The SkyMapper Search for Extremely Metal-Poor Stars*

Gary Da Costa

Research School of Astronomy & Astrophysics,
Australian National University

on behalf of:

Martin Asplund (ANU), **Mike Bessell** (ANU), Andy Casey (IoA), Anna Frebel (MIT), Alex Heger (Monash), Karin Lind (MPIA), Dougal Mackey (ANU), Fabiola Marino (ANU), Simon Murphy (ADFA), John Norris (ANU), Brian Schmidt (ANU) and David Yong (ANU)

* In the Galactic Halo, see Martin for the related search in the Galactic Bulge
• The SkyMapper photometric survey of the southern sky has the discovery of extremely metal-poor (EMP) stars as one of its main science aims. This is accomplished by the inclusion of a narrow-band ‘\(v\)' filter centred on the Ca II H+K lines to generate a photometric index that is sensitive to metallicity.

• During the commissioning of the telescope, a ‘commissioning survey’ for EMP stars was carried out. Despite generally poor image quality, this survey led to the discovery of the most iron-poor star known: SMSS J031300.36-670839.3 which has \([\text{Fe/H}] < -6.5\) (3D, NLTE - see Nordlander et al 2016).

• The commissioning survey also led to the discovery and analysis of a further 41 new EMP stars with \([\text{Fe/H}] < -3\) (Jacobson et al 2015).
• The ‘commissioning survey’ ended when the telescope became operational and since March 2015 the SkyMapper Southern Sky Survey has been on-going.

• The survey program was initially dominated by relatively short exposure images that will ultimately provide the photometric calibration for the full survey.

• The limiting magnitudes of the short exposure data ($v \sim 17.3$, $g \sim 17.7$, $i \sim 17.7$ AB mags) are perfect for searching for EMP stars bright enough to follow-up with high dispersion spectroscopy on 8-10m class telescopes.
• The first data release from the SkyMapper survey is the **EARLY DATA RELEASE (EDR)** that was made public to the Australian community in May this year.

• The EDR is intended to provide the Australian community with experience with SkyMapper data prior to the first ‘official’ data release (DR1) that will occur in early 2017.

• The EDR covers ~6700 sq deg of the southern sky and includes all SkyMapper fields with low reddening, that have at least two images in each filter, and for which seeing < 5 arcsec.

• The EDR images are not sky-limited as regards the photometry errors - there are substantial bias residuals and fixed pattern noise (fixed for DR1). The zero point calibration (from APASS) has potential field-to-field issues and reddening corrections are also problematical (again improved in DR1). Photometry of crowded fields not handled well. **NEVERTHELESS…**
We are using the SkyMapper EDR photometry to search for EMP candidates. Basic approach is:

- Select candidates from EDR photometry
- Observe the candidates with low-resolution spectroscopy using the 2.3m telescope + WiFeS spectrograph at SSO
- Follow-up best candidates at high dispersion at either Magellan or Keck.
• So first question is “Does the EDR contain information useful for the EMP project?”.

• Selected from EDR database:

  o class star > 0.9 (high confidence star)
  o photometry flag ≤ 3 (Source Extractor photometry OK)
  o >1 measurement in all ugriz, ≥2 measures for v
  o g_psf < 16 (allows high dispersion follow-up)
  o tabulated photometry errors ≤0.03 g, i; ≤0.05 v
  o E(B-V) < 0.20 (Schlegel et al scale)
  o no other EDR or 2MASS detection with 5arcsec

This selection yields 2.75 million objects....
To investigate the usefulness of this diagram we cross-matched our EDR sample with a compilation of high dispersion abundance measurements ([Fe/H] < -2.0). There 111 stars in common, after minimizing the effects of photometry errors and reddening by selecting known abundance stars in the EDR to have E(B-V) < 0.1 and photometric uncertainties \( \leq 0.02 \) mag for all of \( v, g \) and \( i \).
Generally the location of known metal-poor ([Fe/H] < -2) stars in the diagram seems (mostly) sensible. The ones that are very discrepant are generally very carbon-rich.
The isochrones and the location of known metal-poor stars are (mostly) consistent.
• Given that metallicity sensitive diagram seems to show the expected sensitivity, how should we go about selecting candidates for low resolution spectroscopy at the 2.3m?

• The previous plot suggests we should concentrate on giants because for the hotter stars the isochrones are relatively close together (i.e., metallicity sensitivity is reduced) and the known metal-poor stars are not as well separated from the large number of solar-type dwarfs. So we have chosen:

  0.4 ≤ (g-i)_0 ≤ 0.9
  -0.25 ≤ m_index ≤ 0.11

The upper m_index value allows for errors in the m_index (which are potentially as large as 0.085 mag) while the lower cutoff is approximately the location of the -2.0 isochrone.

This selection yields about ~8000 candidates for g < 16 and ~3000 candidates for g < 15.
SkyMapper EDR photometry metallicity sensitive 2-colour diagram

The value of the lower cutoff is quite crucial as the number of candidates goes up very steeply as it’s increased. On the other hand it would a pity to miss any “prime” candidates because their $m_{\text{index}}$ errors scattered the star downwards.
• We have then taken the candidate list and proceeded to observe objects from the list with the 2.3m telescope and the WiFeS spectrograph (B3000 setup – $\lambda$ coverage ~3500-6000 Å).

• The reduced 2.3m spectra are flux calibrated and the best fitting model from a grid of MARCS model atmosphere fluxes determined using the “fitter” code developed by Simon Murphy (described in Norris et al 2013). The spectrophotometric model fits provide estimates of $T_{\text{eff}}$, log g and [Fe/H] for each observed spectrum.

• Here we report the outcome of six 2.3m observing runs between Feb and Aug 2016, during which spectra were obtained of 339 EMP candidates in the EDR selection box, plus standards, known abundance stars, etc.

Note: because the 2.3m observing started before the final EDR release, we have observed ~40% more objects than the specific defined sample just discussed. However the on-going observations now use just the EDR photometry defined sample.
• Example Spectrum

360sec exposure. Star has $g = 13.53$ and $m_{\text{index}} = 0.005$ and $(g-i)_0 = 0.58$
• Example of ‘fitter’ output (same star as previous slide)
• One obvious question is how good are the ‘fitter’ [Fe/H] values?

Plot shows a well defined relation between the ‘fitter’ [Fe/H] values (quantized at the 0.25 dex level) and high dispersion spectroscopic values of [Fe/H] from the literature for 23 stars.

Selecting stars with ‘fitter’ abundances at and below -3 is unlikely to significantly bias the actual metallicity distribution of the stars.
The MDF for the 339 EDR selected stars observed at the 2.3m confirms that the selection process is basically working:
- we reproduce the standard simple model result that a 1 dex decrease in [Fe/H] gives a 1 dex reduction in the number of stars;
- the turnover in the metallicities is at [Fe/H] = -2.75, which is where we’d like it. The efficiency is excellent (30% at or below -3).
- There are 6 stars at or below -3.75, whereas extrapolating the line would suggest 14 expected (~1.8\(\sigma\) effect). Need more stars.
Conclusions

• Overall a useful set of candidate EMP stars can be reliably selected from the SkyMapper EDR dataset.

• 2.3m spectroscopic follow-up has produced a number of candidates for follow-up at high dispersion with Magellan.

• EMP stars are nevertheless rare and we will need to continue to pursue the 2.3m program in order to increase the number of candidates at the lowest metallicities. A sample 5-7x larger (~2000 stars) may well be required to find significant number (~dozen) of stars below -4.5.
Improvements

• The photometric quality of DR1 will be much improved – likely to reduce contamination of the selection window by metal-richer objects.

• DR1 may also allow the search to be extended to lower galactic latitudes/higher reddening, a region less well explored compared to the halo.

• So far we have only used, the metallicity index vs g-i 2-colour diagram for selection. We plan to make use of the r, z photometry (and u for DR1) plus 2MASS, WISE to investigate improved selection processes (cross-matches to other surveys are already part of the SkyMapper EDR).
Bias temporally unstable
10+ principal components, changing per night and CCD
Also: CR removal (LACosmics)
Marked stars are HE2139-5432 (left) and HE1310-0536 (right) which have ([Fe/H], [C/Fe]) values of (-4.02,+2.59) and (-4.15,+2.36), respectively.
Issues:

Clearly we would NOT select these very carbon-enhanced EMP stars with the current selection window. They lie ‘low’ in the metallicity index plot because the additional CH-feature absorption in the $\nu$ filter band pass causes them to mimic a more metal-rich object.

The effect of this potential bias remains to be quantified, and it may be possible to isolate stars of this type using additional photometric colours. The bias will be a function of both [Fe/H] and [C/Fe].

We note that the bias may only apply to very strong carbon enhancements ([C/Fe] > +2 at [Fe/H] = -4 ?) because the Jacobson et al 2015 sample did not obviously lack CEMP stars, although it did not contain any stars with [C/Fe] > 1.5. The extremely iron-poor star SMSSJ0330-67 was found and it is very C-rich.
Thanks to all the people at SSO and at Mt Stromlo who keep the SkyMapper Survey running, both in the sense of the telescope and its systems, in the processing of the imaging, and in the distribution of the data products.

Without you the EMP-stars project would not happen!

SkyMapper operations are supported in part by a LIEF Grant from the ARC. SkyMapper Data products can be accessed through the SkyMapper node of the All Sky Virtual Observatory (ASVO). Funding from sources such as NeCTAR and administered by AAL have contributed to ASVO/SkyMapper development.