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新型自准直外掩式日冕仪

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摘 要:为了更好地实现对日冕及日冕物质抛射的观测,并使观测角度更加精准,设计了太阳对准系统,利用对准系统对太阳成像,根据探测器上太阳像的圆心坐标判断是否对准并调整日冕仪观测角度。将太阳对准系统应用在三圆盘外掩式日冕仪上进行实验,该日冕仪视场为 $\pm 20^\circ$,工作波段为 630~730 nm, F 数为 4,焦距为 38 mm,分辨率为 $1.2'/\text{pixel}$ 。对比了单圆盘外掩体与三圆盘外掩体对外掩体边缘衍射光的抑制能力,并提出一种黑洞检测法对日冕仪总杂散光进行检测。实验结果表明,日冕仪指向精度达到 $0.11'$,三圆盘外掩体边缘衍射杂散光低于单圆盘外掩体边缘衍射光,且日冕仪总杂散光抑制水平达到 10^{-13} 量级。杂散光检测方法结果良好,准确性高,对准系统实现了预期功能。

关键词:指向精度;天文仪器;日冕仪;杂散光;外掩体

中图分类号:TH753

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0 引言

太阳活动以及日地空间环境是目前空间科学发展过程中一个非常重要的研究领域。太阳爆发活动常激起太阳风暴侵扰地球空间环境,给人类的航天、通信、导航定位、电网、物探等带来严重危害和巨大损失,造成所谓的空间灾害性天气事件,它的强弱影响到地球物理现象及人类活动^[1-3]。过去,人们往往把观测到的各种日地空间环境扰动,如行星际激波、磁暴和极光等,几乎全部归因于太阳耀斑^[4]。然而,经过近四十年对日冕物质抛射及其相关现象的观测与分析研究,人们越来越认识到日冕物质抛射(Coronal Mass Ejections, CMEs)所造成的日地空间环境扰动并不亚于太阳耀斑^[5]。日冕仪作为观测日冕及日冕物质抛射现象的重要仪器,被用于研究太阳磁场对地球造成的影响,以及对影响地球及日地空间的灾害性空间天气进行预警。

国际上很早就开始了关于日冕仪的研究。1930年,LYOT B发明了首个内掩式地基日冕仪^[6]。1948年,EVANS J对内掩式日冕仪进行结构优化,提出了外掩式日冕仪^[7]。1963年,美国海军研究实验室发射了第一台天基日冕仪,并实现对日观测。之后,随着航天技术的进步,陆续发射了数颗卫星,这些卫星的有效载荷均包含日冕仪^[8-11]。2020年最新发射的 Solar Orbiter 卫星,搭载了 METIS 日冕仪和 Solo HI 日球成像仪,分别对日冕偏振成像和日冕成像^[12-13]。近年来,我国有了许多日冕仪研制计划^[14-17],如“夸父”探测计划,太阳极轨射电望远镜计划及子午工程二期计划。其中,“夸父一号”卫星已于 2022 年 10 月 9 日发射升空。

但目前已有的日冕仪本身不具备对准太阳的功能,无法提供偏移量,需结合其他平台进行对准,本文完成了基于三圆盘外掩式日冕仪的对准系统设计,日冕仪指向精度达到 $0.11'$ 。同时,日冕仪对杂散光抑制要求十分严格,本文提出一种新的检测方法,用于检测日冕仪杂散光抑制水平,并应用于三圆盘外掩式日冕仪进行实验,取得了较好的结果。

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1 对准系统设计

根据日冕仪的工作原理,在日冕仪工作时,需利用外掩体遮拦太阳直射光。为使外掩体能够尽可能完全地遮挡住太阳直射光,不仅需要外掩体的大小合适,还需要外掩体尽可能地对准太阳。因此,设计了太阳对准系统,利用双胶合透镜对太阳成像,用探测器接收,以此判断外掩体与太阳是否对准。

太阳对准系统由镜筒部分和探测器部分组成,其光学系统结构如图1所示,该系统入瞳直径为40 mm,焦距为360 mm,视场为 2° 。镜筒长340 mm,前端设有螺纹调焦结构,镜筒后端接探测器,机械结构如图2所示。探测器有效像素数为 $1\,920 \times 1\,200$,像元大小为 $5.86\ \mu\text{m}$ 。将对准系统镜筒固定在日冕仪腔体外侧,使镜筒前端面与外掩体平面重合,且对准系统光轴与日冕仪光轴平行,见图3。

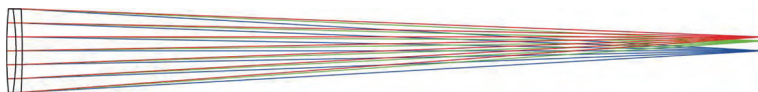


图1 太阳对准系统光学系统结构
Fig.1 Optical system structure of solar alignment system

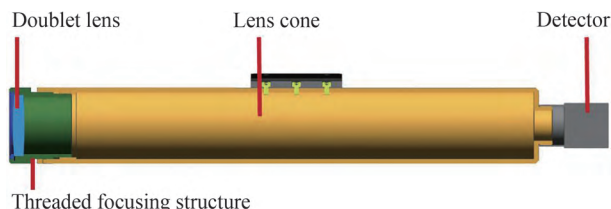


图2 太阳对准系统机械结构
Fig.2 Mechanical structure of solar alignment system

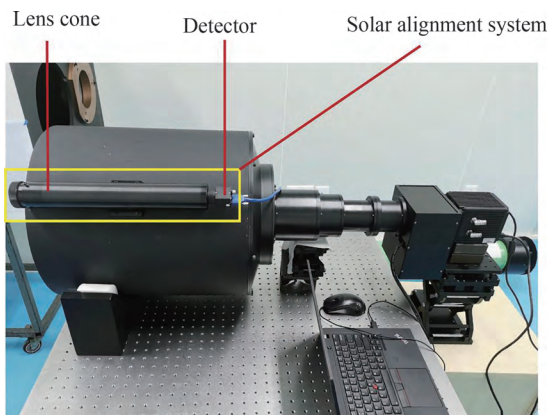


图3 太阳对准系统
Fig.3 Solar alignment system

对太阳成像时,在镜筒前放置 10^{-5} 衰减片,使太阳成像到探测器靶面,太阳像直径大小约占据探测器像元个数 $n=578$ 。

$$\phi = \frac{32'}{n} \times 2 \quad (1)$$

经过实验,日冕仪的指向精度在两个像素,由式(1)计算得到日冕仪指向精度为 $0.11'$ 。经过算法程序识别探测器所呈现圆形太阳像的圆心坐标,依据圆心坐标数据判断是否对准。

图4为对准时指向精度程序界面图,太阳像圆心坐标显示为 $(0,0)$ 。图5为未对准时指向精度程序界面图,太阳像圆心坐标显示为 $(15,-15)$ 。其中,向上和向右偏移,坐标为正。根据坐标及像元尺寸计算偏移量。经计算,太阳像如图5所示时,日冕仪应向下,向右分别移动 $0.825'$ 。

由于日冕仪光轴与对准系统光轴之间还有一段距离,如图6所示,太阳中心与两光轴之间产生一个角度偏差 α 。经式(2)计算,该角度为 $8.426 \times 10^{-11}^\circ$,可以忽略不计。

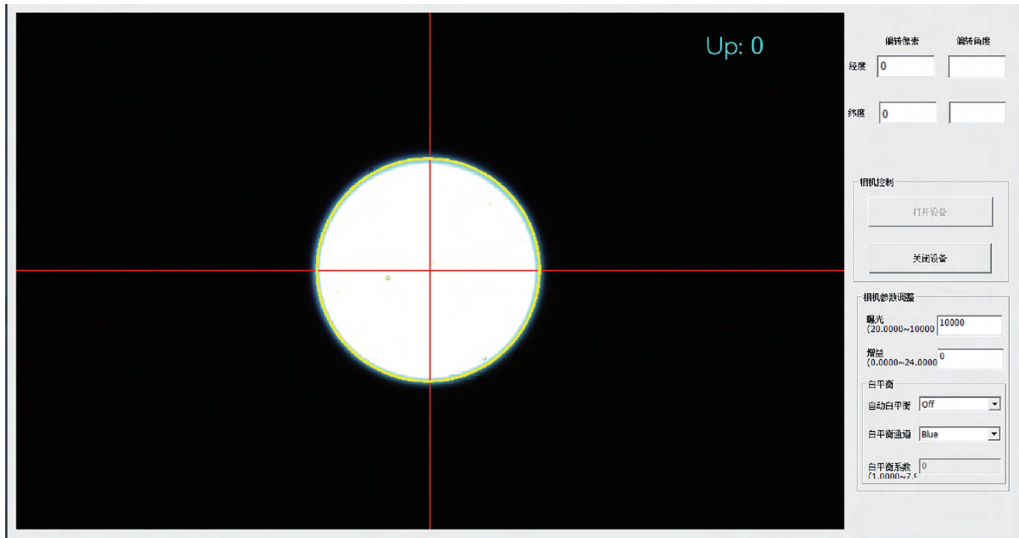


图4 对准时指向精度程序界面
Fig.4 Program interface of pointing accuracy during alignment

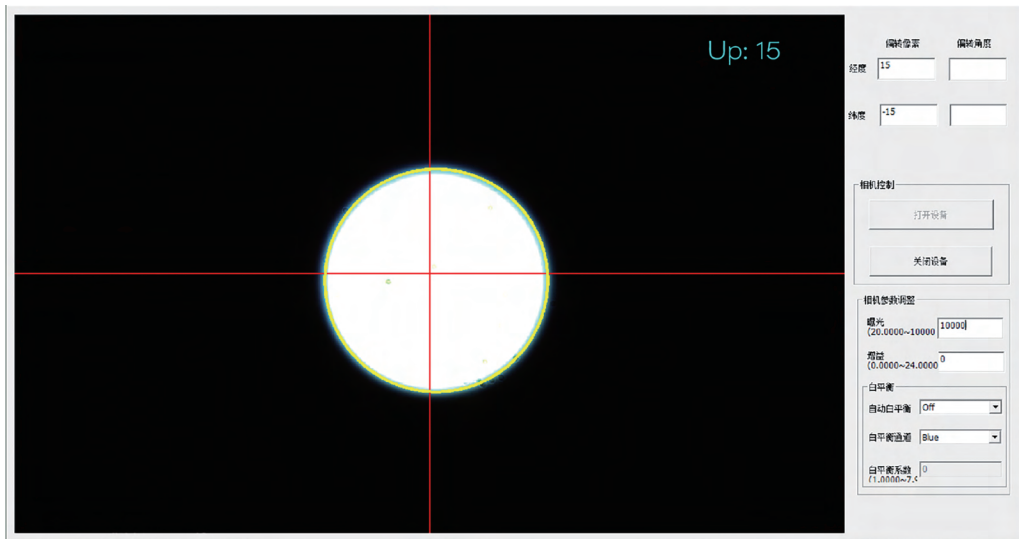


图5 未对准时指向精度程序界面
Fig.5 Program interface of pointing accuracy not aligned

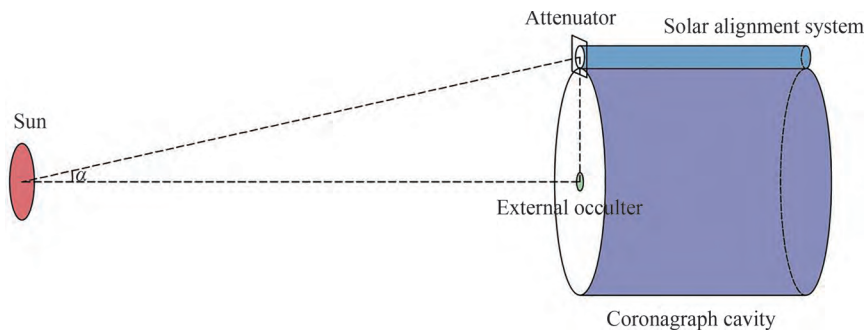


图6 角度偏差计算示意图
Fig.6 Calculation diagram of angle deviation

$$\alpha = \arctan \frac{l}{d} = 8.425\ 85 \times 10^{-11} \text{ } (2)$$

式中, l 是双胶合镜筒中心到外掩体中心的距离 0.22 m , d 是太阳中心到外掩体中心的距离 $1.496 \times 10^{11}\text{ m}$ 。

2 三圆盘型外掩式日冕仪

本实验基于三圆盘型外掩式日冕仪,日冕仪光学系统结构如图7所示,该日冕仪共由12片透镜组成,分为物镜组,场镜组和中继镜组, F 数为4,焦距为38 mm,视场为 $\pm 20^\circ$ 。物镜组是1片双胶合透镜,将进入光学系统的日冕光第一次成像到视场光阑处;场镜组由1片双胶合透镜和5片单透镜组成,用来准直日冕光;中继镜组由5片单透镜组成,将准直后的日冕光成像在像面CCD上。图8为该光学系统的MTF曲线,可以看出在37 lp/mm处,MTF均大于0.6,满足日冕仪成像要求。图9为光学系统的弥散斑点列图,最大弥散斑直径为12.864 μm 小于探测器像元尺寸(13.5 μm)。日冕仪的机械结构由腔体部分、镜筒部分、滤光轮以及CCD相机构成,如图10所示。

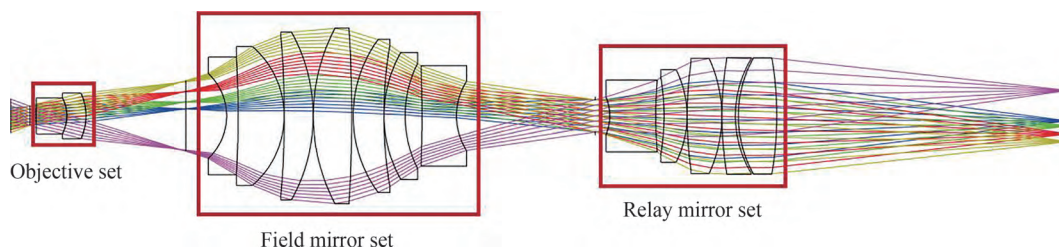


图7 日冕仪光学系统结构

Fig.7 Optical system structure of coronagraph

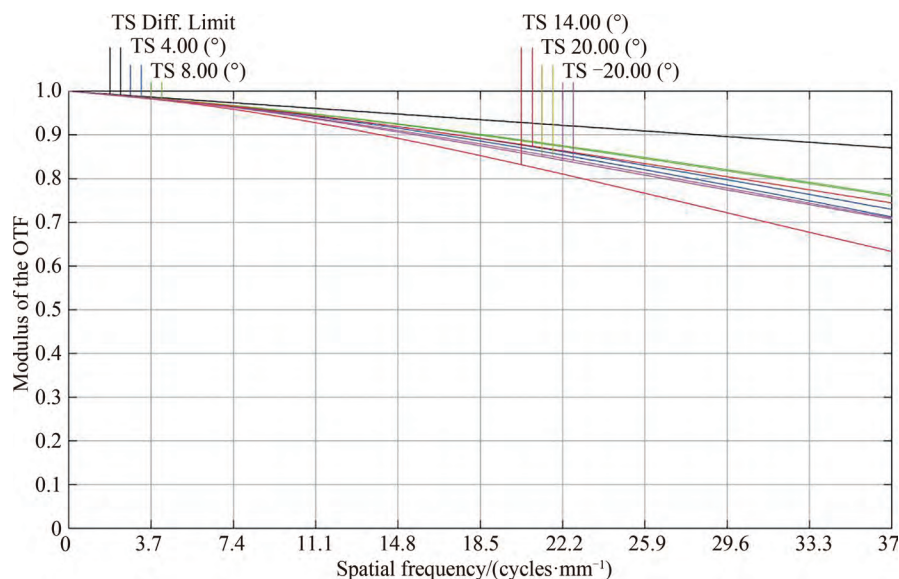


图8 日冕仪传递函数曲线

Fig.8 MTF curves of coronagraph

日冕仪视场为 $\pm 20^\circ$ 。太阳半径 $R_\odot = 6.96 \times 10^8 \text{ m}$, 日地距离 $\text{AU} = 1.496 \times 10^{11} \text{ m}$ 。

$$\frac{\tan 20^\circ \times 1\text{AU}}{R_\odot} = 78$$

经计算,日冕仪视场为 $\pm 20^\circ$,对应于在1AU处可观测范围达到 $78R_\odot$ 。在图11日冕亮度曲线中可以看出, $78R_\odot$ 处的日冕亮度约为 10^{-12} 量级。故日冕仪杂散光抑制水平需达到 10^{-13} 量级。

日冕仪杂散光分析和抑制十分重要。日冕仪的杂散光主要来源可分为太阳直射光,边缘衍射杂散光和散射杂散光三种。日冕仪边缘衍射光又包括外掩体边缘衍射光、外窗口边缘衍射光和入射孔径边缘衍射光。其中,太阳直射光与外掩体边缘衍射光是对日冕仪成像质量影响较大的两类杂散光。

太阳直射光照射日冕仪时,一部分直射光被外掩体遮拦,无法进入日冕仪腔体;另一部分进入腔体的直射光经拒热镜聚焦反射出日冕仪系统。其中,拒热镜为球面反射镜,倾斜放置在腔体底部。外掩体边缘衍射光可以通过优化外掩体形状来抑制,外掩体形状有单圆盘,三圆盘,锯齿形,花瓣形等,图12中给出了前三

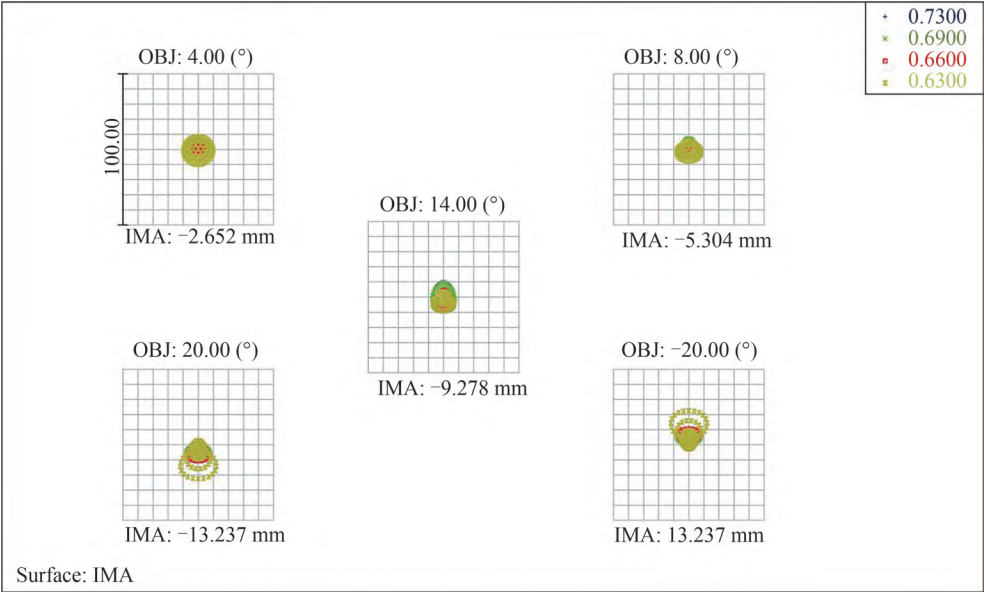


图 9 日冕仪弥散斑点列图
Fig.9 Spot diagrams of coronagraph

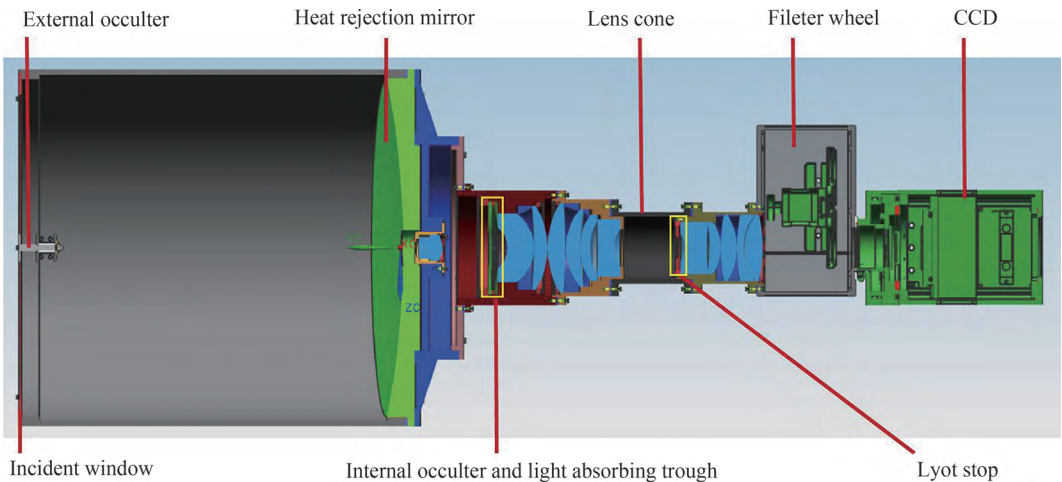


图 10 日冕仪机械机构
Fig.10 Mechanical structure of coronagraph

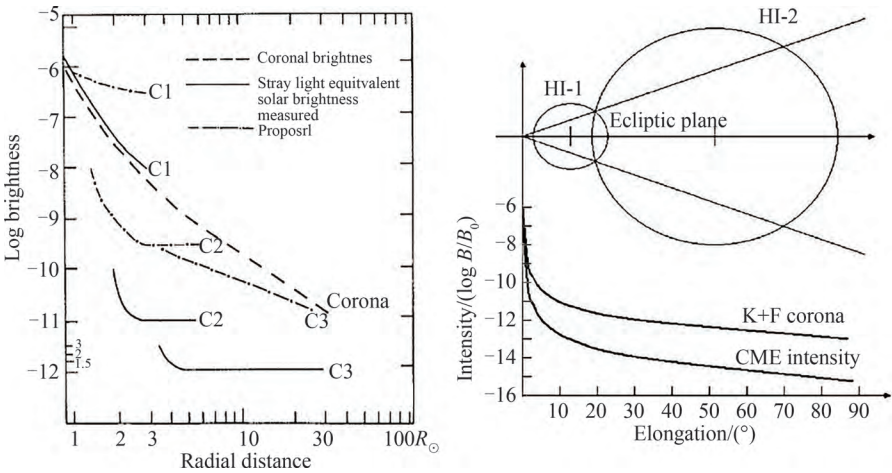


图 11 日冕亮度曲线^[10-11]
Fig.11 Coronal brightness curve^[10-11]

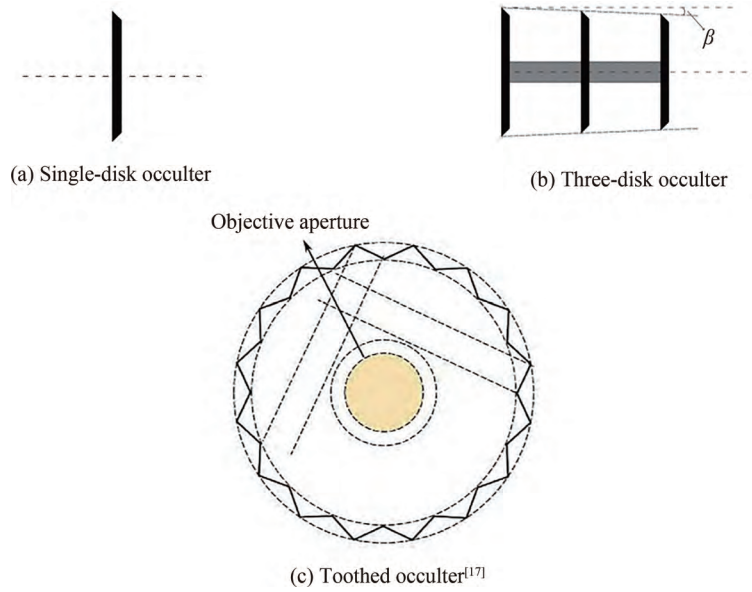


图 12 外掩体形状

Fig.12 External occulter shape

种外掩体示意图。其中,锯齿形外掩体加工难度大,单圆盘外掩体衍射光抑制能力弱。所以本文日冕仪采用三圆盘外掩体,外掩体圆盘之间的关系为后一个圆盘位于前一个圆盘的阴影下,这样可以对前一个圆盘的部分边缘衍射光进行抑制。相比于单圆盘,三圆盘外掩体可以实现对外掩体边缘衍射光的多级遮拦,以减小这种衍射光对日冕成像质量的影响。

根据均匀边界波衍射理论^[18],经数值计算可以得出单圆盘与三圆盘在入射孔径处的衍射光场强度对比,如图 13 所示。三圆盘型外掩体的边缘衍射杂散光强度明显低于单圆盘型。

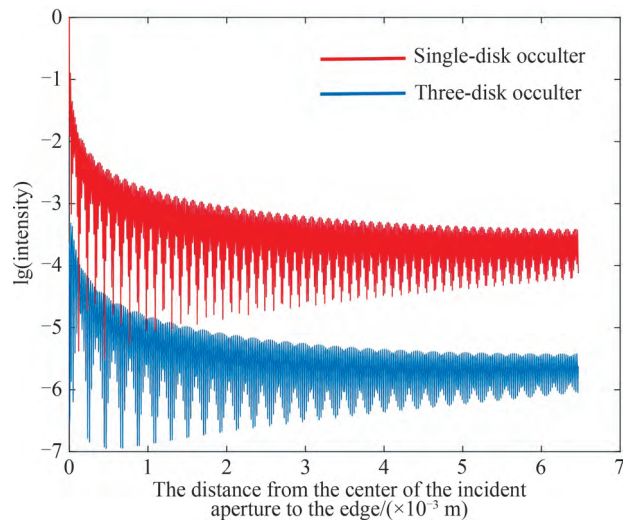


图 13 单圆盘与三圆盘掩体在入射孔径处的场强

Fig.13 Field intensity at the entrance pupil by single-disk and three-disk occulters

3 检测方法

日冕仪检测需要暗环境,且杂散光抑制水平要求很高,需要使用较强的光源进行照射。通常采用激光光源照射,但由于激光光源能量较大,经日冕仪杂散光抑制结构反射后会照亮测试环境,从而影响日冕仪杂散光的检测,如图 14 所示。

因此,本文提出黑洞检测法,在日冕仪视场内放置一黑色箱体,箱体内布满黑色吸光膜,能够吸收入射



图 14 实验室环境光增亮
Fig.14 Laboratory ambient light brightening

到箱体内部的光线,如图 15 所示,以此解决测试环境被激光光源照亮的问题,从而检测杂散光抑制水平。其中,使用的黑色吸光膜是以色列 ACKTAR 公司生产的 Spectral Black™ 杂散光吸收膜,型号为 SB-20×030-1,吸光膜反射率与波长关系如图 16 所示,表 1 给出了吸光膜的相关参数。在图 16 红框部分可以看出,可见光范围内吸光膜的反射率很小,对光的吸收能力强,可以尽可能地减少实验过程中环境光的影响。

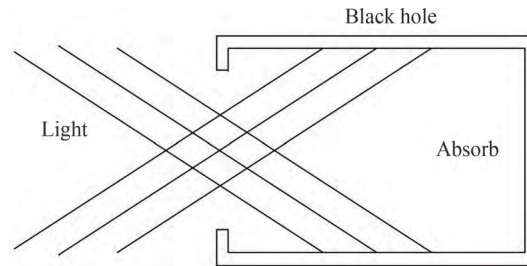


图 15 黑洞示意图
Fig.15 Schematic diagram of black hole

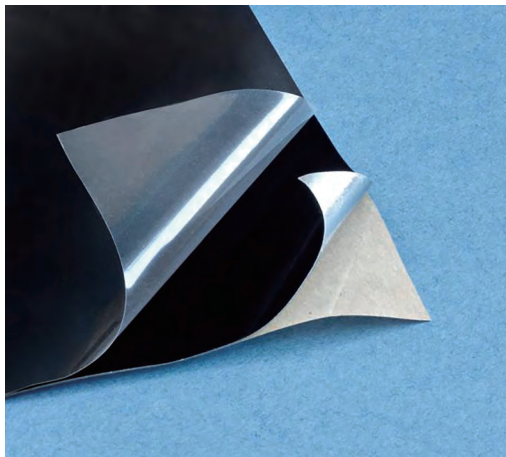


图 16 吸光膜反射率与波长关系
Fig.16 Relation between reflectance of absorbent film and wavelength

杂散光检测时应使日冕仪视场范围内无其它光源照射,则进入日冕仪像面的光全部为杂散光。日冕仪在工作过程中的背景是纯黑的宇宙背景。在地面空间有限的实验室中,利用激光光源模拟太阳,其发出的光以及经拒热镜反射出日冕仪的光会在实验室中经历多次吸收、散射,最终到达相机表面,从而影响杂散光抑制水平检测。而吸光能力强的黑洞可以在一定程度上减少距离有限以及散射光的影响,故黑洞在日冕仪像面位置处的亮度代表的就是日冕仪的杂散光亮度。图 17、图 18 分别给出了在宇宙空间和实验室中检测杂散光的光路示意图。

表 1 吸光膜相关参数
Table 1 Absorbent film parameters

Parameter	Value
Dimensions/mm	200×300
Abrasion resistance	Moderate
Adhesive thickness/ μm	60
Coating	Spectral black™
Coating thickness/ μm	3~7
Foil thickness/ μm	125
Humidity resistance	MIL-C-48497A
Operating temperature/ $^{\circ}\text{C}$	-40 to +121
Wavelength range/ μm	0.3~14
Type	Standard adhesive
Model number	SB-20×030-1

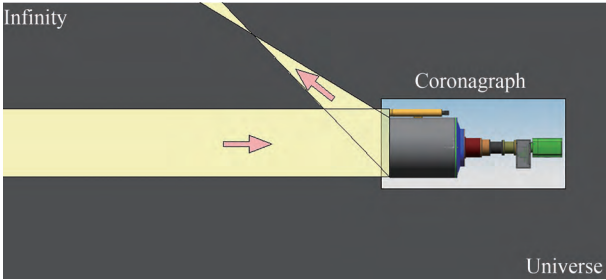


图 17 在宇宙空间检测光路示意图
Fig.17 Schematic diagram of light paths detected in space

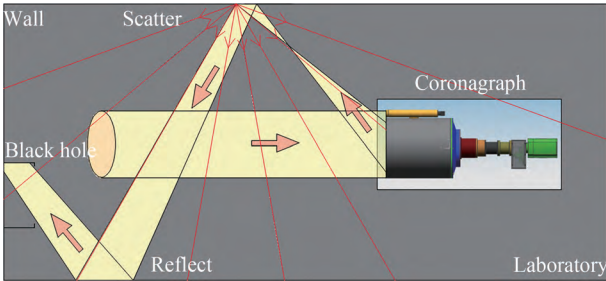


图 18 在实验室检测光路示意图
Fig.18 Schematic diagram of light path detected in the laboratory

该方法降低了对测试环境的要求,简化了检测流程,同时能够获得较为准确的检测结果。在超净间暗室中搭建杂散光检测系统,尽可能减小环境光对检测系统的影响。利用发散角为 $32'$ 的激光光源模拟太阳,将激光光源与日冕仪同轴放置,此时入射孔径位于外掩体的阴影之下。由于用平行光管扩束会降低光源能量,且用相同激光光源扫描日冕仪整个视场时,各处激光均被拒热镜反射出腔体,使用两个光源与使用多个光源结果一致。因此,在实验过程中采用两个完全相同的激光光源,分别照射日冕仪视场中心和边缘,以此来模拟太阳直射光照射。经日冕仪光学系统成像后,由 CCD 相机接收图像,实验装置如图 19 所示。

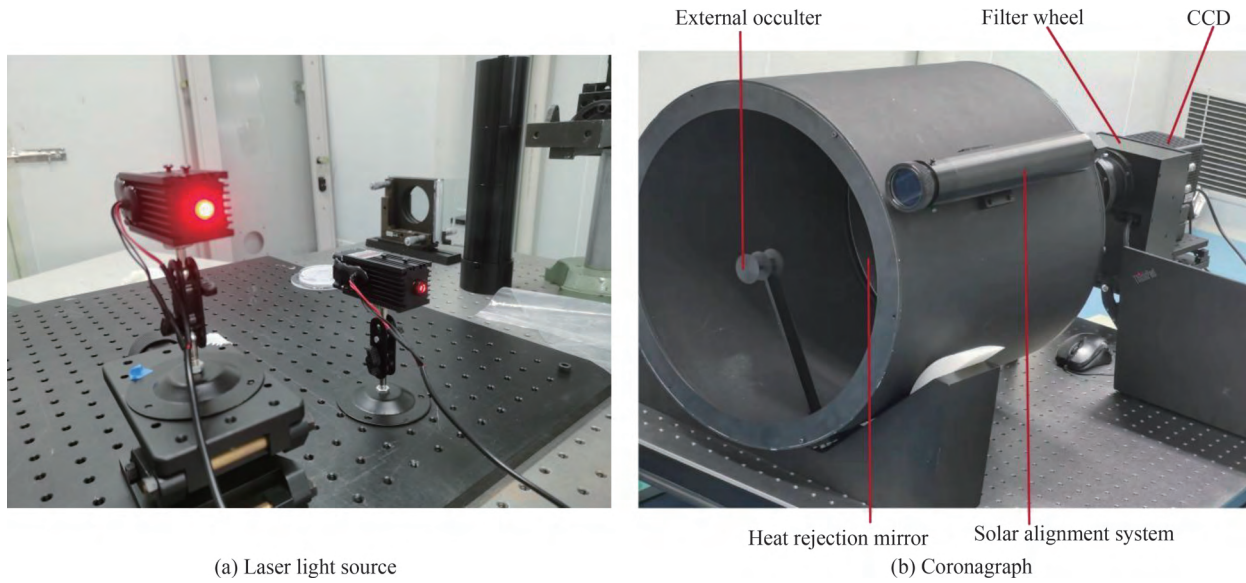


图 19 实验装置

Fig.19 Photos of experimental set-up

4 实验

4.1 外掩体边缘衍射光对比

在暗室中,利用激光光源照射日冕仪,放置单圆盘外掩体,用 CCD 相机接收图像。保持激光器不动,将单圆盘外掩体替换成三圆盘外掩体,保持两次成像参数一致,用相同 CCD 相机接收图像,实验结果如图 20 所示。结果表明:三圆盘外掩体边缘衍射杂散光低于单圆盘外掩体边缘衍射杂散光,实验结果与仿真结果吻合。

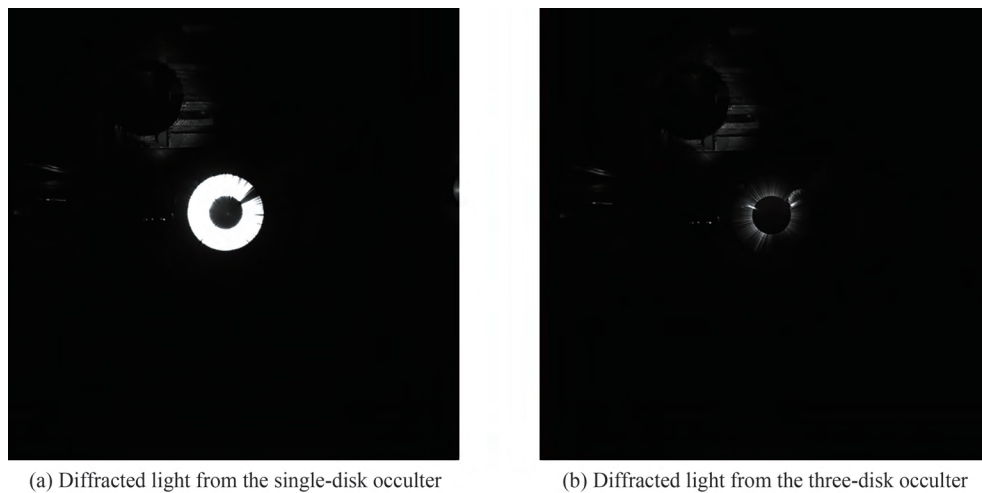


图 20 单圆盘与三圆盘衍射实验图

Fig.20 Single-disk and three-disk diffraction experiment

4.2 杂散光检测

日冕仪系统杂散光抑制水平的评价标准由系统杂散光亮度与太阳直射光亮度的比值来表示,所使用的探测器对光强的响应有良好的线性关系,因此亮度之比即像面图像相同位置处的灰度值之比。

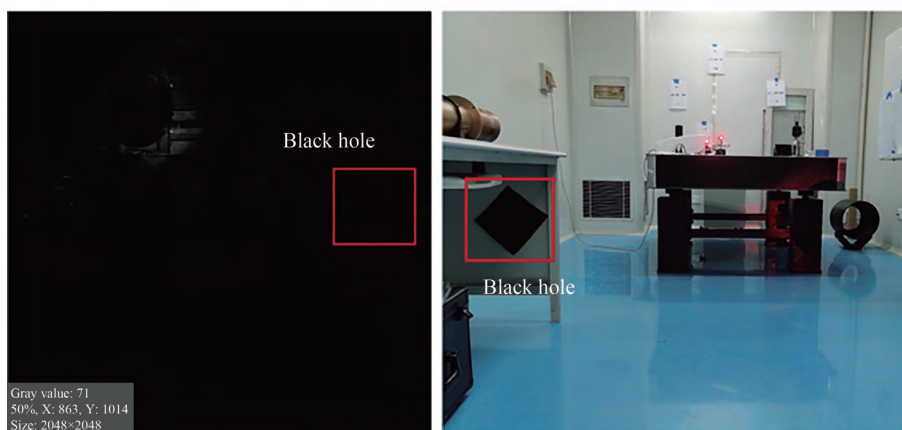
首先,用日冕仪拍摄太阳直射光图像,见图 21(a)。将外掩体与内掩体拆除,保持激光光源与日冕仪同轴放置。在探测器前放置衰减倍率 $K=2.5 \times 10^{-11}$ 衰减片,打开激光光源,使其在探测器上成像,像的半径大小约占据探测器 13 个像素,即 0.176 mm。根据日冕仪焦距和太阳光发散角求得真实太阳经日冕仪成像后的半径大小,计算公式为

$$r = f \times \tan \theta \quad (3)$$

式中, r 为太阳像半径, f 为日冕仪系统焦距, $f = 38 \text{ mm}$, θ 为太阳光发散角一半, $\theta = 16'$ 。经式(3)计算得到太阳像半径为 0.179 mm , 故此时激光光源可以等效为太阳。在软件中读出太阳像中多点的灰度值大小并取平均, 记为 $I_1 = 2507$ 。



(a) Image of direct sunlight



(b) Image of eliminating stray light

图 21 总杂散光检测实验

Fig.21 Total stray light detection experiment

利用日冕仪拍摄系统杂散光图像, 见图 21(b)。重新安装上外掩体和内掩体, 保持激光光源与日冕仪同轴放置。在日冕仪视场内放置黑洞, 调节相机位置, 对黑洞清晰成像, 日冕仪拍摄黑洞位置。在软件中读出其多点的灰度值并取平均, 记为 $I_2 = 71$ 。

根据日冕仪杂散光评价标准, 日冕仪的杂散光计算公式为

$$L = \frac{I_2}{I_1} \times K \quad (4)$$

最后, 经式(4)计算, 日冕仪的杂散光抑制水平为 7.08×10^{-13} , 满足设计要求。

5 结论

本文设计了太阳对准系统, 并应用到三圆盘外掩式日冕仪上进行试验。结果表明, 日冕仪的指向精度达到 $0.11'$ 。实验验证了日冕仪三圆盘外掩体与单圆盘外掩体边缘衍射杂散光强度对比, 三圆盘外掩体具有更强的衍射光抑制能力。同时, 利用黑洞检测法对日冕仪总杂散光进行测量, 获得较为准确的检测结果, 结果达到 10^{-13} 量级, 符合设计要求。

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A New Autocollimation Externally Occulted Coronagraph

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Abstract: Coronal is the outermost layer of the solar atmosphere, which ranges from the chromosphere across several sun radii. Coronal Mass Ejections (CMEs) eject large amounts of magnetized plasma from the sun's atmosphere into interplanetary space, resulting in massive solar explosions. Especially when CMEs spreads to the vicinity of the earth, they will produce geomagnetic disturbances such as geomagnetic

storms, ionospheric storms, auroras, which have a destructive impact on satellite operations and ground infrastructure, and are one of the main driving sources of disastrous weather in space. The corona has long been studied internationally. Observations of the corona and coronal mass ejections help to study the effects of the sun's magnetic field on the earth. Meanwhile, they can monitor the severe space weather events affecting the earth and solar-terrestrial space. To realize the corona and coronal mass ejections observation better, and make more precise observation angles. The solar alignment system is designed in this paper. The entrance pupil diameter of the system is 40 mm, the focal length is 360 mm and the field of view is 2 degrees. With alignment system imaging to the sun, the center coordinates of the solar image on the detector are read through the program, so as to judge whether the coronagraph is aligned with the sun, and the observation Angle of the coronagraph is adjusted according to the coordinate offset calculation. The solar alignment system was applied to the three-disk externally occulted coronagraph for the experiment. The main parameters of the coronagraph are as follows: the field of view is ± 20 degrees; the pixel resolution is 1.2 arcmin; the pixel size is $13.5\ \mu\text{m}$; the wavelength is from 630 nm to 730 nm; the effective F-number is 4; the focal length is 38 mm; and the transfer function is greater than 0.6. Compared with the brightness of the solar photosphere, the brightness of the corona light is very weak, so the suppression of stray light is the key problem of the coronagraph system. Based on the observable range of field of view and corona brightness curve, the design requirements of stray light suppression level of coronagraph are given. The suppression ability of diffraction of external occulter was compared between single-disk occulter and three-disk occulter. The comparison chart of diffraction field intensity between single-disk occulter and three-disk occulter at the incident aperture is obtained by numerical calculation. Coronagraph usually works against a pure black cosmic background. When conducting experiments in the laboratory, as its space is limited, the reflected and scattered light hitting the walls and reaching the camera surface can affect the stray light suppression level detection. Therefore, a black hole detection method is proposed to detect the total stray light of the coronagraph. The black hole refers to the semi-open black box with black absorbing film inside. In the range of visible light, the absorbent film has a very low reflectance and a strong ability to absorb light, which can minimize the influence of ambient light during the experiment. Finally, the detection device is built, the camera is used to shoot the direct solar light image and the stray light image of the system, and the gray value is read in the software to calculate the stray light suppression level. The experimental results show that the pointing accuracy of the coronagraph reaches $0.11'$, the diffraction stray light of the three-disk occulter is lower than the diffraction stray light of the single-disk occulter, and the suppression level of the total stray light of the coronagraph reaches 10^{-13} orders of magnitude. The stray light detection method has good results and high accuracy, and the alignment system has realized its expected function.

Key words: Pointing accuracy; Astronomical instruments; Coronagraph; Stray light; External occulter

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