High-resolution imaging of embedded massive star clusters and other science cases for the Gemini-North Adaptive Optics system

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ABSTRACT

The formation and evolution of young massive star clusters is a key science case for multi-conjugate adaptive optics (MCAO) facilities on ground-based telescopes, probing an extreme mode of the star formation processes. Since massive star clusters represent very crowded fields and the young stars are deeply embedded in the dust and gas from their birth molecular cloud, deep photometry of such objects requires high angular resolution capabilities over a wide field of view (FOV) and near-infrared (NIR) observations less affected by dust extinction. Recent data for embedded massive clusters taken with the Gemini Multi-Conjugate Adaptive Optics System GeMS at the 8-m Gemini-South telescope show the scientific potential of ground-based MCAO facilities. Gemini Observatory is currently developing a next-generation MCAO facility for the Gemini-North telescope, called GNAO. We present an overview of the GNAO project with a focus on the driving science cases.

Keywords: Multi-conjugate adaptive optics, massive star clusters

1. INTRODUCTION

The formation and evolution of star clusters is a fundamental question for star formation studies because a significant fraction of star formation occurs in cluster environments. The high densities and strong UV radiation fields characterizing massive star clusters provide a particularly unique laboratory to study star formation under conditions more similar to those of the high-redshift Universe. Only young star clusters can probe the active phases of star formation in clusters. However, young star clusters are still deeply embedded in the molecular gas from their birth cloud. Observations of the heavily obscured stars are challenging and require NIR wavelengths to see through the dust. In addition, young massive star clusters represent very crowded fields so that high angular resolution is critical for deep photometric measurements down to small stellar masses.[9]

High angular resolution has increasingly become accessible from ground-based telescopes thanks to the progress in adaptive optics (AO) techniques. Single-conjugate AO systems are inherently restricted to narrow FOVs because anisoplanatism causes a rapid degradation in the AO compensation off-axis. This poses a severe restriction for wide field high-angular resolution science cases like the study of embedded massive clusters. MCAO overcomes this SCAO FOV limitation by employing a 3D reconstruction of the atmospheric turbulence based on wave front measurements along multiple line of sights and at least two deformable mirrors conjugated to different altitudes to compensate the wave front aberrations. While the number of existing MCAO facilities is still limited, MCAO is an important concept for the next-generation AO facilities, including at the future Extremely Large Telescopes.

The concept of MCAO was first demonstrated on sky with the prototype Multi-Conjugate Adaptive Optics Demonstrator (MAD) at the Very Large Telescope (ESO).[1] MAD used bright natural guide stars (NGSs) to derive the 3D characteristics of the turbulence volume above the telescope. Due to the restrictions imposed by the availability of bright natural guide stars MAD observations were restricted to a small number of suitable science targets. The use of laser guide stars (LGSs) in addition to NGSs with fainter magnitude requirements

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facilitates MCAO observations of a much wider range of science targets. The Gemini Multi-conjugate Adaptive Optics system GeMS at the 8-m Gemini-South telescope on Cerro Pachon (Chile) uses five LGSs, one to three NGSs, and two DMs conjugated at 0 and 9 km altitude to provide an MCAO-compensated science FOV of 2×2 arcmin at NIR wavelengths.[2–4] GeMS has been offered to the community since 2013 together with the Gemini-South Adaptive Optics Imager (GSAOI),[5] a NIR imager with a 0.02 arcsec pixel scale.

Gemini Observatory is currently developing GNAO – the next-generation laser-assisted MCAO facility for the 8-m Gemini-North telescope on Maunakea (Hawaii).[6] GNAO will build on the observatory's experience with GeMS at the Gemini-South telescope and extend Gemini's MCAO capabilities to the northern sky. The GNAO project is part of the "Gemini in the era of multi-messenger astronomy" (GEMMA) program, funded by the National Science Foundation (NSF). A major requirement for GNAO is to provide a robust queue-operated MCAO facility that enables a wide range of science cases and flexible transient follow-up observations.

Based on example data from recent observations of massive star clusters with GeMS/GSAOI, this paper highlights the benefits of current and future MCAO facilities for science applications requiring high angular resolution over wide FOVs. The scientific motivation for GNAO is presented together with an overview of the driving science cases for the new MCAO facility for the Gemini-North telescope.

2. THE GEMS/GSAOI VIEW ON YOUNG MASSIVE STAR CLUSTERS

30 Doradus is a star forming region in the Large Magellanic Cloud[7] and famously known as one of the brightest HII regions in the Local Group. A major part of the research interest in 30 Dor is driven by the fact that it probes star formation in the more metal-poor and gas-rich environment of the LMC compared to the Milky Way. Furthermore, 30 Dor has been considered as a local counterpart to the more extreme starbursts at high redshift. In this regard, 30 Dor might provide a window into the conditions of star cluster evolution in the distant Universe. The core of 30 Dor hosts the starburst region R136, a super star cluster with a high density of very massive stars.[8] The stellar densities and crowding in R136 pose an observational challenge. Deep photometric measurements down to small stellar masses require a uniformly high angular resolution and a good spatial sampling. The advantages of high-angular resolution for studying the crowded core of R136 have been demonstrated based on extreme AO using the SPHERE instrument at the Very Large Telescope (ESO).[9] However, the SPHERE data cover a limited FOV of 10.9 arcsec $\times$ 12.3 arcsec. Fig. 1 shows a section of a recent GeMS/GSAOI K-band image[*] taken for R136 using MCAO over a wider FOV. The image is compared to a NICMOS2 H-band image of the same region taken with the Hubble Space Telescope.[10] Although the GeMS/GSAOI image was taken at 40 deg zenith distance, i.e. under more challenging conditions for MCAO performance, the improved image quality at NIR wavelengths of the ground-based MCAO assisted image compared to the NICMOS2 H-band image is evident. The potential of MCAO at an 8-m ground-based telescope as a complement to the 2.4-m HST has been a major science driver for GeMS.[2]

The star forming complex LMC-N79 located in the south-west of the LMC is much less prominent at optical wavelengths than 30 Dor. However, IR observations of N79 reveal a significantly larger star formation efficiency than for 30 Dor.[11] N79 has been suggested to be a younger more embedded star forming region that may evolve into a giant HII region similar to 30 Dor in the future. In particular, N79 hosts a very luminous IR source which is a possible precursor to an R136-like super star cluster. The more embedded N79 region is a unique testbed to study the early stages of a star burst in the metal-poor LMC environment. The GeMS/GSAOI images (Fig. 2) provide a high-angular resolution view of N79 at NIR wavelengths[†]. With an FWHM of 120 mas the data resolve the stellar content of N79 down to a few solar masses even though – similar to Fig. 1 – the observations were taken at large zenith distances of 40-45 deg. Such photometric depth is essential for characterizing the low-stellar mass content and for measuring the total stellar mass of the cluster (Andersen et al., in prep.).

The long-wavelength NIR coverage of GeMS/GSAOI is particularly important for observations of deeply embedded stellar populations that suffer from strong extinction at optical wavelengths. G286.21+0.17 is a massive molecular clump in the Milky Way Carina star forming complex.[12,13] The molecular gas shows evidence of gravitational infall and the extent and rate of the molecular gas infall suggest that G286.21+0.17 represents

[*]Gemini program GS-2018B-DD-101
[†]Gemini program GS-2018B-Q-202

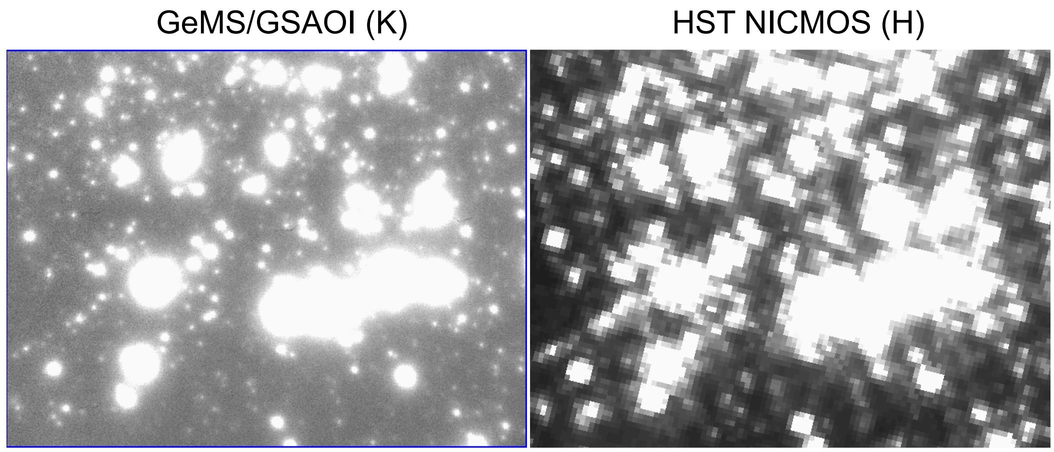

Figure 1. GeMS/GSAOI and HST NICMOS images of a 13 arcsec × 9.5 arcsec region close to the center of the R136 starburst cluster in 30 Dor. The left panel shows a part of the MCAO-corrected NIR K-band image observed with GeMS and the GSAOI camera at the 8-m Gemini-South telescope. The image was taken at about 40 deg zenith distance. The right panel shows a NIR H-band image observed with the NICMOS2 camera onboard the 2.4-m Hubble Space Telescope. The pixel scales of GSAOI and NICMOS2 are 0.02 and 0.075 arcsec/pixel, respectively.

the early stages of massive cluster formation.[12] Hosting a deeply embedded cluster of stars in the infall region, G286.21+0.17 provides the rare opportunity to study the process of massive cluster formation while active star formation is ongoing.[13] This particular phase of cluster formation holds important clues for constraining models for cluster formation. Previous wide-field NIR images obtained under natural seeing[13] did not provide sufficient resolution and sensitivity to probe the low-mass stellar content of G286.21+0.17. Fig. 3 shows high-angular resolution images taken with GeMS/GSAO[‡] and the Wide Field Camera 3 onboard HST in the Ks and H-bands, respectively. The GeMS/GSAOI image achieves an FWHM of 100-110 mas which is smaller than the 150 mas FWHM of the HST image in the H-band. A number of sources are more prominently seen in the GeMS/GSAOI image, which is primarily a consequence of the longer-wavelength observations being less affected by dust extinction. The color information derived from the data shown in Fig. 3 will be used to investigate the low-stellar mass content, to map the extinction, and to determine the fraction of objects with warm circumstellar disks which can be used as a proxy for age assessments (Cheng & Andersen, in prep.).

3. SCIENCE CASES FOR THE NEXT-GENERATION GEMINI-NORTH MCAO SYSTEM

A queue-operated MCAO system on the 8-m Gemini North telescope opens up unique prospects for scientific return[6,14] in the landscape of the upcoming astronomical facilities like the Large Synoptic Survey Telescope (LSST) and James Webb Telescope (JWST). The GNAO facility, currently under development as part of the NSF-funded GEMMA program, will ultimately supersede the aging Gemini-North single-conjugate AO system ALTAIR.[15,16] Building on the experience with GeMS, a major focus of the development for GNAO is system robustness and simplified operations to provide a facility that can be fully integrated into the observatory's queue operation scheme. GNAO's baseline is a ∼2 arcmin AO-compensated FOV that will feed a first-light NIR imager and can serve future visiting instruments requiring an MCAO facility such as, e.g., the Gemini Infra-Red Multiple Object Spectrograph (GIRMOS).[17] Furthermore, the design of GNAO will support a future upgrade to ground-layer AO, depending on the installation of an adaptive secondary mirror. A ground-layer AO mode will enhance the telescope's observing efficiency across the entire suite of Gemini-North seeing-limited instruments.[6]

[‡]Gemini program GS-2019A-DD-103

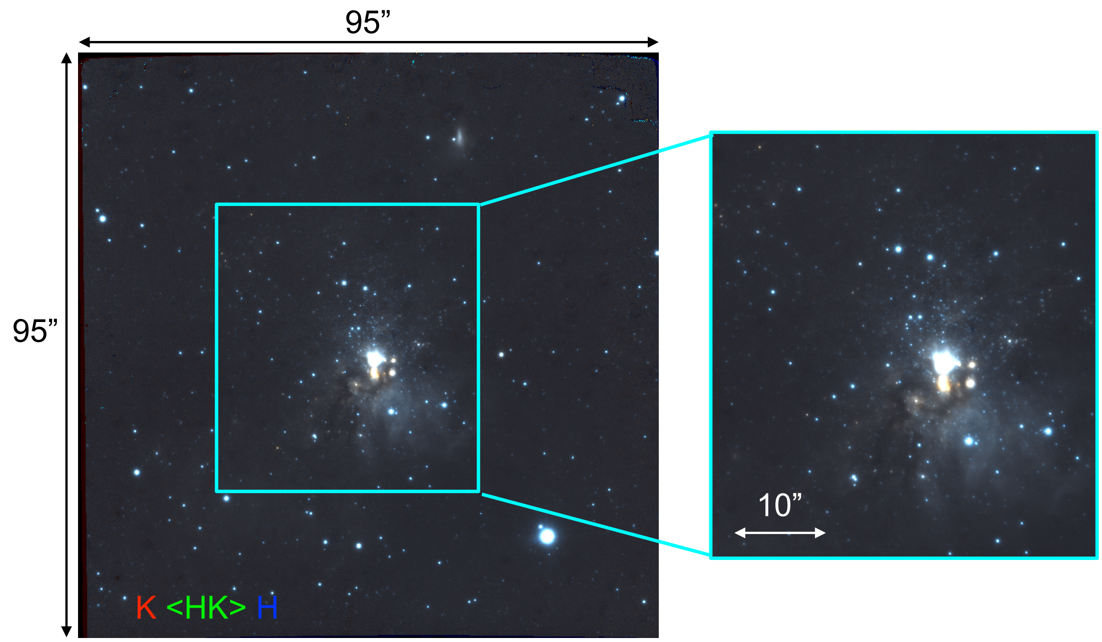

Figure 2. GeMS/GSAOI image of LMC-N79. The image shows a color composite based on two filters: K-band (red channel), H-band (blue channel), average of H and K (green channel). The right panel shows a zoom into the central region highlighting the dusty environment of the embedded star formation. The image was taken at zenith distances of 40-45 deg and shows an FWHM of 120 mas.

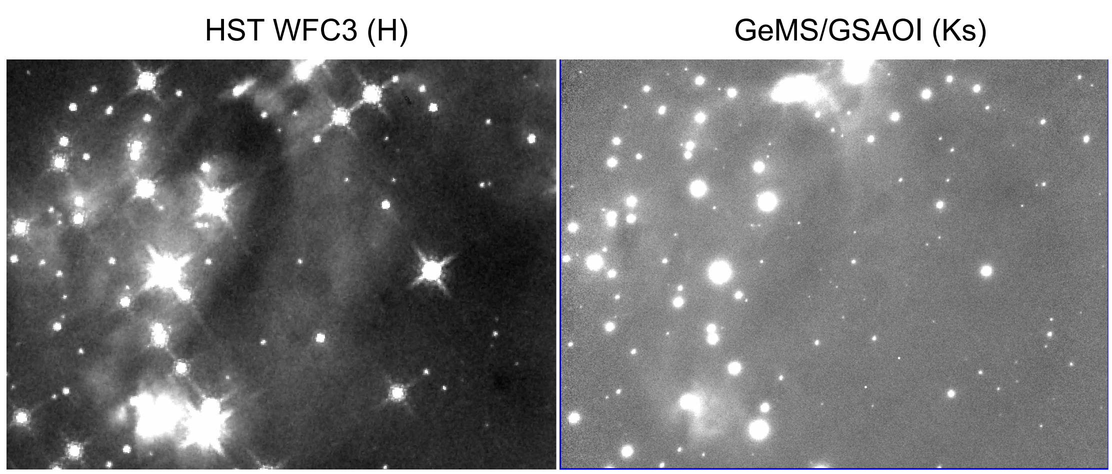

Figure 3. High-angular resolution NIR images of G286.21+0.17. The images show a zoom into a 41 arcsec × 31 arcsec region. Left panel: HST Wide Field Camera 3 image taken in the H-band. The angular resolution is 150 mas. Right panel: GeMS/GSAOI taken in the Ks-band filter. The image shows an FWHM of 100-110 mas.

The primary scientific opportunities with GNAO include a broad range of science cases as well as transient follow-up studies with direct synergy potentials with LSST and JWST (see Blakeslee et al. 2019[14] for more details on the time domain aspects). The science cases are developed by the GNAO science team, a panel of Gemini-internal and external experts on research areas that benefit from AO-asssisted observations. To probe the spectrum of scientific potential of the GNAO facility, the initial science cases were requested without restriction to a specific instrument mode. This has resulted in a broad range of imaging and spectroscopic science covering key topics in extragalactic, Galactic, and solar system research. The science cases are classified as *driving* science cases that are expected to define the GNAO design and return timely science and *enabled* science cases that are expected to take advantage of the GNAO facility. The driving science cases considered for the conceptual design of GNAO are summarized in Table 1.

Table 1. Driving GNAO science cases considered for the conceptual design of the next-generation Gemini-North AO facility.

Research area	Science case
Extragalactic and cosmology	• Survey of $0.7 < z < 2.7$ field galaxies • Nuclear star clusters and disks • Central parsecs around active galactic nuclei • Gravitationally lensed transients
Galactic and nearby extragalactic	• Young massive star clusters • Globular clusters • Galactic center
Brown dwarfs, solar system	• The lowest-mass products of star formation (astrometric orbits and resolved spectra) • Giant planet atmospheres and their disks

The science case study outlines the main scientific parameter space which is used to guide the definition of the top-level scientific requirements for GNAO. While most science cases focus on the $\sim 0.85 - 2.5$ μm spectral region, a few science cases would benefit from observational capabilities up to 5 μm. A few science cases mention added benefit from extended coverage into the optical wavelength region. The required science FOVs cover a wide range. While the majority of science cases profit from a wide AO-compensated field with Strehl ratios around 30-50% in the K-band, a few science cases focus on narrow fields with typically higher Strehl ratio requirements. Accurate astrometric and photometric measurements were identified as a key objective of many of the wide-field imaging science cases. The solar system science cases require a facility that is able to provide non-sidereal tracking. Furthermore, nightly availability and scheduling flexibility were identified as a crucial capability for time domain astronomy.

4. CONCLUSIONS

The science case of embedded massive clusters demonstrates the scientific opportunities offered by ground-based MCAO facilities. Massive cluster studies together with a broad range of key science cases in extragalactic, Galactic, and solar system research areas form the scientific basis for the development of GNAO, the next-generation MCAO facility at the Gemini-North telescope. In addition, the development of a robust queue-operated MCAO system is driven by the synergy potential with the two major upcoming astronomical facilities, the LSST and JWST, especially for time-domain astronomy and transient follow-up. The GNAO project held its conceptual design review in September 2019 and is expected to see first light in October 2024.

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