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Astrometry with MAVIS: Pushing Past the Limits of Gaia to the Crowded Centres of Globular Clusters

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ABSTRACT

High precision astrometry has entered a Golden Age, ushered in by the Gaia mission and surely culminating in the clearest 3D picture of the Milky Way to-date. The Gaia satellite has been revolutionary in many ways and yet, as a relatively small telescope, it is fundamentally limited in its study of both faint and crowded sources. The MCAO Assisted Visible Imager and Spectrograph (MAVIS) is an instrument being designed for the Very Large Telescope Adaptive Optics Facility. Equipped with MAVIS, the VLT will be the only 8m-class telescope, ground-based or otherwise, to operate at its diffraction limit (~ 0.02 arcseconds) in the optical (550 nm). Designed with astrometry in mind, MAVIS must deliver precision astrometry at the 150 micro-arcsecond level, with a goal of 50 micro-arcseconds, the same requirement as the 39 m Extremely Large Telescope. To verify this requirement will be met, we have created the MAVIS Image Simulator (MAVISIM), an image simulating tool to explore MAVIS science cases ranging from stellar to extra-galactic science. MAVISIM accounts for three major errors introduced by adaptive optics, including PSF field variability, along with imager and detector characteristics. In this first test of MAVISIM, we have investigated both the astrometric capabilities of MAVIS and a key science case for the instrument, the presence of intermediate mass black holes (IMBHs) in globular clusters. In this proceedings I will present exciting results from MAVISIM showing that MAVIS will: i) meet its astrometric requirements and ii) be able to detect the kinematic signature of a central 1500 solar mass IMBH in the crowded central region of NGC 3201.

Keywords: Multi-conjugate Adaptive Optics, Globular Clusters, Astrometry, MAVIS, Intermediate Mass Black Holes

1. INTRODUCTION

The Multi-conjugate adaptive optics (MCAO) Assisted Visible Imager and Spectrograph (MAVIS) [33, 34] instrument will usher in a new era of wide field adaptive optics imaging of globular clusters. MAVIS is being designed for the Very Large Telescope Adaptive Optics Facility on Yepun (UT4) [2] and will serve as a workhorse instrument and complement to the Extremely Large Telescope (ELT) MCAO system, MAORY/MORFEO [12, 35] which will operate in the near-infrared (near-IR). Because MAVIS will operate in the visible, from $\sim 370-950$ nm, the spatial resolution deliverable by the system in the V band (~ 18 mas) will be comparable to the diffraction limit of the 39 m ELT in the K-band. Coupling the delivery of near-diffraction-limited light in the visible, with a moderate resolution integral field spectrograph and imager, MAVIS will homogenously deliver detailed spectroscopy and photometry of resolved stellar populations for the first time, ever. This unique parameter space lends itself perfectly to the quintessential MCAO science objects, globular clusters.

Galactic globular clusters (GCs) have long-since acted as the ideal targets for MCAO systems. Beginning with the first MCAO system on-sky, the MCAO Demonstrator (MAD) [15], deep imaging of Galactic GCs formed some of the most exciting scientific results [26, 36] delivered by this groundbreaking instrument. Owing to their proximity ($\sim< 20$ kpc in the case of the majority of Milky Way GCs), brightness (average V band magnitude of ~ 9), projected on-sky size (average projected half-light radius of $63''$) [3, 4, 5] and the accessibility of a large number of bright natural guide stars in the field (cluster members), GCs present a perfect playground for MCAO instruments. The theme of exploring GCs with MCAO instrumentation has continued with the Gemini South MCAO System (GeMS) [32, 28], with numerous papers resolving GCs deep in the Milky Way bulge [38, 39, 37], recovering cluster ages [18, 23, 42] and performing astrometric studies pushing GeMS to its limit [11, 17]. While GeMS has proven to be an excellent instrument for which to explore the astrometric capabilities of MCAO systems, it was never designed with precision astrometry in-mind [27].

Because MAVIS must complement the ELT, the instrument is being designed with high precision astrometry as a core scientific deliverable. The current requirements on the astrometric performance are the following, for high signal-to-noise sources (S/N>200) separated by no more than one arcsecond, MAVIS will provide an astrometric accuracy of 150 μas (with the goal of 50μas). This assumes that at least three astrometric reference sources are present in the field and that the lower order distortion terms can be calibrated out [25]. The requirements are in-line with those of the ELT, where flexibility on the telescope design will aid the MORFEO team in achieving their astrometric deliverables. MAVIS must work with the existing VLT design and compensate for additional distortion terms introduced by the telescope itself [10]. Motivated by the key scientific cases emerging for MAVIS, many of which centre around GCs, we have begun investigating the predicted capabilities of the instrument. Thus far, investigations have centred around the predicted astrometric capabilities of the instrument we which we have modeled through the creation of the MAVIS Image Simulator (`MAVISIM`) [24, 25]. In the future `MAVISIM` will be adapted to investigate both astrometric retrieval techniques to improve precision and to explore photometric science cases. In the following proceedings, we present the scientific motivation behind `MAVISIM`, focusing on resolved stellar populations in GCs and discuss the current implementation of `MAVISIM` as well as future directions.

2. GLOBULAR CLUSTER SCIENCE WITH MAVIS

GCs offer a broad range of motivational science cases, as they act as probes of stellar populations across scales. Beginning on the Galactic scale (∼kpc), GCs offer a chance to probe the accretion history of the Milky Way in the context of Galactic Archaeology [14, 16, 22, 6]. On the cluster scale (tens of parsecs), GCs present a chance to understand the sites of the earliest star formation in the Milky Way (and most likely, the majority of all large galaxies as JWST is now revealing) [8]. Understanding the number and characteristics of surviving GCs relative to GC-like Milky Way field stars (resulting from the disruption of the earliest GCs) is critical to understanding this epoch of early star formation [40, 7]. Finally, at the intra-cluster scale (sub parsecs), testing theoretical predictions of stellar evolution in a coeval population of stars is critical for calibrating models for use across astrophysics. Resolving cluster members photometrically to build colour magnitude diagrams led to some of the earliest lower limits on the age of the Universe through isochrone-fitting [9].

MAVIS will have access to the smallest of these scales (the intra-cluster scale) for the majority of MW GCs, resolving cluster members down to fainter magnitudes and lower masses than the Hubble Space Telescope (HST). Perhaps even more exciting is the opportunity for MAVIS to resolve stars in GCs in external galaxies, like the Fornax dwarf galaxy (at ~ 150 kpc)[19]. To highlight the resolving power of MAVIS and the power of the 8 m VLT, a simulated image of the GC, Fornax 5 (at ~ 150 kpc), produced by MAVISIM (to be discussed in the next section) is presented in Fig. 1. MAVIS will resolve stars into the core of Fornax 5 for the first time, allowing us to study extragalactic GCs as if they were local.

Returning to local GCs (within the MW), MAVIS will provide proper motion measurements of cluster members into the very heart of these dense objects. If the distance to an object is well known, small changes to the position of stars on-sky (measured in milli-arcseconds/year) can be converted to velocities. Measuring the internal kinematics of MW GCs is critical to answer questions as to the formation and evolution of GCs, in particular what giants may lurk deep in their centres. Given the high central density of GCs ($\sim 10^6 - 10^8$ times more dense than Milky Way in the region of the solar neighbourhood [3]), there is the potential for the creation of exotic phenomena in the centre of GCs. One such phenomena may be the creation of an intermediate mass black hole ($\sim 10^3 - 10^5$ $M_\odot$, IMBH) at the centre of GCs.

IMBHs are theorised to form in a number of different ways, including through runaway mergers of stars at early times in GC evolution [13, 31]. Bridging the gap between stellar mass and supermassive black holes, these objects form the missing piece of the puzzle as to the origin of supermassive black holes (found at the centres massive galaxies). As of yet, no undisputed evidence for the existence of an IMBH at the centre of a GC has been found. Dynamically, indirect evidence for an IMBH can be observed as an increase in the velocity dispersion of stars at the centres of GCs. The central velocity dispersion can be measured using proper motions, but these must be made in the most difficult of measurement regimes, even for an AO system. Recently, measurements made by the HSTPROMO collaboration of the GC, M 4, have perhaps come the closest to indirectly detecting evidence of an IMBH through a sharp rise in the GCs central velocity dispersion [46]. However, the uncertainties on the central velocity dispersion, potentially related to HST reaching its crowding limit, were too large to rule out an alternative explaination for the rise in velocity dispersion. While detecting an IMBH at the centre of a GC is only one example of the exciting GC-related science MAVIS will do, it is an excellent science case for which to both justify and verify the astrometric deliverables of the instrument.

3. `MAVISIM`: SIMULATING THE CAPABILITIES OF MAVIS

To simulate the performance of MAVIS before it goes on-sky, we built the MAVIS image simulator (`MAVISIM`). The details of `MAVISIM` are discussed in-depth in the associated reference [25], so we will only provide a broad

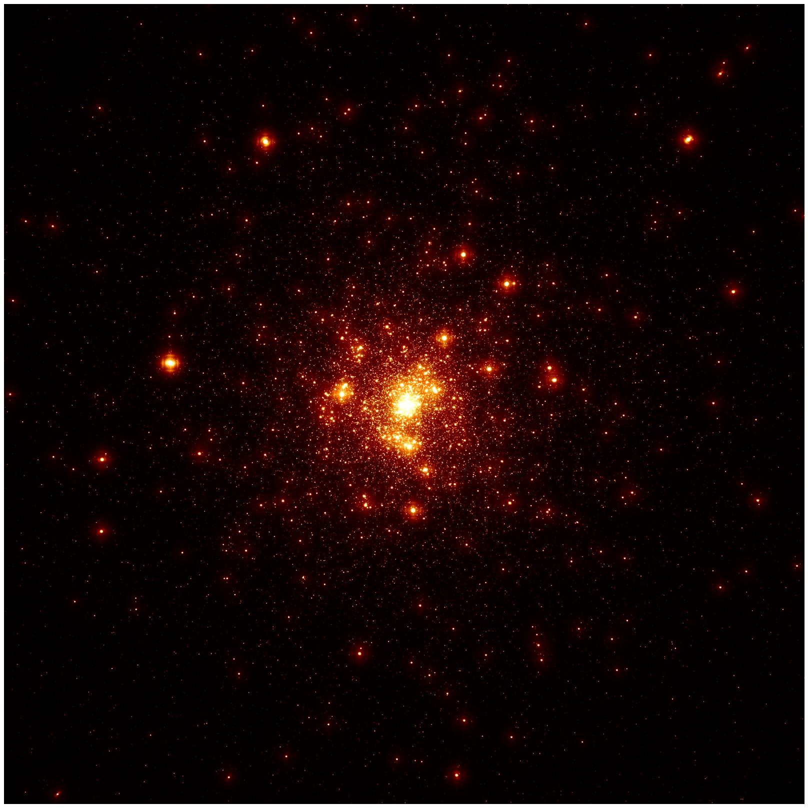

Figure 1. Simulated image of the globular cluster, Fornax 5, found in the Fornax dwarf galaxy at a distance of ~ 150 kpc [19]. The image was created using `MAVISIM` and model for the cluster projected to the correct distance [3]. Note that even the most central stars will be resolvable with MAVIS, facilitating the study of the internal properties of extragalactic GCs.

overview of its capabilities here. `MAVISIM` was designed initially to capture as many sources of astrometric error as possible with the intent of testing real science cases from the resulting images. One source of astrometric error is a spatially variable point spread function (PSF), which `MAVISIM` has built in. It is the first MCAO simulating software to do so. A diagram highlighting the major components of the first version of `MAVISIM` is shown in Fig 2. Moving from left to right, `MAVISIM` 1.0 captures information about the MAVIS AO system within a Fourier approximation of the system PSF [1]. This information is then combined with an error kernel which captured the static distortion from the instrument optics, an estimate of the effect of vibration and charge diffusion and a tip-tilt kernel capturing the spatially-dependent effects of the choice of natural guide stars configuration. Finally, additional instrumental detector characteristics, noise and telescope throughput are applied before generating a simulated monochromatic image at 550 nm.

3.1 Recovering an intermediate mass black hole at the heart of the globular cluster NGC 3201

The first science case which was explored using `MAVISIM` was one of the key science cases presented in the MAVIS Phase A Science Case [20], the recovery of the signature of an IMBH at the heart of a GC. To test this science case, we utilised an N-body catalogue of the Galactic GC NGC 3201, simulated with a 1500 $M_{\odot}$ IMBH at its centre [3]. The GC was simulated at two epochs, time zero and ten years later. In this way the proper motion of the stars could be recovered using PSF-fitting astrometry for optimal extraction (this is discussed more in the next section). We used `DAOPhot`[43, 44] to perform PSF-fitting astrometry and to extract the positions of the stars across the two epochs. The results of the experiment were twofold. The first result was demonstration that, under most-likely idealised conditions (given that we have not accounted for all of the sources of error in the MAVIS system), MAVIS could achieve a velocity precision of ~ 0.20 km/s in the inner $\sim 4''$ of the GC. The

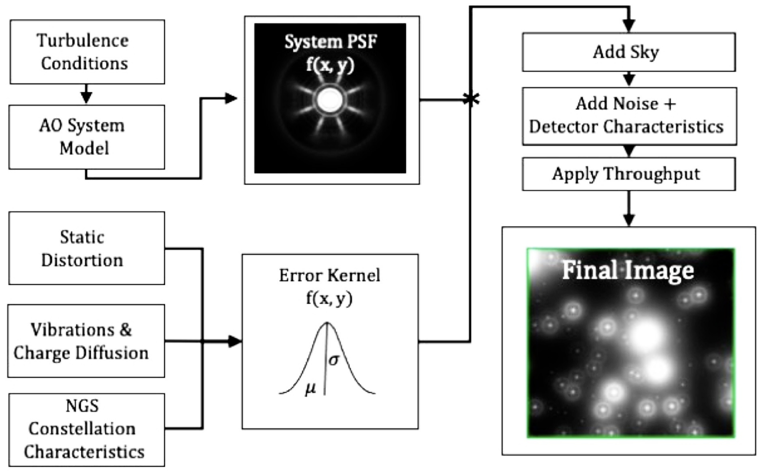

Figure 2. Schematic of the `MAVISIM` 1.0 software and image simulating tool. Details of the various components and relevant reference are given in the text of Sec. 3.

second result was that MAVIS could recover the dynamical signature of an IMBH in a GC centre in the region where HST is crowding-limited. This second result is highlighted in Fig. 3[25].

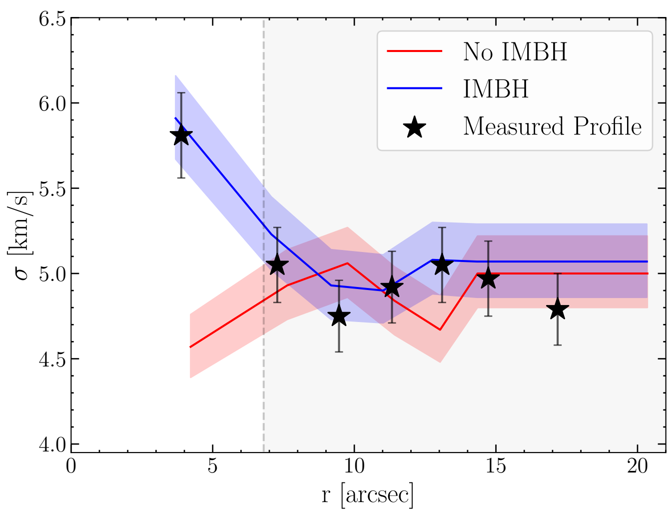

Figure 3. Image taken from Monty et. al 2021 [25] showing the recovery of the dynamical signature of a 1500 $M_\odot$ IMBH at the centre of the GC, NGC 3201. Extraction of proper motions simulated over a ten year epoch using `MAVISIM` revealed that MAVIS could measure motions with ~ 0.20 km/s precision in the inner $\sim 4''$ of a GC.

4. NEXT GENERATION `MAVISIM`

In the next iteration of `MAVISIM` we would like to explore science cases centred around the recovery of high quality photometry. This will require upgrading `MAVISIM` to simulate polychromatic images capturing information across multiple wavelengths. An example science case motivating this upgrade is simulating the recovery of multiple stellar populations (MSPs) in GCs. Once assumed to be composed of single, mono-age populations, almost all MW GCs have now been found to host multiple stellar populations, potentially born at different times. The HST has been incredibly successful at surveying MW GCs to assess the prevalence of MSPs, largely due to its spatial resolution and the impressive quality of the photometry extracted from the images [30, 21]. Extraction of high quality photometry is also a goal of MAVIS, one which will require careful modeling of the instrumental PSF. While the HST PSF benefits from relative temporal stability (when compared to ground-based instruments), MAVIS will not. As such, we are exploring the potential to extract information and/or reconstruct the PSF associated with a specific dataset to aid in photometric extraction. The current lines of investigation are discussed in the next section.

4.1 Improved astrometric recovery using PSF reconstruction techniques

Thus far, `DAOPhot` has proven to be the most popular means of extracting photometry from MCAO images, with many examples published using GeMS data [45, 18, 17, 38, 39, 37, 23]. This is largely due to the success of `DAOPhot` in accurately modeling and capturing the spatial variability of MCAO PSFs. However, `DAOPhot` is limited in that it must create a model of the PSF from the image itself using a selection of isolated, bright reference stars. Other more modern tools, like `StarFinder2`[41] and `SuperStar` (Marasco et al. in prep), are able to both model the PSF sources in the image (like `DAOPhot`) and accept an estimate of the PSF created externally. This second option allows for the PSF to be estimated using PSF reconstruction techniques. Using simulated telemetry data, we are currently investigating the extraction of photometry from monochromatic `MAVISIM` images using the PSF reconstruction software, `TIPTOP` [29].

5. CONCLUSIONS

MAVIS will open up new lines of research into the origin and evolution of ancient globular clusters (GCs). It will do this by delivering homogeneous photometry and spectroscopy into the very heart of these dense objects, for the first time. Resolving the centre of these objects will allow us to probe for the existence of the long elusive intermediate mass black holes (IMBHs) through the recovery of high precision astrometry. To explore the capabilities of MAVIS before it goes on-sky, we created the MAVIS Image Simulator, `MAVISIM`. The first version of `MAVISIM` was used to demonstrate that MAVIS could recover the dynamical signature of a 1500 $M_\odot$ IMBH in the heart of the MW GC, NGC 3201 [25]. The next test for `MAVISIM` will be demonstrating the ability to extract high precision photometry from polychromatic MAVIS images. To do this, we are currently building `MAVISIM` 2.0 to simulate multi-band images of GCs. One science driver for this, is the recovery of MSPs in GCs. Concurrently, we are investigating the use of PSF reconstruction techniques (`TIPTOP`[27]) and new photometric tools like `SuperStar` (Marasco et al. in prep) to improve our PSF-fitting photometry. Preparing for the arrival of MAVIS using `MAVISIM` will ensure that we have a strong understanding of the optimal performance of the system, allow us to investigate as many sources of error as possible, and allow us to supply the scientific community with the tools they need to extract the best possible science from MAVIS.

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