SPECTROSCOPY AND PHOTOCHEMISTRY OF PLANETARY ATMOSPHERES AND IONOSPHERES

The chemical composition of any planetary atmosphere is of fundamental importance in determining its photochemistry and dynamics in addition to its thermal balance, climate, origin, and evolution. Divided into two parts, this book begins with a set of introductory chapters, starting with a concise review of the Solar System and fundamental atmospheric physics. Chapters then describe the basic principles and methods of spectroscopy, the main tool for studying the chemical composition of planetary atmospheres and of photochemical modeling and its use in the theoretical interpretation of observational data on chemical composition. The second part of the book provides a detailed review of the carbon dioxide atmospheres and ionospheres of Mars and Venus and the nitrogen-methane atmospheres of Titan, Triton, and Pluto. Written by an expert author, this comprehensive text will make a valuable reference for graduate students, researchers, and professional scientists specializing in planetary atmospheres.

Now retired, VLADIMIR A. KRASNOPOLSKY was previously a research professor in the Department of Physics at the Catholic University of America, Washington, DC. An expert on spectroscopy and photochemical modeling, he is the author of 3 books, 6 book chapters, and 182 refereed publications. He is one of the most highly cited scientists working on planetary atmosphere research and was awarded the USSR State Prize in 1985 for his studies of Venus. He has worked on many space missions throughout his career and was the principal investigator of the airglow spectrometer on the Mars 5 spacecraft and the Venera 9 and 10 missions to Venus, the three-channel spectrometer on the Vega mission to Venus, and the infrared spectrometer on the Phobos 2 orbiter.

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Mars, Venus, Titan, Triton, and Pluto

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Preface

1 About the Book

This book is based on the author's experience in the field and is intended for senior and graduate students and research scientists specializing in planetary atmospheres. The book comprises two parts, the first of which includes 10 chapters: three chapters (Chapters 1, 2, and 8) present some basic science on the Solar System, atmospheric physics, and effects of solar radiation in atmospheres; five chapters (Chapters 3, 4, 5, 6, and 7) are related to spectroscopy and spectroscopic tools to study atmospheres; and two chapters (Chapters 9 and 10) describe photochemical modeling.

Some chapters are sufficient for practical work in our science, while the others are brief introductions or reviews. For example, the review of different types of spectrographs in Chapter 6 may help in making a choice for a given task but is not supportive for detailed instrument design.

Five chapters of the second part of the book include present data on the structure and composition of the atmospheres and ionospheres of Mars, Venus, Titan, Triton, and Pluto, respectively. There are hundreds of research articles on the subject; my goal was to describe concisely the basic facts with indications of how they were obtained. Therefore only some papers are cited, and many are missing. However, I hope that these chapters on specific atmospheres are complete and will help the reader gain time in studying an atmosphere of interest. This book is not a substitute for the current research literature on specific problems that a researcher may study.

2 About Me

I was born in 1938 in Moscow, Russia (which was part of the Soviet Union at that time). In June 1941, Germany, which controlled most of continental Europe, attacked Russia, approaching the Moscow suburbs in November of that year. My father was an engineer in the aviation industry. The loss of Moscow seemed imminent, and so his institution, with all its employees and their families, moved east to Saratov, a city on the Volga River. However, during the following autumn in 1942, the Germans reached Volgograd

(Stalingrad), where the most critical battle of World War II was to take place. It was to the south of Saratov, and the German bombers appeared from time to time over our city. We returned to Moscow in 1943.

A hundred boys graduated from my school in 1955, and four of us were awarded gold medals and four silver medals. (The schools were separate for boys and girls. My gold medal was number one.) The school program covered the basic sciences and was rather broad, and our classrooms for physics and chemistry were well equipped.

I was a student of the Department of Physics, Lomonosov Moscow State University, in 1955–61. Besides attending lectures and seminars, we spent one day weekly in a physics practicum. For example, Millikan's experiment to measure electron charge was assigned to a student, and he or she was given a booklet with a description of the experimental idea and the equipment to study at home. Then the student had six hours to study the installation directly, make measurements, analyze them, and report the results to a tutor. That was during the first 3 years; later students chose their fields in physics and participated in research at proper university labs or at research centers in Moscow. I took some courses in theoretical physics from the famous theorist Lev Landau. His lectures made the exciting suggestion that physics could be created using only logic and math.

In 1961, I joined a lab headed by Professor Aleksandr Lebedinsky at the Nuclear Research Institute of Moscow State University. Lebedinsky was excited by perspectives of space studies of the Solar System, and our work was not related to nuclear physics. I was a radio amateur during my student years and had some experience in designing and adjusting electronic devices, which proved to be advantageous in developing scientific instruments for space missions. In June 1961 Lebedinsky told me that a mission to Venus with a landing on the planet had been planned for a launch in August 1962 – science fiction at that time. Lebedinsky visited M. V. Keldysh, president of the Academy of Sciences, and proposed a simple instrument to distinguish landing on the solid surface from landing on water. The instrument was based on a mercury level with platinum contacts. The circuit was on if the probe was horizontal within $\pm 3°$ (water) and off on a solid surface with a mean deviation of $\approx 15°$.

Keldysh approved the proposal, and Lebedinsky asked me to be technically responsible for the instrument. I was happy and proud to do that work. Finally, the instrument could also measure the period and amplitude of waves on water and gamma radiation of the surface rocks if the surface was solid. Its mass of 550 g looks reasonable even now. However, the fourth stage of the rocket failed, and the mission was lost. The Mariner 2 flyby of Venus in December 1962 indicated that the intense radio emission of Venus originates in the lower atmosphere, not in the ionosphere, and the hot lower atmosphere rules out liquid water on Venus.

Attempts to reach Venus and Mars continued in Russia, and Lebedinsky was principal investigator (PI) of a UV spectrometer (170–340 nm) onboard the Venera 2 (flyby) and of a photometer on Venera 3 (descent probe) missions. I was technically responsible for both instruments. (Here I exclude other of Lebedinsky's experiments that did not include my participation.) Both missions were launched in November 1965 and were lost before they approached Venus. A mission to Mars was planned to be launched in 1965 as well; however, the launch window was lost because of some delays, and the spacecraft was directed to the Moon as the Zond 3 mission. We had the UV spectrometer at Zond 3 and gathered UV spectra of the Moon's rocks. The UV spectrometer was also installed onboard two Cosmos orbiters that were launched in 1965 and 1966 and gave the first satellite data on the global ozone distribution. In June 1967, I defended my PhD thesis; two months later, Lebedinsky had a heart attack while swimming in the Black Sea and passed away.

Our team prepared a UV spectrometer for the unsuccessful Mars 1969 mission and a dayglow multiband photometer for one of the Cosmos orbiters. In 1971, I transferred to the Space Research Institute, to its planetary department headed by Professor Vasiliy I. Moroz. I proposed and became PI of the visible nightglow spectrometers for the Mars 5 and Venera 9 and 10 orbiters that reached Mars in February 1974 and Venus in October 1975, respectively. Mars' nightglow was not detected with some sensitive upper limits, while the observations of Venus revealed the nightglow spectra, their morphology, and some data on lightning and haze. Analysis and interpretation of the observations and photochemical modeling of the atmospheres of Mars and Venus (with V. A. Parshev), including two books (*Photochemistry of the Atmospheres of Mars and Venus*, Moscow: Nauka, 1982; Berlin: Springer, 1986; *Physics of the Planetary and Cometary Airglow*, Moscow: Nauka, 1987), took up most of my time through the mid-1980s. In June 1977, I defended my thesis for the degree doctor of physics and math, and in 1985, I was awarded the USSR State Prize (for studies of Venus).

In 1981, Russia initiated a complicated Vega mission that involved delivery of a balloon and a descent probe to Venus, while the remaining spacecraft moved to comet Halley using Venus' gravity. A few European countries and the United States participated in the scientific payload of the mission. I was Russian PI of a three-channel spectrometer to study the spatial distribution of various species in the coma of comet Halley. French and Bulgarian teams with their PIs, G. Moreels and M. Gogoshev, respectively, contributed very significantly to that instrument. Two twin spacecraft were launched in December 1984, reached Venus in June 1985, and flew through the coma at 8000 km from the nucleus of comet Halley in March 1986.

Detection of the H_2O emission band at 1.38 μm and total production of water by the comet were among our results. (There had been indirect evidence of water in comets, but direct detection had been lacking.) At a conference on comet Halley in 1987, I was deeply impressed by reports by M. J. Mumma, H. P. Larson, and H. A. Weaver, who observed the H_2O band at 2.7 μm using a high-resolution spectrometer at the Kuiper Airborne Observatory. Except for total production of water, they measured its temperature using the rotational line distribution, gas expansion velocity using the Doppler shift, and temperature of formation using the para-to-ortho hydrogen ratio, offering proof that high spectral resolution can be advantageous even relative to a close distance to the object during missions to planets.

We had an infrared spectrometer for solar occultations at Phobos 2 that orbited Mars for two months in 1989. Vertical profiles of water vapor and dust had been observed. The mission was complicated, and its goal to study Phobos at a close distance down to 50 m with laser evaporation and analysis of the surface material was not achieved.

Three Russian scientists, including me, were invited to be co-investigators for the Voyager 2 flyby of the Neptune system in August 1989. I joined the ultraviolet spectrometer (UVS) team, headed by A. L. Broadfoot, and analyzed the UVS solar occultations of Triton's atmosphere and the data on Triton's haze. Later a photochemical model of Triton's atmosphere and ionosphere was made (with D. P. Cruikshank).

Conditions in Russian science degraded significantly in the 1990s, and I transferred to the United States in 1991. There I was impressed by difficult but possible access to high-level Earth-orbiting observatories, from which some observations could give results that otherwise would require a special instrument on a mission to a planet.

We detected helium on Mars using the Extreme Ultraviolet Explorer (EUVE), and the related modeling showed that He on Mars originates from the captured solar wind alpha particles, not from the radioactive decay of uranium and thorium, as was previously supposed. Then we detected atomic deuterium and molecular hydrogen on Mars using the Hubble Space Telescope (HST) and the Far Ultraviolet Spectroscopic Explorer, respectively. A superior-quality spectrum of Mars dayglow was observed at 90–120 nm as well. Those results changed some aspects of the hydrogen photochemistry and hydrogen isotope fractionation that are related to the evolution of water on Mars. The first UV spectrum of Pluto at 180–255 nm was observed using the HST as well.

Our EUVE and CXO (Chandra X-ray Observatory) observations of comets and analyses of other CXO observations resulted in significant progress in understanding the nature of the unexpectedly bright and initially puzzling X-ray and EUV emissions from comets and in abundances of the solar wind heavy ions that originate these emissions.

Ground-based spatially resolved high-resolution spectroscopy is another powerful tool to study the atmospheres of planets. My long-term observations of Mars and Venus were conducted at the NASA Infrared Telescope Facility using CSHELL and TEXES spectrographs and at the Canada–France–Hawaii Telescope using FTS. The observations of Mars involved variations of the O_2 dayglow at 1.27 μm as a tracer of photochemistry, variations of CO as a tracer of the subpolar dynamics, dayglow of CO at 4.7 μm, detection of CH_4 as a tracer of possible microbial life, and variations of HDO/H_2O related to the evolution of water. The observations of Venus referred to the cloud tops and included the first detections of NO and OCS at these altitudes and variations of CO, HCl, HF, H_2O, and SO_2; night airglow of O_2 at 1.27 μm and OH; dayglow of CO at 4.7 μm; and isotope D/H ratios in H_2O, HCl, and HF.

Significant efforts were made to photochemically model the atmospheres and ionospheres of Mars, Venus, Titan, Triton, and Pluto. Modeling of some other phenomena, e.g., hydrodynamic escape from Pluto, excitation of X-rays in comets by electron capture by the solar wind heavy ions, and excitation of oxygen emissions on the terrestrial planets, has been done as well. Using the British system, with all achievements equally divided among coauthors, my citation index is the best in the field of planetary atmospheres.