FLAMES Observations of Old Open Clusters: Constraints on the Evolution of the Galactic Disc and Mixing Processes in Stars

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Open clusters are populous groups of stars whose members have the same age, chemical composition, and distance from the Sun. Hence, they provide homogeneous samples to investigate several important issues related to stellar and Galactic evolution. We present here an overview and preliminary results of a VLT/FLAMES programme aimed at a detailed study of seven old clusters. Our two main goals are the determination of the radial abundance gradients in the Galactic disc and their evolution with age, and the investigation of internal mixing processes in stars similar to our Sun.

Galactic open clusters (OCs) cover large intervals in age (from a few × 10^7 years to several billion years), metallicity (from about five times below to about twice above the solar value), and position in the Galactic disc (up to 22 kpc from the Galactic centre). OCs represent vital laboratories for stellar astronomy because they provide a means to study the individual properties of stars as a function of age, metallicity, and mass. On the other hand, the global properties of old OCs, and in particular their chemical composition, provide reliable information on the status of the disc at early epochs, which is crucial for a better understanding of the overall Galaxy formation and evolution.

In this article we describe a FLAMES project on old Galactic OCs aimed at addressing two distinct issues: namely, i) the formation and evolution of the Galactic disc, and ii) the study of the evolution of lithium abundances and mixing processes in solar analogues. Final results and conclusions require completion of the analysis of our large data set and detailed comparison with both results available in the literature and theoretical models. Here we provide an overview of the project together with a few examples of preliminary results, with the purpose of emphasising the wealth of information that can be achieved with a relatively small amount of observing time with FLAMES.

The astrophysical problems

1. Formation and evolution of the Galactic disc

Various important quantities related to the evolution of the Galaxy, such as star-formation history (SFH), initial mass function (IMF), or gas flows are still not well known. For example, the question of how much chaotic early accretion of dwarf satellites and star-forming clouds, on one side, and a smoother, dissipative gas accretion, on the other side, concurred to build up the Galaxy is currently one of the hottest open issues concerning galaxy formation (Freeman & Bland-Hawthorn 2002). Radial metallicity gradients and their evolution with Galactic age are among the most useful observational constraints that one can put on those processes and, more in general, on Galactic chemical evolution (GCE) models (Tosi 2000). For example, the predicted gradients can flatten or steepen in time, depending on the different model assumptions on the SFH and infall processes (e.g., Portinari & Chiosi 1999). Hence, empirically proving the flattening or steepening of the gradients with time appears crucial. Knowledge of [α/Fe] abundance ratios and their evolution as well represents an important tool to trace a galaxy SFH and IMF, since the timescales of the variations of the abundance ratios depend on both the SFH and the IMF. More specifically, the mass function affects the ratios of elements synthesised by stars of different mass, while the star formation rate regulates the timing of their production.

Several abundance studies exist for the solar neighbourhood, but we still know little about the chemical composition in other parts of the disc. The mean metallicity gradient has been determined based on different spectroscopic studies of a variety of tracers (H II regions, B stars, planetary nebulae (PNe), OCs). However, these samples provide partial results, mainly because they can only sample a limited range of distances and ages. In particular, indicators such as H II regions and B-type stars give independent estimates of the shape and magnitude of the present-day Galactic gradients, while information about the temporal variation of the gradients can be obtained only from PNe and old OCs. Also, uncertainties arise since different classes of objects (and even objects belonging to the same class) are often analysed using different methods, resulting in possible systematic effects in the derived gradients and in discrepant results. There is indeed a hot debate over whether OCs really present a metallicity gradient or rather a discontinuous distribution of metals with Galactocentric distance (Twarog et al. 1997). Finally, very little is known about [α/Fe] ratios, their radial distribution, and evolution with Galactic age (Friel 2005). It thus becomes mandatory to use a large, homogeneous OC sample – like that presented in this paper – in order to shed more light onto the actual behaviour of the metallicity distribution in the disc.

2. Evolution of lithium and mixing in solar-type stars

Lithium (Li) is destroyed by proton capture at the relatively low temperature of 2.5 MK and it is depleted from stellar atmospheres when a mechanism is present that is able to transport surface material down to the deeper stellar interiors where the temperature is high enough for Li burning. Thus, although the absolute abundance of this element is very small (3×10^{-9} in number with respect to hydrogen, at most), measurements of Li abundance in stars are unique tracers of internal mixing mechanisms. With the exception of very low mass, fully convective stars, the physics driving Li depletion in stars is not well understood. Measured Li abundances in stars of different spectral types (from early-F to late-K) and evolutionary stages (from pre-main-sequence – PMS – to evolved clump stars) strongly challenge the prediction of "standard" models of stellar evolution. With this term we refer to those models that include convection, but neglect other transport phenomena such as diffusion, gravity waves, rotation and angular momentum loss.

Focusing on stars similar to our Sun, standard models predict that they should deplete most of their Li while on the PMS, that they should not undergo any depletion on the main sequence (MS), and that stars with the same age, mass, and chemical composition should deplete a similar amount of Li. At variance with these predictions, observations of Li in field and cluster stars carried out during the last 20 years have shown that solar-type stars suffer very little PMS Li depletion, but do deplete Li on the MS. Li depletion is not a monotonic function of age; rather it seems to be bimodal and otherwise similar stars do not deplete the same amount of Li. Our Sun has a very low Li abundance, a factor of about 100 below the meteoritic value which is indicative of the initial solar abundance, but several stars with similar or even older age exist with a much higher Li. A large dispersion in Li abundances is also seen among MS stars in the solar-age, solar-metallicity cluster M 67 (Jones et al. 1999).

This puzzling scenario and, in particular the evidence for MS Li depletion, has motivated theoreticians to introduce non-standard or extra-mixing physics in the models. Several mechanisms have been proposed, together with the suggestion that an additional parameter, besides age, mass, and chemical composition, must affect Li depletion. Stellar rotation and/or rotational history appear as the most likely additional parameters, and rotational mixing is the extra-mixing process that presently receives the largest consensus; nevertheless, this process is not able to explain other observational results (for example beryllium abundances in M 67) and, as a matter of fact, the mechanism driving MS Li depletion in solar-type stars remains elusive (Randich 2005). We also mention that the effects of chemical composition on Li depletion which are predicted by theory are still rather poorly constrained.

Understanding mixing processes at work in Pop. I stars and their dependence on metals is important not only for a better comprehension of stellar structure and evolution; it also provides a key to investigate whether this mechanism may work for metal-poor Pop. II stars and, possibly, to explain the origin of the discrepancy between primordial ^{7}Li abundance predicted by WMAP and Big Bang Nucleosynthesis and the stellar value based on Pop. II star Li abundances (Romano et al. 2003).

The goals and target clusters

Until the advent of multiplex facilities on 8-m-class telescopes, high spectral resolution studies of OCs were very time consuming and limited to small samples of bright stars in the closest clusters. As a consequence, the open issues mentioned above could not be investigated in a comprehensive and systematic way, due to the lack of accurate, homogeneous abundance data sets for large samples of stars in OCs well sampling the age-metallicity-Galactocentric distance parameter space. By exploiting FLAMES capabilities, our project aims at simultaneously acquiring high-quality spectra of significant samples of evolved (7–14 per cluster) and unevolved (100–200 per cluster) members of seven well-selected OCs. Our specific goals are:

- The investigation of the [Fe/H] radial gradient in the disc and its evolution with Galactic age, based on a homogeneous abundance analysis of evolved cluster members;
- The determination of abundances of α and Fe-peak elements and their ratios to Fe, to study their radial distribution and evolution with Galactic age;
- The determination of cluster membership of photometric cluster candidates that will allow us to "clean" colour-magnitude diagrams. This is crucial in order to (re)derive secure and homogeneous cluster parameters (age, distance, reddening);
- The determination of Li abundances in MS and/or TO cluster members, in order to carry out a systematic study of the evolution of Li in solar-type stars and its dependence on chemical composition.

The multiplexing capability of FLAMES and its high efficiency are perfectly suited to our purposes. Radial velocities and Li abundances (from the Li 670.8 nm line) are determined from Giraffe spectra of unevolved cluster stars, while the detailed chemical analysis is obtained from UVES spectra of cluster clump or RGB members.

Giraffe has been used in MEDUSA mode with the high-resolution gratings covering the ranges 630.8–670.1 nm, 660.7–679.7 nm and 647.0–679.0 nm. With UVES CDs covering 476.0–684.0 nm and 660.0–1060.0 nm have been used, allowing us to target, besides several iron lines, the forbidden lines of O around 630.0 nm, Na at 568.2–568.8 nm and 615.4–616.0 nm, Mg and Ca from several lines, Si from lines around 570.0 nm. The O I triplet at 777.4–777.7 nm, the Na lines at 813–819.4 nm, the N ones around 800.0 nm, and the $^{12}C/^{13}C$ isotope from the CN lines around 800.0 nm are included in the red UVES setting.

The sample clusters are listed in Table 1, while in Figure 1 we show, as an example, the colour-magnitude diagram of Berkeley 32, the most metal-poor cluster in our sample. Table 1 shows that the selected clusters span large intervals in age, distance, and metallicity. Our sample will be complemented by a sample of three additional old OCs observed in the context of the Ital-FLAMES Guaranteed Time (GTO) programme (Pallavicini et al. 2005).

Two observing runs were approved for this programme, for a total of about 50 hrs; one of them was performed in Service Mode, while the other one has been carried out in Visitor Mode. The data were reduced using the UVES pipeline within MIDAS and the Giraffe BLDRS pipeline. Examples of extracted UVES spectra of clump stars in NGC 3960 are plotted in Figure 2, while in Figure 3 we show Giraffe spectra of 16 MS stars in NGC 6253 around the Li I 670.8 nm spectral region.

Cluster	Age (Gyr)	[Fe/H]	R_{GC}(kpc)	D (kpc)	E (B-V)
NGC 3960	0.9	−0.34	8.0	1.7	0.29
NGC 2324	0.9	−0.15	11.6	3.6	0.20
NGC 2477	1.0	−0.13	8.9	1.3	0.28
NGC 2660	1.1	−0.18	9.2	2.8	0.31
NGC 6253	3.0	+0.36	7.0	1.5	0.20
Be 29	3.5	−0.44	22.0	14.8	0.16
Be 32	7.2	−0.50	11.3	3.1	0.15

Table 1: Sample clusters in increasing age order. Cluster parameters (age, [Fe/H], Galactocentric distance, distance from the Sun, and reddening) have been retrieved from different sources in the literature. [Fe/H] values for most of the clusters have been derived from low-resolution spectra or photometry and are not on the same scale. One of the goals of the present project is the homogeneous determination of cluster parameters and abundances.

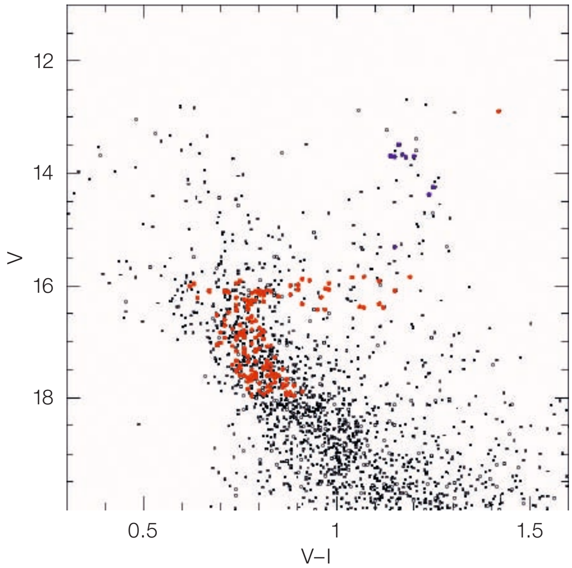


Figure 1: V vs. V-I colour-magnitude diagram of Berkeley 32. Photometry was retrieved from the literature. Two FLAMES pointings on this cluster were obtained and stars observed in both pointings are shown in the figure. UVES targets are denoted as blue symbols, while Giraffe/Medusa targets are indicated as red symbols.

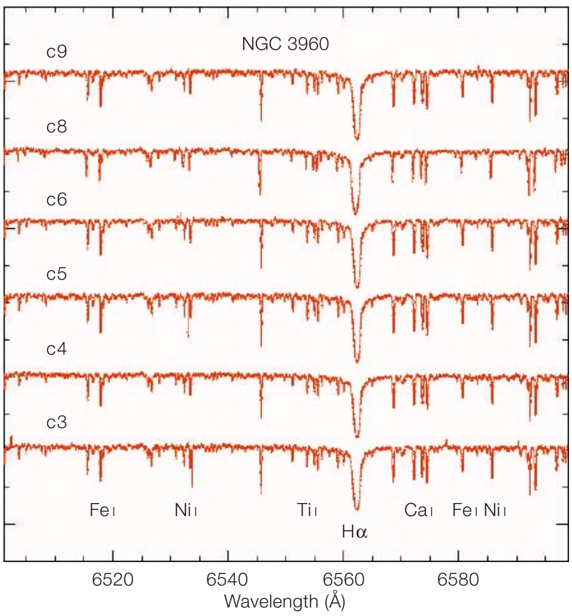


Figure 2: UVES spectra of six clump members of NGC 3960 in a 100 Å wide region around Hα. Besides Hα, a few lines employed for the chemical analysis are indicated. Abundance analysis has been performed using MOOG and Kurucz model atmospheres. The sample stars have magnitudes V ~ 13 and the spectra are the sum of two 45 minute long exposures.

Results: first examples

Cluster membership

In Figure 4 we show the radial velocity histograms obtained from the analysis of Giraffe spectra of 196 and 111 photometric candidate members of NGC 6253 and Be 32 respectively. In both cases the distribution of radial velocities is characterised by a well-defined, narrow peak, implying a small velocity dispersion. Our velocity determination for Be 32 is in good agreement with available velocities for evolved cluster members from the literature. To our knowledge no radial velocity measurements have so far been performed for NGC 6253 and thus our estimate represents the first determination of the cluster velocity. Noticeably, for both clusters the percentage of confirmed members is rather low (slightly above 50 %).

A zoom of the colour-magnitude diagram of Be 32 is shown in Figure 5; radial-velocity members are denoted as red dots. The figure indicates that, when removing non-members, the cluster sequence of confirmed members remains rather broad. This suggests the presence of a significant fraction of photometric binaries and/or differential reddening. Interestingly, we note that all but one of the stars bluer and brighter than the TO, which were classified as possible blue stragglers belonging to the cluster, are instead non-members.

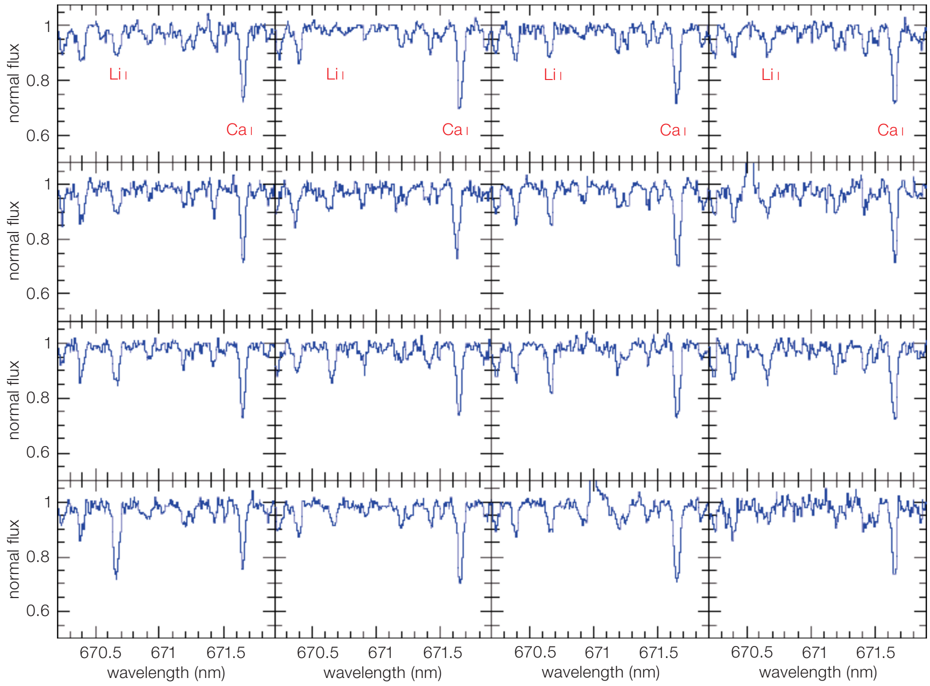
Chemical abundances: NGC 3960

NGC 3960 is one of the youngest and closest clusters in our sample. It hence represents an important extreme for the determination of the radial metallicity gradient and its evolution with Galactic age. A photometric study of this cluster was recently carried out by Prisinzano et al. (2004), who concluded that the cluster has an age between 0.9 and 1.4 Gyr and is characterised by differential reddening. Spectroscopic studies of the cluster are therefore also important to better constrain its parameters.

From the analysis of the UVES spectra of seven clump stars we derive an iron content close to solar ([Fe/H] = −0.02 ± 0.11), at variance with earlier reports of a somewhat lower metallicity ([Fe/H] = −0.34) based on modest-resolution spectra. This result evidences the need for abundance determinations using high-resolution spectra. Also, the previous low-metallicity estimate for NGC 3960 made this cluster one of the most metal-poor ones at its age and Galactocentric distance, significantly contributing to the dispersion in the [Fe/H] vs. age and R_{GC} diagrams at relatively young ages and small distances. This dispersion is considerably reduced when considering the value of [Fe/H] derived by us.

Our [X/Fe] ratios represent the first determinations of these quantities for NGC 3960; we find values close to solar ratios for Mg, Si, Ti, and Ni, while aluminium is slightly underabundant and Na, Ca and Cr appear somewhat enhanced. The mean [α/Fe] ratio is almost solar.

Figure 3: Giraffe spectra of 16 MS members of the metal-rich cluster NGC 6253. The Li I 670.8 nm and Ca I 671.8 nm features are indicated in the upper row. Magnitudes of the sample stars are in the range V = 15.5–16.5 and they were exposed for 45 min. Note the varying strength of the Li feature for stars with similar Ca I line (i.e. of similar spectral type).



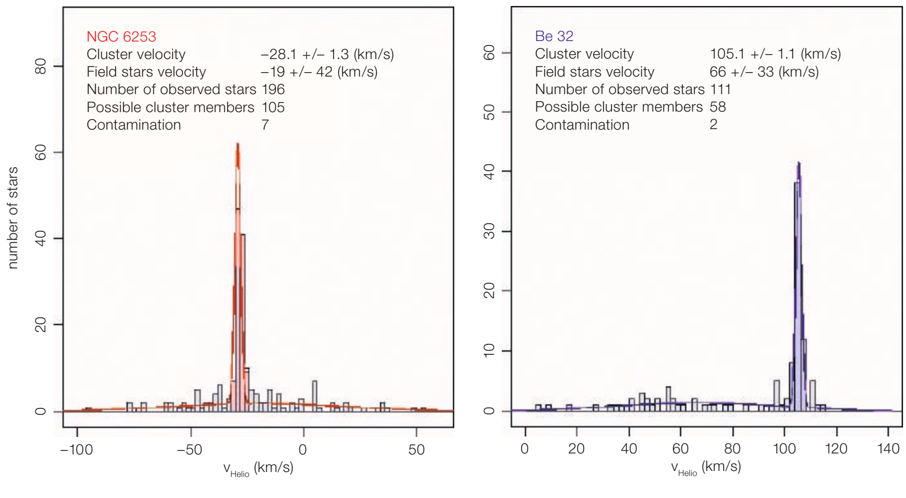


Figure 4: **Left:** Histogram of heliocentric radial velocities of candidate NGC 6253 members observed with Giraffe. The solid line indicates the best fit of the observed distribution obtained using a maximum likelihood fitting procedure. The resulting mean velocities for the cluster and field stars are indicated, together with their standard deviations, the number of possible cluster members, and expected number of contaminants. Individual radial velocities of cluster stars were determined either with our own procedures within the MIDAS or IRAF[1] contexts or using the appropriate recipe within the BLDRS software. As a by-product, we were able to assess the accuracy of the latter and its dependence on the set-up (or spectral range), the reference templates, and the S/N ratio of the spectrum. **Right:** Same as left-hand panel, but the histogram of radial velocities for Berkeley 32 is shown.

[1] IRAF is distributed by the National Optical Astronomical Observatory, which is operated by the Association of Universities for Research in Astronomy, under contract with the National Science Foundation.

Lithium in NGC 6253

NGC 6253 is the most metal rich cluster in our sample and provides a good target to better investigate the dependence of Li depletion on metals, which is predicted by both standard and non-standard models. In particular, at the high metallicity of this cluster a larger amount of Li depletion for a given mass is expected.

In Figure 6 we show the canonical plot of Li abundances vs. effective temperature for NGC 6253 MS stars together with the distribution of M 67. Besides the normal trend of decreasing Li abundance with decreasing temperature (mass), two important features are evident in the figure: 1. Li abundances for stars warmer than about 5 800 K are characterised by a small dispersion, much narrower than that observed among M 67 members. On the other hand, cooler stars do show a dispersion comparable to M 67. Together with the results for other old clusters, this suggests that the presence of the scatter and the temperature/mass at which it is seen are related to some (still unknown) characteristics of the cluster, rather than to the cluster age. The complete analysis of the whole Li data set will shed more light on this aspect. 2. Stars in the upper envelope of NGC 6253 are not more Li depleted than stars in the upper envelope of the about a factor of two more metal poor M 67, suggesting that, at variance with model predictions, even a rather large difference in the overall metal content does not affect the rate of Li depletion, at least in the temperature range considered here.

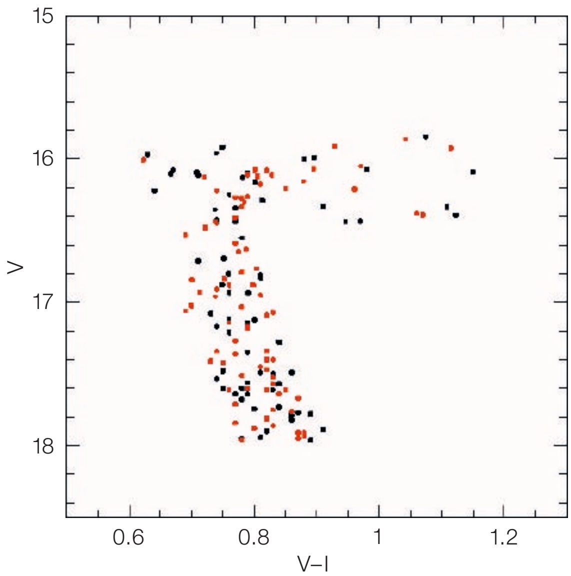


Figure 5: Zoom of the colour-magnitude diagram of Berkeley 32. Only Giraffe targets are plotted. Red and black filled circles indicate confirmed radial-velocity members and stars rejected as members.

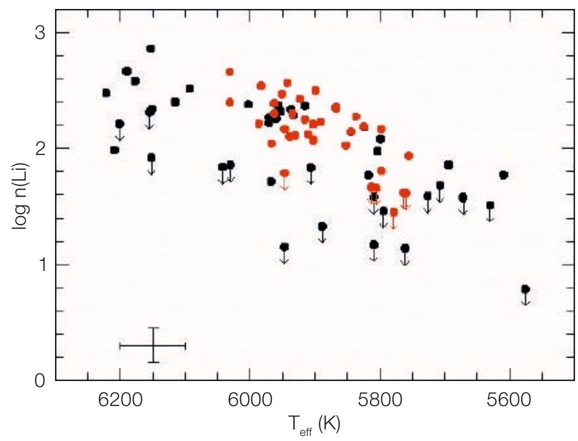


Figure 6: Lithium abundances ($\log n(Li) = \log n(Li)/n(H) + 12$) as a function of effective temperature (T_{eff}) for NGC 6253 (red symbols) and M 67 (black symbols). The sample of NGC 6253 includes only stars covered by one of the two pointings on this cluster, that were confirmed as members, and that are fainter than V = 15.5, i.e., are still on the MS and have not undergone any post-MS Li dilution. Data for M 67 were taken from the literature. NGC 6253 Li abundances were determined using the method that we have used in other studies and consistently with M 67.

In summary, the few preliminary results discussed above already attest the strength of our approach. Radial velocity analysis has been completed for all the sample clusters and we are now ready to determine cluster parameters in a homogeneous way using the synthetic colour-magnitude diagram technique developed by us. At the same time, we will complete the analysis of UVES spectra to derive the chemical composition of the whole sample and the analysis of Giraffe spectra for Li determination. Spectra of the clusters observed in the context of the GTO project mentioned above are also being consistently analysed. The final homogeneous data set of cluster parameters and abundances will let us put stringent and robust empirical constraints on models of Galactic disc formation and evolution, as well as on the physics at work in the interiors of solar analogues during the MS phases. Several spin-off scientific topics will also be addressed.

References

Freeman, K., and Bland-Hawthorn, J. 2002, ARA&A 40, 487
Friel, E. 2005, in Chemical Abundances and Mixing in Stars in the Milky Way and its Satellites, L. Pasquini and S. Randich eds., ESO Astrophysics Symposia, Springer, in press
Jones, B. F., Fisher, D., Soderblom, D. R. 1999, AJ 117, 330
Pallavicini, R., Spanò, P., Prisinzano, L., Randich, S., and Sestito, P., 2005, in Chemical Abundances and Mixing in Stars in the Milky Way and its Satellites, L. Pasquini and S. Randich eds., ESO Astrophysics Symposia, Springer, in press
Portinari, L., and Chiosi, C. 1999, A&A 350, 829
Prisinzano, L., Micela, G., Sciortino, S., Favata, F. 2004, A&A 417, 945
Randich, S. 2005, in Chemical Abundances and Mixing in Stars in the Milky Way and its Satellites, L. Pasquini and S. Randich eds., ESO Astrophysics Symposia, Springer, in press
Romano, D., Tosi, M., Matteucci, F., Chiappini, C. 2005, MNRAS 346, 295
Tosi, M. 2000 in The Evolution of the Milky Way: Stars versus Clusters, F. Matteucci and F. Giovannelli eds. (Dordrecht: Kluwer), p. 505
Twarog, B. A., Ashman, K. M., Anthony-Twarog, B. J. 1997, AJ 114, 2556