Green Line Intensity Distribution in the Inner Corona

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Date: 2023-05-16T00:00:00+00:00

Abstract

The solar corona is a key region of solar atmospheric activity and the source of Sun-Earth space weather. Due to observational limitations, research on the plasma structure and magnetic field state of the lower coronal atmosphere is severely lacking, and internationally, there are very few studies on brightness stratification of the lower corona in the visible wavelength band. This study utilizes coronal green line (FeXIV 5303 Å) observational data from the Lijiang coronagraph YOGIS (Yunnan Green-line Imaging System) to conduct an effective intensity decay analysis of bright structures and their embedded coronal loops in the inner corona region (1.03R -1.25R). By performing exponential decay fitting of the intensity of bright structures along solar radial heights, we find that the decay indices obtained for static inner coronal loops cluster around a fixed value. Subsequently, the more prominent coronal loops are extracted, and by applying the same exponential fitting to intensities at different heights, the resulting decay indices are found to be relatively similar to those in the bright structures, providing a valuable reference for further investigation into the evolution of various physical parameters in the corona.

Full Text

Study of the Intensity Distribution of the Green Line in the Inner Corona

Vol. 61 No. 1
January 2020
Acta Astronomica Sinica
doi: 10.15940/j.cnki.0001-5245.2020.1.00x

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Received 2022-09-20; revised 2022-12-26
Supported by the Joint Fund Project (U1931116), Yunnan Provincial Key Laboratory of High Energy Astrophysics, and the National Natural Science Foundation of China (11873090, 12173086, 11533009)
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Abstract

The corona is a key region of solar atmospheric activity and the source of space weather that affects Earth. Limited by observational constraints, research on the plasma structure and magnetic field state of the lower coronal atmosphere remains severely lacking, and international studies on the brightness stratification of the lower corona in the visible light band are scarce. In this paper, we utilize coronal green line (FeXIV 5303 Å) observations from the Lijiang coronagraph YOGIS (Yunnan Green-line Imaging System) to conduct an effective intensity decay analysis of bright structures and coronal loops within the inner coronal region ($1.03R_\odot$–$1.25R_\odot$). By performing exponential decay fits to the intensity of bright structures as a function of solar radial height, we find that the decay indices obtained for static inner coronal loops cluster around a fixed value. When we extract more distinct coronal loops and apply the same exponential fitting to their intensities at different heights, the resulting decay indices are also similar to those from the bright structures. This provides a valuable reference for further investigations of the evolution of various physical parameters in the corona.

Keywords: Sun: corona, Sun: coronal green line, Sun: coronagraph, Sun: decay index

The corona is the outermost layer of the solar atmosphere, composed of highly ionized, low-density hot plasma with temperatures reaching millions of degrees. It is the origin of large-scale solar activity and catastrophic space weather events, containing extremely rich information and diverse physical processes. Ancient Chinese records of solar eclipses date back over 2000 years, and the first successful photographic observation of the corona during an eclipse occurred in 1851. In 1931, French scientist Bernard Lyot invented the coronagraph and successfully observed the corona without an eclipse for the first time. A prerequisite for direct detection of coronal signals by a coronagraph is that the sky background brightness at the observation site must be as low as possible. To minimize scattered light, coronagraph observations are typically conducted at high altitudes around 3000 m. Under clear weather conditions, the sky brightness near the Sun can be as low as 10^{-5} of the solar disk brightness, enabling observations of the inner corona.

The coronal green line (5303 Å) was first discovered during solar eclipse observations. After Lyot's invention of the coronagraph, this line became widely used for routine coronal observations. The 5303 Å line belongs to the magnetic dipole transition of FeXIV from the ground state, produced by the transition from spectral term ${}^{2P}_{3/2}$ to ${}^{2P}_{1/2}$. Its formation temperature is approximately 1.8×10^6 K, making it the strongest visible emission line in the corona and one of the most widely used lines during total solar eclipses. Through long-term accumulation of ground-based 5303 Å observations, the international community has established the Coronal Index (CI) as an important indicator specifically for studying long-term coronal activity.

Magnetic fields are a crucial physical quantity controlling solar activity, with coronal phenomena such as solar flares and coronal waves all related to magnetic fields. Plasma in the solar atmosphere is primarily confined within magnetic structures. Bright loop-like structures fill the solar atmosphere, as observed in EUV and X-ray bands. Since these loops are much brighter than the surrounding plasma, they indicate relatively enhanced internal pressure and density. These loop structures in the corona, known as coronal loops, are widely distributed in both quiet and active regions, morphologically resembling magnetic structures and serving as excellent tracers of magnetic fields. They also act as energy channels between the photosphere and corona. Different coronal emission lines, such as the red and green lines, can reveal different local structures of the coronal magnetic field.

For the FeXIV green line, Wang et al. (1997) used observations from LASCO-C1 aboard SOHO to study large-scale coronal temperature and intensity distributions, finding them closely related to underlying photospheric magnetic field structures and intensities at loop footpoints. This demonstrated a certain degree of correlation between the coronal green line and magnetic fields, with the correlation coefficient decreasing with height (from $1.5R_\odot$ to $1.15R_\odot$) but showing a clear increasing trend. However, due to C1's field of view, the minimum height was limited to $1.1R_\odot$. Leveraging the advantages of ground-based observations at Lijiang (with a minimum coronal observation height of $1.03R_\odot$), Zhang et al. (2022) recently found that the correlation between loop intensity and magnetic field remains high above $1.1R_\odot$ at different latitudes, first explicitly indicating that the maximum correlation coefficient occurs near $1.1R_\odot$. They also noted higher correlation coefficients near loop tops, suggesting that magnetic fields play a more dominant role in high-temperature coronal radiation within closed loops. This implies that coronal green line data provides valuable reference for future quantitative studies of magnetic fields and coronal intensity. Importantly, their study revealed that weak correlations at loop footpoints reflect different heating mechanisms near footpoints compared to loop tops, suggesting that both DC (dissipation of currents) and AC (dissipation of Alfvén and magnetosonic waves) heating mechanisms may operate throughout the loop system, with DC heating being more significant near loop tops. These results promise to provide observational evidence for further estimating scaling laws related to coronal heating and validating theoretical models of coronal magnetic fields.

Using coronal green line observations combined with other wavelength data, plasma parameters such as density, temperature, velocity, and magnetic field can be derived for coronal physics studies. In recent years, direct measurement of coronal magnetic fields through near-infrared coronal forbidden emission lines such as FeXII 1075 nm has also become possible. Additionally, long-term studies reveal periodic variations in green line intensity distribution with time and latitude, with the correlation coefficient between green line brightness and magnetic field intensity also showing clear periodic variations with latitude. Beyond revealing long-term coronal cycles and their relationships with other solar phenomena, high-resolution green line observations help address questions of coronal heating and solar wind acceleration, including detecting coronal waves and coronal mass ejections near the solar limb.

Coronal radiation intensity is extremely weak relative to photospheric radiation and decreases sharply with height. At the same height above the solar limb, local green line brightness increases significantly around active regions, reaching maximum values near sunspots. We typically observe morphologically complex bright coronal structures near some active regions, reflecting the complexity of coronal magnetic field structures above active regions.

Coronal green line data primarily come from ground-based coronagraphs. Since the LASCO-C1 instrument ceased operation due to low-temperature failure, space-based green line observations have been discontinued. Zhang et al. (2022) analyzed Lijiang green line data together with multi-band coronal data from SDO/AIA, first discovering that 5303 Å shows higher correlation with 211 Å compared to other AIA bands. This enables precise tracking of bright coronal loops or other structures observed at 5303 Å near the limb, potentially linking physical processes at different coronal heights through combined analysis with 211 Å observations. Ground-based coronagraph observations are affected by day-night cycles and local weather conditions, often causing data discontinuities and analytical errors. Continuous space-based observations from AIA 211 Å and other EUV bands may help fill these observational gaps in ground-based green line data.

Therefore, maintaining long-term green line observations is crucial. Through long-term cooperation among multiple international ground-based coronal observation stations, continuous standard green line data spanning several solar activity cycles have been obtained. These valuable data are used to analyze long-term coronal activity patterns, compensating for frequent gaps in later space-based coronagraph data. Current ground-based green line observation sites include Lomnický Peak in Slovakia, Kislovodsk in Russia, and Lijiang in China. The Lijiang coronagraph station was established in 2013 through cooperation between the Chinese Academy of Sciences' Yunnan Observatories and Japan's Norikura station, and has been operating continuously since then.

Although the FeXIV 5303 Å green line has long been used as a coronal monitoring tool, its observational information remains far from fully exploited. In this paper, we select green line observation data from Lijiang since 2020 and perform fitting analysis of green line intensity decay. In Section 1, we introduce the green line observations and data processing methods. In Section 2, we fit the processed coronal bright structures and loops. In Section 3, we present results and discussion. Finally, Section 4 provides conclusions.

In 2013, the National Astronomical Observatories of the Chinese Academy of Sciences, Yunnan Observatories, and the National Astronomical Observatory of Japan collaborated to upgrade and relocate the Norikura 10 cm aperture Lyot coronagraph to the Gaomeigu Observatory in Lijiang. Lijiang Gaomeigu is a low-latitude, high-altitude site with low sky scattered light and excellent atmospheric observing conditions. Statistical results show that under clear skies, the average sky background brightness in the optical band at Lijiang is below 20 parts per million, suitable for coronagraph observations.

The 10 cm coronagraph has now operated successfully at Lijiang for nearly 10 years. The instrument weighs 100 kg with a total length of nearly 3 m, a primary mirror focal length of 1490 mm at 5303 Å, and is equipped with an equatorial tracking system, high-precision narrowband Lyot filter (1 Å FWHM bandwidth centered at 5303 Å), and a CCD camera (1024$×$1204 pixels). Its outstanding advantage is the ability to observe low coronal structures down to $0.03R_\odot$. The terminal imaging system YOGIS (Yunnan Observatories Green-line Imaging System) provides a $64' \times 64'$ field of view (approximately $2R_\odot$ in both x and y directions), suitable for time-series observations of inner coronal structures. The system obtains single-peak, double-peak, and $±$0.45 Å mode images, repeated 8 times to improve signal-to-noise ratio. The Lijiang coronagraph YOGIS system operates in green line observations of low coronal atmospheric morphology and Doppler velocity fields, with time resolution reaching the order of 1 second. It is currently the only coronagraph in China capable of high-precision green line imaging and Doppler velocity field acquisition of the low corona, and it maintains the world's longest record of coronal green line observations.

We first preprocessed the raw data by removing sky background continuum scattered light and applying dark field and flat field corrections. [Figure 1: see original paper] shows a complete coronal green line image taken on October 30, 2021, with minimum coronal height of $0.03R_\odot$ from the solar limb, image resolution of $2.67'' \cdot \mathrm{px}^{-1}$, $1.5R_\odot$ in the x-direction and $1.3R_\odot$ in the y-direction. The left panel clearly shows a region with complex bright structures outlined by the white box, corresponding to solar active region AR12886 with α/α magnetic configuration. Since our goal is to analyze coronal green line intensity decay, we primarily selected the more prominent bright structure portions with stronger green line intensity within the white box. We extracted the region within the white box, shown in the right panel, where loop structures can be identified.

We then applied circular Hough transform to the complete coronal image in Figure 1 to determine the center coordinates and radius of the occulting disk. Using these coordinates, we performed polar coordinate expansion of the image along the left edge of the occulting disk in a 360° counterclockwise direction, with a radial height of $1.25R_\odot$, as shown in [Figure 2: see original paper]. The x-axis represents position angle (0°–360°), and the y-axis represents pixel height from the occulting disk. We extracted radial intensities at each position angle and determined the corresponding bright structure range based on intensity, which lies between the two white lines from 177° to 188°. We selected additional high-quality green line data from other dates since 2020 with clear bright structures and processed them using the same method to obtain intensity values within the bright structure range for all dates.

[Figure 3: see original paper] shows relatively clear coronal loops identified in green line observations from November 3, 2021 and October 30, 2021. We manually delineated the loop contours, determined the loop structures using region growing, and extracted all position coordinate information. The loop structures are marked with red dashed lines. As before, we identified the occulting disk center coordinates and radius using circular Hough transform on the full-disk image. Starting at 1.01 times the occulting disk radius, we extracted concentric circles outward with a step size of 0.005 times the occulting disk radius. Each concentric circle had a width of 2 px ($±$1 px per radius), with portions of these circles at different heights marked by yellow solid lines and the loop top position indicated by blue solid lines. By taking the intersection of different height concentric circles with the coronal loop, we obtained intensity values for the loop at each height.

3 Intensity Fitting of Coronal Bright Structures and Loops

We first averaged the intensities at each y-axis pixel height within the bright structure range (position angle 177°–188°) in Figure 2, using this as the intensity value of the bright structure at a specific height, thereby obtaining green line intensity values for the bright structure at each pixel height. We then selected high-quality green line data from 2020 onward, as listed in , and processed these data using the same method to obtain bright structure intensities for each date. For the loops in Figure 3, we obtained intensity values from the intersections of concentric circles at different heights with the loops, averaging the intensities at each height as the loop intensity at that specific height.

We found that coronal green line intensities from $1.03R_\odot$ to $1.25R_\odot$ sometimes show an initial increase followed by a decrease. This occurs because diffraction at the occulting disk edge significantly increases stray light intensity near the limb. Therefore, we began our measurements from the height of maximum intensity. Using the intensity distributions obtained for different structures, we employed an exponential function of the form $F(x) = a \times e^{b \times x} + c$ to fit the green line intensities of bright structures and loops as a function of solar radial height, where x is the height from the solar limb (in arcseconds), and a, b, c are parameters to be determined. We focus particularly on the value of exponent b. The exponential form was adopted based on the coronal index formulation, where the Coronal Index (CI) is derived from ground-based green line observations to quantify solar irradiance in the 5303 Å band. The CI accounts for different distribution characteristics: high-index decay in the inner corona (below $1.25R_\odot$) and low-index decay in the higher corona. In this paper, we construct a decay index model only for the inner corona using Lijiang data, expecting that a single decay index value can clearly determine the intensity decay law. Therefore, we apply a single exponential function to fit the Lijiang ground-based coronagraph observations of the inner corona.

4 Fitting Results and Discussion

Using the exponential function $F(x) = a \times e^{b \times x} + c$ to fit coronal green line intensities of bright structures and loops as a function of solar radial height, we obtained the results shown in [Figure 4: see original paper] and [Figure 5: see original paper]. Figure 4 presents fitting results for loop intensities along the radial direction from the occulting disk edge for the images in Figure 3, while Figure 5 shows exponential fitting results for bright structure intensities obtained through polar coordinate expansion. We used the standard deviation at each height as the error, indicated by error bars in Figures 4 and 5. Chi-square tests were performed with degrees of freedom determined and significance level $\alpha = 0.05$ to evaluate the goodness of fit.

In Figure 4, the green curves represent exponential fits to the two loops from Figure 3, labeled "loop fit." The loop top heights for these two clear loops are $1.11R_\odot$ and $1.13R_\odot$, yielding fitted indices (i.e., b) of -0.0153 and -0.0156, respectively—very similar values. The χ^2 values are 0.59 and 0.65, with corresponding P-values above 0.995 in the chi-square tests. Using standard deviation as errors, the fitting errors for exponent b are 23% and 9%, respectively.

Figure 5 shows fitting results for all dates in Table 1 using the polar coordinate expansion method, labeled "fit." The error bar distribution indicates larger errors at lower heights of bright structures, gradually decreasing with height, while errors for loop intensities in Figure 4 are more uniform. The obtained index values (i.e., b) are: -0.0153, -0.0148, -0.0154, -0.0149, -0.0148, -0.0145, -0.0282, -0.0154, -0.0146, -0.0153, -0.015, and -0.015. All fitted exponent b values cluster around -0.015 (shown by blue curves), except for -0.0282 (marked by red curve), with other deviations within 0.001 and maximum deviation of 6.7%. Analysis of the fitted coronal data reveals that bright structures are relatively uniformly distributed, with some showing overall loop-surrounded contours. The data yielding -0.0282 have a smaller bright structure range, located closer to the solar limb, with small loop-like structures at the edge of the overall bright structure that are not integrated with the brighter base, decaying significantly slower than the brighter portions near the occulting disk edge. Furthermore, comparison with consecutive observations around this time shows large morphological changes in the bright structure, indicating it is not static but in a dynamic dissipation process. Therefore, its overall integrated fitting result deviates significantly from other values, and we do not consider it a typical static stable green line loop sample. After exclusion, the chi-square test yields χ^2 values of 0.78, 2.64, 0.38, 0.12, 0.79, 0.09, 0.59, 0.37, 1.21, 1.30, and 2.87, with corresponding P-values above 0.995. Using standard deviation as errors, the fitting errors for exponent b range from 1% to 6.4%—smaller than those for loop fits in Figure 4, likely because lower loops have fewer data points, potentially leading to larger fitting errors.

To compare the two fitting approaches, we combined the fits for the two loops and their corresponding bright structures in [Figure 6: see original paper]. In Figure 6, green curves represent loop fits, while blue curves represent fits for the corresponding bright structure portions. For bright structure fits, stray light effects from the occulting disk edge are significant near the limb, causing an intensity enhancement trend. We attribute this to excessive intensity at positions between loop footpoints, affecting bright structures but not significantly impacting loop structures. Therefore, we removed points showing intensity increases in bright structures, which start at higher positions than loops.

At the same solar height, bright structure intensities are greater than loop intensities because the intensity between loop footpoints contributes significantly to bright structures. Consequently, integrated bright structure intensities at the same height are substantially larger than those of corresponding loop structures. Our fitting results are -0.0153 vs. -0.0145 and -0.0156 vs. -0.0154, with loop decay index b values consistently smaller than those of corresponding bright structures. This occurs because loops are located at bright structure edges, while most bright structure intensity comes from the base surrounded by loops, causing loops to decay faster than the overall bright structure and yielding smaller exponent b values.

Although the two fitted index values for coronal green line loops differ only slightly, the close observation dates may not represent the general decay behavior of loops. However, decay indices obtained by identifying loop structures are not significantly different from those derived through polar coordinate expansion and longitudinal slicing, all clustering around -0.015. For other unclear loops within bright structures, we attempted identification and delineation, but fitted indices were nearly an order of magnitude smaller than -0.015. We attribute this to the inherently low intensity of unclear loops, their proximity to the solar surface, mixing with other bright structures, and background field effects that may influence their intensity through integration.

In this study, we analyzed the decay of coronal green line FeXIV (5303 Å) intensity using Lijiang 10 cm coronagraph observations. We performed exponential decay fits to intensities of different coronal structures through polar coordinate expansion and loop selection, comparing intensity distributions extracted by two methods. Results show that decay indices from fits to different coronal structures cluster around a fixed value, with chi-square tests confirming high goodness-of-fit levels. Comparing our results with Rušin (1973), who expressed coronal brightness decay with height as a sum of n exponential terms and showed that $n = 2$ could capture decay for different periods and position angles with different coefficients and indices, our results are consistent with Rušin's exponential representation. After unit conversion, our index values near -0.9 fall within Rušin's fitted range, demonstrating that a single decay function suffices for Lijiang green line data.

Additionally, our selected loop tops are near $1.1R_\odot$, with fitting results showing similar trends for overall bright structure intensity variations with height in the same range. At higher altitudes, bright structure intensity decay tends more toward linear behavior. The low corona is dominated by closed magnetic fields, while the high corona is dominated by open fields, indicating different heating mechanisms in active and quiet regions. During closed-loop heating in coronal loops, both DC (current dissipation) and AC (Alfvén and magnetosonic wave dissipation) mechanisms act throughout the loop system. Wang et al. (1997) using SOHO LASCO/C1 green line data found that plasma density near loop footpoints ($1.15R_\odot$) correlates closely with magnetic field strength, producing calculated coronal morphologies similar to observations, but their data lacked information on lower coronal structures. Using Lijiang green line data, we find that at $\sim 1.1R_\odot$, the statistical correlation between low coronal loop top brightness and extrapolated coronal magnetic field strength is optimal, with different coronal structures showing good agreement in this height range. The advantage of ground-based Lijiang observations enables detailed study of coronal structures closer to the solar limb. In summary, we consider exponent b in the range -0.015 ± 0.001 from all our exponential fits to be consistent with most of our coronal green line intensity data. Finally, ground-based green line observations are typically limited by day-night cycles and local weather conditions, potentially causing observational discontinuities and analytical inaccuracies. Additionally, the small aperture of the Lijiang coronagraph means some conclusions may be incomplete and require future confirmation and improvement through high-resolution coronal observations.

The corona, as the outermost layer of the solar atmosphere, is a key region of solar activity and an important radiation source for geophysical and space phenomena. Coronal research holds special scientific importance with many unresolved questions. Particularly due to observational limitations, studies of plasma structures and magnetic field states in the lower coronal atmosphere are severely lacking, with few international studies on brightness in the visible band of the lower corona. In this paper, using Lijiang coronagraph YOGIS green line (FeXIV 5303 Å) observations, we conducted the first dedicated intensity decay analysis of bright structures and static inner coronal loops in the inner corona ($1.03R_\odot$–$1.25R_\odot$). We extracted green line intensities at different heights through polar coordinate expansion of the solar disk to determine bright structure ranges and by delineating loops. Exponential decay fits to intensities of bright structures and their loops as a function of solar radial height reveal decay indices clustering around a fixed value (-0.015), consistent with historical statistical fits by Rušin (1973) based on spectroscopic scanning photometry. Our loop fits near $1.1R_\odot$ yield results similar to corresponding bright structure fits. Recent green line studies by Zhang et al. (2022) using green line brightness and photospheric magnetic field sensitivity found the highest correlation between brightness and magnetic field intensity occurs at loop top heights of $1.1R_\odot$, confirming the close relationship between green line brightness and magnetic field strength. Magnetic fields play crucial roles in solar activity, and further investigation of the correlation between green line brightness and magnetic field intensity can provide observational evidence for coronal magnetic field measurements. The coronal green line 5303 Å shows the highest correlation with the 211 Å EUV band, with similar coronal morphology. Future multi-wavelength studies may enable precise tracking of limb structures observed at 5303 Å, facilitating combined analysis of physical processes at different coronal heights. We will continue this research focusing on different solar cycle periods and latitudinal distributions.

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Note: Figure translations are in progress. See original paper for figures.