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学位論文題目 Novel Instrumentation to Reach the 0.1% Polarization
Accuracy for the Chromospheric Lyman-Alpha
Spectro-Polarimeter

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論文内容の要旨
Summary of thesis contents

Advances of the last century revealed that the atmosphere of our closest star is highly stratified and complex, with an unexplained rise in temperature by more than two orders of magnitude from the photospheric surface to the corona in the high-atmosphere.

In between the photosphere and the corona lie two layers: the chromosphere, the most dynamic layer of the solar atmosphere as unveiled by recent high-resolution space observation, and the transition region, where the temperature rapidly rises from 10,000K to more than a million degrees in the corona.

Filamentary structures seen in these two regions implies that the dynamic is dominated by the magnetic field: low plasma-beta (gas/magnetic pressure ratio) holds there. This indicates that the magnetic field might be a key component of the heating mechanism in the upper solar atmosphere. However, direct measurements of the weak chromospheric and transition region magnetic fields are extremely difficult, as the Zeeman effect is usually unobservable due to the Doppler width of the line being larger than the Zeeman splitting. Yet, the less-explored Hanle effect can be used, as it changes the polarization emitted from scattering processes in the presence of magnetic field regardless of the line Doppler width. Recent progress in the theoretical field and numerical simulations enabled possible diagnosis of the weak magnetic field via the polarization from the Hanle effect, therefore pushing the need for new instrumentation.

The Chromospheric Lyman-Alpha SpectroPolarimeter (CLASP) was proposed as a sounding rocket experiment designed to measure the linear polarization of the hydrogen Lyman-alpha line (121.6nm). The line is emitted in the upper-chromosphere and transition region, and the Hanle effect is expected to operate in the core of this spectral line for magnetic field between 10 to 250 Gauss. Detecting its polarization signature requires an instrumentation with an unprecedented polarization sensitivity of 0.1% in the vacuum ultraviolet (VUV) range. A dedicated design of the instrument and its experimental verification was crucial to ensure the scientific success of the mission. However, developing a space instrument for VUV also comes with a lot of technical difficulties: tests and calibrations under vacuum condition, molecular contamination requiring careful baking of the instrumental parts to avoid outgassing under vacuum, robust optics able to survive launch vibration, etc. For these reasons, the development of CLASP was unique and very challenging.

The novel experimental solutions developed to ensure the optical and polarimetric performances of the instrument are presented in this work:

-Telescope optical alignment : The telescope is a classical two-mirror Cassegrain design, and adjusting the tilt of the secondary mirror with respect to the primary is

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crucial to ensure the image quality. To avoid experiment under vacuum, the telescope was aligned by measuring its wavefront error using a visible-light laser interferometer. The secondary mirror tilt was adjusted by shimming to remove coma and defocus aberration at the center of the field of view. The alignment was successfully performed, reaching better than the required spatial resolution.

-Spectro-polarimeter optical alignment : The spectro-polarimeter is a inverse-Wadsworth mounting design, where a reflecting diffraction grating separates the light from the slit into two channels, for each a camera mirror re-image the slit onto a CCD detector. Adjusting the grating and camera mirrors tilts is required to meet the spatial and spectral resolution requirement. A unique alignment procedure was developed for spectro-polarimeter optical alignment to minimize the experiment under vacuum. The camera mirrors were aligned in He-Ne (632.8nm) by using a custom-made grating of same diffraction angle as the flight Lyman-alpha grating by tuning its ruling density for the He-Ne wavelength. The camera mirrors were successfully aligned by diagnosing the observed spot shape on the CCD with optical simulation performed prior to the alignment experiment. The visible light grating was then replaced by the Lyman-alpha grating. Then, the Lyman-alpha grating tilts and CCD focus position were adjusted under vacuum by injecting VUV lights from a Deuterium lamp. Optical simulations were used to provide quantitative comparison for the alignment under vacuum, and the spectro-polarimeter was successfully aligned within the required spatial and spectral resolution.

-Telescope focus position adjustment : The telescope focus position was adjusted to the spectro-polarimeter slit using a configuration where white-light was introduced from the back of the slit and where a flat mirror located in front of the telescope aperture reflected the light back into the telescope. By inducing a small tilt on the flat mirror, the image of the reflected slit was observed by the slit-jaw optics and the width of the slit image provided indication on the focus position of the telescope. Several measurements for different shim thickness inserted between the telescope and the spectro-polarimeter parts successfully determined the best focus position of the telescope onto the slit.

-Optical checks through the tests : Two measurement methods were designed to confirm the telescope focus position and the spectro-polarimeter optical performances during the integration of the instrument. Measurements were performed before and after the various vibration tests performed prior to launch and also after shipments from the different locations in Japan and US. Results from every measurements performed showed that changes of the optical performances were within the requirement, ensuring the healthiness of the instrument until launch.

-Polarization calibration : An unprecedented precise polarization calibration of the spectro-polarimeter was performed at Lyman-alpha to estimate the artificial polarization created by cross-talks between the different Stokes parameters and to achieve the required 0.1% polarization accuracy in VUV for the first time ever. The experiment was challenging: a Ly-alpha light-source with linear polarizers able to

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provide a known polarized input under vacuum had to be designed. Long exposures were required to achieve the needed accuracy due to the weak intensity of the Ly-alpha light-source. Two different methods were used to change the polarization input to the spectro-polarimeter: the direct method in which the entire light-source was rotated, and the waveplate method in which a half-waveplate with rotating motor was installed after the light-source. The interpretation of the polarization measured was complex, as the multiple effects of CLASP rotating half-waveplate (i.e. drift of polarization angle over time and non-uniformity during a full rotation), the Lyman-alpha light-source (i.e. illumination angle creating a polarization gradient along the slit and off-axis illumination creating a shift of polarization input) and half-waveplate used for the calibration (i.e. retardance changing the input to the spectro-polarimeter) had to be quantified and taken into account. By combining both methods and removing the previously cited artefacts, the response matrix of the spectro-polarimeter, composed of the spurious polarization, the scale factor and the azimuth error terms, was successfully determined within the required tolerances.

The integration and tests resulted in CLASP instrument satisfying all of its scientific requirements, and the payload was successfully launched on September 3rd 2015. The preliminary results from the limb observation confirmed the scattering polarization in the Lyman-alpha line for the first time and the disc center observation were analysed to confirm the pre-flight polarization calibration. Polarization signals created by the local anisotropy of the solar atmosphere were detected even at disc center. Therefore, a statistical approach was adopted to cancel out the solar fluctuations by summing pixel spatially along the slit. This method revealed a spurious polarization level smaller than the measurement from the pre-flight calibration, determined with a 3-sigma. Further investigations were conducted to understand the origin of the discrepancy on the spurious polarization estimated pre-flight and in-flight. As a result, it appeared that the influence of the cross-talks from the incoming linear polarization to the measured intensity was underestimated during the pre-flight calibration. These terms of the response matrix were thought to only imply an additional error on the other matrix elements, but actually produced a similar effect as of the spurious polarization terms in case of an highly polarized incoming light such as during the pre-flight calibration. Hence, a new method was developed to estimate these two additional terms, along with the spurious polarization, scale factor and azimuth error terms of the response matrix, from the measurements recorded during the pre-flight polarization calibration. The results indicated a much smaller spurious polarization level compared to the previous estimation, which was consistent with the in-flight calibration. However, this new method could not reach the required accuracy on the spurious polarization terms, due to the limitation of the pre-flight calibration measurements. The combined results of the pre-flight polarization calibration response matrix and the spurious polarization derived during the in-flight polarization calibration provided a complete response

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matrix of the instrument, which ensured its 0.1% polarization accuracy.

Summary of the results of the doctoral thesis screening

太陽の彩層 (chromosphere) は、太陽の表面 (光球、6000 度) の上層にあつて温度は約 1 万度であり、さらにその上層には温度 1~2 百万度のコロナが続いている。なぜ光球の上に、より高温の彩層、コロナができるのかは、彩層・コロナ加熱の問題と呼ばれ、太陽物理学の大きな未解決研究課題である。特に近年のひので衛星の観測から、彩層は従来考えられていたよりはるかにダイナミックな振る舞いを示すことが明らかになり注目を集めている。彩層の加熱やダイナミクスの根源は磁場のエネルギーであると考えられているが、彩層の磁場を高い感度と精度で測定する手法はまだ確立していない。本論文は、その有力な手法と考えられている、水素のライマン α 線 (波長 121.6 nm) の偏光観測によるハンレ (Hanle) 効果の検出実験について述べたものである。

太陽からのライマン α 光は地球大気に吸収されて地上には届かないため、ロケット実験 CLASP (Chromospheric Lyman-Alpha Spectro-Polarimeter) が国立天文台、米国 (NASA) およびヨーロッパの研究者との共同で企画され、7 年間の準備を経て 2015 年 9 月に無事飛行に成功した。このプロジェクトは日米欧約 20 名のチームによるものであるが、その中で出願者は、装置開発の中核となる光学系の調整と偏光観測装置の較正を担当し、必要に応じて新しい実験法、解析法を導入し、要求される解像度と偏光測定精度を実験室において達成した。具体的には、望遠鏡の光学調整 (第 2 章)、分光器の光学調整 (第 3 章)、望遠鏡と分光器の相互位置調整 (第 4 章)、偏光変調器の調整 (第 5 章)、偏光解析装置の調整と較正 (第 6 章) である。望遠鏡と分光器の調整は可視光 (He-Ne レーザー光、632.8 nm) でなされ、特に分光器の調整は、ライマン α 光と同じ分散になるよう、別途可視光用の回折格子を製作して実験を容易にする工夫がなされた。最も重要な偏光解析装置の較正では、重水素ランプからの紫外光をブルースター角で二回反射させることにより 100% 直線偏光したライマン α 光を生成する光源の開発、偏光面を真空中で任意の方向に回転させて分光器に入射させるための回転波長板の採用などにより、要求される 0.1% の偏光観測精度よりも、測定誤差と装置による疑似偏光を小さく抑え込むことに成功した。

ロケット実験には現地 (米国ニューメキシコ州) で参加し、飛行前チェック (第 7 章) で性能を確認した。ロケット実験では約 5 分間のデータが得られたが、出願者は、その最初の 15 秒間に得られた較正用データを解析した (第 8 章)。これは、ハンレ効果による偏光が非常に小さいと予想される太陽中心付近を観測したものである。その結果、装置の疑似偏光は確かに 0.1% 以下に抑えられていることを実証した。一方、0.1% 以下のレベルで、光子雑音より大きい偏光度の分布が分光器のスリット方向に見えており、太陽中心といえども完全に無偏光ではなく、ライマン α 光を発する構造が非一様に分布している効果が完全には相殺しないことを示唆している。この結果は、観測結果から彩層の磁場を決めていくプロセスで考慮しなければならない境界条件を与えたといえる。

本論文は、真空中でしか実験ができないライマン α 光の波長で、世界で初めて 0.1% を切る偏光測定精度を達成する装置の調整と較正方法を提案し、実験室での実証後、実際の太陽観測ロケット実験でも実証したもので、今後計画される同様の装置の開発・較正手法に指針を与える重要な成果である。全体はプロジェクトとしてなされたものであるが、その重要部分について出願者が、手法の考案、開発についても主体的に参加し、特に実験結果の解析はそのすべてを実行した。従ってその貢献は極めて大きく、以上を総合して、審査委員全員が博士論文として合格であると判断した。