A Study of the Activity of G and K Giants Through Their Precise Radial Velocity; Breaking the 10-m/sec Accuracy with FEROS

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1. Scientific Background

Asteroseismology is an indispensable tool that uses the properties of stellar oscillations to probe the internal structure of stars. This can provide a direct test of stellar structure and evolution theory. Precise stellar radial velocity (RV) measurements made in recent years have not only discovered the first extra-solar planets, but have also uncovered new classes of low-amplitude variable stars. One such is represented by the K giant stars which exhibit RV variations with amplitudes in the range of 50–300 m/s (Walker et al. 1989, Hatzes & Cochran 1993,1994 ab). This variability is multi-periodic and occurring on two time- scales: less than 10 days and several hundreds of days.

In the most detailed study of a K giant star, Merline (1996) found 10 pulsation modes with periods ranging from 2–10 days in Arcturus. These modes were equally spaced in frequency, the characteristic signature of p-mode oscillations analogous to the solar 5-minute oscillations. The relatively large number of modes that may exist in giant stars means that these objects may be amenable to asteroseismic techniques. Asteroseismology is one of the next milestones in astrophysics, and presently there are relatively few classes of stars on which these techniques can be applied, so it is important when more such objects are discovered.

Asteroseismology can be used to derive such fundamental stellar parameters as mass and radius. This is particularly useful for giant stars as these occupy a region of the H–R diagram where it is difficult to obtain accurate stellar parameters. Furthermore, the evolutionary tracks of main-sequence stars in the spectral range A-G, all converge on the giant branch, so it is impossible to establish the nature of the progenitor star only from these theoretical tracks. Asteroseismology may play a key role in understanding the stellar properties, structure, and evolution of giant stars and their progenitors. In particular, when combining accurate distances (e.g. from HIPPARCOS), the spectroscopic determination of the chemical composition and gravity along with the oscillation spectrum, the stellar evolutionary models will be required to fit all these observations. This could provide an unprecedented test bench for the theories of the stellar evolution. Before this can be done, however, one must derive the full oscillation spectrum (periods and amplitudes) for a significant number of giant stars.

Although the short-period variations in giants can only arise from radial and non-radial pulsation, the nature of the long-period RV variations is still open to debate. Possibilities include planetary companions, rotational modulation by surface structure, or non-radial pulsation. Each of these hypotheses has a high astrophysical impact, and there are strong arguments to support each of them.

When surface structures, such as active regions and spots, move on the visible stellar surface (as a result of stellar rotation), they will also induce variability in the core of deep lines, as the Ca II H and K, which are formed in the chromosphere (see e.g. Pasquini et al. 1988, Pasquini 1992). Since FEROS allows the simultaneous recording of the most relevant chromospheric lines, it will be possible to test directly from our spectra the rotational modulation hypothesis. In Figure 1, CaII K line spectra of one target star taken at different epochs are over-imposed: no evidence for strong variability in the line core is detected.

The expected rotational periods for some giants are consistent with the observed periods and some evidence for equivalent-width variations of activity indicators accompanying the RV variations have been found in two K giants (Larson et al. 1993; Lambert 1987). If the RV variations were caused by surface inhomogeneities, then these would be large enough to be resolved by future ground-based interferometry. These stars will thus make excellent

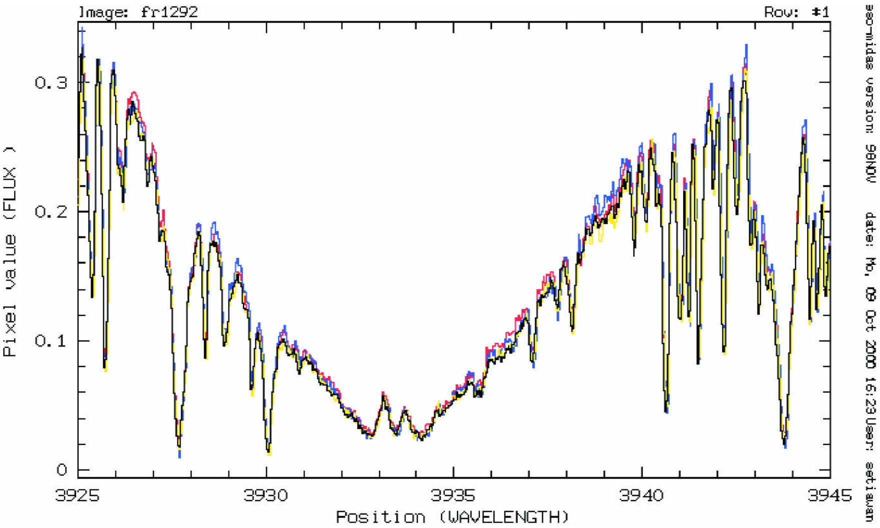

Figure 1: Ca II K line observations of one of the target stars. Observations taken in different nights are overlapped. In case of rotational modulation induced by surface inhomogeneities, the chromospheric core of this line will show detectable variations.

targets for VLTI observations (von der Lühe et al. 1996).

The non-radial g-mode oscillations seem unlikely, since these are not expected to propagate through the deep outer convection zone in these stars, but nature is always full of surprises. Alternatively, these long-period variations may represent more exotic pulsations such as toroidal modes. The planet hypothesis is supported by these periods being long lived (for more than 12 years) and coherent. In the case of the star Aldebaran, the long-period RV variations were not accompanied by line-profile variations (Hatzes & Cochran 1998). Although these seem to exclude rotations and pulsations, conclusive evidence in support of the planetary hypothesis has proved elusive.

2. Observations

K giant RV variability is still a largely unexplored area. Not only is the nature of the long-period variations unknown, but a knowledge of the characteristics of the short-period (p-mode) oscillations as a function of a giant's position in the H–R diagram is also lacking.

For these reasons, in ESO Period 64 (October 1999 – April 2000), we started an unprecedented survey of precise radial-velocity measurements as a Euro-pean-Brazilian collaboration aimed at obtaining a sample of about 100 G-K giants and subgiants along the whole upper part of the HR-diagram (see Fig. 2). We opted for using the FEROS spectrograph (Kaufer et al. 1999), at the 1.52-m telescope, because:

(1) its large spectral coverage allowed the observer to record simultaneously fundamental lines like the H and K of CaII, suitable for investigating rotationally induced modulations (cf. Section 1);

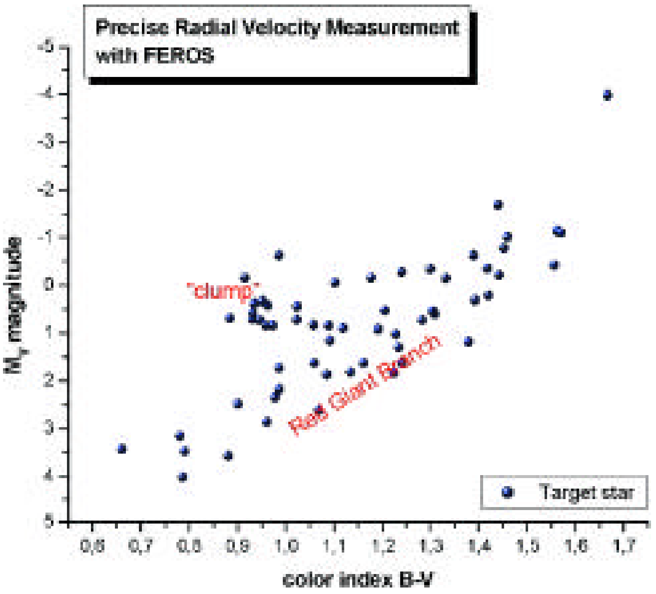

Figure 2: H-R diagram for the 63 stars observed so far for our precise radial velocity survey with FEROS. The sample well covers the Red Giant Branch and the "clump" region.

(2) its high efficiency permitted the acquisition of data on a large sample of stars in one night, and finally,

(3) the radial velocity accuracy of 23 m/s, which was shown during the commissioning period (Kaufer et al. 1999) was at a level adequate for the study of giant variability. We also were confident that the FEROS performances could be improved with a targeted strategy and by upgrading the software and the data analysis.

As part of the ESO time on FEROS we obtained in Periods 64 and 65 a total of 5 full and 6 half nights. An additional 12 half nights were allocated as part of the Brazilian time. Early in our programme, after surveying only 27 stars, we had indications that 80% of our target objects showed variations on the time-scales of a few to hundreds of days. This is consistent with the results of earlier, more limited surveys. Variability in G and K giants may indeed be ubiquitous. In Period 65 we could enlarge the sample which now consists of 63 stars covering a large fraction of the upper HR-diagram. The H-R diagram of the observed stars is shown in Figure 2. From this figure it is clear that the sample spans the whole Red Giant Branch as well as the region of the "clump". The targets were selected on the basis of accurate HIPPARCOS parallaxes in order to ensure a reliable determination of the basic stellar parameters. The high resolution and high S/N ratio of the FEROS spectra will also allow the spectroscopic determination of effective temperatures, gravities and metallicities. With such an extensive data base it will be possible to investigate the dependence of the radial velocity variability on a wide variety of stellar parameters, including the estimated stellar mass and evolutionary status. This is important for calibrating theoretical evolutionary tracks.

While the scientific results of this survey will require many more observations and their full analyses, in this *Messenger* contribution we mostly concentrate on the data-analysis process in order to demonstrate the capabilities of FEROS.

We believe that our results (8.3-m/sec RV accuracy) are so encouraging that they open a new possible use of the FEROS spectrograph as a planet hunter with an RV accuracy approaching that of other, state-of-art techniques. We will outline our methodology in the data reduction and provide some tips for the potential users.

3. Pushing the FEROS Capabilities

Although not conceived explicitly for very accurate radial-velocity measurements (original requirements were set to an accuracy of 50 m/sec), FEROS has been equipped with a double-fibre system, where the second fibre can be used either for recording the sky or for obtaining simultaneous calibration spectra to the science exposure (see Fig. 3, which shows a part of a frame containing the stellar and simultaneous calibration spectra), following the technique pioneered by the Geneva group with ELODIE and CORALIE (Baranne et al. 1996).

By using a simple cross-correlation (Kaufer et al., 1999, see also FEROS user manual) in the commissioning time, it was shown that FEROS could obtain a radial-velocity accuracy of 23 m/sec by observing every night the G star HD10700 (Tau Cet), an object which has been demonstrated to have a radial velocity constant to better than 5 m/s (Butler et al. 1996).

A "constant'' star is extremely useful to estimate the long-term accuracy of FEROS and to provide a standard for optimising the radial velocity analysis. Demonstrating a lack of RV variability in a standard star would make us more confident of our results on variable stars in the programme. For this pur-

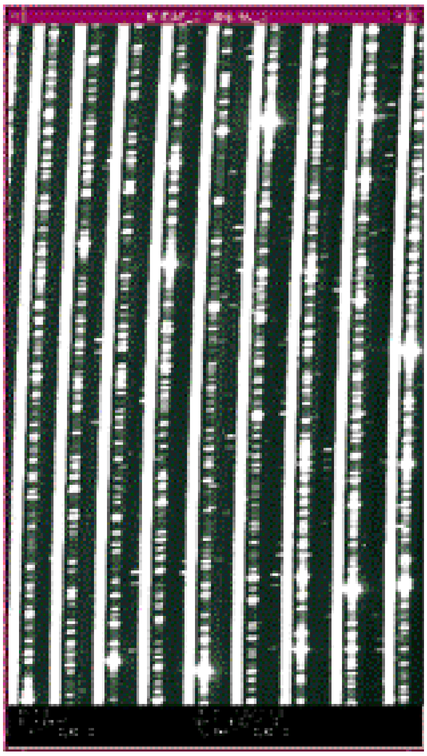

Figure 3: Portion of a FEROS frame showing the stellar spectrum and the simultaneous calibration Th-A spectrum.

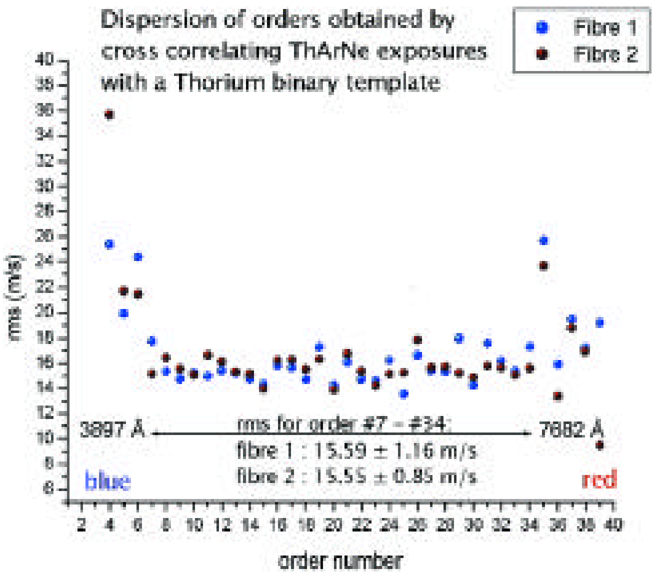

Figure 4: Determining the orders to be used for computing the precise radial velocity by cross-correlating Th-Aspectra from each fibre with the numerical Thorium template.

pose one or two observations of HD10700 were acquired on each night of our programme.

The analysis of the data is in principle straightforward and consists of the following steps:

(1) Wavelength calibration with 2-fibre ("double") Th-A exposures. Wavelength solutions are constructed using two 25-second exposures of a Th-A hollow cathode lamp in the "object-sky" mode.

(2) Spectral extraction. The extraction procedure has been implemented in the FEROS reduction pipeline integrated in MIDAS version 98 and 99. Several extraction options are available.

(3) Removing the blaze function. This is done by the FEROS package using Flat Fields (i.e. observations of spectrophotometric standards are not required).

(4) Rebinning of the spectra. The spectra are rebinned order by order rather than using the merged spectrum normally produced by the FEROS online reduction pipeline.

(5) Order-by-order cross-correlation of the object spectrum with an appropriate stellar numerical mask.

(6) Order-by-order cross-correlation of the calibration spectrum, which is called the "simultaneous Th-A", with a numerical template. This template is based on a Th-A atlas that has been modified for our own purpose. The modification takes into consideration the spectrograph resolution and line blending, and is therefore instrument-dependent. The whole Th-A spectrum needs to be subdivided in small portions and each portion of the mask is "cleaned" by analysing the correspondent cross-correlation function.

(7) Radial-velocity calculation by subtracting the cross-correlations of the stellar and calibration spectra and applying some additional zero-point offset corrections.

The first four steps are easily accomplished by the FEROS reduction in MIDAS without the need for any major modification. Our results testify the excellent work made by the Heidelberg group in the data reduction package, which is also suitable for the stringent needs of precise radial velocity studies. From the three extraction methods available, we prefer the standard extraction mode with cosmic-ray elimination.

Moreover, it is important to have the wavelength rebinning done with a step fine enough to avoid any spurious effects. In our case we use a rebinning step of 0.03 Angstrom. After spectra rebinning, cross-correlations with the appropriate numerical masks (steps 5 and 6) are performed by using the TACOS package, developed by the Geneva observatory.

The required numerical masks have been prepared for FEROS by modifying existing masks kindly provided by the Geneva observatory. The stellar mask is based on a K giant spectrum.

In order to evaluate the FEROS intrinsic capabilities, the La Silla 2.2-m team kindly acquired a series of 10 Th-A spectra with the calibration lamp illuminating the two fibres; these spectra were cross-correlated with the Th-A template mask, to investigate the behaviour of the instrument. We need in fact to evaluate within which limits the separation between the two fibres can be considered constant.

A total of 50 Th-A exposures were acquired for this purpose. The result is shown in Figure 5, where the shift: fibre 1-fibre 2 cross-correlation is shown. The results are extremely encouraging and indicate that the two fibres "follow" each other with an accuracy of better than 2.5 m/sec. This indicates that the spectrograph can deliver excellent RV performances.

In order to determine the optimal spectral range to be used for computing the radial velocity, we checked the dispersion of each order by cross-correlating the double Th-A(fibre 1 and fibre 2) with the Th-A mask prepared for FEROS and the results are shown in Figure 4. Orders 7 to 34 may be suitable for computing of accurate radial velocities (note that the order numbering used in this work is the extraction order number, not the real echelle order number).

We mention that since the binary template for the stars was originally prepared for the ELODIE spectrograph, it covers only the wavelength range from 3600–6997 Angstrom corresponding to the FEROS orders 7 to 31. A more extended mask covering also orders 31–34 will be prepared, and the addition of this signal may improve the final RV accuracy.

4. Computing the Radial Velocity

To get the radial velocity variations, we compute the difference of the cross-correlations of the two fibres order by order. In addition, for each order a zero-point offset is finally applied, considering the velocity difference between the two fibres in the double Th-A exposures. The results found so far are shown in the Figure 6 where the radial-velocity measurements of Tau Cet are shown: in 245 days spanning our observations, the rms around the constant radial velocity is 8.3 m/sec.

This puts FEROS as a full member of the select family of spectrographs capable of obtaining an accuracy below 10 m/s, a regime capable of detecting extra-solar planets.

This is quite remarkable, considering that these performances are more than

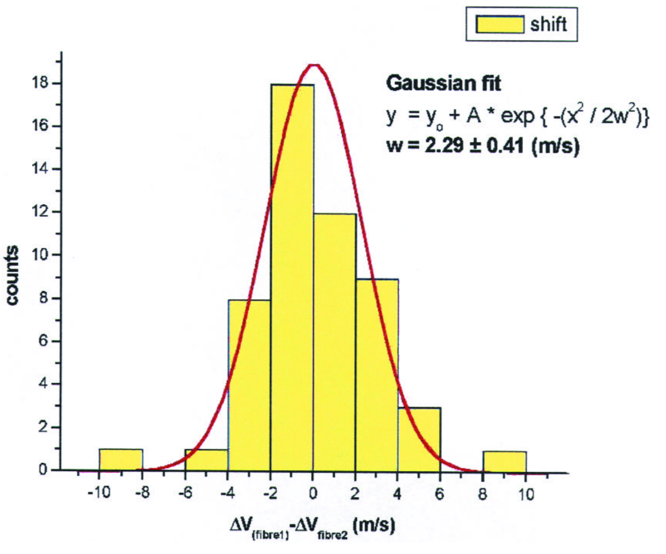

Figure 5: Determining the FEROS calibration stability by checking the shifts between fibre 1 and fibre 2. 50 Th-Aexposures have been taken for this purpose; the results indicate and RMS of 2.3 m/sec.

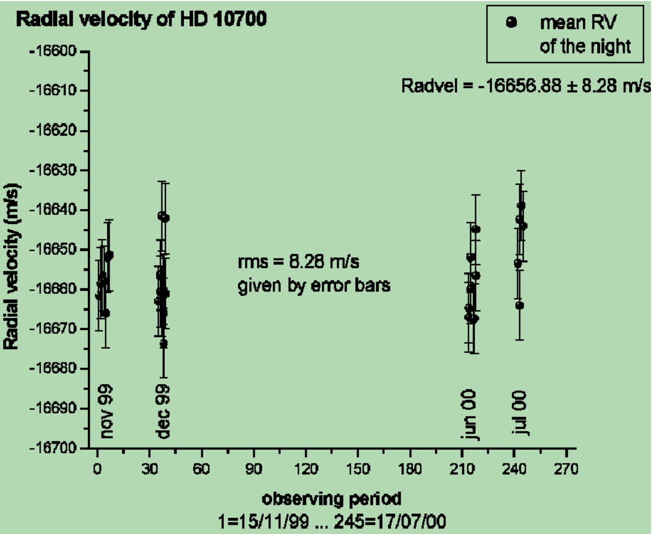

Figure 6: Radial velocity of HD10700 (Tau Ceti) taken for determining the long-term accuracy of FEROS. After monitoring the radial velocity of this constant star for almost one year (245 days), we obtain an rms of 8.28 m/s of constancy.

5 times better than the original specifications of the instrument. But mostly considering that, thanks to its impressive efficiency and large spectral coverage, FEROS is already a quite unique high-resolution spectrograph.

On the technical side, such a good performance is somewhat unexpected since FEROS fibres are not equipped with a light scrambler, and one could image that the spectrograph pupil could suffer from small shifts or variable asymmetries in the light distribution. In addition, FEROS is equipped with an image slicer. While this device will help in scrambling the light, and therefore in mitigating the problem above, the light is divided into two parts (half moons), which will have a slightly different wavelength solution. In principle, if the relative illumination of the slices changes slightly from one observation to the next (remember that 8 m/sec corresponds to ~ 1/300 of pixel), this will be enough to introduce additional noise in the precise radial velocity measurements.

So far, in addition to HD10700, another star has been reduced: the K1 III giant HD18322, and the result is very promising: as shown in Figure 7 the peak-to-peak radial-velocity variations are of ~ 200 m/sec and they are consistent with a 40-day period (which is also shown in the same figure). We stress that due to the small number of points the 40-day period we detect may be an alias of another period. More sampling is needed to determine the period accurately.

5. Some Tips for Potential Users

The real process, of course, is in practice a bit more complex than described in the previous section, and we would like to give to the potential users of FEROS a number of tips on the handling of the data.

1. When rebinning the wavelength within the FEROS pipeline DRS, if the command “REBIN/FEROS” is used, this will apply the barycentric correction also to the simultaneous Th-A spectrum. This should be corrected with the next MIDAS release.

2. The FEROS spectra are automatically corrected for barycentric correction. We use the MIDAS commands “COMPUTE/PREC” and “COMP/BARY” for this purpose, but these will be checked against more accurate methods. This step should be done carefully in order to improve the results. It is also relevant to note that the FEROS pipeline computes the barycentric correction reading the stellar right ascension and declination from the 1.52-m telescope headers and it takes the UTat the beginning of the observations. In our experience, at this accuracy the 1.52-m telescope stellar co-ordinates (contained in the frame FITS headers) may not be accurate enough; also the UT should be computed for the middle of the exposure.

3. The real geographic co-ordinates of the 1.52-m telescope should be used when computing barycentric correction.

We have not developed a full automatic procedure yet, which is supposed to enable computing the radial velocity shortly after the MIDAS pipeline reduction and directly linked to the cross-correlation process using TACOS.

Also, we found that in some observations, one or two of the selected orders depart strongly on the expected solution and they need to be discarded. This operation is at the moment performed manually, and we need to build an algorithm to select the good orders automatically.

We are also conscious that these performances could be improved; there may be effects which we did not take into consideration enough so far; among them we can foresee:

(i) Being interested in giants, our stellar mask spectrum is taken from a K giant template, while Tau Ceti (HD 10700) is a G dwarf. An ad-hoc mask for this star might already improve the results.

(ii) With the help from the Geneva observatory we will try to extend the star template to the red-part regions. This may enable us to gain more information from the spectra.

(iii) FEROS is not equipped with an exposure meter, therefore we can not accurately determine the median time of our observations (in terms of acquired photons); our observations are rather short (a few minutes), but this effect could become relevant in long observations, poor guiding and/or cloudy nights.

(iv) In our first observations we only took two double Th-A exposures every night. Several Th-A observations in the middle of the observing run would be required to monitor any possible shifts during the night and to provide additional calibrations for the offset determining in the radial velocity computation.

6. Acknowledgement

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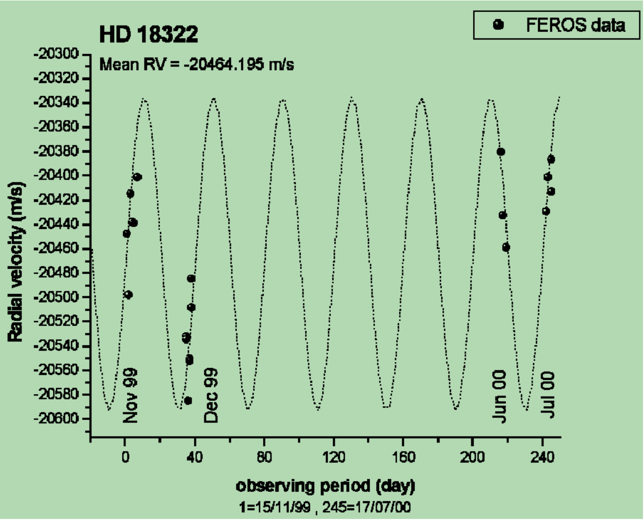

Figure 7: Results of the radial velocity measurements of HD18322. Although there are still many data points missing (no observing runs between December 1999 and June 2000), we are able to show the variability of the star, which is consistent with a periodicity of about 40 days and a peak-to-peak variation of about 200 m/s.

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Crowded Field Photometry with the VLT: the Case of the Peculiar Globular Cluster NGC 6712

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1. Introduction

The Hubble Space Telescope opened up the exciting possibility of carrying out very deep, high-precision stellar photometry in very crowded fields such as those routinely encountered in the core of dense stellar clusters and galaxies. This capability has allowed, for example, the reliable detection of stars all the way down to the bottom of the main sequence (MS) at the centre of nearby globular clusters (GC) six or seven magnitudes below the turn-off (TO) and well into the brown dwarf substellar region of nearby star-forming regions and of resolving the evolved stellar populations in nearby dwarf galaxies. Enormous progress in our understanding of the age, distance, star formation rates, and mass functions of a large sample of stellar populations has been a direct result of the last ten years of HST.

The advent of the VLT with wide-field optical and IR cameras such as FORS and ISAAC present us with a golden opportunity to push further our quest for good quality photometry of faint sources in crowded fields. The potential of very good and stable seeing coupled with the huge collecting area of an 8-m diameter telescope with wide field and broad spectral coverage detectors certainly rivals and even surpasses, in principle, even the exceptional HSTcapability in this endeavour. In order to test these capabilities in practice, our group proposed to study in depth a particularly interesting example of a crowded stellar environment namely the GC NGC 6712.

We report here the preliminary results of our study of this cluster using FORS1 and UT1 obtained with 12 hours of observations during Period 63. We emphasise those aspects of the study that best illuminate the performance of this instrument combination for crowded field photometry that might be of interest to anyone contemplating doing this sort of work with the VLT in the future. Results from a preliminary study of this object using the VLT Test Camera during the UT1 Science Verification period were reported in De Marchi et al. (1999).

2. VLT Observations of NGC 6712

NGC 6712 ($\alpha = 18^h\ 53^m\ 04.3''$, $\delta = -08^o\ 42'\ 21.5''$) is a relatively metal poor, small and sparse GC ([Fe/H] = –1.01 and concentration ratio $c = 0.9$; Harris 1996) located in the midst of a rich star field at the centre of the Scutum cloud (Sandage 1965), which

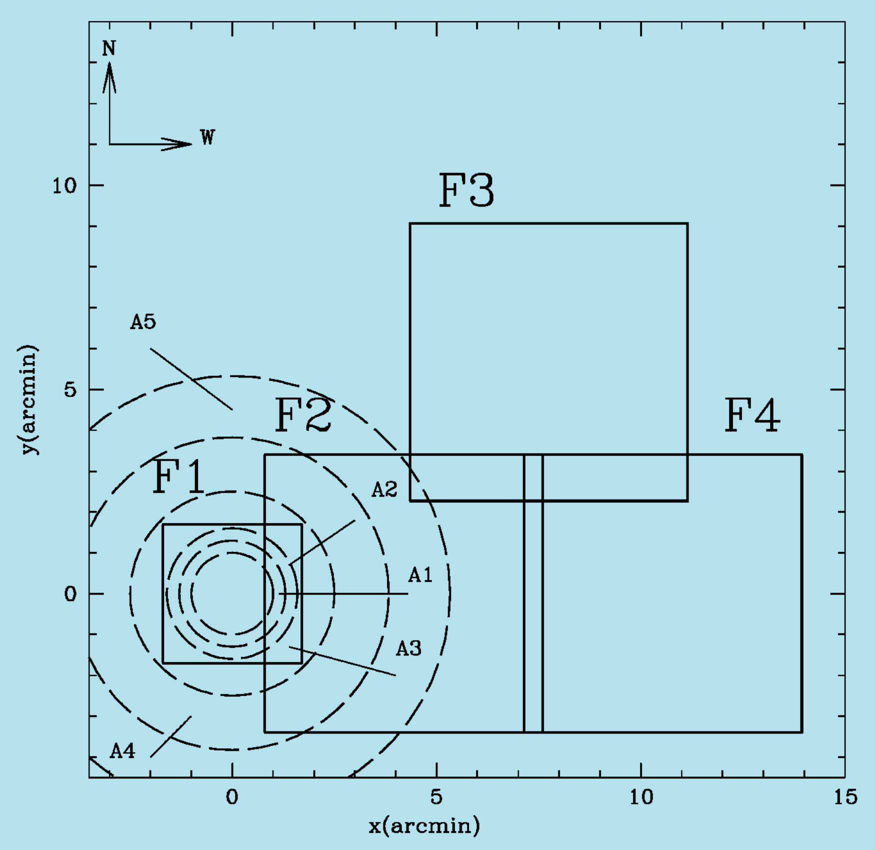

Figure 1: Locations of the four FORS1 fields on NGC 6712. The centre of the cluster is located at the origin of the co-ordinate system.