Charge-injection Device Imaging of Sirius with Contrast Ratios Greater than 1:26 Million

Sailee M. Sawant and Daniel Batcheldor

Abstract

The intrinsic nature of many astronomical objects, such as binary and multiple systems, exoplanets, circumstellar and debris disks, and quasar host galaxies, introduces challenging requirements for observational instrumentation and techniques. In each case, we encounter situations where the light from bright sources hampers our ability to detect surrounding fainter targets. To explore all features of such astronomical scenes, we must perform observations at the maximum possible contrast ratios. Charge-injection devices (CIDs) are capable of potentially exceeding contrast ratios of \( \log_{10}(\text{CR}) > 9 \) (i.e., 1 part in 1 billion) due to their unique readout architectures and inherent anti-blooming abilities. An on-sky testing of a commercially available CID, SpectraCAM XDR (SXDR), demonstrated raw contrast ratios from sub-optimal ground-based astronomical observations that imposed practical limits on the maximum achievable contrast ratios using CIDs. Here, we demonstrate the extreme contrast ratio imaging capabilities of the SXDR using observations of Sirius with the 1.0 m Jacobus Kapteyn Telescope, La Palma, Spain. Based on wavelet-based analysis and precise photometric and astrometric calibrations, we report a direct contrast ratio of \( \Delta m_{1} = 18.54, \log_{10}(\text{CR}) = 7.41 \pm 0.08 \), or 1 part in 26 million. This is an order of magnitude higher compared to the previous CID results.

1. Introduction

Direct imaging of fainter targets in the vicinity of bright sources imposes limitations on the type of contrast observations achievable with ground- and space-based telescopes. The combined effect of small angular separations and large magnitude differences severely impacts the possibility of direct detection of fainter targets (Marois et al. 2008; Oppenheimer & Hinkley 2009). Additionally, the light from bright sources saturates conventional imaging instrumentation, e.g., charge-coupled devices (CCDs) and complementary metal-oxide-semiconductor (CMOS) detectors. Due to their limited full well depth and dynamic range, the directly achievable contrast ratios of these 16-bit detectors are typically restricted to \( \log_{10}(\text{CR}) < 5 \) (i.e., 1 part in 100 thousand).

Several point-spread function (PSF) suppression techniques are implemented to mitigate bright source signals and subsequently achieve higher contrast ratios (i.e., \( 5 < \log_{10}(\text{CR}) < 7 \)). Currently employed techniques, such as coronagraphy (e.g., Schneider et al. 2001), nulling interferometry (e.g., Bracewell & MacPhie 1979; Linfield 2003), integral field spectral deconvolution (e.g., Sparks & Ford 2002), ground-based angular differential imaging (e.g., Marois et al. 2006), and space-based roll subtraction (e.g., Lowrance et al. 2005; Schneider et al. 2010), have complex operational requirements that make faint signal detection a challenge. Additionally, these techniques are optimized when stable PSFs are achieved.

An alternative is to use appropriate instrumentation that can carry out direct extreme contrast ratio (ECR) imaging free from the limitations of currently employed techniques. Charge-injection devices (CIDs) have the intrinsic ability to achieve ECRs of \( \log_{10}(\text{CR}) > 9 \) (i.e., 1 part in 1 billion) owing to their unique readout architectures and inherent anti-blooming abilities (Bhaskaran et al. 2008). A preliminary study of the Sirius field using a commercially available CID at the Florida Tech 0.8 m Ortega telescope reported a raw contrast ratio of \( \Delta m_{2} = 18.3, \log(\text{CR}) = 7.3 \), or 1 part in 20 million at an angular separation of two arcminutes (Batcheldor et al. 2016). However, the atmospheric conditions in Florida imposed practical limitations on the type of contrast ratios that are otherwise achievable using CIDs. Nonetheless, this result...
provided a motivation to carry out a direct CID-based ECR imaging of Sirius from the Roque de Los Muchachos Observatory, La Palma, Spain.

In this paper, we report the results of the direct CID-based imaging of Sirius from La Palma. In Section 2, we provide a brief introduction to CIDs and discuss the details of our observations. Section 3 describes the implemented data reduction and analysis. In Section 4, we present the results of the direct ECR imaging of Sirius. In Section 5, we discuss these results and outline the future prospects for implementing CIDs as astronomical imaging detectors. Section 6 concludes.

2. Instrumentations and Observations

CIDs are an array of X–Y addressable photosensitive metal-oxide-silicon (MOS) capacitors (Michon 1974). First developed in 1970, the original CID imagers incorporated complex on-chip readout electronics and external (i.e., off-chip) amplifiers that delivered a high read noise of $\sim 600 e^-$ (McCreight & Goebel 1981; McCreight et al. 1986). As a result, CCDs (read noise of $< 10 e^-$) have been preferred as astronomical detectors. However, modern CIDs are fabricated with pre-amplifier per pixel (PPP) architectures (active pixel technology), random access decoders, and non-destructive readout (NDRO) mechanisms to deliver read noise levels comparable to CCDs (Ninkov et al. 1994; Eid 1995; Kimble et al. 1995; Bhaskaran et al. 2008).

Unlike CCDs and CMOS detectors, CIDs utilize random access integration to identify, monitor, and control the data acquisition in each pixel. A region of interest (ROI) is then identified in a short pre-exposure (e.g., 0.1 s). The pixels within the ROI are integrated until an NDRO signal threshold (i.e., 75% of the full well capacity) is reached. The detected signal is then read out and stored with a timestamp. The accumulated charge is transferred into the underlying substrate, and the pixel operation is repeated. The data is then combined to create a final image with a wider dynamic range. Since the values of intensely illuminated pixels do not restrict the full well depths of CIDs, the pixels may be integrated, injected, and re-integrated multiple times during a pre-determined exposure. This allows CIDs to extend the upper limit of the dynamic range with 32-bit processors, and deliver a potential contrast ratio of $\Delta m = \sim 24$, $\log_{10}(CR) \sim 9.6$, or 1 part in 4 billion (Bhaskaran et al. 2008).

Due to their unique pixel architecture, true random pixel accessibility, and NDRO capabilities, CIDs offer several advantages over CCDs: negligible charge-transfer losses, extreme radiation tolerance ($> 5$ Mrad), large full well capacity, high fill-factor, broad spectral response (156–1100 nm), and intrinsic anti-blooming abilities (Bhaskaran et al. 2008). Therefore, CIDs are excellent prospects to perform direct ECR imaging with ground- and space-based telescopes.

The data presented here was acquired using the SpectraCAM XDR (SXDR) manufactured by ThermoFisher Scientific Inc.

We installed the SXDR on the 1.0 m Jacobus Kapteyn Telescope (JKT), a facility operated by the Southeastern Association for Research in Astronomy (SARA) at the Roque de Los Muchachos Observatory, La Palma, Spain. The SXDR utilizes a $2048 \times 2048$ 12 $\mu$m pixel Random Access CID820 (RACID) sensor with PPP architecture. The field of view is $10' \times 10'$ with an image scale of $0''30$ pixel$^{-1}$. The pixels have a linear (within 2%) full well capacity of 268,000 $e^-$. They saturate at 305,000 $e^-$. The peak quantum efficiency at 525 nm ($\sim V$-band) is 48% (Bhaskaran et al. 2008). The detector is hermetically sealed and cooled to $-45.6^\circ C$ using an ethylene glycol re-circulation system. At this temperature, the dark current is $5 e^- s^{-1}$ with a conversion gain of 6.2 $e^- ADU^{-1}$. The noise associated with a single read is 44 $e^-$ RMS. This reduces to 5.8 $e^-$ RMS with 128 NDROs for the sampling frequency of 2.1 MHz (Batcheldor et al. 2016).

We conducted observations of Sirius on 2017 March 8th, at an airmass of 1.4. We also observed the Landolt standard star field of SA98 670. All images are acquired with the Johnson-Cousins $B$, $V$, $R$, and $I$ filters. The average Differential Image Motion Monitor seeing was 1.7 FWHM. The moon illumination was 86%.

3. Data Reduction and Analysis

Figure 1 shows a pre-processed $I$-band SXDR image of Sirius with an exposure time of 180 s. The field of view is $10' \times 10'$. The signal from Sirius (R.A. = $06^{h}45^{m}08^{s}.26$, decl. = $-16^{d}43'19''03$) is not saturated. The standard pre-processing routines removed instrumental imperfections; however, it did not suppress the visible artifacts, such as the multiple annular patterns, atmospheric halo, and diffraction spikes.
routines successfully removed instrumental imperfections due to dark and flat-field responses; however, an additional post-processing routine was required to suppress the visible artifacts. The internal reflections from the apochromatic field corrector lenses in the JKT produced multiple ghosts (i.e., annular patterns). It is worth noting that such ghosts are absent in the preliminary observations of Sirius (see Figure 4 in Batcheldor et al. 2016). These artifacts are purely intrinsic to the JKT due to its optical design to acquire a flatter focal plane and a wider field of view (Keel et al. 2016). In addition to this, the atmospheric halo and diffraction spikes dominated the sky background. These effects imposed limitations on the full dynamic range of the image. Therefore, we implemented an additional post-processing routine to mitigate the effects of ghosts, atmospheric halo, and diffraction spikes.

3.1. Wavelet Transformation

For the cases where the background level varies uniformly, a simple median filter is applied to generate a background model, which is then subtracted from pre-processed images (e.g., Bertin & Arnouts 1996; Bradley et al. 2020). Additionally, appropriate sigma-clipping techniques are used to achieve better accuracy (Starck & Murtagh 2002a). Diffused halos from bright sources are suppressed using several methods, such as radial-gradient methods (e.g., Bonnet-Bidaud et al. 2000) and isophotal analysis (e.g., Batcheldor et al. 2016).

However, the presence of multiple ghosts in our data (as seen in Figure 1) resulted in a non-uniform background with abrupt spatial variations. The amalgamation of these patterns with faint source signals highlighted an issue of complex hierarchical structures. Therefore, we applied the à trous wavelet transform to decompose and analyze the SXDR images at different resolution-related scales (Starck & Murtagh 2002b).

This transform yields a discrete, stationary, isotropic, and shift-invariant transformation, which makes it well-suited for astronomical image and data analysis (Starck & Murtagh 2002b; Mertens & Lobanov 2015). We followed the algorithm discussed in Starck & Murtagh (2002a) and applied the à trous wavelet transform to the SXDR images. This yielded a set of resolution-related views for a given input SXDR image, which is described as follows:

\[
f(x, y) = \sum_{j=1}^{J} w_j(x, y) + c_J(x, y),
\]

where \(f(x, y)\) is a mathematical representation of the input SXDR image, \(w_j(x, y)\) is a set of resolution-related views of the image, called wavelet scales, and \(c_J\) is the last smoothed array. The set \(w = \{w_1(x, y), ..., w_J(x, y), c_J(x, y)\}\) is known as the wavelet transform of the input SXDR image (Mertens & Lobanov 2015).

We modeled the noise in the wavelet space to accurately assess the background variation across the input SXDR image. At each resolution scale \(j\), we obtained a wavelet coefficient distribution and carried out a statistical significance test to determine whether a given wavelet coefficient \(w_j(x, y)\) is due to signal (i.e., significant) or noise (i.e., not significant). We defined our null hypothesis, \(\mathcal{H}_0\), as a value that is locally constant across the input SXDR image. We rejected the hypothesis \(\mathcal{H}_0\) when the corresponding \(p\)-value is less than a pre-specified significance level, \(\alpha\) (Miller et al. 2001). Several thresholding techniques exist for multiple hypothesis testing (e.g., \(2\sigma\), \(3\sigma\), and the Bonferroni methods). However, these techniques fail to control a critical quantity, the false discovery rate (FDR), i.e., the fraction of false rejections based on the total number of rejections (Miller et al. 2001). The FDR method outmatches the standard techniques by successfully controlling this quantity (Hopkins et al. 2002). The corresponding FDR ratio is defined as follows:

\[
\text{FDR} = \frac{N_{\text{reject}}}{N_{\text{null true}}}
\]

where \(N_{\text{null true}}\) is the number of pixels that are truly not significant but declared significant (i.e., false positives) and \(N_{\text{reject}}\) is the total number of pixels declared significant. This method ensures that, on average, the FDR is always less than or equal to \(\alpha\) (Miller et al. 2001).

We selected an \(\alpha\) value such that \(0 \leq \alpha \leq 1\). At each scale, we calculated the \(p\)-values of the \(N\) coefficients, sorted from smallest to largest. We defined and evaluated a quantity, \(d\), such that:

\[
d = \max \{i: P_i < P_D\}, \quad P_D = \frac{i\alpha}{c_NN}
\]

where \(P_i\) is the \(p\)-value of the \(i\)th ordered coefficients and \(c_N\) is a constant, which is equal to 1 when the \(p\)-values are statistically independent. We rejected all hypotheses whose \(p\)-values are less or equal to \(P_D\). We then selected the FDR threshold as the wavelet coefficient \(w(x, y)\) with the largest index \(i\) whose \(p\)-value satisfied the above inequality. In this way, we calculated an adaptive significant threshold at each scale. A detailed description of this procedure is discussed in Miller et al. (2001).

We followed the reconstruction algorithm presented in Starck & Murtagh (2002a) and produced a filtered version of the input SXDR image. To avoid the loss of flux due to thresholding, we improved our filtering algorithm by using the Van Cittert iteration algorithm (Starck et al. 1998). We determined the wavelet transform of the filtered SXDR image and ensured that it produced the same significant wavelet coefficients. For each iteration, we calculated the residual signal. We determined the wavelet transform of the residual signal, applied thresholding, and reconstructed the threshold error signal. The residual signal was added back to the filtered SXDR image. We defined our convergence criteria by
calculating the estimated relative error and comparing it to a pre-specified tolerance value, $\epsilon = 0.002$.

### 3.2. Faint Source Detection

We used `photutils.detection`, an affiliated package of AstroPy (Astropy Collaboration et al. 2018; Bradley et al. 2020), to detect sources in the reconstructed noise-reduced SXDR images. This program uses the DAOFIND algorithm (Stetson 1987) to identify local maxima against a user-specified threshold value. To detect the faintest sources, we applied the same detection algorithm to the first filtered resolution-view of the SXDR images. This is only possible in wavelet space because the large-scale features, such as the visible artifacts seen in Figure 1, are suppressed at the smallest scale revealing the faint small-scale sources (Starck & Murtagh 2002c). We extracted the centroid coordinates $(x, y)$ of the detected sources with sub-pixel accuracy. Furthermore, we constrained our detection criteria to extract sources that have an ellipticity of 1.0 (i.e., point sources).

### 3.3. Photometric and Astrometric Calibrations

The process of transforming our instrumental magnitudes to the standard $UBVR_I$ magnitudes was carried out using the Gaia Early Data Release 3 (Gaia EDR3) catalog data (Gaia Collaboration et al. 2016; Riello et al. 2021). We found our photometric accuracy using the $B$, $V$, $R$, and $I$-band images of the Landolt standard star field of SA98 670. The resulting mean absolute percentage errors (MAPEs) in the transformed $B$, $V$, $R$, and $I$ magnitudes of the standard stars of SA98 670 are 0.167%, 0.048%, 0.072%, and 0.068%, respectively.

To match the positions of our detected sources with previously known sources, we acquired the astrometric coordinates of the Gaia EDR3 cataloged sources within the same field of view. We cross-correlated pixel coordinates of the Gaia EDR3 sources with centroids of the detected sources. We compared the cataloged coordinates of the cross-correlated sources with the corresponding calculated coordinates. The resulting mean absolute accuracies in the right ascension (R.A.) and declination (decl.) are $0\farcs321$ and $0\farcs258$, respectively.

### 4. Results

Figure 2 shows the post-processed $I$-band SXDR image of Sirius. The SIMBAD and detected Gaia EDR3 cataloged sources are marked in red and blue, respectively. The SIMBAD cataloged sources are at smaller angular separations because they were observed using CCDs with smaller field of views (Bonnet-Bidaud & Gry 1991; Bonnet-Bidaud et al. 2000).

Figure 3 illustrates the PSF of Sirius and associated artifacts (e.g., ghost patterns) on a logarithmic scale in counts per second (cps). The inset shows the unsaturated signal from Sirius. The horizontal dashed and dotted black lines represent the read noise and dark current, respectively. We calculated direct contrast ratios based on the differences between the calibrated apparent magnitudes of the detected sources and the cataloged magnitudes of Sirius (i.e., $\Delta m$).
These contrast ratios are usually reported as follows:

\[ \log_{10}(CR) = -\frac{\Delta m}{2.5} \]  

Figure 4 shows direct contrast ratios of the detected Gaia EDR3 cataloged sources as a function of angular separation (in arcseconds) from Sirius. Since the Gaia EDR3 catalog does not include data on Sirius, all contrast ratios and angular separations are calculated with respect to the SIMBAD cataloged data of Sirius (Wenger et al. 2000). We acquired the maximum direct contrast ratio of \( \Delta m_r = 18.54 \), \( \log_{10}(CR) = 7.41 \pm 0.08 \), or 1 part in 26 million. For the cases where the Gaia EDR3 cataloged sources are detected with SNRs < 10, we calculated their raw contrast ratios (i.e., contrast ratios based on their cataloged magnitudes). These contrast ratios are marked in red.

Table 1 lists some of the detected faint Gaia EDR3 cataloged sources. These sources are detected at different confidence levels based on their SNRs. The corresponding \( 8'' \times 8'' \) thumbnails are shown in Figure 5. No sources with SNRs < 10 and <20 are detected in the \( V \)- and \( B \)-band, respectively.

Table 1

| Filter | Source ID | Gaia EDR3 Source ID | Calibrated Magnitude (mag) | \( \log_{10}(CR) \) | SNR |
|--------|-----------|---------------------|---------------------------|---------------------|-----|
| \( B \) | 1 | 2947057338479481600 | 15.216 ± 0.079 | 6.67 ± 0.03 | 48.66 |
| \( V \) | 2 | 2947046961838568064 | 16.307 ± 0.189 | 7.11 ± 0.08 | 15.53 |
|        | 3 | 2947046686906084288 | 15.587 ± 0.142 | 6.82 ± 0.06 | 32.46 |
| \( R \) | 4 | 2947063042187126400 | 17.077 ± 0.203 | 7.41 ± 0.08 | 7.39 |
|        | 5 | 2947062939108083456 | 16.753 ± 0.166 | 7.29 ± 0.07 | 11.54 |
|        | 6 | 2947051188086163584 | 16.115 ± 0.113 | 7.03 ± 0.05 | 24.98 |
| \( I \) | 7 | 2947063759445801472 | 16.210 ± 0.170 | 7.06 ± 0.07 | 7.73 |
|        | 8 | 294706297347613824 | 15.560 ± 0.102 | 6.80 ± 0.04 | 12.36 |
|        | 9 | 2947049882416355712 | 14.837 ± 0.063 | 6.51 ± 0.03 | 36.66 |

Note. These sources demonstrate contrast ratios at different SNR levels in each band. No sources with SNRs < 10 and <20 are detected in the \( V \)- and \( B \)-band, respectively.

Figure 4 shows direct contrast ratios of the detected Gaia EDR3 cataloged sources as a function of angular separation (in arcseconds) from Sirius. Since the Gaia EDR3 catalog does not include data on Sirius, all contrast ratios and angular separations are calculated with respect to the SIMBAD cataloged data of Sirius (Wenger et al. 2000). We acquired the maximum direct contrast ratio of \( \Delta m_r = 18.54 \), \( \log_{10}(CR) = 7.41 \pm 0.08 \), or 1 part in 26 million. For the cases where the Gaia EDR3 cataloged sources are detected with SNRs < 10, we calculated their raw contrast ratios (i.e., contrast ratios based on their cataloged magnitudes). These contrast ratios are marked in red.

5. Discussion

Due to the extreme brightness of Sirius, previous ground-and space-based observations have prompted the need for appropriate imaging instrumentation and techniques. For instance, Bonnet-Bidaud & Gry (1991) and Bonnet-Bidaud et al. (2000) used specially designed coronagraphic devices on ground-based telescopes to look for companions around Sirius. Bond et al. (2017) determined several orbital parameters of the Sirius system using an extensive volume of Hubble Space
Telescope (HST) observations and ground-based photographic images. Even with HST, significant observing challenges were encountered; no combination of a filter and short exposure time resulted in an unsaturated image of Sirius (Bond et al. 2017). However, as we have demonstrated here, it is now possible to acquire an unsaturated signal from Sirius using a 1.0 m telescope at an exposure time of 180 s without imposing complex operational requirements.

We also detected Sirius B at an angular separation of 8″401 from Sirius. Figure 6 shows a zoomed-in view of the post-processed $I$-band SXDR image of the field around Sirius. The annotated source is Sirius B. Its separation from Sirius is consistent with the proper motion data (e.g., Wenger et al. 2000; Gaia Collaboration et al. 2016). This is an improvement in the IWA of the SXDR because Sirius B, despite being 8th magnitude, was not detected from Florida (Batcheldor et al. 2016).

Within the 5′ radial field around Sirius, the SIMBAD catalog reports a total of 47 sources out of which [BG91] 1–9 (Bonnet-Bidaud & Gry 1991) are duplicated with [BCL2000] 1–9 (Bonnet-Bidaud et al. 2000). This is due to the proper motion of Sirius over 15 yr; Bonnet-Bidaud & Gry (1991) defined spatial positions as offsets from Sirius, whereas Bonnet-Bidaud et al. (2000) reported the absolute positions. We applied corrections to address these source duplications. Upon analyzing the positions of these sources over the given baseline, we determined no significant proper motion. In addition, the photometric and astrometric uncertainties in the [BG91] data are ±0.3 mag and ±0″7, respectively (Bonnet-Bidaud & Gry 1991). Batcheldor et al. (2016) used the [BG91] and [BCL2000] sample data for their analysis.

Recently, the Gaia EDR3 catalog reports a total of 1181 sources (without duplications) within the central 10′ square field around Sirius. These sources have all-inclusive Gaia photometric and astrometric data with higher precision (see Table 3 in Gaia Collaboration et al. 2021 for statistical details on uncertainties). Therefore, we used the Gaia EDR3 cataloged sources for our photometric and astrometric calibrations.

It is important to note that the contrast ratios reported by Batcheldor et al. (2016) are raw, i.e., differences between the cataloged magnitudes of the detected sources and Sirius. They achieved the maximum raw contrast ratio of 1 part in 20 million (i.e., $\log_{10}(CR) = 7.3$), which is based on the $V$-band magnitude of [BCL2000] 6 (i.e., $m_v = 16.8$). They did not have photometrically calibrated SXDR images because the observing conditions in Florida were unfavorable for performing the required photometric calibrations. Although we detected only a fraction of the GAIA EDR3 cataloged sources, we provided contrast ratios based on the photometrically calibrated SXDR images for the first time. Furthermore, the [BCL2000] 6 source corresponds to the GAIA EDR3 2947051462964006144 source, which has a transformed $V$-band Gaia magnitude of 14.759 mag. This corresponds to a contrast ratio of $\log_{10}(CR) = 6.49$ and not 7.3 as reported by Batcheldor et al. (2016). If we compare this corrected contrast ratio to our result (i.e., $\log_{10}(CR) = 7.41$), we have successfully demonstrated a CID contrast ratio an order of magnitude higher than previous.
Figure 7. Plot of $\log_{10}(CR)$ for a set of simulated sources. The contrast ratios and angular separations (in arcseconds) are calculated with respect to a simulated bright source. The unfilled square markers are contrast ratios of pre-defined simulated sources in a noise-free image. The filled circular markers are recovered contrast ratios of simulated sources from a noisy image. The mean error in the recovered contrast ratios is ±0.004. The horizontal dashed colored lines show the sky-limited contrast ratios of $\log_{10}(CR) = 8.1, 8.2, 8.1,$ and 7.7 in the $B$-band (marked in blue), $V$-band (marked in green), $R$-band (marked in red), and $I$-band (marked in purple), respectively. As demonstrated in Figure 4, we observed fewer sources at shorter wavelengths. This is consistent with the stellar mass function, in which there is a larger population of later spectral types. Furthermore, no sources with SNRs < 10 and <20 are detected in the $V$- and $B$-band, respectively. Since Sirius is an A1V type star, it is brighter through shorter wavelength filters. Consequently, Rayleigh scattering contributed to the overall sky background level, making it a challenge to detect fainter sources in the $B$- and $V$-band.

Nevertheless, we identified several sources with SNRs lower than the minimum threshold. As a result, although visible, these sources did not satisfy our detection requirements. For instance, in the $R$-band, we identified Gaia EDR3 2947063454512704768, 294704998s495334144, and 2947056616924962688 that have direct raw contrast ratios of $\log_{10}(CR) = 7.68 \pm 0.01$, 7.72 ± 0.01, and 7.73 ± 0.01, respectively. Under ideal seeing conditions, it would be possible to detect such sources at $2\sigma$ or $3\sigma$ above the background level.

Even in the presence of practical limitations, we achieved a photometric precision of ±0.019, ±0.049, ±0.041, and ±0.044 mag for $B$, $V$, $R$, and $I$ magnitudes, respectively. As discussed earlier, the contrast ratios acquired from the simulated bright star field data show that the implemented reduction and analysis methods are accurate within a MAPE of 0.016%. Furthermore, we found that the mean absolute accuracies in our astrometric calibration are 0.321 and 0.258 for R.A. and decl., respectively. These methods would deliver even better results for data acquired under ideal observing conditions (e.g., uniform backgrounds and darker skies). Indeed, contrast ratios greater than $\log_{10}(CR) = 7.73$ (i.e., 1 part in 54 million) would be easily achievable using CIDs without any operational prerequisites.

The presence of concentric circular patterns (as seen in Figures 2 and 6) and the distinct shape of the peak signal from Sirius (as seen in the inset of Figure 3) suggest the need for some development in the display tools of the SXDR. Since the ROI is assigned during a short pre-exposure, there is a trade-off between the pre-exposure and the atmospheric scintillation timescale. As the SXDR continues to detect photons, the spatial positions of the brightest pixels change within the ROI due to scintillation. This results in a random pattern of signal within the ROI, which is different from a plateaud saturated signal and a typical Gaussian profile of a point source (Batcheldor et al. 2016). To overcome this issue, a future version of the CID...
technologies would incorporate an option to disable the ROI pixels by floating the gate voltages. This would indeed allow CIDs to act as dynamic coronagraphs (Batcheldor et al. 2016).

We measured the count rate data of the detected Gaia EDR3 cataloged sources (see Figure 2, marked in blue) to analyze the “knockdown” issue. This arises due to the imager’s inability to detect photons when the pixels in the ROI are being reset. Consequently, some flux is lost when the data is combined at the end of the exposure. Depending on their quantum efficiency, the pixels will undergo more resets for wavelengths at which they are more efficient in detecting photons. To quantify the knockdown coefficients, we first calculated the contrast ratios using the cataloged magnitudes of Sirius and the detected Gaia EDR3 cataloged sources (i.e., raw contrast ratios). We then compared these contrast ratios to their corresponding count rate ratios. We found that the mean knockdown coefficients for $B$, $V$, $R$, and $I$-band SXDR images are 0.91, 0.92, 0.90, and 0.92, respectively.

While knockdown impedes our ability to measure the actual flux from the bright source, this issue is beneficial under certain circumstances. For instance, it helps increase the absolute raw contrast range possible since the light from the bright source is unintentionally suppressed. As discussed in Batcheldor et al. (2016) and demonstrated above, knockdown can be easily quantified and calibrated using the cataloged magnitudes of known sources in the bright source fields. Therefore, for the cases where absolute photometry is required, this issue can be resolved using photometrically derived knockdown coefficients.

Since CIDs are capable of achieving contrast ratios of $\log_{10}(CR) > 9$ (Bhaskaran et al. 2008), they are excellent prospective instruments for cost-effective direct ECR observations. However, to achieve these contrast ratios it will be necessary to combine CIDs with existing PSF suppression techniques.

For ground-based direct ECR imaging demonstrations using CIDs, the potential next step is to observe different bright star fields in the presence of previously known practical limitations. At optimal seeing conditions, it would be possible to detect fainter sources and achieve even higher contrast ratios. However, it is important to note that CIDs do not independently suppress the effects of bright source PSFs. To further improve IWAs for such observations, it would be effective to incorporate CIDs with relatively simple observing techniques, such as angular differential imaging (Marois et al. 2006), and software-based PSF modeling techniques. The corresponding demonstrations could provide comparable state-of-the-art observations with much less cost and complexity. This could help push the boundaries of direct ECR imaging.

For the cases where the target PSFs are not stable or well-known, the IWAs would be large, and detecting nearby fainter sources, such as exoplanets, would be challenging. Since PSFs are most stable in space, CIDs would be most beneficial on space-based telescopes. Now that the CIDs are space-qualified to NASA’s technology readiness level 8 (Batcheldor et al. 2020), they are excellent prospects to carry out direct ECR observations with future space-based telescopes. CID-based direct ECR imaging would most likely help us observe and resolve several ECR scenes, including those with binary and multiple systems, exoplanets, circumstellar and debris disks, and quasar host galaxies.

6. Conclusion

We demonstrated a direct contrast ratio of $\Delta m_i = 18.54$, $\log_{10}(CR) = 7.41 \pm 0.08$, or 1 part in 26 million using the SXDR on the 1.0 m JKT. This is an order of magnitude improvement over previous CID observations. We implemented wavelet-based image analysis and acquired filtered SXDR images. We applied photometric and astrometric calibration techniques on the detected GAIA EDR3 sources and calculated contrast ratios with respect to the cataloged magnitude of Sirius. Additionally, we detected Sirius B at a separation of 8.401 from Sirius. The optical design of the JKT and high sky brightness imposed practical limitations on the maximum achievable contrast ratios. However, direct contrast ratios greater than 1 part in 54 million would be easily achievable with CIDs at optimal observing conditions.

This research was supported in part by the American Astronomical Society’s Small Research Grant Program and the Mount Cuba Astronomical Foundation. We are grateful to the SARA for allocating time on the 1.0 m JKT at the Roque de Los Muchachos Observatory, La Palma, Spain. We are thankful to the anonymous referee for providing comments and suggestions that improved the quality and clarity of this paper.

ORCID iDs

Sailee M. Sawant @ https://orcid.org/0000-0002-7987-0310
Daniel Batcheldor, @ https://orcid.org/0000-0002-8588-5682

References

Astropy Collaboration, Price-Whelan, A. M., Sipocz, A. M., et al. 2018, AJ, 156, 123
Batcheldor, D., Foardi, R., Bahr, C., et al. 2016, PASP, 128, 025001
Batcheldor, D., Sawant, S., Jenne, J., et al. 2020, PASP, 132, 055001
Bertin, E., & Arnouts, S. 1996, A&AS, 117, 393
Bhaskaran, S., Chapman, T., Pilon, M., & Vangorden, S. 2008, Proc. SPIE, 7055, 70550R
Bond, H. E., Schaefer, G. H., Gilliland, R. L., et al. 2017, ApJ, 840, 70
Bonnet-Bidaud, J. M., Colas, F., & Lecacheux, J. 2000, A&A, 360, 991
Bonnet-Bidaud, J. M., & Gry, C. 1991, A&A, 252, 193
Bracewell, R. N., & MacPhie, R. H. 1979, Icar, 38, 136
Bradley, L., Sipocz, B., Robitaille, T., et al. 2020, astropy/photutils: 1.0.0, 1.0.0, Zenodo, doi:10.5281/zenodo.4044744
Eid, S. I. 1995, Proc. SPIE, 2415, 292
Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. 2021, A&A, 649, A1
Gaia Collaboration, Prusti, T., de Bruijne, J. H. J., et al. 2016, A&A, 595, A1
Hopkins, A. M., Miller, C. J., Connolly, A. J., et al. 2002, AJ, 123, 1086
Keel, W. C., Osvalt, T., Mack, P., et al. 2016, PASP, 129, 015002
Kimble, R. A., Chen, P. C., Haas, J. P., et al. 1995, Proc. SPIE, 2518, 397
Linfield, R. P. 2003, Proc. SPIE, 4852, 443
Lowrance, P. J., Becklin, E. E., Schneider, G., et al. 2005, AJ, 130, 1845
Marois, C., Lafrenière, D., Doyon, R., Macintosh, B., & Nadeau, D. 2006, ApJ, 641, 556
Marois, C., Macintosh, B., Barman, T., et al. 2008, Sci, 322, 1348
McCreight, C. R., & Goebel, J. H. 1981, ApOpt, 20, 3189
McCreight, C. R., McKelvey, M. E., Goebel, J. H., Anderson, G. M., & Lee, J. H. 1986, Proc. SPIE, 0686, 66
Mertens, F., & Lobanov, A. 2015, A&A, 574, A67
Michon, G. 1974, US Patent 3,786,263
Miller, C. J., Genovese, C., Nichol, R. C., et al. 2001, AJ, 122, 3492
Ninkov, Z., Tang, C., & Easton, R. L. 1994, Proc. SPIE, 2172, 180
Oppenheimer, B. R., & Hinkley, S. 2009, ARA&A, 47, 253
Riello, M., De Angeli, F., Evans, D. W., et al. 2021, A&A, 649, A3
Schneider, G., Becklin, E. E., Smith, B. A., et al. 2001, AJ, 121, 525
Schneider, G., Silverstone, M. D., Stobie, E., Rhee, J. H., & Hines, D. C. 2010, Space Telescope Science Institute Calibration Workshop - Hubble after SM4, 15
Sparks, W. B., & Ford, H. C. 2002, ApJ, 578, 543
Starck, J.-L., & Murtagh, F. 2002a, Filtering (Berlin: Springer), 27
Starck, J.-L., & Murtagh, F. 2002b, Introduction to Applications and Methods (Berlin: Springer), 1
Starck, J.-L., & Murtagh, F. 2002c, Detection (Berlin: Springer), 93
Starck, J.-L., Murtagh, F. D., & Bijaoui, A. 1998, Image Processing and Data Analysis: The Multiscale Approach (Cambridge: Cambridge Univ. Press), Stetson, P. B. 1987, PASP, 99, 191
Wenger, M., Ochsenbein, F., Egret, D., et al. 2000, A&AS, 143, 9