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The RHEA single-mode spectrograph

Tobias Feger[a,b], Christian Schwab[a,b,c], Blaise C. Kuo Tiong[a,b], Michael J. Ireland[d], Adam Rains[d], and David W. Coutts[a,b]

[a]Department of Physics and Astronomy, Macquarie University, Australia
[b]MQ Photonics Research Centre, Macquarie University, Australia
[c]Australian Astronomical Observatory, Australia
[d]Research School of Astronomy and Astrophysics, Australian National University, Australia

ABSTRACT

RHEA is a compact high-resolution single-mode spectrograph that can easily be produced in larger quantities as budgets allow. The instrument will be housed in a temperature-stabilized vacuum chamber which is surrounded by several layers of thermal shielding. The optical design employs cost-effective commercially available components, a cooled CMOS detector, and a double-fiber input which permits simultaneous wavelength calibration.

Keywords: single-mode spectrograph, radial velocity, high-resolution, environmental control, astronomical instrumentation

1. INTRODUCTION

The RHEA spectrograph was designed to search for Jupiter-sized exoplanets around red giants on small telescopes in the visible wavelength range. The instrument is fed by a single-mode fiber to overcome the limitations of modal noise and insufficient fiber scrambling. The single-mode fiber input enables high-resolution spectroscopy at low cost. Our spectrograph was conceived to recover radial velocity (RV) signals smaller than 20 m/s on targets up to V$\sim$5 magnitude, fully limited by photon noise. To reduce the impact of instrumental drifts we aim to achieve an instrumental stability of 1 m/s or better through careful temperature and pressure stabilization of the instrument. Previous tests have shown that it is feasible to achieve $\sim$1 m/s short-term precision by housing the echelle grating in vacuum while the rest of the optics are exposed to atmospheric pressure.[1] However, out-gassing and leakage at the grating chamber, as well as the lack of sufficient thermal control led to unwanted drifts of several tens of m/s on a weekly basis. Larger drifts were measured where the spectrograph was exposed to larger fluctuations of 5–10°C in the ambient air (e.g. at the Macquarie University Observatory).

Improving upon earlier prototypes,[2,3] we have continued our efforts to achieve the desired long-term stability with a strong focus on keeping the unit cost low. The proposed design includes the following changes:

- using a cost-effective CMOS detector with smaller pixels and larger chip to cover a wider spectral range while keeping the order separation fairly large
- integrating the complete instrument into a vacuum chamber
- thermal isolation and precise temperature control
- implementing a second fiber for simultaneous wavelength calibration
- optimized opto-mechanical design for improved stability

In this paper we show the preliminary design of the vacuum-integrated RHEA spectrograph and describe the individual components used in the optical layout. In Section 3 we present a brief characterization of the CMOS detector. Finally, we summarize this paper in Section 4 and discuss future work.

Further author information: (Send correspondence to T. F.)
T. F.: E-mail: tobias.feger@mq.edu.au, Telephone: 61 (02) 9850 4982

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2. OPTICAL DESIGN

RHEA is a cross-dispersed echelle spectrograph that operates in near-Littrow configuration, using the cross-disperser and collimator in double-pass. Two single-mode fibers (460–HP) with a mode-field diameter (MFD) of ∼3.5 micron and numerical aperture (NA) of 0.13 are used to feed the spectrograph. The instrument is composed of commercial off-the-shelf components with the aim of creating a cost-effective and replicable system. The optics are carefully selected to achieve diffraction-limited performance over a wavelength range of 430–700 nm. In Figure 1 we show a Zemax model of the optical layout. A summary of the instrumental properties is given in Table 1.

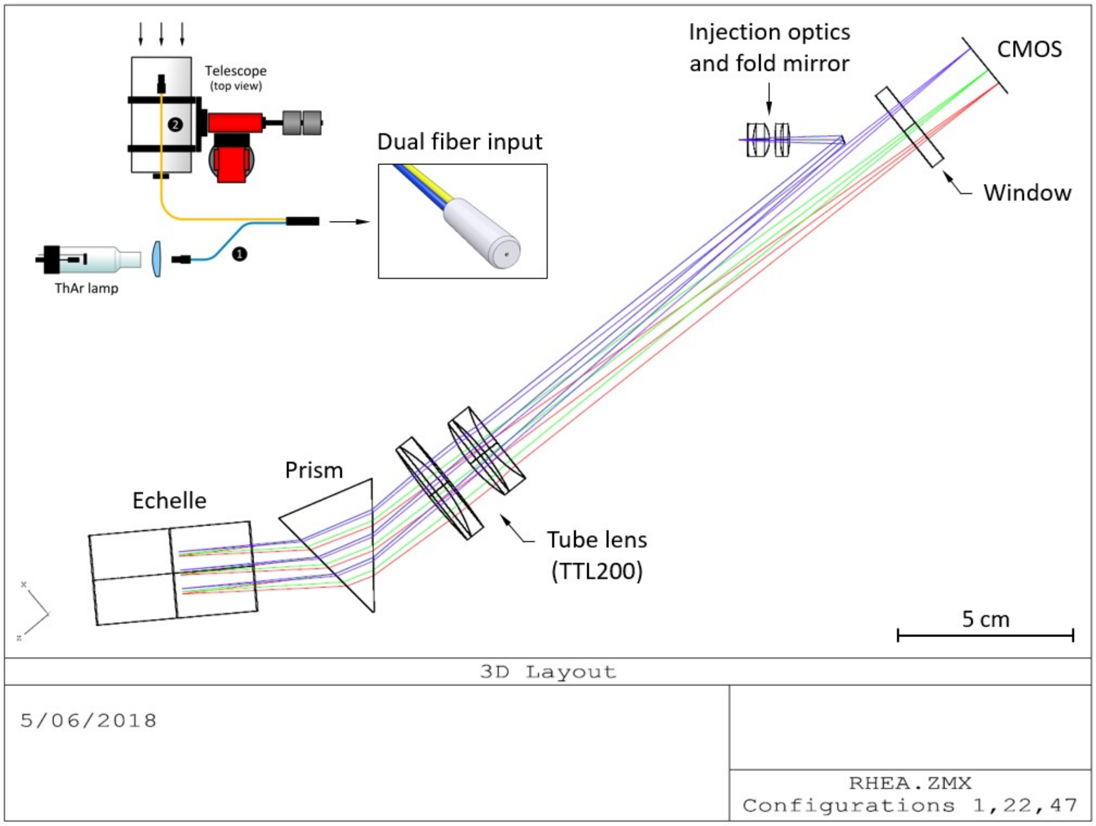

Figure 1. ZEMAX model of the RHEA spectrograph. A single-mode fiber (460–HP) forms the entrance slit of the instrument. Two achromatic doublets convert the fiber NA to a focal ratio of ∼19.4 ($1/e^2$). A fold mirror deflects the beam towards the camera (TTL–200), cross-disperser, and R2 echelle grating. Cross-dispersion is provided by a single N–SF5 prism which disperses the beam twice, perpendicular to the echelle dispersion. The echelle spectrum is imaged on the CMOS detector, after passing through a 4 mm thick vacuum window.

From the Zemax model we derived a map of the encircled energy (EE) as a function of position on the detector. Figure 7 shows the radius which includes 99% of the rays while assuming a Gaussian illumination profile, however, neglecting diffraction effects. Overlaid are the geometrical spots of seven echelle orders. The optical performance is diffraction-limited over the entire field.

Table 1. Summary of the instrument properties.

Instrument parameter	Measured value and vendor specification
Spectrograph working aperture	~f/19.4 ($1/e^2$)
Fiber feed	2×460–HP SMF, 0.13 NA (@1% power level)
Beam size	10.3 mm ($1/e^2$ diameter)
Wavelength range	430–700 nm
Resolving power	$\lambda/\Delta\lambda$ ~76,000 (@550 nm)
Pixel sampling	2.2–3.6 pixel
Injection optics	two doublets (f_1=12 mm, f_2=36 mm)
Collimator / Camera	TTL–200 tube lens (f=200 mm)
Cross-disperser	N–SF5 prism, 44° apex angle
Vacuum window	Fused Silica, 0.5° wedge angle
Echelle grating	R2, 31.6 g/mm, 50×25 mm
Detector	ZWO ASI1600MM Pro cooled, CMOS sensor

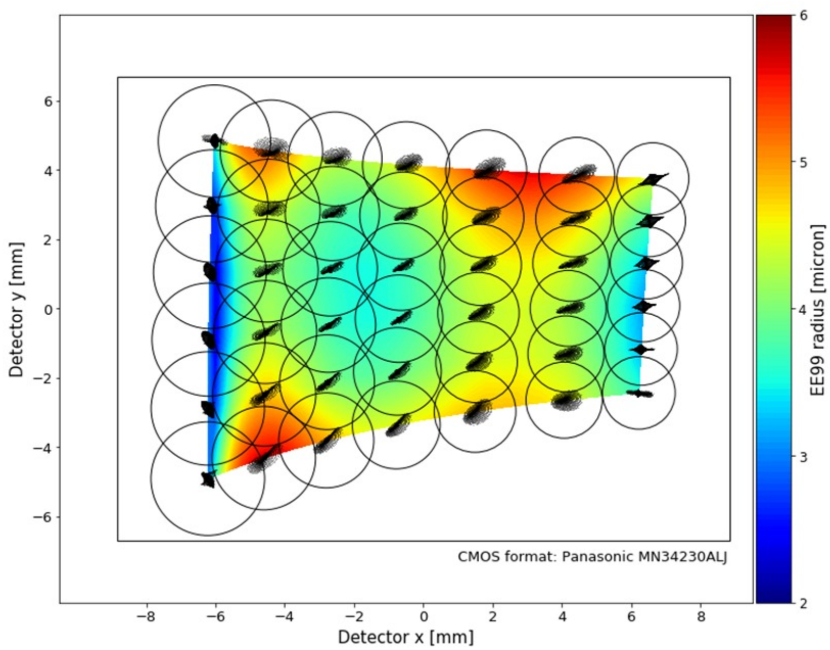

Figure 2. Map of the radius of 99% encircled energy (EE99) calculated for a fiber input displaced 62.5 microns from the optical axis. Overlaid are the geometrical spot diagrams of seven echelle orders. The spots are magnified by a factor of 100. The circles show the approximated Airy ring radius and the rectangular box indicates the size of the CMOS format.

2.1 Fiber injection

The fiber injection optics convert the output of the 460–HP single-mode fibers to a ~f/19.4 ($1/e^2$) beam. We use an aspherized achromat (Edmund 49656) with 12 mm focal length, paired with a standard doublet (Edmund 49655) with 36 mm focal length. The design is calculated for a dual fiber injection with 125 microns core separation. Both fibers are glued into a standard FC/PC multi-mode connector with 260 micron bore diameter (Thorlabs 30260C1). We take care to align the fiber orientation with respect to the echelle such that we achieve an effective core separation of s=20 microns to prevent cross-talk or order overlap. The mechanical layout of the injection optics and a schematic diagram of the fiber alignment are shown in Figure 3.

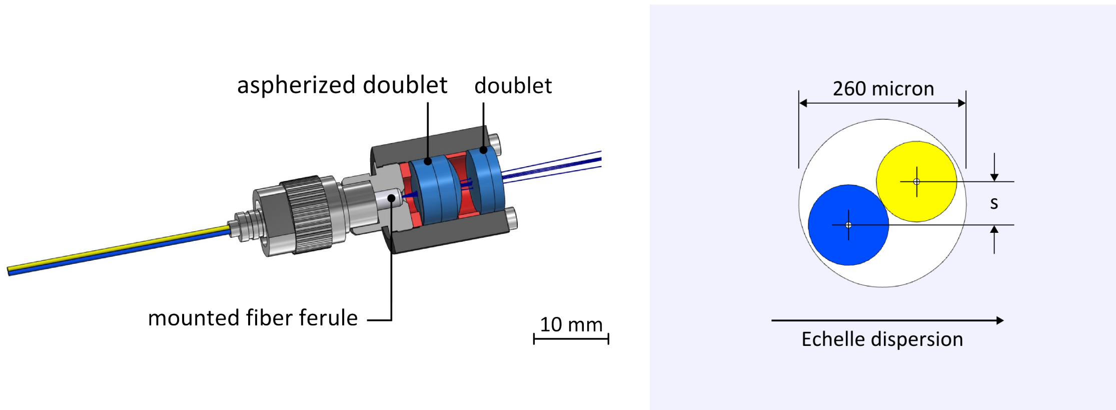

Figure 3. CAD rendering of the fiber injection (left) and end surface of the fiber ferule (right).

2.2 Collimator / Camera

RHEA uses an infinity-corrected tube lens (Thorlabs TTL200) as collimator and camera optics. The TTL200 lens system is designed for widefield imaging in microscopy and is optimized for a wavelength range of 400–750 nm. The lens offers slightly better axial color correction than the Nikon ITL200 tube lens which we used in previous iterations of the RHEA spectrograph.[2] With an effective focal length of 200 mm, and an injection focal ratio of ~f/19.4, the lens produces a collimated beam of ~10.3 mm ($1/e^2$) diameter.

2.3 Cross disperser

Cross-dispersion is provided by an equilateral prism which separates the overlapped echelle orders about ~200 microns in the red and ~380 microns in the blue in the focal plane. The prism is made from Schott N–SF5 glass and has an apex angle of 44 degrees, a side length of 35 mm, a height of 25 mm and a center thickness of ~13 mm. We selected these specifications based on the desired order separation, throughput and the availability of the glass.

2.4 Echelle grating

We use a 50×25×6 mm large R2 echelle grating from Richardson Gratings Labs with a grating constant of 31.6 g/mm. The grating operates in near-Littrow configuration with a wavelength dependent off-plane angle (gamma) of 0.5–2.5 degrees. Previous test have shown that replica of grating master MR152 typically have efficiencies exceeding 70% which is a noticeable improvement over mass-produced gratings from Thorlabs.[4] The projected footprint on the grating has a length of ~23 mm; approximately half the length of the substrate. We mount the grating onto a wedge made from aluminium with the active surface facing upwards.

2.5 Detector

We use a low-cost CMOS camera (ZWO ASI 1600–MM Pro*), based on a Panasonic MN34230 sensor with 3.8 micron pixels. The detector has a quantum efficiency (QE) of ~60%, ~1.7 e^- read noise and a dark current of 0.006 e^-/s at -20 °C. The array has 4656×3520 pixels, which is large enough to accommodate the full spectrum (about 50 echelle orders) without truncating the reddest orders, see Figure 2. The camera is equipped with a two-stage thermoelectric cooler which allows a minimum temperature setpoint of 40–45 °C below ambient.

*https://astronomy-imaging-camera.com

2.6 Spectrograph efficiency

In order to obtain an estimate of the total throughput of the instrument, we developed a transmission model based on the optical parameters from data sheets and measurements conducted in the lab. The predicted design efficiency of the spectrograph is shown in Figure 4. The theoretical peak throughput in the wavelength range from 510–590 nm is greater than 37%, with the maximum being around 520 nm. The throughput is primarily limited by the relatively low QE of the CMOS detector (∼60%). Without taking the detector QE into account, the efficiency of the spectrograph exceeds 65%.

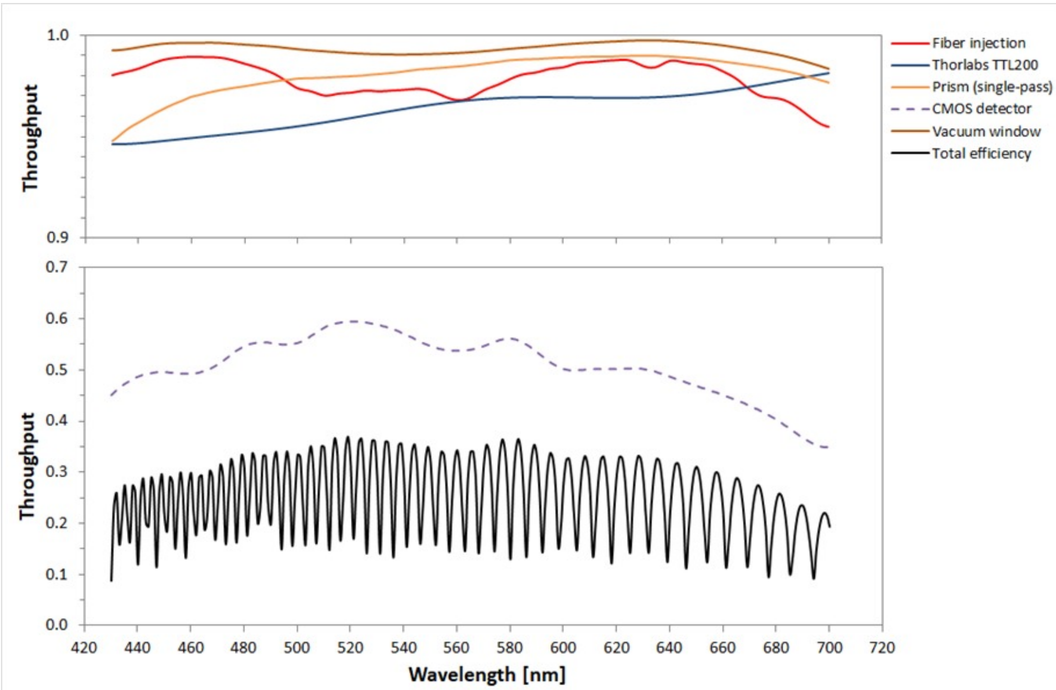

Figure 4. Design efficiency of the spectrograph. The plot shows the free spectral range of 50 echelle orders (82–132) and the efficiencies of all optical components from the fiber tip to the detector plane. The purple (dashed) line shows the approximate QE of the ZWO ASI1600MM Pro detector.

3. MECHANICAL DESIGN

The mechanics are composed of custom-made parts in order to provide an extremely compact and rigid frame for the optical components. To further increase the intrinsic stability of the spectrograph, we housed the optics in an ISO–K 160 vacuum tube of 275 mm length. The vacuum tube is equipped with custom-made lids and sealed with standard Viton O-rings. The optical components are mounted onto a monolithic, 15 mm thick, aluminium bench. The bench itself is thermally isolated from the chamber lid through G10 spacers which greatly reduces heat transfer. A thermal shield covers the optics to attenuate radiation impinging from the chamber walls. The total footprint of the instrument, including a 45 mm thick insulation layer surrounding the vacuum tank, is less than $0.02\,m^3$. A preliminary engineering model of the spectrograph is shown in Figure 5 below.

Temperature stabilization of the instrument is achieved with vacuum grade polyimide heating foils which are applied to the outside surface of the vacuum chamber, and the bottom of the optical bench. Two separate PID loops are implemented on a Labjack T7–Pro data acquisition unit to control the temperature of the instrument. Both loops will run on a slightly different setpoint with the outer loop (i.e. chamber temperature) being ∼1°C lower than the bench temperature. We use two 10 k low-drift NTC thermistors (EPCOS B57560G1103F005) in Wheatstone-bridge configuration as feedback component for the inner PID loop. Two precision resistors with 15 ppm/°C temperature coefficient of resistance complete the circuit. The bridge resistors are mounted to the

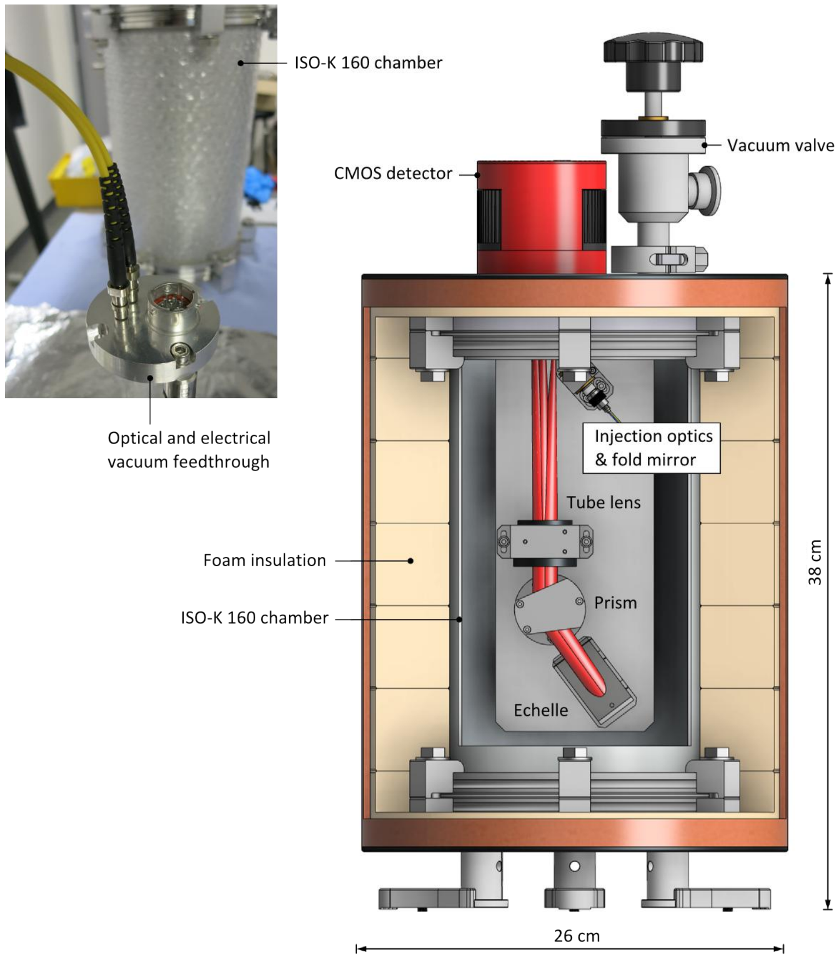

Figure 5. CAD rendering of the RHEA spectrograph mounted inside an ISO–K 160 vacuum chamber. The components are attached to a monolithic bench which is thermally isolated with G10 spacers from the chamber lid. The detector is kinematically attached to the outside of the vacuum tank to minimize thermal impact on the stabilized optical bench. The photograph (upper left) shows the partially assembled chamber and a custom-made vacuum feedthrough.

optical bench inside the vacuum chamber to eliminate temperature-induced drifts. We aim to stabilize the temperature inside the tank to be better than 1 mK.

4. PRELIMINARY DATA / RESULTS

To quantize and measure the cooling performance of our camera, we investigated the dark signal as a function of exposure time and sensor temperature. We recorded dark frames with exposure times ranging from 1 s to 30 min and calculated the average dark signal of six fields of 1500×1700 pixels, tiled across the image. The outer pixels (156 horizontally and 120 vertically) were excluded from the study. A calibrated 30 minute dark frame, acquired at -20 °C and 1×1 binning, is shown in Figure 6. Another set of dark frames was taken at 300 s exposure time while changing the sensor temperature from -20 °C to 10 °C in increments of 5 °C. Figure 7 shows the measured dark signal as a function of exposure time and temperature. The measured dark signal of 0.0056 e^-/s (at -20 °C) is comparable to the value given in the vendor's datasheet.

Bias frames are dark frames typically limited to a fraction of a second, such that the remaining noise is only attributed to read noise. We recorded 50 bias frames at 0.1 s exposure time and combined the sequence into a master bias. From a specific frame of the sequence we subtract the master bias to obtain the read noise frame. The standard deviation of the read noise frame is 26.4 ADU. Converted into 16–bits, while considering a gain conversion of 1.01 e^-/ADU, we obtain ∼1.7 e^- read noise. The low dark signal combined with a low read noise makes the ZWO ASI1600MM Pro CMOS camera suitable for single-mode spectroscopy. We observed bright corners on our dark frames which we suspect to be amplifier glow. However, it is unclear to what extent the electronics glow will limit the observation of dimmer RV targets.

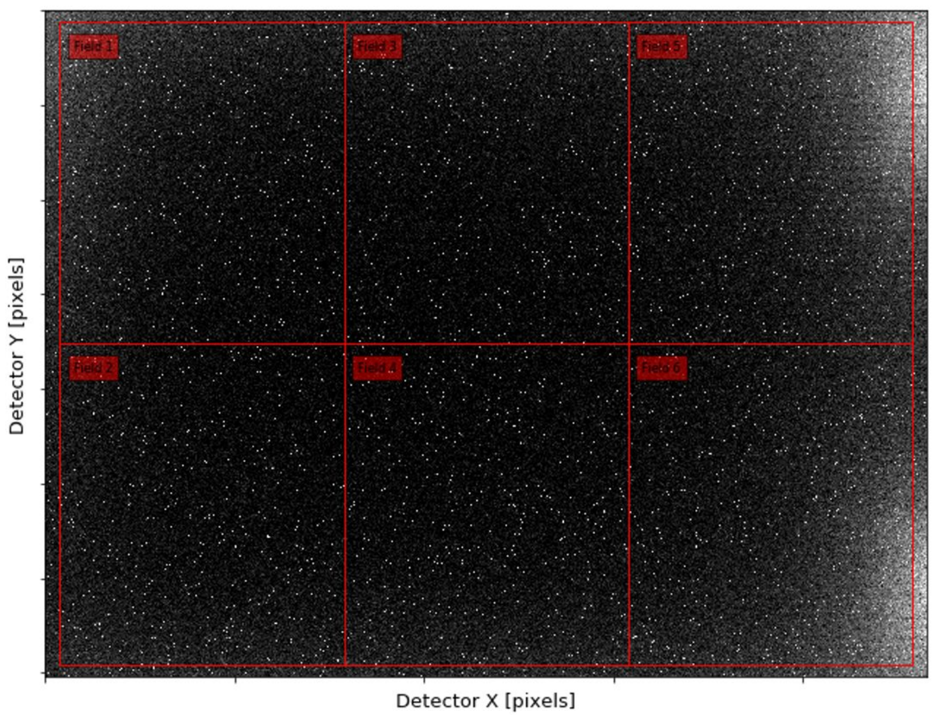

Figure 6. Full-frame 30 minute dark image (master bias removed) taken with the ZWO ASI1600MM Pro CMOS detector in 1×1 binning mode at -20 °C sensor temperature. The three brighter areas located on the left and right hand side of the dark frame indicate the read out electronics glowing.

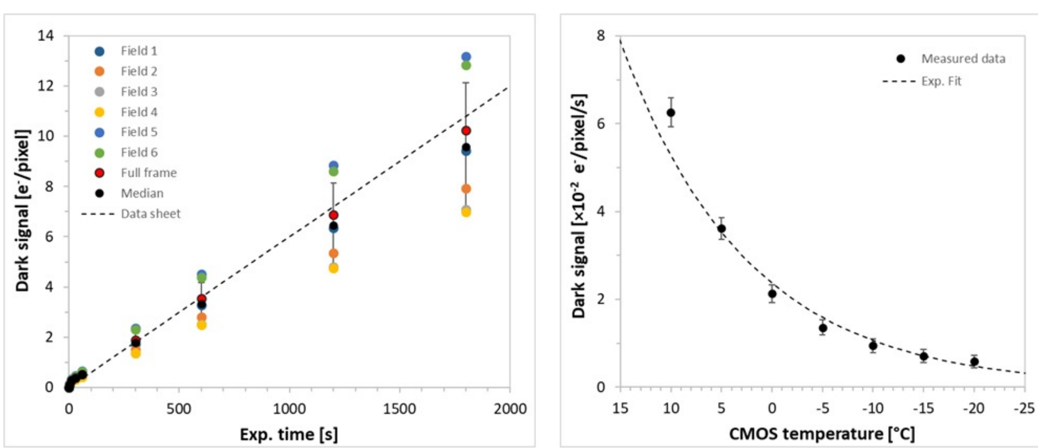

Figure 7. Left panel: dark signal (0.0056 e^-/s/pixel) at -20 °C as function of exposure time. The data show the dark signal obtained from six areas of 1500×1700 pixels as displayed in Figure 6. Right panel: dark signal as a function of sensor temperature. Both measurements were carried out at unity gain (1.01 e-/ADU).

5. SUMMARY

The RHEA spectrograph uses off-the-shelf optical components combined with custom-made mechanics to enable a compact and cost-efficient instrument which is suitable for achieving high intrinsic stability. The detector dark signal and read noise were characterized. Once the spectrograph is fully assembled, we aim to test the intrinsic stability against our Rubidium-traced Fabry-Perot etalon by taking advantage of the dual fiber input. In addition, the RHEA spectrograph will serve as a testbed to explore novel fiber feeds.

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