

論文内容要旨

(NO. 1)

氏名	高見 康介	提出年	令和 2 年
学位論文の 題 目	Retrieval of wind velocity in Venusian nightside mesosphere from CO ₂ absorption observed by mid-infrared heterodyne spectroscopy (中間赤外ヘテロダイン分光による CO ₂ 吸収線を用いた金星中間圏夜面風速の導出)		

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要旨

This study presents a new attempt to retrieve Doppler wind velocity as well as temperature profile in the Venusian nightside from CO₂ absorption spectra resolved by mid-infrared (MIR) heterodyne spectroscopy. The target sensitivity of the Doppler wind velocity retrieval aims to constrain the vertical transition of the wind regime at altitudes below 100 km where the retrograde super-rotational zonal (RSZ) wind changes to the subsolar point to the antisolar point (SS-AS) flow. We aimed to achieve the wind velocity and temperature retrieval requirements with an accuracy better than ± 50 m/s and ± 15 K. These requirements are based on the following considerations. For the wind velocity retrieval, a numerical model study showed that the transition between the RSZ wind and the SS-AS flow occurred at an altitude of ~ 90 km (Alexander, 1992). The wind profile in the dawn side was gradually varied from ~ 50 m/s westward at 80 km to ~ 50 m/s with eastward direction at 100 km. For observational identification of this transition, the accuracy of the wind velocity retrieval should be better than ± 50 m/s. For the temperature retrieval, we considered the VEX SPICAV result which found the warm layer as a reference. This was 30–70 K higher than temperature obtained by previous measurements, and it was interpreted to be caused by the

adiabatic heating during the air subsidence of the SS-AS flow (Bertaux et al. 2007; Gérard et al. 2017). For observational identification of such warming, the retrieved temperature accuracy should be better than ± 15 K.

A method which was supposed in Nakagawa et al. (2016) was used in this study for retrievals of temperature and wind velocity profiles from CO₂ absorption spectra. They showed feasibility of retrieval for Venusian and Martian atmosphere, but do not refer to its verification. Based on the errors originating from uncertainties in a priori profiles, we estimated achievable sensitive altitude and retrieval accuracy using model spectra generated from various temperature and wind profiles with different noise levels. The evaluation suggested that temperature profiles can be retrieved at altitudes of 70 - 95 km range with vertical resolution of 5 km and retrieval accuracy of ± 15 K. The assumed nominal noise level was $1.0 \text{ erg/s/cm}^2/\text{sr/cm}^{-1}$. For data with a higher signal-to-noise ratio (higher radiance and/or lower noise level), the retrieval accuracy can be improved and the upper boundary can be extended to 100 km. By contrast, the wind velocity profile was more difficult to obtain but still could be retrieved at an altitude of approximately 85 km with a vertical resolution of 10 km. For data with a higher signal-to-noise ratio, the retrieval accuracy became better, changing from ± 50 m/s for noise levels of $1.5 \text{ erg/s/cm}^2/\text{sr/cm}^{-1}$ to ± 25 m/s for noise levels of $0.5 \text{ erg/s/cm}^2/\text{sr/cm}^{-1}$. This result provides the first validation of a method for wind velocity retrieval in the Venusian mesosphere at altitudes of 85 - 95 km.

We applied our retrieval method to Venus MIR spectra obtained by HIPWAC observations in May 2012 with data partially in common with the study by Stangier et al. (2015). We confirmed that our retrieved temperature profiles were in good agreement with the results of Stangier et al. (2015) obtained by different retrieval and also with radio occultation studies at coordinate observed point by Pätzold et al. (2007). The agreements supported validity of our method. Next, we retrieved the wind velocity at the altitudes of 80 - 95 km. The retrieved results at 33° S and 3 LT are 35 ± 28 m/s at 84 ± 6 km and 144 ± 70 m/s at the altitude of 94 ± 7 km, corresponding to the SS-AS flows at both altitudes. This result is unexpected because it is in the opposite direction of the RSZ wind. The retrieved results at 67° N and 0 LT were 66 ± 73 m/s at 80 ± 7 km and 112 ± 69 m/s at 90 ± 7 km, indicating the potential meridional circulation toward the equator at both altitudes. These velocities were consistent with the wind profile obtained by GCM of Gilli et al. (2017), but the retrieved wind at 33° S was stronger. Our results suggested that the transition region between the RSZ wind and the SS-AS flow is found lower than 90 km which had been predicted to be the transition altitude.

We conducted observation by our MIR heterodyne instrument MILAHI at the summit of Haleakalā on November 11 - 13, 19, and 20, 2018 targeting wind velocity at the evening terminator in the Venusian mesosphere. Observed points were equator (EQ) at LT of $\sim 22:00$ on November 11 - 13, 33° N at LT of $\sim 23:00$ on 19, and 33° S at LT of $\sim 23:30$ on 20. We could retrieve wind velocities

from four spectra obtained on November 11, 12, 13, and 20. Retrieval showed wind velocities larger than 65 m/s from EQ11 and 150 m/s from EQ12, EQ13 and 33S20. Although mesospheric wind velocity has been expected to approach smaller than 50 m/s from the RSZ wind between 75 km and 95 km by numerical model of Alexander (1992), this observation suggested that there is much stronger wind velocity larger than 150 m/s. We cannot classify the retrieved wind as the RSZ wind or the SS-AS flow due to same wind direction of the dynamics on the dusk side. There is also the possibility of superposition of two dynamics.

This study established the method of retrieving wind velocity and temperature in the Venusian mesosphere using MIR heterodyne spectroscopy by means of radiative transfer and Levenberg-Marquardt method. The retrieved altitude is the region where wind velocity along line of sight has not been observed by remote sensing so far due to its technical difficulty. Additionally, we studied mesospheric wind on both dawn side and dusk side. Retrieved wind velocities were strengthened toward a direction corresponding to the SS-AS flow on both sides. This study could conduct only one observation campaign at each side. We should conduct more MIR heterodyne observations in order to verify dynamics in the mesosphere and investigate temporal and spatial variations. Our advantage is to be able to observe the mesospheric wind continuously by dedicated telescope: Tohoku university 60-cm telescope. The investigations give us important information for comprehensively understanding Venus upper atmospheric structure.

本論文は、中間赤外ヘテロダイン分光法による地上観測から金星中間圏の夜面風速を導出する手法の精度を検証し、これを実際の観測に適用して初めて金星中間圏風速を直接観測することを目的としたものである。具体的には以下の成果を上げた。

1. 風速導出手法の精度検証

金星中間圏の風速は $10\ \mu\text{m}$ 帯の CO_2 吸収線プロファイルからインバージョン法によって気温とともに導出する。導出の目標精度は、風速 $\pm 50\ \text{m/s}$ 、気温 $\pm 15\ \text{K}$ とした。これは、風速についてはこの領域が下層のスーパーローテーション（西向き $50\ \text{m/s}$ 程度）から上層の昼夜間対流（東向き $50\ \text{m/s}$ 程度）への遷移領域であることからその変化を判別するため、気温については過去の観測でそれ以前より $30\text{--}70\ \text{K}$ 高温の層が観測されたことからこれを判別するためである。

精度を検証するには「真値」が分かっている必要があるため、ここでは気温・風速の異なる 533 個の計算スペクトルを用意し、これにノイズを付加したものに対して気温と風速の導出を行い、その結果と「真値」との差を統計的に処理して精度を評価した。その結果、まず気温についてはノイズレベル $1.0\ \text{erg/s/cm}^2/\text{sr/cm}^{-1}$ のスペクトルに対して高度 $70\text{--}95\ \text{km}$ において高度分解能 $5\ \text{km}$ で $\pm 15\ \text{K}$ の精度で導出できることが分かった。また、より低いノイズレベルの場合は導出高度範囲が $100\ \text{km}$ まで広がることを確認した。一方、風速に関しては高度範囲は $85\ \text{km}$ 付近のみであるものの高度分解能 $10\ \text{km}$ で $\pm 50\ \text{m/s}$ 以下の精度で導出できることが分かった。また、ノイズレベルが $0.5\ \text{erg/s/cm}^2/\text{sr/cm}^{-1}$ であれば $\pm 25\ \text{m/s}$ の精度が達成できることも分かった。これにより、この手法で金星中間圏 $85\text{--}95\ \text{km}$ において風速が導出できることを検証した。

2. 金星中間圏風速の観測

1. で検証した手法を実際の金星観測スペクトルに適用し、金星中間圏風速を導出した。まず、2012 年 5 月に NASA/IRTF 3 m 望遠鏡と HIPWAC ヘテロダイン分光計を用いて行われた観測に対して気温・風速を導出した。その結果、気温については過去の結果と一致し、本研究の手法の妥当性を確認した。風速については初の導出であるが、高度 $80\text{--}95\ \text{km}$ で昼夜間対流方向の風速が観測された。この結果は、スーパーローテーションから昼夜間対流への遷移高度が従来考えられてきた $90\ \text{km}$ よりも低いことを示唆している。

次に、2018 年 11 月に著者自身が行ったハレアカラ T60 望遠鏡と MILAHI ヘテロダイン分光計を用いた観測にこの手法を適用した。この観測では未説明の誤差が存在したが、その誤差を考慮してもやはり昼夜間対流方向の比較的強い風速が観測された。また、この解析を通じて今後の観測手法や装置の改善点に関する貴重な知見が得られた。

本論文は、 CO_2 吸収スペクトルから金星中間圏の夜面風速を導出する手法の精度を検証し、高度 $85\ \text{km}$ 付近で精度 $50\ \text{m/s}$ で導出可能であることを示した。さらにこれを実際の観測スペクトルに適用し、この高度では昼夜間対流が卓越していることを示した。論文・プレゼンテーションの内容は、背景となる物理の理解、結論および将来展開への提案等、水準に達するもので、著者が自立して研究活動を行うに必要な高度の研究能力と学識を有することを示している。

以上の理由により、高見康介提出の博士論文は、博士（理学）の学位論文として合格であると認める。なお、本論文の主要部は Earth, Planets and Space 誌に出版済である。