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論 文 内 容 要 旨

In this report we outline our work on spectral libraries of solar system planets and moons and the possible applications to exoplanets.

The primary goal of our research group is to conduct astronomical observations from Dome Fuji (also known as Dome F) in Antarctica. In 2010, we successfully deployed AIR-T-40: The 40 centimeter Antarctic Infra-Red Telescope. With AIR-T-40, it will not be possible to observe faint objects, such as high redshift galaxies. As such we will focus our observations on bright objects such as planets.

However, we learned through reviewing the literature that the data for planet spectra observations are not well organized. While all of the planets, and many smaller objects within the solar system, have been observed, these observations were carried out by dozens if not hundreds of separate research groups. The most complete libraries we were able to find contain data for at most four planets. Simply gathering together spectra for all of the planets from the available literature is difficult. Moreover, observing techniques vary from one group to the next. The resolution, wavelength coverage, response vary from one group to the next. Perhaps more importantly the data processing also differs slightly from one group to the next. (For example, some researchers publish spectra data, some publish reflectivity data, and some normalize to a continuum to highlight particular spectral features). Even within a single observation group, observation techniques change with time.

All of these factors make it difficult, and potentially misleading, to compare data from different reports. In addition, in many cases we had to consult data from the 1970's and 1980's.

To prepare for our Antarctic research, we needed a comprehensive planet spectra library. Therefore we undertook to compile such a library. The Tohoku-Hiroshima-Nagoya Planet Spectra Library (THN-PSL) is the world's first comprehensive library containing data for all of the planets taken with the same instrument and telescope combination. The THN-PSL covers a wavelength range from 0.45 μm to 2.5 μm. Data for dwarf planets and moons was also included where available. We show that on the basis of infrared color alone it is possible to classify the planets as either gas, ice or soil planets.

In addition to our Antarctic research, recently there has been renewed interest in planet spectra, as a reference for exoplanets. Researchers have succeeded in obtaining photometric and spectroscopic data for a small number of exoplanets. We analyze this data in the context of the THN-PSL.

Our work on the THN-PSL proved the merit of spectral libraries. We extended our work further into the visible with observations at Gunma Observatory. These observations form the Tohoku Gunma Planet Spectra Library (TG-PSL). The TG-PSL covers a wavelength range from 400 nm to 800 nm. In addition to all of

the planets, data for Ceres, Luna and Saturn's Ring are also included.

We are able to compare the TG-PSL to results from the EPOXI satellite. While the overall agreement is good, the EPOXI direct observations of Earth are significantly redder than the spectra we calculate from earthshine observations. We explore the possible reasons for this difference. We confirm the findings of other researchers that visible colors can be used to classify the solar system planets and exoplanets. However, the TG-PSL data introduces new data points (Ceres and Saturn's Ring) which cause degeneracies in the classification scheme. Fortunately, most of these can be resolved with supplemental data from the near infrared.

We searched for the answers to two specific questions in the TG-PSL: using visible light is it possible to distinguish between cloudy gas planets (Jupiter, Saturn, Titan) and hazy gas planets (Uranus, Neptune)? And using visible light is it possible to distinguish between Venus like planets and ice planets? We determined it is possible to distinguish between cloudy and hazy gas planets. However, the difference between Venus's colors and ice planet colors is minimal at best.

In addition to their own scientific merits, these spectral libraries have succeeded in inspiring observations for AIR-T-40 at Dome Fuji. Our Antarctic observations offer unique advantages to study topics of current interest in planetary science.

From Dome Fuji it is possible to observe Venus uninterrupted for weeks during the White Night. This is an advantage no other observatory can match for studying the superrotation of Venus's atmosphere.

Methane of an unknown, possibly biological, origin appeared on Mars in 2003. The key to studying this CH_4, is by observing its absorption band at 3.31 μm. Unfortunately this falls between the K and L bands, but simulations show that the Antarctic atmosphere is exceptionally clear at these wavelengths. We are developing the Antarctic Infra Red Camera, AIR-C, to take advantage of this new observation window.

While these questions are scientifically important in their own right, understanding Venus's superrotation and the origin of Mars's CH_4 have broader implications for our understanding of exoplanets.

Using AIR-T-40 we plan to observe secondary transits to gather photometric data in the Rc-J bands. While the THN-PSL shows this color to be useful for characterizing planets, we have not been able to find this color data published for any exoplanets.

論文審査の結果の要旨

本論文は太陽系内天体の広範囲にわたる可視と赤外線の分光観測を基に、太陽系天体の分類法を確立するとともに、その分類法を太陽系外惑星に応用し、それらの物理的性質を解明する方法を論述している。太陽系内天体の観測データは過去、多数得られてきているものの、これまでの観測は波長や分光分解能の異なる様々な観測装置を用いて観測されたものであり、太陽系天体を統一して理解するためのデータは取られていないことを本論文は指摘している。特に、公開されている可視・赤外線データの太陽系分光データはわずか 4 つ惑星のみであった。近年、系外惑星の観測が進み、それらの性質を理解するためには、その標本となるべき太陽系天体の分光サンプルが必須であることに本論文は着眼している。そこで本論文では可視光と赤外線が同時に分光できるユニークな観測装置 (TRISPEC) を用いて、地球を含む太陽系天体の惑星すべてと月を含む衛星の多くの分光観測を行い、その分光データを公表した。ひとつの装置、ひとつの解析方法で太陽系の全惑星を観測したのは世界初であり、その業績は高く評価された。さらに可視光の短波長側にも観測を広げ、太陽系内天体の分光ライブラリを完成した。分光ライブラリを使って天文学で広く使われている可視光と赤外線での測光バンドに準拠した色-色図を求め、その特徴から太陽系天体は、土の惑星、氷の惑星、ガスの惑星に分類できることを初めて示し、その理由を論述している。さらに本論文ではこれらの分類方法が系外惑星の分類に応用できることを示している。系外惑星の直接撮像の例は少なく、特に太陽系天体のように恒星の光を惑星が反射した光をとらえた観測例はない。しかし、将来、大型の地上望遠鏡や系外惑星の観測に特化した衛星望遠鏡などで系外惑星の反射光をとらえることができれば、本論文での分類方法は即、応用できるものと期待される。

以上の論文の内容は、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。したがって、Lundock Ramsey Guy 提出の博士論文は、博士 (理学) の学位論文として合格と認める。