HETERODYNE DETECTION OF CO_2 EMISSION LINES AND WIND VELOCITIES IN THE ATMOSPHERE OF VENUS*

A.L. Betz, M.A. Johnson, R.A. McLaren[+], E.C. Sutton[#]

Department of Physics, University of California, Berkeley
Berkeley, California 94720

Received ______________________

ABSTRACT

Strong 10 μm line emission from $^{12}C^{16}O_2$ in the upper atmosphere of Venus has been detected by heterodyne techniques. Observations of the absolute Doppler shift of the emission features indicate mean zonal wind velocities less than 10 m/sec in the upper atmosphere near the equator. No evidence was found of the 100 m/sec wind velocity implied by the apparent 4-day rotation period of ultraviolet cloud features.

[#] National Science Foundation Fellow.

[+] NATO Postdoctoral Fellow 1974-75
Present Address: Department of Astronomy University of Toronto, Toronto, Canada M5S 1A7

*This work was supported in part by NASA grants NGR 05-003-452 and NGL 05-003-272 and National Science Foundation grant AST 75-20353.

I. Introduction

In the infrared spectral region, heterodyne spectroscopy has been shown to be a useful technique for achieving resolving powers exceeding 10^6 (Peterson et al, 1974). The ability to convert optical frequencies down into the radio frequency domain permits the spectral analysis to be performed electronically, and frees the spectrometer from mechanical constraints as a limit on achievable resolution. In this Letter, we wish to report the heterodyne detection of intense emission lines from the 950 cm^{-1} vibrational-rotational transitions of $^{12}C^{16}O_2$ in the atmosphere of Venus. The observed intensities are much larger than those expected from a gas in LTE and indicate a non-thermal excitation mechanism. The linewidths are typically only 1.4×10^{-3} cm^{-1} and yet the features are well resolved, allowing the line center frequencies to be measured to an accuracy exceeding 3×10^{-5} cm^{-1} (1 MHz).

The observed frequencies have been combined with a knowledge of the transition rest frequencies and the center of mass velocity of the planet to determine the line of sight wind velocities of selected areas on the planet. These Doppler velocities are of interest in measuring the magnitude of any systematic rotational motion of the atmosphere. Apparently, some uncertainty still exists whether the 4-day (100 m/sec) rotational period of ultraviolet cloud features on Venus represents a true motion of the atmosphere, or perhaps only the phase velocity of a wave phenomenon (Young, 1975). Although certain spectroscopic evidence appears to confirm the existence of 100 m/sec retrograde wind motions in the upper atmosphere (Traub and Carlton, 1975), a conclusive theoretical explanation of the phenomenon has not as yet emerged. Since the technique employed in this experiment measures the line of sight velocity in a absolute sense, it can distinguish between a horizontal (tangetial) wind velocity on the limb and any vertical velocity component which may exist at the center of the planet. A wave phenomenon in the atmosphere might be expected to produce periodic vertical motions.

(II) Instrument Description

The general principles of heterodyne detection at infrared frequencies have been reviewed by Blaney (1975), and only the details of this spectrometer are described here. The instrument is installed at the McMath Solar Telescope of Kitt Peak National Observatory* and utilizes one of the two 81 cm auxiliary solar telescopes. As illustrated in Figure 1, the source radiation collected by the telescope falls upon a dichroic mirror which transmits the visible image to an eyepiece and reflects the infrared beam to a focus at a dual beam focal plane sky chopper. The infrared signal is then directed through a 95% transmitting NaCl beamsplitter, where it is combined with a few milliwatts of the output power of a stabilized $^{12}C^{16}O_2$ laser. The laser oscillates on any

---

*Operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

one of a number of vibrational-rotational transitions of the $00^\circ 1 - [10^\circ 0, 02^\circ 0]_I 950\ cm^{-1}$ band of $^{12}C^{16}O_2$. The combined beams are focussed onto a cooled (77 K) mercury-cadmium telluride (HgCdTe) photodiode mixer, which generates a difference frequency current over the radio frequency bandwidth of 0 to 1500 MHz. After amplification, a 200 MHz segment of this intermediate frequency spectrum is converted into the band of 50 to 250 MHz by a single-sideband mixer and directed into a multichannel RF filter bank. The local oscillator frequency for this SSB mixer is calculated to place the Doppler-shifted line center at the mid-frequency point of this filter bank, and is tracked in frequency to correct for changes in Doppler shift caused both by the earth's rotation and by changes in the interplanetary velocity during the course of the measurement. The filter bank then analyzes the 50 to 250 MHz spectrum into 40 independent channels of 5 MHz ($1.7 \times 10^{-4}\ cm^{-1}$) each. The 40 detected power outputs are synchronously demodulated at the sky chopping frequency (150 Hz) and multiplexed into a computer for on-line integration and analysis. After each integration cycle, a blackbody radiation source is placed in the infrared signal beam to calibrate the system. The sensitivity is measured to be 2.7×10^{-16} watts for a signal-to noise ratio of 1 after a 1 second integration in each 5 MHz channel. With an input infrared frequency of about 3×10^{13} Hz, this channel bandwidth implies a spectrometer resolving power of 6×10^6.

(III) Observations

The observations were conducted in 1975, November and December, when Venus was at an average phase of 0.65 and approximately 20 arcsec in diameter, about 5 times the 4 arcsec beam size. An observation cycle consisted of 4 minutes integration in each of the two signal beams, followed by a 2 minute blackbody calibration and zero check, yielding a net 8 minutes integration on the source.

A typical narrow emission line observed in the center of a broader CO_2 absorption feature is shown in Figure 2. This line is the same moleculer transition, $00^\circ1 - [10^\circ0, 02^\circ0]_I$, as that of the CO_2 laser oscillator. As shown in the figure, the strength of the emission appears to be proportional to the solar intensity at the observed area; no emission is seen from the dark half of the planet. The line shape is Gaussian, with a halfwidth consistent with a kinetic gas temperature of about 200K near the subsolar region, and 185K near the terminator. However, the central intensity of the strongest line is 15 times greater than that expected from an optically thick region at a kinetic temperature of 200K. A more detailed analysis of the non-thermal emission mechanism is treated in an accompanying paper by Johnson et al. (1976), along with a discussion of similar emission features observed in the atmosphere of Mars.

From November through December, 1975, the Doppler shift of the receding planet varied from 1160 to 1080 MHz. The tracking oscillator frequency was calculated from the planetary ephemeris for Venus provided in the American Ephemeris and

Nautical Almanac so that an emission line with zero velocity with respect to the planetary center of mass should appear centered in the filter bank. Any deviation of the line frequency from the center of the filterbank could be caused by a combination of the following principal effects:

(1) an offset of the CO_2 laser frequency from the natural frequency of the transition,

(2) an offset of the RF tracking oscillator frequency from the correct value,

(3) a velocity component of the atmospheric emission region with respect to the planetary center of mass velocity, projected along the line of sight towards the earth.

The last effect is the desired quantity of the experiment, while the first two produce systematic errors in an absolute velocity measurement. Errors related to the first effect can in principle be accounted for. Although the laser is frequency stabilized to the center of its gain profile to a precision better than ± 0.2 MHz (Skolnick, 1970), corresponding to a velocity uncertainty of ± 2 m/sec, it does not oscillate at the true center frequency of the transition. For our laser operating on the P(16) transition at a total pressure of 14 Torr, the shift was measured to be 0.7 ± 0.1 MHz to lower frequency, based on a calibration with a low pressure CO_2 absorption cell. Errors of the second type are contributed by the uncertainties in the planetary ephemeris or a lack of precision in setting the tracking frequency, but are estimated to be less than ± 0.2 Mhz (± 2 m/sec) during these observations. The remaining significant source of error lies in the frequency calibration of the filter bank, but the accuracy here is better than ± 0.1 MHz (± 1m/sec). After correcting for the laser frequency shift, the systematic error is less than 6 m/sec in determining the average velocity of any 4 arcsec region on Venus.

(IV) Results and Conclusions

The Doppler velocities measured on 7 days are listed in Table 1 for three different positions along the equator of Venus. Each velocity value is determined from the deviation of the observed line center from the frequency expected for the center of mass velocity. The line center frequency is derived from the center of gravity of the line profile and is consistent with an independent calculation using a least squares fit to a Gaussian profile. The quoted uncertainties in velocity are one standard deviation estimates from the formal statistical error and do not include the effects of any systematic contribution. This statistical error is governed completely by the signal to noise ratio of the line detection, which depends upon the length of integration time, the weather conditions at the time of the observation, and the strength of the signal as a function of the solar illumination on Venus. The latter effect is the dominant one contributing to the larger velocity uncertainties at the center of the planet. Typically the line emission near the terminator is 3 to 5 times less than that of the subsolar limb.

Because the listed velocities correspond only to the component seen along the line of sight, the limb values are tangential or horizontal velocities, while those at the center are, of course, vertical components. A few observations for which the velocity uncertainties exceeded ± 20 m/sec have been omitted from the Table. Generally, these values are from observations attempted under poor weather conditions for which the infrared signal dropped to less than half of its normal value; however, the mean value of all these omitted measurements lie within the bounds of the stated velocities.

The principal conclusion of this investigation is that at no time was a Doppler velocity measured which could be interpreted as a 100 m/sec (4 day) retrograde rotation of the atmosphere. Both the absolute velocity data from the limb and the differential values between the limb and center of the planet are more consistent with a mean rotational velocity near zero. Some of the day-to-day variations, however, do appear significant enough to indicate localized inhomogeneities as large as 20 m/sec. The variations in velocity at the center of the planet also imply that the vertical motions there are of the same scale as the horizontal variation on the limb, although the vertical values are not as well determined due to the larger statistical uncertainties. In comparing these results with previous spectroscopic investigations, one should bear in mind that these emission lines are formed at an altitude near 120 km (Johnson et al. 1976). This is almost twice as high as the altitude of the broader CO_2 absorption lines (Traub and Carleton, 1975) and ultraviolet cloud features, for which large 100 m/sec retrograde velocities have been reported.

Finally it should be emphasized that these results are only a first attempt to utilize heterodyne techniques to determine wind velocities on Venus, and that a number of significant improvements are possible. By stabilizing the laser frequency to the Lamb dip in a low pressure CO_2 absorption cell, a long term absolute frequency accuracy of a few parts in 10^{10} can be achieved (Freed and Javan, 1970). This, when combined with a more accurate planetary ephemeris such as one derived from planetary radar measurements (Shapiro, 1976), should reduce the total systematic error to less than 1 m/sec for absolute Doppler velocity measurements. The uncertainity for the line of sight velocity would then be limited only by the detection statistics to less than $\pm$ 5 m/sec for a 16 minute integration.

The success of infrared heterodyne techniques depends strongly on the latest advances in HgCdTe photodiode technology, and we would especially like to thank D. Spears (Lincoln Laboratory) for developing the devices used in this experiment. The CO_2 laser was constructed from the design of C. Freed (Lincoln Laboratory); the CO_2 absorption cell was provided by R. Jacobs (Lawrence Livermore Laboratory), and the multichannel filterbank was on generous loan from the National Radio Astronomy Observatory, Greenbank, W. Va.
We are grateful to the staff of KPNO for their assistance in the use of Observatory facilities, and we also acknowledge informative conversations with I. I. Shapiro and C.H. Townes.

FIGURE CAPTIONS

Figure 1: Diagram of Experimental Apparatus

Figure 2: $^{12}C^{16}O_2$ emission lines observed at three locations, 4 arcsec in diameter, on the 20 arcsec disc of Venus. Integration times are 16 minutes for positions 1 and 2, and 32 minutes for position 3. The frequency scale is centered on the expected Doppler shift for the center of mass velocity of the planet. The intensities are calibrated as a Rayleigh-Jeans temperature, T_{RJ}, defined as received power density, $W \cdot Hz^{-1}$, divided by Boltzman's constant, k.

REFERENCES

Blaney, T.G. 1975, Space Science Reviews, 17, 5, 691.

Freed, C. and Javan, A. 1970, Appl. Phys. Lett. 17, 2, 53.

Johnson, M.A., Betz, A.L., McLaren, R.A., Sutton, E.C. and Townes, C.H. 1976, (to be published).

Peterson, D.W., Johnson, M.A., Betz, A.L. 1974, Nature 250, 128.

Shapiro, I.I. (1976) private communication.

Skolnick, M. 1970, IEEE, Journ. Quant. Elect., QE-6, 2, 139.

Traub, W.A., Carleton, N.P. 1975, J. Atmos. Sci., 32, 6, 1045.

Young, A. 1975, Icarus 24, 1-10.

TABLE 1

LINE OF SIGHT VELOCITIES (m/sec)*

DATE	LIMB (1)	MID-RADIUS (2)	CENTER (3)
22 Nov 75	-3 ± 8	--------	-7 ± 12
24 Nov 75	-9 ± 6	-13 ± 6	-8 ± 9
25 Nov 75	-2 ± 3	-31 ± 6	-8 ± 13
11 Dec 75	-8 ± 4	12 ± 6	2 ± 17
12 Dec 75	-15 ± 3	--------	14 ± 8
17 Dec 75	-5 ± 3	-7 ± 6	17 ± 10
24 Dec 75	7 ± 9	-12 ± 7	-7 ± 8

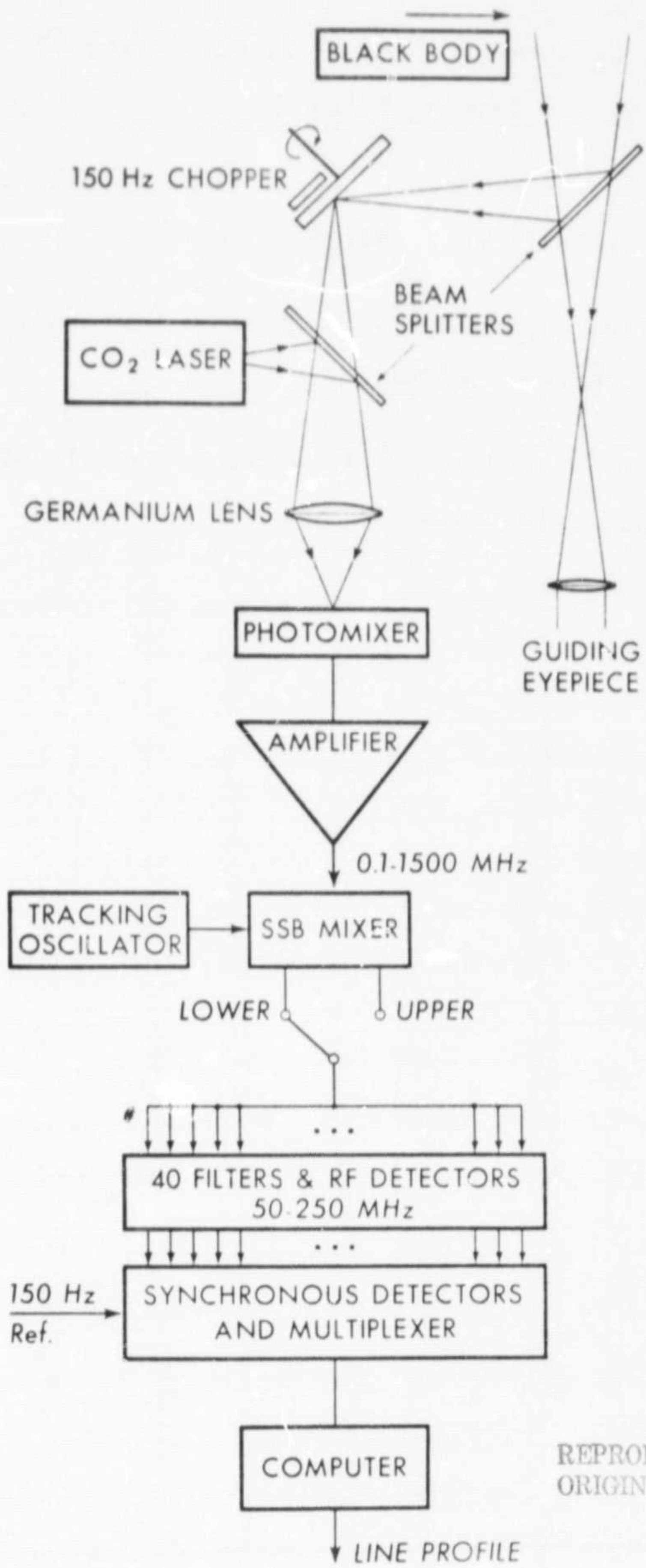
*Absolute line of sight wind velocities with respect to the center of mass of Venus for three positions along the equator. The integration times of individual observations vary from 32 to 88 minutes. Negative velocities imply motion towards the observer.

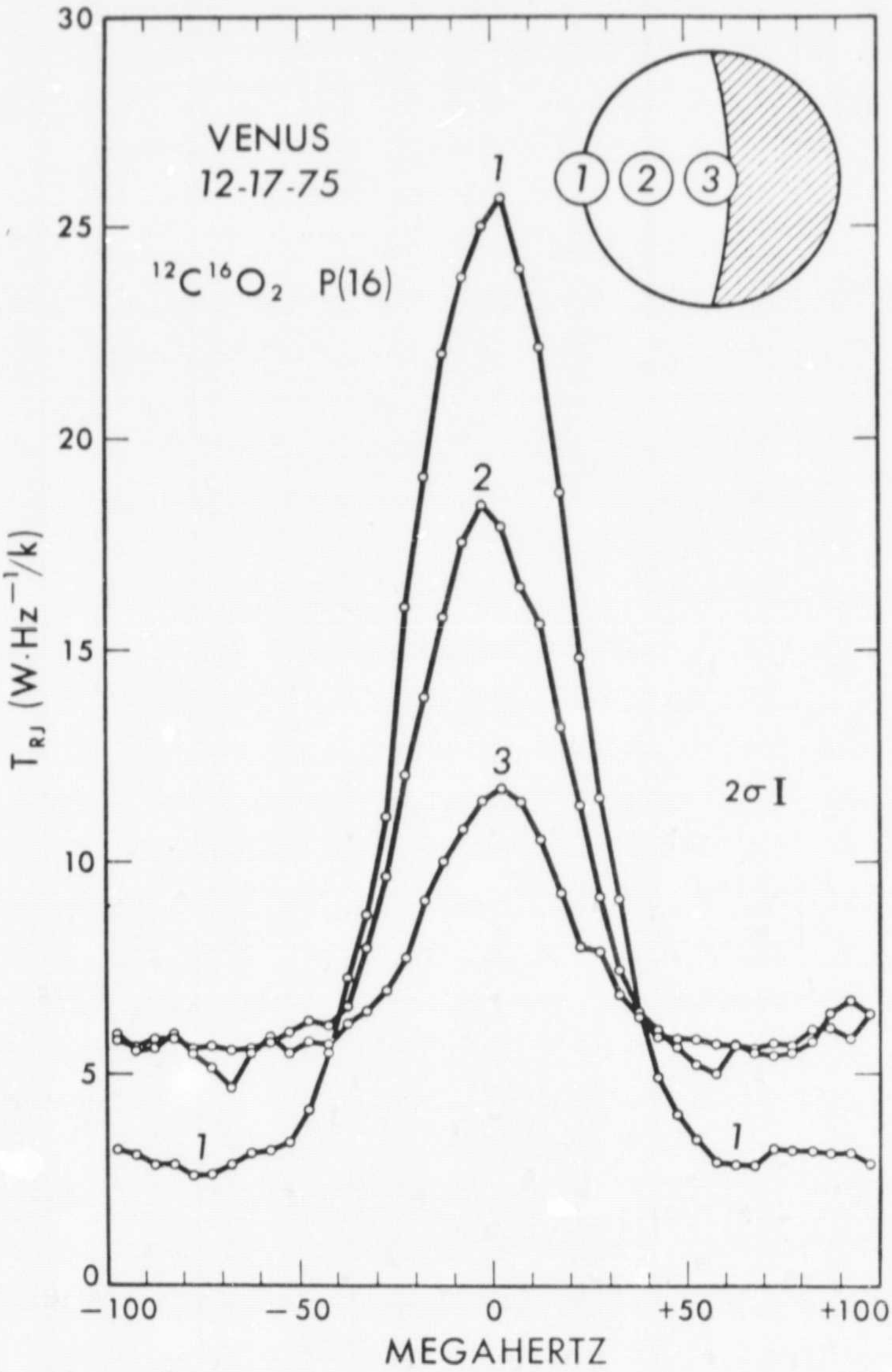
A.L. Betz, Department of Physics, University of California, Berkeley, California 94720

M.A. Johnson, Department of Physics, University of California, Berkeley, California 94720

R.A. McLaren, Department of Astronomy, University of Toronto, Toronto, Canada M5S 1A7

E.C. Sutton, Department of Physics, University of California, Berkeley, California 94720


BLACK BODY
150 Hz CHOPPER
BEAM
SPLITTERS
CO2 LASER
GERMANIUM LENS
PHOTOMIXER
GUIDING
EYEPIECE
AMPLIFIER
0.1-1500 MHz
TRACKING
OSCILLATOR
SSB MIXER
LOWER
UPPER
40 FILTERS & RF DETECTORS
50-250 MHz
150 Hz
Ref.
SYNCHRONOUS DETECTORS
AND MULTIPLEXER
COMPUTER
LINE PROFILE



VENUS
12-17-75
$^{12}C^{16}O_2$ P(16)
1
2
3
2σ
T_{RJ} (W·Hz^{-1}/k)
MEGAHERTZ
30
25
20
15
10
5
0
−100
−50
0
+50
+100

HETERODYNE DETECTION OF CO_2 EMISSION LINES
AND WIND VELOCITIES IN THE ATMOSPHERE OF VENUS*

A.L. Betz, M.A. Johnson, R.A. McLaren[+], E.C. Sutton[#]

Department of Physics, University of California, Berkeley
Berkeley, California 94720

Received____________________

ABSTRACT

Strong 10 μm line emission from $^{12}C^{16}O_2$ in the upper atmosphere of Venus has been detected by heterodyne techniques. Observations of the absolute Doppler shift of the emission features indicate mean zonal wind velocities less than 10 m/sec in the upper atmosphere near the equator. No evidence was found of the 100 m/sec wind velocity implied by the apparent 4-day rotation period of ultraviolet cloud features.

[#]National Science Foundation Fellow.

[+]NATO Postdoctoral Fellow 1974-75
Present Address: Department of Astronomy University of Toronto, Toronto, Canada M5S 1A7

*This work was supported in part by NASA grants NGR 05-003-452 and NGL 05-003-272 and National Science Foundation grant AST 75-20353.

I. Introduction

In the infrared spectral region, heterodyne spectroscopy has been shown to be a useful technique for achieving resolving powers exceeding 10^6 (Peterson et al, 1974). The ability to convert optical frequencies down into the radio frequency domain permits the spectral analysis to be performed electronically, and frees the spectrometer from mechanical constraints as a limit on achievable resolution. In this Letter, we wish to report the heterodyne detection of intense emission lines from the 950 cm^{-1} vibrational-rotational transitions of $^{12}C^{16}O_2$ in the atmosphere of Venus. The observed intensities are much larger than those expected from a gas in LTE and indicate a non-thermal excitation mechanism. The linewidths are typically only 1.4×10^{-3} cm^{-1} and yet the features are well resolved, allowing the line center frequencies to be measured to an accuracy exceeding 3×10^{-5} cm^{-1} (1 MHz).

The observed frequencies have been combined with a knowledge of the transition rest frequencies and the center of mass velocity of the planet to determine the line of sight wind velocities of selected areas on the planet. These Doppler velocities are of interest in measuring the magnitude of any systematic rotational motion of the atmosphere. Apparently, some uncertainty still exists whether the 4-day (100 m/sec) rotational period of ultraviolet cloud features on Venus represents a true motion of the atmosphere, or perhaps only the phase velocity of a wave phenomenon (Young, 1975). Although certain spectroscopic evidence appears to confirm the existence of 100 m/sec retrograde wind motions in the upper atmosphere (Traub and Carlton, 1975), a conclusive theoretical explanation of the phenomenon has not as yet emerged. Since the technique employed in this experiment measures the line of sight velocity in a absolute sense, it can distinguish between a horizontal (tangetial) wind velocity on the limb and any vertical velocity component which may exist at the center of the planet. A wave phenomenon in the atmosphere might be expected to produce periodic vertical motions.

(II) Instrument Description

The general principles of heterodyne detection at infrared frequencies have been reviewed by Blaney (1975), and only the details of this spectrometer are described here. The instrument is installed at the McMath Solar Telescope of Kitt Peak National Observatory* and utilizes one of the two

---

*Operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

---

81 cm auxiliary solar telescopes. As illustrated in Figure 1, the source radiation collected by the telescope falls upon a dichroic mirror which transmits the visible image to an eye-piece and reflects the infrared beam to a focus at a dual beam focal plane sky chopper. The infrared signal is then directed through a 95% transmitting NaCl beamsplitter, where it is combined with a few milliwatts of the output power of a stabilized $^{12}C^{16}O_2$ laser. The laser oscillates on any

one of a number of vibrational-rotational transitions of the $00^{\circ}1 - [10^{\circ}0, 02^{\circ}0]_I$ 950 cm^{-1} band of $^{12}C^{16}O_2$. The combined beams are focussed onto a cooled (77 K) mercury-cadmium telluride (HgCdTe) photodiode mixer, which generates a difference frequency current over the radio frequency bandwidth of 0 to 1500 MHz. After amplification, a 200 MHz segment of this intermediate frequency spectrum is converted into the band of 50 to 250 MHz by a single-sideband mixer and directed into a multichannel RF filter bank. The local oscillator frequency for this SSB mixer is calculated to place the Doppler-shifted line center at the mid-frequency point of this filter bank, and is tracked in frequency to correct for changes in Doppler shift caused both by the earth's rotation and by changes in the interplanetary velocity during the course of the measurement. The filter bank then analyzes the 50 to 250 MHz spectrum into 40 independent channels of 5 MHz (1.7×10^{-4} cm^{-1}) each. The 40 detected power outputs are synchronously demodulated at the sky chopping frequency (150 Hz) and multiplexed into a computer for on-line integration and analysis. After each integration cycle, a blackbody radiation source is placed in the infrared signal beam to calibrate the system. The sensitivity is measured to be 2.7×10^{-16} watts for a signal-to noise ratio of 1 after a 1 second integration in each 5 MHz channel. With an input infrared frequency of about 3×10^{13} Hz, this channel bandwidth implies a spectrometer resolving power of 6×10^{6}.

(III) Observations

The observations were conducted in 1975, November and December, when Venus was at an average phase of 0.65 and approximately 20 arcsec in diameter, about 5 times the 4 arcsec beam size. An observation cycle consisted of 4 minutes integration in each of the two signal beams, followed by a 2 minute blackbody calibration and zero check, yielding a net 8 minutes integration on the source.

A typical narrow emission line observed in the center of a broader CO_2 absorption feature is shown in Figure 2. This line is the same moleculer transition, $00°1 - [10°0, 02°0]_I$, as that of the CO_2 laser oscillator. As shown in the figure, the strength of the emission appears to be proportional to the solar intensity at the observed area; no emission is seen from the dark half of the planet. The line shape is Gaussian, with a halfwidth consistent with a kinetic gas temperature of about 200K near the subsolar region, and 185K near the terminator. However, the central intensity of the strongest line is 15 times greater than that expected from an optically thick region at a kinetic temperature of 200K. A more detailed analysis of the non-thermal emission mechanism is treated in an accompanying paper by Johnson et al. (1976), along with a discussion of similar emission features observed in the atmosphere of Mars.

From November through December, 1975, the Doppler shift of the receding planet varied from 1160 to 1080 MHz. The tracking oscillator frequency was calculated from the planetary ephemeris for Venus provided in the American Ephemeris and

Nautical Almanac so that an emission line with zero velocity with respect to the planetary center of mass should appear centered in the filter bank. Any deviation of the line frequency from the center of the filterbank could be caused by a combination of the following principal effects:

(1) an offset of the CO_2 laser frequency from the natural frequency of the transition,

(2) an offset of the RF tracking oscillator frequency from the correct value,

(3) a velocity component of the atmospheric emission region with respect to the planetary center of mass velocity, projected along the line of sight towards the earth.

The last effect is the desired quantity of the experiment, while the first two produce systematic errors in an absolute velocity measurement. Errors related to the first effect can in principle be accounted for. Although the laser is frequency stabilized to the center of its gain profile to a precision better than ± 0.2 MHz (Skolnick, 1970), corresponding to a velocity uncertainty of ± 2 m/sec, it does not oscillate at the true center frequency of the transition. For our laser operating on the P(16) transition at a total pressure of 14 Torr, the shift was measured to be 0.7 ± 0.1 MHz to lower frequency, based on a calibration with a low pressure CO_2 absorption cell. Errors of the second type are contributed by the uncertainties in the planetary ephemeris or a lack of precision in setting the tracking frequency, but are estimated to be less than ± 0.2 Mhz (± 2 m/sec) during these observations. The remaining significant source of error lies in the frequency calibration of the filter bank, but the accuracy here is better than ± 0.1 MHz (± lm/sec). After correcting for the laser frequency shift, the systematic error is less than 6 m/sec in determining the average velocity of any 4 arcsec region on Venus.

(IV) Results and Conclusions

The Doppler velocities measured on 7 days are listed in Table 1 for three different positions along the equator of Venus. Each velocity value is determined from the deviation of the observed line center from the frequency expected for the center of mass velocity. The line center frequency is derived from the center of gravity of the line profile and is consistent with an independent calculation using a least squares fit to a Gaussian profile. The quoted uncertainties in velocity are one standard deviation estimates from the formal statistical error and do not include the effects of any systematic contribution. This statistical error is governed completely by the signal to noise ratio of the line detection, which depends upon the length of integration time, the weather conditions at the time of the observation, and the strength of the signal as a function of the solar illumination on Venus. The latter effect is the dominant one contributing to the larger velocity uncertainties at the center of the planet. Typically the line emission near the terminator is 3 to 5 times less than that of the subsolar limb.

Because the listed velocities correspond only to the component seen along the line of sight, the limb values are tangential or horizontal velocities, while those at the center are, of course, vertical components. A few observations for which the velocity uncertainties exceeded ± 20 m/sec have been omitted from the Table. Generally, these values are from observations attempted under poor weather conditions for which the infrared signal dropped to less than half of its normal value; however, the mean value of all these omitted measurements lie within the bounds of the stated velocities.

The principal conclusion of this investigation is that at no time was a Doppler velocity measured which could be interpreted as a 100 m/sec (4 day) retrograde rotation of the atmosphere. Both the absolute velocity data from the limb and the differential values between the limb and center of the planet are more consistent with a mean rotational velocity near zero. Some of the day-to-day variations, however, do appear significant enough to indicate localized inhomogeneities as large as 20 m/sec. The variations in velocity at the center of the planet also imply that the vertical motions there are of the same scale as the horizontal variation on the limb, although the vertical values are not as well determined due to the larger statistical uncertainties. In comparing these results with previous spectroscopic investigations, one should bear in mind that these emission lines are formed at an altitude near 120 km (Johnson et al. 1976). This is almost twice as high as the altitude of the broader CO_2 absorption lines (Traub and Carleton, 1975) and ultraviolet cloud features, for which large 100 m/sec retrograde velocities have been reported.

Finally it should be emphasized that these results are only a first attempt to utilize heterodyne techniques to determine wind velocities on Venus, and that a number of significant improvements are possible. By stabilizing the laser frequency to the Lamb dip in a low pressure CO_2 absorption cell, a long term absolute frequency accuracy of a few parts in 10^{10} can be achieved (Freed and Javan, 1970). This, when combined with a more accurate planetary ephemeris such as one derived from planetary radar measurements (Shapiro, 1976), should reduce the total systematic error to less than 1 m/sec for absolute Doppler velocity measurements. The uncertainity for the line of sight velocity would then be limited only by the detection statistics to less than $\pm$ 5 m/sec for a 16 minute integration.

The success of infrared heterodyne techniques depends strongly on the latest advances in HgCdTe photodiode technology, and we would especially like to thank D. Spears (Lincoln Laboratory) for developing the devices used in this experiment. The CO_2 laser was constructed from the design of C. Freed (Lincoln Laboratory); the CO_2 absorption cell was provided by R. Jacobs (Lawrence Livermore Laboratory), and the multichannel filterbank was on generous loan from the National Radio Astronomy Observatory, Greenbank, W. Va. We are grateful to the staff of KPNO for their assistance in the use of Observatory facilities, and we also acknowledge informative conversations with I. I. Shapiro and C.H. Townes.

FIGURE CAPTIONS

Figure 1: Diagram of Experimental Apparatus

Figure 2: $^{12}C^{16}O_2$ emission lines observed at three locations, 4 arcsec in diameter, on the 20 arcsec disc of Venus. Integration times are 16 minutes for positions 1 and 2, and 32 minutes for position 3. The frequency scale is centered on the expected Doppler shift for the center of mass velocity of the planet. The intensities are calibrated as a Rayleigh-Jeans temperature, T_{RJ}, defined as received power density, $W \cdot Hz^{-1}$, divided by Boltzman's constant, k.

REFERENCES

Blaney, T.G. 1975, Space Science Reviews, 17, 5, 691.

Freed, C. and Javan, A. 1970, Appl. Phys. Lett. 17, 2, 53.

Johnson, M.A., Betz, A.L., McLaren, R.A., Sutton, E.C. and Townes, C.H. 1976, (to be published).

Peterson, D.W., Johnson, M.A., Betz, A.L. 1974, Nature 250, 128.

Shapiro, I.I. (1976) private communication.

Skolnick, M. 1970, IEEE, Journ. Quant. Elect., QE-6, 2, 139.

Traub, W.A., Carleton, N.P. 1975, J. Atmos. Sci., 32, 6, 1045.

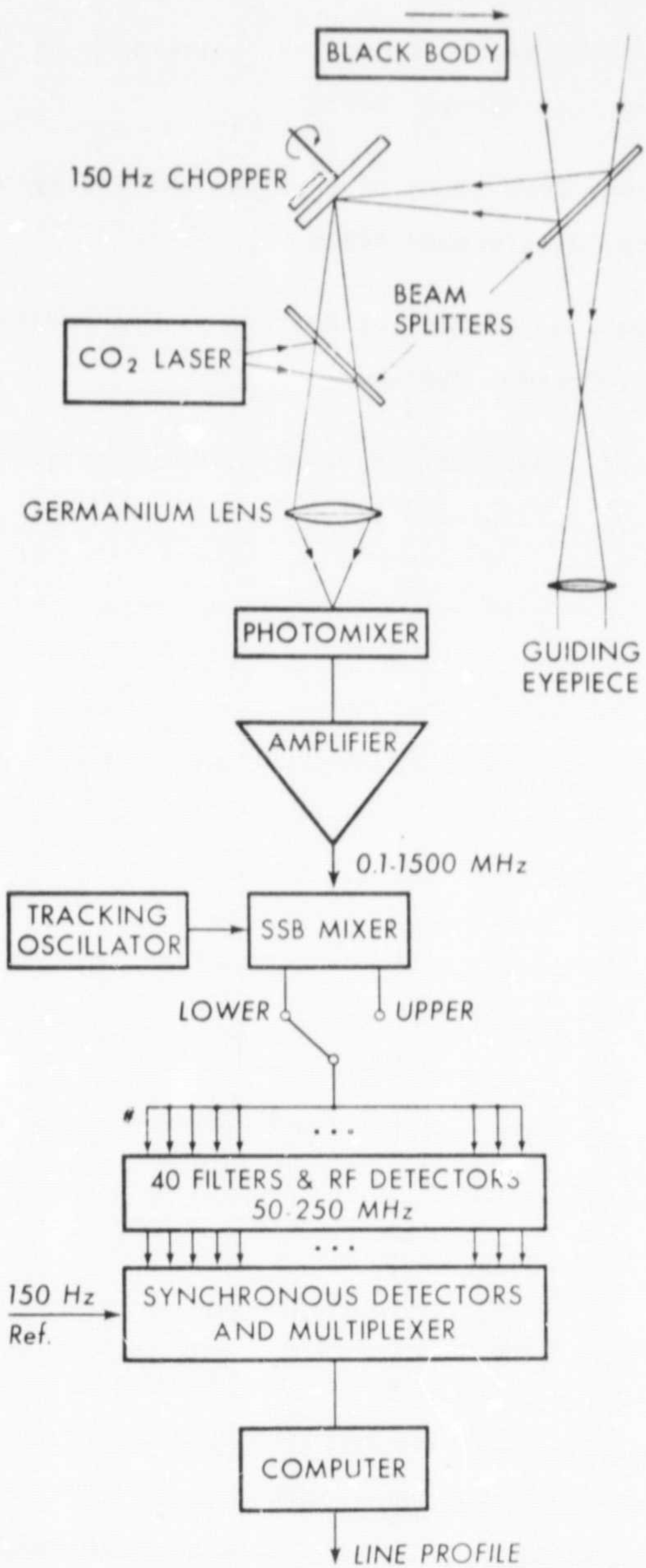
Young, A. 1975, Icarus 24, 1-10.

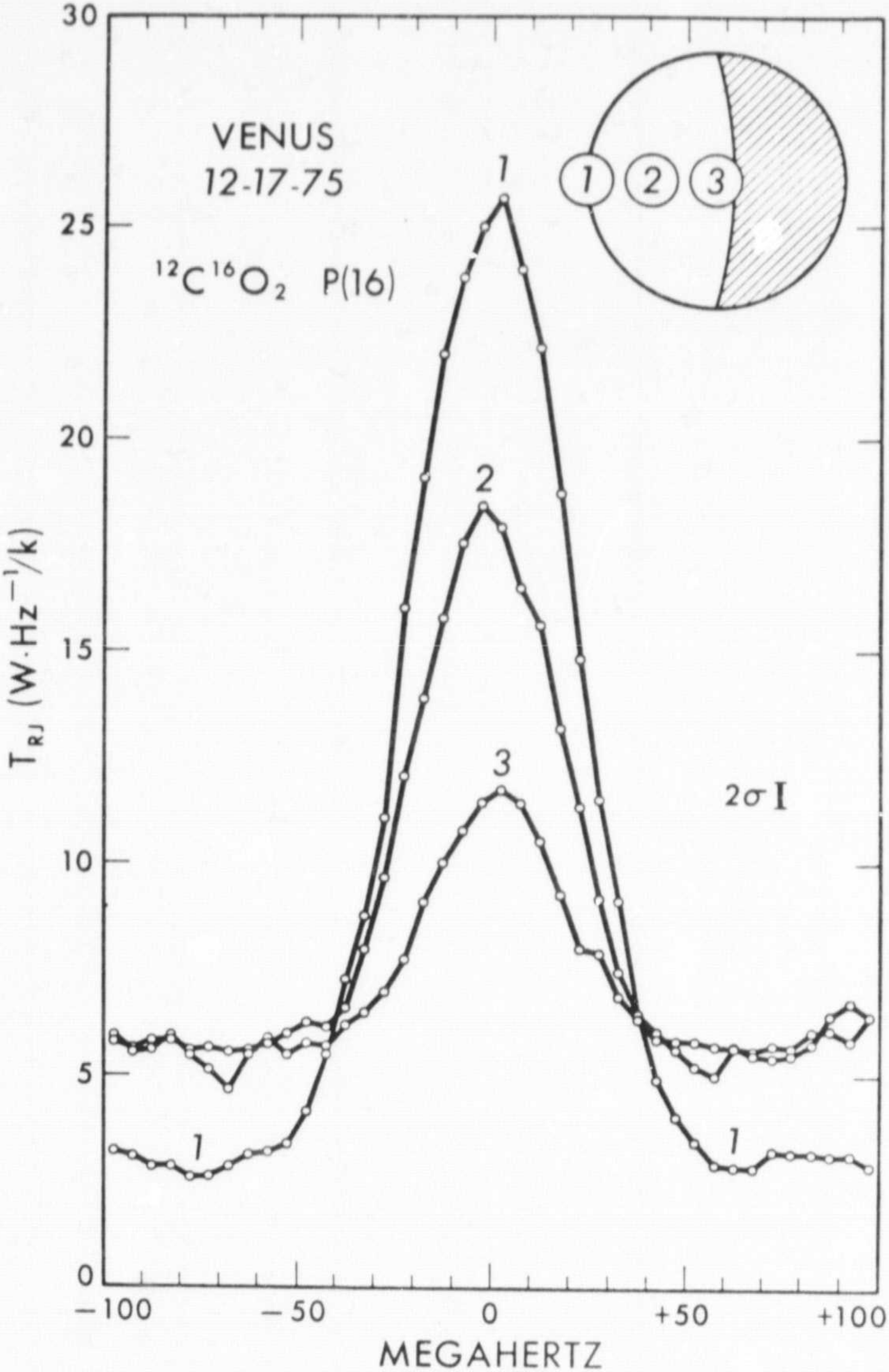
A.L. Betz, Department of Physics, University of California,
Berkeley, California 94720

M.A. Johnson, Department of Physics, University of California,
Berkeley, California 94720

R.A. McLaren, Department of Astronomy, University of Toronto,
Toronto, Canada M5S 1A7

E.C. Sutton, Department of Physics, University of California,
Berkeley, California 94720


BLACK BODY
150 Hz CHOPPER
BEAM SPLITTERS
CO2 LASER
GERMANIUM LENS
PHOTOMIXER
GUIDING EYEPIECE
AMPLIFIER
0.1-1500 MHz
TRACKING OSCILLATOR
SSB MIXER
LOWER
UPPER
40 FILTERS & RF DETECTORS 50-250 MHz
150 Hz Ref.
SYNCHRONOUS DETECTORS AND MULTIPLEXER
COMPUTER
LINE PROFILE



VENUS
12-17-75
$^{12}C^{16}O_2$ P(16)
1
2
3
T_{RJ} $(W \cdot Hz^{-1}/k)$
2σ
MEGAHERTZ
30
25
20
15
10
5
0
−100
−50
0
+50
+100