Go upstream of the "Milky Way"!
A journey to the source of elements

Yuhri Ishimaru (Ochanomizu Univ.),
S. Wanajo (Sophia U.), N. Prantzos (IAP), W. Aoki (NAO), S. G. Ryan (Open U.)
Chemical Components of Pebbles of MW

Big Bang

Stellar Evolution

α-elements

odd-Z elements

Fe-peak elements

n-capture elements

Lanthanoids

Actinoids

α-elements

odd-Z elements

Fe-peak elements

n-capture elements
Inhomogeneous Chemical Evolution Model

Star Formation is assumed to be induced by SUPERNOVAE

**Supernova**
ejects gas & metal
Supernova models;
Nomoto et al. '97 (for $Z_0$ stars)
and Woosley & Weaver '95
(for $0 \sim Z_0$ stars)

**Inter-Stellar Gas**
evolves as standard
1-zone chemical evolution
with outflow (halo)
or inflow (disc)

**Supernova Remnant**
expands and mixed with ISM
The expansion radius is given
from ISM density + metallicity
$$R_{\text{SNR}} \propto \rho_{\text{ISM}}^{-18/49} Z_{\text{ISM}}^{-5/98} E_{51}^{31/98}$$
(Cioffi et al. 1988)

**New Stars**
formed from ISM + SNR
Chemical compositions are given by their mass average
SN Yields

Nomoto et al. '97
Woosley & Weaver '95

Constant yields vs. metal dependent yields

Umeda & Nomoto ‘02

effects of Pop III stars and hypernovae
Dispersions come from variations of SN yields in different mass SNe.

Nomoto et al. 97  Woosley & Weaver 95

Stars from Supernova remnant

- Evolved gas
- Zero-metal gas

Number = SN progenitor mass

$10^-4 \, Z_\odot$ stars
Statistical Comparison of Dispersions

Nomoto et al. 97  Woosley & Weaver 95

Obervational Data

Average of ISM  
Average of Stars  
50% Confidence region  
90% Confidence region

Average  
50% Confidence region

(Norris et al. 2001)
Statistical Comparison of Dispersions

Constant $R_{SNR}$

1.5 $\sigma$ Dispersion in $R_{SNR}$

N97

WW95

50% Confidence - Average

Width of scatters cannot be reduced by gas-mixing efficiency

Width of scatters cannot be reduced by gas-mixing efficiency

yields

mixing length
$\alpha$-elements

$[X/Fe]$ 

$[O/Fe]$ [Mg/Fe] [Si/Fe] [Ca/Fe]

$Z < 10^{-3} Z_\odot : \text{Pop.III (HN)}$ $Z > 10^{-2} Z_\odot : Z_\odot \text{ SN}$
$\alpha$-elements
Iron-peak elements

[Cr/Fe]  [Mn/Fe]  [Co/Fe]  [Zn/Fe]

[Cr/Fe]  [Mn/Fe]  [Co/Fe]  [Zn/Fe]

[Cr/Fe]  [Mn/Fe]  [Co/Fe]  [Zn/Fe]
Iron-peak elements

WW95

N97

UN03
The origin of r-process must be in specific SNe!

However, the origin of r-process has been an open question.

These stars are enriched by only one or a few SNe.

CS22892-052 shows almost pure solar-system r-process pattern.

Dispersions in [r/Fe] of MPS are extremely large!
Possible Sites of R-Process

Synthesis of heavier elements from seed nuclei by neutron capture

- Prompt Shock of SNeII
  - $8 \sim 10 \, M_\odot$
    - (Hillebrandt et al. ‘84; Wheeler et al. ‘98)

- Neutrino Wind of SNeII
  - $> 10 \, M_\odot$
    - (Woosley et al. ‘94)
  - heavier stars
    - (Wanajo et al. 2000)
Enrichment of Eu

If the r-process site is ...

- Prompt shock by SNII:
  Stars of 8~10 $M_\odot$

- Neutrino Wind of SNII:
  Stars of >30 $M_\odot$

cf. Ishimaru & Wanajo '99
Observational Data Can Distinguish?

It was too difficult by previous observations. Observations of stars with $[\text{Fe/H}] < -3$ is required!

A possible telescope is SUBARU!
S01A Observation by Subaru HDS

Observers: Ishimaru, Wanajo, Ryan, Aoki
Observing Date: 07/23/2001~07/24/2001 (S01A)

We selected 3 stars having $[\text{Ba/Fe}] \sim -1$, typical for their metallicities.

<table>
<thead>
<tr>
<th>Target</th>
<th>HD4306</th>
<th>CS22878-101</th>
<th>CS22950-046</th>
</tr>
</thead>
<tbody>
<tr>
<td>$[\text{Fe/H}]$</td>
<td>-2.78</td>
<td>-3.10</td>
<td>-3.34</td>
</tr>
<tr>
<td>$[\text{Mg/Fe}]$</td>
<td>+0.64</td>
<td>+0.51</td>
<td>+0.30</td>
</tr>
<tr>
<td>$[\text{Ca/Fe}]$</td>
<td>+0.50</td>
<td>+0.26</td>
<td>+0.13</td>
</tr>
<tr>
<td>$[\text{Ti/Fe}]$</td>
<td>+0.45</td>
<td>+0.31</td>
<td>+0.15</td>
</tr>
<tr>
<td>$[\text{Sr/Fe}]$</td>
<td>+0.28</td>
<td>-0.15</td>
<td>-0.18</td>
</tr>
<tr>
<td>$[\text{Ba/Fe}]$</td>
<td>-1.09</td>
<td>-0.73</td>
<td>-1.25</td>
</tr>
<tr>
<td>$[\text{Eu/Fe}]$</td>
<td>-0.47</td>
<td>-0.25</td>
<td>&lt;-0.2</td>
</tr>
</tbody>
</table>

Sub-solar values of $[\text{Eu/Fe}]$ at $[\text{Fe/H}] < -3$ are detected for the first time.
New Data for [Eu/Fe]

All of 3 stars show sub-solar [Eu/Fe] !!


The data strongly supports 8~10 M\(_\odot\) as the r-process site!!
Sr enhancements are seen in very metal-poor stars.

If the origin of Sr is identical to that of Ba, \([\text{Sr/Ba}]\) should be constant.

There must be a distinct origin for Sr.
But large Sr enhancements in very metal-poor stars cannot be reproduced by weak s-process. Because weak s-yield is strongly correlated with stellar metallicity.
We Suggest "Weak" R-Process!

While massive r-elements are produced mainly by 'main' r-process, lighter nuclei can be produced also by 'failed' r-process.

Eu & Ba: from SNeII of 8~10 $M_\odot$ stars

Sr: from SNeII of >30 $M_\odot$ stars

If 2 distinct sites of r-process exist, Sr enhancements can be explained.
While main r-process produces heavier elements (Ba, Eu, etc), lighter elements (Sr, etc) are also produced by weak r-process.
But Where Is the Boundary?

How can we determine the upper mass limit of weak r-products?

Intermediate mass nuclei Pd & Ag must provide clues!
Most of elements of these stars agree with solar r-process pattern

Pd also agrees with r-process? But Ag is lower than ss r-process?

Which is the origin of Pd & Ag, main r or weak r?
S02A Observation by Subaru HDS

We selected two types of stars; 1) high [Sr/Ba] stars and 2) low [Sr/Ba] stars

Johnson '02 + Johnson Bolte '02

<table>
<thead>
<tr>
<th></th>
<th>HD165195</th>
<th>BD-11°145</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Fe/H]</td>
<td>-2.31</td>
<td>-2.48</td>
</tr>
<tr>
<td>[Sr/Fe]</td>
<td>0.06</td>
<td>-0.14</td>
</tr>
<tr>
<td></td>
<td>± 0.30</td>
<td>± 0.30</td>
</tr>
<tr>
<td>[Ba/Fe]</td>
<td>-0.33</td>
<td>-0.02</td>
</tr>
<tr>
<td></td>
<td>± 0.20</td>
<td>± 0.23</td>
</tr>
<tr>
<td>[Eu/Fe]</td>
<td>0.45</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td>± 0.20</td>
<td>± 0.20</td>
</tr>
<tr>
<td>[Sr/Ba]</td>
<td>0.39</td>
<td>-0.12</td>
</tr>
</tbody>
</table>

Preliminary Results:

<table>
<thead>
<tr>
<th></th>
<th>HD165195</th>
<th>BD-11°145</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Pd/Fe]</td>
<td>+0.01</td>
<td>-0.22</td>
</tr>
<tr>
<td></td>
<td>± 0.20</td>
<td>± 0.20</td>
</tr>
<tr>
<td>[Ag/Fe]</td>
<td>-0.43</td>
<td>&lt;=-0.56</td>
</tr>
<tr>
<td></td>
<td>± 0.30</td>
<td></td>
</tr>
</tbody>
</table>
Abundance Pattern of HD165195

Abundance pattern seems to follow `weak' r-process

But no enhancement of Pd is seen!

Pd is main-r products?

Again, Ag is significantly lower than r-pattern.
Abundance Pattern of BD-11°145

Abundance pattern shows contamination by s-process

But still Ag is lower than either r-pattern or s-pattern

Ag-deficient must be an interesting problem!
If Pd is produced

i) mainly by main r-process,  
   \[ \frac{[\text{Sr}]}{[\text{Pd}]} \] must correlate with \[ \frac{[\text{Sr}]}{[\text{Ba}]} \].

ii) mainly by weak r-process,  
   \[ \frac{[\text{Pd}]}{[\text{Ba}]} \] must correlate with \[ \frac{[\text{Sr}]}{[\text{Ba}]} \].

But BD-11°145 may be significantly affected by s-process.

\[ \frac{[\text{Sr}]}{[\text{Pd}]} \] seems to correlate with \[ \frac{[\text{Sr}]}{[\text{Ba}]} \].

Pd may be produced by main r-process.

But weak correlation of \[ \frac{[\text{Pd}]}{[\text{Ba}]} \] and \[ \frac{[\text{Sr}]}{[\text{Ba}]} \] may suggest that the weak r/main r ratio of Pd is larger than that of Ba.
SUMMARY
What can we find from pebbles of the Milky Way?

Dispersions in abundances of MPS constrain variations in SN yields

Especially, Eu + Ba & Sr abundances tell...

1) Subaru observation data suggests SNe II of 8~10$M_{\odot}$ stars as the site of `main' r-process

2) Lighter nuclei must be produced by `weak' r-process

3) Pd may be beyond the upper mass limit of weak r products

4) The origin of Ag is problematic

Neither main r, weak r, nor s-process seems to produce plenty of Ag. Some problems may exist in nuclear data or the solar abundance.
In Japanese.....

People say the Milky Way Galaxy as

銀河
Silver River

We will find the origin of Ag from the Milky Way in the near future....