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MIKiS: the ESO-VLT Multi-Instrument Kinematic Survey of Galactic Globular Clusters

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Globular clusters are collisional systems, where stars of different masses orbit and mutually interact. They are the best "natural laboratories" in the Universe for studying multi-body dynamics and their (reciprocal) effects on stellar evolution. Although these objects have been studied since the very beginning of modern astrophysics, little is known observationally about their internal kinematics, thus preventing a complete understanding of their dynamical state, and of their formation and evolutionary history. We present the first results from the Very Large Telescope (VLT) Multi-Instrument Kinematic Survey of Galactic globular clusters (MIKiS), which is specifically designed to provide line-of-sight velocities of hundreds of individual stars over the entire radial extension of a selected sample of clusters. The survey allows the first kinematical exploration of the innermost regions of high-density globular clusters. When combined with proper motion measurements, it will provide the full 3D view in velocity-space for each system. Long-running open issues, such as the accurate shapes of the velocity dispersion profiles, the existence of systemic rotation and orbital anisotropy (and thus the level of relaxation), and the controversial presence of intermediate-mass black holes in star clusters can finally be addressed, impacting our understanding of the formation and evolutionary processes of globular clusters and their interactions with the Galactic tidal field.

Galactic Globular Clusters are gas-free stellar systems, made up of a few times 10^5 stars of different masses (typically from ~ 0.1 to 0.8 $M_\odot$). They are the most populous, and the oldest stellar systems in which stars can be individually observed. Moreover they are the sole cosmic structures that, within the timescale of the age of the Universe, undergo nearly all of the physical processes known in stellar dynamics. Galactic globular clusters are true touchstones for astrophysics. The study of their stellar populations is crucial to validating predictions from stellar evolution theory, and they are invaluable laboratories for multi-body dynamics. Surprisingly, while remarkable progress has been made in the study of Galactic globular cluster stellar populations (see Carretta et al., 2009 and Piotto et al., 2015), the kinematical characterisation of these systems is just in its infancy and the modelling often relies on a set of over-simplified assumptions.

In general, globular clusters are assumed to be quasi-relaxed, non-rotating stellar systems, characterised by spherical symmetry and orbital isotropy, with structural and kinematical properties (surface brightness and velocity dispersion profiles) that are well captured by a truncated Maxwellian distribution function (for example, King, 1966). However, growing observational evidence demonstrates that although this scenario is correct to a first approximation, it is largely oversimplified. Indeed, there is accumulating evidence of significant deviations from sphericity (Chen & Chen, 2010), and from a King density profile, a profile used to fit the observed distribution of stars within a globular cluster as a function of their distance from the centre (see Carballo-Bello et al., 2012; Lane et al., 2010). Signatures of systemic rotation and pressure anisotropy have been detected in several clusters (for example, Watkins et al., 2015; Kamann et al., 2018; and references therein).

Thus, despite its importance, our empirical knowledge of globular cluster internal kinematics from the very centre (where the most interesting dynamical phenomena occur) to the tidal radius (where the effects of the Galactic tidal field are visible) is still critically inadequate. In particular, a detailed knowledge of the velocity dispersion profile and the (possible) rotation curve is still missing in the majority of the cases. This is essentially due to observational difficulties.

In principle, velocity dispersion and rotation can be obtained from different approaches. In practice, however, the standard methodology commonly used in extra-galactic astronomy (i.e., measuring radial velocities from Doppler shifts and velocity dispersions from the line broadening of integrated-light spectra) can suffer from severe shot-noise bias in Milky Way globular clusters, because the acquired spectrum can be dominated by the contribution of just a few bright stars (for example, Dubath et al., 1997). In the case of resolved stellar populations, a safer approach is to determine velocity dispersion and rotation from the velocities of individual stars. By combining the line-of-sight information (measured through resolved spectroscopy) with the two velocity components on the plane of sky (from internal proper motions), a full 3D view of the velocity space of the system can be obtained. This begins to be feasible in Galactic globular clusters.

Internal proper motions require high-precision photometry and astrometry on relatively long time baselines. These are finally achievable thanks to multi-epoch HST and Gaia observations. The former are providing the necessary information on the centres of Galactic globular clusters (even if the innermost regions of the densest systems might still be missed; for example, see Bellini et al., 2014 and Watkins et al., 2015 for recent results). In the meantime, Gaia is providing the complementary measures in the outskirts. The line-of-sight kinematical information over the entire radial extension of Galactic globular clusters is still largely missing, because it requires the collection of large samples of individual stellar spectra, both in highly crowded regions — the central density of the Milky Way globular clusters can reach up to $7 \times 10^5\ L_\odot$ parsec^{-3} (see

Harris, 1996 and 2010) — and over large sky areas (from 20–40-arcminute diameter and even more). This is conceptually easy but operationally challenging and requires a lot of telescope time. To fill this gap in globular cluster studies and overcome these difficulties, we recently conducted a spectroscopic campaign based on a synergic use of three different VLT facilities.

The survey

The Multi-Instrument Kinematic Survey of Galactic globular clusters (hereafter the MIKiS survey; Ferraro et al., 2018) has been specifically designed to provide the velocity dispersion and rotation profiles of a representative sample of Milky Way globular clusters over their entire radial extension. With this aim, it takes advantage of the specific characteristics of three different instruments installed at the VLT, allowing multi-object spectroscopy with the appropriate angular resolution, depending on the radial region surveyed. The survey is based on two ESO Large Programmes (193.D-0232 using the *K*-band Multi-Object Spectrograph [KMOS] and the Fibre Large Array Multi Element Spectrograph [FLAMES], and 197.D-0750 using SINFONI; Principal Investigator Francesco Ferraro) and has been designed with the core scheme described below.

1. Diffraction-limited integral-field spectroscopy with adaptive-optics-assisted SINFONI
These observations are used to resolve stars in the innermost few arcseconds of the highest-density clusters. We adopted the SINFONI *K*-band grating to achieve high Strehl ratios. To symmetrically sample the spatial distribution of stars (which is necessary to properly construct the rotation curve) we planned a mosaic of between 4 and 9 pointings in the 125-millarcsecond mode (125 × 250 milliarcseconds/pixel, 8 × 8 arcseconds field of view). In the densest clusters, an additional central pointing was also planned in the 50-milliarcsecond mode (50 × 100 milliarcseconds/pixel, 3 × 3 arcseconds field of view). With the selected setup (*K* grating, $R = 4000$), radial velocities can be properly measured from molecular CO bandheads in the coolest giants ($T_{eff} < 5000$ K) and from some atomic lines in the warmer stars. Note that, in the MIKiS approach, integral-field spectroscopy is used in a non-conventional way; instead of using integrated-light spectra at various distances from the cluster centre, we extract the spectrum of each distinguishable individual star from the most exposed spatial pixel (spaxel) corresponding to the star centroid in the data cube. Typically several dozens of giants have been observed down to $K \sim 15$ in each cluster with the planned mosaics (see Figure 1).

2. Seeing-limited observations with the multi-integral-field spectrograph KMOS
These observations have been performed for an optimal coverage of the intermediate radial range (a scale of tens of arcseconds). KMOS is a spectrograph equipped with 24 deployable integral-field units (IFUs) that can be allocated within a 7.2-arcminute diameter field of view. Each IFU covers a projected area on the sky of about 2.8 × 2.8 arcseconds, sampled by an array of 14 × 14 spaxels with an angular size of 0.2 arcseconds each. We have used the *YJ* grating covering the 1.00–1.35 μm spectral range at a resolution $R = 3400$. This instrument setup is especially effective at simultaneously measuring a number of reference telluric lines in the spectra of giant stars for an accurate calibration of the radial velocity, despite the relatively low spectral resolution. Typically, 7–8 pointings have been secured in each cluster. We selected red giant targets with $J < 14$, with no stars brighter than $J = 15$ within 1 arcsecond from their centre. In order to minimise the effects of possible residual contamination from nearby stars and/or from the unresolved stellar background, the 1D spectra were extracted manually by visually inspecting each IFU and selecting the brightest spaxel corresponding to each target star's centroid. Normally, one star was measured in each IFU though in a few cases two or more resolved stars were clearly distinguishable in a single KMOS IFU (see Figure 2), and their spectra were extracted.

3. Wide-field multi-object spectroscopy with FLAMES. This has been exploited to sample the external cluster regions, i.e., out to several arcminutes. We used FLAMES in the combined GIRAFFE-MEDUSA mode, which consists of 132

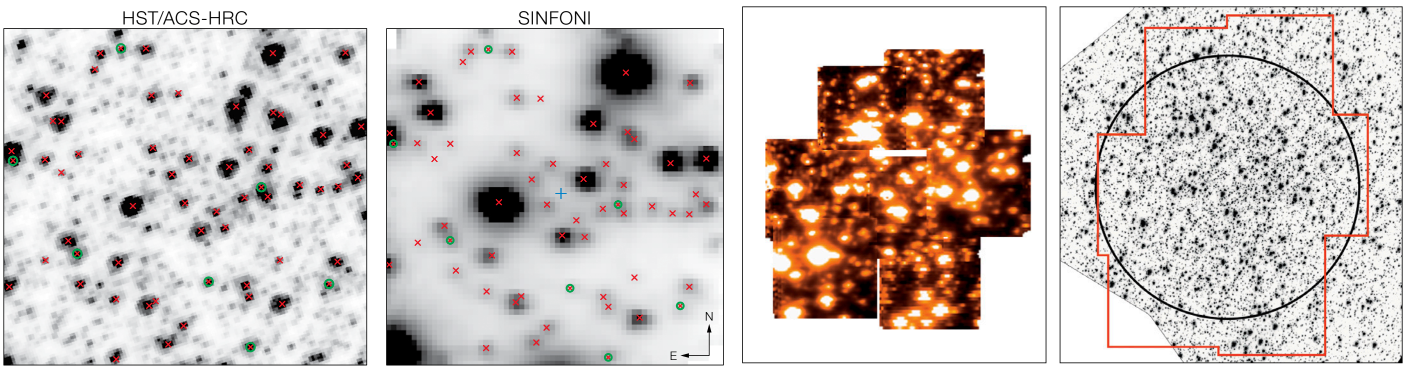


Figure 1. Left panels: Comparison between a reconstructed SINFONI image and an HST/ACS-HR C image of the innermost 3 × 3 arcseconds of NGC 6388. Each SINFONI spaxel provides a spectrum. The red crosses correspond to the stellar centroids identified from the HST image; 52 individual RVs have been measured within 1.5 arcseconds from the cluster centre. Right panels: The same in the case of NGC 2808, where 700 individual spectra of resolved stars were extracted within 10 arcseconds from the centre.

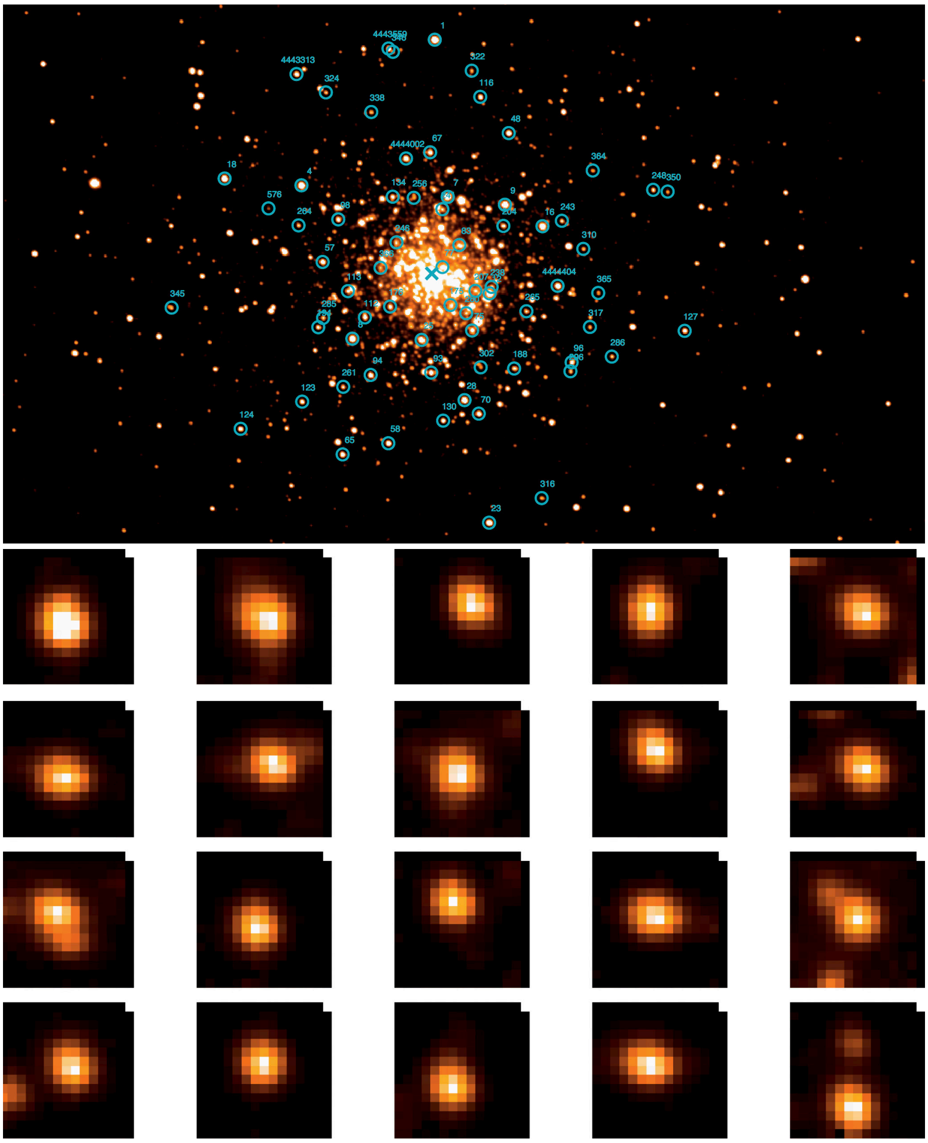


Figure 2. The map in the upper panel shows the location of the targets observed with KMOS in NGC 6388. Lower panel: reconstructed images for 20 IFUs in a typical pointing.

deployable fibres that can be allocated within a 25-arcminute diameter field of view. The adopted HR 21 grating setup, with a resolving power R = 16 200 and spectral coverage from 8484 to 9001 Å, samples the prominent Ca II triplet lines, which are excellent features from which to measure radial velocities. The selected targets are essentially red giant branch stars brighter than I = 18.5. In order to avoid spurious contamination from other sources within the fibres, only isolated stars with no bright neighbours within 2 arcseconds from each target were selected. On average, 3–4 pointings were performed in each cluster.

This approach was first tested, as a proof of concept, on the Galactic globular clusters NGC 6388 (Lanzoni et al., 2013, Lapenna et al., 2015) and NGC 2808 (see Figures 1 and 2). Then, for the MIKiS survey we selected 30 massive globular clusters across the entire Galaxy (Figure 3), sampling both the bulge/disc stellar populations close to the Galactic plane (at z < 1.5 kpc) and the halo ones (at 1.5 < z < 13 kpc).

The targets properly map the parameter space most sensitive to the internal dynamical evolution of the cluster, covering a wide range of central densities and concentration parameters[a] (2.5 < c < 0.5), and sampling all the stages of dynamical evolution, including both pre- and post-core-collapse globular clusters (with a core relaxation time spanning almost 3 orders of magnitude). For a reliable determination of the line-of-sight velocity dispersion profile the selected globular clusters are also populous enough (i.e., more luminous than M_V = −6.5) to provide large samples of giant/sub-giant stars. To measure stars along a relevant portion

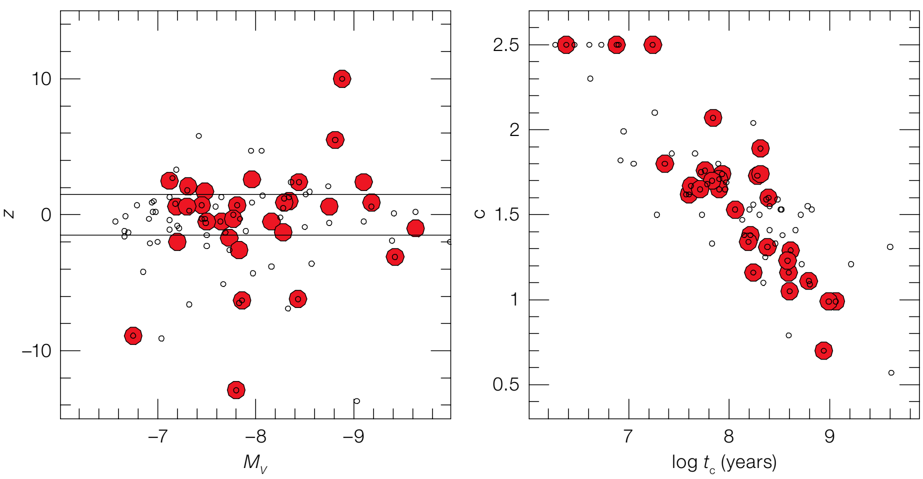


Figure 3. Distribution of the targets selected for the MIKiS survey (large circles) showing the height on the Galactic plane z vs. absolute integrated V-band magnitude M_V (left) and the King concentration parameter c vs. core relaxation time t_c (right). The total Galactic globular cluster population is also plotted for reference (small dots).

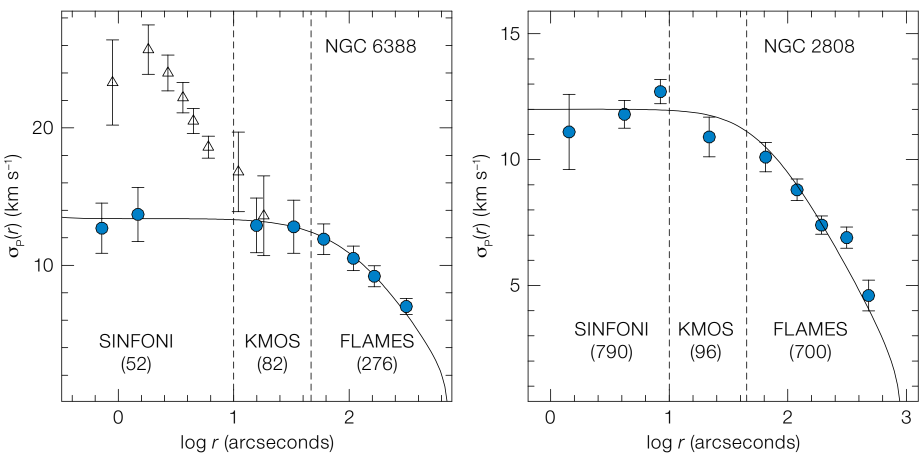


Figure 4. Velocity dispersion profiles of NGC 6388 and NGC 2808 obtained from the radial velocities of individual stars (blue circles) measured following our multi-instrument approach: SINFONI+KMOS+-FLAMES. The number of individual spectra measured with each instrument is labelled. The empty triangles in the left-hand panel show the velocity dispersion profile obtained from integrated-light spectroscopy (Lutzgendorf et al., 2011), which is probably affected by shot-noise bias.

of the red giant branch with good signal-to-noise in reasonable exposure times, the horizontal branch level is always brighter than I = 16.5 (i.e., all the targets are located at distances < 16 kpc). Moreover, we included only globular clusters with [Fe/H] > –1.8, showing metallic lines deep enough to guarantee a few km s^{-1} accuracy in the radial velocities measurements obtained from low-resolution spectra.

As a first step, the MIKiS survey is expected to provide the full characterisation of the line-of-sight internal kinematics of each target cluster, from the innermost to the outermost regions. Once combined with measurements of proper motion, the global project will provide the full 3D view of the velocity space of each system, obtained from hundreds individual stars, with crucial impact on many hot topics of globular cluster science. In particular, the MIKiS survey will provide:

1. The very first sub-arcsecond kinematic exploration of Galactic globular cluster cores, thus allowing a systematic search for signatures of systemic rotation and intermediate-mass (10^3–10^4 $M_\odot$) black holes, providing crucial new insights into the physics and formation processes of both globular clusters and these elusive dark compact objects.
2. The determination of the mass distribution and the global amount of mass in dark remnants (white dwarfs, neutron stars, stellar mass black holes), since the kinematic profiles are sensitive to the whole mass enclosed within stellar orbits. The simultaneous knowledge of the visible matter density distribution and the kinematic profiles can provide reliable estimates of the stellar densities, mass-to-light ratios, and total cluster masses.
3. The exploration of the kinematics in the proximity of the cluster tidal radius, which has major implications for the understanding of the physical origin of recently claimed “extra-tidal structures”, the interplay with the external tidal field, as well as the possible presence of small dark matter halos or modifications to the theory of gravity.
4. A detailed characterisation of the kinematics of multiple populations with different light-element content, to provide crucial constraints to globular cluster formation scenarios.

MIKiS first results

The results obtained so far clearly demonstrate the revolutionary potential of the approach adopted in the MIKiS survey to study the kinematics of collisional systems. In this section, we give an overview of the first set of results. We find that the AO-corrected SINFONI observations attained an angular resolution comparable with that of the HST, thus allowing us to extract individual spectra for 700 resolved stars within 10 arcseconds from the centre of NGC 2808 (see Figure 1), and even 52 individual star spectra within the central 2 arcseconds of the high-density cluster NGC 6388 (see Lanzoni et al., 2013). This is indeed an unprecedented achievement; for the very first time, the radial velocities of hundreds of individual stars have been measured in the innermost core regions of high-density systems, thus finally opening up the possibility of properly exploring the kinematics of Galactic globular clusters at sub-arcsecond scales (see Figures 1 and 4). For comparison, note that no proper motions have been determined in the innermost 10 arcseconds of these dense globular clusters. For example, in the case of NGC 6388, proper motions have been measured at only r > 20 arcseconds (Watkins et al., 2015).

Figure 5 summarises the results obtained from the analysis of 6275 stars sampling the entire radial extension of 11 Galactic globular clusters (Ferraro et al., 2018). This dataset allowed us to accurately determine the systemic velocity and velocity dispersion profile of each system, as well as to investigate the presence of ordered motions. It also provides the first kinematical information for two poorly investigated clusters: NGC 1261 and NGC 6496. In the majority of the surveyed systems we find evidence of rotation within a few half-mass radii from the centre. These results are in overall agreement with the predictions of recent theoretical studies, suggesting that the detected signals could be the relics of significant internal rotation that was set at the epoch of the cluster’s formation. This evidence, combined with other recent results in the literature (see for example, Kamann et al., 2018), suggests that the vast majority of Galactic globular clusters (if not all of them) display some level of internal rotation. This might be the remnant signal of a much larger amount of ordered motion imprinted at birth (at the end of the initial violent relaxation phase) which gradually dissipated via two-body relaxation (see Tiongco et al., 2017).

Figure 6 shows the unprecedented rotation curve derived for M5 (Lanzoni et al., 2018a). The velocity dispersion profile and the rotation curve in this cluster were

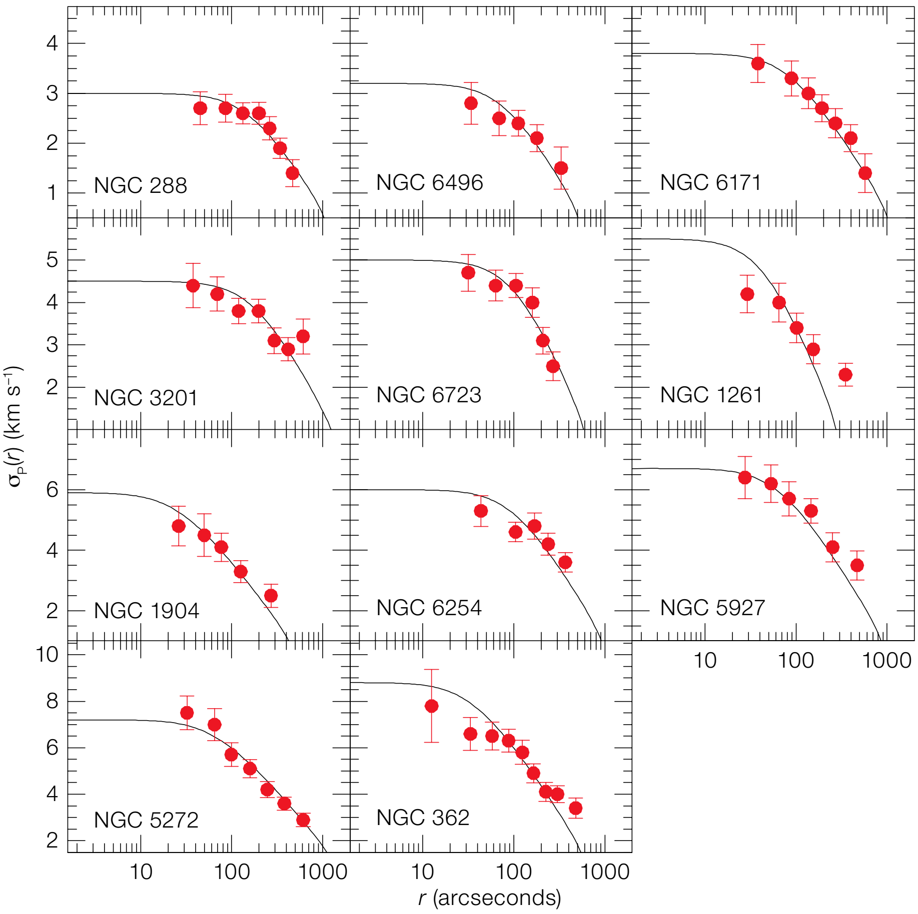


Figure 5. Projected velocity dispersion profiles for 11 Galactic globular clusters observed in the MIKiS survey (red filled circles). The solid lines correspond to the projected velocity dispersion profiles of the King models that best fit the observed density/surface brightness distributions (from Ferraro et al., 2018).

determined from the radial velocity of more than 800 individual stars observed out to 700 arcseconds (~ 5 half-mass radii) from the centre. The rotation curve obtained is the cleanest and most coherent pattern ever observed in a globular cluster. The rotation axis has been measured in distinct concentric annuli at different distances from the cluster centre and it turns out to be strikingly stable (having a constant position angle of 145 degrees with respect to the north-south direction at all surveyed radii). The well-defined shape of the rotation curve is fully consistent with cylindrical rotation. The star density distribution shows a clear flattening in the direction perpendicular to the rotation axis, with the ellipticity (*e*) increasing with increasing distance from the cluster centre, reaching a maximum of $e \sim 0.14$ at $r > 80$ arcseconds. The peak of the projected rotation velocity curve (~ 3 km s^{-1}) has been found at ~ 0.6 half-mass radii, and its ratio with respect to the central velocity dispersion is $V_{peak}/\sigma_0 \sim 0.4$. All of these results suggest that M5 is an oblate rotator that is seen almost edge on.

Figure 7 shows the results obtained in another intriguing cluster: NGC 5986 (Lanzoni et al., 2018b). The velocity dispersion profile (left panel) indicates a significant deviation from the King model in the outer region ($r > 100$ arcseconds) of the system. The clear-cut evidence of systemic rotation is even more impressive. Indeed, the observed rotation curve (right panel of Figure 7) is one of the best examples of solid-body rotation ever found in a globular cluster. This is the first time that these two kinematic features have been jointly observed in a Galactic star cluster, and such co-existence makes the case of NGC 5986 particularly intriguing. In fact, these features may result from the evolutionary interplay between the internal angular momentum of the system and the effect of the tidal field of the host galaxy (Tiongco et al., 2016, 2017). Such a discovery is particularly timely, in light of the growing interest

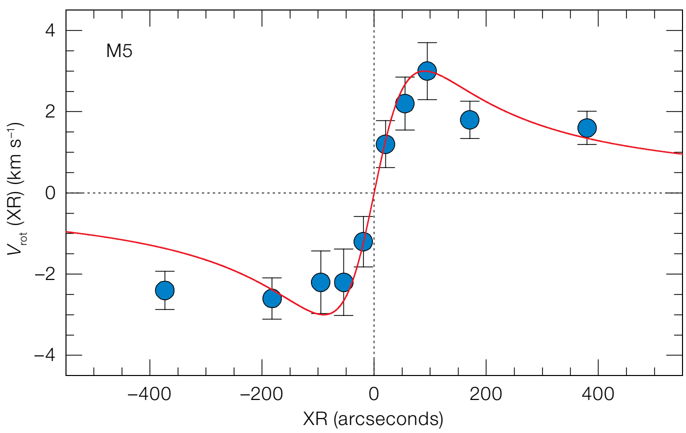
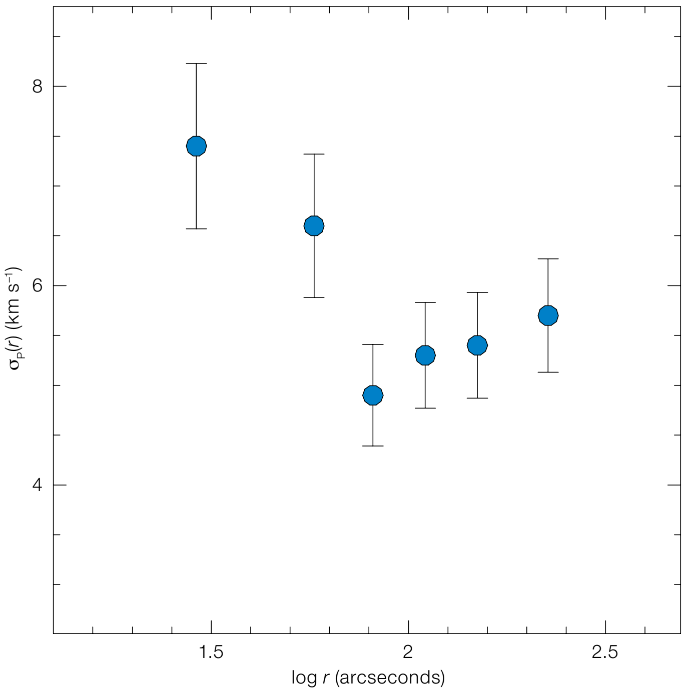


Figure 6. The unprecedented rotation curve obtained for M5 (Lanzoni et al., 2018a). The blue circles mark the mean stellar velocity as a function of the projected distance on either sides of the rotation axis (XR). The red line represents the cylindrical rotation curve, which well reproduces the observed profile.

in the physical interpretation of the structure and kinematics of the peripheries of globular clusters and their possible role as new tools for near-field cosmology.

The first results of the MIKiS survey have highlighted the importance of an appropriate search for rotation signals over the entire cluster extension. In fact, the ubiquity of detections of even modest signatures of rotation in globular clusters indicates that most of these systems were born with significant amounts of ordered motion, thus providing significant constraints on globular cluster formation models. On the other hand, the detection of intriguing features, such as those observed in NGC 5986, sheds new light



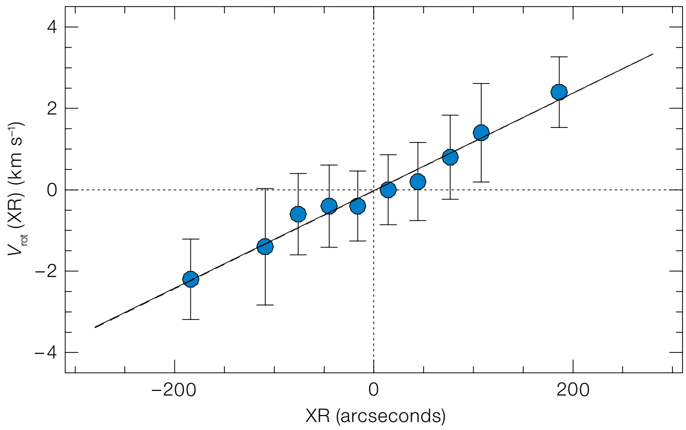


Figure 7. Left panel: Velocity dispersion profile of NGC 5986, showing a clear increasing trend in the outskirts. Right panel: Rotation curve of NGC 5986. The blue circles mark the mean stellar velocity as a function of the projected distance on either side of the rotation axis (XR). The solid line is the best least-squares fit to the observed points (from Lanzoni et al., 2018b).

on the complex interplay between globular cluster internal evolution and the tidal field of the Galaxy.

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Notes

[a] The shape of the profile is fixed by the concentration parameter c, defined as $c = \log(r_t/r_c)$, where r_c is the core radius of the model (roughly corresponding to the cluster-centric distance at which the projected density of stars drops to half of its central value), and r_t is the tidal radius (at which the stellar density becomes zero).

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A drone's eye view of the VLT.