Chemodynamical Simulations of a Milky Way type galaxy

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[Fe/H] and [X/Fe] evolve in a galaxy: stars are fossils that record the formation history of the galaxy.
Nucleosynthesis Yields

SN+HN (CK+ 06); SN+HN+AGB (CK, Karakas, Umeda 2011, MNRAS)

Romano+ 10 for other group’s yields
Type Ia Supernova Rate

- Single Degenerate Scenario; SNIa Lifetime ~ lifetime of companion star
- Companion mass ranges from binary calculation (Hachisu, Kato, Nomoto)

\[ R_{\text{Ia}} = b \int_{m_{1p,\text{min}}}^{m_{1p,u}} \frac{1}{\phi(m)} \, dm \int_{m_{1d,\text{min}}}^{m_{1d,u}} \frac{1}{\phi_d(m)} \, dm \]

- primary WD
- secondary star

\[ R_{\text{Ia,m}} \left[ \frac{\text{M}_{\odot}}{\text{yr}} \right] \]

CK et al. (1998); CK & Nomoto (2009)

Greggio 05; Matteucci+ 06 for other SNIa models

MS, 0.1-1Gyr in spirals or high-z
RG, 1-20Gyr in ellipticals
CK(04): GRAPE-SPH +

Star Formation
(1) $\nabla \cdot \mathbf{v} < 0$
(2) $t_{\text{cool}} < t_{\text{dyn}}$
(3) $t_{\text{dyn}} < t_{\text{sound}}$
Schmidt SFR
$t_{\text{sf}} = t_{\text{dyn}}/c$, $c=0.1$
IMF with $x=1.35$

Cooling:
Z-dependent $\Lambda$
(Sutherland & Dopita 93)

Feedback
100% thermal to 1 kpc

BH, NS, WD

SN II/HN
8-50M⊙
0.2⋅10^{51} (Z/Z⊙)^0.8 erg

M, Z, E dependent yield (Kobayashi et al. 2006)

UV background radiation
(Haardt & Madau 1996)

SD: Kobayashi et al. 1998
primary: 3-8M⊙ WD
secondary: ~1-3M⊙
Z-effect: [Fe/H] > -1.1
1.3⋅10^{51} erg
yield (W7, Nomoto et al. 1997)
The Milky Way Galaxy

Initial Condition: $\lambda$CDM fluctuated sphere with $\lambda \sim 0.1$, $r \sim 3\,\text{Mpc}$, $M_{\text{tot}} \sim 10^{12}\,M_\odot$, $N_{\text{tot}} \sim 120,000$, $M_{\text{gas}} \sim 10^6\,M_\odot$, $M_{\text{DM}} \sim 10^7\,M_\odot$.


$t = 0.00\,\text{Gyr}, z = 23.69$
Aquarius IC

- Code: Gadget-3 + SF+FB+CE (CK, Springel, White 07)
- Aq-5-C ($M_{\text{gas}} \sim 10^5 \, M_{\odot}$), merger @ $z=0.5$.....

$t = 13.56 \, \text{Gyr}, \, z = 0.00$
Star Formation Rate

Bulge $r<1$, Solar Neighborhood: $7.5<r<8.5, |z|<0.5$ kpc

- **solar neighborhood**
- **bulge**
- **5–10 kpc**
- **20–100 kpc**
Metallicity Gradients @ z=0.5

Consistent with lensed spiral galaxies @ z=1.5 (Yuan et al. 2011)
Age-Metallicity Relation

Solar Neighborhood: $7.5 < r < 8.5$, $|z| < 0.5$ kpc

Observation: Holmberg et al. (2007)
Age-Metallicity Relation
Observation: Edvardsson et al. (1993), Bensby et al. (2004), Gratton et al. (2003), Cayrel et al. (2004)
[O/Fe]-[Fe/H] Relation

Chemodynamical Simulation (CK & Nakasato 2011)

Solar neighborhood

- O
- Na
- Mg
- Al
- Si
- S
- Ca
- Cr
- Mn
- Co
- Cu
- Zn
Chemodynamical Simulation (CK & Nakasato 2011)
[X/Fe] Distribution

- Solar neighborhood
- Bulge
- Thick disk
Is this universal?
Very metal-poor DLA

SDSS + follow-up
(Cooke, Pettini et al. 2011)

$z = 2.3400972$

$\log N(\text{HI}) = 20.55$

$[\text{Fe/H}] = -3$

$[\text{C/Fe}] = +1.55$

<table>
<thead>
<tr>
<th>Element</th>
<th>$\log (X/H)^a$</th>
<th>$[X/H]_{\text{DLA}}^b$</th>
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</thead>
<tbody>
<tr>
<td>C</td>
<td>-3.61</td>
<td>-1.47</td>
</tr>
<tr>
<td>N</td>
<td>-4.22</td>
<td>-2.82</td>
</tr>
<tr>
<td>O</td>
<td>-3.34</td>
<td>-2.25</td>
</tr>
<tr>
<td>Al</td>
<td>-5.57</td>
<td>-3.25</td>
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<tr>
<td>Si</td>
<td>-4.49</td>
<td>-2.65</td>
</tr>
<tr>
<td>S</td>
<td>-4.85</td>
<td>$\leq -2.58$</td>
</tr>
<tr>
<td>Fe</td>
<td>-4.55</td>
<td>-3.02</td>
</tr>
</tbody>
</table>

Velocity Relative to $z_{\text{abs}} = 2.3400972$ (km s$^{-1}$)
Carbon-Enhanced Metal Poor (CEMP) Stars

- Mass transfer from AGB star binary systems
  (Suda et al. 2004; Lugaro et al. 2008; Izzard et al. 2009)
  - but Fe-peak elements?

- Mass loss from rotating massive star
  (Meynet, Ekstroem & Maeder 2006)
  - $[\text{N/C}] > 0$, high He. Fe-peak?

- Core-collapse supernova forming a blackhole
  (Umeda & Nomoto 2003; Iwamoto et al. 2005; Tominaga et al. 2007)

- Interstellar accretion
  (Yoshii 1981; Iben 1983; but Frebel, Johnson & Bromm 2009)

10 – 25% of stars with $[\text{Fe/H}] < -2$ (Aoki 2010)
C-rich DLA vs SN models (25M☉, Z=0)


\[ M_{\text{in}} - M_{\text{out}} = 1.76 - 6.14 M_{\odot}, \, f = 0.008, \, M(^{56}\text{Ni}) = 0.0018 M_{\odot}, \, M_{\text{BH}} = 6.1 M_{\odot} \]

\[ M_{\text{in}} - M_{\text{out}} = 2.20 - 6.30 M_{\odot}, \, f = 0.004, \, M(^{56}\text{Ni}) = 0.0014 M_{\odot}, \, M_{\text{BH}} = 6.1 M_{\odot} \]
Conclusions

- At Z>0, the observed elemental abundances are well reproduced with chemodynamical simulations of a MW-type galaxy including “normal” SN, HN(E>10^{51}erg,M>20M_{\odot}), SNIIa(Z), and AGB.

- In CDM picture, without major merger @ z<2
  - “Classical” bulge formed by assembly at z>2, have old age(>10 Gyr (80%)), high [\alpha/Fe], high [(Na,Al,Cu)/Fe], low [Mn/Fe]
  - Disk formed inside-out with continuous SF, have radial/vertical metallicity gradients, younger age (<8 Gyr (50%)), lower [\alpha/Fe]
  - Half of thick disk stars have formed in merging subgalaxies, have high [\alpha/Fe], but [(Na,Al,Cu)/Fe]~0, low [Mn/Fe] can be tested with RAVE, SEGUE, HERMES@AAT(2012), APOGEE, ngCFHT(2020).

- The observed abundance pattern of the very metal-poor C-rich DLA @ [Fe/H]= -3 suggests that chemical enrichment by the first stars is driven not by PISN (170-300M_{\odot} stars) but by core-collapse SNe (~20–50M_{\odot} stars). – consistent with recent simulations of primordial SF (e.g., Greif et al. 11).

- Do not have to change IMF, except for dSphs (very low SF system?)