Reanalysis of Mariner 9 UV Spectrometer
Data for Ozone, Cloud, and Dust Abundances,
and their Interaction over Climate Timescales

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Annual Progress Report

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16. Abstract

Research activities to date are discussed. Selected Mariner 9 UV spectra have been obtained. Radiative transfer models have been updated and then exercised to simulate spectra. Simulated and observed spectra compare favorably. It is noted that large amounts of ozone are currently not retrieved with reflectance spectroscopy, raising large doubts about earlier published ozone abundances. As these published abundances have been used as a benchmark for all theoretical photochemical models of Mars, this deserves further exploration.

   3 manuscripts have been published, and one is in review. Papers have been presented and published at 3 conferences, and are planned for 5 more conferences in the next 6 months. 3 of these conferences are MSATT Workshops. The research plan for the next reporting period is discussed and involves continuing studies of reflectance spectroscopy, further examination of Mariner 9 data, climate change studies of ozone, and presentation of all results in journals and conferences.

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Table of Contents

I.   Abstract for the project (reprinted from the proposal)

Mariner 9 UV spectrometer data would be reinverted for the ozone abundance, cloud abundance, dust abundance, and polar-cap albedo. The original reduction of the spectra ignored the presence of atmospheric dust and clouds, even though their abundance is substantial and can mask appreciable amounts of ozone if not accounted for (Lindner, 1988). The Mariner 9 ozone data has been used as a benchmark in all theoretical models of atmospheric composition, escape, and photochemistry. A second objective is to examine the data for the interrelationship of the ozone cycle, dust cycle, and cloud cycle, on an annual, inter-annual, and climatic basis, testing predictions by Lindner (1988). This also has implications for many terrestrial ozone studies, such as the ozone hole, acid rain, and ozone-smog. A third objective is to evaluate the efficacy of the reflectance spectroscopy technique at retrieving the ozone abundance on Mars. This would be useful for planning ozone observations on future Mars missions or the terrestrial troposphere.

II.   Summary of Research to Date

II.1 Model developement.

The photochemical-radiative transfer model of Lindner (1985; 1988) has been updated. The code has been modified to run on AER's computer system, has been updated to use new cloud and dust scattering parameters as determined by Clancy and Lee (1991), and has been updated with new improvements to the Discrete Ordinate Method by Stamnes et al. (1988). Briefly, the code runs in 3 parts. First a code has been written which sets up the base atmosphere, including photochemistry, and then computes the wavelength-dependent atmospheric opacity,

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single-scattering albedo and phase function. Figure 1 shows the atmospheric opacity as a function of wavelength for one atmosphere scenario. This opacity includes Rayleigh scattering (strongest at 1500 Angstroms, and decreasing rapidly with wavelength), CO_2 absorption (the prominent component of the opacity shortward of 2000 Angstroms), and ozone absorption (the "bump" in opacity between 2000 and 3000 Angstroms). In addition, there is a virtually wavelength-independent opacity of cloud and dust. It is this "bump" that leaves a characteristic signature of the ozone abundance in the measured UV spectra. The radiative transfer model then computes intensities as a function of wavelength based on this atmospheric opacity and scattering. Finally, a code has been written which converts these intensities into a ratio of UV spectra which can be compared to the data.

II.2 Acquire Mariner 9 UV Spectrometer data.

While at the MSATT workshop held in Boulder, Colorado Sept. 23-25, 1991, the principal investigator discussed the procedure for obtaining the Mariner 9 UV Spectrometer data with Steve Lee, the director for the node of the Planetary Database System (PDS) at the University of Colorado. This and subsequent discussions have indicated that the data are not on the PDS system as promised years ago, and are not expected to be on the PDS for several years, due mostly to budget cuts. Steve has offered to help us retrieve the original data, however, we have been denied access to this data by Charles Barth of the University of Colorado, despite our requests to him to release this 20 year old data. Nonetheless, there have been several good spectra published in Lane et al. (1973) and Wehrbein (1977), which are quite adequate for us to complete all of our objectives for this project, although objective 2.2 will
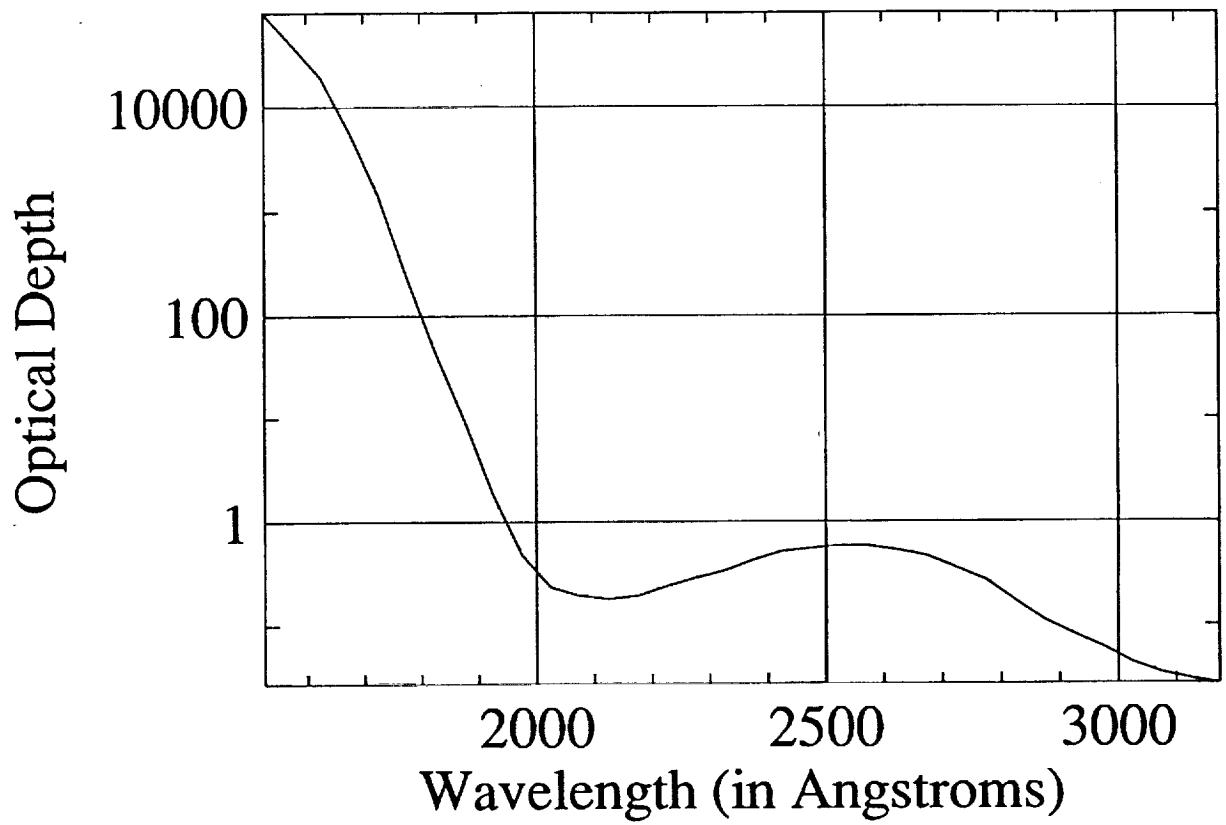
Figure 1. Vertical opacity of the atmosphere for 30 μm-atm of ozone, no dust and no cloud. A winter polar temperature profile is adopted (see Lindner, 1988).

be somewhat reduced in scope. A sample data spectra is shown in Figure 2. Discussions continue with Barth as to this original dataset.

II.3. Simulate UV Spectra.

The theoretical model was run with a variety of inputs to generate synthetic UV spectra. Parameters within the base atmosphere were varied as shown in Table 1 and synthetic spectra were calculated for each case. This is done to examine how changes in atmosphere affect ozone retrieval efficacy, affect errors in retrieved ozone abundance, and affect scatter in data. For ease of comparison to data (see Fig. 2), we have computed ratio of spectra to that at 20N latitude, where little ozone is present. Computed spectra for 20N latitude show little wavelength dependence. Figure 3 shows how spectra can vary for a single base atmosphere depending upon the viewing geometry of the spacecraft. Hence, comparison of synthetic spectra to observed spectra must properly account for the correct geometry. Synthetic spectra for various scenario for base atmospheres are shown in Figures 4 through 7.

TABLE 1

Synthetic spectra calculated for the following ranges in parameters

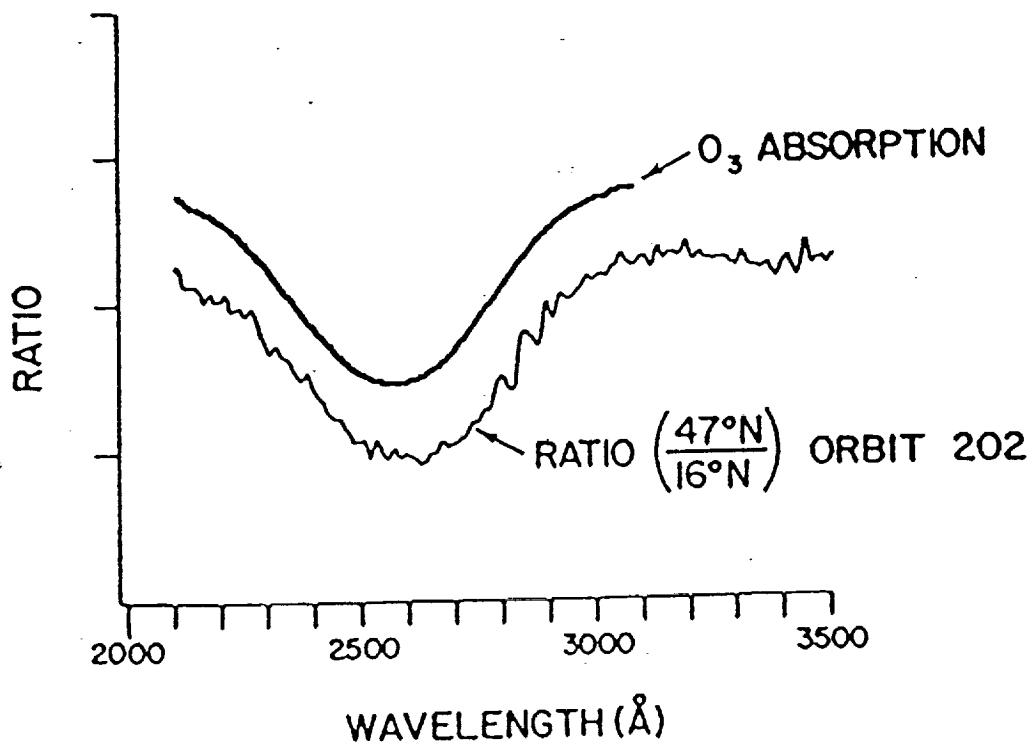|	
Ozone	0 to 100 μm-atm.
Ozone distribution	well-mixed, and concentrated down low
Solar Zenith Angle	50 to 85 degrees
Dust opacity	0 to 1
Cloud opacity	0 to 1
Ice albedo	0.3 to 0.8
Look Angle	0 to 90 degrees
Azimuth of Look Angle	0 to 90 degrees
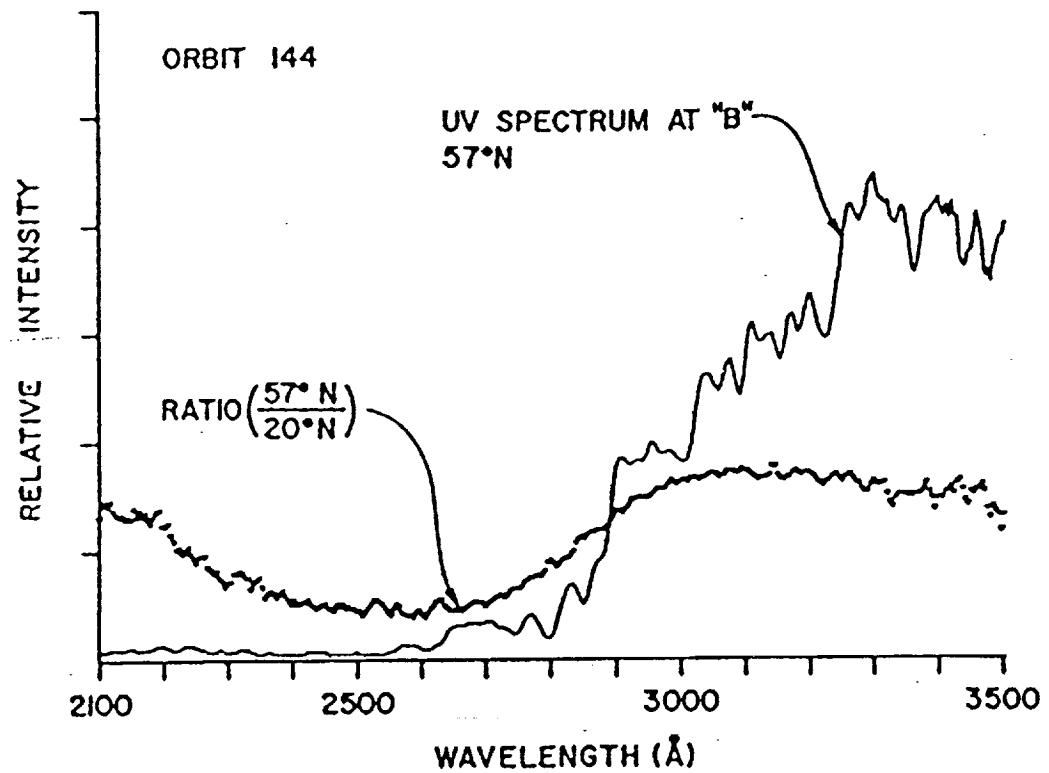
Figure 2   Ultraviolet spectrum measured by Mariner 9 at 57°N latitude on orbit
144 (upper plot). To enhance the ozone absorption feature, this spec-
trum was divided by one obtained at 20°N latitude on orbit 144, where
ozone abundances are minimal. The ozone absorption feature for orbit
202 is compared to laboratory data in the lower plot (laboratory data
is offset to facilitate comparison). Both figures are taken from Lane
et al. (1973).

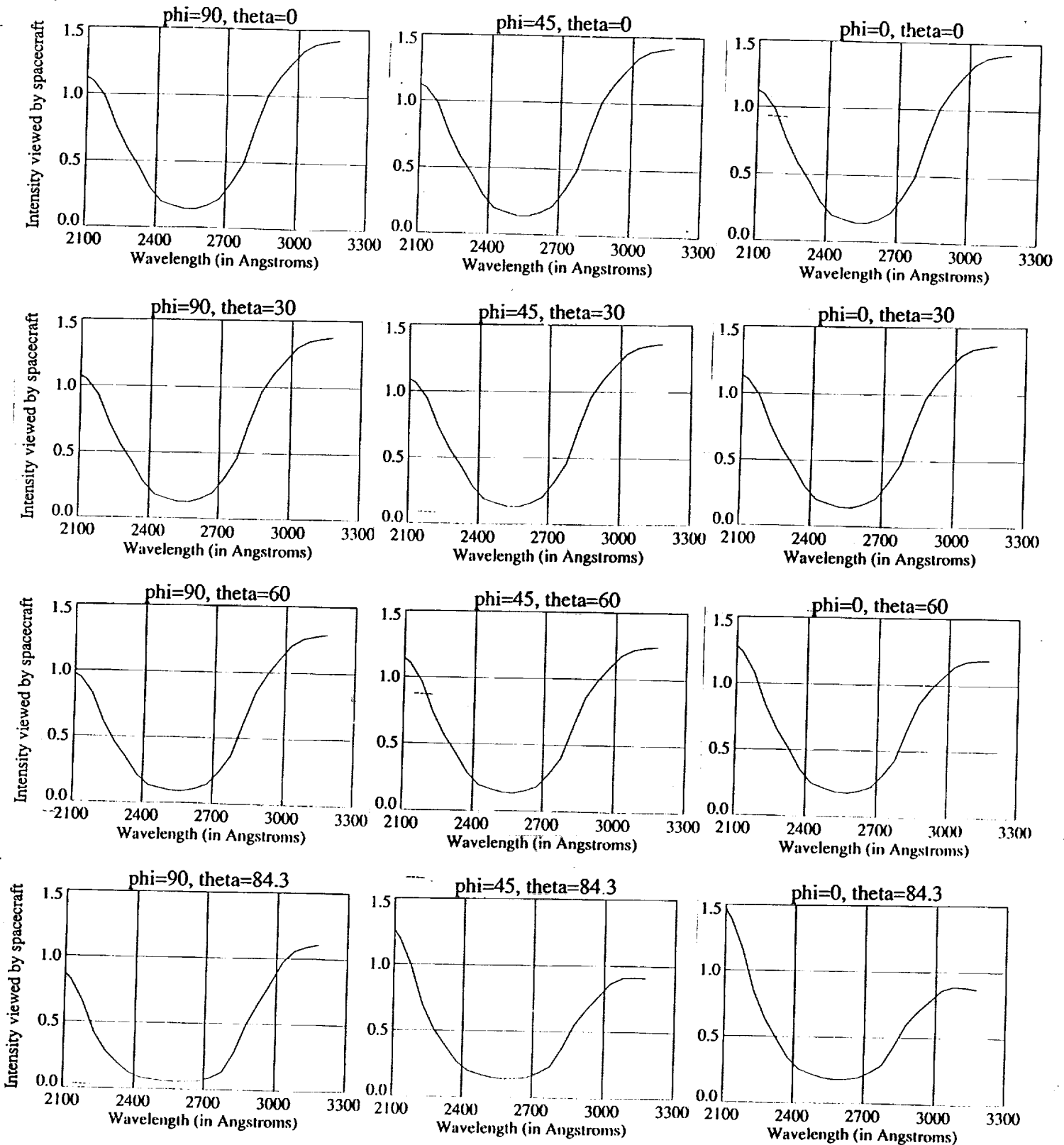Figure 3. Synthetic ultraviolet spectra, ratioed to synthetic spectra for 20N latitude, shown for various viewing geometries (viewing angle theta relative to the zenith and azimuthal angle phi relative to the sun). As with Lane et al. (1973; see Fig. 2), intensity is unitless and relative. 30 μm-atm ozone, no dust or cloud, a solar zenith angle of 75 degrees, ice albedo 0.5, and uniform mixing ratio of ozone are assumed.

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Figure 4. Synthetic ultraviolet spectra, ratioed to synthetic spectra for 20N latitude. Viewing geometry in all cases is viewing angle of 60 degrees, and azimuthal angle of 0 degrees. Atmospheric and surface parameters for the plots are as follows (showing ozone abundance, solar zenith angle (SZA), ice albedo, and cloud and dust opacity):

4(a) Ozone 30 μm-atm, SZA 75 degrees, Albedo 0.5, No dust, No cloud
4(b) Ozone 30 μm-atm, SZA 75 degrees, Albedo 0.5, dust 0.3, cloud 1.0
4(c) Ozone 100 μm-atm, SZA 75 degrees, Albedo 0.5, dust 0.3, cloud 1.0

Figure 5. Synthetic ultraviolet spectra, ratioed to synthetic spectra for 20N latitude. Viewing geometry in all cases is viewing angle of 60 degrees, and azimuthal angle of 0 degrees. Atmospheric and surface parameters for the plots are as follows (showing ozone abundance, solar zenith angle (SZA), ice albedo, and cloud and dust opacity):

5(a) Ozone 30 μm-atm concentrated low in the atmosphere, SZA 75 degrees, Albedo 0.5, No dust, No cloud

5(b) Ozone 30 μm-atm concentrated low in the atmosphere, SZA 75 degrees, Albedo 0.5, dust 0.3, cloud 1.0

5(c) Ozone 100 μm-atm concentrated low in the atmosphere, SZA 75 degrees, Albedo 0.5, dust 0.3, cloud 1.0
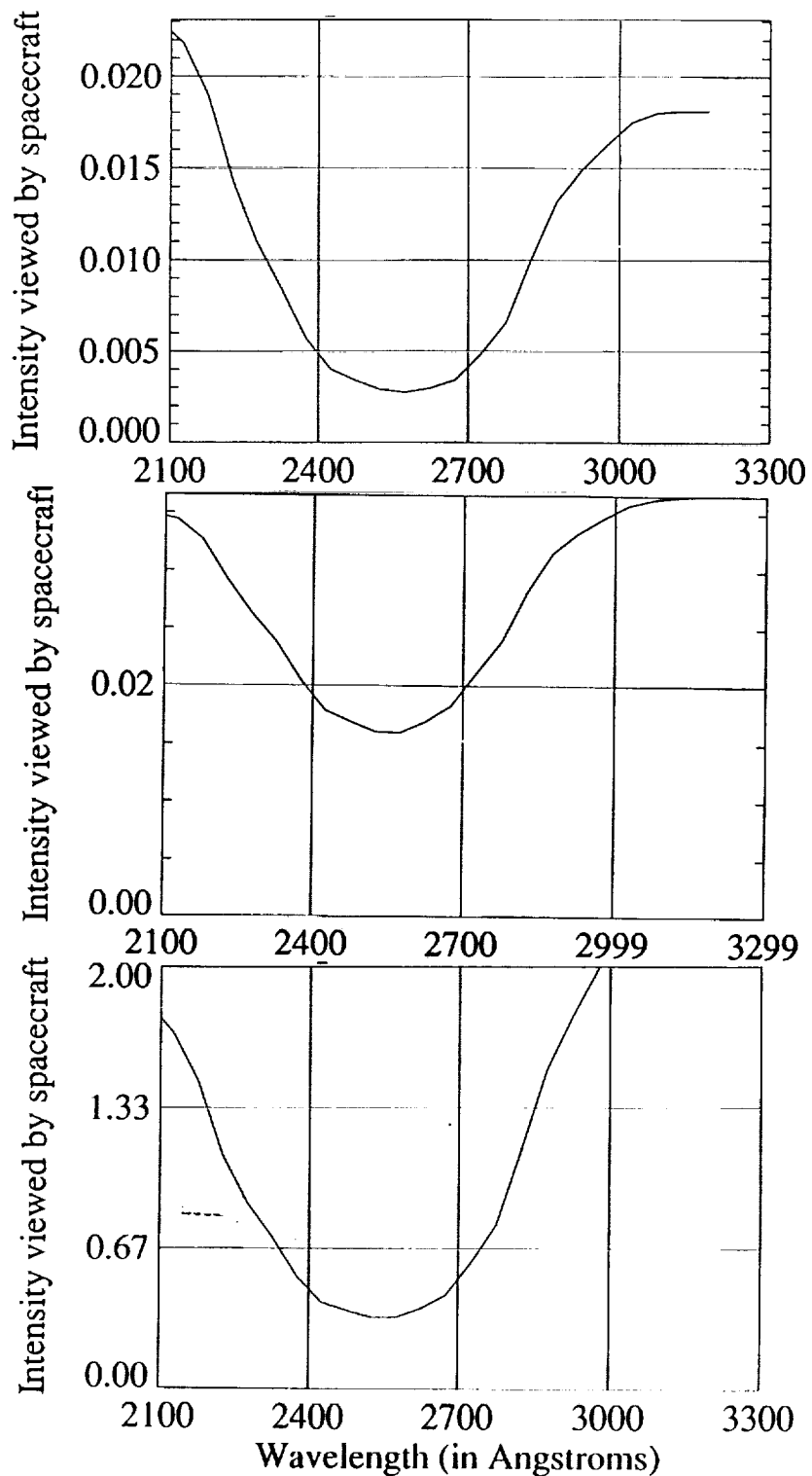
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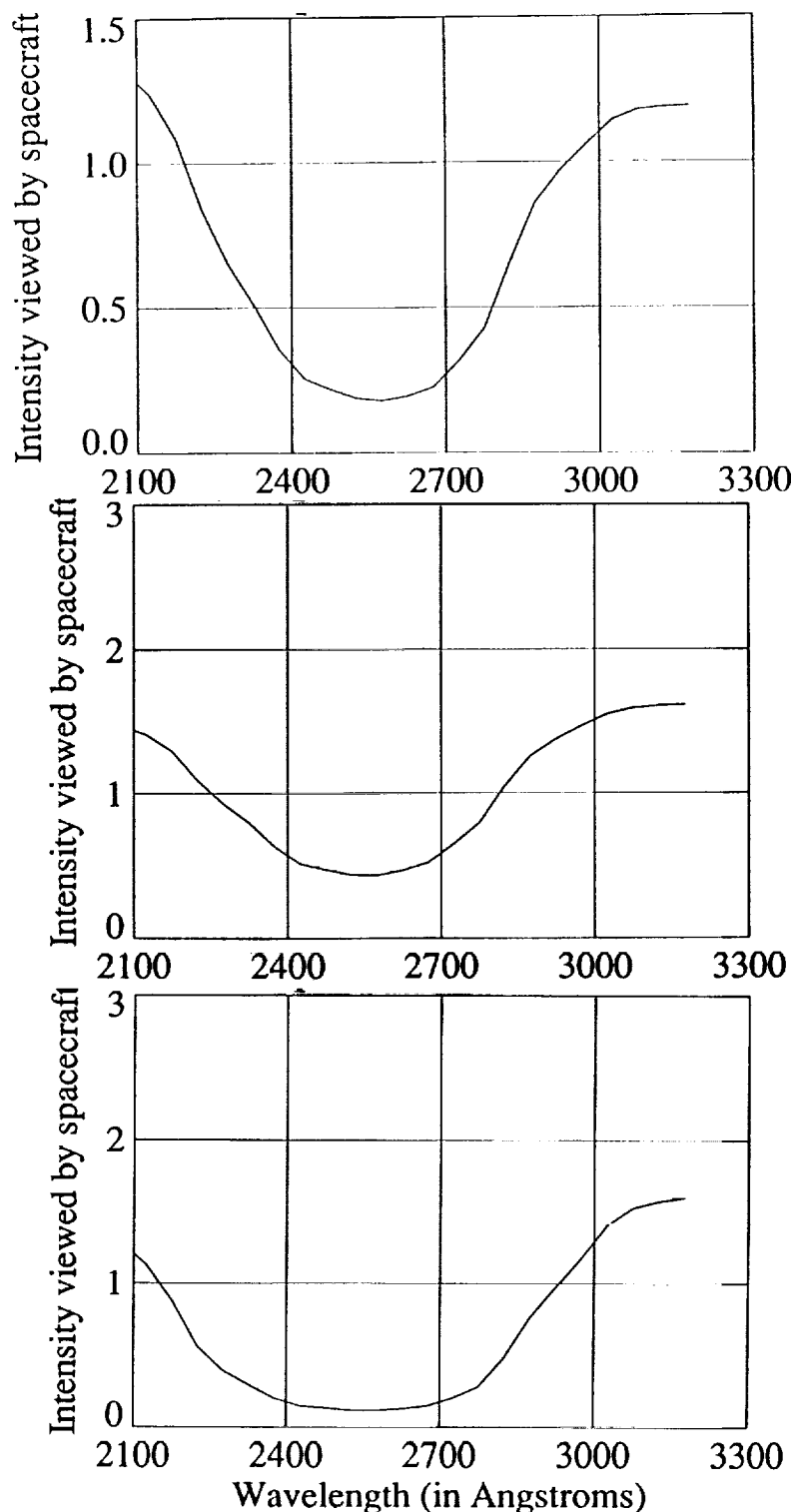
Figure 6. Synthetic ultraviolet spectra, ratioed to synthetic spectra for 20N latitude. Viewing geometry in all cases is viewing angle of 60 degrees, and azimuthal angle of 0 degrees. Atmospheric and surface parameters for the plots are as follows (showing ozone abundance, solar zenith angle (SZA), ice albedo, and cloud and dust opacity):

6(a) Ozone 30 μm-atm, SZA 75 degrees, Albedo 0.5, No dust, No cloud
6(b) Ozone 30 μm-atm, SZA 75 degrees, Albedo 0.5, dust 0.3, No cloud
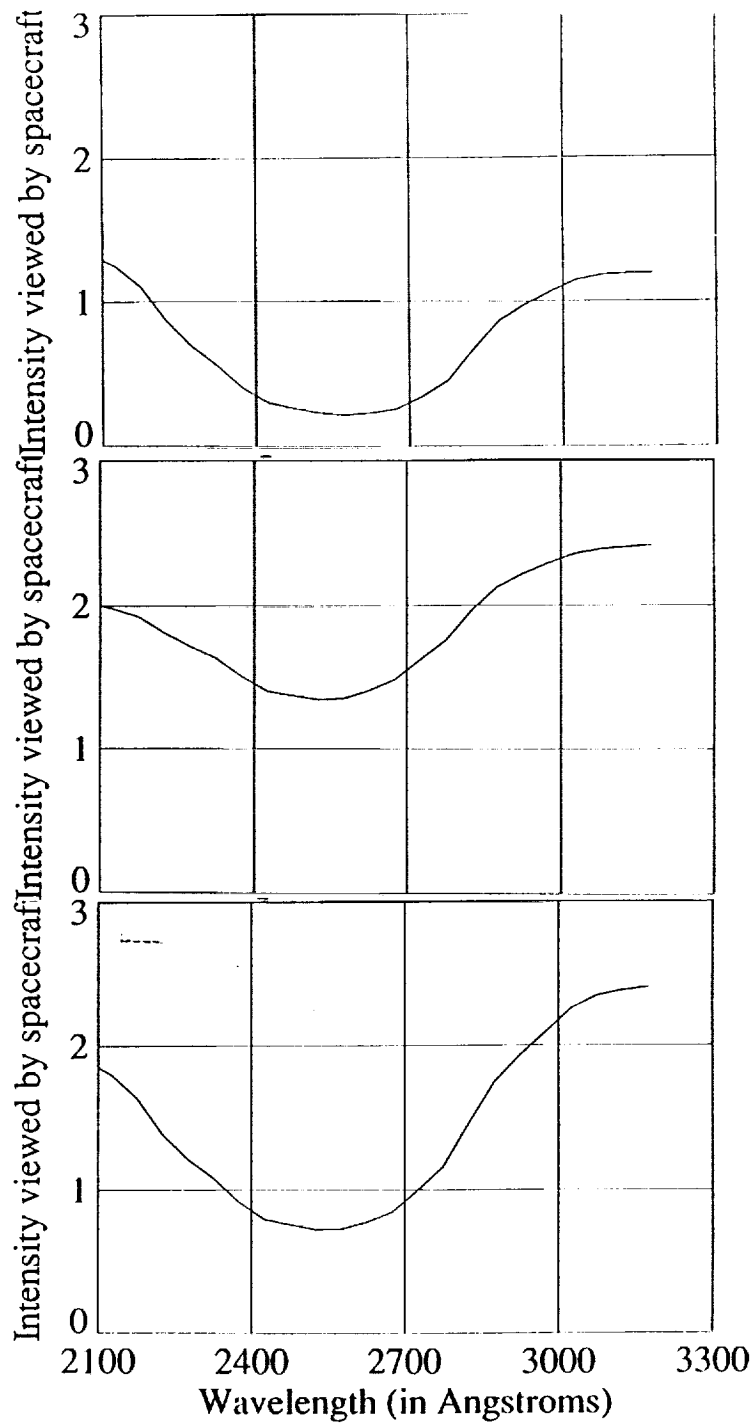6(c) Ozone 100 μm-atm, SZA 75 degrees, Albedo 0.5, dust 0.3, No cloud

Figure 7. Synthetic ultraviolet spectra, ratioed to synthetic spectra for 20N latitude. Viewing geometry in all cases is viewing angle of 60 degrees, and azimuthal angle of 0 degrees. Atmospheric and surface parameters for the plots are as follows (showing ozone abundance, solar zenith angle (SZA), ice albedo, and cloud and dust opacity):

7(a)   Ozone 30 μm-atm, SZA 75 degrees, Albedo 0.5, No dust, No cloud

7(b)   Ozone 30 μm-atm, SZA 75 degrees, Albedo 0.5, dust 1.0, cloud 1.0

7(c)   Ozone 100 μm-atm, SZA 75 degrees, Albedo 0.5, dust 1.0, cloud 1.0
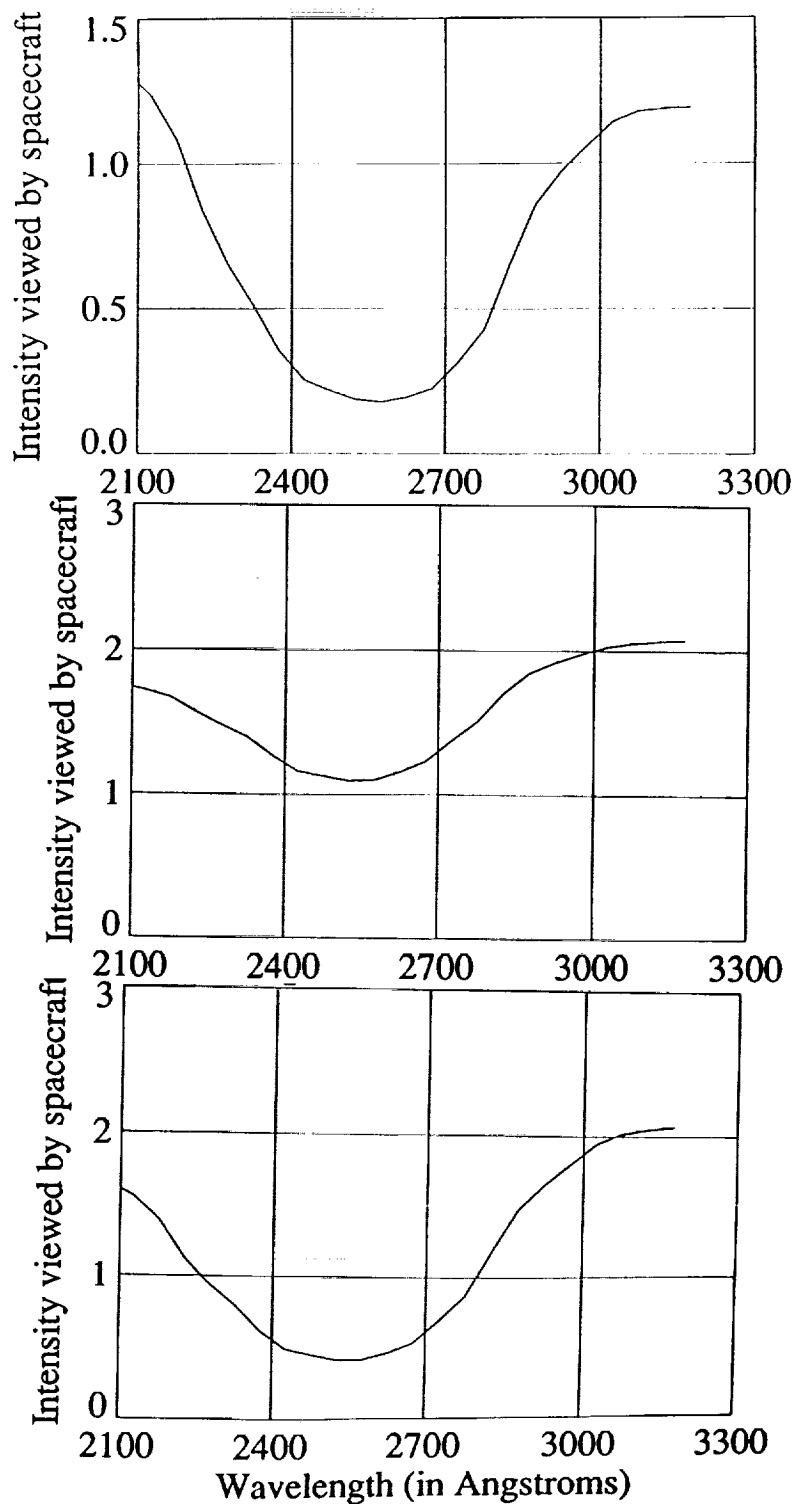
II.4. Compare synthetic and observed spectra.

The synthetic and observed spectra compare quite favorably. In fact, the inclusion of dust and cloud absorption and scattering improve the synthetic fit to the slope in the data from 2100 to 2300 Angstroms. Further comparison will be undertaken in the next year with more spectra, ensuring that all parameters are the same (i.e., particularly look angles and sza's).

Comparison of Figures 4 and 5 shows how difficult it is to try to infer the ozone distribution from UV spectra. Two radically different ozone profiles were used, and yet the spectra exhibit similar behavior. Wehrbein (1977) examined the data in depth to retrieve the ozone distribution, and concluded that ozone is fairly well mixed in the atmosphere. Lindner (1988) also showed that ozone should be fairly well mixed based on theoretical simulations of atmospheric chemistry.

II.5. Error in inferring O_3 without considering dust/cloud.

Ozone has been classically inferred from the spectra by fitting the depth of the absorption at 2500 Angstroms. We have summarized the depth of absorption in Table 2 for many cases we have tried. What can be most clearly seen is that for all the cases we have tried, the amount of ozone inferred from the UV spectra is underestimated by about a factor of 3 when the inversion uses simply ozone absorption (i.e. ignoring cloud and dust). This is seen in Table 2 in that approximately 3 times as much O_3 is needed to produce the same depth in absorption for scenario in which we fully include the masking effects of cloud and dust to the case for which cloud and dust are ignored. This is particularly noteworthy in that even if the effect of cloud and dust is included in the retrieval, the

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TABLE 2

2550/3200 ANGSTROM RATIO

O3	SZA	DUST	CLOUD	ALBEDO	O3 DIST.	RATIO
30	75	0	0	0.5	mixed	0.15
30	75	0.3	1	0.5	mixed	0.43
50	75	0.3	1	0.5	mixed	0.30
100	75	0.3	1	0.5	mixed	0.14
30	75	0.3	0	0.5	mixed	0.27
100	75	0.3	0	0.5	mixed	0.07
30	75	1	1	0.5	mixed	0.52
100	75	1	1	0.5	mixed	0.20
30	75	0	0	0.5	low	0.18
30	75	0.3	1	0.5	low	0.56
100	75	0.3	1	0.5	low	0.30
30	75	0	0	0.8	mixed	0.12
30	75	0.3	1	0.8	mixed	0.41
100	75	0.3	1	0.8	mixed	0.13
30	75	0	0	0.3	mixed	0.21
30	75	0.3	1	0.3	mixed	0.45
100	75	0.3	1	0.3	mixed	0.14
30	85	0	0	0.5	mixed	0.14
30	85	0.3	1	0.5	mixed	0.40
100	85	0.3	1	0.5	mixed	0.10
30	50	0	0	0.5	mixed	0.17
30	50	0.3	1	0.5	mixed	0.35
100	50	0.3	1	0.5	mixed	0.10

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uncertainty in cloud and dust opacity and scattering properties will still leave an uncertainty in retrieved ozone abundance of a factor of 2! Considering that the published ozone abundances retrieved from the Mariner 9 data are used as a benchmark by all photochemical models of the Mars atmosphere, this has important implications for much of the modeling work done over the last 20 years.

Figure 6 shows that even simply ignoring a minimal dust opacity of 0.3 in a cloud-free atmosphere will underestimate the ozone abundance by a factor of 2. This is noteworthy in that dust was completely ignored in the earlier inferences of ozone from the spectra by Lane et al. (1973) and others. Dust abundances are always of this order or higher (Pollack et al., 1979).

Figure 7 shows that for high dust/cloud loading the inferred ozone abundance is a factor of 4 or 5 below what is truly there. Pollack et al. (1979) note that perhaps 20% of the martian year has this extent of dust loading or greater.

Table 2 does show that errors in retrieval are the same for all solar zenith angles we looked at, and for all ice albedo below 0.5. For high ice albedo, ozone becomes even more severely underestimated.

II.6. Reflectance Spectroscopy efficacy.

Figures 3 through 7 and Table 2 show that to properly retrieve the ozone abundance from the Mariner 9 UV spectra with the reflectance spectroscopy technique, the effects of cloud and dust must be considered. Therefore, the efficacy of the reflectance spectroscopy technique is only as good as the accuracy with which we know the opacity and scattering properties of the dust and cloud itself. Clancy and Lee (1991) have done the definitive study to date of retrieving these cloud and dust

parameters. However, even with their study, there remain large uncertainties in the spatial and temporal variability in opacity and scattering properties, and also in the wavelength dependence of these properties. The amount of other spacecraft sensors and observations needed to obtain these properties to the degree needed to obtain ozone abundance to within a 10 to 20 % uncertainty is enormous. This raises serious doubts about the efficacy of this technique for retrieving ozone. We seriously recommend that other techniques be examined before designing future Mars Aeronomy sensors; perhaps detecting ozone at other wavelengths such as in the infrared.

II.7. Presentations made at conferences.

Several conferences were attended which were partly or fully funded by this contract. Reprints of papers and abstracts published at these meetings are included in the Appendix.

IUGG Assembly. I attended the International Union of Geodesy and Geophysics Assembly in Vienna, Austria, in August 11-24 1991, and presented a paper entitled "Mars seasonal CO_2-ice lifetimes and the angular dependence of albedo" in the special Mars climate session. The abstract appeared in the conference proceedings (see Appendix). Half of expenses were paid by NASW-4614 and half were paid by another contract.

PCI Symposium. I attended the International Symposium on the chemistry and physics of ice, held in Sapporo, Japan Sept. 1-7, 1991, and presented a paper entitled "Why is the north polar cap on Mars different than the south polar cap?" in the extraterrestrial ice session. The abstract appeared in the conference proceedings (see Appendix). This trip was personal in nature and was not funded by any grants.

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MSATT Workshop. I attended the Mars Surface and Atmosphere Through Time Workshop, held in Boulder, Colorado Sept. 23-25, 1991, and presented a paper entitled "Simulations of the seasonal polar caps on Mars". The abstract appeared in the workshop proceedings put out by the Lunar and Planetary Institute in Houston (see Appendix). NASW-4614 paid for expenses, but these were limited mostly to airfare and registration due to gratis accommodations, food, and car.

II.8. Publications

A paper entitled "Ozone heating in the martian atmosphere" was published in Icarus, Volume 93, pp. 354-361, 1991. A reprint is included in the Appendix.

A paper entitled "Sunlight penetration through the martian polar caps: Effects on the thermal and frost budgets" has been accepted by Geophysical Research Letters and is in Press. A preprint is included in the Appendix.

A chapter in the book Physics and Chemistry of Ice entitled "CO_2-ice on Mars: Theoretical Simulations" has been published by Hokkaido University Press, Sapporo. A reprint is included in the Appendix.

III. Program of Future Research

III.I. Research Tasks

Considering that we are virtually on schedule to date, we expect the remaining objectives for this contract will be completed in year 3, as originally proposed. Specifically, the next year will begin with more simulations of spectra. We will also examine the ability to accurately retrieve some measure of the cloud and dust opacity and scattering properties from the UV spectra, in order to decrease the uncertainty in

ozone retrieval. We will also examine the ability to simultaneously retrieve the polar cap albedo. We will examine the scatter in Mariner 9 data as to whether this can be explained by cloud and dust masking of ozone (see proposal). Most importantly, we will begin climate studies, as defined in the proposal.

III.2. Conferences

MSATT Workshop. I will attend the Mars Surface and Atmosphere Through Time Workshop on innovative instrumentation for the in situ study of atmosphere-surface interactions on Mars to be held in Mainz, Germany October 8-9. Results presented in this report will be presented in a paper entitled "Does UV instrumentation effectively measure ozone abundance?" (see Appendix). Grant NASW-4614 will pay for at least partial support.

Lab. Research Planetary Atmospheres Conference. I will attend the Fourth International Conference on Laboratory Research for Planetary Atmospheres to be held in Munich, Germany October 10-11. A paper entitled "How well is martian ozone inferred with reflectance spectroscopy?" will present results from this contract (see Appendix). Grant NASW-4614 will pay for at least partial support (note that this conference is concurrent with the MSATT Workshop, limiting costs).

Planetary Science Conference. I will attend the American Astronomical Society Division of Planetary Science Conference to be held in Munich, Germany October 12-16. A paper entitled "Martian polar cap seasonal regression simulations" will be presented (see Appendix). Grant NASW-4614 will pay for at least partial support (note that this conference is concurrent with the MSATT Workshop, limiting costs).

MSATT Workshop. I plan on attending the Mars Surface and Atmosphere Through Time Workshop on The Polar Regions of Mars: Geology, Glaciology, and Climate History to be held in Houston, Texas November 13-15. Grant NASW-4614 will pay for at least partial support.

AMS Annual Meeting Chemistry Session. I plan to attend the American Meteorological Society Annual Meeting Session on Atmospheric Chemistry to be held in Anaheim, California January 1993. A paper entitled "Atmospheric chemistry on Mars" will present results from this contract (see Appendix). The bulk of support will come from another contract, but grant NASW-4614 will at least pay for registration and publication costs for this session.

III.3. Publications in Progress

A manuscript entitled "The hemispherical asymmetry in the martian polar caps" is undergoing review by J. Geophys. Res. for publication in their special MSATT issue commemorating papers presented at the Workshop on the Martian Surface and Atmosphere Through Time. One favorable review has been received, and I am awaiting the other review.

A manuscript describing some of the results presented here will be written, with the intention of submittal to Nature or Science.

Publications wholely or partly under this contract

(reprints are in the appendix)

Lindner, B. L., Ozone heating in the martian atmosphere, Icarus, 93, 354-361, 1991a.

Lindner, B. L., Why is the north polar cap on Mars different than the south polar cap?, Summaries, International Symposium on the Physics and Chemistry of Ice, p. 120-121, held in Sapporo Japan, Sept. 1-6, 1991b.

Lindner, B. L., Mars seasonal CO_2-ice lifetimes and the angular dependence of albedo (abstract), in International Union of Geodesy and Geophys. General Assembly XX, IAMAP Program and Abstracts, p. 309, published by RM-Druck- and Verlagsgesellschaft, Graz, Austria, 1991c.

Lindner, B. L., Simulations of the seasonal polar caps on Mars, in Workshop on the martian surface and atmosphere through time, p. 76-77, published by Lunar and Planetary Institute, Houston, Texas, 1991d.

Lindner, B. L., Martian polar cap seasonal regression simulations (abstract), Bull. Amer. Astron. Soc., 23, in Press, 1992a.

Lindner, B. L., Sunlight penetration through the martian polar caps: Effects on the thermal and frost budgets, Geophys. Res. Lett., in Press, 1992b.

Lindner, B. L., Does UV instrumentation effectively measure ozone abundance?, submitted to Proceedings, Workshop on innovative instrumentation for the in situ study of atmosphere-surface interactions on Mars, published by Lunar and Planetary Institute, Houston, Texas, 1992c.

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Lindner, B. L., CO_2-ice on Mars: Theoretical simulations, in <u>Physics and Chemistry of Ice</u>, N. Maeno and T. Hondoh, ed.s, pp. 225-228, Hokkaido University Press, Sapporo, 1992d.

Lindner, B. L., The hemispherical asymmetry in the martian polar caps, submitted to <u>J. Geophys. Res.</u>, 1992e.

Lindner, B. L., How well is martian ozone inferred with reflectance spectroscopy?, submitted to <u>Proceedings, Fourth International Conference on Laboratory Research for Planetary Atmospheres</u>, held in Munich, Germany, Oct. 10-11, 1992f.

Lindner, B. L., Atmospheric chemistry on Mars, submitted to <u>Proceedings, Special American Meteorological Society Annual Meeting Session on Atmospheric Chemistry</u>, published by American Meteorological Society, Boston, Mass., 1993a.

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Pollack, J. B., D. S. Colburn, F. M. Flasar, R. Kahn, C. E. Carlston, and D. Pidek, Properties and effects of dust particles suspended in the martian atmosphere, J. Geophys. Res., 84, 2929-2945, 1979.

Stamnes, K., S.C. Tsay, W. Wiscombe, and K. Jayaweera, Numerically stable algorithm for discrete-ordinate-method radiative transfer in multiple scattering and emitting layered media, App. Optics, 27, 2502-2509, 1988.

Wehrbein, W. M., Description of the vertical distribution of ozone in the martian atmosphere from Mariner 9 ultraviolet spectrometer data, Ph. D. Dissertation, 174 pp., University of Colorado, Boulder, 1977.

Table 1. Three Year Plan of Work
(as presented in the proposal)

Task	Time

Year 1

3.1	Obtain the Mariner 9 UV spectra	2 man-weeks
3.2	Update the Lindner (1988) model	3 man-weeks
3.3a	Compute simulated UV spectra	2 man-weeks
3.9a	Attend LPSC conference, attend MSATT working. group meeting, prepare Year 1 report to NASA	2 man-weeks

Total ....9 man-weeks

Year 2

3.3b	Compute simulated UV spectra	4 man-weeks
3.4	Compare simulated spectrum to observed spectrum	3 man-weeks
3.5	Study how O_3 changes with cloud and dust opacity	2 man-weeks
3.6	Determine error in deriving O_3 abundances without including dust/cloud absorption/scattering	2 man-weeks
3.9b	Attend conference, prepare Year 2 NASA report	2 man-weeks

Total...13 man-week

Year 3

3.7	Evaluate efficacy of reflectance spectroscopy	3 man-weeks
3.8	Climatic changes in martian photochemistry	5 man-weeks
3.9c	Publish results in journal	3 man-weeks
3.9d	Present results in conference and final report	2 man-weeks

Total ....13 man-week

Total - Three years   35 man-weeks

Appendix
Reprints and preprints of publications made under this contract
(in the order listed earlier)

WHY IS THE NORTH POLAR CAP ON MARS DIFFERENT THAN THE SOUTH POLAR CAP?

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Introduction. One of the most puzzling mysteries about the planet Mars is the hemispherical asymmetry in the polar caps. Every spring the seasonal polar cap of CO_2 recedes until the end of summer, when only a small part, the residual polar cap, remains. During the year that Viking observed Mars, the residual polar cap was composed of water ice in the northern hemisphere [Kieffer et al., Science, 194, 1341, 1976] but was primarily carbon dioxide ice in the southern hemisphere [Kieffer, J. Geophys. Res., 84, 8263, 1979]. Scientists have sought to explain this asymmetry by modeling observations of the latitudinal recession of the polar cap and seasonal variations in atmospheric pressure (since the seasonal polar caps are primarily frozen atmosphere, they are directly related to changes in atmospheric mass). These models reproduce most aspects of the observed annual variation in atmospheric pressure fairly accurately. Furthermore, the predicted latitudinal recession of the northern polar cap in the spring agrees well with observations, including the fact that the CO_2 ice is predicted to completely sublime away. However, these models all predict that the carbon dioxide ice will also sublime away during the summer in the southern hemisphere, unlike what is observed. This paper will show how the radiative effects of ozone, clouds, and airborne dust, light penetration into and through the polar cap, and the dependence of albedo on solar zenith angle affect CO_2 ice formation and sublimation, and how they help explain the hemispherical asymmetry in the residual polar caps. These effects have not been studied with prior polar cap models.

Ozone, Clouds, and Airborne Dust. Since O_3 is more prevalent in the northern hemisphere than in the southern hemisphere, O_3 was suggested as a cause for the hemispherical asymmetry in the residual polar caps by Kuhn et al. (J. Geophys. Res., 84, 8341, 1979). However, Lindner (submitted to Icarus, 1991) has shown that O_3 has a minor effect on the atmospheric temperature, and hence on the infrared radiation which strikes the polar cap, and Lindner (J. Geophys. Res., 95, 1367, 1990) has shown that O_3 absorbs less than 1% of the total solar radiation absorbed by the polar cap. Thus, O_3 is not an important consideration in the polar cap energy budget.

Lindner (1990) has computed the solar and thermal flux striking the polar cap of Mars for various ozone, dust, and cloud abundances and for three solar zenith angles. These calculations have been inserted in the polar-cap models

of Lindner (Eos Trans. AGU, 67, 1078, 1986) and Jakosky and Haberle (J. Geophys. Res., 95, 1359, 1990). Vertical optical depths of dust and cloud ranging from zero to 1 cause little change in the total flux absorbed by the polar cap near its edge but increase the absorbed flux significantly as one travels poleward. Observed hemispherical asymmetries in dust abundance, cloud cover, and surface pressure combine to cause a significant hemispherical asymmetry in the total flux absorbed by the residual polar caps, which helps to explain the dichotomy in the residual polar caps on Mars.

Light Penetration. Penetration of solar radiation into the cap itself is included in my polar cap model, based on the theoretical work of Clow (Icarus, 72, 95, 1987). I find that the inclusion of light penetration slightly decreases the albedo needed in the model to keep CO_2-ice year-round at the south pole by on the order of 1%. The required albedo is decreased because some solar radiation is used to heat the subsurface, and not all of this heat is transported back to the surface. Overall, I conclude that penetration of light into the polar cap has only a small effect on the polarcap energy budget.

Albedo and the Solar Zenith Angle. Warren et al. (J. Geophys. Res., 95, 14717, 1990) has computed the dependence of the albedo of the martian polar caps on solar zenith angle, and these calculations have been included in my polar cap model. Since the albedo of ice increases and becomes more forward scattering at higher solar zenith angles, and since the solar zenith angle becomes higher as one approaches the pole, the albedo is greatest at the pole. This decreases absorption of sunlight, hence increasing survivability of CO_2 ice. In fact, this increases the survivability of ice enough to offset the decrease in survivability of ice due to the radiative effects of clouds and dust.

Discussion. The combination of the effects of solar zenith angle on albedo and the radiative effects of clouds and dust act to extend the lifetime of CO_2 ice on the south pole relatively more than on the north pole, explaining the hemispherical asymmetry in the residual polar caps without the need of a hemispherical asymmetry in polar cap albedo. Another positive aspect this solution is that neither the inclusion of solar zenith angle effects on ice albedo nor the radiative effects of clouds and dust should appreciably change model predictions of the annual cycle of pressure or polar cap recession equatorward of 75° latitude, since approximately 90% of the seasonal CO_2 frost is equatorward of 80° latitude. Hence, the good model agreement noted by prior researchers to the seasonal cycle in atmospheric pressure and to the recession of the polar cap equatorward of 80° latitude is retained.

P - 1

MARS SEASONAL CO$_2$-ICE LIFETIMES AND THE ANGULAR DEPENDENCE OF ALBEDO

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The albedo of the polar caps on Mars brightens appreciably at high solar zenith angle (Warren et al., J. Geophys. Res., 95, 14717, 1990), an effect not included in prior polar-cap energy-balance models. This decreases absorption of sunlight by the polar cap, hence decreasing sublimation of CO$_2$ ice. Lindner (J. Geophys. Res., 95, 1367, 1990) has shown that the radiative effects of clouds and airborne dust will increase sublimation of CO$_2$ ice over that predicted by prior polar-cap energy-balance models. Furthermore, observations hint that more clouds may exist in the northern hemisphere, which Lindner (1990) has shown would sublime CO$_2$ ice more quickly in the north than in the south. I show here that the effects of the solar zenith angle dependence of albedo and the radiative effects of clouds and dust offset each other, but act to extend the lifetime of CO$_2$ ice on the south pole more than on the north pole, possibly explaining the observed hemispherical asymmetry in the residual polar caps without the need of a hemispherical asymmetry in polar-cap albedo required by prior models. Another positive aspect of this solution is that neither the inclusion of the solar zenith angle dependence of albedo nor the radiative effects of clouds and dust should appreciably change prior model agreement with observations of the annual cycle of surface pressure and the recession of the polar caps equatorward of 75° latitude.

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· The Climate of Mars Symposium, Symposium M13

· Oral presentation preferred

· 1 overhead projector

SIMULATIONS OF THE SEASONAL POLAR CAPS ON MARS Bernhard Lee Lindner, Atmospheric and Environmental Research, Inc., 840 Memorial Drive, Cambridge, Mass. 02139-3794, USA

Introduction. One of the most puzzling mysteries about the planet Mars is the hemispherical asymmetry in the polar caps. Every spring the seasonal polar cap of CO_2 recedes until the end of summer, when only a small part, the residual polar cap, remains. During the year that Viking observed Mars, the residual polar cap was composed of water ice in the northern hemisphere [Kieffer et al., _Science_, 194, 1341, 1976] but was primarily carbon dioxide ice in the southern hemisphere [Kieffer, _J. Geophys. Res._, 84, 8263, 1979]. Scientists have sought to explain this asymmetry by modeling observations of the latitudinal recession of the polar cap and seasonal variations in atmospheric pressure (since the seasonal polar caps are primarily frozen atmosphere, they are directly related to changes in atmospheric mass). These models reproduce most aspects of the observed annual variation in atmospheric pressure fairly accurately. Furthermore, the predicted latitudinal recession of the northern polar cap in the spring agrees well with observations, including the fact that the CO_2 ice is predicted to completely sublime away. However, these models all predict that the carbon dioxide ice will also sublime away during the summer in the southern hemisphere, unlike what is observed. This paper will show how the radiative effects of ozone, clouds, and airborne dust, light penetration into and through the polar cap, and the dependence of albedo on solar zenith angle affect CO_2 ice formation and sublimation, and how they help explain the hemispherical asymmetry in the residual polar caps. These effects have not been studied with prior polar cap models.

Ozone, Clouds, and Airborne Dust. Since O_3 is more prevalent in the northern hemisphere than in the southern hemisphere, O_3 was suggested as a cause for the hemispherical asymmetry in the residual polar caps by Kuhn et al. (_J. Geophys. Res._, 84, 8341, 1979). However, Lindner (submitted to _Icarus_, 1991) has shown that O_3 has a minor effect on the atmospheric temperature, and hence on the infrared radiation which strikes the polar cap, and Lindner (_J. Geophys. Res._, 95, 1367, 1990) has shown that O_3 absorbs less than 1% of the total solar radiation absorbed by the polar cap. Thus, O_3 is not an important consideration in the polar cap energy budget.

Lindner (1990) has computed the solar and thermal flux striking the polar cap of Mars for various ozone, dust, and cloud abundances and for three solar zenith angles. These calculations have been inserted in the polar-cap model of Lindner (_Eos Trans. AGU_, 67, 1078, 1986). Vertical optical depths of dust and cloud ranging from zero to 1 cause little change in the total flux absorbed by the polar cap near its edge but increase the absorbed flux significantly as one travels poleward. Observations hint that hemispherical asymmetries in dust abundance and cloud cover exist, and these would combine to cause a significant hemispherical asymmetry in the total flux absorbed by the residual polar caps, which helps to explain the dichotomy in the residual polar caps.
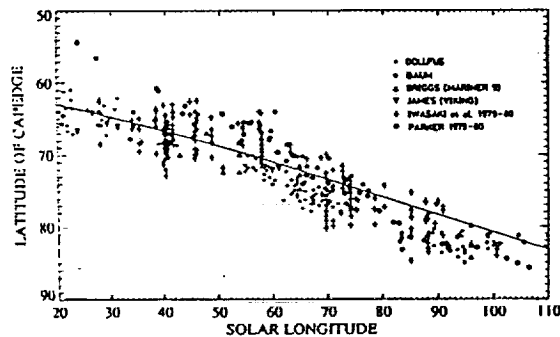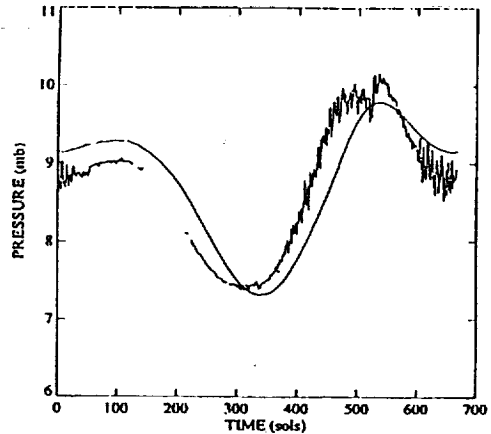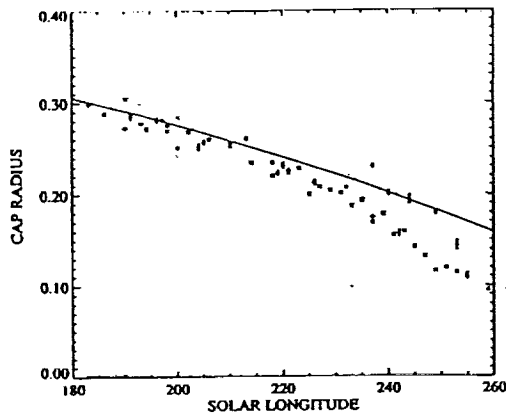
Light Penetration. Penetration of solar radiation into the cap itself is included in the polar cap model of Jakosky and Haberle (_J. Geophys. Res._, 95, 1359, 1990), based on the theoretical work of Clow (_Icarus_, 72, 95, 1987). Lindner and Jakosky (_B.A.A.S._, 22, 1060, 1990) find that the inclusion of light penetration slightly decreases the albedo needed in the model to keep CO_2-ice year-round at the south pole by on the order of 1%. The required albedo is decreased because some solar radiation is used to heat the subsurface, and not all of this heat is transported back to the surface. Overall, we conclude that penetration of light into the polar cap has only a small effect on

the polarcap energy budget.

<u>Albedo and the Solar Zenith Angle</u>. Warren et al. (<u>J. Geophys. Res.</u>, <u>95</u>, 14717, 1990) have computed the dependence of the albedo of the martian polar caps on solar zenith angle, and these calculations have been included in my polar cap model. Since the albedo of ice increases and becomes more forward scattering at higher solar zenith angles, and since the solar zenith angle becomes higher as one approaches the pole, the albedo is greatest at the pole. This decreases absorption of sunlight, hence increasing survivability of CO_2 ice. In fact, this increases the survivability of ice enough to offset the decrease in survivability of ice due <u>to radiative</u> effects of clouds and dust.

<u>Discussion.</u> The combination of the effects of solar zenith angle on albedo and the radiative effects of clouds and dust act to extend the lifetime of CO_2 ice on the south pole relatively more than on the north pole, possibly explaining the hemispherical asymmetry in the residual polar caps without the need of a hemispherical asymmetry in polar cap albedo. This does not imply that a hemispherical asymmetry in polar cap albedo does not exist, but that one is not necessary.

Observations of the regression of the polar caps and the annual cycle in atmospheric pressure are reproduced fairly well by the model, as shown in the figures, although further improvement is needed. When CO_2 ice is retained at the south pole, the model predictions of the annual cycle in atmospheric pressure have a phase shift relative to the data, no matter what model input parameters are used. We are investigating other processes not included in prior polar cap models.

Comparison of the model to atmospheric pressure (upper right), south polar cap regression (upper left), and north polar cap regression (bottom)

SUNLIGHT PENETRATION THROUGH THE MARTIAN POLAR CAPS: EFFECTS ON THE THERMAL AND FROST BUDGETS

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Abstract. An energy balance model of the seasonal polar caps on Mars is modified to include penetration of solar radiation into and through the ice. Penetration of solar radiation has no effect on subsurface temperature or total frost sublimation if seasonal ice overlies a dust surface. An effect is noted for seasonal ice which overlies the residual polar caps. For the case of an exposed water-ice residual polar cap, the temperature at depth is calculated to be up to several degrees warmer and the calculated lifetime of seasonal CO_2 frost is slightly lower when penetration of sunlight is properly treated in the model. For the case of a residual polar cap which is perennially covered by CO_2 frost, the calculated lifetime of seasonal CO_2 frost is very slightly increased as a result of sunlight penetration through the ice. Hence, penetration of sunlight into the ice helps to stabilize the observed dichotomy in the residual polar caps on Mars, although it is a small effect.

Introduction

Computer simulation of the condensation and sublimation of CO_2 frost in the martian polar caps has been fairly successful in reproducing the annual cycle in atmospheric pressure observed by the Viking Landers [Leighton and Murray, 1966; Cross, 1971; Briggs, 1974; Davies et al., 1977; James and North, 1982; Lindner, 1985, 1986]. However, these studies have not been able to uniquely explain why CO_2 frost survives summer in the southern hemisphere and not summer in the northern hemisphere. Several theories have been advanced to explain this discrepancy, including hemispherical asymmetries in albedo [Paige, 1985; Paige and Ingersoll, 1985; Lindner, 1985; 1986], in snowfall [Pollack et al., 1990], in the radiative effects of clouds and airborne dust [Briggs, 1974; James and North, 1982; Lindner, 1990; 1992], in subsurface heat conduction [Jakosky and Haberle, 1990], and in ozone [Kuhn et al., 1979; Lindner, 1988; 1990; 1991]. It is also possible that a permanent reservoir of CO_2 frost from an earlier epoch is being uncovered in the southern hemisphere, although this seems unlikely [e.g., Jakosky and Barker, 1984].

Prior models have used the assumption that all non-reflected sunlight is absorbed at the surface, when in reality sunlight penetrates into the surface, sometimes to several meters depth [Clow, 1987]. This paper describes studies of how this phenomenon affects the thermal and frost budgets of the polar caps and the subsurface.

Modeling Approach

To perform this study, the energy-balance model of Jakosky and Haberle [1990] is combined with the ice microphysics model of Clow [1987]. The energy budget at the surface of the geographic poles involves balance between absorbed sunlight, absorbed and emitted thermal-IR radiation (from the surface to space and from the atmosphere to the surface), conduction to or from the subsurface (the subsurface is taken to begin at the base of the seasonal ice), and condensation or sublimation of CO_2. The instantaneous energy balance at the surface can be written as

$$\frac{S_0}{R^2}(1-A)P(t)\cos(\iota) - \epsilon\sigma T^4(z,t) - K\frac{\delta T(z,t)}{\delta z}\bigg|_{z=0} + L\frac{dm(t)}{dt} = 0 \quad (1)$$

where S_0 is the solar constant at 1 AU corrected for atmospheric absorption and scattering [Lindner, 1985; 1990; Lindner et al., 1990]; R is the distance of Mars from the Sun in AU; A is the bolometric Bond albedo of the surface material at the pole; P(t) is the fraction of non-reflected sunlight which is absorbed by the seasonal polar cap at time t (the remainder being absorbed by the surface underneath the seasonal ice); ι is the solar incidence angle; ϵ is the effective emissivity of the surface; σ is the Stefan-Boltzmann radiation constant; T(z,t) is the temperature at depth z (surface temperature is set to the condensation temperature of CO_2 if CO_2 frost is present); K is the thermal conductivity of the surface and subsurface materials; L is the latent heat of sublimation of CO_2 frost; dm(t)/dt is the time derivative of the CO_2 surface frost abundance (set to zero when no frost is present); and the temperature gradient $\delta T/\delta z$ is evaluated at the surface (z=0).

Sunlight penetration and heat conduction into the subsurface are accounted for by

$$\frac{\delta T(z,t)}{\delta t} = \frac{1}{\rho C}\{K\frac{\delta^2 T(z,t)}{\delta z^2} + \frac{S_0}{R^2}(1-A)(1-P(t))\cos(\iota)\frac{\delta F(z,t)}{\delta z}\} \quad (2)$$

where ρ is the bulk density of the subsurface material, C is its specific heat, and $\delta F(z,t)$ is the fraction of the sunlight which

passes through the seasonal cap and is absorbed within depth δz of the subsurface. The derivatives in (2) apply locally. The values used for ρ and C of the subsurface dust are 0.93 gcm^{-3} and 0.15 cal g^{-1}K^{-1}, respectively, and K is allowed to vary depending on the thermal inertia. The albedo and thermal inertia for dust material is assumed to be comparable to the typical regolith values (0.25 and 0.006 cal cm^{-2}s$^{-1/2}$K^{-1}, respectively). The albedo and thermal inertia for a residual polar cap are taken to be like those of the north residual polar cap (0.45 and 0.03 cal cm^{-2}s$^{-1/2}$K^{-1}, respectively [see Kieffer et al., 1976; Paige, 1985]. When the model uses an albedo of 0.65 for seasonal CO_2 ice, all seasonal ice sublimes during the summer and the underlying surface becomes exposed. Hence, an albedo of 0.65 is used to simulate the case of an exposed residual polar cap. An albedo of 0.74 is needed in this model to retain seasonal CO_2 ice through the summer. While energy is deposited at depth by solar radiation, it is not effectively transported by IR radiation relative to conduction. Optical absorption coefficients are large in the IR, and temperatures are low, both of which inhibit transport by radiation. Hence, IR radiation is not included in (2). Terms in (1) and (2) other than P and F are evaluated as in Jakosky and Haberle [1990].

Clow [1987] calculated the multiple scattering of sunlight by the matrix of water-ice grains and dust particles on Mars by inserting the average single-scattering parameters for these particles into the δ-Eddington method of solving the radiative-transfer equation. Figure 1 shows the integral of net short-wave flux with respect to depth, which Clow calculated for pure snow and dirty snow (1000 ppmw dust) and for fine-grained snow (ice-grain radii of 50 μm, bulk density of 50 kg m^{-3}) and coarse-grained snow (ice-grain radii of 1000 μm, bulk density of 400 kg m^{-3}). Values for P, the fraction of non-reflected solar radiation absorbed by the seasonal polar cap, are extracted from Figure 1 using the thickness of the seasonal polar cap as predicted by the energy balance model. Values for F(z), the fraction of non-reflected solar radiation absorbed by the surface under the seasonal ice, are then computed by taking the remainder (1-P) of the non-reflected solar radiation and apportioning it with depth as shown in Figure 1.

Kieffer [1990] and Moore [1988] have both deduced that ice-grain radii in the residual polar cap are over 100 μm and that dust concentrations are less than 1/1000. This means that ice in the residual polar cap is believed to be between fine-grained and coarse-grained and between pure and dirty, as I have defined them. There is no evidence for the grain size and dust content of seasonal ice, although it is likely to be less

dirty and more fine grained than ice in the residual polar cap. I have assumed that the residual polar cap is at least several meters thick, which is believed to be the case [Toon et al, 1980].

The Clow [1987] calculations presented in Figure 1 assume water ice, perfectly valid for the residual polar cap composed of water ice. Recent calculations by Warren et al. [1990] suggest that CO_2 ice on Mars is more absorbing than water ice on Mars. Greater absorption of sunlight by ice would decrease the penetration depth of sunlight shown in Figure 1 (G. Clow, personal communication, 1992). Hence, the penetration of sunlight calculated here for seasonal ice may be an upper limit case, which enhances the conclusions as shown below.

To apply the model, (2) is numerically integrated at the geographic pole through a martian orbit around the Sun, subject to the boundary condition of (1). The model is iterated for six Mars years, by which time convergence is achieved. The subsurface is divided up into discrete layers, each of which is described by a center temperature. A 5 cm surface layer thickness is used. This is required since the layering needs to be on a finer scale than the sunlight penetration depth (see Figure 1) and the thermal skin depth. The thermal skin depth varies from 1 m to 10 m at the pole, depending on the choice of subsurface material. Succeeding layers are thicker by a factor of 1.2 each; this reaches to a depth of 37 m (over 4 annual skin depths). This subsurface thermal model produced excellent agreement to the depth profiles of temperature computed by Kieffer [1990] for the same case he presented in his Figure 3.

Results

In the case where seasonal ice overlies a dust surface, our model calculates no changes in either the frost budget of the polar cap or the thermal structure of the subsurface due to sunlight penetration. The top grains of dust under the ice absorb the solar radiation which passes through the ice, and it is much easier for these top grains to conduct or radiate heat back to the overlying ice than deep into the subsurface. Effectively, all non-reflected sunlight is absorbed by the seasonal frost, as was assumed in previous polar-cap models.

The behavior for seasonal CO_2 ice overlying a residual polar cap is different. Solar radiation which passes through the seasonal ice may penetrate quite deeply into the residual polar cap (see Figure 1). For a water-ice residual polar cap, the sunlight which penetrates the seasonal polar cap heats the residual polar cap by up to 3°K, primarily in late summer when

the seasonal ice is thinnest, with the greatest heating occurring at 1 m depth in the residual polar cap (see Figure 2). Most of the penetrating radiation actually gets absorbed near the surface of the residual polar cap, but that easily conducts or radiates away to the seasonal CO_2 ice, accounting for the low heating rate at the surface of the residual polar cap. Dirty ice exhibits the same behavior seen in Figure 2, but with only half the magnitude of subsurface heating. The results are essentially the same no matter whether fine-grained or coarse-grained ice is used. However, the heating may be less than shown in Figure 2 since the seasonal ice may be more absorbing in the visible than assumed here. Different values for thermal inertia also change the degree of subsurface heating, with lower thermal inertia producing greater heating. For a residual polar cap which contains CO_2 ice, any subsurface heating goes into subliming local CO_2 ice, and does not change the local temperature until all local CO_2 ice has sublimed.

For the case of an exposed water-ice residual polar cap, the maximum surface temperature at the pole occurs just after the last of the seasonal ice sublimes. This is also when the maximum change due to sunlight penetration occurs in the calculated temperature at depth, as shown in Figure 3. I find that surface temperatures are cooler in early summer ($L_s = 270°$ to $L_s = 310°$) for the model with light penetration than for the model which has no penetration. Solar radiation which penetrates into the subsurface must conduct to the surface to heat the surface, which is not as effective at heating the surface as direct absorption of all the solar radiation by the surface. In late summer ($L_s = 310°$ to $360°$), the surface is actually warmer for the model with light penetration, due to the increased heat conduction by the warmer subsurface. After $L_s = 360°$, the surface becomes covered with seasonal CO_2 frost. Again, the maximum subsurface heating occurs at 1 m depth in a water-ice residual polar cap.

The model which includes penetration of sunlight predicts less seasonal ice all year for the exposed water-ice residual cap case, as shown in Figure 4. By allowing solar radiation to be absorbed at depth, the surface does not become as warm in early summer when surface temperatures are their warmest. This decreases the annual-total energy lost as infrared radiation emitted by the surface and increases the amount of energy stored in the subsurface, which in turn decreases the amount of frost condensation needed in the early winter to maintain balance (see equation 1). Thus, there is an increasing difference in predicted frost abundances between the models from $L_s = 0°$ to $180°$. After $L_s = 180°$, the difference in the CO_2

Fig. 2

Fig. 3

Fig. 4

frost amount between the models decreases because some sunlight penetrates the seasonal ice to heat the residual polar cap instead of subliming seasonal ice. However, this effect is not enough to compensate for the increased conduction of heat during early winter, and the net result is that the seasonal ice sublimes away earlier in the year for the model which includes penetration of sunlight. Furthermore, seasonal ice may be more absorbing than assumed here, which will decrease heating of the residual polar cap while seasonal ice is present, resulting in a slightly larger difference between models in Figure 4. The effect of light penetration on the frost budget for dirty ice shows the same behavior as in Figure 4, but only half the magnitude.

Discussion

The inclusion of light penetration in an energy balance model slightly decreases the albedo needed in the model to keep seasonal CO_2 ice on a residual polar cap through the summer. Furthermore, the number of days that an energy-balance model calculates for which an exposed water-ice residual polar cap is free of seasonal CO_2 ice is increased by approximately 5 days when light penetration is included in the model. Thus, since the effect of light penetration slightly decreases CO_2 ice lifetimes when the ice does not exist year-round and slightly increases CO_2 ice survivability when ice does exist year-round, it also enhances the Jakosky and Haberle [1990] conclusion that there are two stable states for the residual polar caps; perennially covered by CO_2 ice or exposed every summer. These results also enhance the conclusion of Jakosky and Haberle that conduction of heat to and from the subsurface plays an important role in the energy balance of the polar cap.

Currently CO_2 ice does not survive summer on the northern residual polar cap while CO_2 ice does survive summer on the southern residual polar cap. The CO_2 ice at the south pole could have originated from an earlier epoch, but that would make the large abundances of water vapor observed in southern summer in 1969 harder to explain [Jakosky and Barker, 1984]. The inclusion of light penetration in an energy balance model makes it slightly easier for energy balance models to maintain seasonal CO_2 ice on an existing CO_2 residual polar cap, as now exists in the south, and to totally sublimate seasonal CO_2 ice on an exposed water ice residual polar cap, as now exists in the north. Hence, the effect of sunlight penetration makes it easier for energy balance models to explain the dichotomy in the residual polar caps.

While of some importance directly at the poles, the penetration of light into the polar cap has only a small effect on the globally-integrated energy budget of the polar cap, specifically the globally-integrated CO_2 sublimation and condensation as inferred by the Viking Lander measurements of atmospheric pressure and as predicted by theoretical models of the general atmospheric circulation. Given the uncertainties currently present in albedo and other parameters, the effect of light penetration is second order, and can be currently neglected in models of the globally-integrated energy budget of the polar caps. Further work remains to be done on other processes involved in the frost budget of the polar caps, as discussed in the introduction. These processes would not affect the major results of our work, but may have a significant impact on the globally-integrated frost budgets.

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Fig. 1. The integral of net shortwave flux with respect to depth for clean and dusty water snow on Mars, using the mean-annual incident solar flux at latitude -38°. Curves (A) correspond to a snow with ice grain radii of 50 μm and bulk density 50 kg m^{-3} while curves (B) are for a snow with 1000-μm ice grains and a density of 400 kg m^{-3}. (Reproduced by permission from Clow [1987]).

Fig. 2. Temperature versus depth in a water-ice residual polar cap for the case where seasonal ice sublimes completely in the summer. The surface is still covered by CO_2 ice at this time (late summer, L_S = 260°). The dashed curve is simulated by the model including the effect of penetration of solar radiation, and the solid curve is simulated by the model with no penetration of solar radiation. Surface values are shown at 1 cm depth. Seasonal ice albedo and thermal inertia is 0.65 and 0.03 cal cm^{-2} s$^{-1/2}$ K^{-1}, respectively. The flux profile for clean, fine-grained ice in Figure 1 is used for seasonal ice and that for clean, coarse ice is used for the residual polar cap.

Fig. 3. As in Figure 2, except after all seasonal ice has sublimed in the model (L_S = 280°, 37 Mars days after Figure 2).

Fig. 4. Annual variation in seasonal CO_2 frost amount at the south pole for the case where seasonal ice sublimes completely in the summer. The difference between the two models is also plotted, using the scale on the right side. The same ice properties as described for Figure 2 are used.
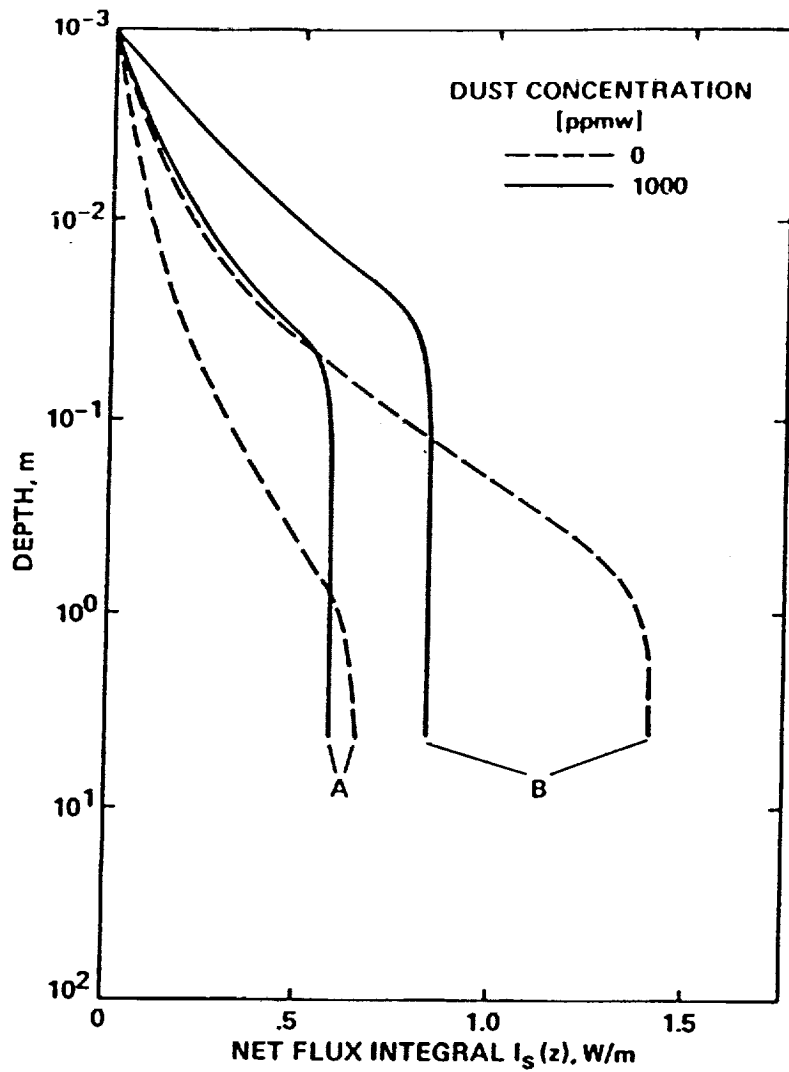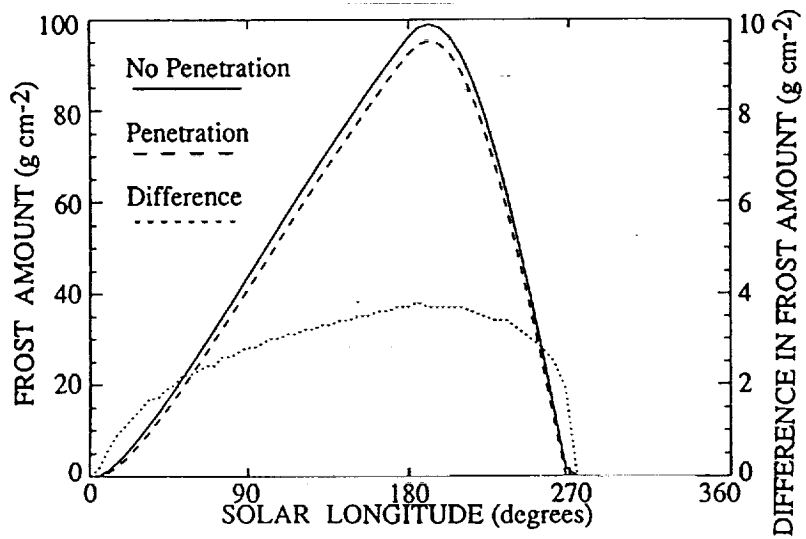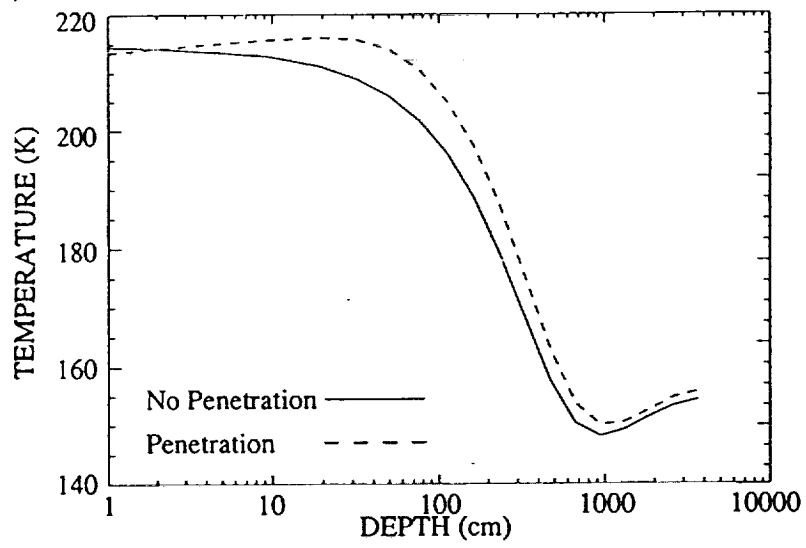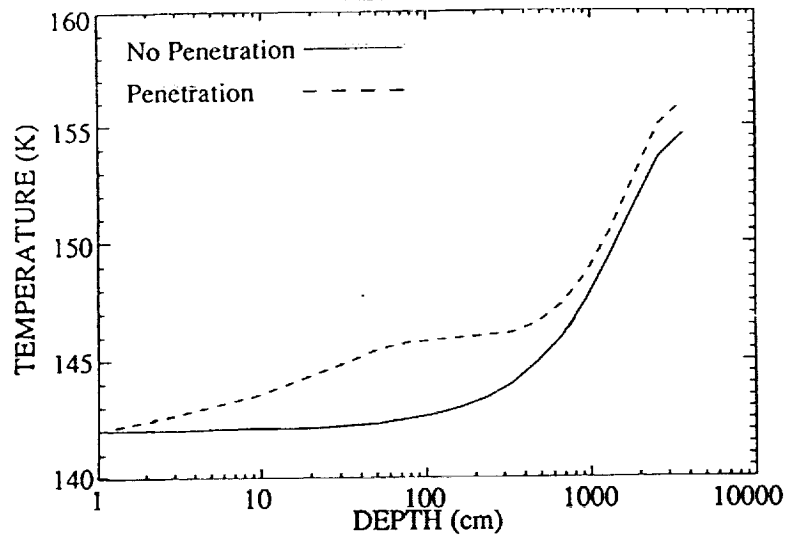
Does UV instrumentation effectively measure ozone abundance?

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Measurements of O_3 on Mars provide significant information about the chemistry and composition of the atmosphere [1], including long-term changes [2]. The most extensive and accurate data were inferred from the Mariner 9 UV spectrometer experiment, some of which are reproduced in Fig. 1. Mars O_3 shows strong seasonal and latitudinal variation, with column abundances ranging from 0.2 μm-atm at equatorial latitudes to 60 μm-atm over the northern winter polar latitudes [1] (1 μm-atm is a column abundance of 2.689×10^{15} molecules cm^{-2}).

The Mariner 9 UV spectrometer scanned from 2100 to 3500 Angstroms in one of its two spectral channels every 3 seconds with a spectral resolution of 15 Angstroms and an effective field-of-view of approximately 300 km^2. Measurements were made for almost half a martian year, with winter and spring in the northern hemisphere and summer and fall in the southern hemisphere. The detectability limit of the spectrometer was approximately 3 μm-atm of ozone. The process used by earlier investigators to extract the ozone abundance from the observed Mariner 9 spectra is as follows [1]. Each spectrum was filtered to remove spurious data points, then compared to the solar flux spectrum and shifted slightly in wavelength in order to compensate for any systematic shift in the wavelength calibration of the spectrometer. Incoming solar radiation was assumed to undergo Rayleigh scattering by CO_2 and Mie scattering by the polar hood, and to be reflected by a wavelength-independent surface albedo. The only atmospheric absorption in the 2000 to 3000 Angstrom region was assumed to come from the Hartley band system of ozone, and therefore the amount of ozone was inferred by fitting this absorption feature with laboratory data of ozone absorption, as shown in Fig. 2. O_3 absorption of sunlight is not strong enough to affect atmospheric temperature on Mars [3], and hence cannot be inferred from temperature measurements.

I use a radiative transfer model based on the discrete ordinate method to calculate synthetic radiance spectra. Figure 3 shows that when typical amounts of dust and cloud are present that significant underestimation of O_3 occurs. A factor of 3 times as much O_3 is needed to generate the

same spectrum as for a clear atmosphere. If the scattering properties of martian clouds and dust were well known, then their appearance would not be a problem, as a model would be capable of retrieving the O_3 abundance. However, these properties are not well known, which raises doubts about the effectiveness of the current UV spectroscopy technique used to measure O_3.

Spatial and temporal variability in temperature and water vapor account have been claimed to account for the scatter of the data points in Figure 1 [4]. A decrease in temperature would result in a decrease in water vapor, if saturated as expected at prevalent temperatures. A decreased water vapor abundance decreases the availability of odd hydrogen, which converts CO and O into CO_2 catalytically, decreasing the abundance of O needed to form O_3. However, water vapor is a small source of odd hydrogen in the winter polar atmosphere, and may not account for most of the variability in Figure 1 [5]. Masking by clouds and dust may also account for some of the observed O_3 variability, because the nature and opacity of the clouds and dust in the polar hood change dramatically in latitude and even on a day-to-day basis. As the maximum O_3 abundance resides near the surface [5], spacecraft must be able to observe through the entire cloud and dust abundance in order to actually see the total O_3 column abundance. If reflectance spectroscopy is used, as on Mariner 9, then the cloud and the airborne dust must be traversed twice; first by the incoming solar flux down to the surface, and then once again upon reflection from the surface out to the space-craft. In addition, the large solar zenith angles at winter polar latitudes mean several times the vertical opacity of cloud and dust must be traversed. Indeed, part of the observed latitudinal variation in O_3 in Fig. 1 may be due to the inability of the spacecraft to observe through the increasing effective optical depths as one goes poleward.

The UV spectrometer on Mariner 9 was incapable of penetrating the dust during dust storms [1]; the single-scattering albedo and phase function of airborne dust and cloud ice are not known to the degree required to extract the small UV signal reflected up from near the surface. The reflectance spectroscopy technique would also have difficulty detecting the total column abundance of O_3 in cases where large dust abundances exist together with the polar hood, especially at high latitudes where large solar zenith angles magnify those optical depths; yet these cases would

contain the maximum O_3, based on theoretical results [5]. It is quite possible that the maximum O_3 column abundance observed by Mariner 9 of 60μm-atm is common. In fact, larger quantities may exist in some of the colder areas with optically thick clouds and dust. As the Viking period often had more atmospheric dust loading than did that of Mariner 9, the reflectance spectroscopy technique may even have been incapable of detecting the entire O_3 column abundance during much of the Mars year that Viking observed, particularly at high latitudes.

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Figure 1. Measurements of the O_3 column abundance inferred from the Mariner 9 UV spectrometer data during the northern winter, $L_S = 330$-360, in the northern hemisphere (see [2]).

Figure 2. Ultraviolet spectrum measured by Mariner 9 at 57N latitude on orbit 144. To enhance the O_3 absorption feature, this spectrum was divided by one obtained at 20N latitude on orbit 144, where O_3 abundances are minimal [1].

Figure 3. Synthetic spectra as would be observed by spacecraft for atmospheres with (A) no cloud or dust and 30 μm-atm O_3, (B) vertical opacities of dust and cloud of 0.3 and 1.0, respectively, and 30 μm-atm of O_3, and (C) vertical opacities of dust and cloud of 0.3 and 1.0, respectively, and 100 μm-atm of O_3. All cases assume a solar a zenith angle of 75 (typical for winter polar observations), and viewing angle of 60, with azimuth angle of 0 (typical for Mariner 9). Polar cap albedo of 0.6.
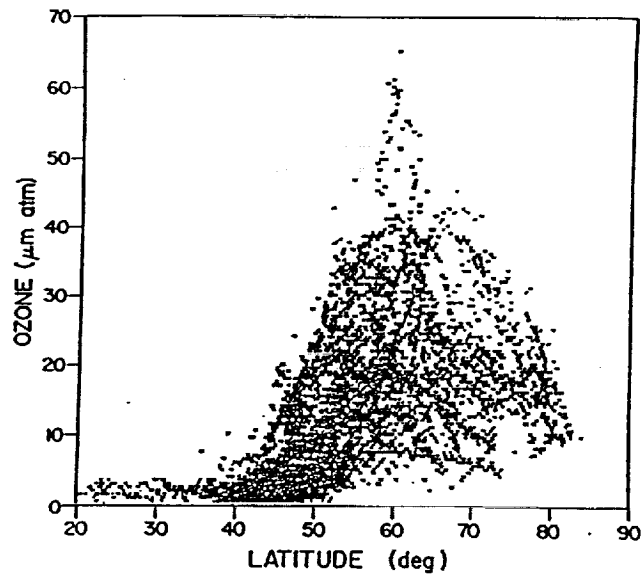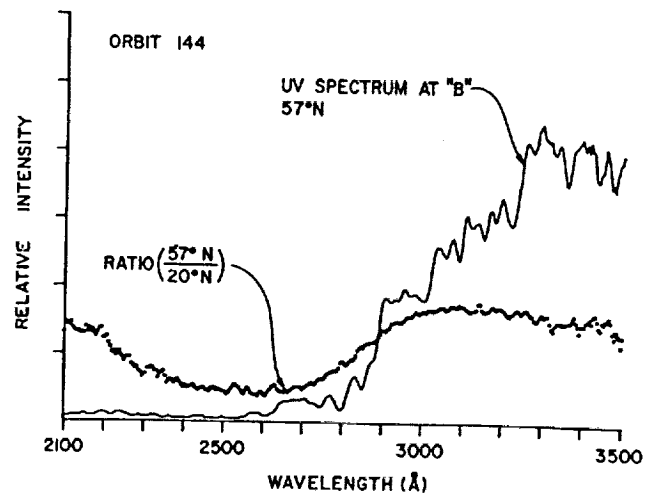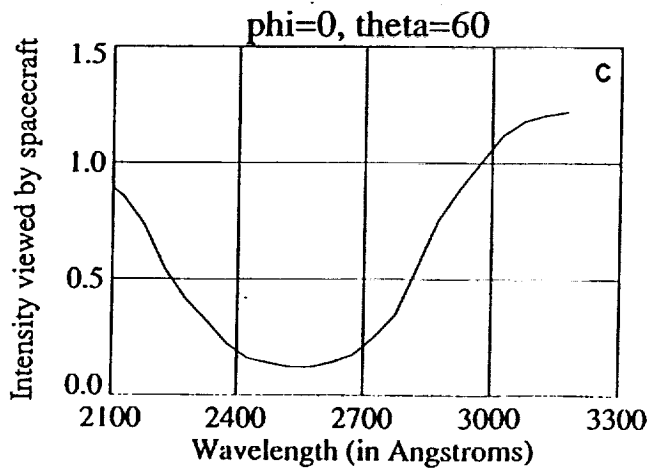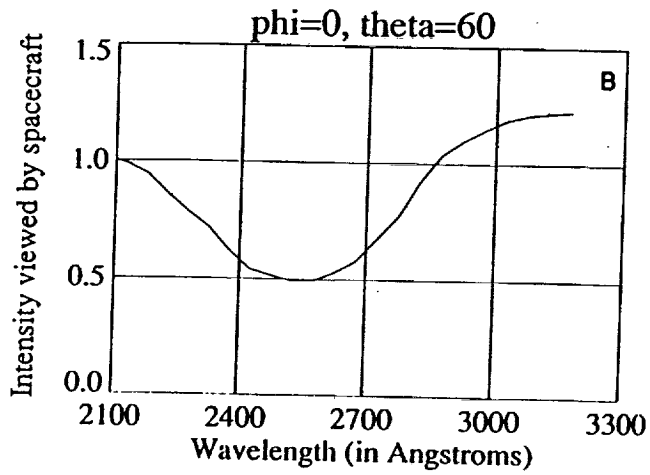
Fig. 1

Fig. 2

A — phi=0, theta=60. Intensity viewed by spacecraft vs. Wavelength (in Angstroms)

B — phi=0, theta=60. Intensity viewed by spacecraft vs. Wavelength (in Angstroms)

C — phi=0, theta=60. Intensity viewed by spacecraft vs. Wavelength (in Angstroms)
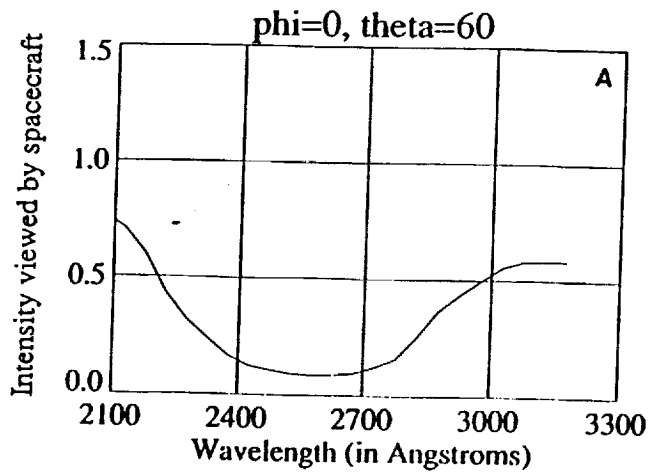
Fig. 3

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ABSTRACT: A theoretical model of the energy budget of the polar caps of Mars has been created which is used to study the hemispherical asymmetry in CO_2 ice. The observations which show survival of seasonal CO_2 ice in the southern hemisphere in summer and not in the northern hemisphere in summer have been reproduced.

1. INTRODUCTION

One of the most puzzling mysteries about the planet Mars is the hemispherical asymmetry in the polar caps. Every spring the seasonal polar cap of CO_2 recedes until the end of summer, when only a small part, the residual polar cap, remains. During the year that Viking observed Mars, the residual polar cap was composed of water ice in the northern hemisphere (1) but was primarily carbon dioxide ice in the southern hemisphere (2). Scientists have sought to explain this asymmetry by modeling observations of the latitudinal recession of the polar cap and seasonal variations in atmospheric pressure (since the seasonal polar caps are primarily frozen atmosphere, they are directly related to changes in atmospheric mass). These models reproduce most aspects of the observed annual variation in atmospheric pressure fairly accurately. Furthermore, the predicted latitudinal recession of the northern polar cap in the spring agrees well with observations, including the fact that the CO_2 ice is predicted to completely sublime away. However, these models all predict that the carbon dioxide ice will also sublime away during the summer in the southern hemisphere, unlike what

is observed, as is shown in Figure 1. This paper will show how the radiative effects of ozone, clouds, and airborne dust, light penetration into and through the polar cap, and the dependence of albedo on solar zenith angle affect CO_2 ice formation and sublimation, and how they help explain the hemispherical asymmetry in the residual polar caps. These effects have not been studied with prior polar cap models.

2. MODEL DESCRIPTION

The energy budget of the surface of Mars has been studied with a model which includes all of the processes shown schematically in Figure 2. The sources and sinks of energy for a square centimeter of surface include solar insolation which strikes the surface, modified for the absorption due to clouds and aerosols; infrared emission by the clear atmosphere and by clouds and aerosols to the surface; infrared emission by the surface to space; penetration of solar radiation into the surface; atmospheric heat transport as represented by a thermal wind; heat conduction in the subsurface; and latent heat of condensation of CO_2. The net gain or loss of energy integrated over one martian day is used to compute either a

change in the surface temperature or a change in the amount of CO_2 frost present. Details on the model are presented elsewhere (9,10,11).

Since O_3 is more prevalent in the northern hemisphere than in the southern hemisphere, O_3 was suggested as a cause for the hemispherical asymmetry in the residual polar caps (12). However, O_3 has since been shown to have a minor effect on the atmospheric temperature (13), and hence on the infrared radiation which strikes the polar cap, and it has been shown that O_3 absorbs less than 1% of the total solar radiation absorbed by the polar cap (9). Thus, O_3 is not an important consideration in the polar cap energy budget.

The solar and thermal flux striking the polar cap of Mars has been computed for various dust and cloud abundances and for three solar zenith angles (9). These calculations have been inserted in earlier versions of polar-cap models (10,11). Vertical optical
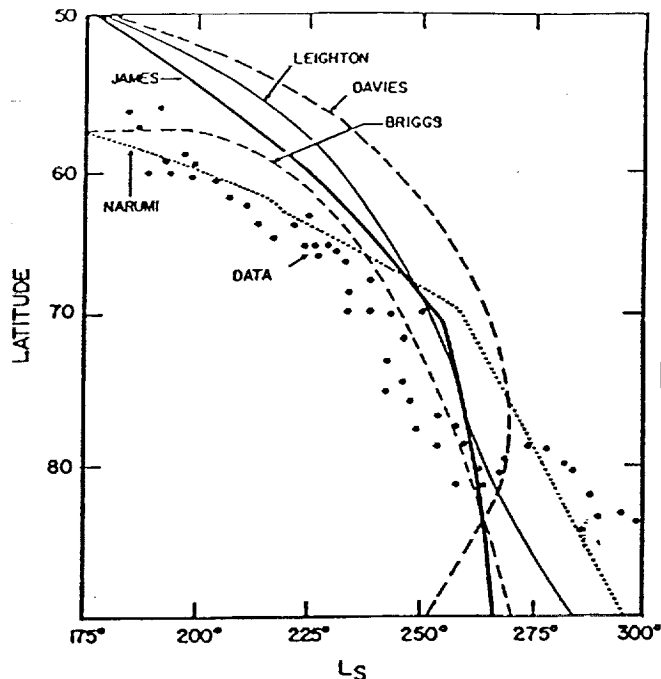

Fig. 1. The seasonal recession of the south polar cap as observed over the last 20 years (3) and as predicted by (4,5,6,7,8). (The aerocentric longitude of the sun, L_s, is the seasonal index; L_s = 0°, 90°, 180° and 270° correspond to northern spring equinox, summer solstice, autumnal equinox and winter solstice, respectively.)
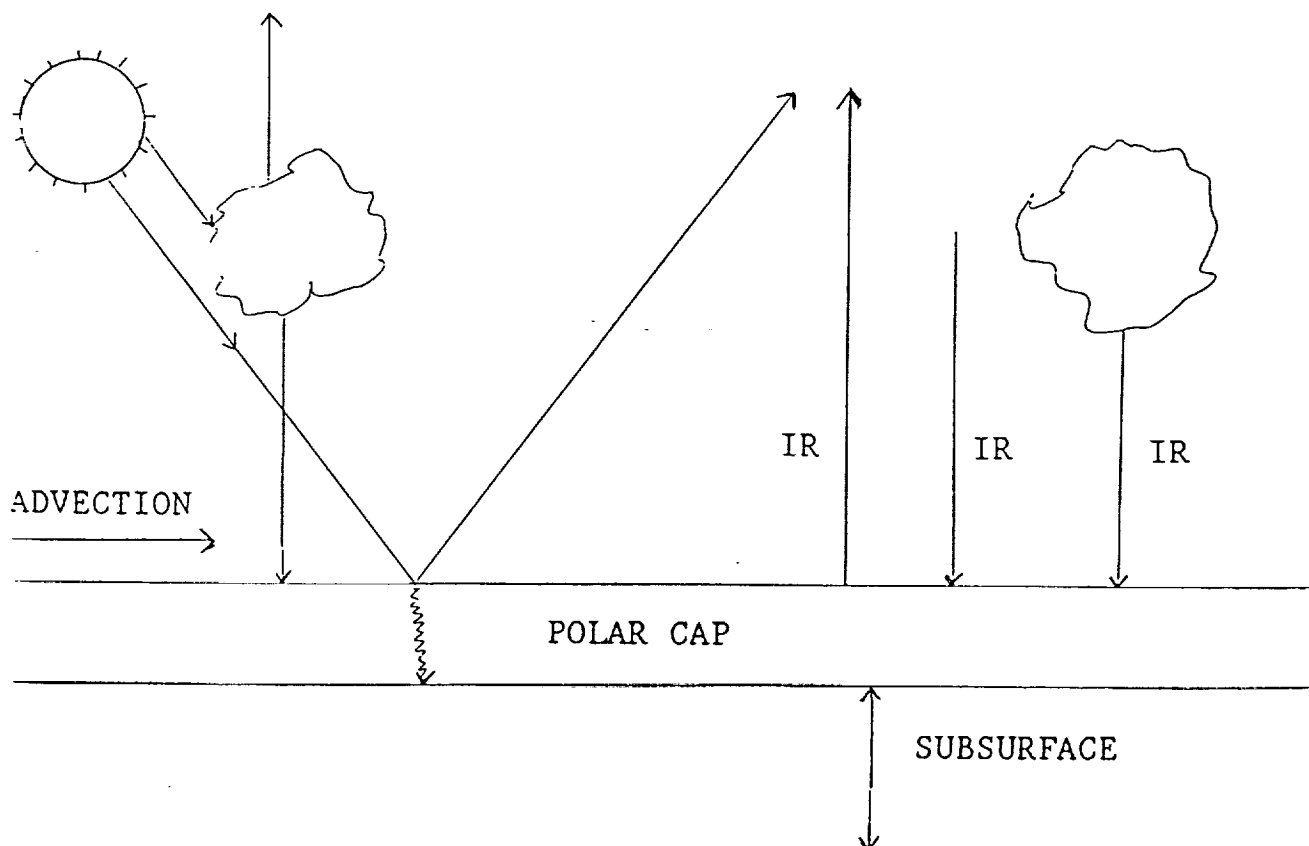

Fig. 2. Schematic of the model for the energy budget of the polar cap, showing the physical processes included.

depths of dust and cloud ranging from zero to 1 increase the absorbed flux significantly in polar night, where the pole spends half of the year, as shown in Table 1 (9). Observed hemispherical asymmetries in dust abundance, cloud cover, and surface pressure combine to cause a significant hemispherical asymmetry in the total flux absorbed by the residual polar caps (9), which helps to explain the dichotomy in the residual polar caps on Mars.

Penetration of solar radiation into the cap itself is included, based on theoretical work (14). The inclusion of light penetration slightly decreases the albedo needed in the model to keep CO_2-ice year-round at the south pole by on the order of 1%. The required albedo is decreased because some solar radiation is used to heat the subsurface, and not all of this heat is transported back to the surface. Overall, penetration of light into the polar cap has only a small effect on the polarcap energy budget.

Calculations of the dependence of the albedo of the martian polar caps on solar zenith angle (15) have also been included in the model. Since the albedo of ice increases and becomes more forward scattering at higher solar zenith angles, and since the solar zenith angle becomes higher as one approaches the pole, the albedo is greatest at the pole. This decreases absorption of sunlight, hence increasing survivability of CO_2 ice. In fact, this increases the survivability of ice enough to offset the decrease in survivability of ice due to the radiative effects of clouds and dust.

3. DISCUSSION

The combination of the effects of solar zenith angle on albedo and the radiative effects of clouds and dust act to extend the lifetime of CO_2 ice on the south pole relatively more than on the north pole, explaining the hemispherical asymmetry in the residual polar caps without the need of a hemi-

TABLE 1. Flux Striking the Surface of the Polar Cap in Polar Night (90°N Latitude, $L_s = 343°$)

Wavelength Interval, μm	Dust Opacity		
	0.0	0.2	0.5
5.4-10.0	0.0	0.7	1.3
10.0-21.0	14.7	29.4	43.4
21.0-99.9	0.0	13.5	29.9
Absorbed flux	14.7	43.6	74.7

The vertical optical depth of dust is given. Flux values are given in units of $J\ cm^{-2}\ sol^{-1}$.

spherical asymmetry in polar cap albedo. Another positive aspect of this solution is that neither the inclusion of solar zenith angle effects on ice albedo nor the radiative effects of clouds and dust should appreciably change model predictions of the annual cycle of pressure or polar cap recession equatorward of 75° latitude, since approximately 90% of the seasonal CO_2 frost is equatorward of 80° latitude. Hence, the good model agreement noted by prior researchers to the seasonal cycle in atmospheric pressure and to the recession of the polar cap equatorward of 80° latitude is retained.

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How well is martian ozone inferred with reflectance spectroscopy?

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Abstract
only

The Mariner 9 UV spectrometer scanned from 2100 to 3500 Angstroms in one of its two spectral channels every 3 seconds with a spectral resolution of 15 Angstroms and an effective field-of-view of approximately 300 km^2. The only gaseous absorption in the 2000 to 3000 Angstrom region was assumed to come from the Hartley band system of ozone, and therefore the amount of ozone was inferred by fitting this absorption feature with laboratory data of ozone absorption[1]. Mars O_3 as inferred from these spectra shows strong seasonal and latitudinal variation, with column abundances ranging from 0.2 μm-atm at equatorial latitudes to 60 μm-atm over the northern winter polar latitudes [1]. The detectability limit of the spectrometer was approximately 3 μm-atm.

I use a radiative transfer model based on the discrete ordinate method to calculate synthetic radiance spectra. When typical amounts of dust and cloud are present, significant underestimation of O_3 occurs. A factor of 3 times as much O_3 is needed to generate the same spectrum for cloudy, dusty atmospheres as for a clear atmosphere. If the scattering properties of martian clouds and dust were well known, then their appearance would not be a problem, as a model would be capable of retrieving the O_3 abundance. However, these properties are not well known, which raises doubts about the effectiveness of the current UV spectroscopy technique used to measure O_3.

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ATMOSPHERIC CHEMISTRY ON MARS

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The current state of our knowledge of atmospheric chemistry on
Mars will be reviewed, and differences with the Earth will be
highlighted. Improvements in modeling work have shown that the
excessively high atmospheric mixing required by earlier models (eddy
diffusion coefficients of 10^8 cm^2s^{-1}) to explain the atmospheric
composition observed by spacecraft is no longer necessary. Also,
recent work has shown that heterogeneous chemistry could be quite
important on Mars.

I will focus on the interactions between ozone and clouds and
airborne dust. The ozone abundance on Mars is sensitive to the
presence of clouds and airborne dust, in part due to the effects
clouds and airborne dust have on photodissociative solar radiation.
Also, the efficacy of the reflectance spectroscopy technique used in
the past to infer ozone abundance on Mars is questioned due to
masking by clouds and dust.