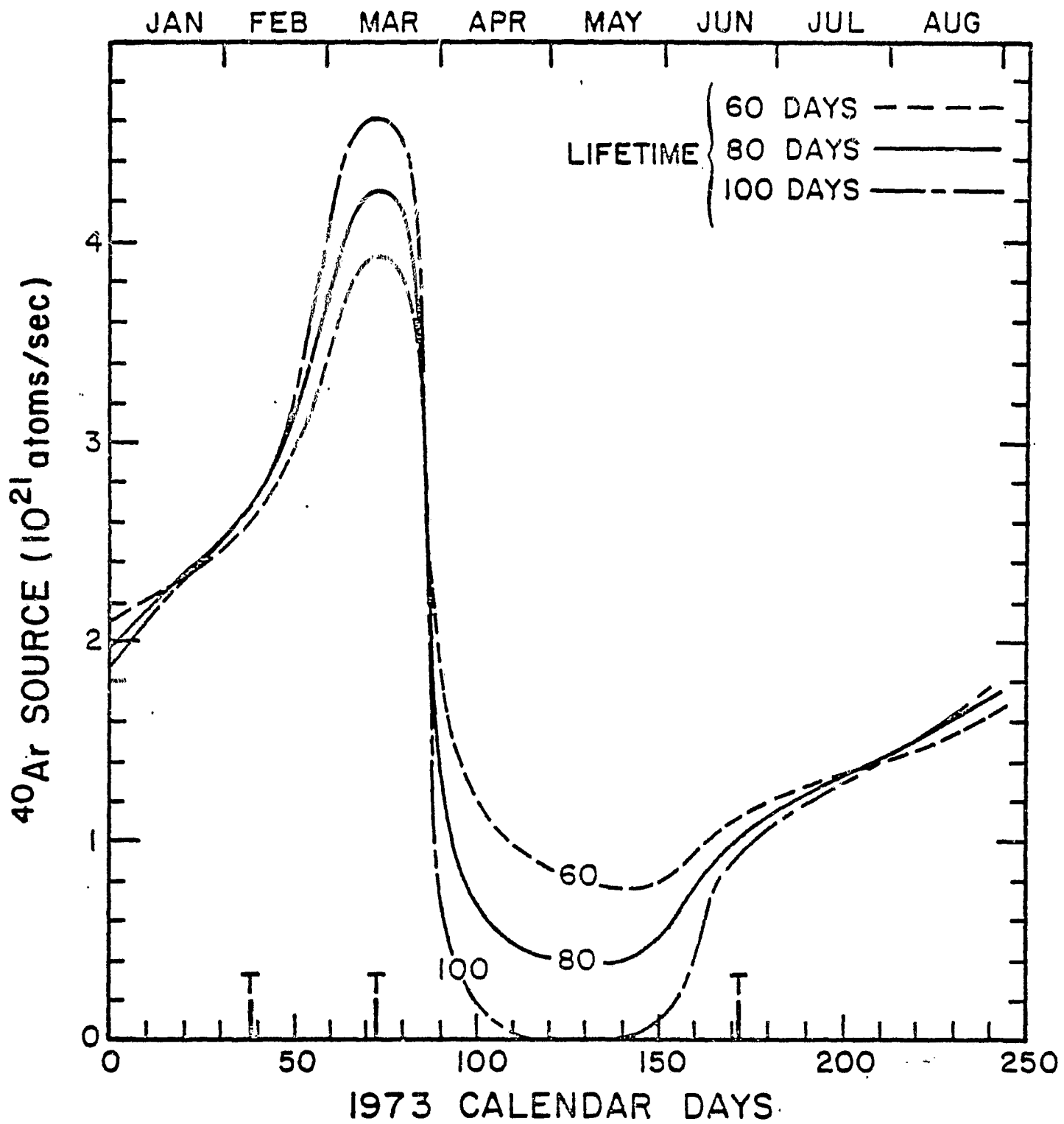
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Figure 2

Rate of release of ^{40}Ar from the moon needed to explain the atmospheric loss rate data in Figure 2. High frequency lunar teleseismic events are denoted by T.

of atmospheric argon is less than the minimum of the supply rate near day 140. The depth of the minimum depends on the lifetime. Theoretical argon atmosphere models for a wide variety of surface parameters have consistently given lifetimes between 80 and 100 days. Shorter model lifetimes (60 to 80 days) occur when adsorption probability is increased near the poles, but this is always accompanied by a sunrise to sunset concentration ratio at the Apollo 17 latitude (20°) which is significantly less than measurements indicate. Thus the best judgment is that the recycling fraction of the total argon photoionization rate is quite small, probably less than 10%, to be consistent with Figure 2 and a lifetime in the 80-100 day range. This constrains the rate of release of retrapped, parentless ^{40}Ar from the regolith.

On the lower abscissa of Figure 2 there are three events each denoted by T. These mark high-frequency lunar teleseismic events reported by Nakamura et al. (1974) during the argon measurement period. It is interesting to note that each of these events accompanies a rise in the argon source. In addition, the event on day 72, which was the largest such event recorded on the moon, coincided with the peak of the argon source. Owing to the inherent smoothing of the total atmospheric argon abundance due to its 100 day lifetime, it is not possible to resolve the argon supply rate data on as fine a scale as the teleseismic events.

The source of atmospheric ^{40}Ar is clearly potassium, but the magnitude and time variability of the argon escape rate have nontrivial implications on the internal structure of the moon. What is needed is the identification of the means by which about 8% of the lunar argon production has access to the atmosphere. In subsequent discussion various depth intervals of the moon are examined in terms of argon production and release mechanisms. It will become apparent that the seemingly obvious source regions are not capable of continual supply of escaping argon at the 1973 rate.

Lunar Surface - Trapped argon in the surface layer of the soil must be released by a solar wind weathering process in a manner similar to the release of implanted solar wind helium (Hodges and Hoffman, 1975). Typical abundances of trapped ^{40}Ar in returned soil samples are within an order of magnitude of 5×10^{-5} cc STP/g. If this number is taken as an estimate of the average abundance of argon in the entire regolith, then the release of the 2×10^{21} argon atoms/sec needed to supply the atmosphere would require a weathering process which removes about 75 cm of soil from the moon per million years. Since this erosion rate is several orders of magnitude greater than the soil escape rate determined by Fireman (1974) it is not reasonable to consider surface weathering to be an important source of atmospheric argon.

Regolith to 25 km Depth - A monatonic increase in seismic velocities with depth to about 25 km has been explained by Toksöz et al. (1972) to indicate a pressure effect on soils and broken rocks near the surface, changing to rocks having micro and macro cracks at greater depth. Argon which has diffused from within rocks to surface or fracture boundaries should be an atmospheric source. The Apollo 15 and 16 orbital gamma ray spectrometer data reported by Metzger et al. (1974) suggests that the average potassium abundance of the surface lunar soil is about 1000 ppm, while geochemical models of Taylor and Jakes (1974) indicate a crust average of 600 ppm. Accepting these as representative estimates of the potassium abundance in the upper 25 km of the moon, the rate of argon production there is in the range of $3-5 \times 10^{21}$ atom/sec. Release of 2×10^{21} atom/sec (the atmospheric escape rate) would imply loss of about half of the argon production. Returned regolith samples do not generally exhibit a depletion of ^{40}Ar that would confirm this loss process. More important, there is no time dependent phenomenon which would vary the argon release rate on the time scales observed

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in the Apollo 17 mass spectrometer data.

Lower Crust and Upper Lithosphere (25 km to 300 km) - Seismic data reveal
the beginning of a competent rock layer at about 25 km depth and an
apparently petrological discontinuity at about 65 km, marking the upper
boundary of the mantle (Toksöz et al., 1972). Nearly constant seismic
velocities suggest a lack of rock fracturing. The geochemical models of
the lunar interior of Taylor and Jakeš (1974) indicate that about 70% of
the moon's potassium has been captured in this region by differentiation.
However, the release of enough radiogenic argon from solid rock to supply
escape is not a practical postulate, even if increasing temperature with
depth is considered to increase the argon diffusion velocity. Again there
is no practical mechanism to cause temporal changes in the release rate.

Lower Lithosphere (300 km to 1000 km) - Differentiation is thought to have
depleted this region of potassium (Taylor and Jakeš, 1974) so it should
not be a source of argon.

Asthenosphere (Below 1000 km) - The central part of the moon is thought
to be semimolten because seismic shear waves are attenuated below 1000 km
(Latham et al., 1973). Two viable, alternate models of this asthenosphere
have been proposed by Taylor and Jakeš (1974). One is a conventional
Fe-FeS core formed early in lunar evolution. If the process of formation
of such a core should have fractionated the entire moon, displacing
all potassium from the core, then there is no apparent explanation of the
atmospheric argon. However, a core in which potassium has been concentrated
is a plausible source of argon.

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The alternative asthenosphere model of Taylor and Jakeš (1974) is
a region of primitive unfractionated material, remnant of an early melting
of the outer 1000 km of the moon. The present partially molten state of
the asthenosphere commenced after fractionation of the lithosphere, and
is maintained by radioactive decay of K, Th and U. About 8% of the moon's
potassium should be trapped below 1000 km if the whole moon average po-
tassium abundance is 100 ppm. This is sufficient to supply the atmosphere
provided that all of the argon escapes, which in turn seems to imply that
either the semimolten state is pervasive of the entire asthenosphere,
or that the asthenosphere has gradually fractionated to form pockets
of material rich in K, Th and U, which are naturally hot and from which
argon can readily escape.

The only apparent, viable explanation of the lunar atmospheric
argon is that it effuses from a semi-molten asthenosphere. In addition,
it is necessary that the potassium abundance in the asthenosphere be at
least as great as the whole moon average of 100 ppm.

The mechanism of conduction of argon from the asthenosphere to the
atmosphere can be conjectured to involve a percolative process in which
the gas collects either in bubble-like areas near the 1000 km depth, or
in voids nearer the lunar surface. Subsequent increasing pressure could
force the opening of deep fissures, causing sudden release of gas to the
atmosphere.

A correlation of increases in the atmospheric argon supply rate with the high-frequency lunar teleseismic events reported by Nakamura et al. (1974) was discussed earlier (cf. Figure 2.) Time resolution of the argon source is not sufficiently accurate to establish that this correlation is not fortuitous, but its existence substantiates the above pressure release hypothesis. In addition, the seismic correlation supports the hypothesis advanced by Hodges and Hoffman (1974a) that argon release may be the cause of some moonquake activity. The amount of seismic energy available from this process has an upper bound equal to the stored energy prior to release (i.e. pressure times volume). At 300 K the average argon escape rate could supply about 2×10^{15} ergs per year, which is of the same order of magnitude as the bound on the total rate of seismic energy release from the moon reported by Latham et al. (1972).

Helium: Solar Wind-Regolith Interaction

The sources of helium in the lunar atmosphere are the α particles supplied by solar wind implantation in the regolith and by decay of ^{232}Th and ^{238}U within the moon. Johnson et al. (1972) have reviewed the available solar wind data and concluded that the average α particle flux is about 4.5% of the proton flux or about 1.3×10^7 cm^{-2} sec^{-1}. This should result in a helium supply of 1.3×10^{24} atoms/sec on the moon. The rate of production of radiogenic helium in the moon can be estimated by assuming the bulk moon abundance of Th to be 0.23 ppm and U to be 0.06 ppm (cf. Taylor and Jakeš, 1974). Decay of these elements to stable lead results in a total helium source of 1.2×10^{24} atoms/sec. If K, U and Th distributions in the moon are similar then the mechanism for release of helium should be the same as that of ^{40}Ar, and hence the rate of supply of radiogenic helium to the lunar atmosphere should be about 10^{23} atoms/sec. Thus the total available source of lunar atmospheric helium is about 1.4×10^{24} atoms/sec.

Figure 3 shows theoretical and average experimental data on the synodic variation of helium at the Apollo 17 site (20° latitude). The solid line represents a numerically smoothed model obtained from a Monte Carlo calculation in which 180 impact zones were distributed longitudinally in the 20° latitude region. Amplitude of the model distribution is based on a source equivalent to the average solar wind influx of 1.3×10^{24} atoms/sec.

The experimental data points in Figure 3 are from Hodges and Hoffman (1974b). Each point corresponds to an average of all available measurements in an 18° increment of longitude. Error bars represent the standard deviation of these blocks of data, but they indicate systematic

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temporal changes in helium abundance rather than a useful parameter of the statistical distribution of the data. The measurements were confined to lunar nighttime because of instrument operational constraints, but they suggest a qualitative correspondence of the actual atmosphere with the theoretical model.

In Figure 3 it is evident that the actual helium abundance is only about 70% of the model value, and hence the average helium source in 1973 was probably about 9×10^{23} atoms/sec. Subtracting the radiogenic source, the solar wind must have supplied about 8×10^{23} atoms/sec, or about 60% of the average solar wind α particle influx. An explanation of the apparently low atmospheric supply rate is presented later.

A detailed history of the helium data, shown in Figure 4, reveals numerous deviations from the smooth model of the synodic variation. In these graphs the data has been subjected to 3 hour averaging, corresponding roughly to the atmospheric equilibration time, so that the ratio of the measured concentration to the model value at the same longitude is proportional to total atmospheric abundance at any time. The obvious deviations from the model distribution could only have occurred as responses of the atmosphere to sudden increases in the total amount of helium on the moon. Their amplitudes appear to be too great to be accounted for by variations in the rate of effusion of radiogenic helium from the interior of the moon.

The analysis of Hodges and Hoffman (1974b) showed a correlation of the variability of lunar atmospheric helium with the geomagnetic index
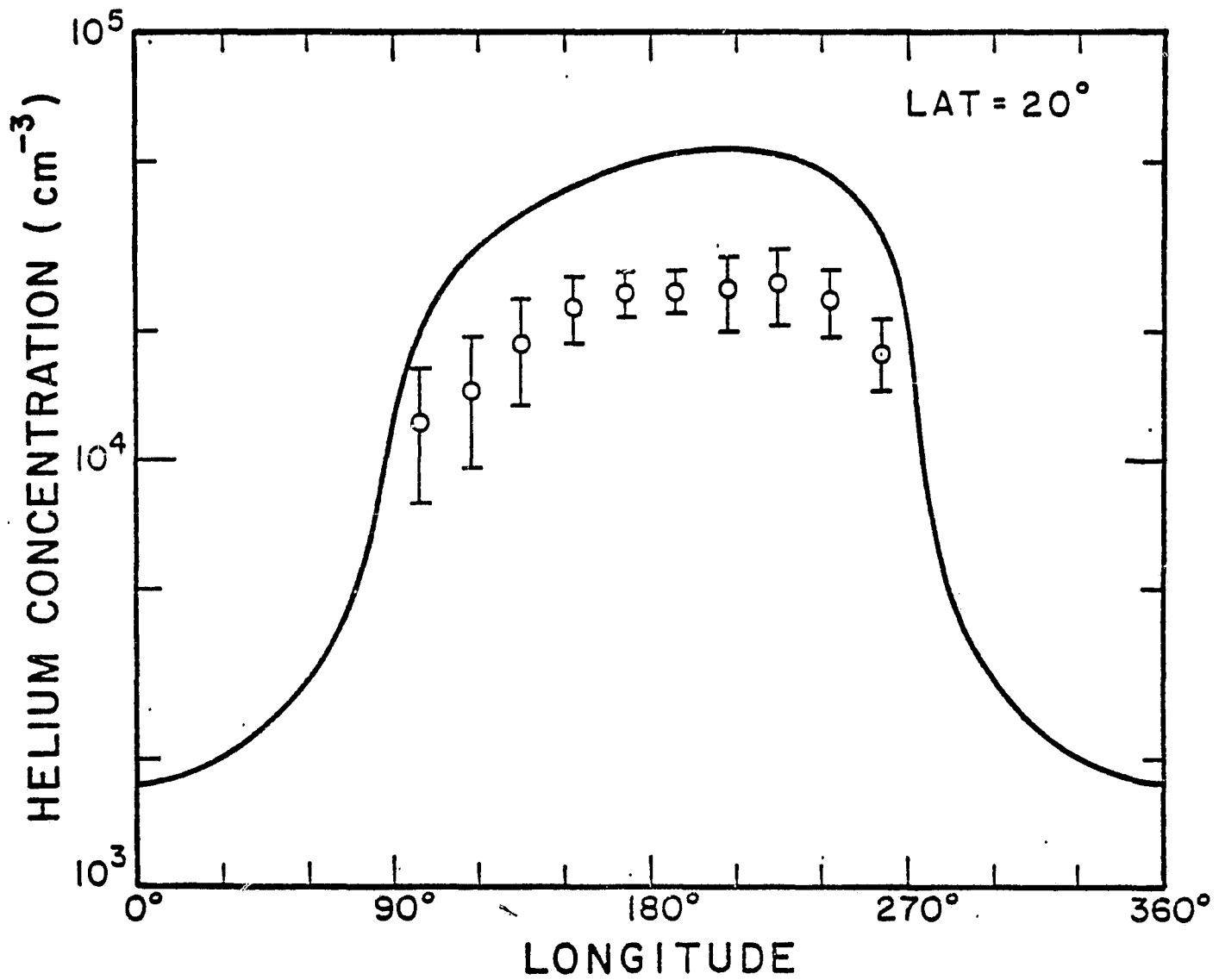
Figure 3

Synodic variation of the helium concentration at the Apollo 17 site.
Solid curve is the atmospheric model with escape equal to solar wind
influx. Data points are averages on all measurements in 18° intervals
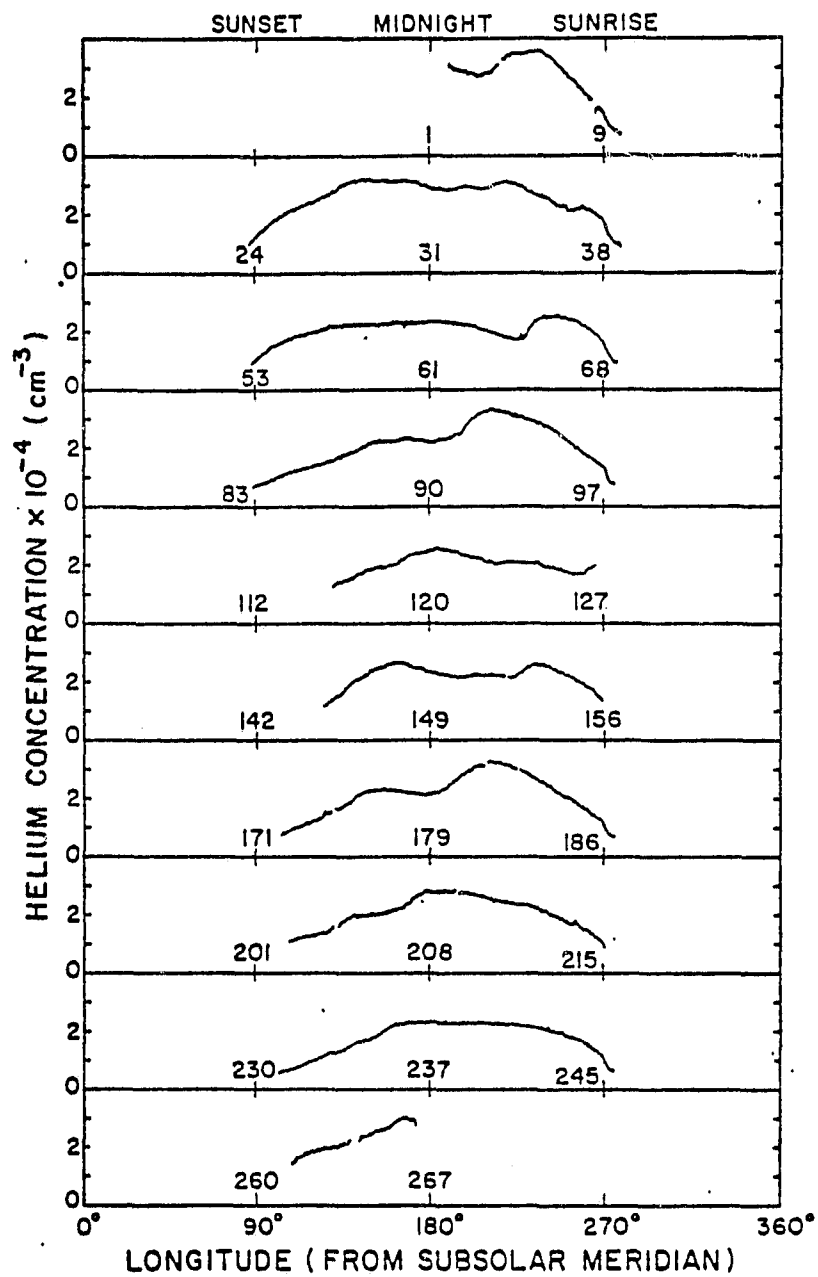of sun reference longitude.

Figure 4

Detailed history of the helium concentration at the Apollo 17 site.

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Kp, and hence with the solar wind. This analysis was based on the equation of continuity

$$\phi_s = \phi_o \left\{ \frac{n}{n_o} + \tau \frac{d}{dt}\left(\frac{n}{n_o}\right) \right\} \tag{2}$$

where ϕ_s is the equivalent solar wind source flux of α particles necessary to supply atmospheric escape, ϕ_o is the flux used in the model calculation (1.35×10^7 cm^{-2}sec^{-1}), n is the three hour average of the measured concentration, n_o is model concentration at the corresponding longitude, and τ is the average atomic lifetime for helium on the moon. Note that the instantaneous escape rate is ϕ_o n/n$_o$. The average atomic lifetime for helium, τ, based on Monte Carlo atmospheric modeling appears to be about 2×10^5 sec.

Figure 5 shows the correlation of ϕ_s, the equivalent solar wind α particle flux, with the geomagnetic index Kp for the 2×10^5 sec lifetime. Circles represent average flux values in each increment of Kp, while error bars give the standard deviations of these fluxes. The upper graph gives the number of hours of data available at each value of Kp. Individual flux values are plotted for the infrequent condition Kp > 6+.

The straight line shown in Figure 5 gives the linear mean square regression of all of the flux versus Kp data. It shows that the equivalent solar wind α particle flux needed to supply the lunar atmosphere has the approximate relationship

$$\phi_s = (5.6 \pm 1.9 + 0.44 \times Kp) \times 10^6 \text{ cm}^{-2}\text{sec}^{-1} \tag{3}$$
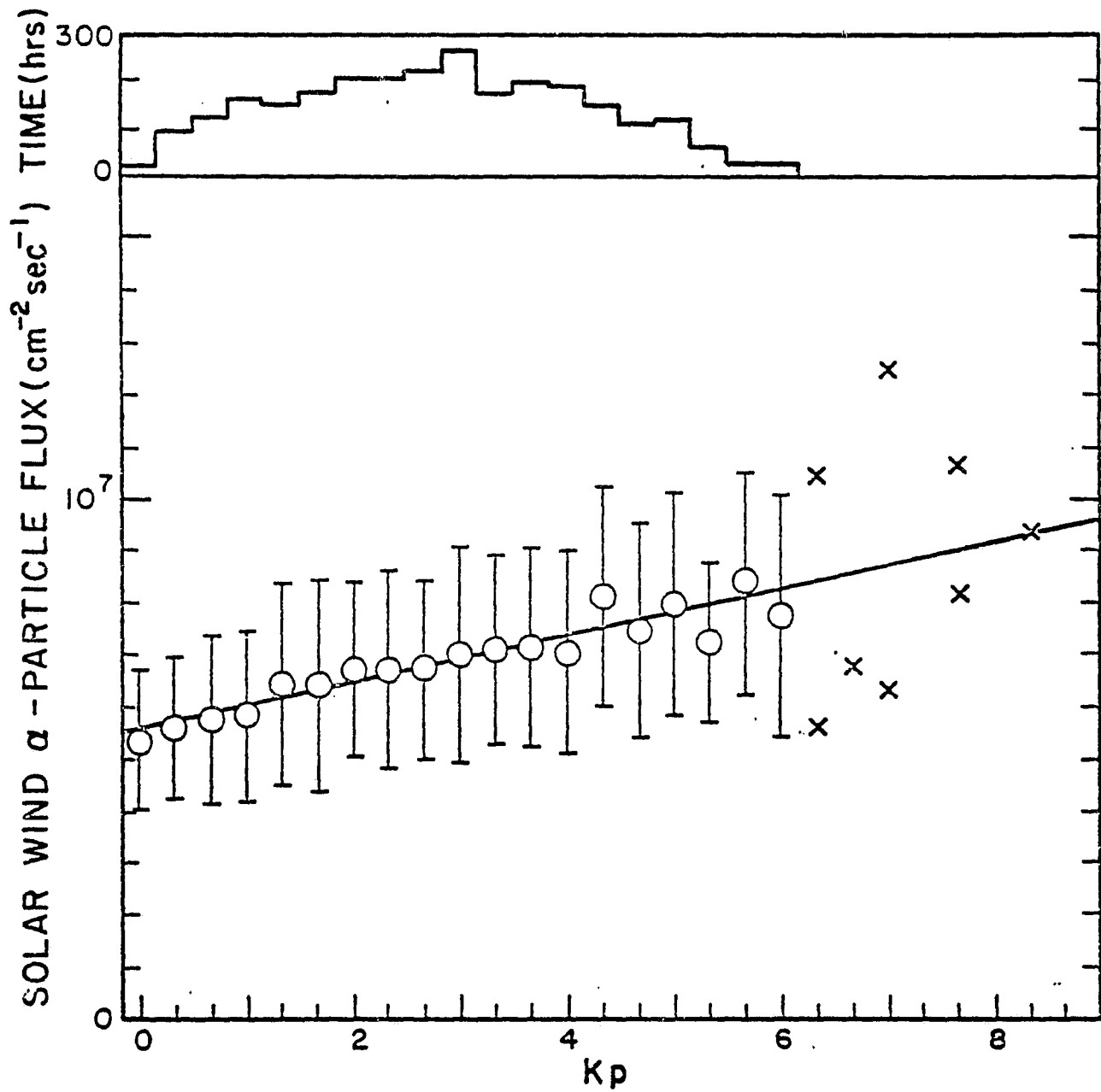
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Figure 5

Correlation of Kp with the equivalent solar wind source flux needed to supply helium escape.

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The slope of the regression line in Figure 5 is not as steep
as might be expected from the data on Kp correlations with the solar
wind reported by Wilcox et al. (1967) and the results of Hirshberg et
al. (1972). However, the apparent relationship of the equivalent lunar
atmospheric source flux data and Kp has been numerically confirmed to have
a correlation coefficient of 0.31. Therefore, it can be concluded that
while the lunar atmosphere may depend on several helium source mechanisms,
one of these is clearly related to Kp and hence to the solar wind. Since
α particles impact the moon with energies of about 4 keV, the solar wind
mechanism probably does not involve the immediate neutralization of
impacting α particles, but rather a process of release of previously
trapped solar wind helium from soil grains.

Presumably the average rate of accretion of α particles by
the lunar regolith nearly equals the average rate of release of previously
trapped helium from the soil, with a slight unbalance due to the absorp-
tion of helium by previously unexposed material which has recently been
brought to the lunar surface by meteor impacts. Diffusion must account
for part of the release of trapped helium from the soil, but the solar
wind related component is probably of greater importance.

A weathering process due to the solar wind could account for
the solar wind correlated part of the helium source (Hodges and Hoffman,
1975b). The proton influx may cause sputtering of soil grain surface

material, resulting in volatilization of many elements, including trapped helium. This mechanism has been proposed by Housley (1974) as an important means of both lateral transport and escape. The fact that the present data seem to show a deficit of atmospheric helium, based on the average solar wind source, suggests that some helium may be lost from the moon as sputtered ions or as superthermal atoms which would not have been detected by the Apollo 17 mass spectrometer because its field of view was limited to nonescaping, downcoming atoms. The low energy fraction of sputtered helium could be the solar wind correlated source of lunar atmosphere.

If the hypothesis of release of trapped solar wind helium from the lunar soil by sputtering is correct, then the α particle fraction of the solar wind is not related to the unexpectedly low helium abundance in the lunar atmosphere in the 1973 measurements. The sputtered helium effusion rate must represent a very long term average of the solar wind helium implantation rate, modulated by variations in the weathering agent: the instantaneous influx of solar wind momentum.

In summary it appears that the average rate of escape of helium from the thermalized lunar atmosphere is about 9×10^{23} atoms/ sec, of which 10% is probably supplied by radioactive decay of Th and U in the moon. The remaining atmospheric helium escape amounts to 60% of the average solar wind inflow of α particles. The correlation of atmospheric helium with the geomagnetic index Kp suggests solar wind weathering of the soil to be an important mechanism for release of previously implanted solar wind helium. A superthermal or ionized component of the helium released by the surface weathering process seems to be needed to account for escape of the 40% of the solar wind helium which does not participate in the formation of the lunar atmosphere. Recent Monte Carlo calculations show that a neutral atom release temperature of 1900°K would explain the Apollo 17 data.

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