GEOPHYSICAL RESEARCH LETTERS, VOL. 18, NO. 9, PAGES 1659-1662, SEPTEMBER 1991

SOURCE PROCESSES FOR THE ALKALI METALS IN THE ATMOSPHERE OF MERCURY

D. E. Shemansky
Lunar and Planetary Laboratory, University of Arizona, Tucson
T. H. Morgan
National Aeronautics and Space Administration, Washington, DC

Abstract. A large (fivefold) increase in Mercury's potassium(K) column abundance on 14 October 1987, has been reported by *Sprague et al.*[1990](SKH), who attributed the enhancement to diffusion through the surface in the Caloris Basin, from depths of order 10 km. The postulated source rate is much larger than any previously estimated diffusion rate, and if true certainly affects consideration of the origin of other atmospheric species. However, *Killen et al.*[1991] have pointed out that the claim is not supported by the published observations of K or sodium(Na) as a whole. *Sprague et al.*[1991] have responded by further hypothesizing the existence of several other sources of gas diffusing out of the regolith, all of which are time variable. In any case the SKH data indicate large variations in abundance, and it is important to understand the cause. With this issue in mind we have examined the available abundance estimates for correlation with possible controlling physical parameters. We have found a significant correlation between the average zenith K column abundance and indices of solar activity, although we are left with the intrinsic uncertainty of a small data set.

Introduction

Observations of K in the atmosphere of Mercury show a low abundance relative to Na, the other known alkali metal constituent. According to *Potter and Morgan*[1990], Na shows moderate global variability in abundance, but strong localized and temporal variation. The measurements of K are fewer in number but all show a low abundance with the exception of two occasions reported by SKH. Twelve observations of K in the atmosphere of Mercury have been published to date. One of these is the discovery measurement by *Potter and Morgan*[1986], and the remainder are reported by SKH. The average abundance derived from the measurements provides an atmospheric abundance ratio $[\mathrm{Na}]\ell/[\mathrm{K}]\ell \sim 100$, where ℓ is effective path length. The dates of the observations with derived abundances, and geometric quantities are shown in Table 1. The average of the derived vertical abundances excluding the data obtained at the longitude of the Caloris Basin and it's antipode, is $[\mathrm{K}]\ell = 0.5 \times 10^9$ cm^{-2} (Table 1), while the average value on 14 October 1987 (Table 1) was $[\mathrm{K}]\ell = 2.3 \times 10^9$ cm^{-2}. The latter measurement forms the basis of the SKH argument for enhanced outgassing through the Caloris Basin near 220° longitude.

Large changes in atmospheric abundance are of considerable interest because the behavior provides the opportunity to identify source processes. SKH consider only one possibility as an explanation for the enhancement of 14 October 1987, although they do not entirely rule out other processes. *Sprague et al.*[1991] have expanded on the diffusion hypothesis in response to criticism by *Killen et al.*[1991] by indicating that there must now be several source locations in addition to the Caloris Basin and its antipode, and all of the sources must now be time variable. Since the variability has no evident relationship to particular features on Mercury, it is a matter of considerable interest to determine whether it depends on any plausible physical source process. Initial inspection of solar activity indices immediately reveals that the two observations on which the SKH postulation depends were obtained on days in which the sunspot count was 92 and 66 (14 October 1987 is described as a D4 disturbed Sun)[see *Coffey*, 1987]. The remaining observations in the data set were obtained at times when the sunspot count was zero. On further investigation we find that the set of derived abundances show a remarkably strong correlation to the variation in solar physical quantities, and we argue that the observed phenomenon may be related to solar activity. These considerations are discussed in more detail below.

Characteristics of the data

Data Quality. The available data on the K atmosphere do not provide extensive coverage of conditions needed for definitive information on source processes, limiting the ability to draw firm conclusions. The strong enhancement of 14 October 1987 consists of measurements of the D1 and D2 lines respectively (Table 1) separated by 50 minutes in time. The latitudinally averaged vertical abundance obtained from the D2 line is a factor of 3.6 below the value from the D1 line. If the lifetime of K is limited by photoionization, roughly 2 hours, it is very unlikely that a real decline in abundance can occur with a time constant of 30 minutes. *Sprague et al.*[1991] originally suggested that the lifetime is limited by adsorption to the surface, but they no longer support this explanation[*D. M. Hunten, private comm.*, 1991]. This suggests that the factor of 3.6 may be spurious, rather than a rapid variation in abundance. A similar difference occurs in abundances obtained from the D1 and D2 lines on 13 March 1987, in measurements separated by 26 minutes. However the data as a whole indicate no systematic differences between abundances obtained separately with the D1 and D2 lines. Although SKH do not discuss details of data quality, it appears that the uncertainty is not limited by photon counting statistics. The main source of error in determining the atmospheric column is expected to be due to the effects of atmospheric seeing[*Killen*, 1988], and possibly to the location of the spectrograph slit on the planet. We note that the D1 line

Paper number 91GL02000
0094-8534/91/91GL-02000$03.00

TABLE 1
MEASUREMENTS OF POTASSIUM
IN THE ATMOSPHERE OF MERCURY

DATE	EMISSION	$[K]\ell^{a}$	$[K]\ell_E/[K]\ell_P{}^{b}$	$\mathcal{F}_{10.7}{}^{d}$	PHASE(deg)	ELON(deg)
TIME(UT)	LINE	(10^9 cm^{-2})	$[K]\ell_N/[K]\ell_S{}^{c}$	H Lyα	r(AU)	ESM(deg)
11:16:1985	D1	0.72	1.2	581	109	21E
21:48			1.05	20.4	.355	55
06:19:1986	D2	0.47	1.4	395	88	24E
02:53			0.54	14.1	.416	68
06:19:1986	D2	0.64	1.5	395	88	24E
03:01			0.55	14.1	.416	68
06:19:1986	D2	0.70	1.2	395	88	24E
03:12			0.83	14.1	.416	68
12:02:1986	D1	0.24	2.1	561	68	20W
13:34			1.10	20.2	.364	-89
03:13:1987	D1	0.36	—	378	118	22W
13:15			—	13.2	.433	-86
03:13:1987	D2	0.14	—	378	118	22W
13:41			—	13.2	.432	-86
06:08:1987	D1	0.72	2.1	436	108	24E
22:06			0.75	14.2	.430	79
06:09:1987	D2	0.84	1.2	438	108	24E
02:51			0.81	13.4	.433	79
10:14:1987	D1	3.6	4.2	683	107	22E
21:32			0.95	18.5	.395	51
10:14:1987	D2	1.0	1.7	683	107	22E
22:22			1.10	18.5	.395	51
01:22:1988	D2	2.1	—	899	32	17E
01:10			—	24.9	.332	56

[a] Zenith abundance from *Sprague et al.*[1990] and *Potter and Morgan*[1986]. The quantities derived from the data are the average zenith column which is the average of the north, equatorial, and south data if that is available, and the average value reported if no spatial data is given.

[b] Zenith abundance ratio equator to mean of polar regions.

[c] Zenith abundance ratio north to south polar regions.

[d] Solar flux quantities from *Coffey*[1985–1988] and the SME data facility, LASP, University of Colorado. Flux units are standard for $\mathcal{F}_{10.7}$ and $10^{11} cm^{-2} s^{-1}$ for H Lyα. Values are calculated for Mercury's radial position, and adjustments are made for solar phase, but not for possible intervening temporal variations(see text).

intensity on 14 October 1987 is very sharply peaked at the equator, and the large latitudinally averaged abundance is heavily weighted by the equatorial value.

Morphology of the Observations. In all cases the slit of the spectrograph was placed across the apparent, seeing–broadened disk aligned N–S and passing over the poles. The observations were generally made at phase angles near 90 degrees with the sub-solar point near the bright limb. The apparent diameter of the planet was generally 7–9 arcseconds. The spectra were spatially resolved along the slit, but in most cases, the observers binned the data into just three sectors. The distribution of longitudes in the observational coverage is limited mainly to the 180° – 330° region, so that uniform statistics are not available in this domain. We therefore have no information as to whether similar events occur when longitudes in the range 90° – 180° are illuminated. In addition, the data span a time interval from November 1985 to February 1988, and on the scale of a solar cycle long term effects are not easily identifiable.

The K data shows a large range of values (from 0.14×10^9 atoms cm^{-2} to 3.6×10^9 cm^{-2}). In contrast, there is no evidence in the Na data for changes in the global column by equivalent factors of 25. It is possible that Na would not show similar variability because of a longer intrinsic atmospheric lifetime, and to some degree spatial variations are moderated by optical thickness. Surface composition variations are another source of variability that have not been previously mentioned. Strong regional variations in the surface expression of K are found on the Moon. Large increases in the K exosphere are possible, because of the low atmospheric abundance.

Statistically significant correlations

Since there is no case for a persistent source near longitude 220°, are there any significant correlations with other processes? At any epoch the average zenith column of K might depend on a number of factors in addition to the portion of the planet in the sunlit planetocentric disk -- distance from the Sun, radiation pressure, and solar wind anomalies. In Table 1, we give the observed average zenith column densities of all the K observations, the ratios $[K]\ell_E/[K]\ell_P$ and $[K]\ell_N/[K]\ell_S$, two indices of solar activity, the 10.7 cm flux ($\mathcal{F}_{10.7}$) and the H Lyα flux, which are available for every day in the table. The solar flux indices given in Table 1 are adjusted in solar phase for the position of Mercury. It is not clear that this is the most appropriate correction because of possible solar temporal effects. A calculation, using indices for the day of observation(i.e., uncorrected for phase differences) shows slightly but not significantly better correlations with the data. The observations were made near solar minimum with early 1988 on the rising tail of the 11 year cycle. Solar activity was such that the 28 day cycle was not recognizable in the data, with daily variability in H Lyα emission generally at the ± 5% level. Using standard correlation theory, the data were examined for statistically significant correlations with the indices of solar activity, distance from the Sun, and radiation pressure. A list of calculated correlations is given in Table 2. Briefly, three strong correlations (R = 0.8 or better) were found: (1) The correlation between the average zenith column of K and the $\mathcal{F}_{10.7}$ flux; (2) the correlation between the average zenith column of K and solar H Lyα; and (3), the correlation between the ratio abundances at the north and south poles ($[\mathrm{K}]\ell_N/[\mathrm{K}]\ell_S$) and the $\mathcal{F}_{10.7}$ flux. The corresponding value of correlation required at several significance levels are also given in Table 2. Figure 1 shows a plot of the $\mathcal{F}_{10.7}$ flux, adjusted for Mercury's radial position and phase relative to the Earth, against derived K abundance. A linear regression line is drawn through the data points, calculated excluding the 14 October 1987 abundance obtained from the D1 line (solid point shown in Figure 1). The solid point in Figure 1 is clearly well away from the linear regression line, indicating that the event was either controlled by additional physical factors, or as we suggest above on the basis of timing, the quality of the measurement was poor. The linear correlation coefficient (R) for the result in Figure 1 is R = 0.83, giving a $< 1\%$ confidence level that the data are uncorrelated (Table 2). A similar result is obtained for the solar H Lyα line, but at a $< 2\%$ confidence level. A calculation of the correlation of the abundance with range to the Sun shows a significant value, similar to but lower than H Lyα, suggesting that the correlation may simply reflect the role of radial position in determining the magnitude of the solar flux at Mercury. The ratio $[\mathrm{K}]\ell_E/[\mathrm{K}]\ell_P$ appears to show no correlation to the solar quantities (Table 2), but the ratio of polar abundances $[\mathrm{K}]\ell_N/[\mathrm{K}]\ell_S$ does have a surprisingly high correlation with $\mathcal{F}_{10.7}$ as shown in Figure 2 and Table 2. The correlation of H Lyα with $[\mathrm{K}]\ell_N/[\mathrm{K}]\ell_S$ is not particularly good, at the $< 10\%$ level (Table 2). The trend of higher correlation of the observed quantities with $\mathcal{F}_{10.7}$ is consistent throughout the tested data. The correlation of $\mathcal{F}_{10.7}$ with the latitudinally separated components of K abundance is also shown in Table 2 (see *Killen et al.*[1991] for a description of the latitudinal binning of the data). The R value declines from north latitude to south with values in the south tending to a null result. This presumably explains the basis for the strong correlation of $\mathcal{F}_{10.7}$ with the $[\mathrm{K}]\ell_N/[\mathrm{K}]\ell_S$ ratio, at the $< 1\%$ confidence level.

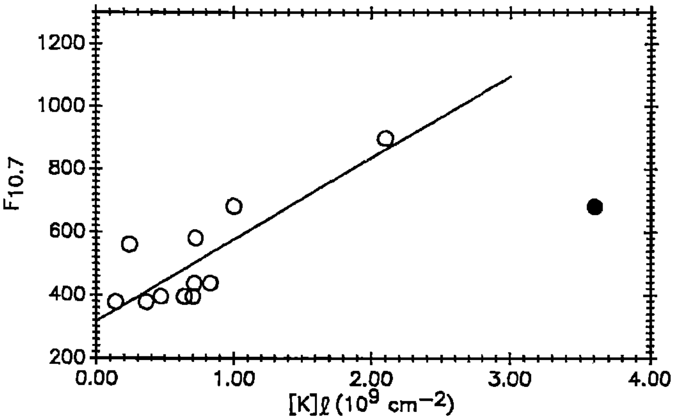

Fig. 1. The relationship between the $\mathcal{F}_{10.7}$ Solar flux at Mercury and the measured zenith abundance of potassium (see Table 1). The line drawn on the plot is the linear regression fit to the data, calculated by excluding the data point plotted as a solid circle (see text). The linear correlation coefficient is R = 0.83 (see Table 2).

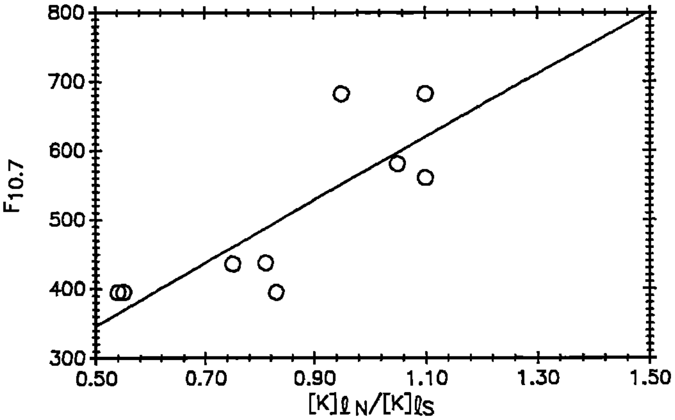

Fig. 2. The relationship between the $\mathcal{F}_{10.7}$ Solar flux at Mercury and the measured ratio of zenith potassium abundances ($[\mathrm{K}]\ell_N/[\mathrm{K}]\ell_S$) in the north and south polar regions. The line drawn on the plot is the linear regression fit to all of the available data. The linear correlation coefficient is R = 0.82 (see Table 2).

Table 2

CORRELATION FACTORS FOR ATMOSPHERIC POTASSIUM ABUNDANCES AND SOLAR QUANTITIES

Y[a]	X[b]	N[c]	R[d]	Confidence level[e]		
				0.10	0.02	0.01
$[\mathrm{K}]\ell$[f]	$\mathcal{F}_{10.7}$	12	0.75	0.497	0.658	0.708
$[\mathrm{K}]\ell$[g]	$\mathcal{F}_{10.7}$	11	0.83	0.521	0.685	0.735
$[\mathrm{K}]\ell$[g,h]	$\mathcal{F}_{10.7}$	10	0.91	0.549	0.716	0.765
$[\mathrm{K}]\ell$[g]	H Lyα	11	0.68	0.521	0.685	0.735
$[\mathrm{K}]\ell$[g,h]	H Lyα	10	0.85	0.549	0.716	0.765
$[\mathrm{K}]\ell$[g]	r^{-2}	11	0.65	0.521	0.685	0.735
$[\mathrm{K}]\ell$[g,h]	r^{-2}	10	0.83	0.549	0.716	0.765
$[\mathrm{K}]\ell_E/[\mathrm{K}]\ell_P$[f]	$\mathcal{F}_{10.7}$	8	0.01	0.707	0.789	0.834
$[\mathrm{K}]\ell_E/[\mathrm{K}]\ell_P$[f]	H Lyα	8	0.25	0.622	0.789	0.834
$[\mathrm{K}]\ell_N/[\mathrm{K}]\ell_S$[f]	$\mathcal{F}_{10.7}$	9	0.82	0.582	0.750	0.798
$[\mathrm{K}]\ell_N/[\mathrm{K}]\ell_S$[f]	H Lyα	9	0.57	0.582	0.750	0.798
$[\mathrm{K}]\ell_N$[h]	$\mathcal{F}_{10.7}$	8	0.78	0.622	0.789	0.834
$[\mathrm{K}]\ell_N$[g,h]	$\mathcal{F}_{10.7}$	7	0.78	0.669	0.833	0.875
$[\mathrm{K}]\ell_E$[g,h]	$\mathcal{F}_{10.7}$	7	0.70	0.669	0.833	0.875
$[\mathrm{K}]\ell_S$[h]	$\mathcal{F}_{10.7}$	8	0.62	0.622	0.789	0.834
$[\mathrm{K}]\ell_S$[g,h]	$\mathcal{F}_{10.7}$	7	0.31	0.669	0.833	0.875

[a] Potassium observational data quantity.
[b] Solar data; see Table 1.
[c] Number of data elements; statistical dimension = N−2.
[d] Linear correlation coefficient.
[e] Correlation coefficient limit for indicated confidence that a null result is obtained[*Fisher and Yeates*, 1957].
[f] All available data numbers.
[g] Excluding 14 October 1987 D1 data.
[h] Excluding 02 December 1986 data.

The sense of the dependence on the solar flux quantities is that both the total column of K and the relative concentration toward the north pole increases as the flux in H Lyα and $\mathcal{F}_{10.7}$ emissions increase. In terms of the location within the solar cycle, the K emission column is small near solar minimum (September 1986) and reaches a maximum near solar maximum. Near minimum the abundance of K near the north pole on the planet is depressed relative to the southern region, and reaches parity near solar maximum. The magnitude of the dependence indicates that the K abundance varies with greater amplitude than the solar quantities tested. The reality of these correlations are clearly testable by continuing the observations of K over the rest of cycle 22 (1986 – 1997).

An investigation of the relationship of K abundance to solar wind activity obtained no detectable correlation.

Discussion and Conclusions

Our examination of the available measurements of K in the Mercury atmosphere leads to the conclusion that the data as a whole shows a strong correlation with solar physical quantities, particularly in the $\mathcal{F}_{10.7}$ emission flux. The uncertainty in this conclusion lies in its dependence on a small data set. Most of the data was obtained when the solar flux quantities at Mercury showed variation of only ~ 25 %. The time of the measurement of the D2 line in January 1988 (see Table 1) was the only occasion in which the solar flux quantities obtained a full factor of 2 in modulation above minimum values. Short wavelength radiation such as the He^+ line at 304 Å evidently has a larger variability, and if this and shorter wavelength emissions play a role, then significant variations could occur during solar minimum. With the exception of sunspot count the solar quantities tested show less modulation than the derived K abundances, as we have pointed out in the previous section. It is known that $\mathcal{F}_{10.7}$ is more closely correlated with short wavelength solar flux than with H Lyα, and generally has a larger variability.

Taking the step from correlation of solar indices to inference of physical processes is not a simple matter, since it is not clear which solar quantity is the direct causal factor. The $\mathcal{F}_{10.7}$ and H Lyα fluxes are both related to the EUV solar emission, and it seems plausible that photon induced desorption processes play a role. *McGrath et al.*[1986] have suggested that the Na atmosphere on Mercury is controlled mainly by solar photon interaction at the surface. However, in the *McGrath et al.*[1986] description, the solar photons which electronically excite the subsurface molecules are a source of heat and dissociation products for eventual diffusion and thermal desorption at the surface. However, the strong observed variability requires a prompt response. Experimental work indicates that EUV photons can promptly remove atoms from the subsurface by the production of energetic dissociation (atomic) fragments through electronic excitation by secondary electrons. The physics of desorption processes has been referenced and discussed recently by *Morgan and Shemansky*[1991]. An enhanced source of K may be produced by the dissociative ejection mechanism through hardening of the solar spectrum along with increased flux. The spatial and temporal morphology of Na is complex, not consistent with thermal desorption, and the evidence seems to indicate that other processes control the source[*Killen et al.*, 1990; *Potter and Morgan*, 1990; cf. *Ip*, 1990; *Smyth*, 1986].

The fact that the K abundance varies with greater modulation than either of the solar sources tested and shows better correlation with $\mathcal{F}_{10.7}$, suggests that the effective radiation for the process is at wavelengths shortward of 500 Å , if we assume that there are no significant regional differences in surface concentration. The latter assumption could easily be wrong, leading to peculiar deviations from a linear regression line. It is unlikely that the source would be composed of atoms recycled to physical adsorption at the surface, since atoms in this state have a very short lifetime. Moreover the adsorbed atoms tend to retain their atomic properties and therefore are expected have a small cross section for desorption as neutrals by EUV photons. The suggestion in the data that the abundance in the north polar region is depleted during solar minimum implies complexity in the source processes, and possible hemispheric surface differences. Long term studies of the K and Na exosphere will be required to begin to understand these phenomena.

Acknowledgements. This work is supported by NASA grants NAG 5-560 to the University of Arizona, and NAS5-30442 to the Goddard Space Flight Center.

References

Coffey, H. E., *Solar–Geophysical Data (World Data Center A for Solar–Terrestrial Physics)*, NOAA., Boulder, CO 80302., 1985–88.

Fisher, Sir R. A., and F. Yeates, *Statistical Tables for Biological, Agricultural, and Medical Research*, p. 138, Oliver and Boyd., London., 1957.

Ip, W. H., On solar radiation–driven surface transport of sodium atoms at Mercury, *Astrophys. J.*, *356*, 675-681, 1990.

Killen, R. M., Resonance scattering by sodium in Mercury's atmosphere I. The effect of phase and atmospheric smearing, *Geophys. Res. Lett.*, *15*, 80–83, 1988.

Killen, R. M., A. E. Potter, and T. H. Morgan, Spatial distribution of sodium vapor in the atmosphere of Mercury, *Icarus*, *85*, 145–167, 1990.

Killen, R. M., A. E. Potter, and T. H. Morgan, Detecting potassium on Mercury, *Science*, *262*, 974–975, 1991.

McGrath, M. A., R. E. Johnson, and L. J. Lanzerotti, Sputtering of Sodium on the planet Mercury, *Nature*, *323*, 694–696, 1986.

Morgan, T. H., and D. E. Shemansky, Limits to the lunar atmosphere, *J. Geophys. Res.*, *96*, 1351–1367, 1991.

Potter, A. E., and T. H. Morgan, Potassium in the atmosphere of Mercury, *Icarus*, *67*, 336–340, 1986.

Potter, A. E., and T. H. Morgan, Evidence for magnetospheric effects on the sodium atmosphere of Mercury, *Science*, *248*, 835–838, 1990.

Smyth, W. H., Nature and variability of Mercury's sodium atmosphere, *Nature*, *323*, 696–699, 1986.

Sprague, A. L., R. W. H. Kozlowski, and D. M. Hunten, Caloris Basin: An enhanced source for potassium in Mercury's atmosphere, *Science*, *249*, 1140–1143, 1990.

Sprague, A. L., R. W. H. Kozlowski, and D. M. Hunten, Detecting potassium on Mercury: Response, *Science*, *262*, 974–974, 1991.

D.E. Shemansky, Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona.

T.H. Morgan, National Aeronautics and Space Administration, Washington, D.C.

(Received May 13, 1991;
revised June 25, 1991;
accepted July 19, 1991.)