

CCD Calibration and Photometric Analysis of Stellar Variability

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1 Introduction

Photometry is one of the most important techniques in observational astronomy because it allows the brightness of astronomical objects to be measured quantitatively. Modern photometric observations are typically obtained with charge-coupled device (CCD) detectors, which convert incident photons into digital counts. However, raw CCD images contain not only astrophysical signal, but also instrumental effects introduced by the detector and optical system. These include electronic readout offsets, thermally generated electrons, and variations in pixel-to-pixel sensitivity. As a result, raw data must be calibrated before scientifically reliable measurements can be made.

The purpose of this laboratory exercise was to study the reduction and interpretation of CCD photometric data. The first part of the lab focused on the construction and application of master bias, dark, and flat-field frames, followed by aperture photometry of the target star HAT-P-32b in order to study the relationship between exposure time, detected flux, and signal-to-noise ratio (SNR). The second part of the lab focused on differential photometry of variable sources, using the systems GW Cephei and WASP-10b as examples. Their light curves were used to infer the physical origin of the observed variability.

2 CCD Calibration

2.1 Bias, Dark, and Flat Frames

Three types of calibration frames are required to correct CCD images. A **bias frame** is a zero-exposure image taken with the shutter closed; it records the electronic offset introduced during CCD readout. A **dark frame** is obtained with the shutter closed but with a nonzero exposure time; it measures thermally generated electrons, or dark current, in the detector.

A **flat-field frame** is an image of a uniformly illuminated field; it records spatial variations in detector response, including pixel sensitivity differences, dust shadows, and vignetting.

These three frames correct different instrumental effects and are all necessary for accurate reduction of science data. Because individual calibration frames contain random noise, many frames are combined to form master calibration images. Combining many frames reduces random fluctuations and produces a more stable estimate of the detector response. In general, the noise decreases approximately as $N^{-1/2}$ when N frames are combined.

The bias frames were averaged because they are dominated by a stable electronic offset plus small random fluctuations. The dark and flat frames were median combined in order to reduce the influence of outliers such as cosmic rays, hot pixels, and other transient artifacts. New calibration data must also be obtained during each observing run because detector properties, temperature conditions, and optical system characteristics can change with time. A calibration set from a different night would therefore not necessarily provide an accurate correction.

2.2 Calibration Equation and Correction Logic

The signal recorded in a raw CCD image may be written schematically as

$$\text{Raw Image} = (\text{True Signal} + \text{Bias} + \text{Dark}) \times \text{Flat Response}. \quad (1)$$

To recover the astrophysical signal, the additive components must be subtracted and the multiplicative response must be divided out. Thus the calibrated image is obtained from

$$\text{Calibrated Image} = \frac{\text{Raw Image} - \text{Bias} - \text{Dark}}{\text{Flat}}. \quad (2)$$

This also explains why the calibration frames themselves must be corrected before being applied to science data. Since bias is present in all CCD images, it must be subtracted from both the master dark and the master flat. In addition, the flat may contain a dark-current contribution if its exposure time is nonzero, so the bias-corrected dark must also be subtracted from the flat. Without these additional corrections, the same instrumental effects would be removed more than once.

3 Results of Calibration

3.1 Initial and Corrected Master Calibration Frames

The initial master calibration frames displayed the expected qualitative behavior. The master bias frame showed random electronic structure with a noticeable bright band near the

top edge. The master dark frame showed thermal signal and large-scale structure, while the master flat frame displayed a broad nonuniform illumination pattern across the detector, including spatial sensitivity variations.

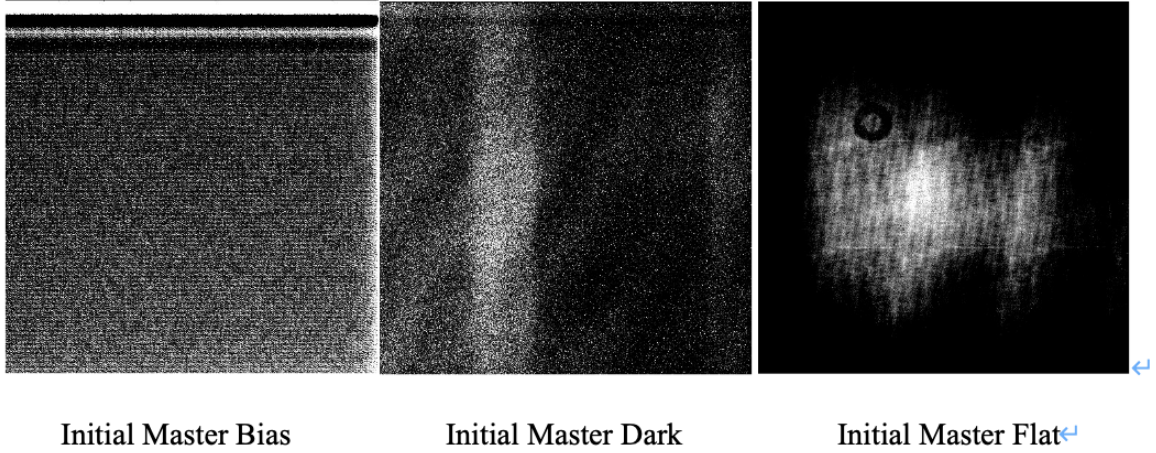


Figure 1: Initial master calibration frames: master bias, master dark, and master flat.

After subtracting the bias from the master dark and the master flat, and then subtracting the dark from the flat, the corrected calibration products appeared cleaner and more appropriate for use on science images. In particular, the corrected dark and flat no longer contained the same obvious bias contribution, and the flat field more clearly represented multiplicative response variations across the detector.

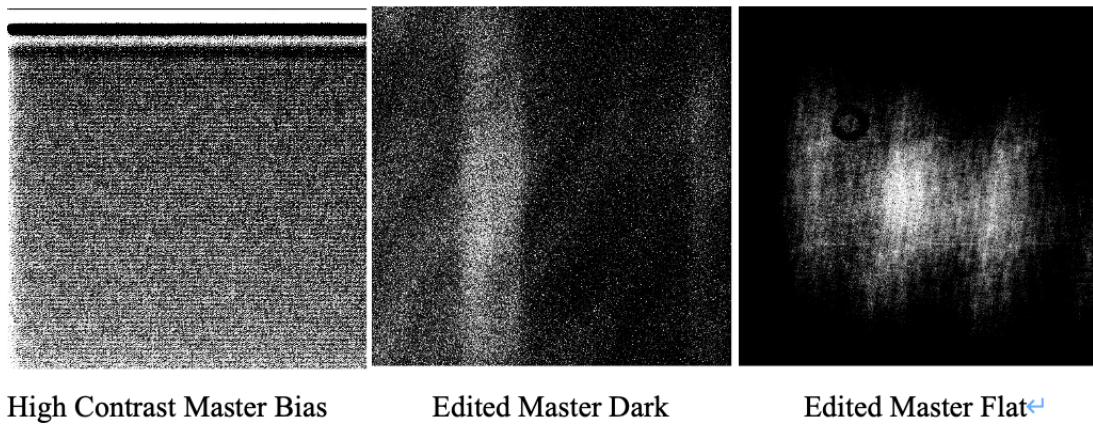


Figure 2: Corrected calibration frames after removal of the appropriate bias and dark contributions.

These results are physically reasonable. Bias is expected to appear in both dark and flat

images because it is added during readout, and dark current may contribute to flat images whenever the flat exposure is not strictly zero. The corrections applied here are therefore necessary to isolate the specific detector effects that each master frame is meant to represent.

3.2 Science Images Before and After Calibration

Two science images of the same field, labeled 241r and 008r, were compared with the calibration products. Before calibration, high-contrast display revealed structure consistent with the instrumental signatures seen in the master calibration frames, indicating that bias, dark, and flat-field effects were indeed present in the raw science data.

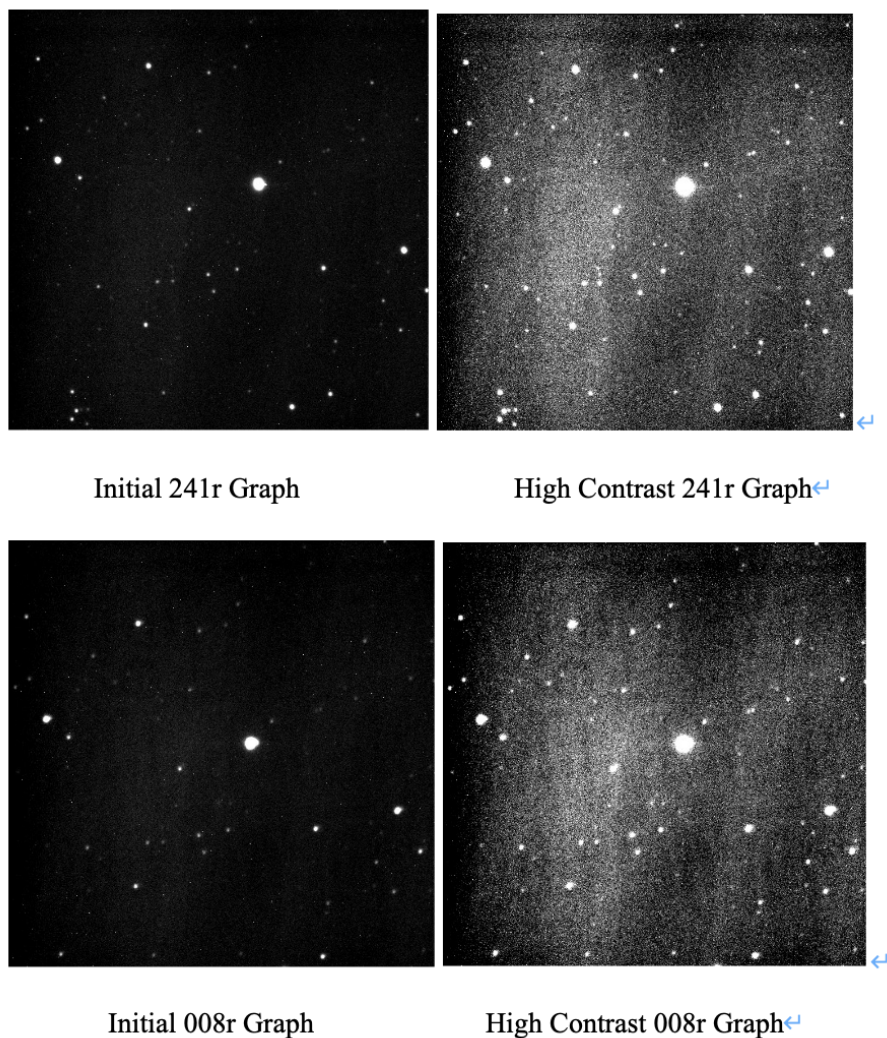


Figure 3: Science images shown in normal and high-contrast display before final calibration. Instrumental structure is visible more clearly in the high-contrast versions.

After applying the corrected master bias, dark, and flat frames, these instrumental arti-

facts were largely removed, and the science images appeared much cleaner. The calibrated frames were therefore suitable for quantitative photometric analysis.

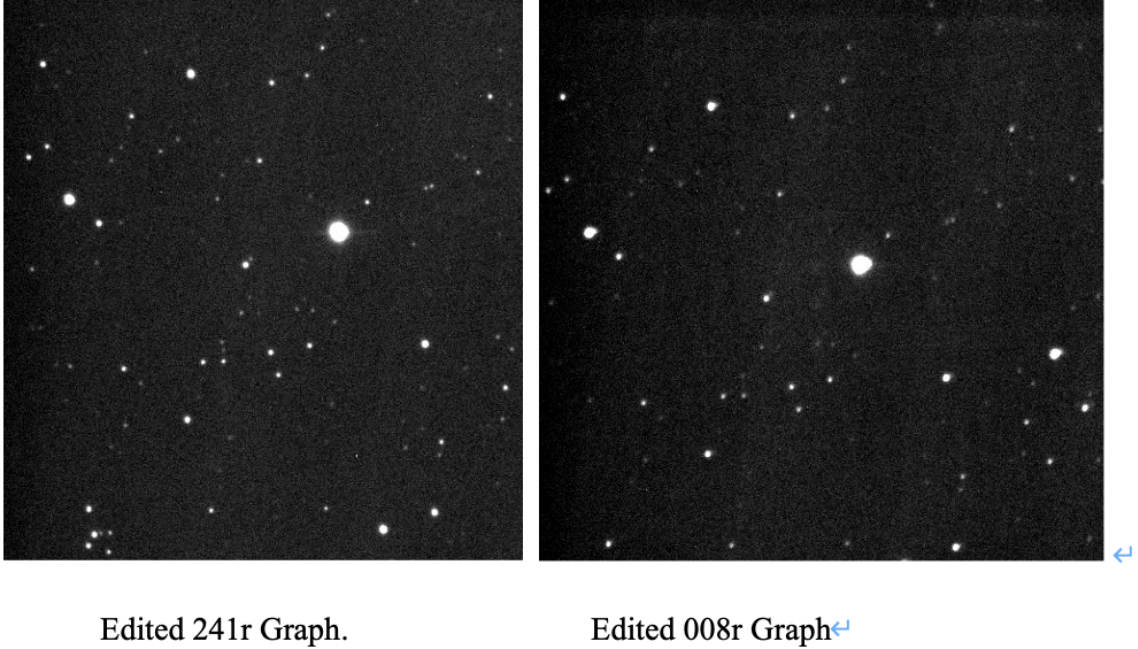


Figure 4: Science images after calibration. The large-scale instrumental artifacts are significantly reduced.

The FITS header information indicated that the two images had the same field center, right ascension, declination, and exposure time, but were taken at different times during the night. Visually, the 241r image appears sharper and more compact, with stellar profiles that are closer to point-like and symmetric. The 008r image appears slightly less concentrated, with broader or somewhat extended stellar profiles. Because stars are point sources, the more compact appearance of the 241r image suggests that the seeing and/or tracking were better for that exposure. The difference is therefore likely due to observing conditions rather than a difference in target field.

4 Calibrated Data: Aperture Photometry of HAT-P-32b

4.1 Image Quality and Exposure-Time Comparison

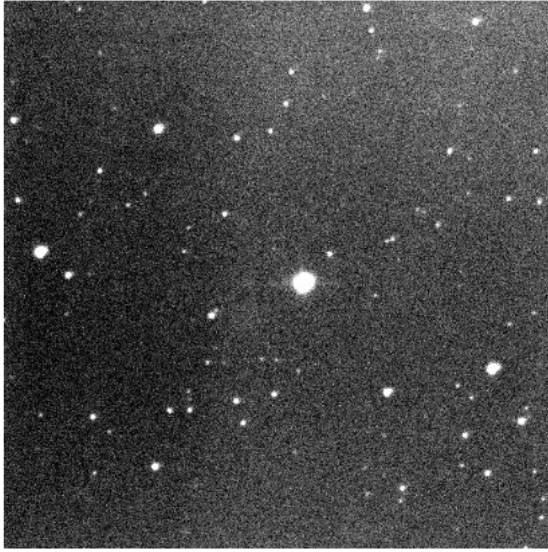
A calibrated 1-minute exposure of HAT-P-32b was first inspected for evidence of poor reduction. No obvious residual artifacts were seen that would indicate failed bias subtraction, dark

subtraction, or flat-field correction. The image appeared suitable for photometric analysis.



Figure 5: Contrast-adjusted 1-minute calibrated image of HAT-P-32b.

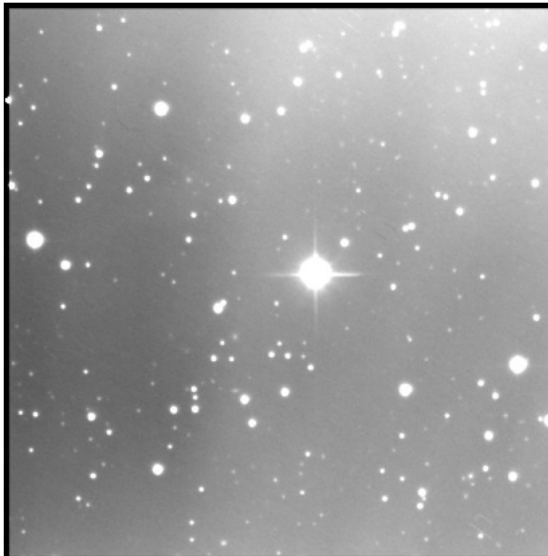
Comparison of the 1-minute, 5-minute, and 379-minute exposures showed that progressively longer integrations reveal more stars in the field. This is expected because a longer exposure collects more photons and therefore improves detectability for fainter sources. At the same time, the extremely long 379-minute exposure appears strongly overexposed, indicating that the CCD approaches or reaches saturation for the brightest sources.



Contrast adjusted 1 min ET graph



Contrast adjusted 5 min ET graph↵



↵
↵
↵
↵
↵
↵
Contrast adjusted 379 min ET graph↵

Figure 6: Contrast-adjusted calibrated images of HAT-P-32b for different exposure times. Longer integrations reveal more faint stars, while the 379-minute image shows clear overexposure/saturation effects.

Because the calibrated science images in this part of the lab were all reduced using the same fixed set of calibration products, the longer-exposure frames can still become limited by saturation even though their instrumental backgrounds were corrected. The 379-minute exposure is therefore useful for illustrating the gain in sensitivity with integration time, but it is not ideal for precise photometry of the brightest objects in the field.

4.2 Aperture Photometry Method

Aperture photometry was used to measure HAT-P-32b. In this method, the stellar signal is estimated by summing the counts inside a circular aperture centered on the source, while the local sky background is estimated from an annulus surrounding that aperture. The choice of aperture radius, gap width, and annulus thickness is important: an aperture that is too small may exclude some stellar light, while one that is too large may include extra background or light from neighboring sources. Likewise, the background annulus should be far enough from the star to avoid the stellar profile, but close enough to sample the local background accurately.

4.3 Flux and SNR as Functions of Integration Time

The measured maximum flux and SNR for HAT-P-32b were plotted as functions of exposure time. As shown in Figure 7, the flux increases strongly and approximately monotonically with increasing integration time, which is expected because longer exposures collect more photons from the target.

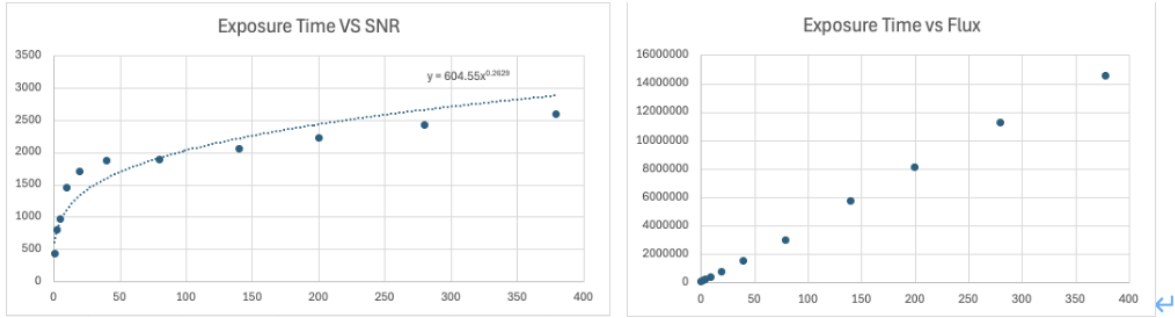


Figure 7: Measured signal-to-noise ratio and flux as functions of exposure time for HAT-P-32b. The flux increases strongly with integration time, while the SNR shows three regimes: approximate square-root-like growth at short exposure times, values above the fitted trend at intermediate exposure times, and values below the fitted trend at the longest exposure times.

The SNR also increases with exposure time, but its behavior is more complicated than a single ideal square-root trend. For the shortest integrations (1, 3, and 5 minutes), the measured SNR values rise in a relatively gentle way that is broadly consistent with the expected behavior for photon-limited observations. However, the intermediate exposure times (10, 20, and 40 minutes) lie noticeably above the fitted curve, indicating that the measured SNR in this range is somewhat higher than the simple trend would predict. At still longer integration times (80, 140, 200, 280, and 379 minutes), the measured SNR values fall below the fitted curve, even though the flux continues to increase.

This pattern shows that although longer exposures do improve the detectability of the source, the improvement in SNR is not uniform across all integration times. In particular, the data suggest three observational regimes: a short-exposure regime that approximately follows the expected increase, an intermediate regime with somewhat higher-than-expected SNR, and a long-exposure regime in which the measured SNR increases more slowly than the fitted trend. Thus, the SNR does not simply scale upward in a perfectly smooth way over the full exposure-time range.

This also explains why observers usually select an exposure time based on a *minimum acceptable SNR* rather than attempting to maximize SNR indefinitely. Once the target has reached a sufficiently good SNR for the scientific goal, extending the exposure further may not produce proportionally better data. Very long integrations also reduce time resolution, decrease the total number of observations that can be obtained in a night, and increase the likelihood of saturation and other observational limitations.

4.4 Photon-Counting Statistics and Noise Sources

If photon-counting statistics were the only important source of noise, then the SNR would be expected to scale approximately as

$$\text{SNR} \propto \sqrt{t}, \quad (3)$$

where t is the integration time. Under this assumption, tripling the SNR relative to the 3-minute exposure would require increasing the exposure time by a factor of $3^2 = 9$. Therefore, the required exposure time would be

$$t_{\text{new}} = 9 \times 3 \text{ min} = 27 \text{ min}. \quad (4)$$

This is the ideal prediction for a purely photon-limited measurement. The observed data, however, do not follow a perfect square-root relation over the full range of exposure times. The shortest exposures are roughly consistent with the expected trend, the 10–40 minute measurements lie above the fitted curve, and the longest integrations lie below it. This behavior indicates that photon-counting statistics are important but are not the only source of uncertainty in the dataset.

The departure from a single square-root trend suggests that additional effects become important, especially at longer exposure times. These may include sky-background noise, detector read noise, dark-current fluctuations, imperfect flat-fielding, seeing variations, guiding or tracking effects, and the onset of saturation in the longest exposures. Therefore, while photon statistics provide the basic theoretical expectation for the growth of SNR, the actual measurements show that the total noise budget is influenced by multiple factors and becomes

increasingly non-ideal at long integration times.

5 Differential Photometry of Variable Sources

5.1 General Method

In differential photometry, the brightness of a target star is measured relative to other stars in the same field. One star is chosen as a reference star and assigned a fixed magnitude, while additional stars are used as check stars to monitor the stability of the measurement. This method reduces the influence of atmospheric transparency changes and instrument drift because all stars in the frame are observed simultaneously.

Before carrying out the variable-star analysis, the calibration products supplied with the second dataset were inspected. They showed the same general kinds of detector structure as the calibration products studied in Part 1. However, the master calibration frames produced earlier in the lab would not automatically be sufficient for these later science data, because calibration data should match the observing run and detector conditions of the specific dataset being reduced.

5.2 GW Cephei

For GW Cephei, one comparison star was selected as the reference star and assigned an arbitrary magnitude of 10, while two other stars were used as check stars. The differential magnitude curve produced by MaximDL shows that the reference star is a perfectly straight line, as expected, because it defines the zero point of the relative-magnitude scale. The check stars are not perfectly straight; instead, they show small scatter and low-level variation. This indicates that the photometry contains nonzero measurement uncertainty and that the sky and/or detector conditions are not perfectly constant.

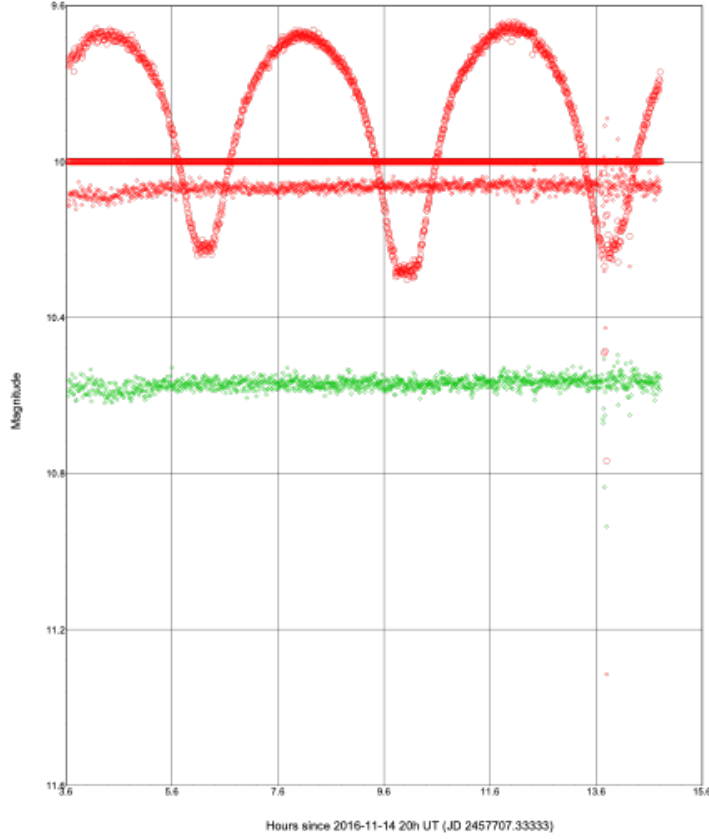


Figure 8: Differential magnitude plot for GW Cephei produced in MaximDL. The reference star is the straight line, while the check stars show small variations and the target shows clear periodic variability.

The light curve of GW Cephei itself shows clear periodic behavior with an amplitude of roughly 0.3 magnitudes and a period of about 4 hours. This periodic modulation indicates that GW Cephei is a genuine variable source. The repeating shape of the curve is most consistent with an eclipsing binary system, in which orbital motion causes periodic changes in observed brightness as one component passes in front of the other.

The corresponding intensity plot shows the same overall variability trend, although the intensity representation contains several discontinuous gaps. The existence of these gaps does not change the fact that the overall modulation remains consistent with the periodic behavior seen in the magnitude curve.

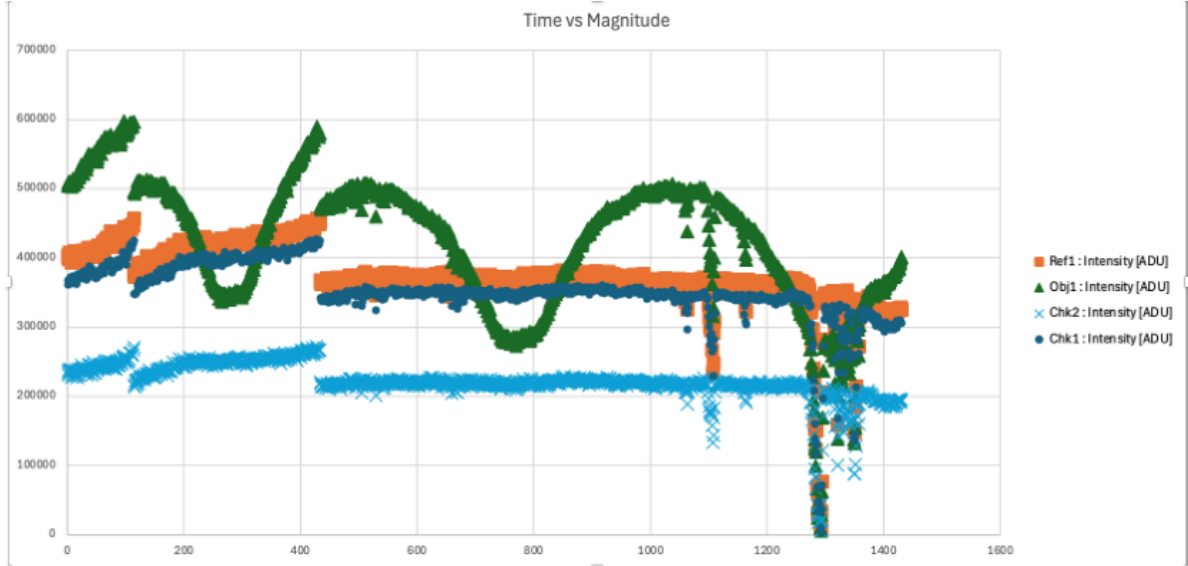


Figure 9: Intensity-versus-time plot for GW Cephei and the associated reference/check stars. The overall trend is consistent with the periodic variability seen in the magnitude plot, although the intensity representation contains several gaps.

Magnitude and intensity plots do not look identical because they represent brightness in different ways. Magnitude is a logarithmic quantity related to flux by

$$m = -2.5 \log_{10}(F), \quad (5)$$

where F is the measured flux. As a result, the same physical variation can appear with a somewhat different shape when plotted in magnitude units than when plotted directly in intensity units. In this dataset, however, both representations support the same conclusion: GW Cephei is a periodic variable, and the most plausible classification is an eclipsing binary.

5.3 WASP-10b

The same differential-photometry procedure was repeated for the WASP-10 system, except that the reference star magnitude was taken from the finder chart rather than being set to an arbitrary value. The resulting light curve shows a relatively small and smooth decrease in brightness followed by a return toward the original baseline level.

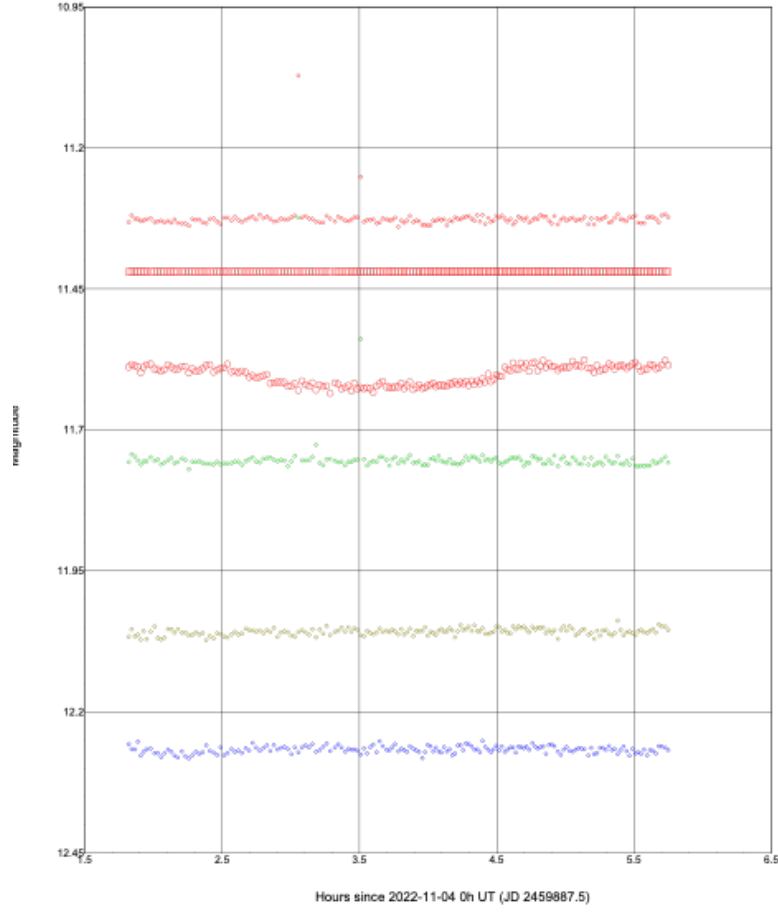


Figure 10: Magnitude-versus-time plot for the WASP-10 field. The target exhibits a shallow dip in brightness, while the reference and check stars remain comparatively stable.

A corresponding photometric plot of the WASP-10 field is shown in Figure 11. In this representation, the target again displays a shallow brightness decrease followed by recovery.

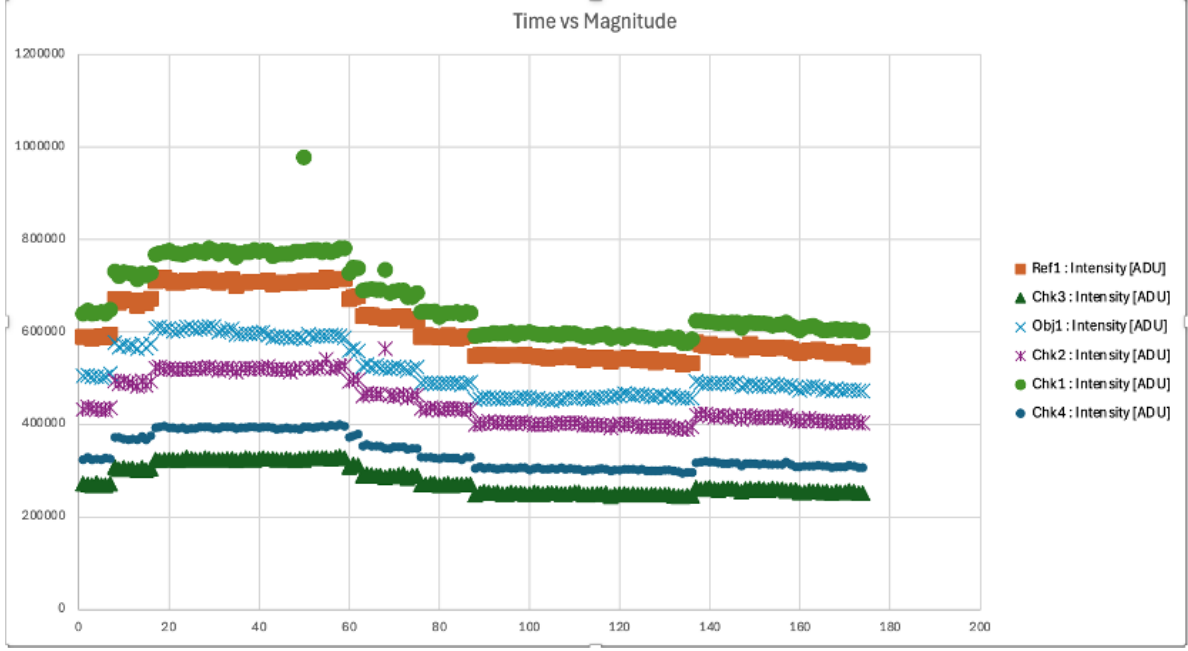


Figure 11: Photometric plot for the WASP-10 field. The target displays a shallow brightness decrease followed by recovery.

This behavior is consistent with a planetary transit rather than the larger-amplitude variations expected from most eclipsing binaries or pulsating stars. In a transit event, an orbiting planet passes in front of its host star and blocks a small fraction of the stellar light, causing a shallow, temporary decrease in observed brightness. The shape, amplitude, and temporary nature of the observed variation therefore support the interpretation of WASP-10b as a transiting exoplanet system.

After comparing these classifications with the known identities of the sources, the interpretation appears consistent with the expected nature of both objects: GW Cephei behaves like a variable binary system, while WASP-10b behaves like a system containing a transiting exoplanet.

6 Conclusion

This lab demonstrated the full path from raw CCD data to astrophysical interpretation. In the first part, master bias, dark, and flat frames were constructed and applied to science data in order to remove additive and multiplicative detector effects. Comparison of the science images before and after calibration showed that the instrumental artifacts were significantly reduced. The two science frames of the same field also showed different image quality, with the 241r frame appearing sharper and more compact, likely due to better seeing and/or tracking.

In the calibrated HAT-P-32b dataset, aperture photometry showed that the measured flux increases strongly with exposure time, while the SNR also improves but with diminishing returns. Using the 3-minute exposure as a reference, tripling the SNR under photon-limited conditions would require a 27-minute exposure. The observed trend, however, suggests that additional noise sources beyond pure photon statistics are also present.

In the second part of the lab, differential photometry was used to study two variable systems. GW Cephei exhibited clear periodic variability with an amplitude of about 0.3 magnitudes and a period of approximately 4 hours, consistent with an eclipsing binary interpretation. WASP-10b showed a much smaller and shallower dip in brightness, consistent with a planetary transit. Together, these results illustrate how CCD calibration, aperture photometry, and differential photometry can be combined to extract physically meaningful information from astronomical imaging data.