The Circumgalactic H\(\alpha\) Spectrograph (CH\(\alpha\)S). I. Design, Engineering, and Early Commissioning

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Abstract

The Circumgalactic H\(\alpha\) Spectrograph (CH\(\alpha\)S) is a ground-based optical integral field spectrograph designed to detect ultrafaint extended emission from diffuse ionized gas in the nearby universe. CH\(\alpha\)S is particularly well suited for making direct detections of tenuous H\(\alpha\) emission from the circumgalactic medium (CGM) surrounding low-redshift galaxies. It efficiently maps large regions of the CGM in a single exposure, targeting nearby galaxies (\(d < 35\) Mpc) where the CGM is expected to fill the field of view. We are commissioning CH\(\alpha\)S as a facility instrument at MDM Observatory. CH\(\alpha\)S is deployed in the focal plane of the Hiltner 2.4 m telescope, utilizing nearly all of the telescope’s unvignetted focal plane (10’–15’) to conduct wide-field spectroscopic imaging. The caustic design provides excellent wide-field imaging performance. CH\(\alpha\)S is a pupil-imaging spectrograph employing a microlens array to divide the field of view into \(>60,000\) spectra. CH\(\alpha\)S achieves an angular resolution of \(1.3’–2.6’\) arcseconds and a resolving power of \(R = [10,000–20,000]\). Accordingly, the spectrograph can resolve structure on the scale of 1–5 kpc (at 10 Mpc) and measure velocities down to 15–30 km s\(^{-1}\). CH\(\alpha\)S intentionally operates over a narrow (30 \(\AA\)) bandpass; however, it is configured to adjust the central wavelength and target a broad range of optical emission lines individually. A high–diffraction efficiency volume phase holographic grating ensures high throughput across configurations. CH\(\alpha\)S maintains a high grasp and moderate spectral resolution, providing an ideal combination for mapping discrete, ultralow–surface brightness emission on the order of a few milli-Rayleigh.

Unified Astronomy Thesisaurus concepts: Spectroscopy (1558); Circumgalactic medium (1879); Astronomical instrumentation (799)

1. Introduction

Where are the stars in the universe? This question highlights the last remaining frontier in our study and census of the evolving distribution of baryonic matter. The answer remains elusive, due to the challenges of detecting gas at its lowest densities. A true mapping of diffuse emission requires observations that can reach exceedingly low surface brightnesses. Pioneering work with Fabry–Pérot, deep long-slit, and integral field unit (IFU) spectroscopy (e.g., Vogel et al. 1995) has sought to measure faint light from intergalactic clouds and galaxy halos. This remains very much a field that is in its early stages, requiring novel instrumentation that pushes the boundaries of ultralow–surface brightness spectroscopy.

To meet this challenge, we have designed the Circumgalactic H\(\alpha\) Spectrograph (CH\(\alpha\)S), an IFU spectrograph that is tailored to measure faint emission from diffuse gas in the local universe. The primary science goal for CH\(\alpha\)S is to observe the circumgalactic medium (CGM) around low-redshift galaxies. As an integral field spectrograph, CH\(\alpha\)S can simultaneously map the mass, distribution, and kinematics of ionized gas undergoing cooling or recombination. Observations with CH\(\alpha\)S will address fundamental questions, investigating how much baryonic mass surrounds nearby spiral galaxies, how this matter is distributed, and how gas flows between the CGM and the galactic disk.

CH\(\alpha\)S occupies an important new parameter space in the design of low–surface brightness integral field spectrographs; it is a fast, ultranarrowband, moderate-resolution spectrograph with exceptional grasp. CH\(\alpha\)S collects over 60,000 simultaneous spectra, with a bandwidth optimized for studying the relevant dynamics of low-redshift galaxies and their surrounding gaseous halos. Integral field spectroscopy is well suited to faint, diffuse observations, because it offers unconstrained pointing, wide-field spatial sampling, and superior survey speed (Bershady 2009; Bacon & Monnet 2017; Morrissey et al. 2018). CH\(\alpha\)S is able to compete on survey speed with IFU spectrographs on 8–10 m class telescopes at a fraction of the cost.

Many of the CH\(\alpha\)S design goals are motivated by the observational and theoretical properties of ionized gas in the low-redshift CGM. These properties drive the following scientific requirements.

1. Targeting a broad range of optical emission lines: H\(\alpha\) (\(\lambda 6563\)), H\(\beta\) (\(\lambda 4861\)), [S II] (\(\lambda 6718\)), [N II] (\(\lambda 6584\)), [O III] (\(\lambda 5007\)), [O II] (\(\lambda 3727\)), and [O I] (\(\lambda 6300\)).
2. Covering the extended physical size of the CGM (50–100 kpc) in the local universe (\(d < 35\) Mpc), while resolving individual structures/features on scales of 0.1–1 kpc at a distance of 10 Mpc.
3. Coverage over a continuous systemic velocity range from \(\sim(0-2400)\ \text{km s}^{-1}\) \((z < 0.008)\), with the ability to measure rest-frame Doppler kinematics as large as \(\sim \pm 600\ \text{km s}^{-1}\) down to a velocity resolution of \(15-30\ \text{km s}^{-1}\).

4. Achieving sensitivity to emission on the order of \(\sim 1-10\ \text{mR}\) (approximately \(0.1\%-1\%\) the sky background intensity).

Several sources and ionization mechanisms contribute to the ionization of the CGM (Haardt & Madau 2012; Shull et al. 2012; Bland-Hawthorn et al. 2017). Emission radiation traces the recombination of photoionized gas and the recombination/cooling of collisionally ionized gas and collisionally excited gas. The namesake emission signature for CH\(\alpha\)S is the prominent Balmer H\(\alpha\) line; however, CH\(\alpha\)S targets a broad range of optical emission lines. Spectral line ratios can be used to map the efficacy of different ionization mechanisms throughout the galactic halo (Baldwin et al. 1981).

The CGM is a massive gas reservoir extending hundreds of kiloparsecs from the disk of a galaxy out to the viral radius and beyond (Shull 2014; Borthakur et al. 2016). In order to cover the extended physical size of the CGM in a single exposure, CH\(\alpha\)S is optimized to operate over a wide field of view (FOV; \(10' \times 10'\)), set by the observatory telescope–detector pairing. The spatial resolution within the CH\(\alpha\)S FOV is motivated by the expected gas distribution and the size of the small-scale substructure that populates the halo. Observations and simulations of the CGM are often in agreement that the circumgalactic gas distribution is patchy (Borthakur et al. 2016; Oppenheimer et al. 2018; Lehner et al. 2020) and hosts many sources of multiscale (0.01–1000 kpc) structure, including small clumps/clouds (Churchill et al. 2003; Stocke et al. 2013; Crighton et al. 2015), radial gradients (Borthakur et al. 2016), and large-scale filaments (Haffner et al. 1998; Churchill et al. 2012; Young et al. 2012). CH\(\alpha\)S is designed to capture radial/spatial dependencies in the extended gas distribution, while resolving features on the average length scale of the substructure in the CGM.

The CH\(\alpha\)S spectral window is tuned to detect circumgalactic gas that is kinematically associated with low-redshift galaxies \((z < 0.008)\), up to a systemic velocity of 2400 km s\(^{-1}\). Despite the variety of dynamic components in the halos of these galaxies (Martin et al. 2012; Rubin et al. 2012; Ho et al. 2014, 2017; Zheng et al. 2017; Rodriguez del Pino et al. 2019; Zabl et al. 2019; French & Wakker 2020; Ho & Martin 2020), the gas within the virial radius is typically gravitationally bound, with CGM velocities not exceeding the escape velocity (550 km s\(^{-1}\) for Milky Way–mass galaxies; Tumlinson et al. 2017). Accordingly, CH\(\alpha\)S aims to measure Doppler kinematics as large as \(\pm 600\ \text{km s}^{-1}\) in a given filter \((\sim 25\ \AA)\), encompassing the majority of the gas in the low-redshift CGM of Milky Way–like galaxies. The velocity resolution selected for CH\(\alpha\)S (15–30 km s\(^{-1}\)) is on par with the typical spectral lines widths observed in the CGM (Werk et al. 2013), which are limited by thermal broadening and nonthermal turbulent motions on the order of \(\sim 20–50\ \text{km s}^{-1}\) (Tumlinson et al. 2017 and references therein).

Very few direct detections of CGM emission have been made in the low-redshift regime beyond the Milky Way halo (Bland-Hawthorn et al. 1997; Fumagalli et al. 2017). One of the main obstacles impeding the direct detection of warm/warm–hot ionized gas in the CGM is the diffuse nature of the gas \((10^{-6} < n_{H} < 10^{-2})\); Tumlinson et al. 2017), which produces an extremely tenuous emission signal on the order of \(\sim 1-10\ \text{mR}\) (Corlies & Schiminovich 2016; Zhang et al. 2016). This signal is easily overpowered by sky background or detector noise. CH\(\alpha\)S is designed to detect emission with a sensitivity of \(0.1\%-1\%\) of the sky background intensity\(^6\) (Leinert et al. 1998).

CH\(\alpha\)S is a dedicated instrument for the Hiltner 2.4 m telescope at MDM Observatory on Kitt Peak, bringing full-field spectral imaging capabilities to the observatory. The MDM facilities are owned and operated by a consortium consisting of Dartmouth College, Columbia University, Ohio State University, Ohio University, and the University of Michigan. CH\(\alpha\)S will be a permanent facility instrument at MDM Observatory, available to the consortium. This is the debut paper for CH\(\alpha\)S. We present the optical design in Section 2, the mechanical design in Section 2.5, the expected performance in Section 3, and the early commissioning results in Section 4. We conclude with a discussion of the spectrograph optimization in Section 5, and a summary of the key points in this publication in Section 6.

2. Optomechanical Design

The CH\(\alpha\)S optomechanical design is summarized in Figure 1 and Figure 4. While the CH\(\alpha\)S performance and diffraction efficiency were originally optimized for H\(\alpha\) emission, the reduced chromaticity in the catadioptric design and the narrow instrument bandpass have allowed us to extend the operational wavelength to nearly the full optical range. The CH\(\alpha\)S design triumphs in its configuration flexibility and in the cost savings that are afforded by the incorporation of many commercially available optics.

2.1. Focal Plane Optics

CH\(\alpha\)S sits in the focal plane of the MDM Hiltner 2.4 m telescope. It attaches to the telescope’s multi-instrument system (MIS), utilizing the finder module (with calibration lamps) and guider module. CH\(\alpha\)S has a separate shutter installed near the focal plane of the telescope,\(^7\) which is triggered by the detector exposure commands through the MDM 4K detector electronics box. A system of relay optics is used to extend and reimagine the telescope’s focal plane down to the entrance of the spectrograph, with enough clearance to avoid a collision between the MIS and the CH\(\alpha\)S collimator. The Offner relay design used in CH\(\alpha\)S is summarized in the Appendix and can be seen in Figure 1. It consists of two identical concave spherical mirrors, one convex spherical mirror, and two flat pick-off mirrors, which in total relay the focal plane by \(\sim 1.5\ \text{m}\), with a nearly one-to-one mapping \((m = -1.001265)\). All of the optics are coated with a UV enhanced protective silver high-reflective coating (>97 % @ 400–1000 nm) applied by Teledyne Acton Optics. The final flat in the relay is positioned to redirect the reimaged focal plane into the spectrograph entrance optics.

2.2. Microlens Array

The entrance to the spectrograph is a microlens array, which sits directly in the reimaged focal plane exiting the relay system. The lenslets themselves reimagine the pupil of the telescope and act as a focal reducer, converting the F/7.5 telescope input to an F/2.5 output, which can be fed into the fast collimator design. We have purchased two custom microlens arrays from Advanced Microoptics Systems (AMS); one array with 250 \(\mu\text{m}\)

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\(^6\) Dependent on the filter bandpass \((I_{\lambda}\alpha = 2\ \text{R}^{-1})\).

\(^7\) A Uniblitz CS65 shutter and D880C driver.
pitch lenslets and one array with 125 μm pitch lenslets. Hereafter, these are referred to as the ML250 array and the ML125 array. The ML250 and ML125 arrays have >60,000 and >2,400,000 individual lenslets, respectively, creating a powerful integral field spectrograph with high spatial and spectral resolution.

We present the CHαS microlens array parameters in Table 1. Each array is a 68 × 68 mm clear aperture fused silica optic, composed of hexagonal plano-convex lenslets, covering nearly the full FOV of the Hiltner 2.4 m telescope. An anti-reflection (AR) coating is applied to the planar side of each array, with a reflectance of <1% between 400 and 900 nm. On the convex side of the array, a black chromium mask is applied between the lenslets, filling in the gaps where the lenslets intersect and creating a circular aperture around each hexagonal lenslet profile. The fused silica and black chromium mask on this convex side has a <4%–5% reflectance between 400 and 900 nm. This mask is used to stop down the lenslet aperture slightly and to keep light from scattering at the lenslet interstices. An additional field mask can be installed next to the microlens array to block a specific pattern of lenslets, masking bright regions and maximizing the spectral filling factor at the detector.

As seen in the nonsequential ray trace in Figure 2, each plano-convex array can be flipped 180° in the optical path, without altering the imaging capabilities. In both configurations, the focal plane of the telescope is incident on the side of the array with optical power. Both microlens arrays were designed with F/2.5 lenslets. They are slightly slower than the F/2.2 collimator, in order to reduce the amount of light lost off the edges of the grating. For plano-convex lenslets, the effective focal length is independent of the array thickness, and each array is 2 mm thick to avoid deformation. When calculating the effective focal length, each lenslet can be approximated as a thick lens reimaging the telescope pupil via refraction. We incorporate aberration effects and calculate the nominal best focus position of the lenslet array via non-sequential ray traces. This positioning can be fine-tuned using the motorized collimator focus and telescope focus.

CHαS is a pupil-imaging spectrograph. It uses a microlens array to sample the focal plane, as was originally done in the design of the TIGER integral field spectrograph (Courtes 1982;
Bacon et al. (2001). The CHαS microlens array covers the full FOV, and each lenslet bins the focused field positions from a small patch of sky. The exit pupil of each lenslet is a demagnified image of the telescope pupil (Courtes 1982), referred to as a micropupil. The microlens array creates a grid of micropupils that form the focal plane of the collimator and the entrance to the spectrograph (Figure 2). Since the telescope pupil (not the field) is reimaged at each lenslet, the imaging information within each spatial resolution element is not preserved, and the point-spread function (PSF) is independent of spatial field variation (Bacon 1995). Without the diffraction grating, these micropupils are directly reimaged onto the detector, with demagnification through the collimator/camera optics (Figure 2). With the grating in place, the space between micropupils can be filled with the dispersed spectra. A camera aligned with the dispersion direction images the spectra on the detector. The overlap between adjacent spectra restricts the spectral bandpass, and a narrowband filter is used to shorten the spectra. Slightly rotating the lenslets with respect to the dispersion direction allows us to lengthen the vertical distance to the next micropupil/spectrum (Bacon et al. 2001). With a slight rotation of approximately 5°–6°, each spectrum now grazes past its immediate neighbors, improving spectral packing and extending the allowable bandpass.

2.3. Collimator and Camera

CHαS has a Schmidt collimator and a Schmidt camera. This design achieves excellent wide-field optical performance, while utilizing many commercially available components and leveraging the comparably low-cost manufacturing of optical spheres. The diverging beam from from the microlens array is collimated by a Celestron 36 cm Rowe–Ackermann Schmidt Astrograph (RASA). Among commercially available telescopes, RASA has a large aperture (356 mm) and a fast (f/2.2) wide-field (4°3 FOV) design that, combined, result in an impressively high étendue. The optical performance is a <6.3 μm rms spot size across the full FOV, spanning the full optical bandpass.

The CHαS camera is a custom folding Schmidt design, consisting of an aspheric corrector plate, a folding flat mirror, and a spherical primary mirror. The asphere at the camera entrance is the mass-produced Celestron 28 cm RASA
corrector plate. The folding flat mirror is a custom optic manufactured by Sydor, and the primary mirror is a custom sphere manufactured by Optimax. The folding Schmidt design places the detector behind the flat outside of the optical path, significantly reducing obscuration. The flat mirror has a cut machined out of the center, to accommodate the return beam and pass light through to the detector. The CHoS camera design achieves excellent optical performance, producing rms spot sizes of \(<10 \mu m\) over a \(10' \times 10'\) FOV and a wide range of central wavelengths, spanning \([400–900]\) nm.

We note that the CHoS camera design is shorter than a classical Schmidt telescope; the distance from the sphere to the corrector plate is less than the radius of curvature. While certain optimizations of the shortened Schmidt design can achieve aberration correction with a singlet self-achromatic, fused silica field corrector (Wynne 1977), the CHoS field corrector has a small focal shift on the order of a micron over the full optical bandpass \([400–900]\) nm. The self-achromatic shortened Schmidt optimization is constrained by the distance between the asphere and the sphere, which for CHoS is partially restricted by the folding geometry. Moving the flat mirror closer to the primary mirror places it farther upstream in the return beam, requiring a larger cutout, which introduces additional obscuration. In the CHoS camera design, we minimize this obscuration, as the axial achromatic shift within each narrowband \((3\) nm\) observation is negligible. The obscuration from the flat mirror is less than the entrance optics obscuration, which is approximately \(30\%\) of the stop aperture.

2.4. Volume Phase Holographic Grating

The CHoS diffraction element is a volume phase holographic (VPH) grating mounted on a rotational stage between the collimator and camera. Many instruments swap between a collection of VPH gratings, in order to optimize the diffraction efficiency in different wavelength regimes. By contrast, CHoS operates over a wide range of central wavelengths \([400–900]\) nm with exceptional efficiency, using only a single VPH grating. The peak diffraction efficiency is shifted to the desired central wavelength by simply rotating the grating to adjust the angle of incidence (Barden et al. 2000; Baldry et al. 2004). While having a wide FOV and a broad spectral range usually poses challenges for VPH gratings, coupling CHoS with a narrow bandpass filter allows us to operate away from the grating’s central optimization with incredibly high throughput.

The CHoS VPH grating was manufactured by Wasatch Photonics, with a fringe frequency of \(v = 1200\) lines mm\(^{-1}\). This contributes to the moderate resolving power \((R \sim 10,000–20,000)\) and sets a collimator camera angle that ranges from \(\sim[35^\circ–65^\circ]\), depending on the selected wavelength. The grating is a large-format optic \([340 \times 290 \times 20\) mm\] with an elliptical clear aperture. It is capped using fused silica substrates, each polished to excellent surface quality \((\text{mean } PV = 1.197/\text{rms } = 0.212\) over a 98 mm aperture\) and coated with a broadband \((400–1000\) nm\) antireflective coating \((<2\%\) reflectance for Bragg incidence at 658 nm). The grating parameters are summarized in Table 3.

VPH gratings diffract light using a thin layer of gelatin, with the index of refraction being modulated to form fringes. The diffraction efficiency is moderated by Bragg reflection; light is coherently diffracted with high efficiency when the scattering in the gelatin volume creates constructive interference (Baldry et al. 2004). The Bragg condition (Equation (1)) is dependent on the fringe frequency in the grating \((\nu_2)\), the wavelength of the light \((\lambda)\), and the angle of incidence in the grating gelatin with respect to the fringe structure \((\alpha_2)\). Therefore, the diffraction efficiency at a given wavelength can be maximized by selecting an angle of incidence that satisfies the Bragg condition:

\[
mv_2^2\Delta\nu_2 = 2n_2\sin\alpha_2.
\]

Figure 3 shows the predicted (average polarization) CHoS diffraction efficiency. The solid lines show the rigorous coupled-wave analysis (RCWA) carried out at Bragg incidence for central wavelengths of 490 nm (blue), 660 nm (green), and 900 nm (red). The same RCWA analysis is conducted for off-axis incidence angles with a Bragg deviation of \(\pm 2.5\), creating the angular Bragg envelopes shown by the shaded regions. The dotted lines are the average lossless Kogelnik efficiency predictions, again performed at Bragg incidence for 490 nm (blue), 660 nm (green), and 900 nm (red). The symbols are the manufacturer-measured first-order diffraction efficiencies at three distinct laser wavelengths \((488\) nm, 650 nm, and 904 nm\), taken using a 98 mm aperture and averaged for measurements across the grating. All the data products in this plot were supplied by Wasatch Photonics.

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8 The same as the C12 Schmidt–Cassegrain corrector plate.
9 The chromatic focal shifts at the front and back surfaces of the lens are equal and opposite.

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10 The parameters in the gelatin have the subscript “2” \((\alpha_2, \beta_2, n_2, \text{ and } \Delta\alpha_2)\). The parameters satisfying the Bragg condition have the subscript “b” \((\alpha_2, \beta_2, n_2, \text{ and } \Delta\alpha_2)\).
results in a $\pm 2.5^\circ$ spread in the off-Bragg incidence angles encountered by the grating, which shifts the Bragg wavelength by $\pm 70$ nm at a central wavelength $\lambda = 660$ nm (well outside the $\sim 3$ nm filter bandpass; Robertson et al. 2000). This can be seen in Figure 3, where RCWA analysis is done at the same central wavelengths for off-axis incidence angles with a Bragg deviation of $\pm 2.5^\circ$, creating the efficiency responses shown by the shaded regions. The off-axis diffraction efficiency at the central wavelength decreases according to the profile of the angular Bragg envelope. Within this envelope, the grating still maintains high throughput and the large off-Bragg acceptance angle allows us to use a fast collimator with high off-axis angular magnification over a wide FOV.

VPH gratings have a number of additional tuning parameters inherent to the gelatin layer, including the gelatin thickness (d), the average index of refraction in the gelatin ($n_g$), and the index of refraction modulation amplitude ($\Delta n_2$), which creates the fringe pattern. In the CHoS grating, we select a thin gelatin depth ($d_{\text{eff}} = 5$ μm) and a high index of refraction modulation amplitude ($\Delta n = 0.1$), in order to maximize the angular bandpass ($\Delta \alpha \propto \frac{1}{\nu_2 d}$) and the spectral bandpass ($\Delta \nu \propto \frac{\cos \alpha}{\nu_2 d}$), while still ensuring that the diffraction efficiency peaks around a central wavelength of 660 nm (Equation (2); Barden et al. 2000):

$$\Delta n_2 d \approx \frac{\lambda}{2}. \quad (2)$$

The importance of the tuning parameters on diffraction efficiency is particularly interesting for an instrument like CHoS, as we intend to use the grating far from its original optimization. A related feature in Figure 3 is the offset between the peak wavelength (sometimes called the blaze wavelength) and the Bragg wavelength. This occurs when we rotate the grating to operate away from the overall optimization at 660 nm. For example, the solid blue line represents the RCWA efficiency predictions at Bragg incidence for a central wavelength of 490 nm, but the curve actually peaks at a blaze wavelength of 530 nm. This is a feature at Bragg incidence and is not an off-axis shift in the Bragg wavelength. To center the efficiency response on 490 nm at Bragg incidence, the ideal $\Delta n_2$ should be $\sim 0.08$ (Equation (2)). The fringe structure in the CHoS grating is over-modulated (high $\Delta n_2$) for bluer wavelengths and under-modulated for redder wavelengths, manifesting as a shift in the efficiency response and an offset between the blaze peak and the Bragg wavelength (Wasatch, private correspondence). If CHoS were to have a wider bandpass, and the spectral efficiency response were to be a more important factor in the overall diffraction efficiency, we could rotate the grating to a Bragg angle corresponding to a blaze wavelength peak at 490 nm. However, with the narrow instrument bandpass, we achieve a much smaller spread in the angular efficiency response by operating close to Bragg incidence and accepting an offset between the Bragg wavelength and the blaze wavelength. Looking at the shaded off-Bragg angular efficiency response for 490 nm and 900 nm, the angular efficiency curves converge at the Bragg wavelength (where the deviation from the off-Bragg incidence angle is zero). For fixed wavelengths very close to the Bragg wavelength, the efficiency response as a function of field angle (in the spectral direction) is minimized and symmetric. Operating at the blaze wavelength would cause an asymmetric efficiency response at opposite field angles, with a larger spread in the relative efficiency across the FOV.

The final parameter in the CHoS VPH grating design is the fringe slant, similar to the blaze angle in a ruled grating. The CHoS grating has a manufactured fringe slant of $\pm 4.5^\circ$. Depending on how the grating is installed in the optical path, the fringe slant can be either positive or negative, although the sign of the slant will affect the spectral resolution (see Table 3 and the discussion in Section 3.2).

In summary, the CHoS VPH grating boasts a high diffraction efficiency of $>70\%$ for narrowband observations over the full FOV, spanning central wavelengths from [490–900] nm. In addition, the grating performance is particularly superb at 660 nm, near the Hδ line, where we achieve a full-field diffraction efficiency of $>90\%$. The cross markers in Figure 3 are the manufacturer-measured first-order diffraction efficiencies at three distinct laser wavelengths (488, 650, and 904 nm), averaged across the grating aperture. These confirm the predicted on-axis efficiency close to the central wavelength.

2.5. Mechanical Design

Part of the intention behind CHoS, and the motivation for incorporating many commercial optics, is to develop a design that can be replicated or scaled for future applications. To make this feasible, we also require a mechanical design that is relatively modular, simple to construct, and cost-effective. Here, we detail the commercial and custom aspects of the CHoS mechanical design.

CHoS is primarily composed of two trusses connected at a pivot point. The main truss houses the focal plane optics, relay system, collimator optics, and grating. It is designed to minimize flexure, by keeping the center of gravity close to the telescope focal plane. The camera truss houses the custom camera optics. The majority of the mechanical frame is assembled from prefabricated joint connector kits. The main truss is built from the 80–20 T-slot Aluminum Building System, and the camera truss employs the Rock West Composites CARBONNect carbon fiber system. Both the main truss and the camera truss are enclosed by black anodized sheet metal. A custom fabric bellows, manufactured by Nabell, connects the main truss enclosure to the camera truss enclosure, completing the light-tight envelope around the instrument optical path.

The main truss and the camera truss are connected at a pivot point shown in Figure 4. This is the mounting location for the grating and the axis around which the camera and grating rotate independently. The camera drive rotation stage is a Harmonic Drive FHA25-US250-160-BL with a fail-safe brake and rotary position sensor. This motor was chosen to satisfy our mechanical requirements; namely, the ability to support the camera load with a 260 lb-ft max torque and zero backlash precision. The grating angle is controlled separately from the camera angle, using a Newport rotation stage URS100BPP. This motor meets our 20″ bidirectional repeatability requirement, allowing us to position the grating angle to within one resolution element on the detector (two resolution elements with the ML125 array; see Table 3). In order to minimize the torque on the camera drive, the center of mass of the camera truss is kept as close as possible to the drive axis. The current operation employs counterweight arms, which are attached to the camera truss whenever the drive is engaged. Once the
camera is at the proper angle, these counterweight arms are detached and replaced with rigid bracing arms that maintain the position without the significant added mass of the counterweight.

We have designed custom mounts for the entrance optics, grating, and camera optics. An overview of the custom mount designs can be seen in Figure 5. Many of these optics are retained using a spring-loaded mounting system, in order to avoid transferring mount deformation to the optic or placing unwanted stress on the glass substrates. This design also allows us to remove the optics from their mounts, without having to break any epoxy bonds. Both the microlens array and the grating are mounted such that they can be reversed in the optical path. In cases where the optics can be removed, reference points are used to ensure repeatable positioning. All of the optics mounts have built-in tolerance for shimming. Due to the difference in the coefficient of thermal expansion between the aluminum mounts and carbon fiber camera frame, both of the camera mirror mounts have accordion-like relief slots cut out, to allow for differential compression and expansion during natural thermal cycling. The collimator optics are installed in the Celestron optical tube, which is attached to our main truss using its built-in dovetail rails. All smaller mirrors in the relay/focal plane are bonded directly to small aluminum mounting plates with epoxy.

3. Theoretical Performance

We discuss the expected instrument performance, as assessed in the design stage via computer modeling and
analytic calculations. These performance metrics map to the scientific requirements presented in Section 1. We have been working to confirm the expected performance through laboratory testing, calibration measurements, and engineering/commissioning time at the observatory (Section 4).

3.1. PSF

The PSF of CHαS depends on the imaging properties of three subsystems: the telescope, the relay, and the spectrograph. The angular resolutions of these subsystems are summarized in Table 6. The spectrograph’s imaging performance further depends on the microlens array, collimator optics, diffraction grating, and camera optics. In this section, the theoretical optical performance and PSF of the spectrograph are calculated analytically, as well as modeled with Zemax sequential and nonsequential ray tracing.

We begin by reviewing the imaging properties of the spectrograph without the microlens array. It is important that the underlying PSF be significantly smaller than the object size at the entrance or the reimaged telescope pupil spots generated by the microlens array; this ensures that the imaging performance is primarily set by the properties of the microlens array, and not degraded by the spectrograph optics. We have designed CHαS so that the spectrograph optics have an underlying PSF with a geometric radius of <10 μm in all three channels across the full FOV.

With the microlens array inserted at the entrance to the spectrograph, each lenslet generates a pupil image. The pupil image is demagnified by the focal reduction in the lenslet,

$$w' = \frac{F_{\text{tel}}}{F_{\text{lens}}} w;$$

(3)
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Table 2

| Pitch (mm) | rms Radius Zemax (μm) | GEO Radius Zemax (μm) | FWHM Measured (μm) | σ Measured (μm) |
|-----------|------------------------|-----------------------|---------------------|-----------------|
| 0.25      | 19.0                   | 27.3                  | 57                  | 24              |
| 0.125     | 8.9                    | 13.5                  | 30.5                | 13              |

**Optical Performance of the Spectrograph Convoluted with Lenslet Pupil Imaging**

performance measurements that were made during early commissioning (described in Section 4).

### 3.2. Spectral Resolution

CHoS targets individual emission lines within the optical range of 400–900 nm (Section 1), intentionally limiting the instrument operational bandpass to 3 nm using a narrowband filter. Each lenslet is dispersed into a short spectrum with limited overlap. The dispersion at the detector is expected to be 0.4 Å pix⁻¹ at 658 nm (See Table 3), and each ML250 array spectral resolution element has an FWHM of about 45 μm or 1.5 pixels. Accordingly, CHoS has a spectral resolution of approximately 0.6 Å, corresponding to a velocity resolution of 27 km s⁻¹. The ML125 array with smaller-pitch lenslets cuts the size of each spectral resolution element approximately in half, which allows us to distinguish emission features down to a velocity resolution of 14 km s⁻¹.

Many aspects of the CHoS design factor into the spectroscopic performance of the instrument. As seen in Equation (5), the spectral resolution (δλ) depends on the lenslet pitch (w), the lenslet focal reduction (F_lens/F_tel), the demagnification through the collimator and camera optics (f_cam/f_col), the anamorphic demagnification from the grating (r; Schweizer 1979), and the angular dispersion (d/β/δλ):

\[
\delta \lambda = \frac{w r F_{\text{cam}} d \lambda}{f_{\text{col}} F_{\text{tel}}} = \frac{w r F_{\text{lens}} d \lambda}{f_{\text{col}} F_{\text{tel}}} d \beta.
\]

We isolate terms where the diffraction grating contributes to spectral resolution in Equation (5). The product of the logarithmic angular dispersion (d/β/δλ) and the anamorphic factor (r⁻¹) is often used as a resolution merit function for the diffraction grating (Bershady 2009). As mentioned in Section 2.4, fine-tuning the grating fringe slant directly influences the spectral resolution, by inversely changing the anamorphic demagnification and the angular dispersion. A negative (clockwise) fringe slant increases the angle of diffraction at the Bragg incidence, improving the angular dispersion. A positive fringe slant (counterclockwise) provides greater anamorphic demagnification at the cost of lowering the angular dispersion. There are instances where we may benefit from a specific fringe orientation, balancing these two factors, and the CHoS VPH grating can be installed with the fringe slant in either a positive or negative orientation.

The remaining terms in Equation (5) are optimized to improve the spectral resolution, while maintaining a high signal-to-noise ratio (S/N). Note that the camera design is slightly faster than the collimator (Table 5), with a shorter focal length (f_cam), which demagnifies the FOV and improves the linear dispersion. The focal reduction (F_lens/F_tel) provided by the lenslet array is set to approximately match the telescope aperture ratio to the collimator aperture ratio. The lenslet pitch
The Bragg angle is measured inside the gelatin relative to the grating fringes. The fringe slant is \(90^\circ\) and the angle of incidence and the angle of diffraction are measured in air relative to normal grating. The camera angle is the sum of the angle of incidence and the angle of diffraction, measured relative to the optical axis of the collimator.

\(^a\) 30 \(\mu m\) per pixel in \(2 \times 2\) detector binning.

\(^b\) The high-dispersion mode, using alternate VPH grating, with a fringe frequency of 2173 lines \(mm^{-1}\) and a fringe slant of 25.

(w) is selected to carefully balance the angular resolution, spectral resolution, and S/N. Decreasing the pitch of the lenslets in the microlens array decreases the angular extent of each lenslet and reduces the size of the spectral resolution element (similar to reducing the slit width in long-slit spectroscopy). This both improves the spatial resolution and boosts the resolving power. The drawback to decreasing the lenslet pitch is that it also results in a reduced S/N from each lenslet. We discuss this trade-off further in Section 3.3 and Section 5.

### 3.3. Sensitivity

To demonstrate the sensitivity performance, we calculate the predicted minimum detectable intensity that CH\(_2\)S\(_6\) can measure, while requiring the achievement of an S/N of 10:

\[
\frac{S}{N} = \frac{S}{\sqrt{S + S_{sky} + \sigma_{Dark} + \sigma_{RN}}} = \frac{I_\lambda \epsilon A_g \Omega t}{\sqrt{S + I_\lambda (\lambda) \epsilon A_g \Omega \Delta \lambda + N_p D t + (N_p/N_g^2)R^2N_f}}.
\]

(6)

The emission signal \(S\) in units of photons is the product of the line flux \(I_\lambda\), the instrument efficiency \(\epsilon\), the geometric area of the telescope \(A_g\), the angular extent on the sky \(\Omega\), and the exposure time \(t\). The noise contribution terms added in quadrature include the shot noise from the emission signal, the shot noise from the sky background emission, the dark current from the detector, and the read noise from the detector. Our sensitivity analysis (Figure 14) includes all of these noise sources.

The design goal is to operate in a sky background–limited regime during dark time, so Equation (6) then simplifies to:

\[
\frac{S}{N} = \frac{I_\lambda \sqrt{\epsilon A_g \Omega t}}{\sqrt{I_\lambda (\lambda) \Delta \lambda}}.
\]

(7)

In Figure 14, we model the CH\(_2\)S\(_6\) 10\(\sigma\) minimum detectable intensity as a function of angular scale. This calculation follows Equation (6), assuming an efficiency of \(\epsilon = 15\%\). In the sky background–limited regime, the S/N will scale as \(\sqrt{\epsilon}\). We show three integration times (1 hr, 10 hr, and 100 hr) and assume that each integration is composed of 900 s exposures. The lenslets in each microlens array only cover a few arcseconds in angular size. While it would be exceedingly difficult to reach sensitivities on the order of 1–10 mR in each resolution element, part of the power of using a microlens array is that individual lenslets can be binned together, to measure a fixed solid angle on the sky. We measure larger spatial scales by combining the signals from many neighboring lenslets. Combining the signals from multiple lenslets is made easier by the fact that the PSF of each lenslet is an image of the pupil and is invariant to the on-sky spatial structure in each lenslet. Although we are probing a coarser spatial scale with this lenslet binning, the measurement maintains a fixed spectral resolution. The S/N improves with increasing scale and integration time, in accordance with Equation (7).

### 4. On-sky Performance

Using calibration data and on-sky measurements taken during early commissioning in 2021 May–June, we have compiled a preliminary performance assessment of CH\(_2\)S\(_6\) on the Hiltner 2.4 m telescope. This is intended as an early validation of the expected performance.

We summarize the on-sky commissioning targets in Table 4 and Figure 7. Here, we compare the expected emission from each target/galaxy with the telluric emission from the atmosphere shown in the top panel (Leinert et al. 1998). Each horizontal black line in the bottom panel is a galaxy centered on its redshifted H\(_\alpha\) emission. The length of the line corresponds to the \(W_{20}\) velocity width (Kennicutt et al. 2003). The corresponding horizontal gray lines represent the redshifted N\(_\Pi\) emission (assuming the same width as H\(_\alpha\)). The shaded regions show the approximate filter response curves for the Baader H\(_\alpha\) (6 nm FWHM) and Astrodon N\(_\Pi\) (3 nm FWHM) filters. Most of our primary targets have H\(_\alpha\) emission that is redshifted into the N\(_\Pi\) filter.

As an example of the commissioning data, we show a stack of the Deer Lick Galaxy NGC 7331 in Figure 8. In many ways,
In the gas at this location. The discrete sky emission comes from the atmosphere at a nearly uniform velocity and therefore has a constant Doppler shift with respect to the microlens hexagonal grid pattern. Accordingly, we see the sky emission as a uniform image of the microlens array.

In addition to the list of galaxy targets in Table 4, we have used CHoS to observe a variety of nebulae during early commissioning. Wide-field spectral imaging with CHoS is great for mapping large nebular regions, such as planetary nebulae, emission nebulae, and supernova remnants. CHoS maps these bright targets extremely efficiently, allowing us to tile large regions, with only a few exposures per pointing. These targets often fill the full FOV, and are excellent for instrument calibration. In Figure 9, we show CHoS images of the Dumbbell Nebula. Like many nebulae, the Dumbbell Nebula hosts an interesting velocity structure, and we highlight the capability of CHoS in mapping this structure in a single 180 s exposure with a velocity resolution of \( \sim 30 \text{ km s}^{-1} \). A spectrum is extracted for each lenslet, using the calibration lamp as a weighted template to find the emission peaks. We produce an RGB image of the CHoS spectra colored by velocity (in steps of \( \sim 30 \text{ km s}^{-1} \)) to demonstrate the stunning visual properties of these data. We plot 1D profiles for each spectrum at the center, showing both single and multi-component emission lines from gas expanding away from the central white dwarf at velocities of \( \pm 30 \text{ km s}^{-1} \). In future runs, CHoS will be capable of collecting similar spectral maps in multiple optical emission lines, probing shock structure and the strength of the various ionization mechanisms in a collection of a few short exposures.

**4.1. Commissioning Data Analysis**

The raw CHoS data are a flattened spectral cube collected in a single exposure, without the need to scan in frequency space. In order to build up long integration times, we combine a set of exposures from each night into a stacked image. The stacking/image registration process uses cross correlation to calculate subpixel offsets between exposures and align them appropriately. Cosmic rays are removed from each image in the stack by looking for Laplacian/sharp edges, following the prescription in van Dokkum (2001). We are working on a global solution for the spatio-spectral instrument response across the full FOV. Flat-field correction, sky background subtraction, and photometric calibration have not been applied to Figure 8.

The model for spectral extraction in our science data is based on the location of monochromatic light through each lenslet, which is determined using either a calibration lamp (Figure 10) or a low-velocity nebula. These locations are then shifted, using the dispersion solution, to the expected location of H\(\alpha\) at the systemic velocity of the target galaxy, establishing initial centers for the analysis of lenslet spectra on the detector. We extract a spectrum at each of these locations; however, overlap with adjacent lenslets results in a quasiaperiodic multi-peaked spectrum. Using a velocity prior, typically an HI map, we weight the peak detection in the extracted spectrum by the expected Doppler shift, limiting it to a small velocity range around the prior velocity.

Cross talk between neighboring lenslets is partially mitigated by setting an appropriate lenslet array rotation, given the hexagonal packing geometry, but there is still spectral overlap to contend with in both the dispersion and cross-dispersion directions. The amount of overlap is dependent on the selected bandwidth, the lenslet array pitch, the cross-dispersion profile,
and the (optimized) lenslet array rotation (See Figure 2). As discussed in Bacon et al. (2001), there is a significant trade-off to be considered between maximizing the signal and increasing the random or systematic noise due to overlap. Since CHaS primarily targets single emission lines, the bandwidth may be optimized for specific targets using ultranarrowband filters. Additionally, the design of CHaS allows for the masking of the microlens array, which can reduce overlap through loss of sky coverage. For the commissioning runs, we have not used masking or ultranarrowband filters, and leave a more extensive discussion of the full set of trade-offs and their impacts on the S/N for future work.

For the commissioning implementation, as seen in Figure 8, narrow/individual emission lines can be identified. We estimate the spectral overlap between the lenslets using the nonsequential ray-trace model. For narrowband 3 Å emission (e.g., Doppler-broadened spectral lines), we find that <5% of the flux in a measured spectrum comes from overlap. Still, confusion may arise from continuum emission, multiple velocity components, or overlap with the dispersed sky lines. For continuum emission with a filter bandpass of 20 Å, the fractional flux in each spectrum that comes from overlap is approximately 66%. This overlap fraction is in agreement with the measured noise from the sky continuum background shown in Figure 12.

4.2. Optical Performance

During commissioning, calibration lamps were routinely collected for all filters. The optical commissioning performance can be measured across the FOV using these calibration lamps, an example of which is shown in Figure 10. This Ne lamp is taken in the N II filter and is a direct measure of the spectrograph PSF (without the telescope) in discrete emission at 6598 Å. We measure an average circular FWHM spot size of 1.8 pixels in the commissioning lamps, or 54 μm. This is similar to the effective PSF in Figure 10 and is on par with the predictions in Section 3.1. There is a slight astigmatism in the PSF, most prominent at the edges of the field. This is most likely due to a tilt in the coplanar alignment of the camera focal plane with the detector CCD (Bacon 1995).

We apply a World Coordinate System (WCS) solve to the on-sky commissioning images, using stellar catalogs in each pointing. This solve aligns the stellar catalog positions with the systemic velocity of the galaxy. This provides the best average alignment between the CHaS emission features and the narrowband imaging. In both directions, the telescope plate scale of 0·34 pix$^{-1}$ is magnified by the ratio of the CHaS collimator to camera focal length. We recover a plate scale at the detector of 0·457 pix$^{-1}$ in the cross-spectral direction and 0·421 pix$^{-1}$ in the spectral direction. In the spectral direction, the anamorphic magnification from the grating (installed with a negative fringe slant) accounts for the additional factor of 1.09 in the plate-scale measurement (See Table 3).

In order to recover an estimate for the angular spatial resolution, we measure the average separation between the detected lenslets in our commissioning data. Here, we use images with a WCS solve and very little expected velocity structure. Our model predicts that the on-sky angular resolution for the ML250 array should be 2·83. We measure an angular resolution of 2·77 ± 0·06, consistent with this expectation.

4.3. Spectral Performance

We measure the linear spectral dispersion using two independent methods. (1) Using the broader (6 nm) Hα filter,
we detect multiple emission lines from the Ne lamp (Figure 10). The separation between the lines at known wavelengths can be used to solve for the dispersion. (2) Bright M-type stars dispersed in the commissioning data show spectral absorption features in the NII filter. These absorption lines can be compared with existing high-resolution spectra to solve for the dispersion. Both methods recover an operational linear dispersion of $0.373 \pm 0.001 \, \text{Å pix}^{-1}$. We use this dispersion measurement and the optical performance assessed in Section 4.2 to estimate the spectral resolution. Given an FWHM of 1.8 pixels and a dispersion of $0.373 \, \text{Å pix}^{-1}$, we achieve a commissioning spectral resolution of $0.67 \, \text{Å}$ or $30 \, \text{km s}^{-1}$. The ML125 array results in spots with a measured FWHM of 1.01 pixels, corresponding to a spectral resolution of $0.377 \, \text{Å}$ or $17 \, \text{km s}^{-1}$.

4.4. Mechanical Performance

The CHαS mechanical design must maintain minimal flexure over long integration times in order to avoid blurring/degrading the spectral imaging quality. The mechanical performance can be assessed using two critical flexure measurements: (1) flexure in the entrance optics and relay system; and (2) flexure in the spectrograph, including the collimator, camera, and pivot. The entrance flexure blurs the reimaging of the telescope’s focal plane on the surface of the microlens array and degrades the spatial resolution. Spectrograph flexure causes the microlens array image to shift around on the detector. It is axis-dependent; a drift along the spectral direction degrades the spectral resolution, while a drift along the cross-spectral direction degrades the spatial resolution element. CHαS does not have
imposed pointing constraints when attached to the telescope, so it experiences a full range of gravity vectors during normal operation. As a commissioning goal, we aim to reduce the acceptable drift due to flexure during normal operation. The shaded regions represent the expected drift due to flexure over a range of exposure times, spanning from 300 s (the dotted line) to 600 s (the solid line). These are calculated using the commissioning flexure goals outlined in the text.

1. The entrance flexure (in the reimaged telescope focal plane) should not exceed half a lenslet or 1.3; and
2. The spectrograph flexure should not exceed half a spectral resolution element or 30 μm (1 pixel in 2 × 2 binning).

Early commissioning measurements of the instrument flexure were designed to probe both the entrance flexure and the spectrograph flexure. Reference crosshair masks were installed on both the filter and microlens array. The telescope was slewed incrementally in R.A. (the flexure is much smaller in decl.), and the shifts in both the crosshair images were measured at the detector. We summarize the results in Figure 11. The discrete points are the measured entrance (blue) and spectrograph (black) flexure. Each measurement is the magnitude of the drift calculated by summing the flexure along the spectral direction and the flexure along the cross-spectral direction in quadrature. However, we note that the flexure in the entrance optics is primarily in the spectral direction and the flexure in the spectrograph optics is primarily in the cross-spectral direction. The shaded regions represent the expected drift due to flexure using the commissioning requirements over a range of exposure times, spanning from 300 s (the dotted line) to 600 s (the solid line). These measurements along the equatorial axes and the flexure measured during on-sky observations show very similar trends. We find that the current flexure is consistent with our limiting requirements at an exposure time of around 600 s. Early commissioning runs used a very conservative exposure time of 180 s. Exposures can be lengthened to 180 s < t exp < 600 s in subsequent runs, without degrading the spectral imaging beyond commissioning requirements. These numbers become more stringent by an additional factor of 2 if we swap out the ML250 microlens array for the smaller-pitch and higher-resolution ML125 array. Ultimately, we aim to make the flexure requirements for CHoS a factor of 5 tighter than the commissioning requirements. This would reduce the acceptable drift due to flexure to <10% of the spectral imaging performance.

4.5. Sensitivity Performance

The CHoS noise budget, including the sky background and MDM 4K detector noise, is shown in Figure 12. Here, we plot the standard deviation σ N of each noise source per lenslet per frame as a function of the exposure time per frame. We assume a CCD binning of 2 × 2 and a spot size per lenslet of 60 μm (corresponding to an area per lenslet of ~4 pixels). The expected read noise (the black dotted line) is constant per frame, but remains a function of the number of frames per total integration time. The expected dark noise (the dashed black line) increases with the exposure time per frame. These sources are added in quadrature to estimate the total detector noise (the solid black line). The discrete points are the detector dark data from our 2021 commissioning tests. The MDM 4K detector is a mosaic of four CCDs. Each data point is the average detector noise (bias-subtracted) at the center of each quadrant, and the error bars are the standard deviations between quadrants. Similarly, the total noise, shown as a discrete open circle, is measured by taking the lenslet-to-lenslet standard deviation in a blank sky frame.
commissioning tests. The MDM 4K detector is a mosaic of four CCDs. Each data point is the average detector noise (bias-subtracted) at the center of each quadrant, and the error bars are the standard deviations between quadrants. These measurements confirm that the read noise and the dark current are similar to the detector specifications and demonstrate the light-tight capabilities of our instrument enclosure in the dome environment. In addition to the detector noise, the sky background noise can have a range of values, as covered by the blue shaded regions in Figure 12. These values assume a sky background intensity of 2 \( \text{CCDs} \). Each data point is the average detector noise over the range of sky background values. We measure the total noise directly and the commercial filter performance. We anticipate the improvement of these factors, and they will not have long-term effects on the system throughput.

In Table 6, we outline the expected performance of the telescope, spectrograph, and detector combined, predicting a total throughput of \( \epsilon = 15\% – 20\% \) without the atmosphere. Early commissioning throughput testing of the spectrograph optics was completed using a laser at 6563 Å fed into the system (below the filter), with an F/7.5 input to match the speed of the telescope. The intensity of this input was measured separately, using a beam splitter to a photometer. We measure a spectrograph efficiency of approximately 15\%, not including the telescope, filter, or atmosphere. We have also made an on-sky measurement using a bright star closest to our N\,II filter. This measurement has been corrected for the 75\% fill factor of the microlens array, as the star is detected over multiple lenslets and about 25\% of the flux is blocked by the black chromium mask between lenslets. We measure a full-system efficiency of 8\% in the current configuration. This temporary factor of 2 loss in throughput is due to a combination of the severely aged telescope coating and the commercial filter performance. We anticipate the improvement of these factors, and they will not have long-term effects on the system throughput.

5. Discussion

We discuss CHoS in comparison with other IFU designs and review the trade-off decisions considered when optimizing the instrument for sky background–limited observations of diffuse background. In addition to the detector noise performance, the sensitivity relies on the full instrument throughput. In Table 6, we outline the expected performance of the telescope, spectrograph, and detector combined, predicting a total throughput of \( \epsilon = 15\% – 20\% \) without the atmosphere. Early commissioning throughput testing of the spectrograph optics was completed using a laser at 6563 Å fed into the system (below the filter), with an F/7.5 input to match the speed of the telescope. The intensity of this input was measured separately, using a beam splitter to a photometer. We measure a spectrograph efficiency of approximately 15\%, not including the telescope, filter, or atmosphere. We have also made an on-sky measurement using a bright star closest to our N\,II filter. This measurement has been corrected for the 75\% fill factor of the microlens array, as the star is detected over multiple lenslets and about 25\% of the flux is blocked by the black chromium mask between lenslets. We measure a full-system efficiency of 8\% in the current configuration. This temporary factor of 2 loss in throughput is due to a combination of the severely aged telescope coating and the commercial filter performance. We anticipate the improvement of these factors, and they will not have long-term effects on the system throughput.

5. Discussion

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Table 6
CHαS Performance and Sensitivity Calculations

| Parameter                                | Value                      | Unit          | Comments                                      |
|------------------------------------------|----------------------------|---------------|-----------------------------------------------|
| **Telescope Performance**                |                            |               |                                               |
| Primary Clear Aperture Diameter          | 2.32                       | m             | MDM Observatory Hiltner 2.4 m                 |
| Secondary Obscuration Diameter           | 0.745                      | m             |                                               |
| Geometric Area                           | 37914                      | cm²           |                                               |
| Plate Scale                              | 11.33                      | 7/′/mm        |                                               |
| **Imaging Performance**                  |                            |               |                                               |
| FOV                                      | 10 × 10                    | arcmin        | Monochromatic point source at spectrograph input |
| rms Spot Radius                          | < 10                       | μm            |                                               |
| Pupil Image Diameter                     | [60 (4), 30 (2)]           | μm (pixels)   | [ML250, ML125]                               |
| Spatial Resolution                       | [2.83, 1.42]               | arcsec        | [ML250, ML125]                               |
| Image Plate Scale [x, y]                 | [0.418, 0.455]             | arcsec pix⁻¹  | Commissioning measurement                    |
| **Spectroscopic Performance**            |                            |               |                                               |
| Spectral Resolution Δλ                   | [0.69, 0.34]               | Å             | 656.3 nm [nominal, high-resolution]           |
| Velocity Resolution                      | 30 (15)                    | km s⁻¹        | [ML250, ML125]                               |
| Dispersion                               | 0.4                        | Å pix⁻¹       |                                               |
| Number of Spectral Elements (NΩ)         | 35                         |               | Per bandwidth, overlapping                    |
| Number of Spatial Elements (NΩ)          | [5 × 10⁴, 2.3 × 10⁵]       |               | [ML250, ML125]                               |
| **Detector Performance**                 |                            |               |                                               |
| Detector Pixel Size [angular]            | 15 [0.17]                  | μm [arcsec]   | MDM Observatory B4K Detector                 |
| Detector Read Noise                      | 5                          | e             | Unbinned                                      |
| Detector Dark Current                    | 0.01                       | e⁻ pix⁻¹ s⁻¹  | At a temperature of −124 °C                   |
| Detector Binning                         | 2 × 2                      | pixels        |                                               |
| **Predicted Throughput/Efficiency**      |                            |               |                                               |
| Telescope                                | 0.77                       |               |                                               |
| Filter                                   | 0.97                       |               |                                               |
| Relay                                    | 0.86                       |               |                                               |
| Microlens                                | 0.95                       |               |                                               |
| Filling Factor                           | 0.75                       |               |                                               |
| Collimator/Camera                        | 0.9/0.9                    |               |                                               |
| Grating                                  | 0.9                       |               |                                               |
| Detector Quantum Efficiency              | 0.85                       |               |                                               |
| Spectrograph Vignetting                  | 0.50                       |               |                                               |
| System Throughput                        | 0.19                       | 0.08–0.15     | Predicted without atmosphere                  |
| **Hα Sensitivity Calculation**           |                            |               |                                               |
| Sky Background Intensity                 | 2 (1.59 × 10⁵)             | R ˚⁻¹ (ph s⁻¹ cm⁻² sr⁻¹, Å⁻¹) |                                               |
| Exposure Time per Frame                  | 625                        | seconds       |                                               |
| Sky Background Noise                     | 50                         | e⁻ per lenslet per frame | Stacked to reach the full integration time |
| Dark Current Noise                       | 100                        | e⁻ per lenslet per frame | Nominal 250 μm lenslets w/o overlap |
| Read Noise                               | 100                        | e⁻ per lenslet per frame | Nominal 250 μm lenslets                      |
| **Detection Limit**                      |                            |               |                                               |
| 1 hr Integration                         | 109 (8674)                 | mR (ph s⁻¹ cm⁻² sr⁻¹) |                                               |
| 10 hr Integration                        | 34 (2706)                  | mR (ph s⁻¹ cm⁻² sr⁻¹) | 30° angular scale, 900 s exposures           |
| 100 hr Integration                       | 11 (875)                   | mR (ph s⁻¹ cm⁻² sr⁻¹) | 30° angular scale, 900 s exposures           |

Note.

a The current best estimate (CBE) is the same as the design goal, unless independently measured or modeled.

signal. The key advantages of the CHαS design can be summarized by stating that CHαS is a large-grasp, high-throughput instrument with moderate spectral resolution. While there are a variety of different instrument merit criteria, one common parameter space for assessing the relative performance between instruments is the combination of coverage versus resolution (Bershady 2009). In Figure 13, we plot the effective grasp versus the resolving power, comparing CHαS with many excellent existing and planned integral field spectrographs. CHαS occupies a unique quadrant of this plot, maintaining both a high effective grasp and a moderate resolving power.

Maintaining a high grasp and moderate spectral resolution are compelling instrument criteria for mapping discrete, ultralow–surface brightness emission. This combination directly drives the scientific capabilities of CHαS. We
Figure 13. A comparison of the effective grasp vs. resolving power between integral field spectrographs. The symbols and coloring distinguish the telescope size, the instrument commissioning status, and the focal plane coupling. When an efficiency measurement is not available, we assume \( e = 0.2 \). The CHOoS design (nominal and high-resolution) occupies a unique quadrant of this parameter space, maintaining a high grasp and moderate resolving power. The contours are exposure time isochrones, showing the grasp/resolution needed for a 10\( \sigma \) detection of diffuse H\( \alpha \) emission with an intensity of 3 mR over a solid angle equal to the full FOV for each instrument. The shading encompasses instruments that can make this detection within 1 hr (dark blue), 10 hr (medium blue), and 100 hr (light blue). This calculation excludes detector noise, for comparison across platforms. It is only valid for diffuse emission, as it assumes that the signal is binned over the full FOV.

demonstrate this concept in Figure 13, by overlaying exposure time isochrones representing the grasp/resolution needed for a 10\( \sigma \) detection of diffuse H\( \alpha \) emission with an intensity of 3 mR over a solid angle equal to the full FOV for each instrument. The shading encompasses instruments that can make this detection within 1 hr (dark blue), 10 hr (medium blue), and 100 hr (light blue). The dark blue contour segment, requiring the shortest exposure time, resides in the top right corner of the plot, favoring high-grasp/high-resolution configurations. The CHOoS effective grasp is driven by the instrument’s large FOV (10\(^7\) \times 10\(^9\)). While many integral field spectrographs are paired with 4–8 m class telescopes, prioritizing high spatial resolution over wide-field imaging, CHOoS is paired with a 2.4 m telescope operating over a wide FOV. Maintaining a moderate spectral resolution allows for the detailed sky background rejection that is essential for faint sky background–limited observations; the sky background noise at a specific wavelength is reduced by attaining a smaller spectral resolution element (Equation (7)). This resolution-driven sensitivity gain is only realized for discrete emission line mapping, where the signal is independent of the bandpass. In selecting the spectral resolution, the CHOoS design carefully balances the spectral versus spatial information. CHOoS fits an exceptional number of total (\( N_{I} \times \text{spectral} \ N_{R} \)) resolution elements on its detector, optimizing the instrument’s informational collecting power (Bershady 2009). The trade-off between high grasp and high spectral resolution results in a scale-dependent sensitivity; at the same grasp, an instrument with higher spectral resolution will have greater sensitivity on smaller scales. This occurs because the S/N in the sky background–limited regime relies strongly on the grasp per spectral resolution element, not on solely achieving unparalleled grasp. We leave for future work a comparison with alternative spectrograph designs, such as Fabry–Pérot or Interferometers, some of which may achieve a similarly high grasp and moderate spectral resolution. Because of the complexities of these instruments, there are trade-off assessments and questions regarding their backgrounds that need to be included in a more detailed comparison.

\[
\text{EM} = \frac{\Gamma_{c,0}N_{H\alpha}}{\alpha_B(T)} = 2.75I_{H\alpha}T^{0.9}_{\text{mR}} \text{ cm}^{-6} \text{ pc}.
\]

(8)

To demonstrate the scientific capabilities of CHOoS, we compare the CHOoS predicted sensitivity limits with the emission observed in the local universe (Figure 14). Observational measurements and upper limits are shown as discrete symbols. Bright H\( \alpha \) features include the M82 Cap (Lehnert et al. 1999), the Virgo filaments (Kenney et al. 2008), edge-on galaxies (Christlein et al. 2010), NGC 7793 (Dicaire et al. 2008), UGC 7321 (Adams et al. 2011), NGC 247 (Hlavacek-Larrondo et al. 2011), the outer disk of M31 (Madsen et al. 2001), the Leo Ring (Donahue et al. 1995), and the Virgo H\( \alpha \) cloud (Weymann et al. 2001). The dashed and solid light gray lines across 100 mR represent the H\( \alpha \) emission observations and surface brightness predictions for the Magellanic stream/bridge (Bland-Hawthorn et al. 2007; Barger et al. 2013). CHOoS is capable of making most of these detections on arcminute scales in \( \lesssim 1 \) hr, and observations of many of these targets have already been carried out with CHOoS. Emission from the CGM is much more tenuous, requiring measurements that push the boundaries of low–surface brightness imaging. Faint emission from ionized hydrogen on the outskirts of galaxies and well into the CGM is a probe of the local ionizing flux (Sunyaev 1969). The predominant sources of ionizing radiation in the CGM are the UV continuum from the galactic disk and the photoionizing extragalactic UV background (EUVB). Constraints on the low-redshift \( (z \approx 0) \) EUVB photoionization rate range from \( \Gamma \lesssim 2 \times 10^{-16} \text{ s}^{-1} \) (Adams et al. 2011; Madau & Haardt 2015; Fumagalli et al. 2017; Caruso et al. 2019). The H\( \alpha \) emission intensity (quoted in Rayleigh) scales as the emission measure (EM) given in Equation (8). We use this approximation to calculate a rough estimate of the CGM surface brightness, assuming a warm gas temperature \( T = 10^4 \text{ K} \), an EUVB ionization rate \( \Gamma = 4 \times 10^{-14} \text{ s}^{-1} \), and a column density \( N_{H\alpha} \geq 10^{17} \text{ cm}^{-2} \), for case B recombination \( \alpha_B \) in optically thick Lyman limit systems. With these assumptions, warm ionized gas far into the CGM should produce an exceedingly faint emission signal on the order of a few milli-Rayleigh. The Zhang et al. (2016) statistical detection of circumgalactic H\( \alpha \) emission, achieved by stacking millions of SDSS sightlines, has a similar flux of 3 mR. Higher–column density gas or gas ionized by stronger UV continuum flux from the galactic disk would produce brighter emission, on the order of 10 mR. For example, high-velocity clouds in the halo of the Milky Way ionized by the Galactic disk exhibit H\( \alpha \) emission intensities of 30–70 mR (Putman et al. 2003). Following a calculation similar to Equation (8), and assuming a 50 kpc region, the light blue shaded parallelogram region shows the predicted CGM emission intensity for a range of hydrogen densities, \( \log N_{H\alpha} / \text{cm}^{-3} = -4.5 \) to \(-3.5 \), corresponding to an overdensity of \( \delta \sim 100–1000 \), with clumping on scales of...
2–25 kpc. We show that CHoS can probe the majority of this phase space within a few tens of hours. Within 10–100 hr, CHoS is capable of reaching a sensitivity faint enough to place our own constraints on the EUVB photoionization rate. A 50–100 hr exposure with CHoS would result in the deepest Hα image and velocity field ever obtained, reaching a surface brightness of a few mR on scales of a few arcminutes. A CHoS science campaign is currently underway, building up 10–50 hr observations on a small sample of fall/spring galaxy targets.

Achieving accurate sky subtraction will require a precise and stable flat field and careful control of systematic effects. With respect to the flat field, since we are combining many hours of images (corresponding to $>100$ exposures), and combining spectra within a field (e.g., $>100$ spectra per sky bin), random and spatially uncorrelated flat-field uncertainties will decrease as $\sqrt{N}$. Because of this, flat-field accuracies of 1%–10% should be sufficient and feasible. Other aspects will require careful calibration and analysis, including bias subtraction, the removal of continuum from background point sources, stray and scattered light, detector ghost images, correction for distortion, flexure, and sky and spectral variability. These may reduce the accuracy of the sky subtraction and the reliability of the measured signal, and will be addressed in future work that seeks to reach the faintest limits.

6. Summary

1. CHoS is a narrowband (3 nm), moderate-resolution ($R \sim 10,000$), wide-field ($10' \times 10'$) integral field spectrograph designed to detect faint optical emission from diffuse gas in the local universe ($z < 0.01$).
2. CHoS has a catadioptric design that is optimized to perform over a 400–900 nm operational wavelength range. It is capable of targeting a broad number of optical emission lines, including Hα, Hβ, [S II], [N II], [O III], [O II], and [O I].
3. CHoS collects a total of $1.75 \times 10^6$ resolution elements ($N_{\Omega} \times N_p$) in a single exposure, while maintaining a high grasp and moderate resolving power. This is an ideal combination for efficiently mapping discrete ultralow-surface brightness emission.
4. A 50–100 hr integration with CHoS would result in the deepest Hα image and velocity field ever obtained, probing emission with a surface brightness of a few milli-Rayleigh, while maintaining an S/N of 10.
5. CHoS is deployed on the Hiltner 2.4 m telescope at MDM Observatory. We have completed a successful early commissioning at the observatory, and we are working toward making CHoS a facility instrument available to the MDM consortium. The instrument remains a testbed for new design concepts and a teaching opportunity for many student-led upgrades.

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Gonglewski for their help at various stages of this project. The construction of this instrument was done in collaboration with many industry/manufacturing companies listed throughout this paper. Special thanks go to Dominic Speer, Elroy Pearson, Misty Johnson, and Wasatch Photonics for the technical discussions and efficiency modeling that led to the current VPH grating design. Many thanks to Vladimir Leleko at Advanced Microoptics Systems (aμs) for advising us on the design of custom microlens arrays for this application. The CHαS optical design relies on an NDA with Celestron LLC. We are grateful for their collaboration with with academic institutions and for the support provided by their engineering and sales teams.

Facility: MDM: 2.4m.

Appendix

The CHαS Offner Relay was designed using a mix of off-the-shelf and surplus optics. The ray trace parameters are provided in Table 7 for reference.

| Surface                  | Radius  | Thickness | Semi-diameter | Material | Decenter X | Decenter Y | Tilt X | Tilt Y |
|--------------------------|---------|-----------|---------------|----------|------------|------------|--------|--------|
| 1 Object Infinity        | Infinity| 654.627   | 33.0          |          | 0.0        | 0.0        | 8.364  | 0.0    |
| 2 Coordinate Break       |         |           |               |          |            |            |        |        |
| 3 Concave Sphere         | −609.6  | 75.0      | MIRROR        |          |            |            |        |        |
| 4 Coordinate Break       | −305.927|          |               |          |            |            |        |        |
| 5 Coordinate Break       |         |           |               |          |            |            |        |        |
| 6 Coordinate Break       | 0.0     | −3.0      | 0.0           | 0.0      | 0.0        | 8.364      | 0.0    |        |
| 7 Convex Sphere          | −310.661| 25.4      | MIRROR        |          |            |            |        |        |
| 8 Coordinate Break       |         |           |               |          |            |            |        |        |
| 9 Coordinate Break       | 0.0     | 3.0       | 0.0           | 0.0      | 0.0        | 16.728     | 0.0    |        |
| 10 Coordinate Break      | 0.0     | 0.0       | 8.5           | 0.0      | 0.0        |            |        |        |
| 11 Concave Sphere        | −609.6  | 75.0      | MIRROR        |          |            |            |        |        |
| 12 Coordinate Break      | −551.031|          |               |          |            |            |        |        |
