Hot stars in the Gaia-ESO Survey

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Abstract. The Gaia-ESO Survey will produce spectra of about 100 000 stars, using the VLT FLAMES instrument. This includes hot, massive stars in a number of selected clusters. I describe the on-going cluster selection as well as the work package responsible for analyzing the hot-star spectra.

1. Large surveys
Astronomy has recently entered the era of large surveys. Many photometric surveys, as well as a few spectroscopic ones, are currently underway or are planned for the near future. A (non-exhaustive) list of these surveys is given in Table 1.

Astronet, the consortium of the largest funding agencies for astronomy in Europe, recently reviewed the situation of the European 2- to 4-meter class telescopes (ETSRC 2010). One of the recommendations of the Review Committee was that some of these telescopes be used for complementary programmes in support of European space missions. Where needed, new instrumentation will be developed to efficiently achieve these goals. As a consequence, these telescopes will no longer be available for individual astronomers, or small groups of them, but only for larger consortia of astronomers.

Finally, the upcoming Gaia mission promises to deliver high-accuracy positions, distances, proper motions and photometry of 1 billion stars, with each star being observed (on average) 80 times. Spectroscopy of 150 million stars will also be obtained, on average 40 times for each star.

All the above makes it clear that we have entered the age of ‘industrial’ astrophysics. This will imply considerable changes in the way that astronomers do their research.

2. Gaia and massive stars
2.1. The Gaia satellite
The Gaia satellite\(^1\) will provide astrometry and photometry down to magnitude \(G\approx20\) (for hot stars, the Gaia-band \(G\) magnitude is approximately equal to the Johnson \(V\) magnitude). Radial velocities will be determined for all stars down to \(G_{\text{RVS}}\approx17\), and stellar atmosphere parameters down to \(G_{\text{RVS}}\approx13\) (again, for hot stars, the magnitude in the Radial Velocity Spectrometer filter \(G_{\text{RVS}}\) is approximately equal to the Johnson \(V\) magnitude). However, for massive early-type stars the spectroscopic estimates may be too optimistic, as the spectral windows are not

\(^1\) For the expected science performance of Gaia, see: http://www.rssd.esa.int/index.php?project=GAIA&page=Science_Performance
Table 1. Non-exhaustive list of current and near-future surveys.

| acronym | name | distinguishing features |
|---------|------|-------------------------|
| SDSS    | Sloan Digital Sky Survey | images of 350 million objects, spectra of 1.5 million |
| UKIDSS  | UKIRT Infrared Deep Sky Survey | JHK photometry over 7500 square degrees down to K=18.3 |
| IPHAS   | INT/WFC Photometric H-alpha Survey of the Northern Galactic Plane | photometry in Hα, r and i filters |
| UVEX    | UV-Excess Survey of the Northern Galactic Plane | photometry in U, g, r and He i 5876 |
| VPHAS+  | VST/OMEGACAM Photometric H-alpha Survey of the Southern Galactic Plane | southern counterpart to IPHAS and UVEX |
| SkyMapper | SkyMapper | photometry southern sky in uvgriz filters, down to mag 22 |
| Pan-STARRS | Panoramic Survey Telescope & Rapid Response System | photometry down to mag 24; whole sky will be observed 3 times in each lunar cycle |
| VVV     | VISTA Variables in the Via Lactea | deep IR atlas in 5 passbands |
| LSST    | Large Synoptic Survey Telescope | photometry of billions of objects; entire visible sky every 3 nights for 10 years; down to mag 24-25 |
| RAVE    | RAvelocity Experiment | spectra of up to 1000000 stars. Outside the Galactic Plane, so no significant number of hot stars are observed. |
| LEGUE   | LAMOST Experiment for Galactic Understanding and Evolution | multi-fibre spectroscopy with 4000 fibres. Will observe Galactic halo stars, stars in the anticentre, and bright Galactic disk stars. This includes a complete census of OB stars in the Galactic plane \((20° < l < 230°)\). |
| GALAH   | GALactic Archaeology with HERMES | high resolution spectra of over a million Galactic disk stars. Uncertain if many OB stars will be included. |
optimized for those stars. The expected precision in radial velocity for a B1 V star is 1 km s\(^{-1}\) at \(V=7\) and 9 km s\(^{-1}\) at \(V=12\), and the precision will quickly degrade for fainter stars.

2.2. Number of massive stars
To better understand the important contribution that Gaia will make to massive-star research, we can estimate how many currently unknown massive stars will be detected by Gaia. There are various ways to obtain a rough values for this number. Shara et al. (2011) estimate the number of Wolf-Rayet stars to be in the range 1000 – 6500. Taking a factor of 10 more O-type stars than W-R stars, there should be 10 000 – 65 000 O-type stars. An alternative estimate starts from the viewpoint that there should be about 100 clusters of the 30 Dor type in the Galaxy (Hanson & Popescu 2008). Based on that we estimate that there should be of the order of 100 000 massive stars. A third possibility is to look to the Besançon Universe model, which predicts that Gaia will observe about 900 000 B-type stars (Jordi and Carrasco 2007).

However, the number of O and early B-type stars currently known is quite small compared to these predictions. The most extensive catalogue is the one maintained by Reed\(^2\) (2003). It is based on spectral type determinations that have been published in the literature. It lists 19766 stars of type O and early-B (the catalogue is known to be incomplete for main-sequence stars later than spectral type B2).

Figure 1 plots the histogram of the Reed catalogue as a function of \(V\) magnitude. It is clear that the catalogue becomes incomplete around \(V=10\). If we require also some spectroscopic information (red line), we lose another magnitude.

![Histogram of the Reed catalogue](image)

**Figure 1.** Histogram of the Reed catalogue, as a function of \(V\)-magnitude (black line). The red line indicates the histogram limited to those stars for which spectroscopic information is available.

\(^2\) See also: [http://othello.alma.edu/~reed/obnotes.doc](http://othello.alma.edu/~reed/obnotes.doc)
2.3. *Gaia contribution to hot-star research*

The good news therefore is that Gaia will provide at least one order of magnitude more hot stars than are currently known. Furthermore, we will know the distance to all of them with considerably higher accuracy than before. This improved census of massive stars will allow us to address a number of scientific questions, such as the organization of the Galactic Plane and the spiral arms. It will allow crucial quantitative tests of massive star evolution, and it will improve the number statistics of various evolutionary phases, including the better detection and statistics of the important, short-lived phases (LBVs, binary mergers, ...).

The bad news is that we will have little or no spectroscopic information for most of these stars. The Gaia spectroscopy does not reach the same magnitude limits as the astrometry and the photometry. Furthermore the spectroscopic domain is limited to 847 – 874 nm; for hot stars we will mainly detect a number of Paschen lines in that wavelength range, but little else.

Recognizing the massive stars will therefore have to be done using the Gaia photometry. That, however, will be complicated by the so-called $A_V - T_{\text{eff}}$ degeneracy. Due to noise in the data, a unique determination of effective temperature ($T_{\text{eff}}$) and interstellar extinction ($A_V$) is never possible. But, in addition to that, the confidence regions of the best-bit solution do not show a nice error-ellipse in the $T_{\text{eff}}, A_V$ plane, but rather an extended “ridge” (Bailer-Jones 2010). This effect is especially serious for the hotter, more massive stars (Blomme et al. 2011). One possible way to reduce the impact of this problem is to use the fact that massive stars frequently are found in clusters. By assuming a constant interstellar extinction in that cluster, the effective temperatures will be better determined (although that assumption may not always be valid).

3. *Gaia-ESO Survey (GES)*

3.1. *Overview of the survey*

To obtain more spectroscopic information for all types of Galactic stars, the Gaia-ESO Survey (GES) was proposed. The project is led by G. Gilmore and S. Randich and includes more than 250 Co-Investigators. It will use the VLT FLAMES instrument (on the UT2 telescope), with both the Giraffe and UVES fibres. It will require 300 nights, spread over 5 years. We expect that of order $10^5$ Giraffe spectra will be taken, and of order $10^4$ UVES spectra. The proposal was recommended for implementation by the ESO Observing Programmes Committee (OPC) and the Survey Management Plan is currently (Summer 2011) being developed.

The main goal of the GES is to study the formation and evolution of the Milky Way and its stellar populations. This includes determining the substructure of the halo, the nature of the bulge, studying the formation of the thick and thin disks, as well as the dynamical and stellar evolution of open clusters. The GES will therefore sample all these major components of the Milky Way. As part of the survey, about 60 old clusters will be studied (these are defined as having an age larger than 100 Myr) and 40 young clusters. Among those young clusters, 13 were chosen specifically for their massive-star content.

3.2. *Massive stars in the GES*

Our specific interest is in the O, B and A-type stars in these clusters. A number of scientific issues can be addressed with the spectra that will be collected for these types of stars. We will determine the stellar parameters and compare their position in the Hertzsprung-Russell diagram with theoretical evolutionary tracks and isochrones. This will lead to critical tests of stellar evolution modelling. The data will also help to constrain the upper part of the Initial Mass Function (IMF). For those stars where the Hα emission is strong enough, we will determine the mass-loss rates. The radiatively driven winds of these stars are known to be clumped, and the large number of stars studied will allow us to get a handle on this clumping issue.
Further analysis will also lead to the determination of abundances for a number of elements. From evolutionary calculations, it is known that the Nitrogen abundance is strongly influenced by rotation. While these predictions hold well in the Small and Large Magellanic Clouds, the situation is more confused in our Galaxy (Hunter et al. 2009).

The hot stars can also be used to study Galactic abundance gradients. Because of their high luminosity, they can be seen over larger distances than the cooler stars, thus providing a larger baseline. Because they are also much younger, they provide abundance values much closer to the present-day ones. By comparing the gradient based on young hot stars with that inferred from older populations, one can derive the time evolution of the gradient; this is one of the most powerful constraints on models of thin disc formation.

The data will also be relevant to Be stars. By systematically comparing Be stars to normal B stars, we can better understand the origin of the Be phenomenon. A higher fraction of Be stars is predicted for either higher masses (Zorec et al. 2005), or for more evolved main-sequence stars (Ekström et al. 2008). A large sample of high-resolution spectra will allow a much more accurate age determination for more stars, and thus will disentangle the mass and age effects.

3.3. Observation strategy
We expect spectra of approximately 1500 O, B, A stars to be observed as part of the GES.

The observation strategy for hot stars is different from that for cooler stars. The latter are observed in Giraffe gratings that are more in the red part of the spectrum (HR10, HR15N, and HR21). For the hot stars we use gratings in the blue part of the spectrum, as well as one that covers the H\(_\alpha\) line (see Table 2). The table also lists the spectral lines that are of specific relevance to hot stars either to determine the stellar parameters or the abundances.

Besides the Giraffe gratings, we also intend to use the six fibres of the UVES spectrograph with the CD3 520 nm setting. To position all fibres, we will use astrometry from the 2MASS survey. We aim to achieve a S/N = 100 in O, B stars: this will result in a radial velocity accuracy of 0.5 km s\(^{-1}\) (for slow and medium-fast rotators). With a per-pixel S/N of 50 for UVES, good abundance determinations will be possible.

3.4. Cluster selection
A preliminary selection of the massive star clusters to be studied has already been done. A major selection criterion is of course the science interest of the cluster. But a number of technical issues play a role as well. We need to be reasonably sure about the cluster membership of the stars. While this may be less of a problem for the earliest spectral types, it does become more problematic when we consider the A-type stars.

Furthermore, we also need a sufficient number of stars within a limited magnitude range, so we can efficiently use the 131 FLAMES fibres to make a simultaneous integration, resulting in spectra with usable S/N. An example is shown in Fig. 2, where we plot the histogram of the cluster stars in bins of B-magnitude (we prefer to use the B-magnitude, because most of our gratings are in the blue part of the spectrum). To indicate what spectral types these bins correspond to, we correct the observed B-magnitude for interstellar extinction and distance, and convert it into spectral type, assuming that the stars are on the Zero-Age Main Sequence (ZAMS). The upper part of the figure shows the three proposed pointings of the FLAMES instrument: one for the magnitude range 10.0 to 13.0 (with \(n = 57\) targets), one for magnitude 13.0 – 15.0 (\(n = 104\)) and one for magnitude 15.0 – 17.0 (\(n = 98\)).

Taking into account the procedures outlined above, we made a preliminary list of massive-star clusters for the GES (see Table 3). This list will most probably undergo changes and extensions, before it becomes final.
Table 2. FLAMES settings to be used in GES for hot star observations.

| Giraffe gratings | wavelength range (Å) | spectral lines |
|------------------|---------------------|----------------|
| HR03             | 4033–4201           | Hδ 4102        |
|                  |                     | He I 4121, He I 4144, Si IV 4089, Si IV 4116, Si II 4129 |
|                  |                     | O II 4075, 4133, 4157, 4185 |
| HR05A            | 4340–4587           | He I 4387, He I 4471, He II 4542 |
|                  |                     | Si III 4552, Si III 4568, Si III 4575, Mg II 4481 |
|                  |                     | N II 4447, O II 4350, 4367, 4396, 4415, 4452 |
| HR06             | 4538–4759           | He I 4713, He II 4541, He II 4686 (wind line) |
|                  |                     | Si IV 4631, Si IV 4654, Si III 4560 |
|                  |                     | C III 4650, N II 4601, 4614, 4631, 4643, O II 4595, 4640-70, 4700 |
| HR14A            | 6308–6701           | Hα 6563 (wind line) |
|                  |                     | He I 6678, He II 6527, He II 6683, Si II 6347 |
|                  |                     | C II 6580 |

UVES settings

CD3, 520 nm 4140–6210 overlaps with HR03, 05A, 06. Also includes Hγ.

UVES fibres will be used for the brightest stars only.

Table 3. Preliminary list of GES clusters selected for their massive-star content. Also listed is the number of proposed pointings.

| cluster       | # pointings | cluster       | # pointings |
|---------------|-------------|---------------|-------------|
| NGC 3293      | 3           | NGC 4755      | 3           |
| Trumpler 16   | 4           | Dolidze 25    | 3           |
| NGC 3766      | 2           | Collinder 228 | 2           |
| Trumpler 27   | 2           | Westerlund 2  | 1           |
| NGC 6649      | 5           | IC 2944       | 2           |

4. Work package on hot stars

One of the work packages of the GES is responsible for the analysis of the O, B and A-type stars. It is led by the author and its task is to determine stellar parameters and abundances from the observed spectra of O, B, A stars.

First of all, the effective temperature and surface gravity will be determined. As these stars are part of a cluster, we will also have a good estimate of the distance (and another work package will be responsible for refining that value). Given the distance, we can also derive the luminosity, radius and mass. By comparing these values to evolutionary tracks, we can also determine the age and initial mass. Where appropriate, we will also measure the mass-loss rate (assuming no clumping) from the observed Hα line profile.
Figure 2. Histogram of the stars in the cluster NGC 3293, in bins of $B$-magnitude. The interpretation as spectral types assumes that the star is on the ZAMS. The top of the figure shows the three proposed pointings for this cluster, each pointing covering a specific magnitude range.

The techniques we will use for this are the classical ones where the observed spectra (or equivalent widths of the lines) are compared to synthetic spectra. A number of groups have volunteered to help in the effort needed for this work package.

5. Conclusions
A large number of astronomical surveys are currently running or are planned for the near future. The Gaia satellite will add substantial information to the ever-growing amount of data. The Gaia-ESO project will complement all this with a large number of high-resolution spectra. Specifically for hot stars, we expect to make a substantial addition to the number of stars studied, which will lead to interesting results in this field of research.

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References
Bailer-Jones C A L 2010 MNRAS 403 96
Blomme R, Frémat Y, Lobel A and Martayan C 2011 Gaia: At the Frontiers of Astrometry EAS Publications Series vol 45, ed C Turon et al (Les Ulis: EDP Sciences) p 373
Ekström S., Meynet G., Maeder A and Barblan, F. 2008 A&A 478 467
ETSRC 2010 Report by the European Telescope Strategic Review Committee on Europe’s 2-4m telescopes over the decade to 2020 http://htdocs.factory02.com/astronet/IMG/pdf/PlaquetteT2_4m-final-2.pdf
Hanson M M and Popescu B 2008 *Massive Stars as Cosmic Engines* IAU Symposium 250, ed F Bresolin et al (Cambridge: Cambridge University Press) p 307

Hunter I et al 2009 *A&A* **496** 841

Jordi C and Carrasco J M 2007 *The Future of Photometric, Spectrophotometric and Polarimetric Standardization* ASP Conference Series vol 364, ed C Sterken (San Francisco: Astronomical Society of the Pacific) p 215

Reed B C 2003 *AJ* **125** 2531

Shara M M, Faherty J K, Zurek D, Moffat A F J, Gerke J, Doyon R, Artigau E and Drissen L 2011 A Near-Infrared Survey of the Inner Galactic Plane for Wolf-Rayet Stars II. Going Fainter: 72 More New WR Stars *Preprint* astro-ph/1106.2196

Zorec J, Frémat Y and Cidale L 2005 *A&A* **441** 235