The A-Star Puzzle
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Observational challenges of A-type stars

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Abstract. In the last few years, new instruments mounted at modern large telescopes, as well as satellite instruments, have given to us the possibility of obtaining observations of much higher quality than in the past. Yet, the large majority of observations of A-type stars are performed with small to middle size class telescopes. In this paper I discuss the scientific case for the use of large size class telescopes for the A-star research.

Keywords. Instrumentation: interferometers, instrumentation: spectrographs, instrumentation: polarimeters, telescopes

1. Introduction

Observational astronomy has changed considerably in the last few years. Although it is not easy to have a complete and detailed overview of the worldwide available instrumentation, it is pretty clear that a substantial fraction of the technological and economical efforts are concentrated in projects that involve very, extremely, up to overwhelmingly large telescopes, or expensive space missions. Just limiting ourselves to ground based observations, at the moment there are 14 optical-IR telescopes already operating or under construction that have a 8-m mirror or larger. In less than two decades from now, these that today are our largest telescopes will appear as minuscule facilities if projects such as, for instance, OWL will become reality. On the one hand, we can ask ourselves how much science for A type stars is done with the large telescopes. On the other hand, a lot of science has been done and is still being carried out with $0.5 - 2.0$ m telescopes, and we may want to address the question if these facilities are bound to become obsolete.

It should be noted that astronomical observations are not changed only in terms of available instrumentation, but also in terms of the way observations are carried out. I refer to the possibility to perform observations in *service mode*, as opposite to the more familiar *visitor mode*, when the astronomer is present at the telescope and personally takes care of the observations. Rather than with hardware, astronomers may have much more to do with electronic forms and sheets. (For an overview of the rationale and of the performances of the service observing mode implemented at ESO, see Comeron *et al.* 2003.)

Finally, some problems that we want to address may be solved using observations that have already been obtained. The success of our future research will also crucially depend on our capabilities to efficiently search for and retrieve archived observations.

The session "Observational Challenges of A type stars" has been included in this Symposium with the purpose of discussing the new observational tools that we have at our disposal to address the open questions related to the physics of A stars. In this paper I will present some practical examples of how modern instruments attached to the largest telescopes can be efficiently used for the A-star research. The role played by archived observations is discussed by Padovani (2005).

Since it is not possible to discuss all the observational aspects that are related to the A-star research, I decided to consider a specific topic and to see how (some) present and forthcoming instruments at the large telescopes may be used to address it. Such topic (a study of the evolution of magnetic Ap stars) is shortly introduced in Sect. 2. Instrumental aspects are discussed in Sect. 3. In Sect. 4 I present some concluding remarks about the projects to construct giant telescopes. This work is clearly biased toward the instruments of the ESO Very Large Telescope (VLT). However, most of the VLT instruments are not unique. FORS1 at the VLT and FOCAS at the Subaru telescope are very similar Faint Object Cameras and Spectrographs, both equipped with polarimetric optics. Gemini South is equipped with PHOENIX, and the VLT will be soon equipped with CRIRES. PHOENIX and CRIRES are both high resolution infrared spectrograph operating in the $1-5\,\mu$m region. The VLT and the Subaru telescope are both equipped with high resolution optical spectrographs (UVES at the VLT, and HDS at the Subaru telescope). The only remarkable exception, in terms of an instrument of the ESO VLT with "unique" features, is represented by the multi-object, medium-high resolution spectrograph FLAMES.

2. Studying the evolution of chemically peculiar A-type stars

The magnetic Ap stars have rotation periods that are much longer than those of non-magnetic stars of similar spectral class (e.g., Stępień 2000). Abt (1979) claims that Ap stars loose angular momentum during their life on the Main Sequence, whereas North (1998) states that observations are fully consistent with conservation of angular momentum during the star's life in the Main Sequence. Consistently with the finding by North (1998), Stępień (2000) and Stępień & Landstreet (2002) have presented a model that explains how a magnetic Pre-Main Sequence star may loose angular momentum through interaction between magnetic field and circumstellar material. Abt (1979) suggests that the incidence of chemical peculiarities increases with the star's age. Instead, Gomez *et al.* (1998) found that chemical peculiar stars occupy the whole width of the Main Sequence, and Pöhnl *et al.* (2003) found several chemical peculiar stars close to the Zero-Age Main Sequence. Hubrig *et al.* (2000) claimed that, for chemically peculiar stars with masses less than $3\,M_\odot$, their magnetic fields appeared when the stars had spent at least 30 % of its life on the Main Sequence. However, Bagnulo *et al.* (2003a) found in the young cluster NGC 2516 a strongly magnetic star of $2.1\,M_\odot$ that has spent about 16 % of its life in the Main Sequence. In conclusion, there is some confusion about the evolution of the magnetic chemically peculiar stars, and we simply do not know if and how the chemical peculiarities and the magnetic field depend upon the star's evolutionary stage. By contrast, knowing how the magnetic field and the chemical abundances change during the life of the star in the Main Sequence band would help to clarify the problem of the *origin of the magnetic field* and would set precise constraints to the *diffusion theory.*

To properly address this problem one has to observe a large number of stars and find their positions on the HR diagram. For each one should study the magnetic field topology and perform an accurate chemical abundance analysis, taking into account a nonhomogeneous distribution of the elements both horizontally and vertically. This project will benefit from the outputs of many different techniques, such as, e.g., astrometry and parallax measurements; photometry in the various flavours (UBV, possibly with extension to the infrared, Strömgren, Geneva, etc.); bolometry; spectroscopy; spectro-polarimetry; interferometry, etc.

2.1. *Determining the age of Ap stars*

I will start with the problem of locating the star in the HR diagram. The first step is to measure the stellar temperature. This could be done for instance using Strömgren

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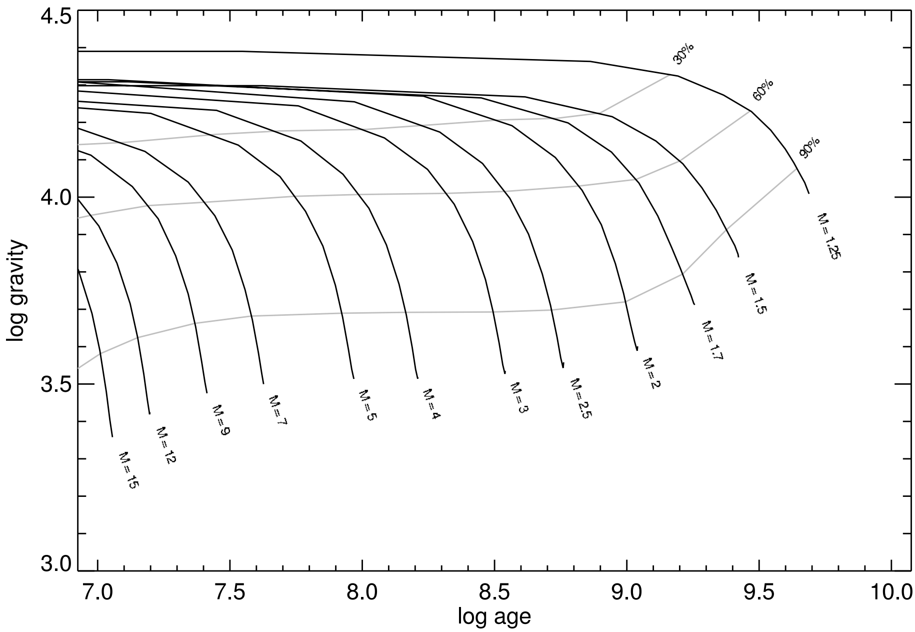

Figure 1. How $\log g$ changes with time according to the evolutionary models by Schaller *et al.* (1992) for stars of various masses. See also a similar figure in North & Kroll (1989). Models include overshooting and are calculated for a metallicity of $Z = 0.02$.

photometry (see Moon & Dworetsky 1985; see also the user friendly web tool `TEMPLOGG2` at `http://ams.astro.univie.ac.at/templogg/`) or from Geneva photometry through the use of special calibrations algorithms (e.g., Hauck & North 1993), or from more accurate spectroscopic studies. In principle, once the temperature is known, one could determine $\log g$ either from the photometry or from spectroscopy. Then, from evolutionary considerations, one could determine the stellar age. However, as explained in North & Kroll (1989), $\log g$ is not very sensitive to the stellar age for young stars – see also Fig. 1. The variation of $\log g$ with time during the first 30 % of fraction of life spent on the Main Sequence is nearly negligible (compared to the accuracy of the $\log g$ estimates), especially in the case of lower mass A-type stars. Thus it is practically impossible to identify the age of a young A star through the $\log g$ measurement (see North & Kroll 1989).

A better method is to measure the absolute luminosity of the star, which is possible if the parallax is known, and directly find the position of the star in the HR diagram. This approach has been followed, e.g., by Hubrig *et al.* (2000). However, this method is not particularly accurate. Figure 2 shows the example of a star for which the temperature is known with an accuracy of 300 K, and the absolute luminosity with an accuracy of about 20 %. The left panel of Fig. 2 shows the position of the star in the HR diagram, and the right panel shows how the uncertainties in the position of the star in the HR diagram affect the determination of its age. Fig. 2 shows the need for better determinations of the stellar temperatures and the luminosities of Ap stars than what is generally possible today. This situation can be improved only by constructing a database of Ap stars for which fundamental parameters are known from direct measurements (see Sect. 3.1).

An alternative approach to study the evolution of Ap stars consists in considering open cluster members. From the observed HR diagram of the cluster, and based on an evolutionary model, one can determine the open cluster age. Then, the evolutionary

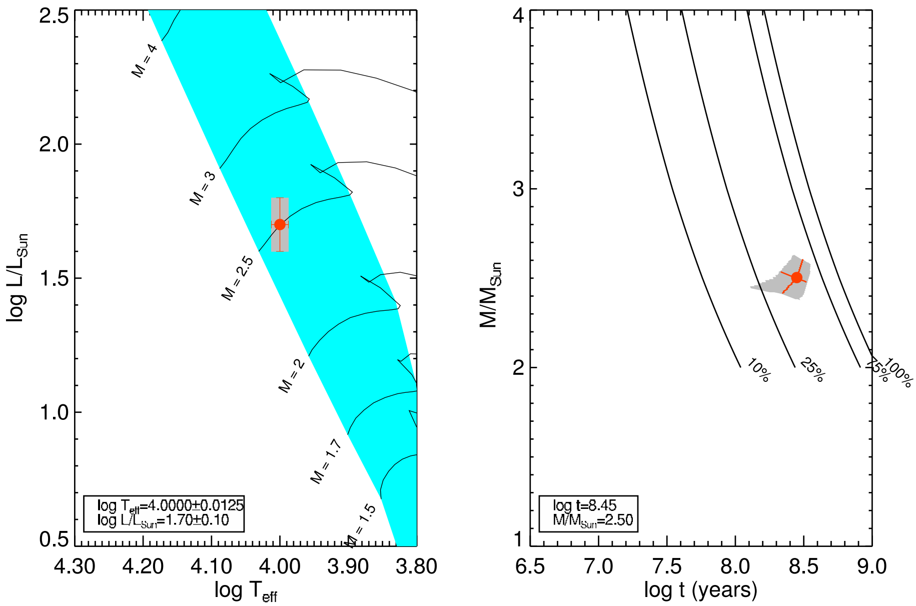

Figure 2. The left panel shows the position in the HR diagram of a star with a temperature $T_{\rm eff} = 10000 \pm 300\,{\rm K}$ and a luminosity $\log L = 1.7 \pm 0.1\,L_{\odot}$. The right panel shows how the uncertainties in a star's $T_{\rm eff}$ and L parameters affect the determination of the evolutionary state of the star. The solid lines represent the percentage of the time spent by the star on the Main Sequence as indicated in the labels for the mass given in the y axis of the plot.

model gives mass, log g, and fraction of life spent on the Main Sequence for those cluster members for which an effective temperature is known. The advantage with respect to the study of field stars is that one gets rid of the uncertainties in the stellar age and mass introduced by the error in the absolute luminosity.

Studies of open cluster Ap stars have been done, e.g., by North (1993). Fraga & Kanaan (2005) concluded that, to determine if the chemical peculiarities depends on age, it is necessary to observe at least 2700 stars in three range ages ("young", "intermediate", and "old"). The importance of chemical analyses of A-stars belonging to the same open cluster has emphasized by Monier & Richard (2005). From the photometric point of view, important work has been done by Maitzen, Paunzen, and their group with Δa photometry (see, e.g., Paunzen *et al.* 2003 and references therein). We will see that FLAMES, a multi-object, intermediate and high resolution spectrograph attached at the Unit 2 Kueyen of the ESO VLT is an ideal instrument for cluster studies and it may possibly replace Δa photometry (Sect. 3.2). In Sect. 3.3 we will see that FORS1 can also be used for the detection of the magnetic fields in open cluster stars, and in Sects. 3.4–3.6 I present some instruments that permit a detailed analysis in terms of magnetic field mapping and abundance analysis of individual targets.

3. Observing A-type and related stars with the instruments at the large size class telescopes

3.1. *Interferometry and A-type stars*

Interferometry has received little attention in this Symposium. However, there is a large number of applications in the field of A stars, for instance, studies of circumstellar material around Herbig Ae/Be stars (e.g., Eisner *et al.* 2003, Millan-Gabet *et al.* 2001). It

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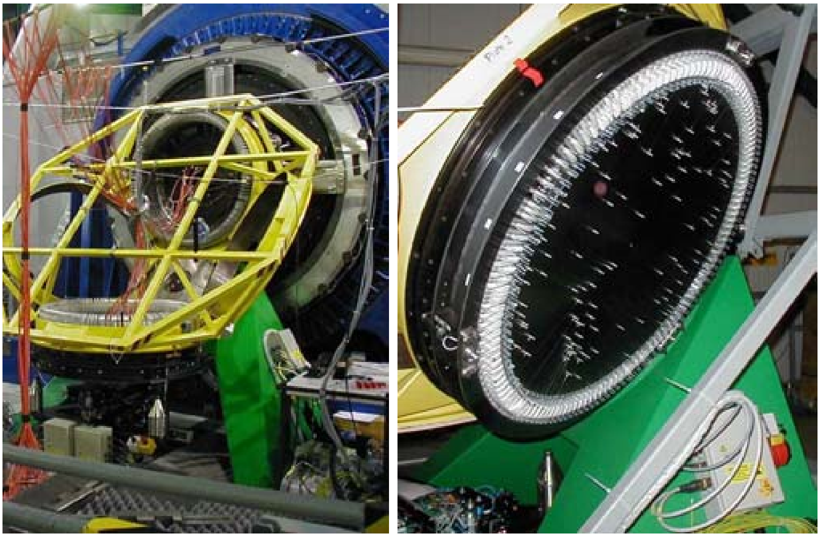

Figure 3. FLAMES: the whole structure supporting the two observing plates (left photo) and the details of one observing plate (right photo): the buttoms carrying the fibers are visible.

is also interesting to recall that with an interferometric technique, van Belle *et al.* (2001) have recently performed angular size measurements for the A star Altair, that indicate a noncircular projected disk brightness distribution. Altair is the first Main-Sequence star for which direct observations of an *oblate* photosphere have been reported.

Probably, the most important application of interferometry to A star research is the determination of stellar diameters, as the combination of the Bolometric flux and the star's angular diameter provide the most direct determination of the stellar temperature. Hanbury Brown *et al.* (1974) have determined the angular diameter of Sirius as 5.89 ± 0.16 mas. In a recent work based on VINCI + VLTI data, Kervella *et al.* (2003) have measured the Sirius diameter as 6.039 ± 0.019 mas. The measurement accuracy is nearly 10 times better than the previous estimate by Hanbury Brown *et al.* (1974). Kervella *et al.* (2003) note that the largest uncertainity in the star's linear diameter is no longer given by the stellar angular diameters, but by the (Hipparcos) parallax of the star. The diameter of a large number of (nearby) A stars may be measured using AMBER + VLT (Petrov *et al.* 2000). For better than Hipparcos parallaxes, we will have to wait for the Gaia mission (see, e.g., `http://astro.estec.esa.nl/GAIA`). There is still the need to better know the actual spectral energy distribution of Ap stars, something that may be achieved with the ASTRA spectrophotometer (Adelman *et al.* 2005) which uses a 0.5-m telescope.

3.2. *Multi-object medium-high resolution spectroscopy: FLAMES*

FLAMES is a quite complex instrument. Attached to the Nasmyth focus of the telescope is the Nasmyth corrector, a system of lenses that allows the exploitation of the full 25 arcminutes diameter field of view delivered at the Nasmith focus of the VLT, correcting the field aberrations and reducing the field curvature. After the corrector comes the fiber positioner, hosting two plates (see Fig. 3). While one plate is attached to the focus during the exposure, the other one is positioning the fibres for the subsequent observation. One hundred thirty-two fibers feed the GIRAFFE spectrograph, and eight fibers feed the red arm of the high resolution spectrograph UVES (see Sect. 3.5). (In addition, there are

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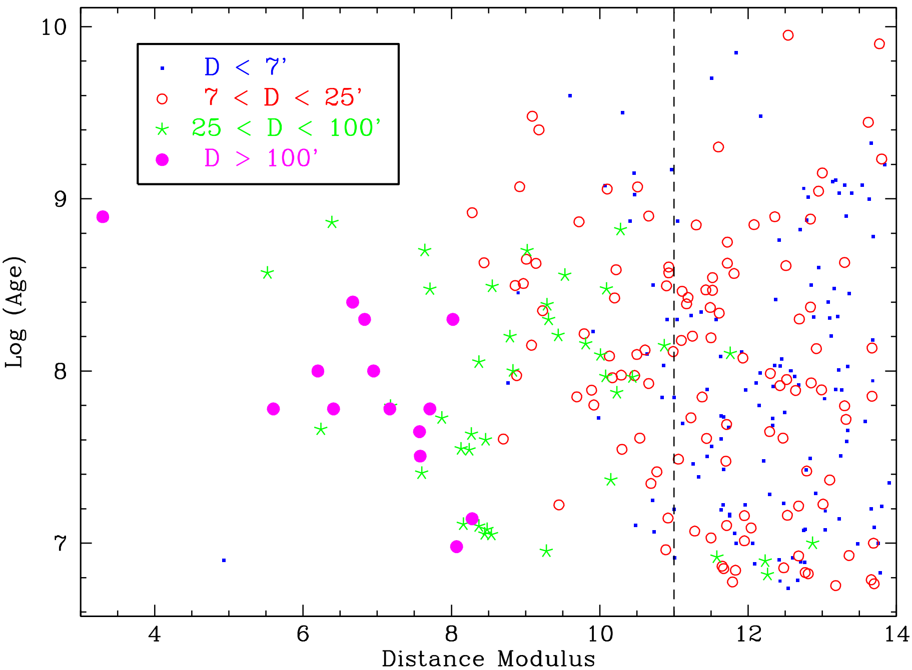

Figure 4. The positions in the log (Age) vs. Distance Modulus diagram for the open clusters selected according with the criteria explained in the text. Symbols refer to the angular size of the clusters expressed in arcminutes, to be compared with the FORS field of view (6.8×6.8 arcmin) and with the FLAMES field of view (25×25 arcmin). Data are taken from the WEBDA site developed and maintained by Jean-Claude Mermillod (`http://obswww.unige.ch/webda/`.)

four fibers that are used to point four reference stars with the purpose of centering and guiding, plus one large and 20 small integral field units.)

FLAMES-GIRAFFE is a medium-high resolution spectrograph for the entire visible range 370-900 nm. GIRAFFE has two gratings: high and low resolution. High resolution gratings offer a variety of different settings, covering a wavelength range of 17 up to 50 nm, and with a spectral resolution of about 20000. The low resolution grating offers a number of settings covering a wavelength range from 50 to 120 nm, and with a spectral resolution of about 7-8000. For further details about the instrument see Kaufer *et al.* (2004). In about 2 h of telescope time (i.e., including shutter time plus overheads), FLAMES + VLT permits one to obtain a $R = 20000$ spectrum around Hβ (from 470 nm to 500 nm) with a signal-to-noise ratio of 100 in a $V = 15$ A2 star. The range in age of open clusters that can be easily observed with FLAMES is shown in Figure 4, where all open clusters at $\delta \leqslant +20°$, with ages known from the literature, that have a distance modulus less than 14, are plotted.

3.3. *Multi-object low-resolution spectro-polarimetry: FORS1*

FORS1 is a multi-purpose instrument capable of doing optical imaging and spectroscopy, equipped with polarimetric optics (see Fig. 5). In the spectropolarimetric mode it allows one to obtain *IQUV* Stokes profiles with a resolution up to about 2000. Bagnulo *et al.* (2002) has shown that FORS1 can be used to detect the circular polarization of the Hβ lines of Ap stars and determine the mean longitudinal field with an accuracy better than 100 G (see also Wade *et al.* 2005). Here I just would like to add up that FORS1 has a multi-object capability that allows one to observe simultaneously up to 9 stars at once

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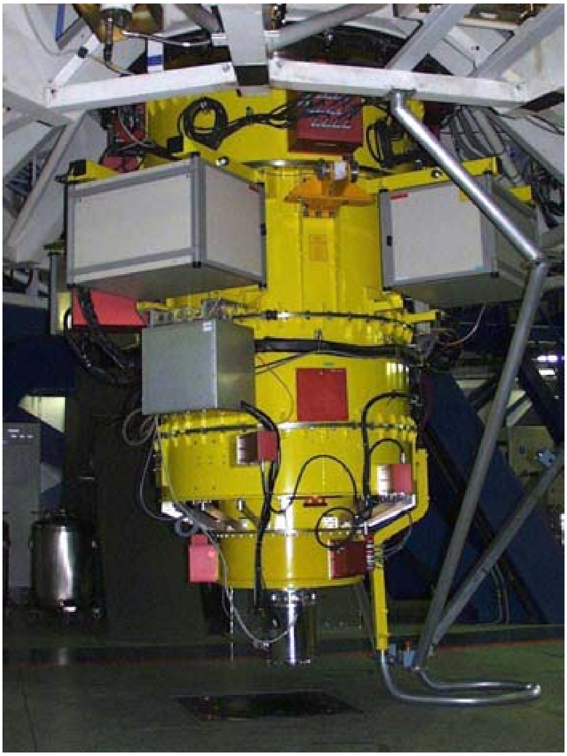

Figure 5. The FORS1 instrument of the VLT Unit 2 Kueyen permits one to obtain Stokes $IQUV$ profiles in the optical range with a spectral resolution up to about 2000.

in a 6.8×6.8 arcmin field of view in polarimetric mode. Hence, FORS1 is an instrument also suitable for open cluster studies, although the efficiency in terms of targets that can be observed simultaneously is much lower compared to FLAMES. To detect longitudinal fields, spectro-polarimetric observations must be characterized by a very high signal-to-noise ratio. Therefore the limiting magnitude of FORS1 is brighter than for FLAMES. If we use 11 as a conservative upper limit for the distance modulus, we can still reach a large number of clusters of various ages, as shown in Fig. 4. FORS1 has been frequently used for studies of (magnetic) open cluster Ap stars (e.g., Bagnulo *et al.* 2003a).

Obviously the scientific case of large telescope is not limited to evolutionary studies of open cluster A stars. Spectroscopy and spectropolarimetry of individual objects are extremely important for a variety of applications. For instance, Hubrig *et al.* (2004) used FORS1 for a search of magnetic field variability in roAp stars along the pulsation cycle. Drouine *et al.* (2005) used FORS1 to search for magnetic fields in Herbig Ae/Be stars.

3.4. *High resolution spectropolarimetry in the optical*

Low-resolution spectropolarimetry of Balmer lines is the most efficient method to detect magnetic fields in *fast* rotating stars ($v \sin i \geqslant 50\,\mathrm{km s^{-1}}$), whereas high-resolution spectropolarimetry is more efficient in *slow*-rotating stars because it allows one to resolve many (metal) lines, thus increasing the amount of information that can be gathered in an exposure. Furthermore, data obtained with FORS1 and other low resolution spectropolarimeters cannot be used for a detailed abundance analysis magnetic mapping of the target star. Unfortunately, the large size class telescopes are not equipped with high resolution spectropolarimeters. The only exception *may* be the PEPSI spectrograph, that

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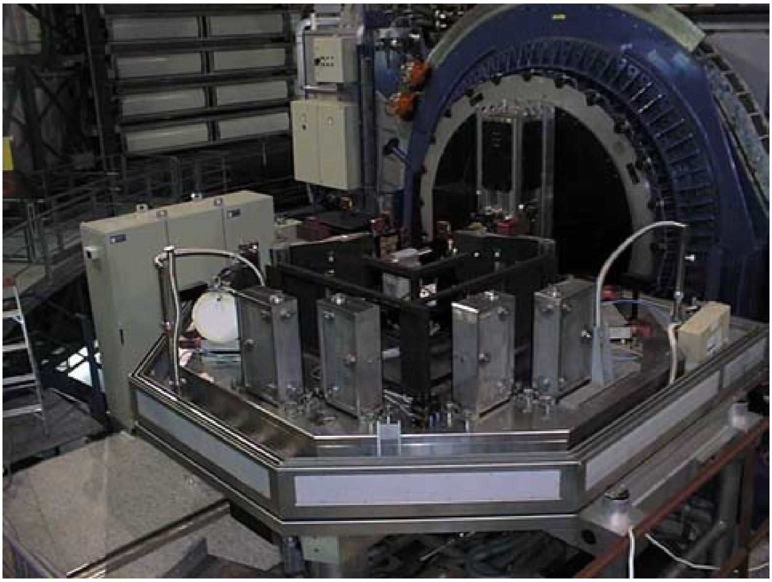

Figure 6. The high-resolution UV and Visible spectrograph UVES of the ESO VLT.

will be attached at the Large Binocular Telescope (LBT). The current project is to have two polarimeters (one for each telescope) that will feed the (single) PEPSI spectrograph. A total of four spectra per echelle order will be imaged onto the detector. The spectrograph is designed for a resolution-slit product of $R = 40000$ for 1 arcsec entrance slit and will allow a wavelength coverage from 390 to 1050 nm in three exposures (selected by using different cross-dispersers). For further details see `http://www.aip.de/pepsi/`.

Up to now, the only high-resolution spectropolarimeter publicly available was the echelle MuSiCoS spectrograph at the 2 m Telescope Bernard Lyot (TBL) of Pic-du-Midi observatory (see Wade 2003 for a review of the scientific output of MuSiCoS). Things have changed with the beginning of the operations of ESPaDOnS, a $R = 70000$ spectrograph equipped with polarimetric optics, that can cover the wavelength range between 370 and 1000 nm with a single exposure. Attached to the 3.6 m CHFT, ESPaDOnS has been offered to the community starting with the first semester of 2005. ESPaDOnS + CHFT is expected to be about 100 times more efficient in gathering light than MuSiCoS + TBL. Observations of Stokes profiles of magnetic Ap stars obtained with ESPaDOnS will meet the strict requirements in terms of spectral resolution and signal-to-noise ratio that have to be satisfied for a succesfull application of the Zeeman Doppler Imaging (Kochukhov & Piskunov 2002). A copy of ESPaDOnS, NARVAL, will soon replace MuSiCoS at Pic-du-Midi.

3.5. *High resolution spectroscopy in the near UV and visible: UVES*

Probably the most important tools for A star research, and for stellar studies in general, is high resolution spectroscopy. One of the most interesting instruments available is the Ultraviolet-Visible Echelle Spectrograph, UVES, attached at the VLT Unit 2 Kueyen (see Fig. 6). In stand alone configuration, UVES can observe simultaneously in two arms, the blue arm and the red arm. Using the two available dichroics (i.e., with two subsequent exposures) the observed spectra cover almost the entire spectral range from 300 to 1000 nm, with the exceptions of a few gaps. UVES has been extensively used for A star studies, see, e.g., Kurtz (2005), who has presented the applications for high time

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resolution, high spectral resolution of roAp stars Kurtz *et al.* 2003). Probably, the most natural way to exploit UVES capabilities is just to perform a spectral analysis based on an unprecedented amount of lines. A publicly available library of high-resolution stellar spectra obtained with UVES has been presented by Bagnulo *et al.* (2003b). Additional specific applications to A-type stars include, for instance, the study of the wing-core anomaly of Balmer lines in Ap stars by Kochukhov *et al.* (2002).

3.6. *High resolution spectroscopic and spectropolarimetry in the IR*

Zeeman effects increases with wavelength. With an IR high-resolution spectropolarimeter one expects a substantial increase of the magnetic sensibility compared to the optical regime (although IR lines are substantially weaker and much less numerous in the IR than in the optical). CRIRES, a high resolution spectrograph equipped with polarimetric capabilities in the region between 1 and 5 μm, will soon become operational at the VLT. CRIRES will be a very useful instrument for the Ap star research even in its spectroscopic mode (i.e., without using it in polarimetric mode). An example of application of CRIRES to the A star research has been given by Mathys (2005). Optical observations of sharp line Ap stars reveal a lack of stars with a field modulus smaller than 2.8 kG (Mathys *et al.* 1997). However, observations in the optical cannot reveal mean field modulus less than about 1.7 kG (Mathys *et al.* 1997). The magnetic sensibility of high-resolution spectroscopy in the IR is much higher, and observations with CRIRES will permit one to verify the puzzling result obtained by Mathys *et al.* (1997) down to a much lower field modulus limit.

For a practical example of an IR spectroscopic study of Ap stars see Leone *et al.* (2003).

4. Conclusions: the future giant telescopes

The techniques to build and operate 6 to 10 m telescopes are now well established, and many efforts are devoted to build Extremely Large Telescopes (ELT, about 25 m size). ESO is skipping this step, and is undertaking the design of a giant, optical and near-infrared telescope with a 100 m diameter, dubbed Overwhelmingly Large Telescope (OWL).

OWL design and construction relies extensively on modular design, integration and maintenance of a large numbers of identical parts, components and modules as pioneered by Gustave Eiffel in 1899 for his eponymous tower, and, as far as the spherical primary segmented mirror is concerned, as pioneered by the Hobby-Eberly Telescope in the 1990. The OWL primary 100 m mirror is composed of 3084 hexagonal segments, each of them 1.6 m in size. The secondary mirror is 25 m in diameter, and is composed of 216 hexagonal segments, each of them is again 1.6 m in size. The modular approach can break the time-versus-diameter law of approximately 1 year per 1 m of diameter, and OWL may become operational in less than 20 years from now!

A lot of efforts are now invested in large telescopes, and the small telescopes are often sacrificed for budget reasons. The experience acquired so far with the VLT instruments shows that the A-star community can have access to the large size class telescopes, and perhaps will also benefit from the use of giant telescopes such as OWL. However, it should be noted that in the future it may become easier to have access to telescope time to obtain spectra of extragalactic A-stars, than to measure light curves of bright stars. I do not know how serious is this drawback, but it is something that deserves some attention.

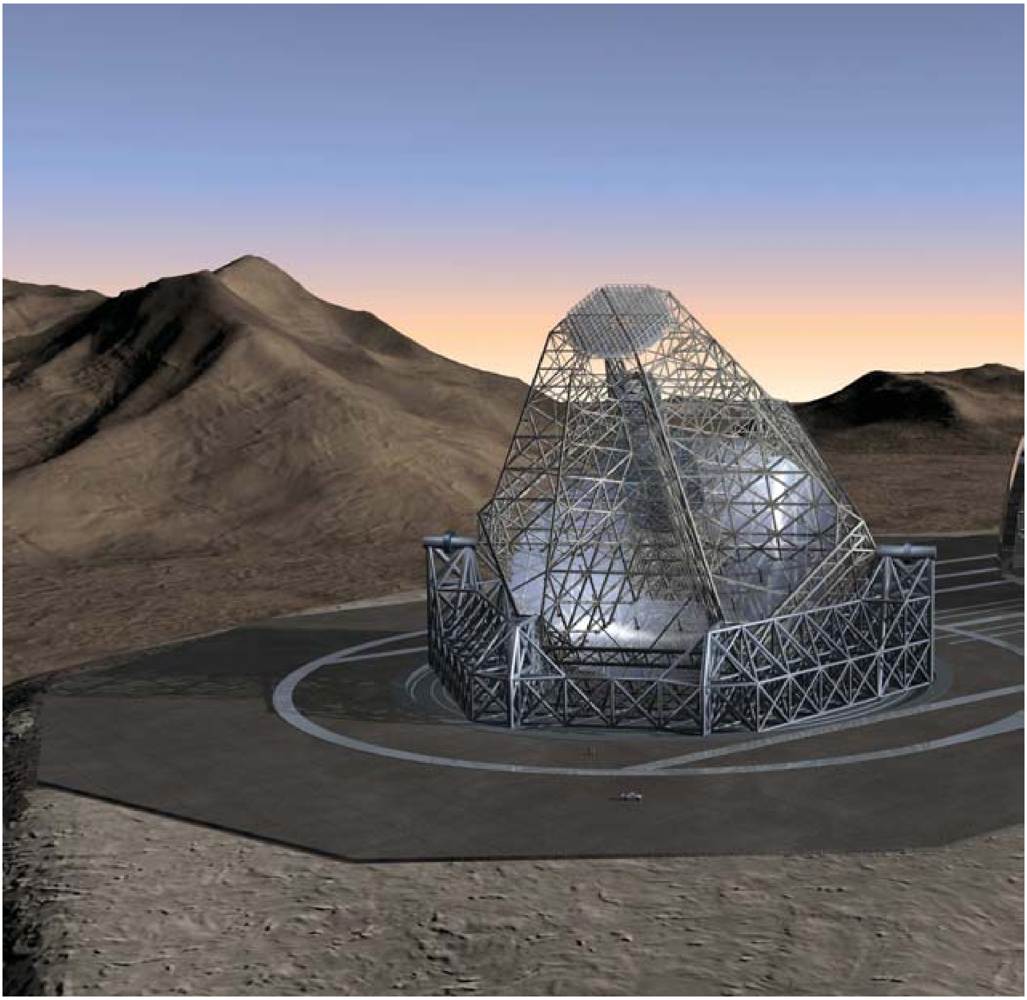

Figure 7. OWL

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Discussion

Khalack: I understand that the OWL telescope is only a project. It seems to me that the problem of the simultaneous correction of the position of the segments in an extremely short time scale does not have a technical solution at a sufficiently high quality level at present.

Bagnulo: Segments must be re-adjusted in position a few times per second to cope with flexures and thermal changes. Misalignments are measured by edge sensors that are calibrated with a phasing sensor located at the focus of the telescope. The phasing sensors used in the Keck telescopes should theoretically work with up to about 4000 segments; others kinds of sensor have been shown to work in laboratory experiments and are being developed for on-sky testing (see `http://www.eso.org/projects/owl/FAQs.html`)

Dworetsky: Following the project to obtain 400 spectra for a public UVES library, is it possible to do a twilight service observing project to observe many other stars, once each?

Bagnulo: The major problem is that now all the foci of the Unit 2 Kueyen are equipped with instruments (instead, when UVESPOP was being carried out, UVES was the only instrument operating at Kueyen). In particular, FORS1, attached at the Cassegrain focus, needs frequent skyflat calibrations that must be taken during twilight. It is not impossible to use twilight time to do science with UVES, but it is not so "painless" as it was in the past.

Smalley: Another way to obtain fundamental parameters of stars is to use eclipsing spectroscopic binaries which allows us to determine model-independent and This is especially worth in open clusters where age and distances are constrained (see Southworth *et al.* 2005)