Carbon-Enhanced Metal-Poor Stars in SDSS/SEGUE

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Abstract

The publicly available stellar database from SDSS contains many hundreds of metal-poor stars with large enhancements of carbon. The Galactic extension of SDSS, SEGUE, will identify several thousand more. Many of these Carbon-Enhanced Metal-Poor (CEMP) stars are likely to be enhanced in s-process elements created by AGB companions and dumped to the surviving member of a binary pair through either Roche-Lobe mass transfer or the operation of a stellar wind (CEMP-s stars). Based on previous high-resolution investigation of CEMP stars, an interesting subset of this sample is expected to show little or no s-process enhancement (CEMP-no stars).

Our present methodology for the estimation of [Fe/H] and [C/Fe] for CEMP stars is based on a calibration of line indices (e.g., for the CaII K line and the CH G band) discussed by Rossi et al. (2005). In some extreme cases, the presence of rather strong molecular carbon bands renders such approaches less than optimal. We are exploring spectral synthesis methods, based on a new library of carbon-enhanced MARCS model atmospheres, and synthetic $ugriz$ colors generated from these models, in order to better constrain the determination of metallicity and carbon abundance for the CEMP stars discovered in SDSS. Based on this approach, we derive a new estimate of the frequency of CEMP stars as a function of metallicity. We also report on the feasibility of using the detection or non-detection of Sr and Ba as a means for roughly separating CEMP stars into the CEMP-s and CEMP-no classes.

Background

A number of recent papers have noted that the frequency of carbon-enhanced stars seems to increase with declining metallicity, reaching on order 20% at the lowest metallicity ranges. This suggests that understanding the origin of this carbon production may be of critical importantance to a full understanding of the chemical evolution of the Milky Way. As such, it becomes increasingly important to correctly quantify the frequency of carbon-enhancement as a function of declining metallicity. In order to determine this vital statistic, it becomes crucial to accurately and precisely determine the metallicity, [Fe/H], and carbon abundance, [C/Fe], for as large a sample of stars as possible. A large sample of stars, like that produced by SDSS, is thus even more significant.

Line Index Method

Current Method - KP and GP line indices

- [Beers et al.(1999)]: Psuedo-equivalent width measurements of the CaII K line and the CH G-band, as illustated in Figure 1.
- With B-V colors, can be used to determine values for [Fe/H] and [C/Fe]
- [Rossi et al.(2005)]: Uses J-K colors, a more complete coverage of parameter space, and calibrated using carbon-enhanced stars

The Potential Flaw to the Technique

- For CEMP stars, a C_2 feature in the side band of the KP index can suppress the continuum
- This will affect the calculated [Fe/H] and [C/Fe] for the most carbon-enhanced stars

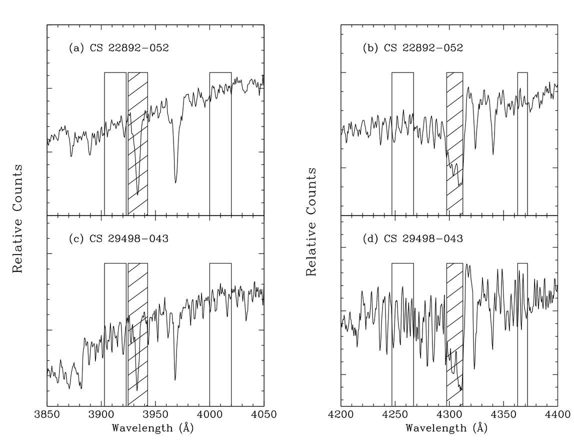

FIGURE 1: Location of the line indices KP and GP for two CEMP stars. See Rossi et al. (2005) for details

The Data

We are analyzing subsets of the spectrophotometric calibration stars (PHO) and reddening estimation stars (RED) from the Sloan Digital Sky Survey(SDSS). The particular sample studied here was selected by taking all stars with [Fe/H] $<=$ -1.0 and [C/Fe] $>=$ 0.5 from those two samples. Both of these samples are made up primarily of near turn-off stars. We have plans to analyze the full sample of PHO and RED stars in the near future, to better constrain the frequency of carbon-enhancement.

Spectral Synthesis

For extreme carbon-enhanced stars:

- Line analysis code MOOG [Sneden(1973)]
- 1D LTE Stellar atmosphere models [Castelli & Kurucz(2003)]
- Vary effective temperature, surface gravity, metallicity, and individual abundances to achieve the best fit.

Start with first guess parameters

- Determined using the traditional line index method
- Temperature and surface gravity are calculated from de-reddened J-K colors using the following equations:

$$T_{eff} = 6861 - 3504(J-K)_o$$
$$log(g) = 5.232 - 6.091(J-K)_o$$

- Current grid of model atmospheres is spaced with T_{eff} to the nearest 250 K, log(g) to the nearest 0.5, and [M/H], or overall metallicity, to the nearest 0.5.
- Then vary individual abundances until an appropriate fit is reached

Synthesize CaII K to get [Fe/H]

- Assume [α/Fe] = 0.4, typical for giant halo stars with [Fe/H] $<= -2.0$, to get [Fe/H] from calcium abundance

Synthesize CH G-band to get [C/Fe]

- May only be able to determine an upper limit, as in lower panel of Figure 3
- May need to refit CaII K with new carbon abundance, although this has not yet proven necessary

Can also measure neutron-capture elemental abundances

- For instance s-process elements, like barium or strontium, expected due to their close association with the production of carbon in the atmospheres of asymptotic giant branch stars
- Need higher signal-to-noise
- May only determine approximate abundances or upper limits

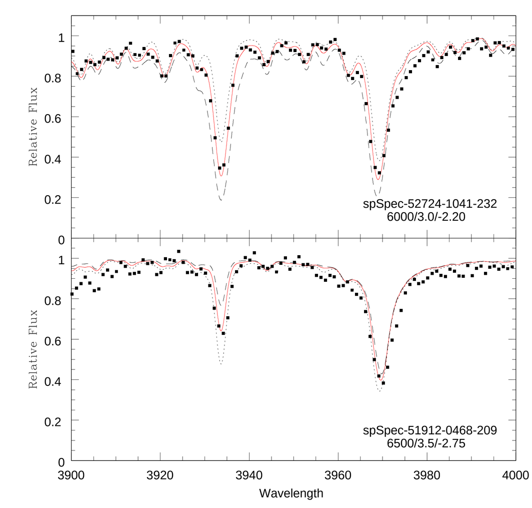

FIGURE 2: Best fits for the CaII K line at 3933Å. For all plots, the black lines represent abundances ± 0.5 dex of the best fit.

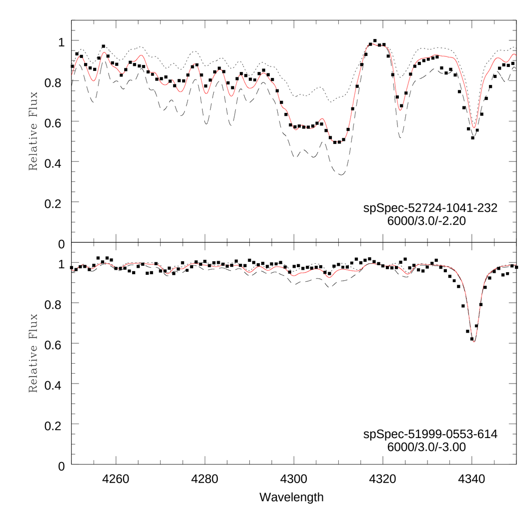

FIGURE 3: Best fits for the G-band at 4304Å. In the lower plot, only an upper limit can be determined.

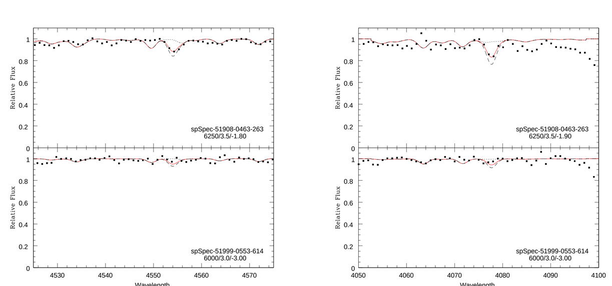

FIGURE 4: Best fits for barium(left) and strontium(right). Lower plots only give upper limits.

References

[Beers et al.(1999)] Beers, T.C., Rossi, S., Norris, J.E., Ryan, S.G., & Shefler, T. 1999, AJ, 117, 981
[Castelli & Kurucz(2003)] Castelli, F., & Kurucz, R.L. 2003, IAU Symposium, 210, 20P
[Rossi et al.(2005)] Rossi, S., Beers, T.C., Sneden, C., Sevastyanenko, T., Rhee, J., & Marsteller, B. 2005, AJ, 130, 2804R
[Sneden(1973)] Sneden, C. 1973, ApJ, 184, 839

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Results

A comparison of the spectral synthesis results to the previous line index results of the same stars is shown in Figure 5. In both plots, blue and black squares correspond to measurements of carbon abundances for the PHO and RED sample, respectively, while red and magenta arrows represent upper limits. As you can see, the line index method, relative to the spectral synthesis method, consistently underestimates the metallicity of stars. The shift is about 0.3 dex, although both sets of results are within the errors.

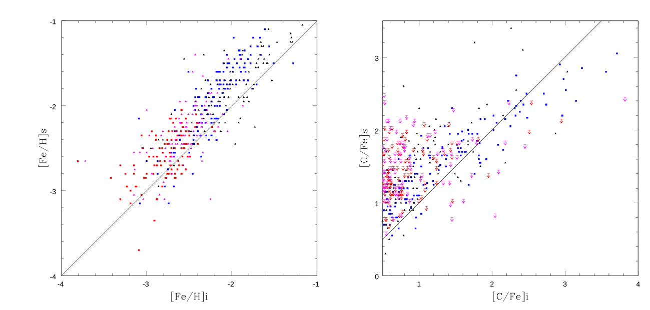

FIGURE 5: Comparisons of the two methods, the line index versus the spectral synthesis results. [Fe/H] comparison on the left, [C/Fe] on the right.

For [C/Fe], the line index method, again relative to the synthesis method, underestimates the carbon abundance at low [C/Fe] but overestimates at high [C/Fe] with a crossing point at just over [C/Fe] = 2.0. The underestimation at low carbon abundances is likely due to the line index method being affected more by noise at these abundances.

In Figure 6, we see a plot of [C/H] versus effective temperature on the left. We look at [C/H] instead of [C/Fe] to remove the metallicity dependence. There is a clear distinction between measured points and upper limits, with a noticeable temperature dependence. Warmer stars need higher carbon abundances before the G-band strength is noticeable, while cooler stars need very little carbon for this feature to be detectable.

In the right plot, we see [C/Fe] versus [Fe/H]. Here again we see a clear discrimination between stars with measurable abundances and those for which just upper limits have been determined. The slope of this separating line is likely just due to metallicity effects, i.e. iron deficiency rather than carbon abundance. It is, therefore, suggestive that a new definition for carbon- enhancement which is not based on iron should be used, and the temperature plot suggests that this definition should have some dependence on temperature and possibly on the evolutionary state of the star.

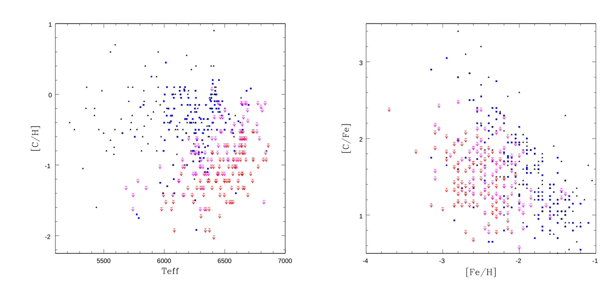

FIGURE 6: Carbon abundance as a function of temperature(left) and metallicity(right). The blue and black represent determined values, while red and magenta arrows are upper limits.

Conclusions and Future Work

Fixing the current problem

- The line index method has potential limitations for extreme C-enhanced and low temperature stars
- Spectral synthesis can help, but results depend on current models and the resolution of the grid space
- New carbon-enhanced models are currently being generated by Plez, which will be especially useful for cooler stars
- Determine corrections from 3D and/or NLTE effects on our models.
- Model lines can generally be differentiated at the 0.05 - 0.10 dex level
- Internal errors on abundances may be as good as perhaps 0.15 dex.

An automated approach using χ^2 fitting:

- More objective results, significantly faster, and able to handle incoming large samples of stars

Other abundances to determine

- Look for barium and strontium to differentiate between CEMP-s and CEMP-no stars
- Plans are also underway to obtain abundances for nitrogen and oxygen

Getting back to the Line Index Method

- Check results with existing high-resolution data to determine systematic errors, or problems with models
- Determine an empirical correction of the line index method for these extreme stars
- Line index method is more efficient for large samples of stars, like that produced by SDSS