The Visible Integral-field Spectrograph eXtreme (VIS-X): high-resolution spectroscopy with MagAO-X

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ABSTRACT
MagAO-X system is a new adaptive optics for the Magellan Clay 6.5m telescope. MagAO-X has been designed to provide extreme adaptive optics (ExAO) performance in the visible. VIS-X is an integral-field spectrograph specifically designed for MagAO-X, and it will cover the optical spectral range (450 – 900 nm) at high-spectral (R=15,000) and high-spatial resolution (7 mas spaxels) over a 0.525 arcsecond field of view. VIS-X will be used to observe accreting protoplanets such as PDS70 b & c. End-to-end simulations show that the combination of MagAO-X with VIS-X is 100 times more sensitive to accreting protoplanets than any other instrument to date. VIS-X can resolve the planetary accretion lines, and therefore constrain the accretion process. The instrument is scheduled to have its first light in Fall 2021. We will show the lab measurements to characterize the spectrograph and its post-processing performance.

Keywords: high-contrast imaging, high-resolution spectroscopy, exoplanets, adaptive optics

1. INTRODUCTION
Young stars form in dense clouds that collapse under their own gravity. The angular momentum that is present at the beginning of this process forces the material to clump together into a disk around the young star. Planets form inside these disks either through instabilities in the disk that cause the formation of dens clumps or through pebble accretion. Multiple pathways to the formation of planets have been proposed and there is no clear answer yet on what each process’s contribution is. A thorough understanding of the formation and evolution of exoplanets will allow us to gain an understanding of not only the origin of Earth, but possibly life. To this end we will need to characterize exoplanets in all stages of their evolution, from young to old. However, the most common characterization technique utilizes the transit method which suffers from astrophysical limitations such as constraints on the orbital geometry or astrophysical noise due to e.g. star spots or circumstellar material. Direct imaging plays an important role to overcome these observational limitations. For both the young and old systems, the influence of the star, and possible circum-stellar material, can be significantly reduced by spatially resolving the planet from its environment, allowing detailed characterization of the planet.

The past few years has seen a large step in the capabilities of direct imaging instruments. Instruments such as SPHERE\textsuperscript{1} or MagAO\textsuperscript{2} have observed the environment around many young stars in search of giant proto-planets;

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planets that are still accreting material from their birth environment. Young proto-planets sweep up the gas and dust within the proto-planetary disk. The accretion of gas releases a large amount of energy when the gas falls onto the planet, or its circum-planetary disks. Most of this energy is released by specific line emission such as the hydrogen emission lines. These signatures are therefore one of the strongest signposts of accreting gas giants. Several instruments contain sets of narrowband imaging filters that image the emission lines and the nearby continuum. Recent observations have shown that medium to high-resolution spectroscopy is ideal to observe accreting proto-planets. However, no direct imaging instrument has the capability of visible light high-resolution integral-field spectroscopy.

The Magellan Adaptive Optics eXtreme (MagAO-X) system is a new adaptive optics for the Magellan Clay 6.5m telescope at Las Campanas Observatory (LCO). MagAO-X has been designed to provide extreme adaptive optics (ExAO) performance in the visible. It will ultimately deliver Strehl ratios of 90% at 0.9 µm and nearly 80% at Hα (Males et al., 2018). The performance of MagAO-X in the visible is comparable to what other direct imaging instruments achieve in H or K-band, making MagAO-X the ideal instrument to push exoplanet characterization to the visible range. However, MagAO-X does not have any spectroscopic capability. The Visible Integral-field Spectrograph eXtreme (VIS-X) is a spectrograph for MagAO-X that will cover the optical spectral range at high-spectral and high-spatial resolution. Sections 2 will expand on the primary science case and the instrumental requirements. Then Section 3 will discuss the instrument design and the first lab results.

2. PRIMARY SCIENCE CASE FOR VIS-X: ACCRETING PROTO-PLANETS

The accretion process of sub-stellar companions is a key part of the information that can be used to discriminate between the different formation processes. The ability to accrete gas at all and the actual mass accretion rate will allow us to discriminate between formation pathways. Gas accretion on massive planets is thought to be a very energetic process, and the emitted accretion luminosity can become comparable to the total internal luminosity of the planet. Therefore, visible-light High-Contrast Imaging (HCI) is a promising approach to detect these young protoplanets, because it provides access to strong accretion tracers such as Hα. The huge potential of Hα imaging has been demonstrated by recent detections of actively accreting companions with HST/WFC (Zhou et al. 2014), Magellan/MagAO, and more recently VLT/MUSE. Haffert et al. 2019 show that integral-field spectroscopy is a very powerful technique to unambiguously detect proto-planets. Conventional high-contrast imaging techniques, such as Angular Differential Imaging (ADI), often lead to point-like features that are caused by either residual instrumental artifacts or due to the presence of non-symmetric circumstellar disks. With high-resolution integral-field spectroscopy we can eliminate the star and the circum-stellar disk by removing a scaled stellar spectrum from each spatial pixel (spaxel). The signal from the circum-stellar disk is also removed during this procedure because the light from the disk in the visible range consists mainly of reflected star light and is therefore identical to the stellar spectrum.

The emission lines from accreting planets are very narrow. Marleau et al. in prep show that the Hα emission line starts to be resolved around a resolving power of 15,000 (20 km/s). This implies that optimal SNR can be achieved when the resolving power of the instrument is 15,000. If the resolving power is increased even further the light from the proto-planet will be smeared out over more detector pixels, which will increase the detector noise contribution. The signal to noise (SNR) of the Hα measurement is,

\[
\text{SNR} = \frac{TF_{\text{H}α,P}}{\sqrt{T(F_{\text{phot},S} + F_{\text{H}α,S})C(\theta_P) + N \sigma_D^2}}.
\]

Here \(T\) is the throughput from the top of the atmosphere to the camera, \(F_{\text{H}α,P}\) and \(F_{\text{H}α,S}\) are the Hα flux of the planet and star, \(F_{\text{phot},S}\) is the stellar photospheric emission, \(C(\theta_P)\) the contrast of the observations at angular separation \(\theta_P\), \(N\) is the number of pixels that are used to sample an unresolved emission line and \(\sigma_D\) is the detector noise (read noise + dark current). Under favourable conditions the Hα line of the star is separated from the Hα line of the planet due to an intrinsic radial velocity difference. At high enough spectral resolution the stellar Hα flux will not contribute at all at the velocity position of the planet. The flux of the stellar continuum
is proportional to the bandwidth of a single spectral slice. Taking this into account we arrive at the following
SNR for the Hα detection,

$$\text{SNR} = \frac{TF_{\text{Hα}, P}}{\sqrt{T\langle F_{\text{Phot}, S} \rangle \delta \lambda C(\theta_p) + N\sigma_D^2}}.$$  \hspace{1cm} (2)

Here the photospheric flux of the star has been replaced by the average flux density times the bandwidth of a
single spectral channel. The bandwidth $\delta \lambda = \lambda / R$, where $R$ is the resolving power of the spectrograph. In the
regions where photon noise dominates, the SNR is

$$\text{SNR} = \frac{F_{\text{Hα}, P} \sqrt{TR}}{\sqrt{T\langle F_{\text{Phot}, S} \rangle \lambda C(\theta_p)}}.$$ \hspace{1cm} (3)

This shows that the expected SNR scales with $\sqrt{R}$, under the assumption that the spectral line is unresolved.
A high-resolution spectrograph at $R = 15,000$ can have a large gain in sensitivity compared to narrowband
imaging ($R = 100$ for MagAO, and $R = 120$ or $R \sim 650$ for the broadband and narrowband Hα filters in
SPHERE, respectively). A rough order of magnitude in SNR improvement is $\sqrt{15000/100} \approx 12.3$. This shows
that significant gains can be made by using high-resolution integral field spectroscopy for accreting proto-planets.

### 2.1 Post-processing gain

There are several aspects of high-resolution integral-field spectroscopy for emission line imaging. The first and
foremost advantage of HRS, is that it is easier to disentangle light from the emission lines from the neighboring
continuum. Only two images are taken with the classic approach of dual band imaging. In post-processing, the
continuum image is magnified by $\lambda_1/\lambda_2$ to take care of the chromatic scaling due to diffraction. For accurate
subtraction of one channel from the other, the flux total flux has to be scaled. This is usually achieved by
measuring the total flux within the Airy core. After the flux correction, the images can be subtracted from each other,

$$\delta I = I(\lambda_1) - aI(\lambda_2) - b.$$ \hspace{1cm} (4)

Here $I(\lambda_i)$ is the observed image at spectral channel $i$, $a$ is the linear scale parameter, and $b$ is the background.
This approach can be used to gain in contrast, however the gain is limited because this model assumes that
the diffraction pattern and speckles can be modeled by a global linear scaling. This approach would work for
a system without any wavefront aberration. However, any amount of wavefront aberration will introduce non-
linear chromatic behavior in the focal plane speckles. This is especially true when amplitude errors are also
present. The pupil plane electric field can be represented by,

$$E_p = A(1 + g)e^{i2\pi \delta}.$$ \hspace{1cm} (5)

Here $E_p$ is the pupil plane intensity, $A$ the pupil function, $g$ the amplitude aberrations and $\delta$ the wavefront error.
For high-contrast imaging instruments $\delta$ is usually small and the exponential can be expanded into its Taylor
series,

$$E_p = A(1 + g)e^{i2\pi \delta} \approx A(1 + g) \left(1 + \frac{2\pi i}{\lambda}\right).$$ \hspace{1cm} (6)

The propagation from the input pupil plane through the optical system to the final science focal plane is repre-
sented by the linear operator $C$. With this operator in hand, the focal plane electric field is $E_f = CE_p$. This
representation holds for any type of IFS implementation, such as micro-lens array based IFS’s or dual band
imagers. Detectors can not measure the electric field directly and measure the intensity. This means that the
final intensity that we measure is,

$$I_p = |CP + CP \frac{2\pi i}{\lambda}|^2 = |CP|^2 + |CP \frac{2\pi i}{\lambda}|^2 + 2\Re \left\{ CP \left( CP \frac{2\pi i}{\lambda} \right) \right\}.$$ \hspace{1cm} (7)

From this it is clear that even in the small-aberration regime, there are terms that have a different chromatic
behavior. The aberration-free term has no chromatic scaling except for the chromatic magnification due to
Figure 1. The radial 1-σ contrast curve after post-processing. For the DBI method we applied the optimal scaling of the two spectral channels. Each color represents a different amount of wavefront aberration. The solid curves are the contrast curves after DBI post-processing and the dashed curves are the contrast curves for the IFS post-processing. For the DBI method the contrast decreases when the wavefront error is increased, while for the IFS observations the residuals increases slightly and always stays well below the DBI residuals. When no wavefront errors are present the 1-σ contrast for the DBI method is between $10^{-7}$ and $10^{-8}$.

Diffraction. And the other two terms both scale differently with wavelength. In this example, the wavefront error was achromatic and the higher-order terms have been neglected. Such a simple example already shows why there is no global linear relation between two different spectral channels, and also explains why DBI will not remove all aberrations.

More spectral channels have to be measured to accurately model the chromatic behavior of the stellar speckles. A IFS provide such an opportunity. However, having many spectral channels is not the only requirement. Chromatic scaling due to diffraction happens on spectral resolving powers of $R = N$, with $R$ the resolving power and $N$ the field of view in units of $\lambda/D$. Typical instruments have a field of view of $\approx 100\lambda/D$. The instrument should have a $R \gg 100$ to accurately measure the speckles. However, most if not all direct imaging IFS have low spectral resolving power, e.g. SPHERE-IFS has 50, CHARIS/SCEXAO has 20-80 and ALES at the LBT has 40. Speckle removal with higher-resolution spectroscopy has already proven itself to work better than DBI.\textsuperscript{14}

The post-processing of HR-IFS data uses the assumption that diffraction and instrumental effects happen at low-spectral resolution and can therefore be modeled by low-order polynomials. This means that the spectrum at every pixel can described by a reference stellar spectrum multiplied by a low-order polynomial. There are many spectral channels available for each spatial pixel(spaxel) in the IFU, therefore a different polynomial model
can be estimated for each spaxel. This is described by,

\[ I_j(\lambda) = \sum_i a_{ij} \phi_i(\lambda) S(\lambda). \]  

(8)

A Linear Least-Squares (LLS) solution can be found for the polynomials coefficients because the model is linear in the coefficients. A good choice of low-order polynomials are Chebyshev or Legendre polynomials. These are orthogonal and create robust matrices for the matrix inversion step.

The results of the post-processing gain are shown in Figure 1. The high-resolution observations are well below \(10^{-8}\), which is more than sufficient to detect accreting proto-planets. The DBI mode can have strong residuals, depending on the exact chromatic behavior of the speckles. The DBI method is limited to \(>10^{-6}\) at the inner regions for smallest wavefront errors. This simulation only considered a single phase screen in the pupil. Real systems are expected to contain stronger and more complex chromatic behavior which will push the post-processed contrast to the \(0.5\lambda\) curve.

2.1.1 First end-to-end simulations

End-to-end simulations of an \(R = 15000\) Hα spectrograph coupled to MagAO-X have been performed to investigate the gain in performance. We have simulated a system with 50 actuators across the pupil driven by a unmodulated pyramid wavefront sensor. The star itself was an 8th magnitude star. Median atmospheric conditions of the Las Campanas site have been assumed \((v = 15 m/s, r_0 = 0.16 \text{ at } \lambda = 550 \text{ nm})\). A separate static phase screen with 50 nm rms has been used to simulate non-common path errors. The sensitivity curves are shown in Figure 2. The derived contrast curves show that VIS-X will indeed add roughly a factor 10 to the sensitivity of MagAO-X. MagAO-X itself will already be more sensitive than any other instrument because the instrument has been optimized to operate as an xAO system in the visible. VIS-X shows the largest gain in the inner few \(\lambda/D\), exactly where we expect to find the most planets. This demonstrates the benefit of high-resolution IFU observations of the Hα emission line. Additionally, due to the higher resolution it may become possible to study the line shapes and derive the physical state of the accretion process.

3. VIS-X DESIGN AND FIRST MEASUREMENTS

Due to constraints on detector real estate there is a trade-off between spatial sampling, field-of-view, spectral bandwidth and spectral resolution. Maximizing the field of view and spectral resolving power requires a large format detector. In the past few years there has been a significant amount of progress of in the quality of back-illuminated CMOS detector technology. SONY released the imx455 sensor in 2019 with 9600x6422 pixels, a quantum efficiency close to 80 percent at Hα and a peak efficiency close to 90 percent (at 550 nm) and a 1 electron read noise at the highest gain setting. With a water-based cooling it is possible to reduce the dark current to below 0.001 electron/s/pixel. These properties make this an ideal sensor for visible integral-field spectroscopy.

With an internal UA seed grant, we developed a prototype micro-lens array (MLA) based integral-field spectrograph that can operate in a narrowband (6 nm) around Hα using the new imx455 sensor. MLA based IFUs are in use in all direct imaging instrument and are considered a mature technology and therefore a low risk design. The prototype has been designed to deliver a resolving power of \(R \sim 15000\) at Hα, with a fixed spectral bandwidth of 5nm. The prototype has a limited field of view of 0.5° in diameter. Figure 3 shows a schematic of the spectrograph within the available space envelop of MagAO-X. We use two spherical mirrors as an achromatic relay that magnifies the F/69 beam of MagAO-X to sample the PSF with 3 spaxels per \(\lambda/D\) at Hα with the MLA. This will keep us Nyquist sampled down to Hγ (434 nm). On-sky experience with the MUSE IFU at the VLT showed us that well sampled LSF’s are critical for accurate post-processing. The relay itself has a theoretical wavefront rms of \(\lambda/100\) because we are working with slow beams (F/69 to F/870). The performance is therefore mainly determined by the manufacturing quality of the relay mirrors. We found that \(\lambda/4\) mirrors are fitting for our purpose, and lab measurements confirmed that there is no indication of degradation of the PSF after the relay, see Figure 4 for an extracted PSF. The extracted PSF contains roughly \(\lambda/10\) rms defocus which is well within the correction range of the NCPA DM of MagAO-X.
Figure 2. The radial 1-σ contrast curve after post-processing. The red dashed curve represents the sensitivity of MagAO-X with dual band imaging, while the blue dashed curve shows the sensitivity with VIS-X. Both curves are compared to actual observations from MUSE and SPHERE. This figure has been adapted from \textsuperscript{6}

The PSF is sampled by a micro-lens array with a 192 $\mu$m pitch and a 3.17 mm focal length (F/16.5). The spectrograph’s backend is kept as simple as possible by using a first-order layout with identical lenses (Thorlabs TTL200MP) for the camera and collimator both having a focal length of 200 mm. The current design has diffraction-limited performance over $\pm 0.25$ arcseconds on-sky, but the performance rapidly degrades outside this small field of view. The monochromatic PSFs of the spaxels can be seen in Figure 5.

4. CONCLUSION
This manuscript has described the rational and design of a new IFU, VIS-X, for MagAO-X. It’s main priority it focused on accreting proto-planets by observing H$\alpha$ at high spectral resolution. We expect that VIS-X will provide a gain in sensitivity of a 100 compared to other direct imaging instrument. This would enable us to search for fainter proto-planets at smaller angular separations. VIS-X has its first light scheduled for Fall 2021.

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Current layout of VIS-X

Figure 3. A schematic drawing of VIS-X in the available space envelop of MagAO-X. The beam from MagAO-X enters from the top right and follows the path in the direction of the arrow. A spherical mirror-based relay will magnify the PSF onto an MLA. The MLA output is then dispersed by a first-order grating spectrograph.

Figure 4. The reconstructed PSF from VIS-X. There is a slight defocus visible ($\lambda/10$ rms), and some extraction artifacts on the lower left due to the low SNR of the calibration files. The middle figure shows the fitted PSF model, and the right figure shows the residuals. The residuals are on the order of $\sim 10^{-2}$.

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Figure 5. The PSFs of several spaxels. The area that is shown here is part of the center of the IFU. All spaxels are well separated from each other and show diffraction-limited image quality.

REFERENCES

[1] Beuzit, J.-L., Vigan, A., Mouillet, D., Dohlen, K., Gratton, R., Boccaletti, A., Sauvage, J.-F., Schmid, H. M., Langlois, M., Petit, C., et al., “Sphere: the exoplanet imager for the very large telescope,” Astronomy & Astrophysics 631, A155 (2019).

[2] Close, L. M., Males, J. R., Follette, K. B., Hinz, P., Morzinski, K., Wu, Y.-L., Kopon, D., Riccardi, A., Esposito, S., Puglisi, A., et al., “Into the blue: Ao science with magao in the visible,” in Adaptive Optics Systems IV, 9148, 91481M, International Society for Optics and Photonics (2014).

[3] Aoyama, Y., Marleau, G.-D., Mordasini, C., and Ikoma, M., “Spectral appearance of the planetary-surface accretion shock: Global spectra and hydrogen-line profiles and fluxes,” arXiv preprint arXiv:2011.06608 (2020).

[4] Close, L. M., Follette, K., Males, J., Puglisi, A., Xompero, M., Apai, D., Najita, J., Weinberger, A., Morzinski, K., Rodigas, T., et al., “Discovery of ha emission from the close companion inside the gap of transitional disk hd 142527,” The Astrophysical Journal Letters 781(2), L30 (2014).

[5] Haffert, S. Y., Bohn, A. J., de Boer, J., Snellen, I. A. G., Brinchmann, J., Girard, J. H., Keller, C. U., and Bacon, R., “Two accreting protoplanets around the young star PDS 70,” Nature Astronomy 3, 749–754 (Jun 2019).

[6] Xie, C., Haffert, S., de Boer, J., Kenworthy, M., Brinchmann, J., Girard, J., Snellen, I., and Keller, C., “Searching for proto-planets with muse,” Astronomy & Astrophysics 644, A149 (2020).

[7] Stamatellos, D. and Herczeg, G. J., “The properties of discs around planets and brown dwarfs as evidence for disc fragmentation,” Monthly Notices of the Royal Astronomical Society 449(4), 3432–3440 (2015).
[8] Mordasini, C., Marleau, G.-D., and Mollière, P., “Characterization of exoplanets from their formation-iii. the statistics of planetary luminosities,” Astronomy & Astrophysics 608, A72 (2017).

[9] Wu, Y.-L., Sheehan, P. D., Males, J. R., Close, L. M., Morzinski, K. M., Teske, J. K., Haug-Baltzell, A., Merchant, N., and Lyons, E., “An alma and magao study of the substellar companion gq lup b,” The Astrophysical Journal 836(2), 223 (2017).

[10] Wagner, K., Follette, K. B., Close, L. M., Apai, D., Gibbs, A., Keppler, M., Müller, A., Henning, T., Kasper, M., Wu, Y.-L., Long, J., Males, J., Morzinski, K., and McClure, M., “Magellan Adaptive Optics Imaging of PDS 70: Measuring the Mass Accretion Rate of a Young Giant Planet within a Gapped Disk,” ApJ 863, L8 (Aug 2018).

[11] Eriksson, S. C., Torres, R. A., Janson, M., Aoyama, Y., Marleau, G.-D., Bonnefoy, M., and Petrus, S., “Strong hα emission and signs of accretion in a circumbinary planetary mass companion from muse,” Astronomy & Astrophysics 638, L6 (2020).

[12] Marois, C., Lafrenière, D., Doyon, R., Macintosh, B., and Nadeau, D., “Angular Differential Imaging: A Powerful High-Contrast Imaging Technique,” ApJ 641, 556–564 (Apr 2006).

[13] Ligi, R., Vigan, A., Gratton, R., De Boer, J., Benisty, M., Boccaletti, A., Quanz, S. P., Meyer, M., Ginski, C., Sissa, E., et al., “Investigation of the inner structures around hd 169142 with vlt/sphere,” Monthly Notices of the Royal Astronomical Society 473(2), 1774–1783 (2018).

[14] Hoeijmakers, H. J., Ehrenreich, D., Heng, K., Kitzmann, D., Grimm, S. L., Allart, R., Deitrick, R., Wyttenbach, A., Oreshenok, M., Pino, L., et al., “Atomic iron and titanium in the atmosphere of the exoplanet kelt-9b,” Nature 560(7719), 453–455 (2018).

[15] Close, L. M., “The separation and hα contrasts of massive accreting planets in the gaps of transitional disks: predicted hα protoplanet yields for adaptive optics surveys,” The Astronomical Journal 160(5), 221 (2020).

[16] Por, E. H., Haffert, S. Y., Radhakrishnan, V. M., Doelman, D. S., van Kooten, M., and Bos, S. P., “High contrast imaging for python (hcipy): an open-source adaptive optics and coronagraph simulator,” in [Adaptive Optics Systems VI], 10703, 1070342, International Society for Optics and Photonics (2018).