氏名・(本籍)	つちやふみのり 土屋史紀
学位の種類	博士(理学)
学位記番号	理第1241号
学位授与年月日	平成21年4月22日
学位授与の要件	学位規則第4条第2項該当
研究科，専攻	
学位論文題目	Development of Iitate Planetary Radio Telescope and investigation on the dynamics of Jupiter's radiation belt (飯舘惑星電波望遠鏡の開発および木星放射線帯ダイナミクスの研究)
論文審査委員	(主査) 准教授 三澤浩昭 教授 岡野章一，笠羽康正 准教授 熊本篤志

論文目次

論 文 内 容 要 旨

Non-thermal particle accelerations in space are one of central issues of space plasma and magnetospheric physics. Charged particles trapped by the closed magnetic field of the planets are accelerated into relativistic energies and form radiation belts. In Jupiter's magnetosphere, intense radiations are stably trapped in the inner magnetosphere. One of the outstanding questions on Jupiter's radiation belt is what causes the time variability in the radiation belt, particularly in the short-time scale of a few days to a month (*e.g.* Bolton *et al.* 2004). Magnetospheric phenomena with such a time scale will be related to energy transfer processes from the sun and the solar wind to the planetary atmospheres and magnetospheres. Although the short-term variation has been actually identified by the previous radio observations of Jupiter's synchrotron radiation (JSR) (Klein *et al.* 1997, Miyoshi *et al.* 1999, Misawa and Morioka 2000, Galopeau and Gerard 2001, Bolton *et al.* 2002), mechanisms to cause the short-term change are not understood. The current theory shows that it is difficult to account for the increase and the subsequent decrease in JSR on the short-time scale (de Pater and Goertz 1994). In order to clarify the cause of the short-term changes in the radiation belt, it is necessary to make detailed observation of them. While the variability in the radiation belt on this time scale has been difficult to observe by spacecraft, ground-based observations of JSR are the most useful tool for investigating it.

Based on these considerations, it is necessary to develop a radio telescope which has a high sensitivity enough to observe the total radio flux and spectrum of JSR in low frequency ranges and to investigate the origin of the short-term variations in Jupiter's radiation belt. For the purpose of this, Iitate Planetary Radio Telescope (IPRT) which measures radio waves in the frequency range from 300 to 800 MHz was developed at the Iitate observatory of Tohoku University (Iitate village, Fukushima prefecture, Japan; 37°42'N, 140°41' E) (Misawa *et al.* 2001). JSR has mainly been observed in high frequency ranges above 1 GHz, except for campaign-based observations, and only a few regular observations have been done below 1 GHz (Misawa and Morioka 2000, Nomura 2007). Some previous observations suggested that observations of JSR at low frequencies might reveal the time variable behavior in the radiation belt (Schardt and Goertz, 1983, de Pater *et al.* 2003). In addition, it is expected that the time variability of the radio spectrum including the low frequency has important information on the physical process in the radiation belt (*e.g.* Bolton *et al.* 2004). It is therefore expected that regular observations by IPRT provide us new information on the dynamic behavior of Jupiter's

radiation belt.

The purposes of this thesis are listed as follows:

1. Development of observation systems (radio telescope antenna and receivers) in order to enable the absolute total flux measurement of JSR in low frequency ranges and evaluation of their performance.
2. Establish the observation method to extract the total flux density of JSR considering errors such as background confusions and instrumental instabilities, and continuous observation of JSR to identify the characteristics of the short-term variations.
3. Investigation on origins of the short-term variation in Jupiter's radiation belt by using a 2-dimensional radial diffusion model which includes fundamental physical processes on a radial transport and losses of the trapped electrons.

IPRT is fully steerable offset paraboloid radio telescope.

The antenna of IPRT is composed of two separate rectangular sections whose total physical aperture area is 1023 square meters and installed on an altitude-azimuth mount. Receiver systems at 325 and 785 MHz were set up at IPRT in 2002 and 2006, respectively. The receiver system has a function to measure the system gain and noise temperature, which compensates the long-term change in the receiver characteristics.

Developments of the primary feed antenna and the low noise amplifier (LNA) installed in the front-end receiver had been done by the previous studies (Watanabe *et al.* 2001, Kudo 2003, Misawa *et al.* 2003, Imai *et al.* 2006). The performances of IPRT have been evaluated as follows:

- The aperture efficiencies of IPRT were evaluated to be about 65 and 40 ¥% for the 325 and 785 MHz system, respectively, and typical system noise temperatures are 150 and 100 K at 325 and 785 MHz, respectively. Based on these evaluation, the minimum detectable flux is confirmed to be 0.1 Jy (1 Jy = 10^{-26} W m^{-2} Hz^{-1}) under the receiver bandwidth of 10 MHz and integration time of 10 seconds.
- The pointing accuracy at 325 MHz is sufficiently good since the intensity fluctuation caused by the pointing error is at most ~1 %. The accuracy at 785 MHz is somewhat marginal since it will cause 3 - 8% intensity fluctuations at the beam center. The intensity fluctuation caused by the pointing uncertainty was actually confirmed to be < 1% at 325 MHz.
- The actual sensitivity of the receiving system was examined by the Allan test and found the typical sensitivity of 0.4-0.5 Jy and the minimum of 0.2 Jy when the receiver was in stable states. It is known that the total flux density of JSR varies between 3 and 6 Jy (*e.g.* Bolton *et al.* 2002). Therefore, it is confirmed that the sensitivity of IPRT is suitable for detecting natural variations in JSR.

The regular observations of JSR have been started from 2003 with the 325 MHz system and 2007 with 785 MHz. In this thesis, observations with dual-frequency system in 2007 are described in detail. Jupiter and standard flux calibrators were observed with the drift scan method. Besides the observation of JSR itself, the galactic background flux just behind Jupiter was also observed in order to compensate the background confusion by subtracting it from the observation data of JSR. From the observation, we found the results listed as follows:

- We established the observation method to extract the total flux density of JSR considering uncertainties caused by the background confusions and instrumental instabilities.
- From the observation of JSR in 2007, It is found that the flux density of JSR at both frequencies showed short-term increases and subsequent decrease with a time scale of several days and amplitude of ±20 -

30%.

- Comparison between the variability in JSR and the solar UV/EUV indices shows the positive correlation, but the variations in JSR were preceded by those of the solar indices by several days. This time delays are identified for the first time by the observation at IPRT.
- Some enhancements in JSR suggest the time response to changes in dynamic pressure of the solar wind. This suggests the interesting possibility that the solar wind influence is responsible for short-term variations in JSR on time scales of a few days to a week.

Further continuous observations of JSR are needed to elucidate such a behavior observed at low frequencies.

The time variation in JSR is also investigated by using a two-dimensional numerical simulation based on the radial diffusion model. The model includes fundamental physical processes in Jupiter's radiation belt such as the radial diffusion, energy degradation by the synchrotron radiation, and several loss processes (sweeping effects by satellites and rings, wave-particle interactions, and coulomb interactions with the thermal magnetospheric electrons). Two kind of diffusion model are considered: the normal diffusion model in which the radial diffusion coefficient is adopted from Goertz *et al.* (1979) and a fast diffusion model where the diffusion coefficient is 10 times greater than the Goertz's value. First of all, we tried to find equilibrium solutions which were consistent with the empirical radiation belt model (Divine and Garrett 1983).

The factors in each loss rate were justified to bring the numerical results into correspondence with the empirical model. Next, the time variability in the radiation belt and the synchrotron radiation were investigated by using the equilibrium distribution as an initial condition. Two hypotheses were examined as possible mechanisms to cause the intrinsic variation: (1) temporal changes in the radial diffusion rate associated with the solar UV/EUV heating in Jupiter' thermosphere and (2) temporal change in external source strength. Results from the modeling study are listed as follows:

- We found reasonable radial profiles which matched those of the empirical model at four different electron energies of 1, 5, 10, and 20 MeV for both normal and fast diffusion models.
- It was also found that an unadjustable disagreement between the numerical model and the empirical one was appeared if the energy dependent loss rate by the Amalthea sweeping effect was introduced in the numerical model. This implies that there is an unknown process which diminishes the strong energy dependence in the satellite sweeping loss at the orbit of Amalthea.
- In the time dependent model, the quantitatively same results as Miyoshi *et al.* (1999) and de Pater and Goertz (1994) were found in the case of the normal diffusion model. However, the normal model did not account for the fast decrease in JSR seen in the observation.
- In the case of the fast diffusion model, we found a suitable solution which accounted for not only the increase and decrease in JSR on the short-time scale but the time delay of several days between the UV/EUV indices and JSR. This suggests that the radiation belt of Jupiter is dominated by the radial diffusion and the diffusion rates are much faster than it has previously been thought.

Finally, we examined a future observation plan of JSR by using a two-element interferometer which consists of IPRT and a new radio telescope in order to investigate time variability in the structure of Jupiter's radiation belt.

論文審査の結果の要旨

巨大惑星木星には、惑星表面から数惑星半径程の領域に、数MeV～数10MeVの高いエネルギーを持つ粒子が多数存在する放射線帯（JRB）が存在する。JRBの高エネルギー粒子は木星の強い磁場の下、数10MHz～数GHzでシンクロトロン放射を行うが、この木星シンクロトロン放射（JSR）は直接探査が困難なJRBを探る貴重なプローブとなっている。JSRは1950年代にその存在が同定されて以来、50年以上に渡り観測がなされてきたが、放射強度が微弱なため大型の電波受信装置が必要であること、特に低周波数域ではJSRに比較し強い銀河背景放射（BG）が存在するため観測が容易でないことから、数100MHz帯では十分な観測がなされていなかった。JSRの周波数は近似的に放射粒子のエネルギーに対応するが、数100MHz帯のJSRは主に数MeVの粒子から放射され、数GHz帯のJSRに較べ、より低エネルギーの粒子情報を持つ。このエネルギー帯の粒子は、より低エネルギーの太陽風や磁気圏のプラズマが如何にエネルギーを得てJRB粒子に加速され、また、消失していくのか、そのダイナミカルな過程を解明する上で重要な情報を担っている。

本博士論文は、電波観測装置の開発、および、観測とモデリングにより、この低エネルギー放射線帯粒子の変動原因の解明を目指した研究である。研究では、約5 MeVの放射線帯粒子から放射される325MHzのJSRを、従来に無い高精度で観測し得る惑星電波望遠鏡装置を開発し、その装置による数ヶ月にわたる連続観測を実施しJSRの短期変動を検出した。さらに、JRB粒子の動径拡散と損失過程の再評価も加えた粒子変動の物理モデルを構築し、観測された時間変動特性の考察を行うことで、低エネルギー放射線帯粒子のダイナミクスの理解に革新的な示唆を与えた。

本論文では、低エネルギーのJRB粒子のダイナミクスを究明するため、先ず、高感度電波望遠鏡の開発を実施した。2000年度に東北大学惑星圏飯舘観測所に惑星電波望遠鏡（IPRT）のアンテナ系が設立されたが、本研究ではIPRTをJSR観測が可能な装置として立ち上げることをテーマとした。即ち、本研究ではJSR強度の10%以上と目される短期変動を確実に捉え得る、2%の最小検出感度を要求性能として設定し、この値を実現するために、特に、①アンテナ駆動系指向誤差の低減化と、②受信系利得不安定性の低減化を図った。①では位置が既知の複数天体の観測に基づく指向誤差の定量化と、その値を用いた誤差解析に基づく指向補正により、1%の誤差でのJSR強度導出を可能とした。②では利得変動抑制のため受信系の恒温化を図り、JSR強度導出に必要な時間約30分で4%の誤差での安定化を実現した。この値は要求性能には及ばないものの、Dicke型受信系の付加で0.4%程度まで安定性が改善される可能性を示した。次に、開発した受信系を用いたJSRの連続観測を実施し、2007年に数ヶ月に渡るデータを得た。この観測では、受信系の利得安定性を考慮した数分間隔の利得較正と、325MHzでのBG強度の存在を考慮した観測法（Drift scan法）を適用した。その結果、数日～1週間の時間スケールで約50%のJSR固有の強度増減が生じていたことを明らかにした。また、これらの変動は、より高エネルギーのJRB粒子の変動同様に太陽紫外線強度と正相関を示すこと、但し、約4日の時間遅れがあることを示した。

本論文ではさらにJRB粒子の動径拡散と各種損失過程を考慮した物理モデルを構築し、観測されたJSR増減の時間スケールと太陽紫外線変動との遅延に着目してJRB粒子ダイナミクスの考察を行った。この結果、観測された変動は、太陽紫外線により駆動される動径拡散の速度、および、JRBを周回する衛星や木星大気による粒子損失が、従来提唱されていた値よりそれぞれ約1桁大きい場合に矛盾無く説明され得ることを示した。本結果は近年その存在が同定されたJRB粒子短期変動の物理過程に初めて具体的な解釈を与えたもので、JRB粒子ダイナミクスの理解に革新的な貢献を成し得た。他、本論文では、特に速いJSR強度変動を示す現象の起源探究に有効と考えられる電波干渉計観測の提言を行う等、JRB粒子ダイナミクス研究に重要な将来展望も示し得た。

本博士論文の主たる成果は、これまで国内外の学会・研究会及び研究会集録等で公表されるとともに、特にJSR短期変動の観測結果とその解釈については学術誌に掲載予定となっている。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。従って土屋史紀提出の博士論文は、博士（理学）の学位論文として合格と認める。