Mars: Microwave Detection of Carbon Monoxide

Abstract. *The 115-gigahertz microwave line of carbon monoxide has been detected in the spectrum of Mars. The measurement is sensitive to carbon monoxide between the surface and an altitude of approximately 50 kilometers in the martian atmosphere. This extends the altitude region to well above that previously sensed.*

Since detecting the $J = 0 \rightarrow 1$ CO rotational transition at 115 Ghz (2.6-mm wavelength) in the upper atmospheres of the earth and Venus (*1, 2*), we have detected this transition in the spectrum of Mars. It is the first microwave line to be observed in the martian spectrum and appears as a narrow absorption feature against the continuum emission from the planet. The line width of the CO absorption feature indicates that it originates between pressure levels of about 5 and 0.02 mbar in the martian atmosphere, corresponding to altitudes between the surface and approximately 50 km. This microwave measurement of Mars samples much higher altitudes than did previous infrared measurements.

The first observation of CO on Mars was made by Kaplan *et al.* (*3*), using infrared techniques. They deduced a CO abundance of 5.6 ± 1 cm atm, a surface pressure of 5.3 ± 1.5 mbar, and a CO concentration of $8 \pm 3 \times 10^{-4}$ by volume from the measurements of Connes *et al.* (*4*). Working with the same spectra of Connes *et al.* and taking various experimental uncertainties into consideration, Gray Young (*5*), obtained a CO abundance in the range 27 to 57 cm atm and a mean rotational temperature of 205 ± 7 K for the disk of Mars.

Our microwave detection of martian CO was made on 9 November 1975 with the 11-m radio telescope of the National Radio Astronomy Observatory (NRAO) located on Kitt Peak, Arizona. At the CO frequency of 115,271.2 Mhz the antenna has a half-power beam width of ~ 1 arc min and did not resolve the martian disk, which had a diameter of 0.24 arc min. The NRAO cooled mixer receiver with a single sideband system noise temperature of 600 K was used. Two 256-channel filter receivers, one with 0.25-Mhz resolution and the other with 0.100-Mhz resolution filters, provided spectral analysis of the received signal.

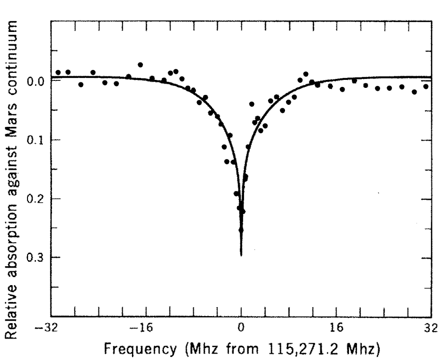

Fig. 1. Observed (•) and calculated (−) Martian atmospheric spectrum near 115,271 Mhz, assuming a constant CO mixing ratio of 1.9×10^{-3} and a background continuum temperature of 200 K, as described in the text. The relative root-mean-square noise was 0.01.

The spectral line was observed in the upper sideband of the double sideband receiver. The receiver gain difference and the terrestrial atmospheric attenuation in the two sidebands were measured by observing the stronger CO absorption line of Venus as a function of elevation angle both with and without a Fabry-Perot rejection filter blocking the lower sideband of the receiver. The values obtained were 0.45 and 0.20 for atmospheric attenuation in the upper (115,271 Mhz) and lower (105,771 Mhz) receiver sidebands, respectively, and 1.05 for the ratio of upper to lower sideband gain. The Venus CO signal appeared slightly broader and somewhat less intense at line center than when we first detected it. Since the phase of Venus for this second measurement was 0.51 as opposed to 0.005 for the initial detection, these measurements indicate relatively more CO at higher altitudes during the Venus night.

Observations were performed by using the position switched mode in which the antenna beam is alternately switched between Mars and blank sky every 30 seconds. The measured continuum antenna temperature with the beam on Mars was 3.2 ± 0.3 K, as calibrated with ambient air and liquid nitrogen loads in front of the antenna feed. This is the value expected with a brightness temperature of 200 ± 20 K, the relative sizes of Mars and the antenna beam, the atmospheric attenuation, and the antenna efficiency of ~ 40 percent.

The measured CO absorption line, after correction for differences in atmospheric attenuation and receiver gain in the two sidebands, is shown in Fig. 1 together with a line calculated for a CO volume mixing ratio of 1.9×10^{-3}, a standard martian atmosphere (*6*), and a background planet-continuum temperature of 200 K. The calculations and interpretation are discussed below. The measurement shown in Fig. 1 was made between 1030 and 1400 universal time on 9 November 1975 and represents an equivalent integration time of 165 minutes. During this time the air mass (secant of zenith angle for angles observed here) through which the observation was made varied between 1.21 and 1.03, with a mean value of 1.06. At this time 94 percent of the martian disk was illuminated.

The absorption line in Fig. 1 is plotted in the martian rest frame and occurs at exactly the frequency of the $^{12}C^{16}O$ $J = 0 \rightarrow 1$ rotational transition when the frequency shift of −3.5 Mhz due to the 9.0-km/sec relative motion of the earth and Mars is accounted for. The measured points farther than 12.5 Mhz from the line center were obtained from the 0.25-Mhz resolution filter bank; points within 12.5 Mhz of the center were obtained from the 0.1-Mhz resolution filter bank. To reduce noise, the points have been averaged in groups: the effective resolution of the points in Fig. 1 is 0.5 Mhz in the range 0 to 4.0 Mhz, 1.0 Mhz in the range 4.0 to 13.0 Mhz, and 2.0 Mhz in the range 13.0 to 31 Mhz from the center. Since the 115-Ghz CO collisional line-width parameter is ~ 4.5 Mhz/mbar for martian atmospheric temperatures and the Doppler line width is 0.1 Mhz, the total observed bandwidth of ± 32 Mhz provides sensing of the martian atmosphere between 5 and 0.02 mbar, corresponding to altitudes between 0 to 50 km. This covers higher altitudes than those sensed by the previous infrared measurements mentioned above.

Our calculations of the martian microwave CO signal were performed in the same way as described earlier for Venus (*1*), except that we used the more recent measurements of the CO collisional line-width parameter by Varanasi (*7*), which indicate a 10 percent larger value than we used for Venus. (This has negligible effect on our earlier Venus interpretations.) The 1974 NASA model I (*6*) was used for the temperature and pressure profiles in the martian atmosphere.

The dominant uncertainty in the interpretation of our measurement in terms of a martian CO mixing ratio profile is due to the uncertainty in the value of the

Table 1. Carbon monoxide volume mixing ratio as a function of the Mars background temperature that best fits the microwave measurement at 115 Ghz.

Mars background temperature (K)	Best-fit CO constant mixing ratio
190	7.5×10^{-3}
200	1.9×10^{-3}
207.5	1.0×10^{-3}
215	0.5×10^{-3}

background continuum temperature of Mars. This value is expected to be 200 ± 20 K (*8*). Our absolute measurements of the Mars continuum temperature are not sufficiently accurate to improve upon this value. To first order, the CO absorption signal observed in the Mars spectrum is proportional to the difference between the average atmospheric temperature in the region where the absorption originates and the background continuum temperature. This difference is of the order of ~30 K. The uncertainty of ~±20 K in the background continuum temperature then corresponds to an uncertainty of ~±70 percent in the Mars CO abundance. The martian atmospheric temperature profile might be expected to vary by approximately ± 10 K from the model we used. This amount of variation introduces an additional uncertainty of ~±30 percent in the CO abundance inferred from our data. Therefore, with the information we have available on the background emission and atmospheric temperature of Mars, the uncertainty in our inferred CO abundance is approximately a factor of 2. Since the martian atmosphere is expected to be well mixed (*9*), we have performed calculations using a constant CO mixing ratio profile to determine which CO mixing ratio value gives the calculated spectral line that best fits our measurements as a function of background continuum temperature. The results are given in Table 1, and the calculation for a continuum temperature of 200 K is shown in Fig. 1. There is a suggestion that the measurement gives slightly less absorption at line center than that calculated from a constant CO mixing ratio profile. If this is the case, then the measurement implies a CO mixing ratio profile that decreases slightly at altitudes above ~ 40 km. More precise microwave measurements of the Mars spectrum and continuum emission at 115 Ghz will resolve these uncertainties.

Note added in proof: We have confirmed, by observations in February and April 1977, the variation of the CO signal from Venus with its phase mentioned here. These data indicate more high-altitude CO during nighttime. A similar diurnal variation was also measured for the CO line in the terrestrial mesosphere.

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References and Notes

1. R. K. Kakar, J. W. Waters, W. J. Wilson, *Science* **191**, 379 (1976).
J. W. Waters, W. J. Wilson, F. I. Shimabukuro, *ibid.*, p. 1174.
3. L. D. Kaplan, J. Connes, P. Connes, *Astrophys. J.* **157**, L187 (1969).
4. J. Connes, P. Connes, J. P. Maillard, *Atlas of Near Infrared Spectra of Venus, Mars, Jupiter, and Saturn* (Centre National de la Recherche Scientifique, Paris, 1969).
5. L. D. Gray Young, *J. Quant. Spectrosc. Radiat. Transfer* **11**, 385 (1971).
6. R. B. Noll, M. B. McElroy, Y. S. Lou, *NASA Spec. Publ. SP-8010* (1974).
7. P. Varanasi, *J. Quant. Spectrosc. Radiat. Transfer* **15**, 191 (1975).
8. D. O. Muhleman, private communication. This value is based on a theoretical model of microwave emission by the surface of Mars and is expected to be more accurate than measurements that have been made near 3 mm. The uncertainty at millimeter wavelengths has been discussed by J. N. Cuzzi and D. O. Muhleman [*Icarus* **17**, 548 (1972)], C. Sagan and J. Veverka [*ibid.* **14**, 222 (1971)], E. Epstein (*ibid.*, p. 214), and M. A. Janssen and W. J. Welch [*ibid.* **18**, 502 (1973)].
9. M. B. McElroy and J. C. McConnell, *J. Atmos. Sci.* **28**, 879 (1971); S. C. Liu and T. M. Donahue, *Icarus* **28**, 231 (1976).
10. This report presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under NASA contract NAS 7-100. The work at the Aerospace Corporation was jointly supported by an internal research program and by NSF grant MP573-04554. The National Radio Astronomy Observatory is operated by Associated Universities Inc. under contract with the National Science Foundation.
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15 November 1976

Petrolacosaurus, the Oldest Known Diapsid Reptile

Abstract. Petrolacosaurus, *an Upper Pennsylvanian reptile, presents a combination of features that place it within a distinct family of the Eosuchia while also evidencing strong relationships to the ancestral reptiles. It is therefore the earliest and most primitive representative of the largest assemblage of fossil and living reptiles, collectively called diapsids.*

The first fossil remains of one of the oldest reptiles, *Petrolacosaurus kansensis*, were found 45 years ago by a field party from the University of Kansas Natural History Museum. This small reptile from the Upper Pennsylvanian deposits of Garnett, Kansas, has since attracted a great deal of attention. Because of the incompleteness of the specimens and the combination of unusual osteological characters and great age, the taxonomic position and phylogenetic significance of *Petrolacosaurus* have been subjects of considerable dispute (*1*).

The study of recently uncovered specimens, reported here, indicates that *Petrolacosaurus* is the oldest known diapsid reptile. Furthermore, it reveals that this reptile possesses an almost ideal combination of primitive and advanced features to bridge the considerable morphological and evolutionary gap between the stem reptiles and the diapsids (*2*). *Petrolacosaurus* thus appears to be at the base of the largest reptilian radiation, which not only includes three of the four orders of modern reptiles and such extinct groups as eosuchians, thecodonts, rhynchosaurs, pterosaurs, and dinosaurs but also eventually gave rise to birds (Fig. 1). Although diapsids have a long evolutionary history extending into the Late Permian, the early history of this assemblage is not well documented in the fossil record. Consequently, the origins and phyletic relationships of the member groups have been open to question (*3*).

Among stem reptiles the family Romeriidae occupies a central position. Of all the known Paleozoic reptiles, only romeriids are sufficiently generalized to be the ultimate ancestors of any of the subsequent lineages (*4*). The retention in *Petrolacosaurus* of a large number of ro-

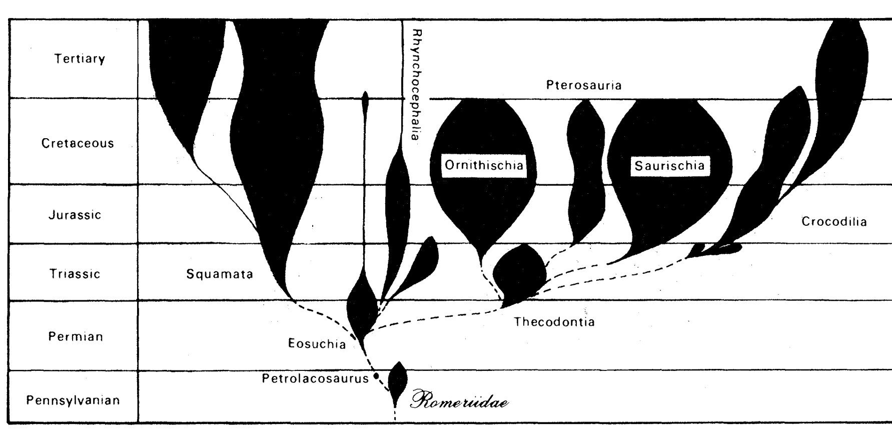

Fig. 1. Phylogeny of diapsid reptiles. The romeriid captorhinomorphs are included at the base of the phylogeny to show the ancestry of *Petrolacosaurus*.