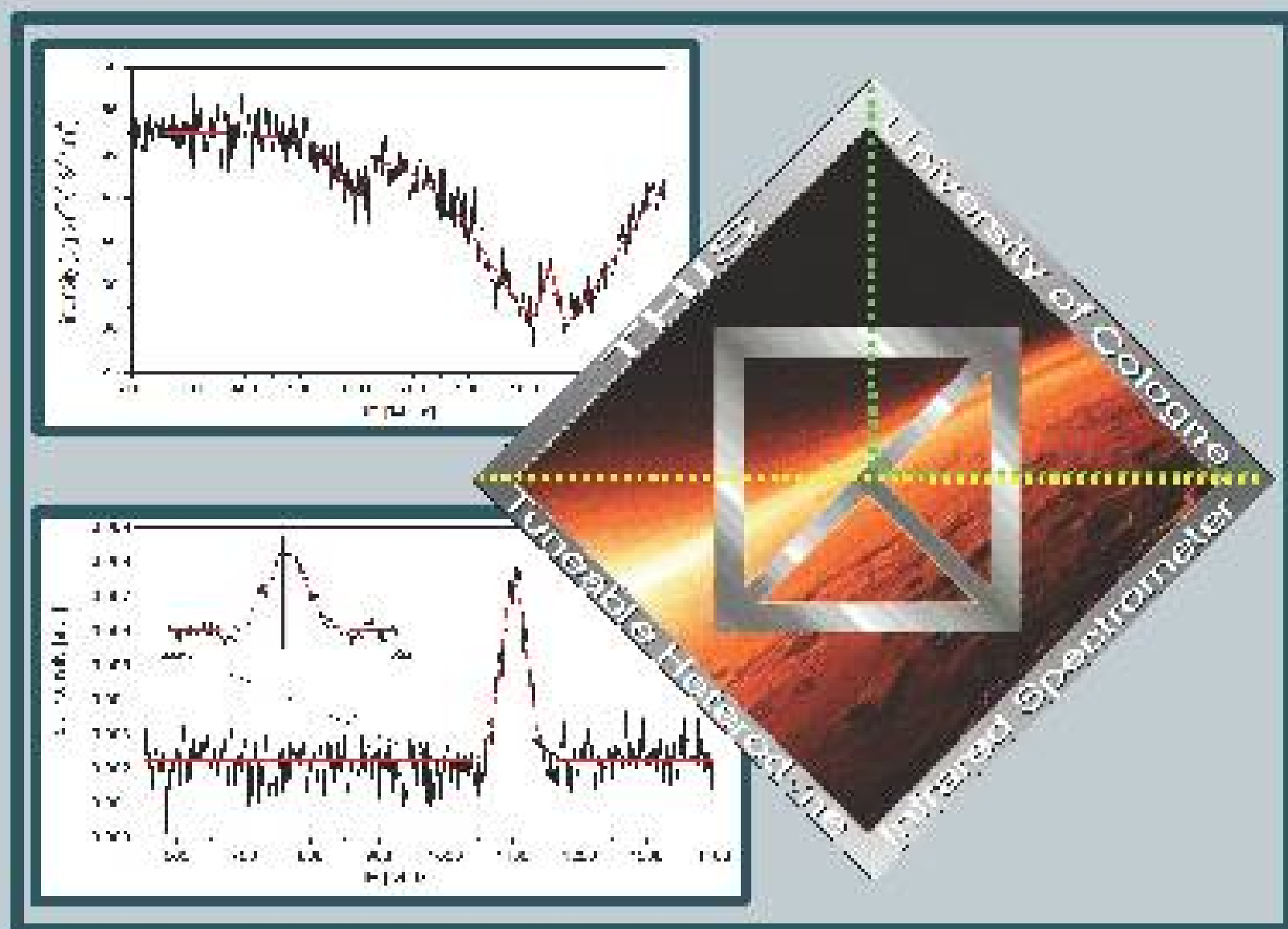


Investigations of Upper Atmosphere Dynamics on Mars and Venus by High Resolution Infrared Heterodyne Spectroscopy of CO₂



Investigations of Upper
Atmosphere
Dynamics on Mars and Venus
by
High Resolution Infrared
Heterodyne Spectroscopy of CO₂

In a u g u r a l - D i s s e r t a t i o n

zur

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Abstract (German)

Ein gutes Verständnis planetarer Atmosphären ist eine Grundvoraussetzung zur Entwicklung von Prognosemodellen. Vorhersagen aus diesen Modellen wiederum tragen wesentlich zum globalen Verständnis dieser Atmosphären bei. Ausgehend von Modellen für die Erdatmosphäre hat die Anpassung und Entwicklung dieser Modelle für Mars und Venus in den letzten Jahren große Fortschritte gemacht.

Wesentlichen Einfluss hatten dabei verbesserte Beobachtungsmöglichkeiten und Raumfahrtmissionen. Zum einen werden Orientierungsdaten für die Parametrisierung benötigt und zum anderen bedürfen Modelle der Bestätigung durch Messwerte. Erdgebundene Beobachtungen insbesondere in höheren Bereichen der Atmosphäre sowie Langzeitbeobachtungen sind daher eine wichtige und kostengünstige Ergänzung zu Weltraummissionen, um Modellvorhersagen zu überprüfen und zukünftige Missionen vorzubereiten.

Eine elegante Methode zur sonst nur schwer möglichen direkten Messung von Windgeschwindigkeiten ist die Beobachtung von nicht-thermischen CO₂ Emissionslinien im Infrarotbereich mit Frequenz hochauflösender Heterodynspektroskopie. Aus beobachteten Dopplerverschiebungen der Frequenzen dieser Linien kann direkt auf die Geschwindigkeiten der CO₂ Moleküle rückgeschlossen werden. Im Unterschied zu Beobachtungen im Radio-Wellenlängenbereich kann im Infraroten auch die notwendige hohe räumliche Auflösung erreicht werden. Zudem ist die ermittelte Windgeschwindigkeit der einzelnen Positionen am Planeten unabhängig von zusätzlichen Informationen wie Temperatur- und Druckprofilen.

Ein derartiges Infrarot Heterodyn Empfängersystem mit dem Namen THIS (Tuneable Heterodyne Infrared Spectrometer) wurde am I. Physikalischen Institut der Universität Köln aufgebaut und im Rahmen dieser Arbeit weiterentwickelt, sodass nunmehr regelmässige Beobachtungen der Mars- und Venusatmosphäre mit diesem Instrument möglich sind.

Die Ergebnisse von Windmessungen in den Atmosphären von Mars und Venus aus insgesamt vier Beobachtungskampagnen im Zeitraum von 2005 bis 2008 werden in dieser Arbeit präsentiert. Die Messungen wurden so weit wie möglich in Koordination mit anderen Beobachtungstechniken durchgeführt und sowohl mit deren Resultaten als auch mit Modellergebnissen verglichen.

Bei Resultaten der Venusbeobachtung stand dabei der Vergleich mit anderen Beobachtungsmethoden, vor allem innerhalb der "Coordinated ground-based campaign to support Venus Express" im Vordergrund, da für Venus noch keine verlässlichen Modellergebnisse in der höheren At-

mosphäre zur Verfügung stehen. Die gemessenen Werte sind im Vergleich zu anderen Beobachtungen grundsätzlich etwas niedriger und im Gegensatz zu diesen konnte nur eine moderate zeitliche Variabilität festgestellt werden.

Im allgemeinen hat die koordinierte Beobachtungskampagne gezeigt, daß die Dynamik der Venusatmosphäre viel komplexer ist, als bisher angenommen. Daher sind zusätzliche Daten besonders bzgl. zeitlicher Variabilität von Windgeschwindigkeiten notwendig. Weitere Messkampagnen mit THIS sind bereits geplant.

Im Gegensatz zu Venus liefern Marsmodelle hingegen mittlerweile sehr detaillierte Informationen bezüglich verschiedenster atmosphärischer Parameter. Die Resultate unserer Beobachtungen konnten die Vorhersagen eines Modells vom Laboratoire de Météorologie Dynamique du CNRS(Paris) in weiten Bereichen bestätigen. Bei Auswertung und Interpretation der Daten wurde dabei hohes Wert auf die Zusammenarbeit mit Modellierern gelegt. Es hat sich gezeigt, dass Messungen mit THIS für eine noch detailliertere Überprüfung der Modelle in Zukunft einsetzbar sind.

Abstract (English)

Understanding of the physical and chemical processes in planetary atmospheres is essential for the development of general circulation models (GCM) and meteorological forecast models. Adopting Earth models to the atmospheres of Mars and Venus has been improved substantially over the last few years due to constraints imposed by improved technology of ground-based observations and data that became available from several space missions.

Observational constraints of the models especially at high altitudes are needed for parametrization and validation. These data can only partially be provided by spacecrafts. Earth-based observations in other atmospheric regions or long term observations are a necessary and cost-efficient complementary observational method to constrain the models and to prepare for future space missions and landers.

An elegant method to measure high atmospheric winds is by observing infrared CO₂ absorption and emission lines with high spectral resolution heterodyne spectroscopy. From line frequency (Doppler) shifts velocities of the emitting and absorbing gas can be directly deduced. In contrast to microwave observations an adequate spatial resolution can be achieved in addition to the high spectral resolution with the infrared heterodyne observing technique. Therefore the retrieved wind velocities at each observed position on the planet are independent from additional assumptions like temperature or pressure profiles.

Such an infrared heterodyne instrument named THIS (Tuneable Heterodyne Infrared Spectrometer) has been developed at the I. Physikalisches Institut at the University of Cologne and has been improved within this work to a level where regular observations of the Martian and Venusian atmosphere are now possible.

Wind velocities measured in the atmospheres of Mars and Venus during four observation runs within a time period from 2005 to 2008 are presented in this work. Observations were accomplished in coordination with other observing techniques and results are compared with them as well as with output parameters of model calculations.

For Venus observations mainly comparison with results from other ground-based observations, in particular within the coordinated ground-based campaign 2007 to support Venus Express, are made due to a lack of reliable model results at higher altitudes. Measured wind values in general are lower than those from other observing techniques and compared to them only a moderate variability with time was observed.

The coordinated ground-based campaign generally showed that the dynamic in the Venusian atmosphere is much more complex than believed

before. Hence additional data especially concerning temporal variability of wind velocities are needed. Further observing campaigns with THIS are already in preparation.

On the contrary global circulation models of the Martian atmosphere have already reached a high level and provide detailed information about various atmospheric parameters. The results of our wind observation validate the predictions of one models developed at the Laboratoire de Météorologie Dynamique du CNRS (Paris) over wide range. Data analysis and data interpretation emphasized exchange with modelers and it has been shown that measurements with THIS are a valuable tool for the future to validate and proof these models even in more detail.

Chapter 1

"If you thought that science was certain - well, that is just an error on your part." (Richard Feynman (1918-1988), American Physicist)

Introduction

Knowledge about properties and processes that shape conditions on Earth gives us the ability to arrange our lives to them. To know about natural[h] potentials (e.g. energy generation, natural resources), to predict conditions (e.g. weather forecast, natural disasters, climate changes) and to understand correlations is the base to use our planet without abusing it.

The arising question now is: "What could be the reason to study other planets?"

- Knowledge about other planets will increase the understanding of our own planet. The physics behind processes on different planets are the same as on Earth. They are determined by parameters like characteristic location in the solar system, specific spin/orbital dynamics, chemical composition and distribution, geological properties and activity, energy budget, etc. Studying other planets will lead to *crossfertilization* of ideas between different planetary environments.
- The description of a global system like the climate is established by complex models. The precision of such models is especially important if predictions are needed (e.g. forecast). Application of the same modeling methodology to more than one planet with enough "common ground" between them opens a new field for validation

and verification and leads to a better understanding of the entire system.

- Eventually, we will need to extend our living space beyond the planet Earth. Therefore the exploration of our solar system neighborhood is mandatory.
- And not to forget there is the natural human "thirst for knowledge" which has always and will always motivate mankind to explore and to find answers to open questions.

Therefore, studying other planets is important for a comprehensive understanding of nature and future environmental developments.

The closest planets which can be addressed are Venus and Mars. Having solid bodies surrounded by a thin layer of atmosphere, Venus, Mars and Earth are called the terrestrial planets. Though different in many ways they show several likenesses. Some relevant parameters are listed in Tab. 1.1.



Figure 1.1: Shown are the terrestrial planets Venus, Earth and Mars (from left to right). The mean radius of the planets are given. Realistic relative sizes are pictured for comparison (NASA [1]).

Venus and Earth have almost the same size whereas the Martian radius is half of the others. The axial tilt of Mars and Earth is substantial and similar causing e.g. seasonal changes while Venus is more or less upside down with only a small inclination to the ecliptic. Also, Venus is the only planet in the solar system to rotate retrograde, i.e. versus its orbital rotation. The orbital rotation period of Venus is very long (243 Earth