CARBON-ENHANCED METAL-POOR STARS IN THE GALAXY

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ASoSS April 18, 2012

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OUTLINE

- Background – an introduction to CEMP stars
- Finding New CEMP stars – a survey based on new selection techniques
  - The pilot study
  - Selection technique revisions
  - Further survey observations and CEMP selection efficiency
- CEMP stars in Milky Way satellites

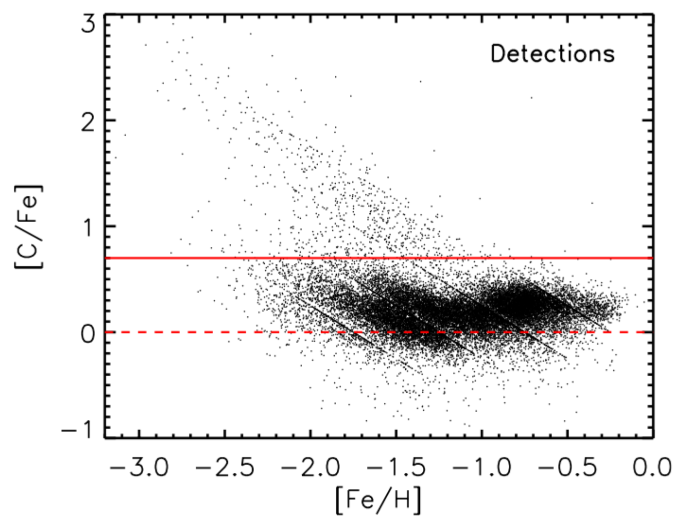
TERMINOLOGY

CEMP: Carbon-Enhanced Metal-Poor

NOT Carbon-enhanced Extremely Metal-Poor

CEMP = [Fe/H] ≤ -1.0 and [C/Fe] ≥ +0.7

[C/Fe] = "Carbonicity"



D. Carollo, T. C. Beers, J. Bovy, T. Sivarani, J. E. Norris, K. C. Freeman, W. Aoki, Y.S. Lee, C. R. Kennedy 2012, ApJ, 744, 195

SOME FACTS ABOUT CEMP STARS

- A significant fraction of metal-poor stars have been shown to have an enhancement of carbon
- This fraction appears to *increase with decreasing metallicity*
  - [Fe/H] < -2.0 ➔ 20%
  - [Fe/H] < -3.0 ➔ 30%
  - [Fe/H] < -3.5 ➔ 40%
  - [Fe/H] < -4.0 ➔ ~~100%~~ until 2011! Now 75%
- This fraction also *increases with distance from the Galactic plane*
- There are several different classes of CEMP stars with different abundance patterns (CEMP-s, CEMP-r, CEMP-r/s, CEMP-no), indicative of *different astrophysical sites of carbon production at early times*

(Lucatello et al. 2006; Christlieb et al. 2002; Frebel et al. 2005; Norris et al. 2007; Caffau et al. 2011; Carollo et al. 2012)

COMMON TYPES OF CEMP STARS

- CEMP-s: Most common type (approximately 80% of observed CEMP stars)
  1. Metal-poor AGB star (where s-process and carbon production occurs) in a binary system
  2. Mass transfer from AGB star to lower-mass binary companion
  3. Binary companion NOW observed as a CEMP-s star
- CEMP-no: Second-most common type (approximately 20%)

  Two leading theories:
  1. Massive, rapidly-rotating, mega metal-poor ([Fe/H] < -6.0) stars would have been proficient producers of CNO with no n-capture element production (Hirschi et al. 2006; Meynet et al. 2006, 2010)
  2. So-called faint early supernovae undergoing extensive mixing and fallback during their explosions lead to heavy CNO production (Umeda & Nomoto 2003, 2005; Tominaga et al. 2007)

LOOKING BACK: WAY BACK!

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

Mon. Not. R. Astron. Soc. **412,** 1047–1058 (2011) doi:10.1111/j.1365-2966.2010.17966.x

A carbon-enhanced metal-poor damped Lyα system: probing gas from Population III nucleosynthesis?★

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Accepted 2010 November 1. Received 2010 November 1; in original form 2010 July 29

ABSTRACT

We present high-resolution observations of an extremely metal-poor damped Lyα system (DLA), at $z_{\rm abs} = 2.3400972$ in the spectrum of the QSO J0035−0918, exhibiting an abundance pattern consistent with model predictions for the supernova yields of Population III stars. Specifically, this DLA has [Fe/H] $\simeq -3$, shows a clear 'odd–even' effect, and is C-rich with [C/Fe] $= +1.53$, a factor of $\sim$20 greater than reported in any other DLA. In analogy to the carbon-enhanced metal-poor stars in the Galactic halo (with [C/Fe] $> +1.0$), this is the first known case of a carbon-enhanced DLA. We determine an upper limit to the mass of ^{12}C, $M(^{12}\mathrm{C}) \leq 200\,\mathrm{M}_\odot$, which depends on the unknown gas density n(H); if $n(\mathrm{H}) > 1\,\mathrm{cm}^{-3}$ (which is quite likely for this DLA given its low velocity dispersion), then $M(^{12}\mathrm{C}) \leq 2\mathrm{M}_\odot$, consistent with pollution by only a few prior supernovae. We speculate that DLAs such as the one discovered here may represent the 'missing link' between the yields of Population III stars and their later incorporation in the class of carbon-enhanced metal-poor stars which show no enhancement of neutron-capture elements (CEMP-no stars).

Key words: stars: carbon – stars: Population III – galaxies: abundances – galaxies: evolution – quasars: absorption lines – quasars: individual: J0035−0918.

HOW CAN WE FIND NEW CEMP STARS?

- CEMP stars have typically been identified from metal-poor surveys
  - Missed intermediate-metallicity CEMP stars ($-2.0 < [Fe/H] < -1.0$)
- Previous CEMP survey by measuring the combination of the strengths of CH, CN, and C_2 bands
  - Missed high-temperature stars

Solution: New identification based solely on the strength of the CH G-band at 4300 Å from HES Objective Prism Plates

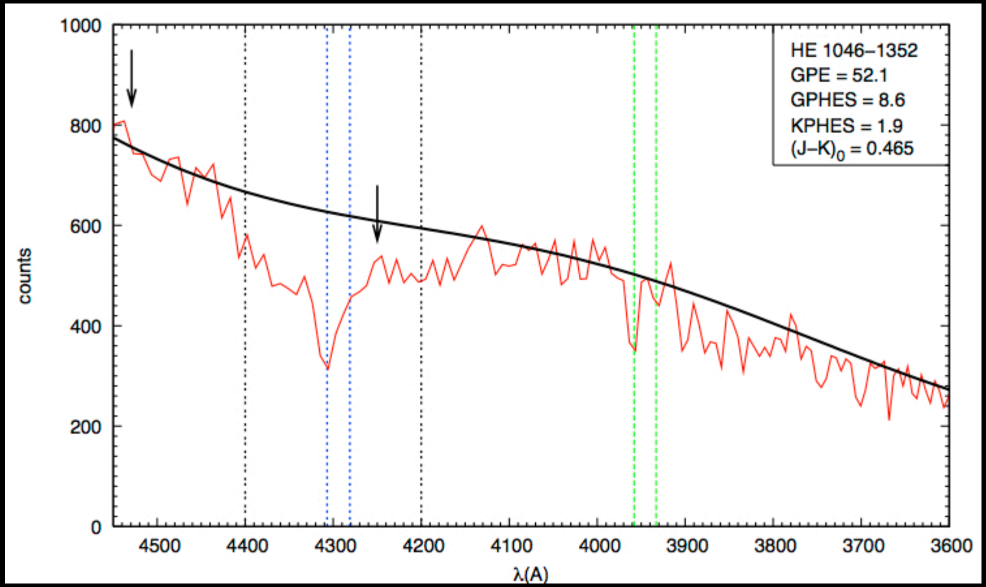
The New G-Band Index

$$GPE = \int_{4200}^{4400} \left(1 - \frac{S(\lambda)}{C(\lambda)}\right) d\lambda,$$

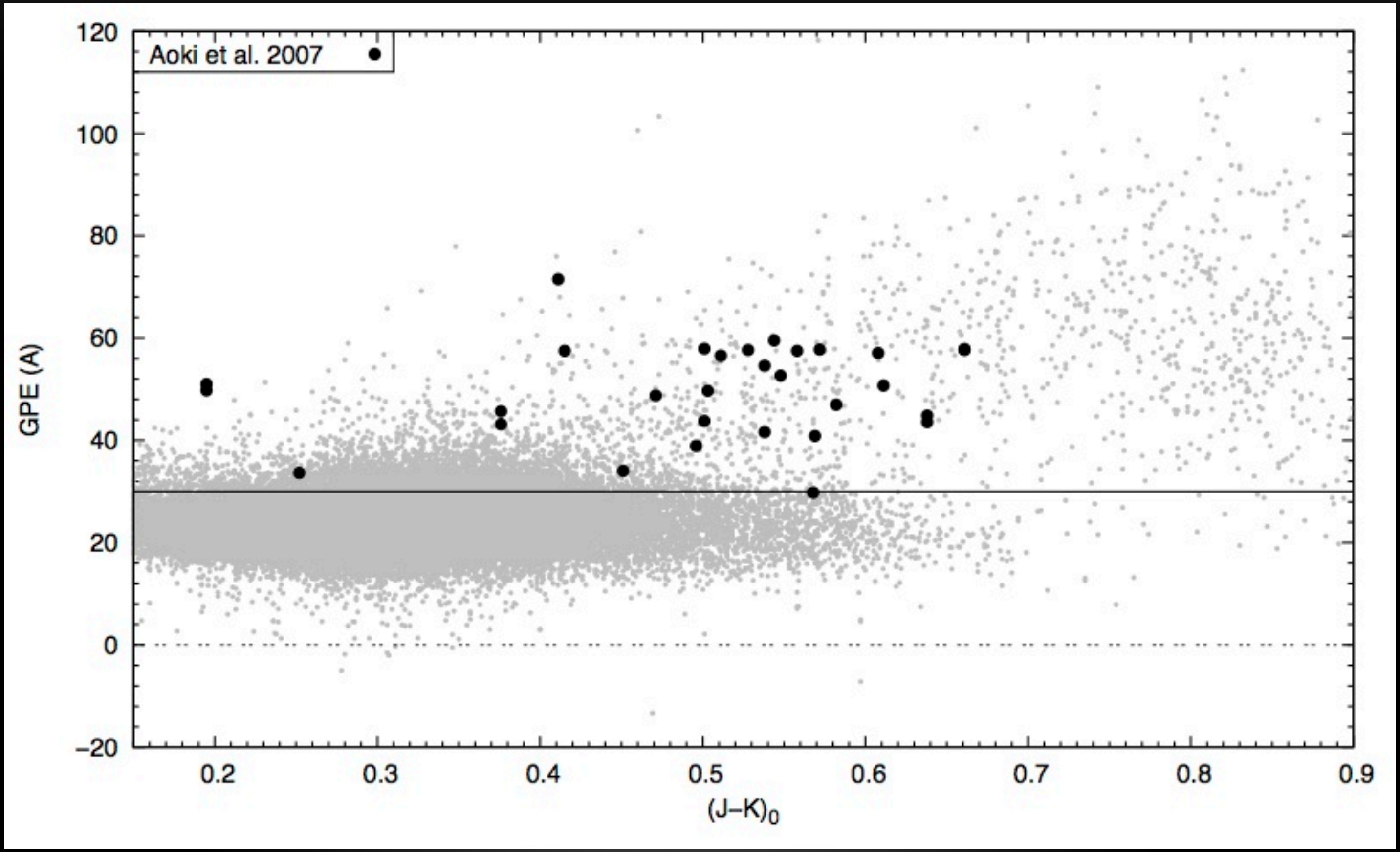
A 200 Å wide band over which the strength of the feature can be estimated.

Here, $S(\lambda)$ is the observed spectrum an $C(\lambda)$ is the local continuum

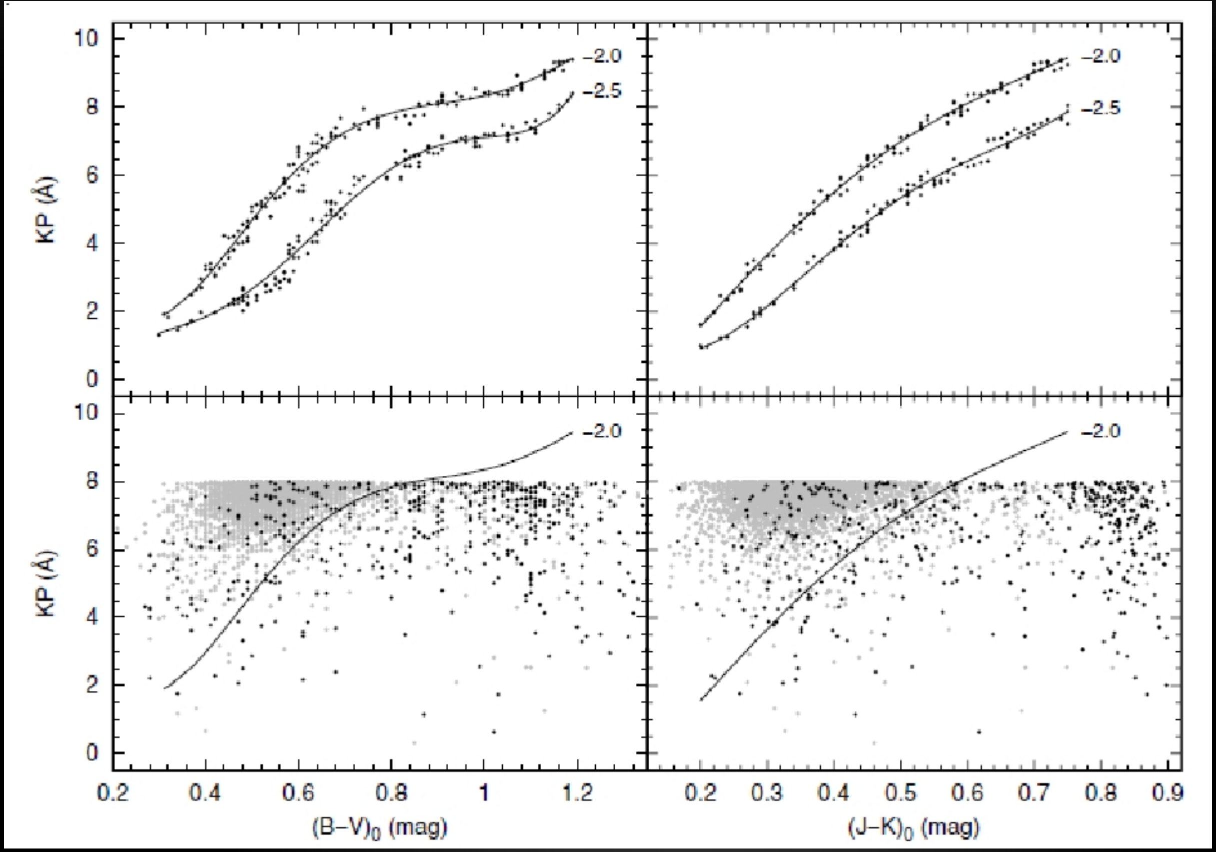
The continuum is fit over the entire region, as opposed to relying on sidebands like previous line indices.



THE GPE CUTOFF VALUE



METALLICITY CUTS



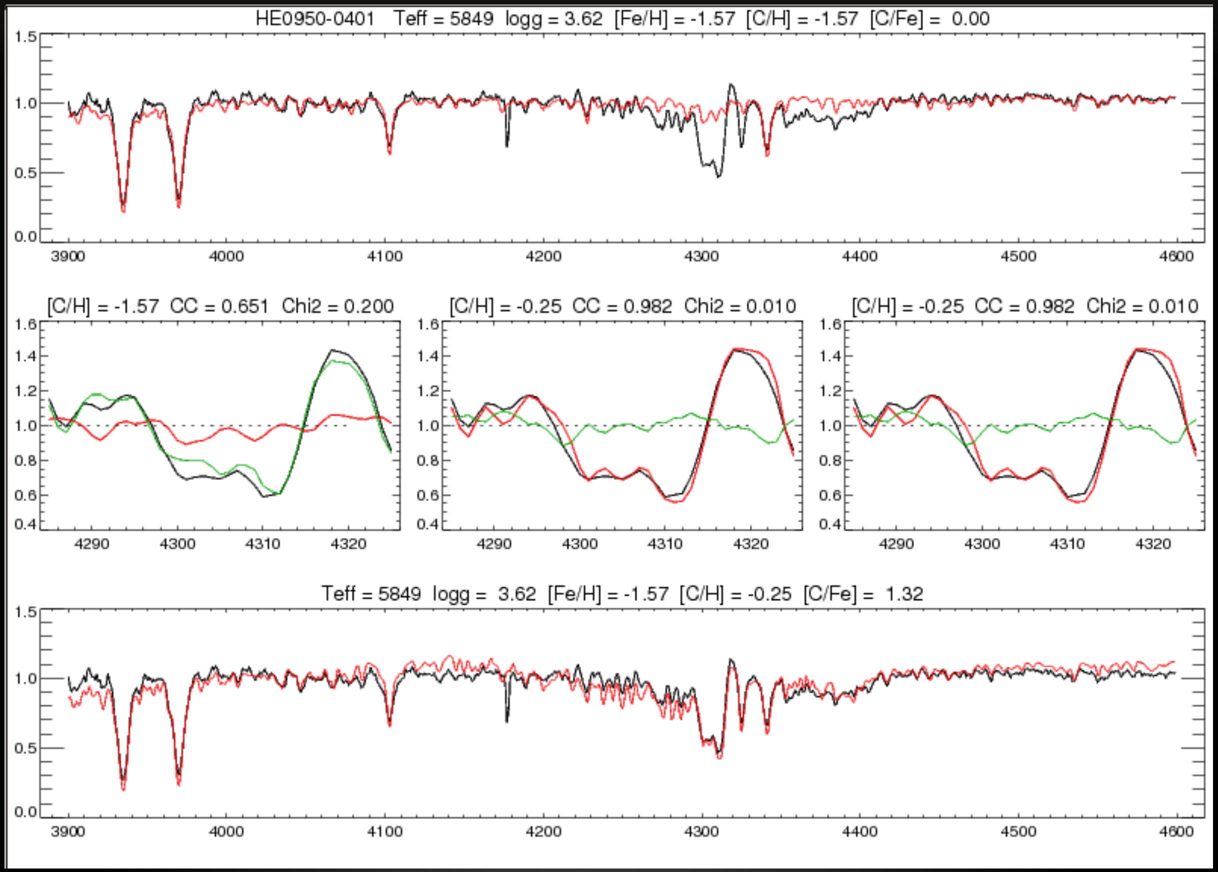
Christlieb et al. 2008

THE PILOT STUDY:
OBSERVATIONS AND ANALYSIS

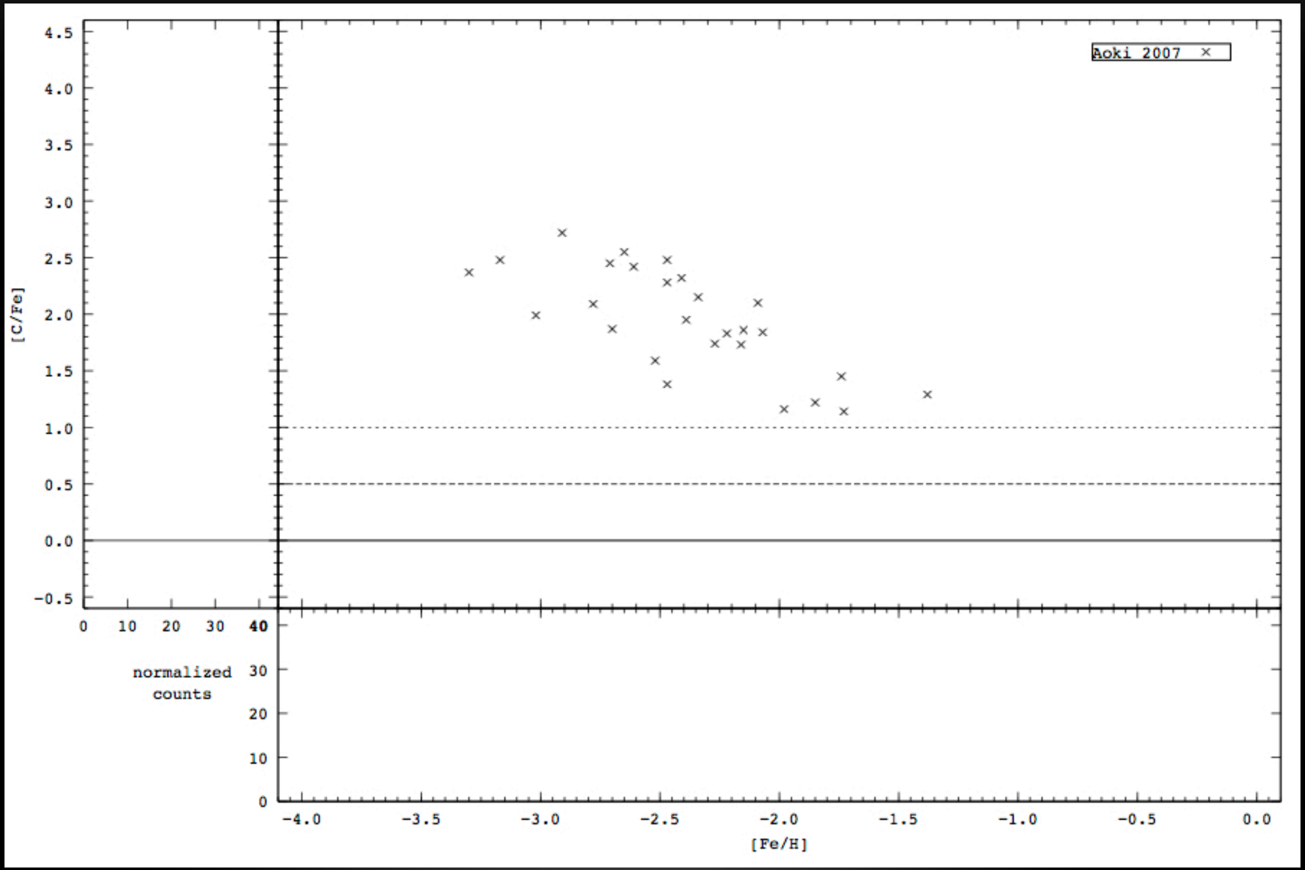
- First subset of stars observed with Goodman HTS on SOAR 4.1 m
- Over 120 stars observed from early 2009 – 2010
- Wavelength range 3600 – 6000 Å
- Exposure times 300 – 1800 s

- Atmospheric parameters determined with new version of SEGUE Stellar Parameter Pipeline (SSPP, Y. S. Lee)
- CH feature fit with synthetic spectra from Kurucz models (T. Sivarani)
- Fit performed over small range, 4285 – 4320 Å

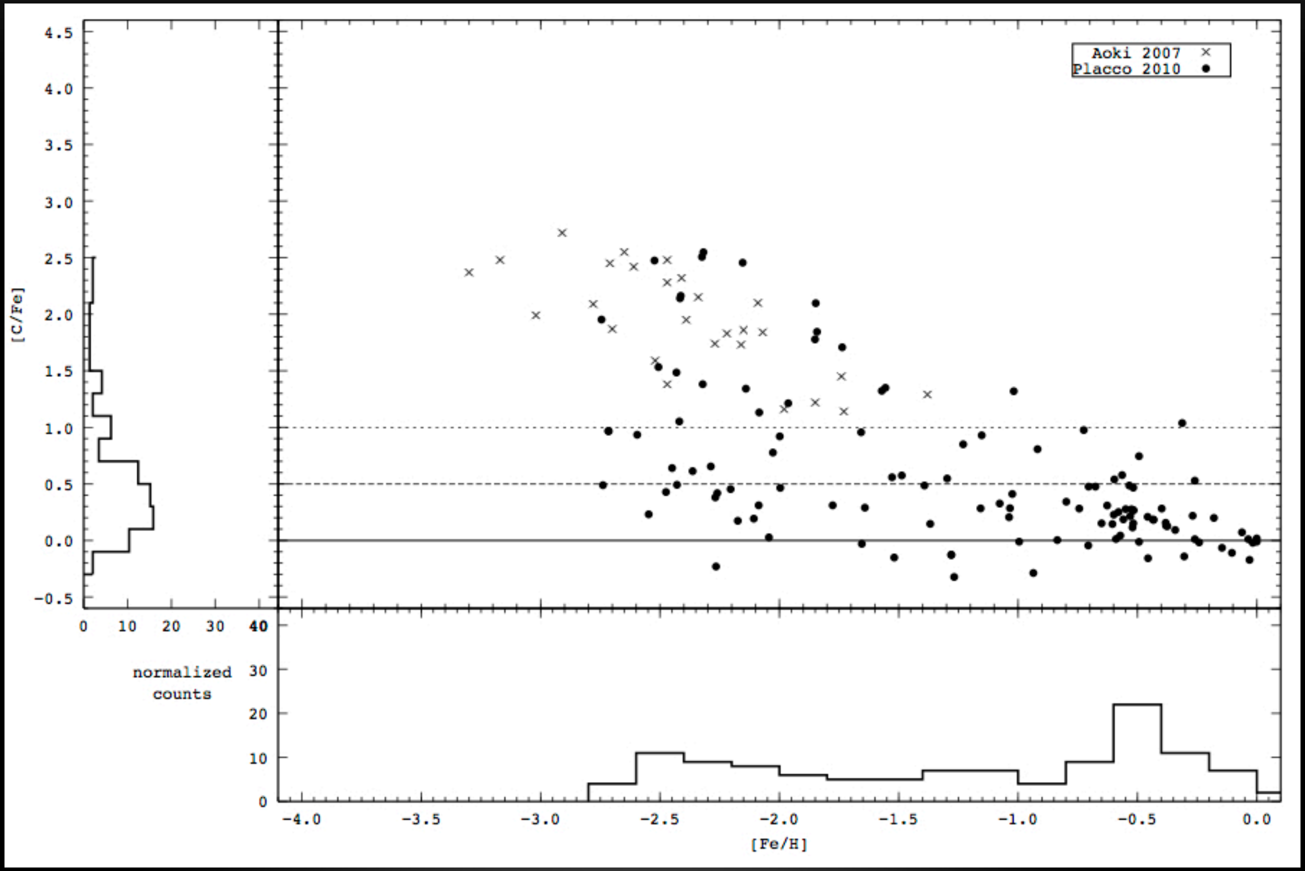
ESTIMATING CARBON ABUNDANCES



PILOT STUDY RESULTS



PILOT STUDY RESULTS



REVISIONS TO THE SELECTION TECHNIQUE

- Defined a new index which eliminates “false-positive” strong CH feature due to strong Hγ line at 4340 Å

$$EGP = -2.5log\frac{\int_{4200}^{4400} I_{\lambda_n} d\lambda}{\int_{4425}^{4520} I_{\lambda_m} d\lambda}.$$

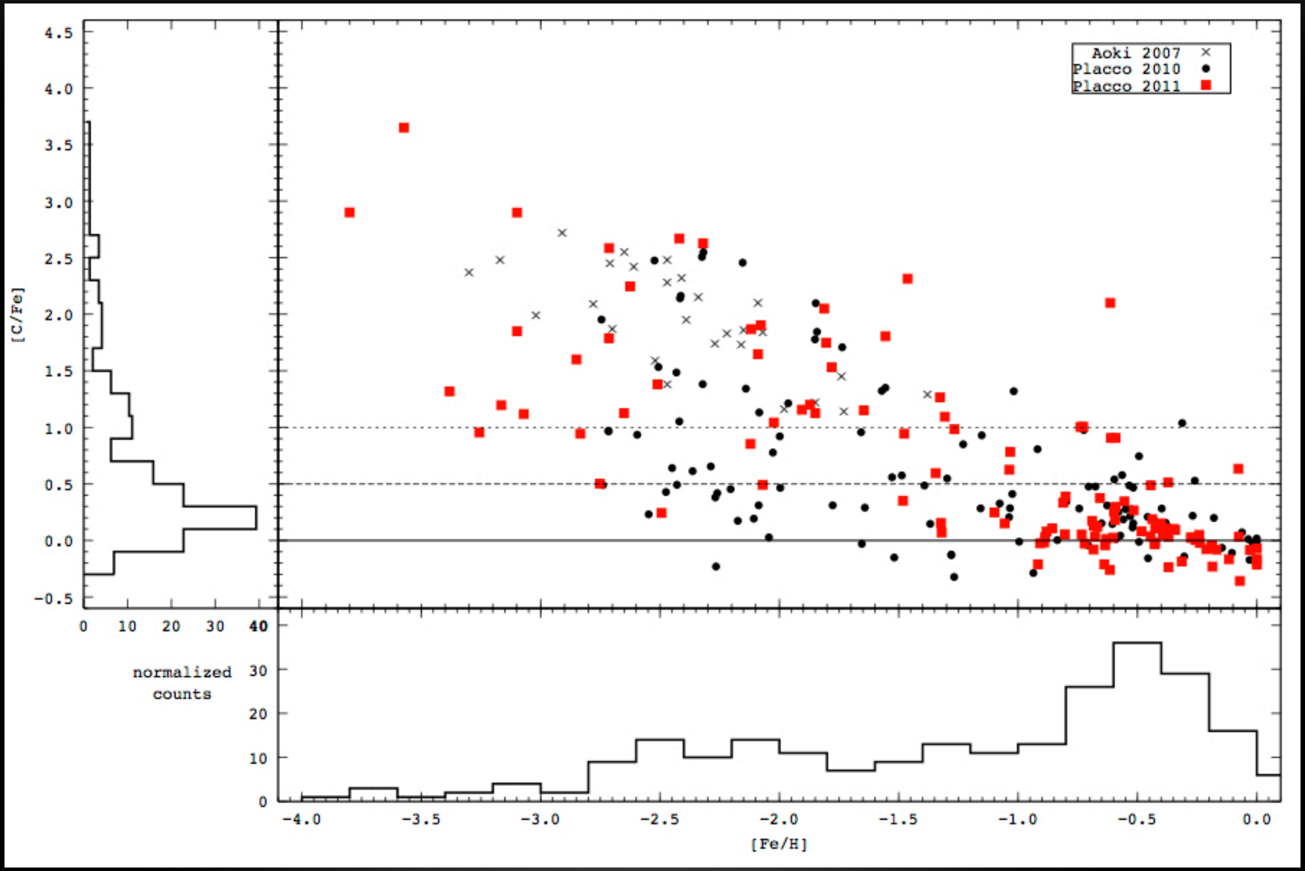
in addition to the original GPE index.

- This type of index is similar to that of Smith & Norris (1983); Morrison et al. (2003)
- Based solely on flux difference between the line band and the redband, not on continuum level
- Added bright objects to the candidate list by applying a saturation correction to the calculated G-band index

FOLLOW-UP OBSERVATIONS: SOAR, GEMINI, ESO NTT

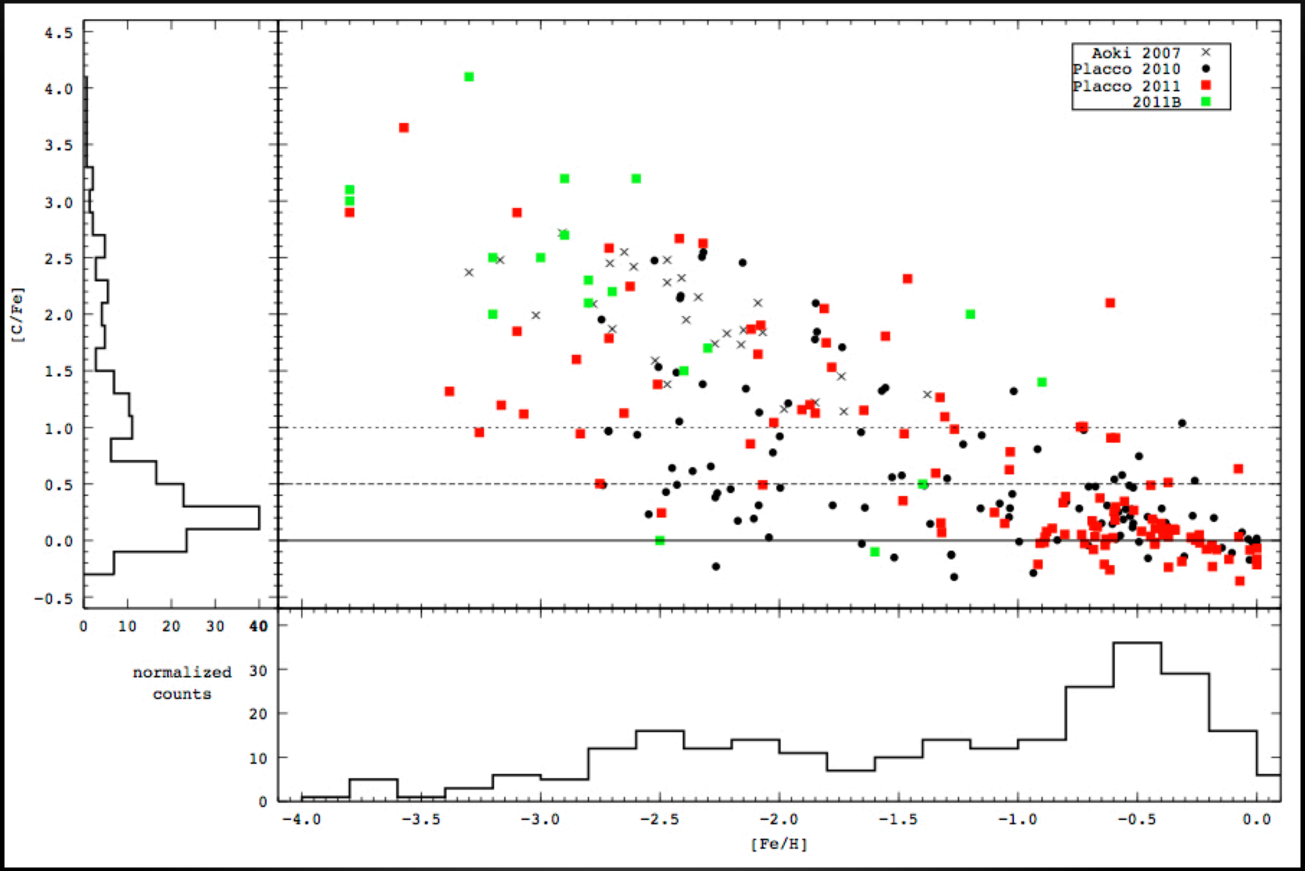
- Added queue-based observations on Gemini telescopes (primarily south)
- Able to observe fainter stars as fast as brighter ones with SOAR, keeping up with the pace of the original survey effort
- Added observations on ESO NTT in recent semesters
- Observing setup for these additions is still compatible with SSPP for atmospheric parameters as well as C-estimating routine

RESULTS



Aoki 2007
Placco 2010
Placco 2011
[C/Fe]
[Fe/H]
normalized counts

MORE RECENT RESULTS



EFFICIENCY OF SURVEY

[Fe/H]	Pilot Study	After Round 2	After Round 3
	% CEMP	% CEMP	% CEMP
< -1.0 (MP)	30	60	63
< -2.0 (VMP)	57	68	86
< -3.0 (EMP)	100	100	100

SURVEY SUMMARY

- At present, ~500 candidates have been observed on SOAR, Gemini, and NTT
- The original efficiency of CEMP selection was 30% for stars with [Fe/H] < -1.0
- Now we have reached an efficiency of > 60%
- We are steadily increasing the number of known CEMP stars which have metallicities lower than [Fe/H] = -3.0
- Upcoming high-resolution observations of the most metal-poor CEMP stars discovered from this survey are soon to come with AAT/UCLES (May 2012) and Magellan/MIKE (June 2012)

CEMP STARS IN MILKY WAY SATELLITE GALAXIES

- Norris et al. 2010 – Segue 1
  - [Fe/H] = -3.52, [C/Fe] = +2.3, [Ba/Fe] < -1.0 confirmed CEMP-no
- Lai et al. 2011 – Bootes 1
  - [Fe/H] = -3.79, [C/Fe] = +2.2 likely CEMP-no
- And more surely to come with the SMS Survey (Stromlo Milky Way Satellites Survey)
- So far, we are finding that the CEMP fraction in Milky Way satellites is consistent with the CEMP fraction among halo stars
- These discoveries add to the growing amount of evidence that suggests that the halo of the Milky Way was built up through accretion of smaller systems like the present-day dwarf galaxies.

CONCLUSIONS

- Since CEMP stars are so prevalent among the most metal-poor stars known, studying their compositions and abundance patterns can reveal much about early nucleosynthesis within stars
- If we are able to determine the possible progenitors of today's CEMP stars, we can understand more about what the very first generations of stars were like, and how they contributed to the overall chemical enrichment of the Universe
- In addition to their existence among field halo stars in the Milky Way, we are beginning to find CEMP stars within ultra-faint dwarf galaxies, further constraining current view of the chemical and the dynamical evolution of the Galaxy
- The presence of carbon-enhanced metal-poor signatures at high redshift confirms that *we are indeed observing stars here in the Galaxy that were born of the material ejected from the FIRST STARS in the Universe!*