The dawn of star formation: a local perspective

Piercarlo Bonifacio
As a gas cloud contracts it heats, $PV=nRT$, thus also pressure increases, tends to balance the gravitational force. If the mass is small, contraction stops. To keep contracting I need to cool the gas.

Line cooling: collisional excitation, followed by radiative recombination.
Collisions with gas particles heat the grains. The energy is then radiated in the IR and these low-energy photons are not absorbed, thus the energy is effectively removed from the thermal pool.
Formation of low mass stars

- Zero metallicity \( \Rightarrow \) FRAGMENTATION (Clarke et al. 2011, never observed)
- Metallicity \( > Z_{cr} \) \( \Rightarrow \)
  - ★ CII & OI fine structure cooling (Bromm & Loeb 2003)
  - ★ dust cooling + fragmentation (Schneider et al. 2011)

From Greif et al (2011)
Such stars are exceedingly rare!!!!

\[ [X/Y] = \log(X/Y) - \log(X/Y) \odot \]
The main source for the EMP candidates in the 1980’s 1990’s was the HK objective prism survey. Short spectra (interference filter) centered on CaII K line, visually inspected with a binocular X 10 microscope to select the candidates (Beers et al. 1985, 1992). Fairly deep, B< 15.5.
2800 deg² North, 4100 deg² South ~ 10000 MP candidates
Towards the end of the 1990’s also the Hamburg ESO objective prism Survey began to provide interesting candidates. Long spectra. Goes about 2 magnitudes deeper than HK (B< 17.5) again ~ 10000 candidates
From the objective prism candidates one had to collect medium resolution spectroscopy \((R=\lambda/\Delta\lambda \sim 2000)\) to confirm the metallicity and only after one could move to high resolution spectroscopy.

### TABLE 3 “Effective yields” of metal-poor stars

<table>
<thead>
<tr>
<th>Survey</th>
<th>(N)</th>
<th>(&lt;-2.0)</th>
<th>(&lt;-2.5)</th>
<th>(&lt;-3.0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HK survey/no (B - V)</td>
<td>2614</td>
<td>11%</td>
<td>4%</td>
<td>1%</td>
</tr>
<tr>
<td>HK survey/with (B - V)</td>
<td>2140</td>
<td>32%</td>
<td>11%</td>
<td>3%</td>
</tr>
<tr>
<td>HES (faint turnoff stars)</td>
<td>571</td>
<td>59%</td>
<td>21%</td>
<td>6%</td>
</tr>
<tr>
<td>HES (faint giants)</td>
<td>643</td>
<td>50%</td>
<td>20%</td>
<td>6%</td>
</tr>
</tbody>
</table>
The HK follow-up

- In the 1990’s 4 groups started to do medium resolution spectroscopic follow-up of the HK Survey, 2 in the South and 2 in the North

- In the North one group used IDS@INT (Rebolo, Allende Prieto, Garcia Lopez, Bonifacio, Molaro)

- In the South one group used ESO 1.5m (R. Cayrel, M. Spite, F. Spite, P. François)

The “First Stars” project

• The idea was then to use VLT to do high resolution follow-up; I and P. Molaro joined the French, under the leadership of R. Cayrel.

• The “First Stars” collaboration, 18 refereed papers (1 letter in Nature).

• This changed my professional life because it was the basis on which I moved to Paris in 2005

First detection of U in a metal poor star (Cayrel et al. 2001, Hill et al. 2002)
The ESO Large Programme "First Stars"

P.I. Roger Cayrel

proposal 165.N-0276

proponents (in alphabetical order):

J. Andersen, B. Barbuy, T.C. Beers, P. Bonifacio, E. Depagne
P. François, V. Hill, P. Molaro, B. Nordström, B. Plez, F. Primas,
F. Spite, M. Spite

Joined the project later (in order of appearance):

T. Sivarani, F. Herwig, S. Andrievsky, J. Gonzalez Hernandez,
H.-G. Ludwig, E. Caffau, C. J. Hansen

Presented by P. Bonifacio

l'Observatoire de Paris
Turn Off Primordial Stars

PI: E. Caffau

28 researchers
12 laboratories
7 countries

EMP stars selected from SDSS
76 stars with X-Shooter
30 stars with UVES
4 HDS (Subaru)

ESO Large Programme
150h @ VLT-ESO
4 semesters
120h X-Shooter
30h UVES

+ 4 approved “normal” programs,
  82h UVES

+ 3 nights Subaru
• P. Bonifacio, E. Caffau, R. Cayrel, P. François, A. Gallagher, F. Hammer, S. Salvadori, M. Spite, F. Spite - GEPI, Observatoire de Paris, France

• Bertrand Plez - Université de Montpellier, France

• N. Christlieb, H.-G. Ludwig, S. Glover, D. Homeier, R. Klessen, A. Koch - ZAH Heidelberg, Germany

• M. Steffen - Leibniz-Institut für Astrophysik Potsdam, Germany

• B. Freytag - Uppsala University Sweden

• A. Chieffi, M. Limongi, P. Molaro, S. Randich, S. Zaggia - INAF, Italy

• L. Monaco - Universidad Andrés Bello, Santiago, Chile

• L. Sbordone - Pontificia Universidad Católica de Chile, Santiago, Chile

• L. Mashonkina - Institute of Astronomy, Russian Academy of Sciences, Russia

• S. Andrievskii, S. Korotin - Astronomical Observatory, Odessa National University, Ukraine
Main Questions

- Understand formation of low mass stars in low metallicity gas
- Do zero-metal low mass stars exist?
- If not: value of the “critical metallicity”
- Derive the fraction of C-enhanced extremely metal-poor (CEMP) stars/“normal” extremely metal-poor (EMP) stars

- Lithium and the primordial nucleosynthesis predictions
  - Li abundance (Li destruction?) in EMP stars

- First massive stars
  - Masses of Pop III massive stars from chemical composition of a large sample of EMP stars
Automatic code to obtain abundance estimates from SDSS spectra
SDSS J102915+172927: the Caffau star

12 Feb 2011

IFU 4”x1.8” ==> 12”x0.6”
R~12600, 2700 sec S/N ~90

The Sun
The star that should not exist

- $[\text{Fe/H}]= -4.9$
- $[\text{C/H}] < -4.5$
- $Z = 5 \times 10^{-5} Z_{\odot}$

EMP star non-enhanced in C,N $\implies$
over-abundance C not necessary to cool EMP gas

According to the theory of Bromm & Loeb (2003) a minimal quantity of C and O is necessary to form low mass stars.
But we have found a star in the forbidden zone

Figure from Frebel et al. 2007
Metallicity Distribution Function

MDF from SDSS-DR9 (182.807 TO stars)

SDSS target observed at higher resolution (X-Shooter and UVES), sample of 87 stars, analysis not completed.
The TOPOS contribution

30 years searches

TOPoS

N

15

10

5

0

[Fe/H]

-5.2

-4.8

-4.4

-4.0

-3.6

-3.2

-2.8
For over twenty years it has been known that among low metallicity stars there is a large fraction of “carbon-enhanced stars”. Larger in fact than among solar-metallicity stars. The actual fraction is debated 15%—35%, in any case rising with lowering metallicity.
Definitions of CEMP (Carbon Enhanced Metal-Poor)

- Traditional: \([\text{C/Fe}] > 1.0\)

- some authors suggest \([\text{C/Fe}] > 0.7\), but such a definition may be ambiguous

- In any case, empirical, no theoretical basis for it

- At metallicity < -3.0 the information on the C abundance comes mainly from the CH G-band
But molecular bands are strongly dependent on granulation effects! (Behara et al. 2010)
CIFIST grid of 3D hydro models

T\textsubscript{eff} [K]

log\textsubscript{10} g [cm s\textsuperscript{-2}]

metallicity [M/H]

-0.5  +0.0  +0.5
-1.0  -1.5  -2.0
-4.0  -3.0  -2.5

running
standard R
high R

M0
K0
G0
F5

T\textsubscript{eff} [K]

F5  G0  K0  M0
Stellar Parameters \((T_{\text{eff}}/\log g/[Fe/H])\)
6250 K/4.0/-3.0

- \(A(C) = 7.39\)
- \(A(N) = 6.78\)
- \(A(O) = 7.66\)
- \(C/O = 0.54\)

Molecular bands in 3D

Stellar Parameters ($T_{\text{eff}}/\log g/[Fe/H]$)
6250 K/4.0/-3.0

$A(C) = 7.39$
$A(N) = 6.78$
$A(O) = 6.06$
$C/O = 21.4$

The carbon abundances in CEMP stars are bimodal.

Bonifacio et al. 2015 A&A 579, A28
9 stars with $[\text{Fe/H}] < -4.5$

Christlieb (2001)

Allende-Prieto - Frebel 2015

Frebel et al 2005

Norris (2007)

Bonifacio 2015

Keller et al (2014)

Caffau et al 2011

Hansen et al (2014)
The carbon abundances in CEMP stars are bimodal

Bonifacio et al. 2015 A&A 579, A28
Three possible scenarios to explain Li-depletion

1. EMP low mass stars were all formed by fragmentation of higher mass clouds. They remain fast rotators through pre-MS. Rotational mixing leads to Li destruction.

2. Pre-MS always depletes all the Li, late accretion of unprocessed material restores the Li to some extent (Molaro, Bressan, Fu,…). EMP stars lack or have an inefficient late-accretion phase.

3. Within the DM mini-halo a significant fraction of the mass (50% ?) is rapidly processed through massive stars, this leads to Li depletion. Low-mass stars only form from this pre-processed material (also some metals ?).
What is in the future?
Researching the “Pristine” Galaxy


Leibniz Institute for astrophysics Potsdam (AIP), Observatoire astronomique de Strasbourg, Observatoire de Paris (GEPI), University of Victoria, University of Toronto, NRC-Herzberg, Observatoire de la Cote d'Azur
The Ca H&K filter

\[ \text{[Fe/H]} = -3.0 \]

Pristine filter is narrower than the Skymapper filter

\[ \text{[Fe/H]} = -3.0, \text{[C/Fe]} = +1 \]

© Pristine filter is narrower than the Skymapper filter

courtesy of E. Starkenburg
The theory

The observations (SDSS metallicities)

Starkenburg et al.
2017 MNRAS in press, arXiv:
1705.01113 (Paper I)
It is important to have also good broad-band photometry

**SDSS**

**APASS**

FEROS observation of a sample of bright stars. The initial photometric estimates were wrong. This because the SDSS photometry is not good below $g \sim 15$. Things are fixed if you use APASS instead. (Caffau et al. 2017 AN submitted; Paper II)
Figure 2. Sample spectra of three Pristine target stars with different metallicities but similar temperatures, as determined spectroscopically by FERRE. These stars are marked in the Pristine colour-colour space as yellow stars in Figure 1. The dotted red line shows the wavelength region (limits at which the transmission falls below 50% of the maximum) for the CaHK filter, and demonstrates the sensitivity of the filter to detecting changes in the strength of the Ca II H & K lines.

The noise spectra as given by the data reduction pipeline and a normal distribution for each instance. The standard deviation of the resulting metallicity distribution is taken as the metallicity uncertainty. Following Aguado et al (2017a, in prep.) we add an additional 0.1 dex to the uncertainties to account for other systematic effects.

Figure 2 illustrates some typical spectra obtained from the INT, and the relevant wavelength region used for the analysis, $\lambda$3750–5210 Å. The three sample spectra shown were specifically chosen to have similar stellar parameters, such that the selection power in the wavelength region targeted by the narrow-band filter can easily be seen. Both the Ca II K (3933.7 Å) and the Ca II H (3968.5 Å) lines generally are smaller in more metal-poor stars of similar stellar parameters. In relatively hot stars, such as shown here, the Ca II H line remains a little stronger, because it is blended with the Hγ line (3970 Å). Therefore, it is particularly the Ca II K line that is a good indicator of a star that is deficient of all metals, including calcium (e.g., Beers et al. 1999).

4.1 SDSS photometry
SDSS was chosen as the principal survey to combine to Pristine because of its large footprint in the Northern Hemisphere and excellent quality of well-calibrated, deep broad-band photometry. We evaluate the photometric information in several of the SDSS broad-band filters combined with the Pristine narrow-band information. The selection criteria that we refined with the spectroscopic sample are described below:

• Non-star contamination: Objects that are not stars may exhibit strange spectral signatures that could make them appear to be metal-poor stars from our photometric selection. We therefore identify and remove as many of these sources as possible during the photometric reduction to minimize this source of contamination. The photometry was reduced using the Cambridge Astronomical Survey Unit pipeline (CASU, Irwin & Lewis 2001), and modified to work specifically for CFHT/MegaCam data (Ibata et al. 2014). Objects identified as being stars are flagged with -1, and we therefore require that the CASU flag = -1 for objects to be considered for further follow-up. In addition, when matching Pristine to SDSS, we only consider sources in SDSS that are labelled as stars, thereby providing another means to remove non-point source objects.
There are some fine points on calibrating HK photometry

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If you want to "tie in" into the SDSS system and compare to theoretical models you need to observe the SDSS primary standards. These are mostly too bright for CFHT. We are doing HK observations with the 1m TUG observatory, to established a fully homogeneous system. Eventually we hope to cross-calibrate TUG and CFHT filters.
Next steps

- The calibration of the CFHT HK colour is already very good (Youakim et al. 2017) when compared to other surveys.

<table>
<thead>
<tr>
<th>Survey</th>
<th>[Fe/H] &lt;-3</th>
<th>[Fe/H] &lt;-2.5</th>
<th>-3 &lt; [Fe/H] &lt; -2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pristine</td>
<td>22%</td>
<td>70%</td>
<td>85%</td>
</tr>
<tr>
<td>HES</td>
<td>3.8%</td>
<td>22%</td>
<td>40%</td>
</tr>
<tr>
<td>SC14</td>
<td>3.8%</td>
<td>-</td>
<td>32%</td>
</tr>
</tbody>
</table>

- With the current observations we are aiming at further improving it, especially for the bin below [M/H]= -3.0

- The improved calibration will be used to select a large sample for follow-up in the WEAVE Galactic Archeology Survey.
Thank you!