Extremely metal-poor stars from the SDSS

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Received 17 September 2008
Accepted for publication 22 September 2008
Published 19 December 2008

Abstract
We give a progress report on the activities within the CIFIST Team related to the search for extremely metal-poor (EMP) stars in the Sloan Digital Sky Survey’s (SDSS) spectroscopic catalogue. So far, the search has provided 25 candidates with metallicities around or smaller than $-3$. For 15 candidates, high-resolution spectroscopy with UVES at the VLT has confirmed their EMP status. Work is under way to extend the search to the SDSS’s photometric catalogue by augmenting the SDSS photometry and by gauging the capabilities of X-shooter when going to significantly fainter targets.

PACS numbers: 95.75.De, 95.75.Fg, 95.85.Kr, 97.10.Ex, 97.10.Tk, 97.10.Yp, 97.20.Tr

1. Introduction
Extremely metal-poor (EMP) stars with [M/H] $<-3$ are exceedingly rare objects but provide crucial information about the first generation of stars and the chemical make-up of the early Universe. The CIFIST (Cosmological Impact of the First STars) project is an EU-funded Marie Curie Excellence Team hosted by the Paris Observatory with the mission of searching for and analysing EMP stars. The following is a progress report of activities within the CIFIST Team related to using the Sloan Digital Sky Survey (SDSS) as a novel source of EMP candidates for high-resolution spectroscopic abundance studies of EMP stars. This includes the SDSS follow-up survey, the Sloan Extension for Galactic Understanding and Exploration (SEGUE).

Traditionally, the HK survey (Beers et al 1985) and Hamburg-ESO survey (HES) (Christlieb et al 2008, Wisotzki et al 1996) are the main sources of candidates in searches for metal-poor stars. Both surveys are fairly deep (HK $B < 15.5$, HES $B < 17.5$) objective prism, low resolution spectroscopic surveys which provided about 10 000 candidates each. Follow-up medium resolution ($R \approx 2000$) spectroscopy was used for confirming EMP candidates, having typically provided yields of a few percent of confirmed EMP stars.

Data release 6 (DR6) of the SDSS (Adelman-McCarthy et al 2008) provides photometric and spectroscopic data for about 10 000 square degrees of the sky at mostly northern Galactic latitudes. The major part of the data consists of photometry in the five SDSS filters ($ugriz$) for $287 \times 10^6$ unique objects. The smaller spectroscopic part consists of medium resolution ($R \approx 2000$) spectra of $218 \times 10^3$ stars earlier than type M, as well as $895 \times 10^3$ spectra of galaxies and quasars. The spectral coverage is 380–920 nm. The spectral coverage and resolution is sufficient to identify EMP stars with high confidence making the SDSS an interesting new source for EMP targets.

2. Metal-poor stars from SDSS spectra
From the SDSS catalogue, we selected objects identified by the SDSS pipeline as stars, and for which spectroscopic as well as photometric information was available. We restricted the search to magnitudes $g < 17$ (g roughly corresponds to Johnson V) allowing us to potentially obtain high-resolution spectra with 10 m class telescopes in a reasonable amount of time. We further used the $g - z$ colour as effective temperature ($T_{\text{eff}}$) indicator to narrow down the selection to stars with spectral type between F and early G. We derived a purely theoretical relation between colour and effective temperature ($T_{\text{eff}}$) giving the following relation:

$$T_{\text{eff}}[\text{K}] = 7126.7 - 2844.2 (g - z) + 666.80 (g - z)^2 - 11.724 (g - z)^3.$$
The rather high effective temperatures of our targets made it likely that we would mainly select dwarfs. This was done in view of later abundance work, and also to ease the task of analysing the SDSS spectra by assuming a typical surface gravity of $\log g = 4.0$ (cgs). To estimate the metallicities, we adapted an automatic abundance analysis code (Bonifacio and Caffau 2003) based on fitting of spectral lines. At extremely low metallicities and the resolution of the SDSS spectra, the Ca II K line is essentially the only remaining metal abundance indicator and was the prime target in our line fitting procedure. The selection of stars from DR6 based on photometric indices provided about 34,000 candidates whose metallicities were subsequently estimated with the fitting code using the photometric temperatures and assuming $\log g = 4.0$.

Figure 1 shows that our $T_{\text{eff}}$ estimates are closely correlated with those provided by the SDSS catalogue, albeit in our case they are shifted to about 150 K lower temperatures. Similarly, figure 2 shows a good correlation of the metallicity estimates, however, again biased towards lower values by about 0.2 dex in our case. To some extent, the lower metallicities are expected due to our lower $T_{\text{eff}}$ estimates. At very low metallicities, there is an extended ‘halo’ of largely discrepant objects. Visual inspection of the spectra has shown that they are commonly objects misclassified by the SDSS pipeline, such as white dwarfs or accretion disc objects with nonstellar spectral characteristics. Although one might wonder about the remaining systematics in the stellar parameter estimation, for our purpose of identifying EMP candidates, the achieved metallicity precision was sufficient.

Figure 3 shows the metallicity distribution obtained in our selection procedure. During the course of the SDSS project, spectra of stars have been mainly taken for calibration purposes with the tendency to pick blue objects. Hence, there was a bias towards metal-poor objects. $ugriz$ colours do not allow one to distinguish metallicities below about $-2$. Arguably (Carollo et al. 2007), the distribution at lower metallicities is thus free from selection effects, and it reflects the intrinsic stellar distribution. Anyway, we did not attempt to investigate this issue further, and just remark that our distribution can be fitted by a power law with an index of about 0.7 in the range $-4.0 < [\text{M/H}] < -2.5$. At the lowest metallicities, the distribution is unreliable due to the strong contamination by misclassified objects.

**3. High-resolution follow-up spectroscopy**

We have obtained so far a total of six nights of observing time at the Very Large Telescope (VLT) with Ultraviolet and Visual Echelle Spectrograph (UVES) for 25 EMP candidates. For 15 objects the observations are completed, and we obtained spectra with a resolution of $R \approx 21,000$. The abundance analysis is not completed yet so that only qualitative results can be presented here. Figure 4 shows a comparison of three of our SDSS stars in comparison to the metal-poor dwarf CS 22888-031 which has a metallicity of $[\text{Fe/H}] = -3.3$. All spectra have a similar resolution, and all stars share about the same effective temperature and gravity. Most of the visible features that are not labelled are Fe lines. It is obvious that our EMP candidates are at least as metal-poor as CS 22888-031. Up to now, our selection procedure has proven to be very effective, and no object with metallicity noticeably higher than that expected was found in the high-resolution spectroscopic follow-up.
Figure 4. Comparison of UVES spectra of three EMP stars extracted from the SDSS with the known EMP dwarf CS 22888-031 ([Fe/H] = −3.3).

Figure 5. Response of the Ca II K filter for giants.

In our sample of EMP stars from the SDSS, carbon-rich objects are quite common. Already expected from apparently strong G-bands in the SDSS spectra, their high carbon content has also been always confirmed by the high-resolution spectra.

4. Tapping into the SDSS photometry

Unfortunately, already the rather modest number of EMP stars found so far in the SDSS spectroscopy has started to exhaust the reservoir of solid EMP candidates. One would wish to access the substantially larger reservoir of photometric data. As stated previously, the SDSS photometry as such does not allow one to segregate EMP stars from moderately metal-poor objects. To overcome this limitation, in a pilot study, we try to augment the SDSS photometry by narrow-band photometry centred on the Ca K line. We utilized the available filter number 865 on the ESO 2.2 m telescope equipped with the Wide Field Imager. Figures 5 and 6 show the theoretical filter response curves for gravities typical of giants and dwarfs, respectively. The filter provides good discrimination to low metallicities, however, not in the F-type temperature range but for cooler temperatures. In the filter, we have imaged 10 square degrees of the sky which has been covered by the SDSS and are in the process of extracting the photometry. If workable, this procedure might open up a large sample of K-type stars for the search for EMP objects. We expect the technique not to be as effective as making use of SDSS-like spectra for identifying candidates, but nevertheless comparable to the yields previously obtained from the HK survey and HES.

5. Going deeper with X-shooter

Soon the X-shooter spectrograph at the VLT will see first light. X-shooter provides a wide spectral coverage with $R \approx 7000$ between the UV and 500 nm, and $R \approx 12000$ from 500 to 1000 nm. This kind of resolution is not ideal but nevertheless sufficient for some abundance work. The outstanding efficiency of X-shooter allows one to go to noticeably fainter targets than with UVES. We obtained two nights of guaranteed time observations for testing the capabilities of X-shooter for observing EMP stars. We selected ten candidates from the SDSS in the range $18.3 < g < 19.4$ of which a subset (depending on semester) will be observed. It will be exciting to see what this machine can do for finding the most metal-poor stars in the local Universe.

Acknowledgments

This work was made possible by financial support from EU grant MEXT-CT-2004-014265 (CIFIST) which is gratefully acknowledged.

Appendix. Discussion

Q: (Poul Erik Nissen) In the SDSS metallicity distribution there is a minimum at [Fe/H] $\simeq -1.4$. What is the reason for that?
A: I am not completely sure, however, the metallicity distribution contains disc and halo stars so that the bi-modal distribution might simply be an outcome of a particular combination of both. Keep in mind that
the distribution is heavily affected by the difficulty to quantitatively estimate selection effects.

Q: (Harm Habing) How much will your photometric selection of metal-poor stars be affected by the interstellar Ca II K line?
A: I cannot give you a quantitative answer. However, qualitatively the interstellar absorption leads to an overestimate of the intrinsic stellar metallicity so that the selection of metal-poor candidates stays on the conservative side.

A: (Norbert Christlieb) Usually the interstellar Ca K is quite weak in these halo stars, but in rare cases like HE1327-2326 it can lead to an overestimation of [Fe/H]: In this case, we estimated [Fe/H] ≈ −4.0 from the moderate-resolution spectrum, while the star has in fact [Fe/H] = −5.4.

Q: (Bengt Edvardsson) SEGUE is an excellent survey for stars. When will the catalogue be released and what data will be released?
A: Data from SEGUE have already been released according to the progress of the survey. The catalogue contains photometric and spectroscopic data as well as data products like radial velocities, and estimates of fundamental stellar properties.

Q: (Norbert Christlieb) How many of the SDSS stars that you find at [Fe/H] < −4.0 were rejected during the visual inspection of the spectra, and what were the reasons for rejecting them?
Q: I do not have the exact number in mind but it was a sizeable fraction. The reasons were the presence of white dwarfs, misclassified galaxies, and objects apparently affected by emission from accretion discs.

Q: (Sofia Feltzing) How do your [Fe/H] determinations compare to those derived using the pipeline developed for SEGUE? It is very useful to get an independent check of these values.
A: Ignoring extreme outliers (presumably due to misclassification of objects as stars) we obtain a similar metallicity distribution albeit shifted towards lower metallicities by about 0.2 dex.

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