論　文　内　容　要　旨

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学位論文の 題　　　目	Studies of variation mechanisms of the Jovian radiation belt based on radio-interferometric and optical observations （電波干渉計と光学観測による木星放射線帯変動メカニズムの研究）		

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Abstract

Jupiter's synchrotron radiation (JSR) is the emission from relativistic electrons in the strong magnetic field of the inner magnetosphere, and it is the most effective probe for remote sensing of Jupiter's radiation belt from the Earth. Although JSR has been thought to be stable for a long time, recent intensive observations for JSR reveal short term variations of JSR with the time scale of days to weeks. *Brice and McDonough* [1973] proposed a scenario for the short term variations (hereafter the B-M scenario): the solar UV/EUV heating for Jupiter's upper atmosphere drives neutral wind perturbations and then the induced dynamo electric field leads to enhancement of radial diffusion. If such a process occurs at Jupiter, brightness distribution of JSR is also expected to change. That is, it is suggested that the induced dynamo electric field produces dawn-dusk electric potential difference and the dawn-dusk asymmetry in the electron spatial distribution. Then dawn-dusk asymmetry of the brightness distribution of JSR is produced. Previous studies have confirmed the existence of the short term variations in total flux density and its variation corresponds to the solar UV/EUV variations [*Miyoshi et al.*, 1999; *Tsuchiya et al.*, 2011]. However, confirmation of the scenario is limited. The purpose of this study is to examine the B-M scenario based on radio interferometer and optical observations, and reveal precise physical processes of the inner magnetosphere.

Total flux density of JSR

We made simultaneous observations of the Giant Metrewave Radio Telescope (GMRT) and the NASA InfraRed Telescope Facility (IRTF) in 2011 and 2014, in order to reveal whether the Jovian thermosphere responses to the solar UV/EUV and whether this actually causes variations of the total flux density and brightness distribution of JSR.

In the 2011 campaign, the total flux density of JSR at 610 MHz increased from Nov. 6 to Nov. 13 by about 5%, corresponding to the solar UV/EUV variations. Intensity of H_3^+ also increased and temperature variation was estimated to be about 10 K. These results support the B-M scenario. On the other hand, peak position of brightness distribution of JSR shifted outwards, which is inconsistent with enhancement of radial diffusion. We considered the possibility that the outward shift might be due to the enhancement of some strong inside loss processes and examined it using the radial diffusion model from the Fokker-Planck equation. The results showed that the expected lifetime inside loss process is 10^5 sec for 10 MeV

electrons. We examined the lifetime for the interactions with the Halo dust and waves. The expected lifetime for interaction with the Halo dust is too slow for the strong inside loss process (the order of 10^9 sec), however, if charged dust acts as coulomb interaction, loss rate of the dust interaction might be faster. Concerning the wave particle interaction, the expected strong diffusion limit is about 700 sec around the peak positions of JSR [*Schulz*, 1974] which is sufficiently shorter than the required lifetime, the interaction also might cause the inside loss process.

In the 2014 campaign, the total flux density, rotational temperature of H_3^+, and solar EUV flux showed a similar decreasing trend until Jan. 10. These results support the B-M scenario. On the other hand, the total flux density and the temperature increased after Jan. 12 even when the solar EUV flux decreasing almost monotonically. A numerical simulation study of the Jovian upper atmosphere suggests that the high latitude Joule heating is induced by solar EUV radiation, and it affects the mid-low latitude thermosphere [*Tao et al.*, 2014]. The enhancement of the temperature and the total flux density after Jan. 12 might be caused by the high latitude heating. In addition to that, if high latitude heating is caused by some processes other than the solar UV/EUV, it is expected that this also affects the mid-low latitude temperature and the radiation belt: one of such the effects might be brought by enhancement of field aligned currents flowing into the high latitude region, which is driven by some global magnetospheric variations.

From combined simultaneous observations, we found that the solar UV/EUV enhancement causes the variations in thermospheric temperature and intensity of JSR had correlation, which is consistent with the B-M scenario. It is also suggested that two points should be taken into account in addition to the original B-M scenario: strong inside loss processes and the high latitude heating effect on the mid-low latitude thermosphere.

Averaged dawn-dusk asymmetry of JSR

We made the VLA data analysis to investigate the effect of the diurnal wind system on averaged dawn-dusk peak emission ratio. From the VLA data analysis, it is found that averaged dawn-dusk ratio is larger than unity, which supports the B-M scenario. Then, we estimated the diurnal wind velocity from the observed dawn-dusk ratio by using the equatorial brightness distribution model of JSR constructed in this study. The estimated neutral wind velocity is a few ten m/s, which reasonably corresponds to the numerical simulation of Jupiter's upper atmosphere [*Tao et al.*, 2009]. It is therefore suggested that the averaged dawn-dusk asymmetry is caused by the steady diurnal wind system and its wind velocity is expected to be a few ten m/s.

Short term variations in the dawn-dusk asymmetry of JSR

We tried to find the mechanism of short term variations in the dawn-dusk asymmetry of

JSR. The correlation between solar EUV flux and dawn-dusk ratio of JSR was examined by using the VLA archived data observed in 2000. From the data analysis, it is shown that variations of the dawn-dusk ratio did not correspond to those of the solar UV/EUV flux: the observed variation feature of the dawn-dusk ratio cannot be simply explained by the solar UV/EUV heating, which is not consistent with the B-M scenario. The atmospheric modeling study by *Tao et al.* [2009] also suggests that neutral wind variation corresponding to the observed solar UV/EUV variation is insufficient to cause the observed short term variations of the dawn-dusk ratio.

Then, as a new candidate, effect of a global dawn-dusk electric field in the Jovian magnetosphere was examined. We analyzed the simultaneous observational data of the GMRT and HISAKI in 2014. We used dusk-dawn EUV emission ratio of the Io torus as an index of dawn-dusk electric field. We found that the dusk-dawn emission ratio of the Io plasma torus showed local maximum around Jan. 2 and Jan. 12, and increase and decrease tendencies of the dusk-dawn ratio of JSR also corresponded to those of the Io plasma torus. The variations of dusk-dawn ratio of JSR were about 0.04, which corresponded to the electric field variations of 4 mV/m. This value is consistent with *Schneider and Trauger* [1995], which reported the fluctuation of dawn-dusk electric field of $¥pm$ 2 mV/m from the observations of the Io plasma torus. Hence, the dawn-dusk electric field is expected to affect the short term variations in the dawn-dusk asymmetry of JSR. The driving mechanism of the dawn-dusk electric field is still unknown, however solar wind dynamic pressure and/or plasma outward flow from the Io orbit might be the candidate of the generation of the dawn-dusk electric field.

Throughout this study, especially following points are deferred to future studies which lead to further understanding of physical mechanisms in the Jovian radiation belt and thermosphere. More precise temperature measurement and detection of the wind velocity variations are needed for further confirmation of the B-M scenario, which provide the observational evidence whether the thermospheric disturbance of temperature and wind velocity can cause the radial diffusion of energetic electrons. It is also expected that if some other processes cause enhancement of field aligned currents flowing into the high latitude region, such processes drive the high latitude heating and affect the mid-low latitude thermosphere. Furthermore, particle precipitation into the mid-low latitude, heat transportation from the high latitude, and atmospheric gravity wave should take into account. These attempts are directly linked to understand the heating mechanism of the Jovian thermosphere which has been unknown for a long time.

論文審査の結果の要旨

木星には地球同様に高エネルギー粒子が多量に含まれる放射線帯が存在する。この粒子は探査機に多大な損傷を与えるため、放射線帯は直接観測が難しい領域であり、強い磁場の下で粒子が放射するシンクロトロン電波(JSR)の観測が放射線帯環境を探る重要な手段となっている。従来、JSR は変化に乏しいものと見なされてきたが、近年の観測から数日スケールの変動が含まれることが明らかにされ、この短期変動を引き起こす物理過程の究明が新たな課題となっている。本論文はこの未確定の短期変動過程について、特に 1970 年代に提唱され、その真偽が不明確であった一つの仮説に対する観測的査定を行うことにより、短期変動過程の解明を試みた研究である。この仮説は太陽紫外線量の変化が木星放射線帯を変動させることを提唱した説である。そのシナリオは「太陽紫外線は木星超高層大気の加熱源となり昼夜間対流等の風を駆動するが、紫外線変化が風系を変化させ、粒子衝突を介して電離圏プラズマに変化を及ぼす。この変化が磁力線を介して放射線帯粒子の拡散を進行させ、結果として短期変動を生じさせる」とするものだが、紫外線変化による大気の加熱や風系の変化、また、対応した放射線帯変化の観測的実証は今まで為されていなかった。

本研究では、木星超高層大気の変化については米国の大型赤外望遠鏡 IRTF を用いた赤外線観測を、放射線帯変動についてはインドの大型電波干渉計 GMRT を用いた JSR 観測を同時期に実施した。この観測の解析と、放射線帯粒子運動の数値解析および共同研究者と行った太陽紫外線による超高層大気加熱の数値解析に基づく考察から、1)太陽紫外線変化に伴い大気加熱が起こっている可能性が高いこと、同時に、2)放射線帯に拡散の進行が生じること、を明らかにし、仮説が正しいことを観測的に実証した。しかし、その一方で、提唱された仮説ほど実際の短期変動過程は単純ではないことも併せて示した。即ち、3)短期変動に関係する中～低緯度の超高層の大気加熱は太陽紫外線によるものだけでなく、高緯度域への荷電粒子降込みによるジュール加熱とその低緯度域への伝搬も効く可能性があること、4)木星にごく近い放射線帯内には拡散した粒子を効率的に消失させる未知の過程が存在しなければならないこと、を新たに見出した。更に、米国の大型電波干渉計 VLA で過去に観測された JSR のデータと、日本の惑星観測望遠鏡衛星「ひさき」が観測した木星磁気圏プラズマのデータの解析から、5)放射線帯粒子は太陽紫外線による超高層加熱が原因となり平均的には朝夕非対称に分布すること、但し、木星磁気圏プラズマの移動に関係した大規模電場の変動によりその粒子分布に変化が生じる可能性があること、も新たに見出した。3)～5)は今後の更なる観測的な確認が必要であるものの、2016 年以降に予定される木星直接探査の観測課題とも関連を持つ、将来展開が期待される重要な成果である。

本論文の主たる成果は、これまで国内外の学会・研究会で公表されるとともに、一部は学術論文として国際誌に公表済み、また、複数の学術論文として国際学術誌に投稿準備中である。これらは論文提出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、北 元 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。