Producing Type Ia Supernovae from Hybrid CONe White Dwarfs with Main-sequence Binary Companions at Low Metallicity of Z = 0.0001 Postprint

Authors: Boyang Guo, Xiangcun Meng, Zhijia Tian, Jingxiao Luo and Zhengwei Liu

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Abstract

The nature of progenitors of Type Ia supernovae (SNe Ia) and their explosion mechanism remains unclear. It has been suggested that SNe Ia may have resulted from thermonuclear explosions of hybrid carbon-oxygen-neon white dwarfs (CONe WDs) when they grow in mass to approach the Chandrasekhar mass limit by accreting matter from a binary main-sequence (MS) companion. In this work, we combine the results of detailed binary evolution calculations with population synthesis models to investigate the rates and delay times of SNe Ia in the CONe WD + MS channel at a low metallicity environment of Z = 0.0001. For a constant star formation rate of 5 M yr−1, our calculations predict that the SN Ia rates in the CONe WD + MS channel at low metallicity of Z = 0.0001 is about 0.11−3.89 × 10−4 yr−1. In addition, delay times in this channel cover a wide range of 0.05−2.5 Gyr. We further compare our results to those given by a previous study for the CONe WD + MS channel with a higher metallicity of Z = 0.02 to explore the influence of metallicity on the results. We find that these two metallicity environments give a slight difference in rates and delay times of SNe Ia from the CONe WD + MS channel, although SNe Ia produced at a low metallicity environment of Z = 0.0001 have relatively longer delay times.

Full Text

Preamble

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Study on Real-time Monitoring Method for Dust-scattered Stray Light in the Spectral Imaging CoronaGraph of the Chinese Meridian Project Phase II

Da-Yang Liu[1], Xiao-Yu Yu[1], Hong-Xin Zhang[2], Zheng-Hua Huang[1], Li-Dong Xia[1], Ming-Zhe Sun[1], Xian-Liang Mao[1], Bo-Yu Sun[1], Ning Tang[1], Hui Fu[1], Wei-Xin Liu[1], Chao Zhang[1], and Jian-Ping Han[1]

[1] Shandong Provincial Key Laboratory of Optical Astronomy and Solar-Terrestrial Environment, Institute of Space Sciences, Shandong University, Weihai 264209, China; sunmingzhe2003@126.com [2] Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130033, China

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Abstract

Dust-scattered stray light in an inner-occulted coronagraph primarily arises from dust particles on the surfaces of the objective lens. Due to the random accumulation of dust on lens surfaces, monitoring this type of stray light has proven challenging, and no practical application for its real-time monitoring existed until now. This study presents a system and method to address this issue, which have been successfully applied to the Spectral Imaging CoronaGraph (SICG) of the Chinese Meridian Project. The method is based on two key relationships established in the laboratory: the relationship between dust particle sizes and their corresponding stray light levels at the imaging plane, and the relationship between the actual sizes of dust particles and their spatial occupancy on the imaging plane. To monitor stray light levels attributable to dust, only a single image of the objective lens is required, which can be provided by the auxiliary imaging system specially incorporated into SICG. Our tests demonstrate that the method' s errors are less than or approximately 2%, providing strong confidence in its accuracy. This approach offers a convenient tool for monitoring dust levels on the SICG objective lens and has significantly improved the efficiency of the stray light control pipeline.

Key words: Sun: corona –techniques: image processing –instrumentation: miscellaneous –methods: analytical –scattering

1. Introduction

A coronagraph is an optical system specially designed to observe the solar corona (Su 1959). It requires careful system design to suppress scattered light in order to detect the extremely faint corona against the intense background from the solar photosphere. An inner-occulted coronagraph represents one such design, featuring an occulter placed at the focal point of the objective lens to block the focused image of the solar disk. Stray light in an inner-occulted coronagraph can be categorized into two types based on its intensity variation: static stray light and dynamic stray light.

Static stray light primarily includes diffraction at the edges of the coronagraph’s apertures, ghost images caused by multiple reflections from the objective lens, and scattering resulting from microscopic surface roughness of the objective lens (Huang et al. 2023). These static stray light components are generally considered fixed once the instrument is constructed (Zhang et al. 2009). In contrast, dynamic stray light, caused by scattering from dust particles accumulated on the objective lens surfaces, varies during observation. Consequently, real-time monitoring of dust-scattered stray light is essential to guide the cleaning procedures for optical lenses (Elmore 2007).

Numerous efforts have been undertaken to assess dust-scattered light in coronagraphs. Gallagher et al. (2016) used the Harvey-Shack BSDF model to simulate the scattering distribution based on the cleanliness level of the objective lens for the Coronal Solar Magnetism Observatory Large Coronagraph (COSMO-LC), demonstrating that the dust-scattered stray light level at 1.1 solar radii was approximately 3×10^{-6} when the objective lens cleanliness was set to Class-200. Thompson et al. (2003) simulated dust-scattered stray light levels for the COR1 coronagraph on the STEREO satellite, finding that the overall stray light level increased from 10^{-6} to 10^{-4} as the objective lens cleanliness deteriorated from Class-100 to Class-500. This result demonstrates that dust on the objective lens significantly influences the overall stray light level. Spyak and Jenkins conducted experiments by randomly contaminating a smooth objective lens with polystyrene spheres ranging from 1 to 85 m in diameter and measured the dust-scattering light at a wavelength of 632.8 nm (Spyak & Wolfe 1992a, 1992b; Jenkins et al. 2006). Their experiments showed excellent consistency with modified Mie scattering theory. Based on the 10 cm coronagraph NOGIS located in Lijiang, Sha et al. (2023) imaged dust on the objective lens surface and carefully analyzed coronal images contaminated by dust-scattered light, successfully obtaining the distribution of scattered light with respect to heliocentric distance and removing the dust-scattered light component from the coronal images. In previous work, Liu et al. (2023) performed measurements of dust-scattered stray light levels using an experimental 70 mm inner-occulted coronagraph. By correlating the relative magnitude between ghost images and dust-scattered light, we developed a method to calculate dust-scattered stray light through ghost image measurements, enabling rapid assessment of dust-scattered light levels in laboratory settings. Although these studies have advanced our understanding of dust-scattered stray light in coronagraphs, real-time monitoring and correction of this type of scattered light during instrument operation remained unresolved.

In the optical system of an inner-occulted coronagraph, the objective lens is directly exposed to sunlight, making dust on its surfaces the primary source of dynamic scattered stray light that affects the quality of scientific data. During coronagraph operation, dust accumulates on the objective lens surfaces, leading to a gradual increase in overall stray light levels. During maintenance of the HAO MK4 coronagraph, Nelson (2006) revealed that the instrument’ s overall stray light level could decrease by nearly an order of magnitude after dismantling and cleaning the lenses. Furthermore, increased dust-scattered stray light can introduce large errors in the inversion of coronal intensity data (Zhang et al. 2022a, 2022b). These studies highlight that stray light caused by dust accumulated on the objective lens is a major factor in the stray light level of a coronagraph during routine operation. Other lenses, such as field lenses, are not directly exposed to sunlight, and scattered light caused by dust on their surfaces is several orders of magnitude lower than that from the objective lens.

Aiming at real-time monitoring of stray light scattered by dust on the objective lens, this study develops a real-time monitoring method for dust-scattered stray light in an inner-occulted coronagraph, specifically for the Spectral Imaging CoronaGraph (SICG) of the Chinese Meridian Project. The method first simulates scattering from individual dust particles using micro-pinhole plates and a He-Ne frequency-stabilized laser. By measuring the scattered light from pinhole plates with different diameters, the scattered stray light levels of individual dust particles of various sizes on the coronagraph’ s image plane are obtained. These results are then combined with the statistical distribution of dust on the objective lens surfaces to calculate the total dust-scattered stray light. The method’ s accuracy is verified by measuring stray light levels on the coronagraph’ s objective lens under different cleanliness conditions. In the verification experiments, a simulated light source illuminates the coronagraph, and stray light levels are measured under various dust conditions. Image processing techniques are employed to isolate dust-scattered stray light, and the results are compared with those obtained using the statistical method. This method requires only a single image of the objective lens for statistical analysis of surface dust, making it useful for monitoring dust-scattered stray light during routine coronagraph operation. Additionally, since the method focuses specifically on dust-scattered images, it achieves high accuracy as it is less affected by environmental stray light.

The structure of this paper is outlined as follows. Section 2 briefly introduces the working principles of the inner-occulted coronagraph. In Section 3, we describe the structure of a simulated dust scattering device on the objective lens surface and present tests of scattered light from individual dust particles with various diameters. The scattered stray light levels are then calculated based on the statistical distribution of dust particle sizes. In Section 4, we first measure stray light levels under different dust conditions using a test device. Then we separate the dust-scattered stray light and validate the measurements from Section 3 using the isolated dust-scattered light data. Finally, we discuss the sources of error in the dust-scattering statistical measurement method and its significance in practical applications. Section 5 provides the conclusions of our study.

2. SICG and Experiment Setup

This study focuses on the SICG constructed as part of the second phase of China’ s Meridian Project (CMP-II). Its operating wavelengths are 637.4 nm and 530.3 nm. The coronagraph features a 200 mm objective lens with a focal length of 2000.2 mm at 637.4 nm and 1983.3 mm at 530.3 nm. It has a field of view ranging from 1.05 to 2 solar radii (R). Wavelength selection and switching are achieved through a combination of pre-filters and a four-stage Lyot filter.

The CMP-II/SICG is a typical inner-occulted coronagraph, and its design principle is illustrated in Figure 1. The coronal signal is first imaged by the objective lens O1 onto the field stop A2. The image is then relayed through the remaining lens group to the image plane. The solar disk is focused by the objective lens O1 onto the inner occulter D1, which is designed as an oversized occulter with an angular diameter 1.05 times that of the solar disk. Diffraction light produced by the aperture stop A1, which is illuminated by direct sunlight, is imaged onto and blocked by the Lyot stop A3. A2 serves as the field stop, determining the instrument’ s field of view along with D1. Since O1 is directly exposed to sunlight, multiple reflections on its front and rear surfaces generate ghost images. The field lens O2 re-images these ghost images onto the front surface of the relay lens O3, where they are blocked by the Lyot spot D2. The tunable filter F is used to select specific wavelengths for coronal observation, and the imaging lens O4 re-focuses the output from F onto the image plane.

To enable real-time monitoring of dust-scattered light, the CMP-II/SICG incorporates an auxiliary imaging system designed specifically for objective lens imaging, in addition to the traditional inner-occulted coronagraph setup. This auxiliary system, through a beam-splitting optical path, allows simultaneous imaging of both the objective lens surface and the observed objects. Consequently, both the coronal image and the dust-scattered light from the objective lens surface can be captured simultaneously. The optical design of the CMP-II/SICG is shown in Figure 2, while the actual fabricated device is displayed in Figure 3.

3. Construction and Experiments for the Dust Scattering Measurement System

3.1. The Simulated Dust Measurement System

Since dust particles of various diameters and quantities on the objective lens surface have different impacts on the overall stray light level of the coronagraph, the total dust-scattered stray light can be obtained by statistically measuring the number of dust particles on the objective lens surface. Here, the quantitative measurement of scattered light produced by individual dust particles of different diameters is simulated using a laser-illuminated pinhole. A strong laser beam is used to amplify scattering from a single dust particle, making it measurable. The simulation system is constructed using a He–Ne frequency-stabilized laser and a set of micro-pinhole plates. The pinholes have various diameters to represent dust particles of different sizes. The laser beam diverging through the pinhole simulates the scattered light produced by individual dust particles when illuminated. The micro-pinhole plates are positioned near the surface of the coronagraph objective lens to simulate the dust scattering effect. The scattered light passes through the coronagraph optical system, reaching the image plane where its intensity is recorded by a detector. The scattered light intensity for each pinhole is measured and recorded. The measurement process is repeated for various pinhole sizes to simulate scattered light intensity from different particle diameters.

The laser source is a highly frequency-stabilized He-Ne laser from REO, equipped with a stabilized power supply, emitting light at a uniform wavelength of 633 nm. The laser is used to simulate direct sunlight incident on the coronagraph objective lens. The micro-pinhole plates, manufactured by Thorlabs and Daheng Optics, are made of stainless steel and used to simulate the scattering effect of dust on the objective lens. The detectors include the Dhyana 95 V2 high-speed CMOS camera from Tucsen Optoelectronics that records imaging data at very high frequency, and the back-illuminated CCD camera from Andor that offers low dark current and readout noise for measuring scattered light intensity at the coronagraph’ s image plane. A schematic diagram of the dust-scattering detection system is illustrated in Figure 4, and the actual setup is depicted in Figure 5.

3.2. Experimental Procedures and Data Processing

The first part of the simulation experiment involves measuring the intensity of scattered light from simulated dust. This is achieved by measuring the scattered light intensity at the coronagraph’ s image plane for dust particles of different diameters and comparing it with the direct light intensity from the laser source at the image plane. The goal is to determine the dust-scattered stray light levels for particles of different diameters. The specific procedures are as follows.

In the test, micro-pinhole plates with apertures of 25 m, 50 m, 100 m, 200 m, and 250 m are placed in front of the He-Ne frequency-stabilized laser to simulate scattering from dust particles of different sizes. The laser is mounted on a one-dimensional X-axis translation stage, and its position is shifted at 2 mm intervals from one side of the objective lens surface (objective lens diameter: 200 mm). For each position, a CCD camera records the scattered light intensity at the image plane (with 100 measurements for each simulated dust particle). The average scattered light intensity for each pinhole diameter is noted as I (25-250 m). After removing the pinhole plates and the coronagraph’ s inner occulter, a set of neutral density filters is placed in front of the CCD camera to measure the direct light intensity at the image plane, denoted as Iz. The ratio of scattered light intensity to direct light intensity is then used to calculate the stray light level L for each simulated dust particle size (25-250 m).

By comparing the scattered light intensity from simulated dust particles with different diameters, the distribution of simulated dust-scattered stray light levels is obtained, as shown in Figure 6. From Figure 6, it can be seen that the scattered light intensity at the image plane from smaller dust particles is relatively uniform, whereas larger dust particles exhibit a diffraction ring pattern in their intensity distribution. This occurs because smaller pinholes result in more pronounced diffraction, and for very small diameters, the diffraction effect causes only the zeroth-order component to appear, leading to a more uniform intensity distribution. As the aperture size increases, diffraction rings become denser, and more fringes appear at the image plane.

In the data processing, two averaging steps were employed. First, the scattered light from dust particles was measured at 100 different positions, and the average scattered intensity for a single particle size was obtained. This approach facilitates the subsequent statistical distribution calculation. In reality, the dust-scattered light at the image plane is a statistical accumulation of scattered light from dust particles of varying sizes and positions. After statistical accumulation, the dust-scattered light can be considered approximately uniform at the image plane, making this averaging step statistically reasonable. Second, after averaging the scattered light distribution at the image plane, another averaging step was performed. This study does not aim to consider the intensity distribution of individual dust particles but instead calculates the average scattered intensity at the image plane, using this as an indicator for monitoring dust accumulation on the objective lens.

After applying the two rounds of averaging to the stray light distribution values from different simulated dust particles as exemplified in Figure 6, the average stray light levels L for simulated dust particles of different diameters were calculated as 1.02×10^{-9} (25 m), 2.06×10^{-9} (50 m), 4.57×10^{-9} (100 m), 7.8 $\times 10^{-9}$ (200 m), and 9.66×10^{-9} (250 m), while the corresponding standard deviations are 1.33×10^{-10} (25 m), 2.53×10^{-10} (50 m), 4.39×10^{-10} (100 m), 1.40×10^{-9} (200 m) and 7.67×10^{-10} (250 m). The fitted curve of the relationship between the stray light level L and the particle diameter D for individual simulated dust particles is plotted in Figure 7. From Figure 7, it can be seen that the relationship between the stray light level L at the image plane for simulated dust particles and their corresponding diameter D, as determined by fitting the sample points, is described by the following formula:

$\mathrm{L} = 3.57 \times 10^{-16} \times \mathrm{D}^3 - 1.87 \times 10^{-13} \times \mathrm{D}^2 + 6.53 \times 10^{-11} \times \mathrm{D} - 5.97 \times 10^{-10}$.

This function can be used to directly calculate the stray light level for dust particles of different diameters.

The second part of the simulation experiment involves using dust particles of known diameters to calibrate the size of dust on the coronagraph' s objective lens. Since dust particles appear as a certain number of pixels on the detector during imaging, it is necessary to establish a relationship between the number of pixels occupied by dust in the image and the actual diameter of the dust on the objective lens. A 100 m pinhole plate is used to simulate dust for calibration. The CMOS camera captures multiple images of the 100 m simulated dust on the objective lens, and these images are averaged for further analysis. The intensity distribution along the X-axis of the image, corresponding to the 100 m simulated dust scattering point, is then normalized to obtain an intensity distribution curve, as shown in Figure 8. From the intensity distribution curve, we can see that it is advantageous to select the position where the normalized intensity reaches 1% as the threshold for determining the edge of the dust-occupied area. The number of pixels occupied by the 100 m simulated dust on the CMOS camera is 14 pixels along the X-axis, which corresponds to each pixel representing a size of 7.14 m on the objective lens surface.

After imaging the coronagraph's objective lens and obtaining the dust scattering point distribution, the diameter of dust particles on the lens surface can be calculated. By removing the simulated dust setup, a uniform white light source is used to illuminate the objective lens, and the same CMOS camera captures an image of the dust particles on the objective lens surface, as shown in Figure 9. Additionally, we examine the shape of dust on the objective lens surface as projected onto the image plane. From the dust image on the objective lens surface, four dust particles of different diameters (indicated by the red boxes labeled as 1-4 in Figure 9) were selected for diameter calculation. The dust intensity along the X-axis was normalized at the center of each particle, and the corresponding intensity distribution curves were generated. These intensity distribution curves are shown in Figure 10. From the images, it is evident that the intensity distribution of individual dust scattering points follows a pattern of strong intensity at the center, tapering off toward the edges. Using a threshold at 1% of the normalized intensity, we define the boundary of each dust particle and find that the number of pixels occupied by Dust 1-4 was measured as 13.0 pixels, 15.0 pixels, 20.0 pixels, and 30.0 pixels, respectively. Based on the calibration results, the diameters of Dust 1-4 on the objective lens surface were calculated as 93 m, 107 m, 143 m, and 214 m respectively.

By extending this diameter calculation across the entire dust image on the objective lens surface, the statistical distribution of dust particles of different diameters can be obtained. The statistical counting of dust particles of various diameters on the objective lens surface is achieved through image processing of the image in Figure 9. The corresponding steps are as follows. First, dark field subtraction is applied. Second, a background threshold is set to subtract background light, minimizing its impact on the dust scattering point count. Finally, a binarization process is applied, where dust scattering point regions are assigned a value of 1 and all other areas are set to 0. This approach simplifies the subsequent statistical analysis. The original image of dust scattering from the objective lens surface and the binarized image used for statistical analysis are shown in Figure 11.

By combining the binarized image of the dust with statistical values of their number and area, the number of dust particles of different diameters can be calculated, which in turn allows determination of the dust-scattered light levels. First, the binarized image is processed by segmenting the data to calculate the number of pixels occupied by each independent scattering point. The scattering points are then sorted based on the area they occupy in terms of pixel count, facilitating further analysis. Each scattering point is approximated as a circular shape, and the equivalent diameter of each dust particle is obtained. The diameter of the dust particles on the objective lens is then determined by applying the formula obtained from Figure 7. The number of dust particles with different diameters is statistically analyzed, and their diameter distribution is obtained. Finally, by correlating the dust particle diameter statistics with the simulated dust scattering light levels, the current level of dust-scattered stray light on the objective lens is determined. In Figure 12, we show the area-labeled image of the dust scattering points, and the histogram distribution of the dust diameters obtained in the experiment is shown in Figure 13. From Figure 13, it can be seen that most dust particles on the objective lens have diameters under 100 m, with a smaller fraction in the range of 100–200 m, and only a few particles exceeding 200 m. The larger dust particles are likely due to improper cleaning processes (e.g., large particles left behind due to incomplete air-blowing during cleaning). By multiplying the number of dust particles N for each diameter range by the corresponding stray light level obtained from the previous simulations, the current total dust-scattered stray light level on the objective lens surface is calculated to be 1.63×10^{-6}.

4. Experimental Validation

The accuracy of the dust scattering statistical measurement method is validated by measuring stray light levels under different dust conditions on the coronagraph' s objective lens surface. The statistical measurement method described in Section 3 was applied to different dust conditions on the objective lens, and the corresponding dust-scattered stray light levels were calculated for varying cleanliness levels. The objective lens of the coronagraph was disassembled in the laboratory and placed face-up (with the external surface of the objective lens facing upward). It was left undisturbed in the laboratory for dust accumulation periods of 1, 2, 4, and 8 hours. After each exposure period, the objective lens was reassembled onto the coronagraph, and the dust distribution was imaged using a CMOS camera. The dust conditions on the objective lens were recorded as LV1, LV2, LV3, and LV4, representing dust conditions after 1, 2, 4, and 8 hours of exposure, respectively. The dust distribution on the objective lens surface after 1, 2, 4, and 8 hours of exposure in a cleanroom environment is shown in Figure 14, and the statistical results of the dust conditions are presented in Figure 15.

From the statistics shown in Figure 15, we can see that dust particles with diameters between 0 and 100 m are most affected by accumulation time. Dust particles in other diameter ranges showed only slight increases or remained nearly constant as accumulation time increased. This is likely due to the laboratory environment being a Class-1000 cleanroom, where larger dust particles are scarce. Based on the dust particle counts from Figure 15 and the dust-scattered stray light levels obtained from simulations, the stray light levels corresponding to dust conditions LV1-LV4 on the objective lens were obtained as 1.75×10^{-6}, 1.79×10^{-6}, 1.83×10^{-6}, and 1.98×10^{-6}, respectively.

The measurement of stray light levels under different dust conditions on the objective lens surface is performed using the coronagraph' s stray light measurement system. This system is based on the traditional stray light measurement setup for inner-occulted coronagraphs (Liu et al. 2023). The measurement process is as follows. First, the overall stray light levels for the coronagraph' s objective lens are measured under various dust conditions. A CCD camera is placed at the image plane of the coronagraph, and the stray light intensity at the image plane, I_0 to I_4, is recorded for each condition. Next, the internal occulter is removed, and a neutral density filter set is inserted to measure the direct light intensity Iz. By combining the recorded stray light intensity and the direct light intensity, the total stray light levels, SL_0 to SL_4 (where SL_0 is measured immediately after cleaning the objective lens), are obtained. Since the stray light measurements provide a two-dimensional matrix of the coronagraph' s total stray light levels across the field of view, the stray light levels are averaged radially from the center of the field outward. This produces the coronagraph' s stray light levels at different locations in the field of view, as shown in Figure 16.

From Figure 16, we can observe that the increase in dust from LV0 to LV4 on the objective lens surface leads to a rise in the relative stray light levels. However, the coronagraph' s stray light increase is small compared to the overall stray light levels due to the high cleanliness of the laboratory' s Class-1000 cleanroom environment. Compared to the stray light level for the LV0 dust condition, the level for the LV4 condition shows an average increase of 3×10^{-7}, which is consistent with the stray light level increment calculated using the dust scattering statistical measurement method. This increment accounts for approximately 10% of the initial average stray light level of the coronagraph' s objective lens. Therefore, when the coronagraph' s objective lens is left exposed for extended periods, the increase in dust-scattered stray light can significantly affect the overall stray light level. This effect would be much more pronounced when the coronagraph operates at an observatory site (i.e., an outdoor environment).

Since the stray light levels on the coronagraph' s image plane are positively correlated with the stray light intensity at the Lyot stop (Liu et al. 2023), a method is employed to effectively distinguish between dust-scattered light and other stray light by separating their respective intensities at the Lyot stop. The specific separation method is as follows. The conjugate image of the objective lens at the Lyot stop is analyzed. Dust-scattered light appears as highly focused scattering points at the Lyot stop, while other types of stray light are more uniformly distributed. By using image processing techniques, the intensities of dust-scattered stray light and other stray light at the Lyot stop can be separated, and their relative contributions are calculated. These correspond to the contributions of both types of stray light at the coronagraph’ s image plane. For example, the separated intensity image of dust-scattered stray light and other stray light at LV0 of the objective lens is shown in Figure 17. After summing the separated intensities of the two types of stray light and dividing them by the total intensity before separation, we determined that dust-scattered stray light accounts for 55% and other stray light for 45% of the total.

Using the total stray light level under the LV0 condition from Figure 16, the average level of dust-scattered stray light can be calculated as: $0.55 \times \mathrm{SL}_0 = 1.58 \times 10^{-6}$. Since the increase in stray light from LV1 to LV4 is solely due to dust accumulation on the objective lens, while other types of stray light remain constant, the difference in total stray light levels between LV1-LV4 and LV0 can be attributed to dust-scattered stray light. Thus, the dust-scattered stray light levels under the LV0 condition serve as the initial value. By adding the difference in total stray light levels between LV1-LV4 and LV0 to this initial value, the dust-scattered stray light levels for LV1-LV4 are obtained as: 1.67×10^{-6}, 1.77×10^{-6}, 1.82×10^{-6}, and 1.97×10^{-6} respectively, which are very consistent with the values obtained by our aforementioned method (see Table 1).

As shown in Table 1, the differences in dust-scattered stray light levels between the two methods are around 2%, indicating good correspondence between the results. This demonstrates the accuracy and effectiveness of the method based on dust scattering statistics. Several factors may contribute to the observed discrepancies. First, measurement error from simulated dust: the simulated dust measurements were conducted using standard circular pinhole plates that cannot perfectly simulate real dust particles, which may lead to some measurement errors when correlating simulated dust results with real dust particles. Second, error in the relationship between the real size of a dust particle and its occupancy on the imaging plane: the dust scattering levels were measured using only five standard pinhole diameters (25 m, 50 m, 100 m, 200 m, and 250 m). To obtain scattering levels for other diameters, data interpolation and fitting were applied. Since the number of fitting sample points was limited, this introduces error into the fitting function. Custom-designed pinhole plates with additional diameters could improve the fitting function and thereby enhance the precision of the measurement method.

Third, error from stray light detection of the coronagraph: in the stray light detection processes, environmental stray light and fluctuations in the intensity of the simulated solar light source could have introduced detection errors in the overall stray light levels of the coronagraph, which in turn affected the measurement of dust-scattered stray light. Improvements could be made by enhancing the cleanliness of the detection environment, measuring and correcting for the effects of environmental stray light, and calibrating the intensity fluctuations of the simulated solar light source. These steps would reduce detection errors and improve the accuracy of dust-scattered stray light measurements. Fourth, when the instrument is deployed in an outdoor environment (e.g., in Lijiang), environmental dust of various diameters may accumulate on the objective lens. For dust particles smaller than 25 m, their contribution to the overall stray light is minimal and can be approximated as negligible. For dust particles larger than 250 m, however, their significant impact on the coronagraph’ s overall stray light necessitates cleaning the objective lens to prevent accumulation of such large-diameter dust. Although these factors may introduce some measurement errors to the dust scattering statistical method, we find they do not affect the overall effectiveness of this method in monitoring dust-scattered stray light when tested under different dust conditions. The dust scattering statistical method simplifies the complex laboratory measurements of dust-scattered stray light into a more manageable process of measuring the number and diameter of dust particles on the objective lens surface.

5. Summary

This paper presents a dust scattering statistical method for monitoring dust-scattered stray light levels on the objective lens of a coronagraph through statistical measurement of dust particles on the lens surface. The method calculates the dust-scattered stray light level by correlating measurements of simulated dust with real dust conditions on the objective lens. Experimental validation was conducted using stray light level measurements under different dust conditions on the objective lens. The dust-scattered stray light levels on the objective lens of CMP-II/SICG measured using this method ranged from 1.6×10^{-6} to 2×10^{-6} for various cleanliness conditions. The validation experiments showed that differences between the measured dust-scattered stray light levels and the calculated values from this method were about 2%, providing strong confidence in the method’ s effectiveness and accuracy. This method provides a convenient tool for monitoring the dust level on the SICG objective lens and guides the cleaning routine. The method has been applied to the instrument at the observing site and has significantly improved the efficiency of the stray light control pipeline.

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