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Planetary Atmospheres

Microwave Spectroscopic Studies of Planetary Atmospheres

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Ground-based spectroscopic observations of isotopes of CO in the atmospheres of Mars, Venus, and Titan have been collected over the 1982-1990 period. These observations have been analyzed to obtain information on the photochemistry, dynamics, and thermal profiles of these planetary atmospheres. In the cases of the mesosphere (80-100 km altitude) of Venus and the lower atmosphere (0-70 km altitude) of Mars, the primary conclusion of this research is that significant interannual variations in the global thermal and compositional structures of these atmospheres occur over 10 year periods. The Titan studies have focussed on pinning down the true atmospheric CO abundance. A more detailed summary of the results for each of these planetary atmospheres is provided below.

Mars - Three publications regarding microwave studies of the Mars atmosphere have been completed during the course of this 3 year grant (see accompanying list of publications). We have developed a technique of combining observations of the optically thick ^{12}CO microwave spectrum with the optically thin microwave ^{13}CO spectrum to retrieve both the CO mixing ratio and the temperature profile (0-70 km altitude) of the Mars atmosphere. Since we do not resolve the disk of Mars, these measurements refer to low-to-mid latitude average properties of the Mars atmosphere. A comparison of such measurements taken in 1975, 1980, 1982, 1988, 1989, and 1990 leads to two important conclusions. To within the accuracy of the CO mixing determination (~15%), there exists no evidence for the large CO abundance variations proposed by Hunten (1974). We also show that the measurements of 100 % variations in Mars CO by Lellouch et al. (1989) were based on incorrect analysis of their data. Secondly, we show that the Mars atmosphere is much colder for the period corresponding to our microwave observations than was observed during the dusty periods corresponding to Viking and Mariner 9 measurements of the thermal state of the Mars atmosphere. The thermal profiles we derive from the microwave spectra are much more consistent with the radiative-convective profiles calculated for the clear, dust-free Mars atmosphere (Gierasch and Goody, 1968). We conclude that the 1980-1990 period was a period of relatively low dust loading in the Mars atmosphere, which may be more representative of the Mars atmosphere than the conditions observed during Viking and Mariner 9. A complete discussion of these results and further implications is provided in Clancy et al. (1990), a much briefer presentation (Clancy and Muhleman, 1990) is included with this report.

Venus - Studies of the Venus atmosphere are based on the same technique described above for Mars. However the Venus CO spectra return information on temperatures and CO abundances in the mesosphere of Venus, which is a transition region between the massive zonally rotating lower atmosphere and the upper atmosphere, or cryosphere, in which subsolar-to-antisolar circulation drives extreme thermal and compositional gradients. We find that both the temperatures and global distribution of CO in the Venus mesosphere exhibited dramatic variations over the 1982-1990 period of our observations. These variations can be characterized by a global scale warming of low-to-mid latitude temperatures in the mesosphere between 1984 and 1986, accompanied by factors-of-ten changes in the diurnal gradient of CO mixing ratios. The accompanying preprint (Clancy and Muhleman, 1991) presents the analysis and conclusions of this study in great detail.

Titan - New observations of the microwave spectra of CO and HCN in the atmosphere of Titan were obtained in 1989 and 1990. These spectra have been analyzed to provide preliminary results. We obtain a CO abundance which agrees with our previous broadband result (Muhleman et al., 1984). This result is in disagreement with the microwave observations of Marten et al. (1988), but it is in agreement with the infrared observations of Titan CO by Lutz et al. (1983). The HCN profile we measure agrees with the upper stratospheric determination by Tanguy et al. (1990), but our broadband, high frequency (354 GHz) spectrum appears to require that HCN freezes out at a higher altitude in the lower stratosphere that previously thought. These results will be developed in more detail in a forthcoming publication.

Publications:

Clancy, R.T. and D.O. Muhleman, Corrections regarding the Lellouch et al. (1989) analysis of Mars atmospheric ^{12}CO and ^{13}CO spectra, *Icarus*, **85**, 120-129, 1990.

Clancy, R.T., D.O. Muhleman, and G.L. Berge, Global change in the 0-70 km thermal structure of the Mars atmosphere derived from 1975 to 1989 microwave CO spectra, *J. Geophys. Res.*, **95**, 14,543-14,554, 1990.

Clancy, R.T. and D.O. Muhleman, Measurements of a cold-clear state for the Martian atmosphere, *Ad. Space. Res.*, submitted, 1990.

Clancy, R.T. and D.O. Muhleman, Long term (1979-1990) changes in the thermal, dynamical, and compositional structure of the Venus mesosphere as inferred from microwave spectral line observations of ^{12}CO, ^{13}CO and $C^{18}O$, *Icarus*, in press, 1991.

Measurements of a Cold-Clear State

for the Martian Atmosphere

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ABSTRACT

An analysis of ground-based microwave spectra of CO in the atmosphere of Mars yields the 0-70 km atmospheric temperature profile for periods of observations in 1975, 1980, 1982, 1988, 1989, and 1990. The derived atmospheric temperatures are ~20K cooler than observed by Viking spacecraft observations in 1976-1977. Seasonal (L_s) variations of 20K are apparent (maximum near L_s=270°) for atmospheric temperatures up to an altitude of ~50 km. It is inferred that the atmosphere of Mars is often much clearer of dust and colder than indicated by the Viking and Mariner 9 periods of observation during the 1970's.

INTRODUCTION

Ground-based microwave (1.2-2.6 mm) observations of ^{12}CO and ^{13}CO in the atmospheres of Mars and Venus provide a means to monitor both the global abundance of CO and atmospheric temperatures. Such microwave spectra possess several advantages in terms of their analysis. They are usually self-calibrating in that a well-defined continuum level of microwave emission, due either to surface or broadband atmospheric radiation, accompanies the spectral line absorption/emission within the atmosphere. The spectral line radiative transfer is also relatively straightforward. Atmospheric scattering processes are negligible at microwave frequencies, LTE holds to very low pressures (<nanobar), the source function is very nearly linear with the local temperature, and the lines are typically well separated. Another particularly useful feature of microwave spectral lines in planetary atmospheres is that collisional broadening exceeds thermal broadening for atmospheric pressures > 0.1 mbar. As a consequence, it is possible to retrieve mixing profiles of molecular species from remote, non-limbing sounding geometries.

MICROWAVE CO SPECTRA

Our recent microwave studies of CO in the Mars atmosphere are documented in Clancy, Muhleman, and Berge (1990)/1/. Microwave opacities of the 1.3 mm transition of ^{12}CO are sufficiently large to provide temperature weighting functions from the surface of Mars to an altitude of 70 km (figure 1). The photochemical lifetime of CO in the Mars atmosphere is long enough (>3 years; e.g., Hunten, 1974)/2/ to ensure that it is vertically well mixed. We measured the optically thin 1.2 mm transition of ^{13}CO in November of 1988 to determine the CO volume mixing ratio ($6.0 \pm 1.5 \times 10^{-4}$), which was found to be consistent within measurement uncertainties with the 1967 infrared determination ($8 \pm 2 \times 10^{-4}$) by Kaplan et al. (1969)/3/. Figure 2 indicates the observed spectrum of ^{13}CO with the best-fit synthetic spectrum, corresponding to a CO mixing ratio of 6×10^{-4} and a Mars atmospheric temperature profile (figure 4) consistent with the observed ^{12}CO spectrum (figure 3). Observations of the ^{12}CO

spectra provide an accurate measure of atmospheric temperatures because they are more sensitive to ±10K perturbations in atmospheric temperatures (figure 3a) than they are to ±50% uncertainties in the CO mixing ratio (figure 3b). Lellouch et al. (1989)/4/ performed a similar analysis of microwave ^{12}CO and ^{13}CO spectra observed in 1986-1987, however their analysis was shown to be in error (Clancy and Muhleman, 1990)/5/. Lellouch, Paubert, and Encrenaz (1990)/7/ have since analyzed very high signal-to-noise spectra of ^{12}CO and ^{13}CO observed in 1988. Their analysis of these observations indicates a CO mixing ratio of $8 \pm 2 \times 10^{-4}$, and that the fall-off in the CO mixing ratio in the lower 10-20 km of the Mars atmosphere as inferred from Phobos ISM observations (Rosenquist et al., 1990)/6/ does not occur on a global scale.

MARS ATMOSPHERIC TEMPERATURES

Clancy, Muhleman, and Berge (1990) focussed on the derivation of Mars atmospheric temperature profiles (0-70 km) from microwave spectra of ^{12}CO. The predominant source of uncertainty in such derived temperatures results from ±5K uncertainties in the solid-body continuum radiation of Mars, which is used to self-calibrate the CO line emission/absorption. CO spectra of the whole-disk of Mars, observed in 1975, 1980, 1982, 1988, and 1989, were analyzed to retrieve low-to-mid latitude average atmospheric temperatures for Mars (figure 4). A basic conclusion from this work is that the Mars atmosphere is colder, and presumably clearer, during all of the periods observed relative to the warm, dusty state of the Mars atmosphere observed by Viking in 1976-1977 and by Mariner 9 in 1971-1972. Although the 1988-1989 temperatures of figure 4 compare well with the Viking profiles, they were measured at a solar longitude (L_s) corresponding to 40% increased solar flux relative to the L_s of the Viking profiles. The 1980 and 1982 microwave temperature profiles, which are 20-40 K cooler than the Viking profile at all altitudes, were measured at roughly the same L_s as the Viking profiles. In figure 5b, we show the L_s dependence of 0.5 mbar level (~25 km altitude) atmospheric temperatures inferred from Viking descent observations (Seiff, 1978)/8/, Viking IRTM (Martin, 1981)/9/, and Mariner 9 IRIS radiances (Conrath, 1975)/10/; compared to that exhibited by the microwave observations, including two new 1990 measurements. Both data sets indicate ~20 K variations with L_s, but the microwave temperatures are 20 K cooler overall. Figures 5a and 5c demonstrate that the seasonal (L_s) variations and the generally cooler temperatures extend over the 3 mbar (~7-8 km) to .05 mbar (40-48 km) region. Only the Viking descent and ground-based microwave measurements are included in figures 5a and 5c, since observations comparable to the IRTM 15 μm brightness temperatures are not available to document seasonal variations at these levels.

CONCLUSION

The cold atmospheric temperatures we infer for Mars have several implications. Colder temperatures are an indicator of much reduced dust loading (Pollack et al., 1979)/11/, and can affect the latitudinal and vertical distributions of atmospheric H_2O and clouds. Perturbations to atmospheric H_2O and H_2O_2 may also affect the vertical and latitudinal distributions of atmospheric O_3 (Clancy, Muhleman, and Berge, 1990). Furthermore, the altitude-density profile for the Mars atmosphere changes significantly between the warm-dusty and cold-clear states of the atmosphere. Atmospheric densities for the same L_s change by as much as a factor-of-three at the 50 km altitude level, between these states. We assert that the Mars atmosphere observed by the Phobos mission was much colder and clearer than observed during the Viking mission; and that such a cold-clear state may be more representative of average conditions within the Mars atmosphere.

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FIGURE CAPTIONS

Figure 1. Nadir temperature weighting functions for the 230 GHz ^{12}CO line. The various functions correspond to different frequency offsets, $\nu-\nu_o$, from the line center. Higher opacities closer to the line center lead to weighting functions which peak at higher altitudes.

Figure 2. Measured (jagged line) and best-fit (solid line) 230 GHz ^{13}CO spectra, observed in November of 1988. The best-fit spectrum corresponds to a CO mixing ratio of 6×10^{-4} and the November, 1988 temperature profile presented in figure 4. Dashed lines correspond to $\pm 1\sigma$ errors of $\pm 1.5 \times 10^{-4}$ for the CO mixing ratio.

Figure 3. Measured (jagged line) and best-fit (solid line) spectra of the $J=1 \rightarrow 2$ ^{12}CO transition, observed in November of 1988. Dashed line synthetic spectra correspond to independent perturbations of (a)±10K in the solution atmospheric temperature profile; and (b) ±50% to the CO mixing ratio.

Figure 4. Mid-to-low latitude average temperature profiles for the Mars atmosphere, derived from ^{12}CO spectra observed in a) May and November of 1988 and January of 1989; and b) November of 1975, March-April of 1980, and January of 1982. A CO mixing ratio of 6×10^{-4}, derived from November, 1988 ^{13}CO spectra, was used to calculate all six of the microwave temperature profiles. A Viking reference profile (Seiff, 1978)/8/ and a radiative convective equilibrium profile (Gierasch and Goody, 1968)/12/ are included for comparison.

Figure 5. Atmospheric temperature, at pressure levels of a) 3.0 mbar; b) 0.5 mbar; and c) 0.05 mbar, versus Mars season (L_s). The microwave-derived temperatures are represented by circles, the average of the Viking 1 and 2 lander descent measurements (Seiff, 1978) are presented by squares. For the 0.5 mbar level, the Viking IRTM data (diamonds, Martin, 1981)/9/ are the 15 micron brightness temperatures, averaged over 40S-40N and 10AM-6PM. The Mariner 9 IRIS data are for 9-10AM measurements at 20S-30S latitudes (asterisks; Conrath, 1975)/10/.

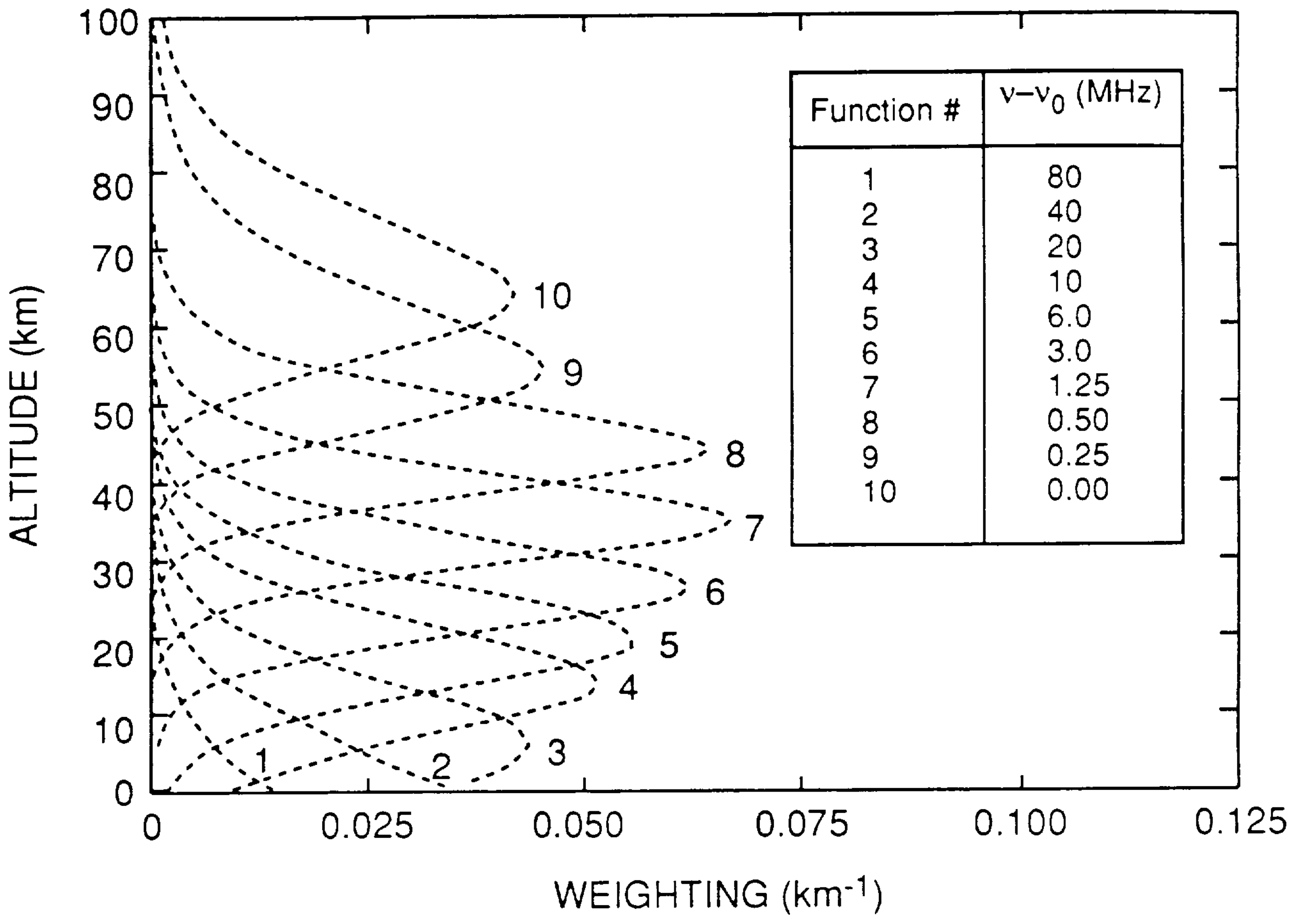
ALTITUDE (km)
0
10
20
30
40
50
60
70
80
90
100
WEIGHTING (km-1)
0
0.025
0.050
0.075
0.100
0.125
1
2
3
4
5
6
7
8
9
10
Function #
ν−ν0 (MHz)
1 80
2 40
3 20
4 10
5 6.0
6 3.0
7 1.25
8 0.50
9 0.25
10 0.00

Figure 1

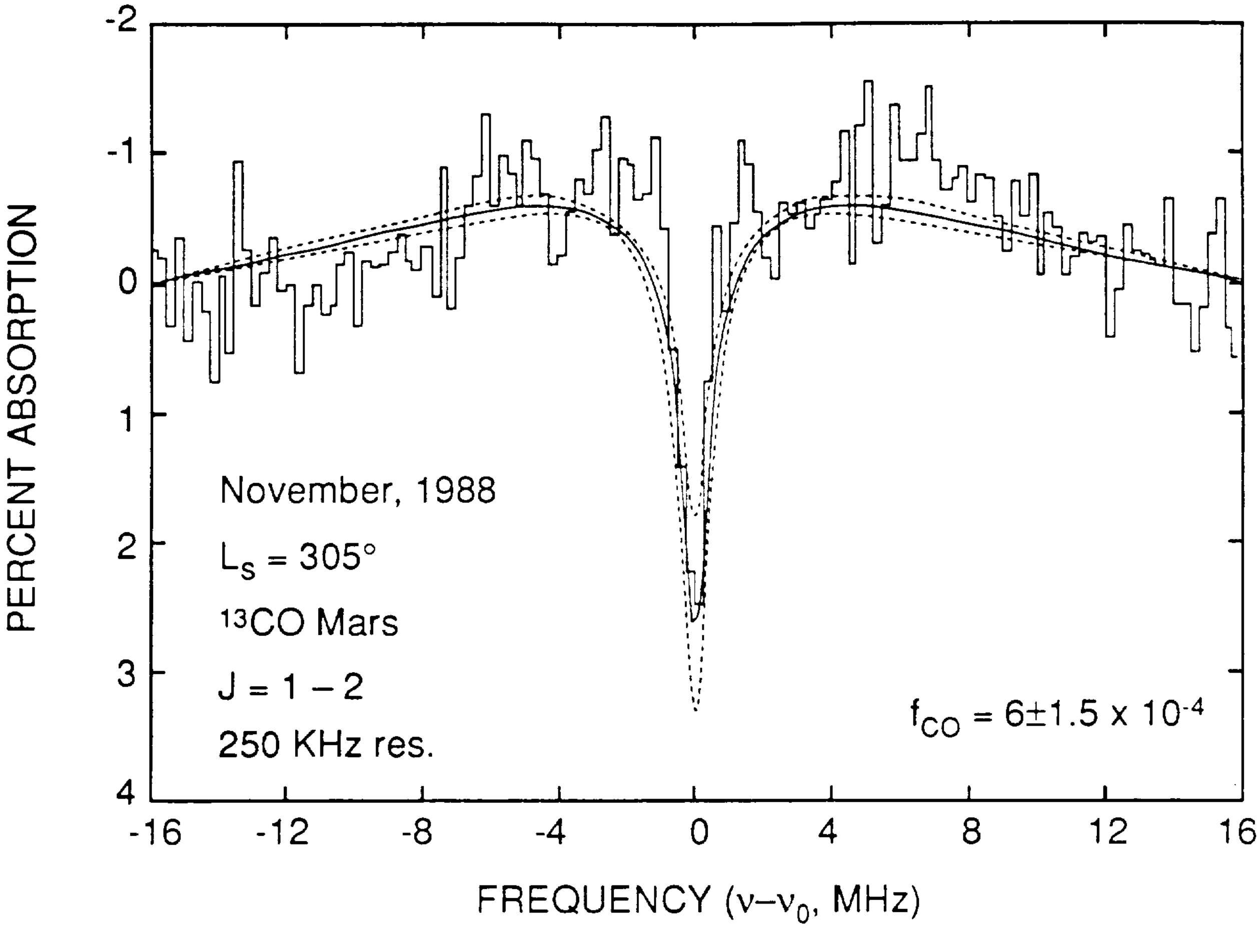

Figure 2

6-90 Clancy
CIRA Mars F2

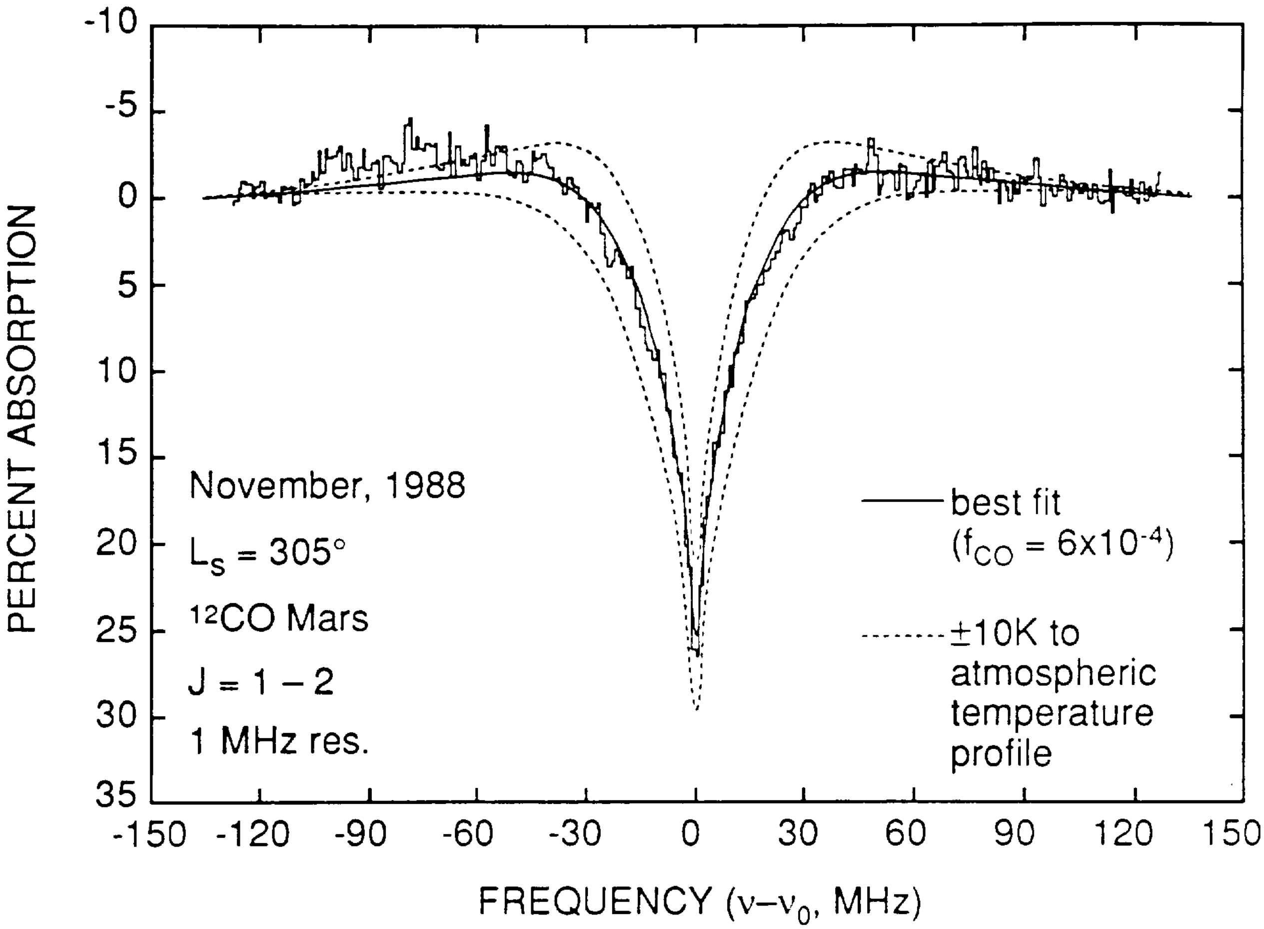
PERCENT ABSORPTION
-10
-5
0
5
10
15
20
25
30
35
-150 -120 -90 -60 -30 0 30 60 90 120 150
FREQUENCY (ν−ν0, MHz)
November, 1988
Ls = 305°
12CO Mars
J = 1 – 2
1 MHz res.
best fit
(fCO = 6x10-4)
±10K to
atmospheric
temperature
profile

Figure 3a

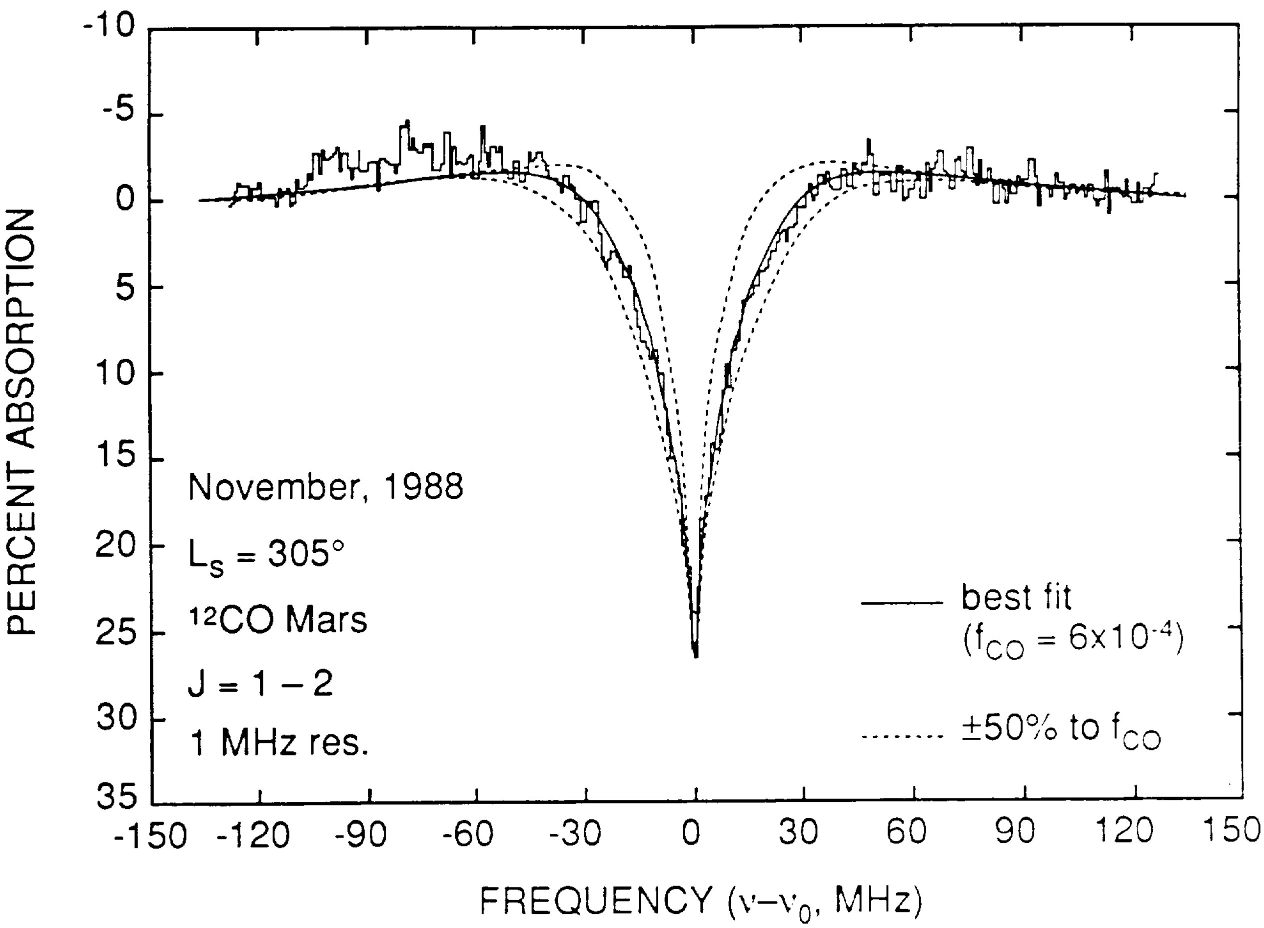

Figure 3b

6-90 Clancy
CIRA Mars F3b

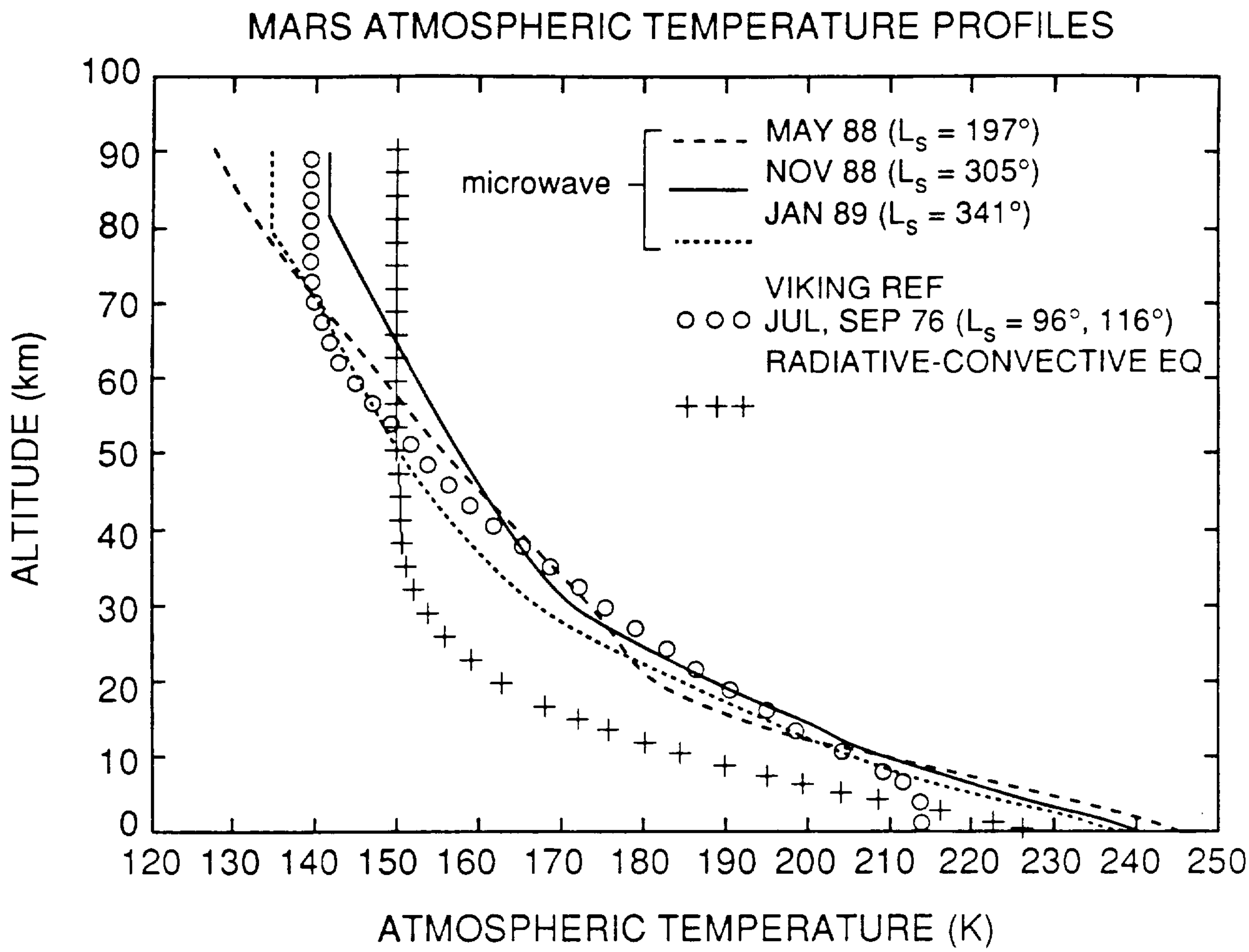
MARS ATMOSPHERIC TEMPERATURE PROFILES
microwave
MAY 88 (Ls = 197°)
NOV 88 (Ls = 305°)
JAN 89 (Ls = 341°)
VIKING REF
JUL, SEP 76 (Ls = 96°, 116°)
RADIATIVE-CONVECTIVE EQ
ALTITUDE (km)
ATMOSPHERIC TEMPERATURE (K)
0
10
20
30
40
50
60
70
80
90
100
120 130 140 150 160 170 180 190 200 210 220 230 240 250

Figure 4a

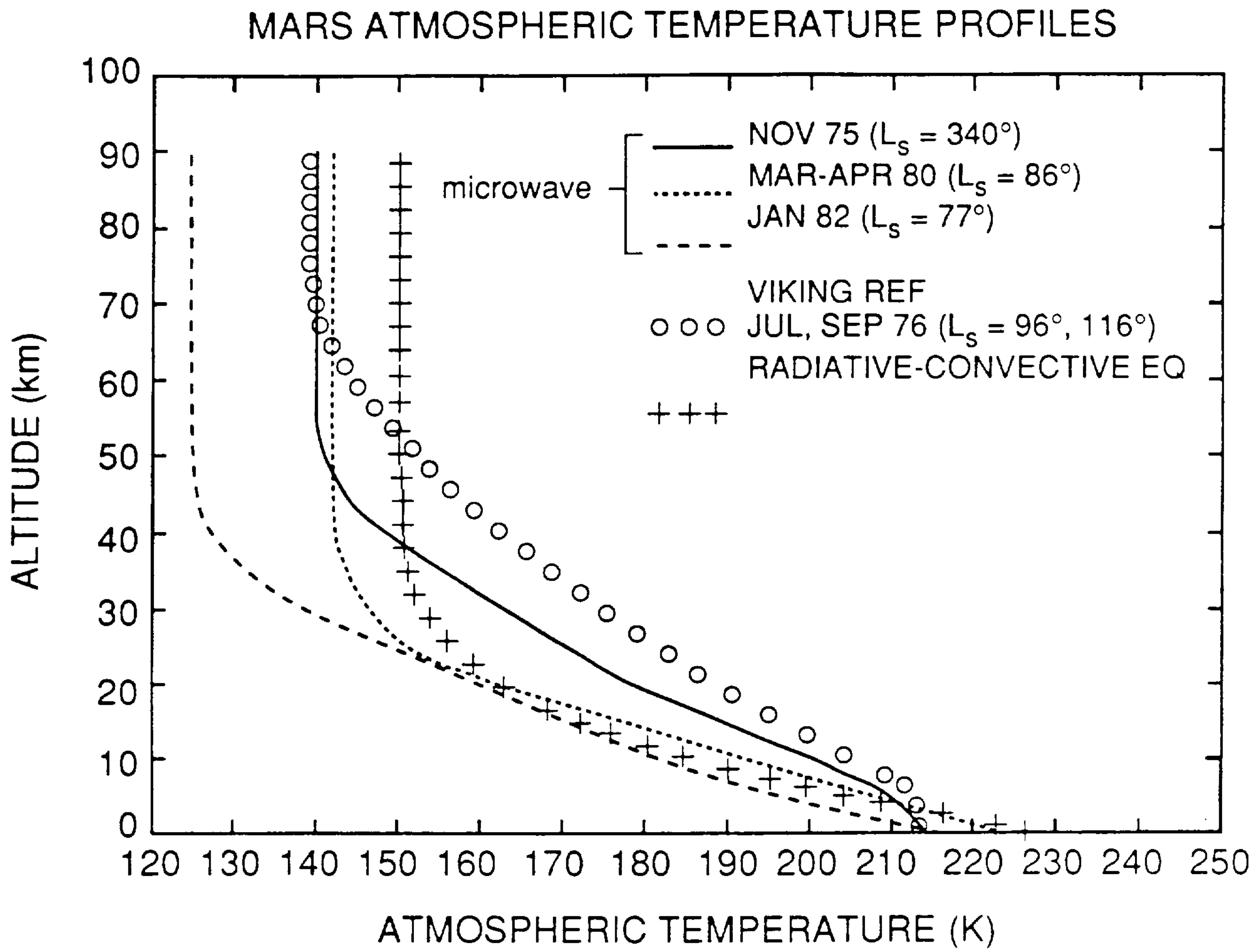

Figure 4b

6-90 Clancy
CIRA Mars F4b

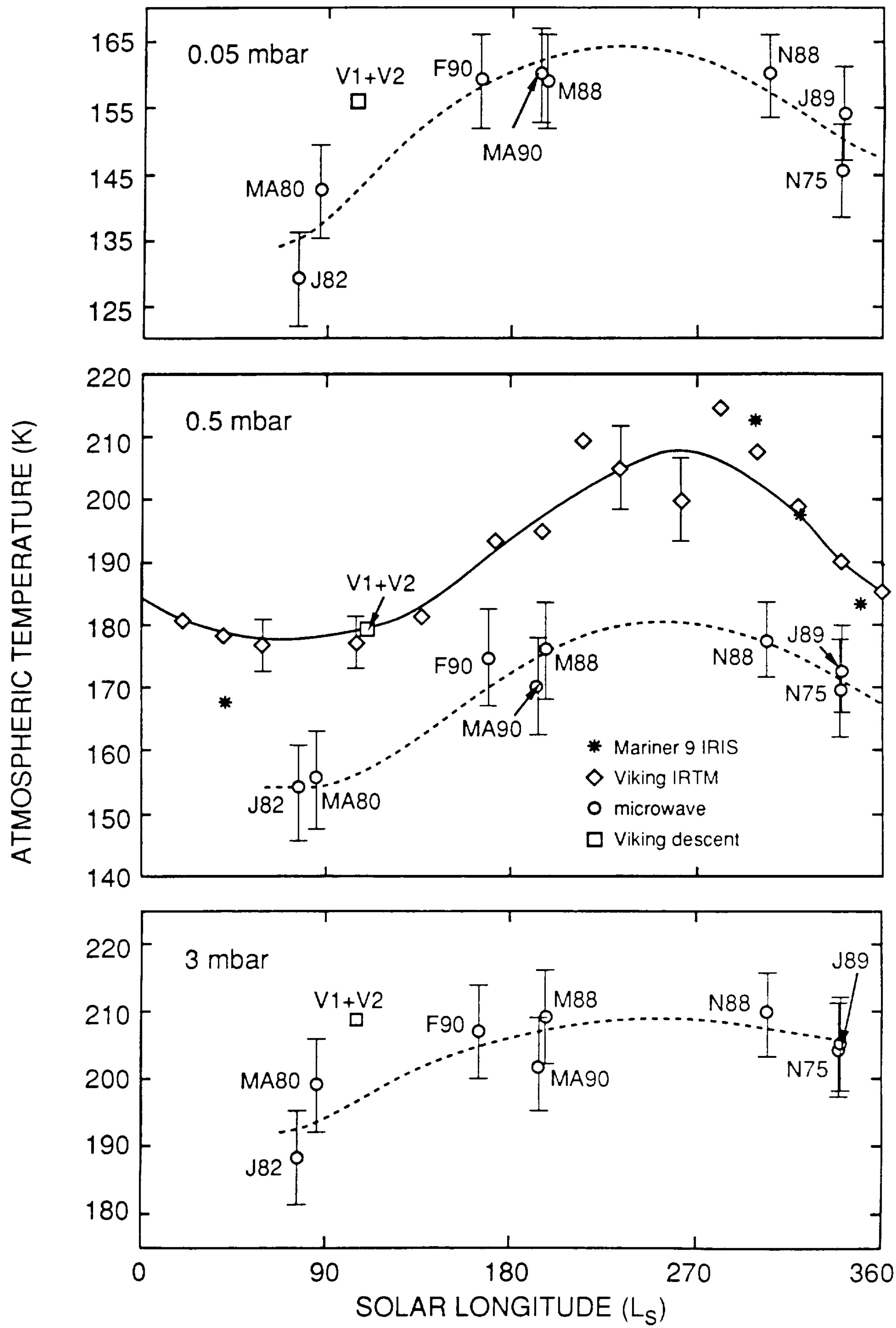

Figure 5

6/90 Clancy
CIRA Mars F5