Chemical Evolution
Models vs Theory

Martin Obergaulinger, MPA Garching

Advisorseminar, 09.VII.2004
Overview

- What is chemical evolution (CE)?
- Observational facts of CE
  - The solar abundance pattern
  - Abundances in different astrophysical environments
- The evolution of gas and stars in galaxies
  - Dynamics of stars and gas
  - Formation and nucleosynthesis of stars
  - Enrichment of the gas
- Models of CE, their merits and drawbacks, and uncertainties
The subject of CE

• CE tries to understand the evolution of the chemical composition of the universe based on our knowledge on the contributions of the individual NS sites, and on the evolution of cosmic structure.

• CE is linked to many subjects;
  – All phases of stellar evolution
  – Galactic dynamics and evolution
  – Cosmology
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Chemical Evolution

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Measuring abundances

Elemental and isotopic abundances inferred from

- spectroscopy of absorption lines and of decaying radioactive isotopes in the solar atmosphere, in other stars, and in the ISM,
- samples collected from meteorites, comets, planets and moons.

Fig. 39. A very strong absorption line of Mg I in the solar spectrum, dominated by damping wings. Adapted from the Liège Atlas (Delbouille et al. 1973).

Pagel, 1997
The local abundance pattern

Basic characteristics of the solar abundance pattern

- H, He, metals: $X = 0.7$, $Y = 0.28$, $Z = 0.02$,
- minimum at Li, Be, B,
- smooth trend of decreasing abundance from C to iron group,
- iron group: enhancement, NSE abundances,
- r- and s-process peaks above iron-group elements,
- reflections of nuclear structure: odd/even ratios and shell effects.
The local abundance pattern

Solare Häufigkeiten

(Mi²8 = 10⁶)

Müller, 2003
Abundances in the galaxy

- Kinematic structure of the stellar populations and gas distribution in different galactic regions (bulge, thick and thin disks, and halo) is correlated with gradients in the abundances of elements: Metal-rich centre and metal-poor halo (gradient of -0.07 dex kpc⁻¹)
- Distribution of the stars as a function of metallicity, and correlation of metallicity and age of stars.
- Abundance ratios of individual (e.g. signs of massive-star NS in old, extremely metal-poor) stars, and of a larger sample of stars (e.g. isotopes of different origin, such as [O/Fe] vs [Fe/H]).

➔ Important constraints on the formation and the history of the galaxy.
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$\Rightarrow$ Important constraints on the formation and the history of the galaxy.

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Table 1. Milky Way properties

<table>
<thead>
<tr>
<th></th>
<th>Mean age (Gyr)$^a$</th>
<th>Mean [Fe/H]$^a$</th>
<th>Scale height (kpc)</th>
<th>Scale length (kpc)</th>
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</thead>
<tbody>
<tr>
<td>Halo</td>
<td>14</td>
<td>-1.78</td>
<td>Effective radius $\sim 2.7^b$</td>
<td></td>
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<tr>
<td>Thick disk</td>
<td>11</td>
<td>-0.78</td>
<td>$\sim 0.75^c$</td>
<td>3.5$^c$</td>
</tr>
<tr>
<td>Thin disk</td>
<td>5–7</td>
<td>-0.14</td>
<td>$\sim 0.33^c$</td>
<td>2.25$^c$</td>
</tr>
<tr>
<td>Bulge</td>
<td>10</td>
<td>0</td>
<td>Effective radius $\sim 1.2^d$</td>
<td></td>
</tr>
</tbody>
</table>

$^a$ Robin et al. (2003)
$^b$ de Vaucouleurs profile — Buser et al. (1998)
$^c$ Chen et al. (2001)
$^d$ de Vaucouleurs profile — Yoshii & Rodgers (1989)

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Chem
Abundances in the galaxy

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Sneden et al., 2003
Abundances in the galaxy

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\[ \text{Gustavson, 1998} \]
Extragalactic abundances

- Correlation of morphology (Hubble sequence), star-formation activity, stellar populations and distribution of elements in different galaxies
  - Low gas content, low SFR and old, metal-rich stars in giant ellipticals vs gas-rich, star-forming spirals or LMC/SMC-like irregular systems
  - Peculiar stellar populations like young globular clusters in M31
- X-ray spectroscopy: significant iron fraction in the hot cluster IGM.
- Metal absorption lines in high-redshift systems (QSO absorbers)

➔ Understand the assembly and evolution of galaxies, their stellar populations and their interaction with their environment.
The Cosmic Cycling of Matter

- dense molecular clouds
  - star formation (~3%)
  - $10^3 \text{ y}$
  - $M \sim 10^{-6} M_\odot$

- interstellar medium
  - in-fall
  - mixing

- Galactic halo

- SNR's & hot bubbles
  - $10^2 - 10^8 \text{ y}$
  - SN Ia
  - SN explosion
  - winds
  - $\approx 90\%$

- SNR's & hot bubbles

- compact remnant (WD, NS, BH)

- galaxy collisions...
The actors on the stage of chemical evolution

- Dark matter (DM): gravitational interaction with stars and gas
- Stars, divided according to their NS properties into
  - low-mass stars (LMS), with life time > galactic evolution
  - intermediate-mass stars (IMS) ==> ejection of matter in the planetary nebulae (PN) phase
  - high-mass stars (HMS) ==> ejection of matter in core-collapse SN
  - stellar remnants (SR) ==> thermonuclear SN (SN Ia) or mergers
- The gaseous components can be sub-divided into (e.g.)
  - cold/cloudy medium (CM)
  - warm and hot inter-cloud medium (ICM)
- Supermassive black holes
Processes and interactions of CE

• Gravity of the collision-less components (DM and stars) and the gas.

• Hydrodynamics of the gas components with
  - In-/outflows from the extragalactic medium
  - Mass loss to the stellar components by star formation (SF)
  - Mass input from stars by winds and the final stages of stellar evolution (PN, SN, mergers)
  - Energy input by heating due to winds, PNe, SNe, mergers
  - Exchange between CM and ICM by heating/cooling, condensation/evaporation, and interaction by dragging of gas.
  - Energy dissipation in cloud-cloud collisions.
  - Accretion onto, activity of the galactic SMBH, ...
Processes and interactions of CE

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- Energy dissipation in cloud-cloud collisions.
- Activity of the galactic SMBH...
Processes and interactions of CE

<table>
<thead>
<tr>
<th>Chemo-Dynamical Model</th>
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<tbody>
<tr>
<td><strong>Chemistry</strong></td>
</tr>
<tr>
<td>- star formation</td>
</tr>
<tr>
<td>- energy dissipation</td>
</tr>
<tr>
<td>- heating/cooling</td>
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<tr>
<td>- stellar evolution</td>
</tr>
<tr>
<td>- condensation/evaporation</td>
</tr>
<tr>
<td>- drag</td>
</tr>
<tr>
<td><strong>Dynamics</strong></td>
</tr>
<tr>
<td>- hydrodynamical equations</td>
</tr>
<tr>
<td>- moment equations</td>
</tr>
<tr>
<td>- poisson equation</td>
</tr>
<tr>
<td>- closure relation</td>
</tr>
</tbody>
</table>

**Stellar and Gaseous Components**

- InterCloud Medium (ICM)
- Cloudy Medium (CM)
- High Mass Stars (HMS)
- Intermediate Mass Stars (IMS)
- Low Mass Stars and stellar remnants (LMS)
- Dark Matter (DM)

Samland et al., 1997
Dynamics

- N-body description for the DM and the stellar components.
- Hydrodynamic equations for the evolution of the gas components:
  - mass conservation ($i$ denotes the chemical components):
    \[
    \frac{\partial}{\partial t} \rho^i + \nabla \cdot (\rho^i \vec{v}) = S^i_{\text{mass}}
    \]
  - momentum equation:
    \[
    \frac{\partial}{\partial t} \rho \vec{v} + \nabla (\rho \vec{v} \cdot \vec{v} + P) = S_{\text{mom}}
    \]
  - energy conservation:
    \[
    \frac{\partial}{\partial t} e + \nabla \cdot (e \vec{v}) = S_{\text{energy}}
    \]
- The source terms for mass, momentum, and energy have to be parametrised according to some assumptions on inflow, SF, stellar NS, energy exchange, ...
Dynamics: homogeneous one-zone model

- Neglect spatial dependence and focus on the integral quantities total mass, total gaseous, stellar, dark-matter mass, average abundances). Basic assumption: fast mixing of the matter inside the galaxy

- The total mass of the system is given by:

  \[ M = M_g + M_s ( + M_{DM} = \text{const.} ) \]

- The mass of the gas changes due to inflows \( f \) and outflows \( e \), and due to star formation (at a rate \( \Psi \) (total mass of stars formed per unit time and unit volume)) and stellar mass ejection \( E \):

  \[ \frac{d}{dt} M_g = f - e - \Psi + E \]

Stellar mass changes due to star formation and mass ejection:

\[ \frac{d}{dt} M_s = \Psi - E \]
Star formation

- Goal: know, how many gas is turned into stars of a given mass $m$ at time $t$ from the gaseous medium ==> birthrate function $B(m,t,x)$.

- The total star formation in the physical domain is given by the integral of the birthrate

$$\Psi(t) = \int \int B(m,t,x) \, dx \, dm$$

- Decompose the birthrate into the initial-mass function (IMF) $\xi(m)$ and the star-formation rate (SFR) $\Lambda(t)$:

$$B(m,t) = \xi(m) \, \Lambda(t).$$

- The exact dependence of the SF is not crucial due to self-regulation: over-production of stars ==> more SNe ==> enhanced heating ==> depletion of cold medium ==> lower star formation possible equilibrium state of star formation
Initial-mass function

- Distribution of stellar masses at birth. Definitions:
  - number fraction of stars formed per interval \([m, m+dm]\) = \(\phi(m)\)
  - mass fraction of stars formed ... \(m\phi(m) = \xi(m)\)

normalisation: \(\int_{m_{\text{min}}}^{m_{\text{max}}} m\phi(m)\,dm = 1\)
  min, max are minimum and maximum stellar masses

- Observations: star counts in the local region (take into account the life time of the stars), star counts in star-forming regions.

- Analytic approximations: (piecewise) power-laws. The simplest case is the Salpeter IMF:
  \[\xi(m) \propto m^{-1.35}\]

- Uncertainties: no detailed understanding of SF process yet, IMF at low metallicity
Initial mass function

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Pagel, 1997
Star-formation rate

- SFR $\Lambda$ describes the total amount of (cold) gas transformed into stars.

- Observations:
  IR radiation (heated dust), UV radiation (young massive stars), OB stars, HII regions (recombination lines)
  - SFR dependent on the galactic morphology
  - star-burst galaxies, probably correlated with galactic interactions (close encounters with tidal distortion, mergers)

- Analytic approximations:
  - global laws for one-zone models (exponentially decay, ...)
  - Schmidt-type laws take into account the fact that stars are formed from the cold medium by relating the SFR to the (surface) density of the cold medium in the form of a power law.
Stellar nucleosynthesis

During their evolution and at their death, stars release processed matter. The NS products (yields) depend on stellar mass and composition. CE requires detailed knowledge of stellar life times and NS yields.

### TABLE III. The origin of the light and intermediate-mass elements.

<table>
<thead>
<tr>
<th>Species</th>
<th>Origin</th>
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<th>Origin</th>
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<td>(^1)H</td>
<td>BB</td>
<td>(^{30})Si</td>
<td>C, Ne</td>
<td>(^{51})V</td>
<td>(\alpha, \lambda)-det, xSi, xO, (\nu)</td>
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<td>(^2)H</td>
<td>BB</td>
<td>(^{31})P</td>
<td>C, Ne</td>
<td>(^{50})Cr</td>
<td>xSi, xO, (\alpha, \lambda)-det</td>
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<td>(^3)He</td>
<td>BB, L*</td>
<td>(^{32})S</td>
<td>xO, O</td>
<td>(^{52})Cr</td>
<td>xSi, (\alpha, \lambda)-det</td>
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<td>(^4)He</td>
<td>BB, L*, H</td>
<td>(^{33})S</td>
<td>xO, xNe</td>
<td>(^{53})Cr</td>
<td>xO, xSi</td>
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<td>(^6)Li</td>
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<td>(^{34})S</td>
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<td>(^{54})Cr</td>
<td>nse-lAMCh</td>
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<td>(^7)Li</td>
<td>BB, (\nu, L*, CR)</td>
<td>(^{35})S</td>
<td>He(s), C, Ne</td>
<td>(^{55})Mn</td>
<td>Ia, xSi, (\nu)</td>
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<td>(^9)Be</td>
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<td>(^{10})B</td>
<td>CR</td>
<td>(^{37})Cl</td>
<td>He(s), xO, xNe</td>
<td>(^{57})Fe</td>
<td>Ia, xSi</td>
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<tr>
<td>(^{11})B</td>
<td>(\nu)</td>
<td>(^{36})Ar</td>
<td>xO, O</td>
<td>(^{58})Fe</td>
<td>xSi, Ia</td>
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<td>(^{12})C</td>
<td>L* , He</td>
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<td>xO, O</td>
<td>(^{59})Co</td>
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<tr>
<td>(^{13})C</td>
<td>L* , H</td>
<td>(^{40})Ar</td>
<td>He(s), C, Ne</td>
<td>(^{58})Ni</td>
<td>(\alpha)</td>
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<td>L* , H</td>
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<td>(^{60})Ni</td>
<td>(\alpha), He(s)</td>
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<td>(^{15})N</td>
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<td>(^{61})Ni</td>
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<td>(^{64})Zn</td>
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<td>(^{45})Sc</td>
<td>(\alpha, C, Ne, \nu)</td>
<td>(^{67})Zn</td>
<td>He(s)</td>
</tr>
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<td>(^{24})Mg</td>
<td>C, Ne</td>
<td>(^{46})Ti</td>
<td>xO, (\lambda)-det</td>
<td>(^{68})Zn</td>
<td>He(s)</td>
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<td>(^{25})Mg</td>
<td>C, Ne</td>
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<td>(\nu)-wind</td>
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<td>(^{26})Mg</td>
<td>C, Ne</td>
<td>(^{48})Ti</td>
<td>xSi, (\lambda)-det</td>
<td>(\rho)</td>
<td>xNe, O</td>
</tr>
<tr>
<td>(^{27})Al</td>
<td>C, Ne</td>
<td>(^{49})Ti</td>
<td>xSi</td>
<td>(s(A&lt;90))</td>
<td>He(s)</td>
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<tr>
<td>(^{28})Si</td>
<td>xO, O</td>
<td>(^{50})Ti</td>
<td>nse-lAMCh, He(s)</td>
<td>(s(A&gt;90))</td>
<td>L*</td>
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<td></td>
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</tbody>
</table>

Woosley, Heger, & Weaver, 2002

Chemical Evolution

Martin Obergaulinger, MPA
Stellar nucleosynthesis

During their evolution and at their death, stars release processed matter. The NS products (yields) depend on stellar mass and composition. CE requires detailed knowledge of stellar life times and NS yields.
Stellar nucleosynthesis and mass ejection

- Ejected matter is mixed into the gas. One star of mass \( m \) (life time \( \tau(m) \)) contributes to the enrichment of a nuclear species \( i \) according to its return function \( R^i(t,m) \)

\[
E^i(t, m) = \int_0^{\tau(m)} R^i(t, m) \, dt
\]

- Assumption: all matter is ejected in a single event (i.e. on a timescale negligible compared to the galactic-evolution timescales) and mixed into the (local) gas (“instantaneous recycling”).

\[
R^i(t, m) = \delta(t - \tau(m)) \ R^i(m)
\]

- \( R^i \) is the mass of species \( i \) that is ejected by the star: the initial mass at formation, minus the remnant \( (w^m_i) \), plus the production \( (p^m_i) \)

\[
R^i(m) = m X^i(t - \tau(m)) - w^m_i + m p^m_i
\]

- For an ensemble of stars with a birthrate \( B(t,m) \)

\[
E^i(t) = \int_{\text{min}}^{\text{max}} B(m, t - \tau(m)) \ R^i(m) \, dm
\]
Enrichment of the gas component

- Total gas ejection from stars
  \[ E(t) = \int_{\text{min}}^{\text{max}} (m - \nu_m) \Lambda(t - \tau(m)) \xi(m) \, dm \]

- Abundance of a species \( i \) in the gas changes due to star formation, stellar ejection, inflows (with abundance \( X_i^f \)), and outflows:
  \[ \frac{d}{dt} (X^i M_g) = -X^i \Lambda + E^i + X^i_f f - X^i e \]
Energy budget of the gas

- Heating by absorption of radiation and dissipation of kinetic energy:
  - by stellar radiation, (metal-dependent) winds, expanding HII regions, supershells around OB associations
  - by stellar death, in particular SN

- Radiative cooling of the gas. Dependent on density, temperature, metallicity.

- Transition layers between cold and hot gas with condensation, evaporation ==> mixing and homogenising of ISM, balancing of temperature.

- Inter-cloud collisions dissipate kinetic energy and ram pressure exchanges momentum between the gas phases.

- For many of the processes, self-regulation works.
Chemical evolution models

- One-zone models: perfect mixing in the homogeneous physical domain
  - Closed-box models
  - Open box models: some prescription of infall and outflows

- Multi-zone models: coupled open-box models with inter-zone mass transfer

- Chemo-dynamical models: (multi-dimensional) self-consistent treatment of the entire galaxy with all/some of the components and interactions described above.
One-zone models

- Assume homogeneity in the physical domain (galaxy,...) due to fast mixing, neglect spatial derivatives and therefore large-scale coupling ==> equations for the integral quantities gas mass and stellar mass, and for the (spatially constant) abundances, star-formation rates, ...

- Boundaries closed (the “Simple model”) or open (replenishment of the gas by infall of (primordial) matter, outflow of processed gas).

- Initial conditions: no stars, only gas with primordial composition.

- Allow to understand basic effects like the age-metallicity relation and the distribution of stars with metallicity
Assume homogeneity in the physical domain (galaxy, ...) due to fast mixing, neglect spatial derivatives and therefore large-scale coupling $\Rightarrow$ equations for the integral quantities gas mass and stellar mass, and for the (spatially constant) abundances, star-formation rates, ...

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Initial conditions: no stars, only gas with primordial composition.

Allow to understand basic effects like the age-metallicity relation and the distribution of stars with metallicity

**One-zone models**

![Graphs showing abundance over time and star fraction](image)

*Arnett, 1996*

Fig. 14.4. One-Zone Models
One-zone models

- Assume homogeneity in the physical domain (galaxy,...) due to fast mixing, neglect spatial derivatives and therefore large-scale coupling
  ==> equations for the integral quantities gas mass and stellar mass, and for the (spatially constant) abundances, star-formation rates,...

- Boundaries closed (the "Simple model") or open (replenishment of the gas by infall of (primordial) matter, outflow of processed gas).

- Initial conditions: no stars, only gas with primordial composition.

- Allows to understand basic effects like the age-metallicity relation and the distribution of stars with metallicity.

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**Fig. 14.5. Metallicity Distribution**

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Arnett, 1996

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Martin Obergaulinger, MPA
Chemo-dynamical models

- Simulate the dynamical and chemical evolution of a galaxy self-consistently, tracing a limited number of species.

- Initial condition:
  - parametrisation of an early state of the galaxy
  - obtained from a cosmological simulation of the evolution of large-scale structure starting at high redshift.

- Comparison with observations by determination of
  - the morphological and kinematic structure
  - the star-formation rate and the rates for PN, SN
  - the distribution of elements over the galaxy
  - the stellar populations (==> theoretic spectra)
Simulate the dynamical and chemical evolution of a galaxy self-consistently, tracing a limited number of species.

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Chemical models

Advisorseminar, 09.VII.2004
Samland & Gerhard, 2003
Chemical Evolution
Martin Obergaulinger, MPA
Chemo-dynamical models

- Simulate the dynamical and chemical evolution of a galaxy self-consistently, tracing a limited number of species.

- Initial condition:
  - parametrisation of an early state of the galaxy
  - obtained from a cosmological simulation of the evolution of large-scale structures on high redshift.

- Comparison with observations by determination of:
  - the morphological and kinematic structure
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G-dwarf abundance distribution
[Samland & Gerhard, 2003]
Properties of model subcomponent selected by metallicity. Columns from left to right show all stars with [Fe/H] <-1.9 ("Extreme halo"), -1.9< [Fe/H] <-0.85 ("Inner halo"), -0.85< [Fe/H] <-0.6 ("Metal-weak thick disk"), -0.6< [Fe/H] <-0.15 ("Thick disk"), -0.15< [Fe/H] <0.17 ("Thin disk"), and [Fe/H] >0.17 ("Inner bulge"). For each of these components, the panels from top to bottom show the face-on projection onto the disk plane, edge-on projection, distribution of formation times, [O/Fe] distribution, eccentricity distribution, and distribution of rotation velocities. The top two panels in each row show an area of . Star formation in the model starts at time 1.2 Gyr.

[Samland & Gerhard, 2003]
Successes and Problems

• CE models are able to reproduce the evolution of many CE parameters in the Milky Way and other galaxies such as abundance patterns, star-formation rates and stellar populations,

• Major uncertainties are
  
  – Limited data sets on (extra-)galactic chemical abundances and their evolution
  
  – Stellar astrophysics:
    reaction rates, convection, binary effects, rotation and magnetic fields, formation of black holes or neutron stars, mass cut
effects of low metallicity on stellar evolution and explosion
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  – Cosmology:
    cosmological model, initial data, ...
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Fig. 2. Observed and predicted gas distribution along the Galactic disk. The data and the models are indicated in the figure.

Samland et al., 1997
Matteucci & Chiappini, 1998

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Fig. 1. The predicted oxygen abundance along the Galactic disk by three different models.

Matteucci & Chiappini, 1998

Fig. 2. (Left) Radial variation of O/H, expressed in terms of the optical radius. The solar value is indicated by the horizontal dashed line. The dashed-dotted lines indicate fits to the abundance measurements. Typical error bars are indicated in the lower left corner. (Right) Radial variation of A_v, expressed in terms of the optical radius. The average Galactic value of extinction towards each galaxy is indicated by the horizontal dashed line. The dashed-dotted lines indicate fits to the radial variation of A_v.
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