Stellar Spectroscopy of Individual Stars in Local Group Galaxies with the VLT: Kinematics and Calcium Triplet abundances

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The large collecting area and high-throughput multi-object instruments on the VLT make it possible to carry out detailed studies of stellar properties and distributions in environments well beyond our Galaxy.

The high resolution spectrograph, UVES, has provided outstanding data for the study of stellar abundances in extragalactic environments. It is possible to observe red giant branch (RGB) stars at high resolution in galaxies as far away as Leo I (250 kpc) with UVES (Shetrone et al. 2002; Tolstoy et al. 2002), and to look at super-giants up to 1.5 Mpc away at the boundary of the Local Group (e.g., Venn et al. 2003; Kaufer et al. 2004). These studies have been, of necessity, painstakingly long integrations of individual stars down to the faint limit of the instrument ($I \sim 19.5$).

The multi-fibre instrument, FLAMES, is providing a dramatic increase in multi-plexing with a 25 arcmin diameter field of view, and 130 fibres in Medusa mode (mag. limit $I \sim 18.5$), over selectable wavelength ranges (per setting), at resolutions useful for stellar spectroscopy ($R \sim 20000$), and 8 fibres feeding UVES over a longer wavelength range, with a typical UVES resolution ($R \sim 40000$). This field of view and density of fibres is a good match to the size of the central regions of nearby dwarf spheroidal galaxies, and the number of RGB stars at magnitudes bright enough to obtain good quality high resolution spectra.

However, FLAMES is not always the best instrument for every stellar project. Due to light loss from fibre transmission, and restrictions on choice of resolution and on placing fibres close to each other, FLAMES is well suited for abundance studies of stars in uncrowded regions of our nearest neighbour galaxies (within $\sim$220 kpc). If we want to look at more crowded regions (e.g., the bar of the LMC), or if we want to use the VLT to push beyond the galaxies in and around the halo of our Galaxy to look at a completely separate and independent environments, we have to use the slit spectrographs, FORS1 and FORS2. These instruments also have enhanced multiplexing capabilities such as slit masks, and with a blocking filter, FORS2 can match or even exceed the capabilities of FLAMES. Of course this means fewer lines from a single element at lower resolution, but the converse is that we can look at significantly fainter stars, probing a more distant and varied set of environments.

A commonly used abundance indicator at intermediate resolution is the Ca II triplet (CaT), a set of three absorption lines near 8500 Å. The equivalent widths of these lines (ie. the line flux with respect to the continuum luminosity of the star) have been shown to correlate very well with high resolution [Fe/H] abundance (see Armandroff & Da Costa 1991; Rutledge 1997). We have also made a comparison of our own, not matched on individual stars, but using preliminary results from the HR FLAMES data we are collecting for 100+ stars in the Sculptor galaxy (Hill et al., in prep.). We compare the distribution of [Fe/H] abundances found with FLAMES with those measured on the basis of the CaT from a previous FORS1 study of Sculptor (Tolstoy et al. 2001). As can be seen in Figure 1, there is good agreement between the two samples, although we note that the FLAMES results are preliminary.

The FORS2 spectrograph, combined with the red-optimised MIT/LL CCDs, is a uniquely powerful instrument for measuring the metallicities of RGB stars as faint as $I =$

Figure 1: The solid line in the (normalised) histogram of [Fe/H] is for a sample of RGB stars observed in the Sculptor dwarf spheroidal in the CaT region (by Tolstoy et al. 2001) with FORS1. The dotted histogram comes from the preliminary results of the FLAMES LP and GTO time which are based on high resolution spectra for ~100 RGB stars in Sculptor. The samples are not overlapping, but both are randomly chosen on the RGB. The FLAMES samples are necessarily nearer the tip of the RGB. The FORS1 sample was chosen lower down the RGB, at somewhat fainter magnitudes.
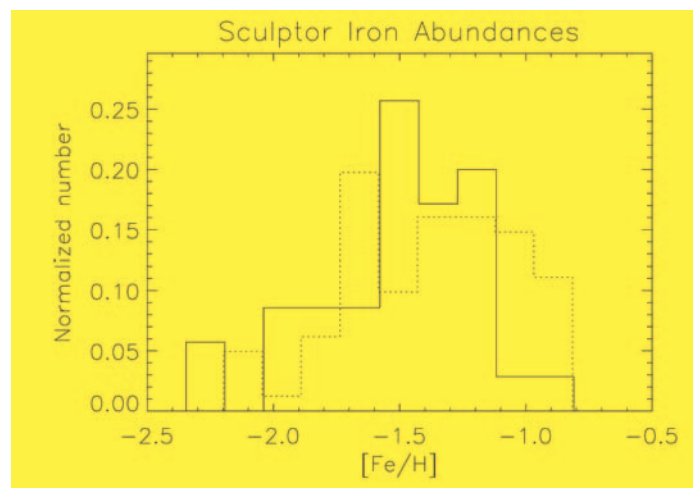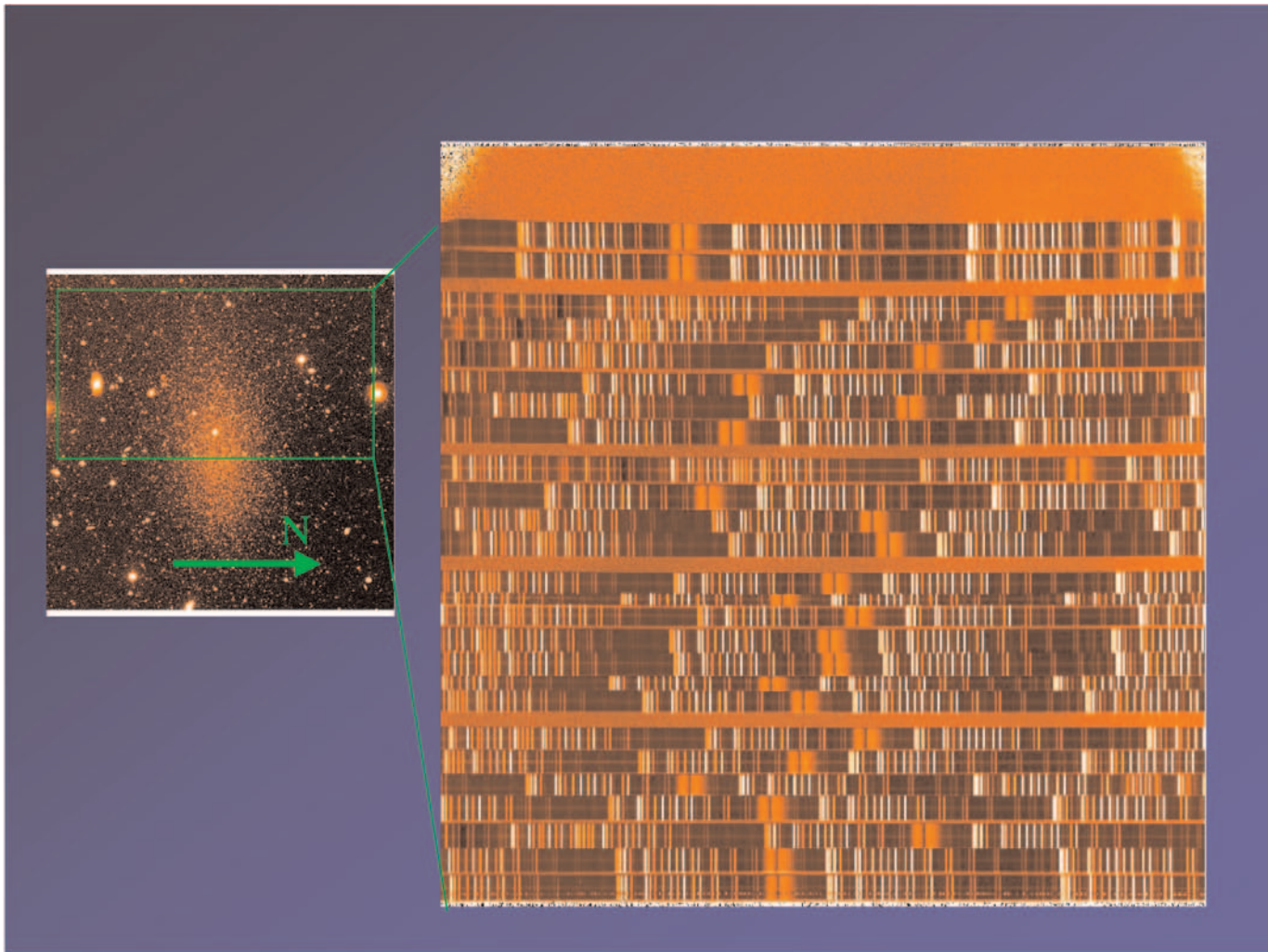
Figure 2: A FORS1 *R*-band image of Tucana taken in August 1999. The green outline shows the region covered by the MXU slit mask, and thus the region where spectra were obtained. The CCD image on the right is the raw spectra on one of the two FORS2 CCDs (the "master" CCD) for our spectra of stars in Tucana.

22. This brings every Local Group galaxy outside the Galactic zone of avoidance into range for kinematic and metallicity studies of intermediate-age and old stars. FORS1/2 can thus be used to efficiently look at samples of stars in galaxies which are too distant to allow high resolution abundances or even fibre spectroscopy (e.g., Tucana, Fraternali et al. 2004, in prep.). The field of view of the FORS1/2 spectrograph and the number of slits are a good match to the density of RGB stars in low surface brightness dwarf galaxies out to the edge of the Local Group.

In Figure 2 we can see the raw data obtained for the Tucana dwarf spheroidal galaxy, and the field of view covered by FORS2/MXU on the galaxy. Out of 47 targets placed on the slits 25 could be successfully extracted. The rest were too faint for a successful extraction. Of these successfully extracted stars 18 were considered of good enough quality to determine velocities, and of these 3 were quite distinct from the average velocity of the majority of stars. These cluster around the systemic velocity of Tucana, determined now for the first time to be 182 km/s. In Figure 3 we show the histogram of these velocities.

With this reasonably large sample of stars across the Tucana galaxy we can see if there are any obvious kinematic patterns. Figure 4 shows the velocities of the stars observed in Tucana with their positions in the galaxy. The blue crosses have velocities less than systemic, and red crosses have greater than systemic velocities. The two green crosses are at systemic velocity. There is intriguing evidence for one side of the galaxy appearing to recede and the other to be approaching. This could be interpreted as rotation, or possibly some indication of a tidal disturbance, although Tucana's isolated position in the Local Group mitigates against the latter possibility. Although the number
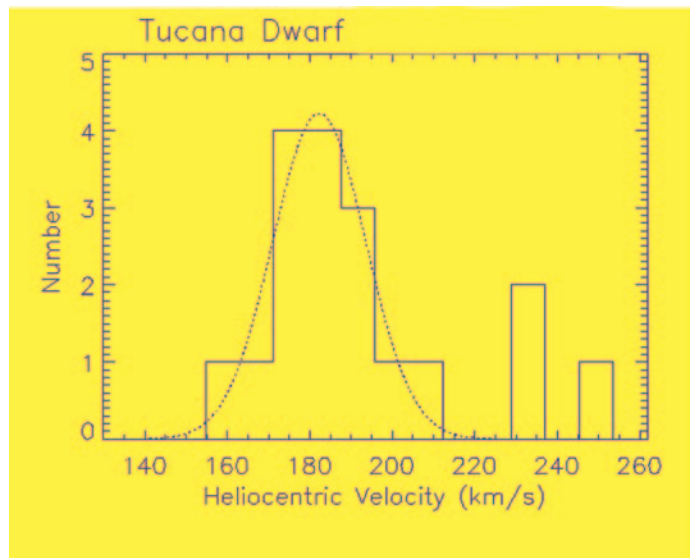

Figure 3: Histogram of the radial velocities measured from the CaT region for 18 stars in the Tucana dwaf spheroidal galaxy. The gaussian fit gives a central, systemic, optical velocity of Tucana of 182 km/s, with a dispersion on 12 km/s.

Figure 4: A 20′ by 14′ field of view centred on Tucana, taken from DSS plates. The blue crosses represent those stars with velocities less than v_{sys} (182 km/s) and the red crosses greater than systemic. The green crosses are those stars at systemic velocity. North is up and East to the left.
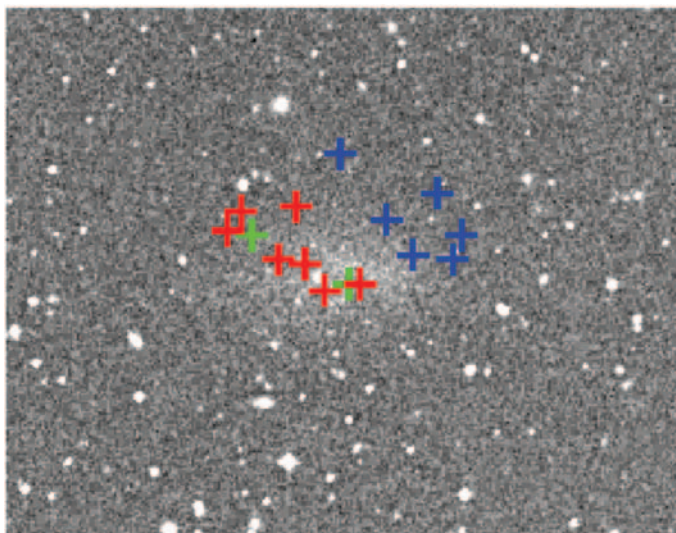
statistics are still very small, interestingly, if this is rotation it would be, as expected, rotation about the minor axis.

In Figure 5 we show preliminary results from the CaT metallicities of these stars in Tucana. The spread in abundances looks quite similar to Sculptor (from Tolstoy et al. 2001). From this plot, and taking into account the velocity and position of Tucana in the Local Group it is clear that the properties of Tucana are consistent with those of nearer Galactic satellite dwarf spheroidal galaxies, such as Sculptor.

The efficient use of FORS1/2 is not restricted to the faintest stars; the same techniques can be successfully applied to much nearer galaxies. Here, the efficiency with which it is possible to change the slit configuration, the ease of target acquisition based on pre-images and slit configurations created with the FIMS software, together with seeing of 0.7 arc-seconds have allowed major new studies of crowded regions like the center of the LMC bar (e.g., Cole et al. 2004, in prep.). With a surface brightness of 20.6 mag/arcsec^2, RGB stars in the bar were beyond the capabilities of spectrographs on 4-meter class telescopes. Crowding problems can be minimized by target selection from pre-images taken in good seeing, and the difficulties of sky fiber placement can be completely avoided by using slits that span many arc-seconds around each target. These capabilities ensure a valuable place for FORS even after the advent of large fibre systems such as FLAMES.

In nearby galaxies, where targets are bright, the speed with which high signal-to-noise spectra can be acquired becomes a tremendous advantage of FORS1/2. Comparing CaT spectra of RGB stars in the LMC obtained in a large survey of field stars, UT4/FORS2 yields higher signal-to-noise in 1200 second exposures (Cole et al. 2004) than CTIO-Hydra in exposures 10 times as long (Smecker-Hane et al. 2004, in prep). Because the metallicity distribution

functions of galaxies are not well constrained, sample size is a crucial aspect of any chemical evolution study. Sparse samples, measuring only a few stars, can all too easily miss minority populations which may be critical for understanding the chemical (and dynamical) evolution of the host galaxy.

There are several galaxies in the Local Group for which we do not have even the most basic information, such as the optical radial velocity. This is especially important for dwarf spheroidal type galaxies which have no (observable) gas. Once the stellar velocity of the system is known it is possible to look more carefully for associated gas and to analyse possible orbital trajectories to its current location.

We have used the FORS spectrographs to determine the optical velocities, previously unknown, of Antlia (Tolstoy & Irwin 2000), and Tucana (Fraternali et al. 2004) and a reassessment of the optical velocity of

Phoenix (Irwin & Tolstoy 2002). In the case of the Tucana dwarf spheroidal, it has always been held to be an unusual object because of its extreme distance from the Galaxy and M31, unlike all other Local Group dwarf spheroidals (at least prior to the discovery of Cetus).

In the case of the Phoenix and Antlia dwarf galaxies it is possible for the first time to make clear the association of the optical galaxy with the HI gas seen near these objects. Without a reliable optical velocity this association remained uncertain. These kinematic studies therefore have far reaching implications for our understanding of evolutionary processes in nearby dwarf galaxies.

There are currently two large programmes at ESO to use FLAMES to increase the number of stars with velocity and abundance measurements to improve detailed modelling in several nearby galaxies (e.g., 171.B-0588, PI Tolstoy), for which the first results will be available soon. This ability to look at individual stars in different galaxies with such accuracy over such a large range in distance means we can probe the properties of stars in many different environments - metal poor, metal rich, dense, sparse etc. This is an exciting era for understanding the detailed properties of resolved stellar populations across the Local Group, which naturally will have implications for studies of the most distant galaxies.

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Figure 5: The black crosses are the measurements of the CaT widths of the two strongest lines in our FORS2/MXU spectra of stars in Tucana plotted against the difference in their magnitude with that of the horizontal branch in Tucana (V_H). The dashed lines are the relations calibrated by Tolstoy et al. 2001 corresponding to where stars of different metallicity should lie. The red crosses are the CaT measurements taken with the same instrumental set up and processed in the same way for stars of known metallicty in Galactic globular cluster, M15.