tration of O than values indicated in Fig. 3. Alternatively, the discrepancy could be removed if small adjustments were made in the rate constants for the reactions

$$CO_2^+ + O \rightarrow CO + O_2^+ \tag{5}$$

and

$$O_2^+ + e \rightarrow O + O \tag{6}$$

Figure 4B shows a comparison of observed and computed values for the concentration of NO. We obtained curve a by using cross sections for the electron impact dissociation of N_2 as measured by Winters (*11*) with a quantum yield for $N(^2D)$ taken equal to 50 percent (*12*). Curve b allowed for an increase in the cross sections for e + N_2 by a factor of 5 for all energies below 40 ev, an adjustment suggested by recent laboratory measurements by Zipf (*13*). The quantum yield for $N(^2D)$ was set equal to 50 percent in curve b. It was increased to 75 percent in curve c, for which the cross section for e + N_2 was taken equal to three times the value given by Winters (*11*) at impact energies below 40 ev. Model calculations are in satisfactory accord with observational data. It would appear that the remaining uncertainties may be removed as a result of suitable laboratory experimentation.

The analysis given here implies mixing ratios for N_2, Ar, and O_2 in the bulk atmosphere of magnitude 2.4×10^{-2}, 1.5×10^{-2}, and 1.6×10^{-3}, respectively. The upper atmosphere is enriched in CO and NO relative to the composition of the lower atmosphere, for which we derive mixing ratios of 8×10^{-4} and between 10^{-8} and 10^{-9}, respectively.

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12 November 1976

Structure of the Neutral Upper Atmosphere of Mars: Results from Viking 1 and Viking 2

Abstract. *Neutral mass spectrometers carried on the aeroshells of Viking 1 and Viking 2 indicate that carbon dioxide is the major constituent of the martian atmosphere over the height range 120 to 200 kilometers. The atmosphere contains detectable concentrations of nitrogen, argon, carbon monoxide, molecular oxygen, atomic oxygen, and nitric oxide. The upper atmosphere exhibits a complex and variable thermal structure and is well mixed to heights in excess of 120 kilometers.*

The scientific payload of the Viking landers VL1 and VL2, which landed on Mars on 20 July 1976 and 3 September 1976, respectively, included mass spectrometers designed to measure properties of the neutral atmosphere over the approximate height range 120 to 200 km. The upper atmosphere of Mars consists mainly of CO_2, with trace-detectable quantities of N_2, Ar, CO, O_2, O, and NO (*1, 2*). The isotopic composition of carbon and oxygen in the martian atmosphere is similar to that observed for the terrestrial atmosphere. The martian atmosphere is enriched, however, in ^{15}N relative to ^{14}N (*2, 3*). The ratio $^{15}N/^{14}N$ for Mars exceeds the value for Earth by a factor of about 1.75, a result which may be taken to indicate a denser nitrogen atmosphere for Mars in the past (*2, 4*). The enrichment of ^{15}N is thought to be due to past selective escape of ^{14}N (*2, 4, 5*).

This report gives an updated account of results obtained by VL1, together with a preliminary report on data from VL2. We emphasize results relevant to the question of atmospheric structure. An analysis of the manner in which the density of CO_2 varies as a function of altitude may be used to obtain information on the thermal structure of the upper atmosphere of Mars. The variation in the densities of other gases, N_2 and Ar in particular, with altitude may be used to study the extent to which the upper atmosphere is influenced by mass mixing processes, associated perhaps with the dissipation of inertial gravity waves. The upper atmosphere of Mars is surprisingly cold and variable. Mass mixing is more efficient for Mars than for Earth. If we use as a measure of the mixing process an effective eddy diffusion coefficient, it is clear that this parameter must have values in the range 10^8 to 10^9 cm^2 sec^{-1} over the altitude interval 120 to 150 km on Mars, which may be compared to a value of order 10^6 cm^2 sec^{-1} thought to apply at similar altitudes in Earth's atmosphere (*6*).

The data discussed here were obtained with instruments mounted on the spacecraft aeroshell, with open ion sources which allowed gas to freely enter the ionizing region of the spectrometers (*7*). The sensitivity of the instruments was enhanced by the ram effect produced as a result of the high speed of the spacecraft, about 4.5 km sec^{-1}. Complications introduced by the ram effect are well understood, and the raw data may be reliably interpreted to yield ambient densities, on the basis of reduction techniques discussed elsewhere (*8*).

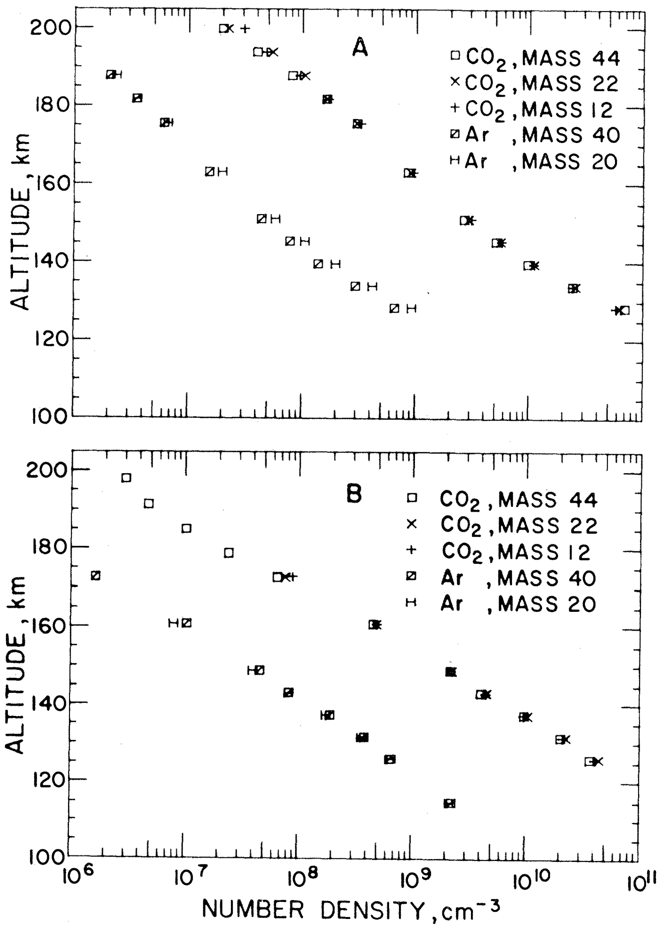
The experiment has a number of redundant features which may be exploited in order to enhance confidence in the interpretation of the measurements. There are a variety of mass peaks which may be used to obtain information on the density of individual species. For example, ionization of argon by 75-ev electrons, one of two energy options used on Viking, leads to peaks at mass numbers 40 and 20, associated with the formation of Ar^+ and Ar^{2+}. The relative magnitude of these peaks, about 5 to 1, is known on the basis of preflight calibration of the instruments. Ionization of CO_2 gives peaks at mass numbers 44, 28, 22, 16, and 12 associated with CO_2^+, CO^+, CO_2^{2+}, O^+, and C^+. The presence of CO may be inferred from peaks at mass numbers 28, 16, 14, and 12. Because CO is a minor constituent of the martian atmosphere, most of the signal at mass number 12 may be attributed to C^+ formed by the dissociative ionization of CO_2. Molecular nitrogen may be detected at mass numbers 28 and 14, and indeed most of the signal at mass number 14 is due to N^+ formed by the dissociative ionization of N_2. The concentration of O_2 may be inferred from an analysis of the mass peak at 32. The presence of NO may be deduced from an anomalously high peak at mass number 30.

Figure 1 summarizes results obtained for CO_2 and Ar. The mass peaks at 44, 22, and 12 yield essentially identical results for CO_2. Results obtained for Ar from mass peaks at 40 and 20 are also remarkably consistent. Densities are shown here as functions of altitude above the mean martian surface defined by an isobar at 6.1 mbar. We may conclude immediately that the atmosphere probed by VL2 is significantly colder than that seen by VL1. The density of CO_2 at 130 km in VL1 (Fig. 1A) is about 5×10^{10} cm^{-3}, which may be compared with a density of 2.6×10^{10} cm^{-3} at the same altitude in VL2 (Fig. 1B). The density of CO_2 falls off more rapidly with altitude in VL2, reaching a value of 6.2×10^6 cm^{-3} at 190 km, which may be compared to a value of 7.8×10^7 cm^{-3} at a similar altitude for VL1.

Figure 2 gives height profiles for the densities of CO_2, N_2, CO, O_2, and NO for both VL1 and VL2. The densities of CO_2 as shown here were obtained from an analysis of the mass peaks at 44. The density of O_2 was found directly from the mass peak at 32. Information on N_2 and CO was derived from a combination of the mass peaks at 28 and 14 after suitable correction for contributions due to the dissociative ionization of CO_2. The densities for N_2 and CO were obtained from the solution of a pair of simultaneous equations incorporating all known sources of signal at the relevant mass numbers, 28 and 14.

Figure 2 includes a simple fit to the height profiles for CO_2. We assumed an exponential decay of density with increasing altitude. The change of density with height was determined in the conventional fashion by the scale height H, defined by $H = kT/mg$, where k denotes Boltzmann's constant, T is the temperature, m is the mass of CO_2, and g is the acceleration of gravity. We allowed temperature to vary from an average value of 117°K at low altitudes in VL1 to a somewhat higher value of 190°K at intermediate altitudes, declining to 151°K at higher altitudes. The temperature in Fig. 2B for VL2 is about 142°K at low altitudes. It decreases to about 109°K at intermediate altitudes and appears to rise to a value in excess of 130°K at higher altitudes. The results shown here indicate that the upper atmosphere of Mars exhibits an unexpectedly complex thermal structure. The results obtained by VL2 are significantly different from those found by VL1.

Spectra obtained by both VL1 and VL2 show distinct peaks at mass numbers 16, 17, and 18. The peaks at 17 and 18 are most probably due to water vapor. Scale heights indicated by these features are consistent with a molecule of mass number near 18. The magnitude of the peaks appears too large, however, for ambient martian H_2O. It seems more probable that the peaks are associated with terrestrial H_2O, bound to the surface of the instruments. The molecules



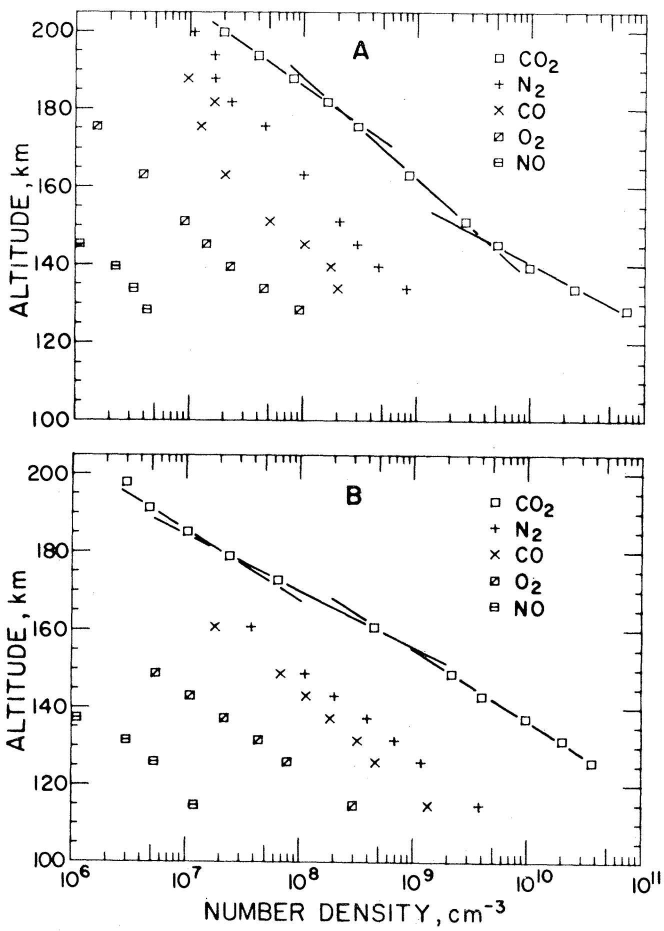


Fig. 1 (left). (A) Number densities of CO_2 and Ar found during the descent of VL1 determined from an analysis of the mass peaks at 44, 22, and 12 amu in the case of CO_2, and of the mass peaks at 40 and 20 amu in the case of Ar. (B) Same as (A) for VL2. Fig. 2 (right). (A) Number densities of CO_2, N_2, CO, O_2, and NO found during the descent of VL1. The straight line fits to CO_2 indicate results from a simple thermal analysis as discussed in the text. (B) Same as (A) for VL2.

would be released as the martian atmosphere struck the surface, a phenomenon seen earlier during perigee passes of the Earth orbital satellites Explorer C, Explorer D, and Explorer E. The mass peak at 16 includes contributions from CO_2, CO, O_2, and H_2O, in addition to a residual most probably due to O. A quantitative analysis is difficult, however, since O may be expected to react rapidly with surfaces in the instrument. It is hoped that further laboratory studies will clarify these matters, and that they might eventually permit a more quantitative estimate for the concentration of O.

The densities of NO, as shown in Fig. 2, were obtained from a detailed analysis of the peak at mass number 30. Figure 3 gives a scale representation of a typical spectrum obtained by VL1 at an altitude near 130 km. Slightly more than half of the signal at mass 30 may be attributed to $^{12}C^{18}O^+$ formed by the dissociative ionization of $^{12}C^{18}O^{16}O$. After correction for $^{12}C^{18}O^+$ from both CO_2 and CO, there remains a component whose magnitude significantly exceeds the noise level of the amplifier. This component is most reasonably attributed to NO, and it is seen in all spectra for which the peak at mass 30 exceeds the amplifier noise background. The data indicate a mixing ratio for NO relative to CO_2 of approximately 10^{-4}. The density of NO in the upper atmosphere of Mars is thus significantly higher than the density of NO at comparable levels of Earth's atmosphere.

It is clear from even a casual inspection of the data in Fig. 2 that the martian atmosphere must be mixed to heights greater than 130 km. This observation implies an eddy diffusion coefficient of at least 5×10^7 cm^2 sec^{-1}. One would expect a density for N_2 of about 5×10^7 cm^{-3} at 190 km in VL1, or about 10^8 cm^{-3} at 160 km in VL2, if diffusive separation should occur above 130 km. The measured densities at these altitudes are only 2×10^7 cm^{-3} and 4×10^7 cm^{-3}, respectively. The densities as measured for CO are also consistent with the assumption of rapid vertical mixing, as discussed elsewhere (*9*).

The upper atmospheric mass spectrometers on both VL1 and VL2 used Mattauch-Herzog geometry (*10*), which allowed for simultaneous collection of ions with different masses. Two collectors were used to measure ions differing in mass by approximately a factor of 7 (*7*). The heavy collector was sensitive to the mass range 7 to 49 atomic mass units (amu), whereas the light collector recorded ions in the range 1 to 7 amu. Because of weight restrictions imposed at an early stage of the project, we were obliged to use electrometer amplifiers rather than electron multipliers. The background fluctuations of these amplifiers were in the range (1 to 5) × 10^{-14} amp. The instrumental sensitivity on Viking was therefore less than that for similar instruments flown on sounding rockets and terrestrial satellites, by about a factor of 10^3. The low-mass spectra are currently being analyzed: preliminary results suggest upper limits for the mixing ratios of H_2 and He relative to CO_2 of about 10^{-4}.

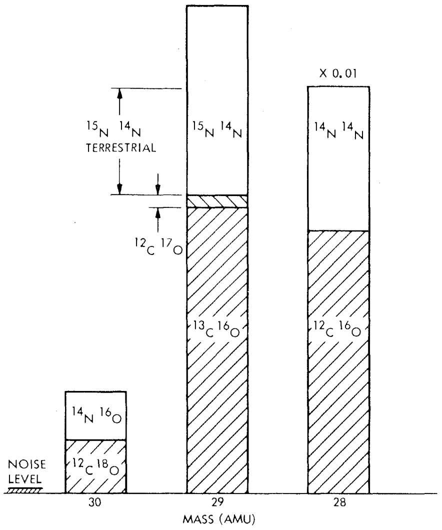


Fig. 3. Block diagram representing to scale the relative heights for the mass peaks at 30, 29, and 28 amu in a spectral scan obtained near an altitude of 130 km during the descent of VL1. The diagram shows the contribution of CO^+ (from the fragment due to the dissociation of CO_2 in the ion source and from ambient CO) to the several peaks. The remainder, in the case of the peaks at mass 29 and 28, is attributed to ambient N_2. The excess peak at mass 30 is attributed to ambient NO. The diagram also illustrates that both the excess peak at mass 30 and the excess peak at mass 29 (beyond that expected if the nitrogen has a terrestrial isotopic composition) are well above the noise level of the amplifier which measured the ion currents.

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Structure of Mars' Atmosphere up to 100 Kilometers from the Entry Measurements of Viking 2

Abstract. *The Viking 2 entry science data on the structure of Mars' atmosphere up to 100 kilometers define a morning atmosphere with an isothermal region near the surface; a surface pressure 10 percent greater than that recorded simultaneously at the Viking 1 site, which implies a landing site elevation lower by 2.7 kilometers than the reference ellipsoid; and a thermal structure to 100 kilometers at least qualitatively consistent with pre-Viking modeling of thermal tides. The temperature profile exhibits waves whose amplitude grows with altitude, to ~ 25°K at 90 kilometers. These waves are believed to be a consequence of layered vertical oscillations and associated heating and cooling by compression and expansion, excited by the daily thermal cycling of the planet surface. As is necessary for gravity wave propagation, the atmosphere is stable against convection, except possibly in some very local regions. Temperature is everywhere appreciably above the carbon dioxide condensation boundary at both landing sites, precluding the occurrence of carbon dioxide hazes in northern summer at latitudes to at least 50°N. Thus, ground level mists seen in these latitudes would appear to be condensed water vapor.*

The second Viking lander entered the atmosphere of Mars on 3 September 1976 at about 3:49 p.m. Pacific Daylight Time (P.D.T.), and landed at 3:58:20 p.m. P.D.T. in Utopia Planitia at 47.66°N latitude and 225.78°W longitude at 9:06