THE METAL PRE-ENRICHMENT OF THE GALACTIC DISK: SOLVING THE G-DWARF PROBLEM

M. SAMLAND AND G. HENSLER
Institut für Astronomie und Astrophysik
Universität Kiel, D-24098 Kiel, Germany

1. Introduction

The stellar metallicity distribution of low-mass stars is one of the major touchstones for models describing the chemical evolution of our Galaxy. In contrast to the gaseous components, the abundances of the stellar components also reflect the temporal enrichment. Hence, the stellar metallicity distribution is a stringent test for evolutionary models of galaxies.

During the last decades many models describing the chemical evolution of galaxies have been developed. The majority of these models belong to the category of closed box models or modified ones, which only use a parametrized and a very rough description of gas infall or outflow, or neglect dynamical effects totally. Since the box models always have a number of free parameters like gas inflow/outflow, the stellar initial-mass function or heating processes which do not depend on local physical properties, it is not surprising that different evolutionary models can explain the observations with nearly the same accuracy. The paucity of old metal-poor stars in the solar neighbourhood can, for example, be a result of infall of processed gas (Ostriker & Thuan, 1975), metal-enhanced star formation (Talbot & Arnett, 1975), a prompt initial enrichment (Truran & Cameron, 1971), infall of unprocessed gas (Lynden-Bell, 1975) or a combination of these processes.

A different approach to describe the galactic evolution is provided by hydrodynamical and N-body models. The hydrodynamical simulations (Larson, 1975/1976, Burkert & Hensler, 1988), however, predict a too rapid collapse of a protogalactic cloud, which is inconsistent with observations, e.g. the age difference between halo and disk. The main reason for these discrepancies is the insufficient description of the interstellar medium (ISM) and its interactions with the stellar components. In order to understand the evolution

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of galaxies, it is therefore necessary to use self-consistent chemo-dynamical models including the dynamical treatment of the most important stellar and gaseous components and all interaction processes between them. So far these chemo-dynamical models have only been applied one-dimensionally to describe the evolution of giant and dwarf elliptical galaxies (Theis et al., 1992, Hensler et al., 1993).

2. The 2D chemo-dynamical model for disk galaxies

We have developed a 2D chemo-dynamical model in order to self-consistently simulate the evolution of disk galaxies. A detailed description of the model will be published soon (Samland & Hensler, 1994); the model will therefore be only roughly outlined here.

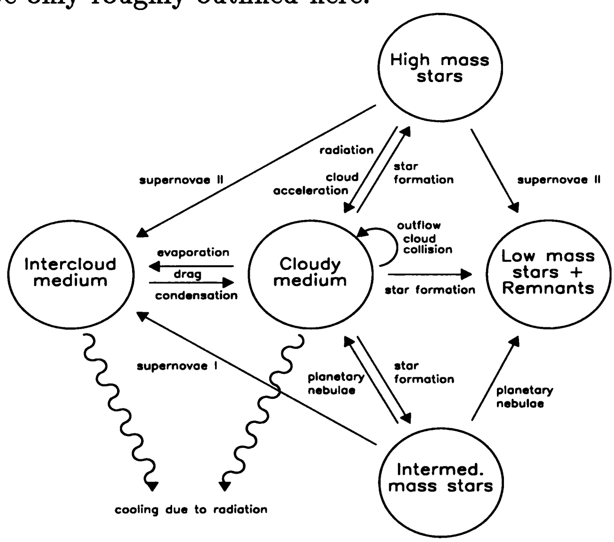

Figure 1. The different gaseous and stellar components are connected via mass, momentum and energy exchange. The most important interaction processes are shown in this diagram.

The ISM is divided into different phases, a cloudy phase (CM) consisting of cold cloud cores ($T < 100$K) with warm gas envelopes ($T \approx 8000$K) and a hot ($T \approx 10^5 - 10^7$K) intercloud medium (ICM). The CM and ICM are assumed to be in pressure equilibrium and connected by mass-, momentum-, and energy-exchange. Furthermore, the CM can dissipate kinetic energy by means of cloud collisions. Beside these gas-gas-interactions there are a number of star-gas-interactions. One of the most important processes is the star formation, which takes place in the cold cores of the CM. The formation itself is self-regulated (Köppen et al., 1994), because of the cloud heating by the newly formed OB stars. As stars of distinct masses evolve very differently, a multi-component description of the stellar population is required. The model includes massive stars, with masses between $10-100\ M_\odot$, which evolve within $3\cdot10^6-2\cdot10^7$ years and explode as supernovae type II (SNII) and intermediate mass stars, with $1-10\ M_\odot$ and main-sequence lifetimes of $2\cdot10^7-1.2\cdot10^{10}$ years. The latter end their evolution with a significant mass loss in the red giant and planetary nebulae phase before they become white dwarfs. Stars with masses less than 1 $M_\odot$ have main-sequence lifetimes of the order of the Hubble time or more. Their influence during the galactic evolution restricts to gravitational forces. Therefore in the dynamical description they can be embraced with the stellar remnants in a third component. Apart from these interactions, the 2D chemo-dynamical model (see Fig. 1) includes supernovae of type I, molecular outflow in the star forming regions, heating of the CM due to Lyman-continuum photons, radiative cooling of the gaseous phases, and drag forces between clouds and the ambient medium.

3. Initial conditions and evolution of the galaxy

The initial model is a purely gaseous rotating Kuzmin-Plummer model (Satoh, 1980) consisting of 99% CM and 1% ICM without dark matter. The total mass and angular momentum of the protogalaxy is $3.7\cdot10^{11}\ M_\odot$ and $2\cdot10^{17}\ M_\odot pc^2 Myr^{-1}$, respectively. From this a spin parameter $\lambda=0.05$ can be derived. Beginning from an equilibrium state the kinetic energy of the CM is dissipated due to cloud collisions and the protogalaxy begins to collapse. The violent collapse phase has a duration of about $2\cdot10^9$ years. During that time the density in the central region rises by more than a factor 100 to $0.2\ M_\odot pc^{-3}$. In the following $13\cdot10^9$ years the central mass density rises by another order of magnitude to a value of $3.6\ M_\odot pc^{-3}$. The duration of the collapse is much longer than the dynamical free-fall time ($\approx 2.5\cdot10^8$years), because the star formation rate (SFR) increases with the CM density and by this also the rate of SNII which stir up the CM efficiently and thus prevent the galaxy from a rapid collapse. The SNII, however, not only increase the velocity dispersion of the clouds, but also eject a large amount of hot metal-rich gas, which is driven, due to its high overpressure, out of the star-forming regions into the halo and the disk. Moreover, at that time the clouds which are embedded in the hot gas begin to evaporate, so that about 90 % of the outflowing material originates from the CM. Therefore the average metallicity of the outflow is approximately solar. During the first 10^9 years the heavy-element abundance increases almost independently of the radial distance from the galactic centre (Fig. 2). As most of the halo stars are formed during that time, they show no significant abundance gradient. Subsequently, the abundances begin to rise faster in the outer parts of the galaxy than in the bulge, although most of the SNII explode near the galactic centre. This can be explained by a closer consideration of the enrichment process. The enrichment of the CM is determined not only by the number of SNII, but also by the mixing between their metal-rich ejecta and the star-forming clouds. The condensation of gas onto cloud surfaces or the cloud formation depends on the thermal energy density of the gaseous phases. During the collapse phase the total SFR is high ($30-50\ M_\odot$/yr) but peaks strongly in the center. Therefore the SN gas will not cool near the star forming regions, but is expelled into the halo or outer disk, cools efficiently there and condensates there on already existing clouds or forms new clouds. After $2.5 \cdot 10^9$ years the SFR begins to decrease while the collapse of the galaxy continues. Therefore the condensation front where the enrichment is effective moves inwards. At $t = 6 \cdot 10^9$ years most of the ejected metal-rich gas condenses close to the star-forming regions. Now the local enrichment exceeds that from gas coming from other parts of the galaxy.

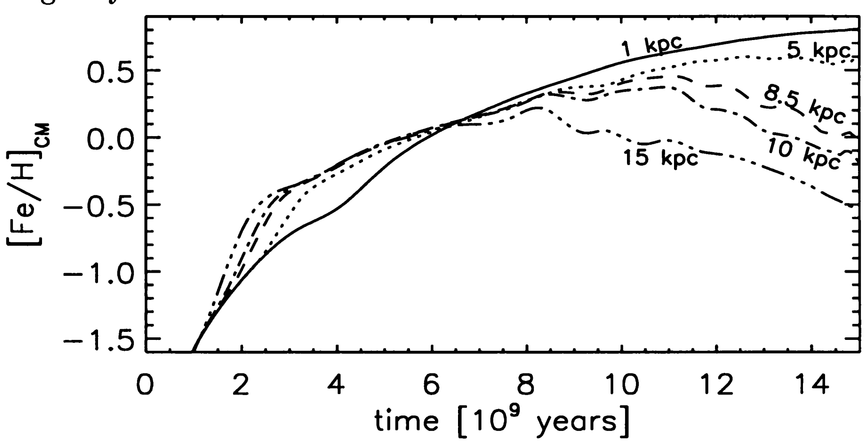

Figure 2. Temporal evolution of the iron abundance in the cloudy medium at different galactocentric radii in the equatorial plane.

4. Results

Fig. 3 shows the calculated oxygen gradient in the CM after $15 \cdot 10^9$ years in comparison with observed values of HII-regions in our Galaxy. It is clearly decernible that the observed abundance gradient is not simple linear and that within the error margin the chemo-dynamical models agree well with the observations. Especially at large galactocentric radii the model predicts a rather shallow gradient of only -0.01 dex/kpc. In the disk the

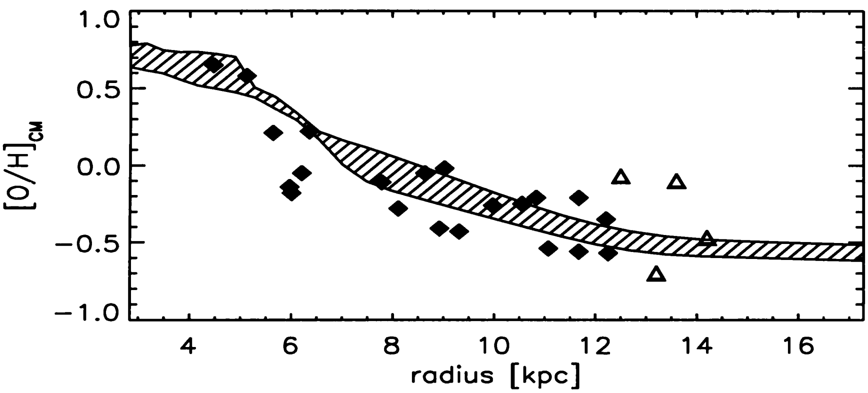

Figure 3. Oxygen abundance in the cloudy medium as a function of radial distance in comparison with the abundances of galactic HII regions. The observations are from Shaver et al., 1983 (rhombi) and from Fich & Silkey, 1991 (triangles). The result of the chemo-dynamical simulation is displayed as hatched area.

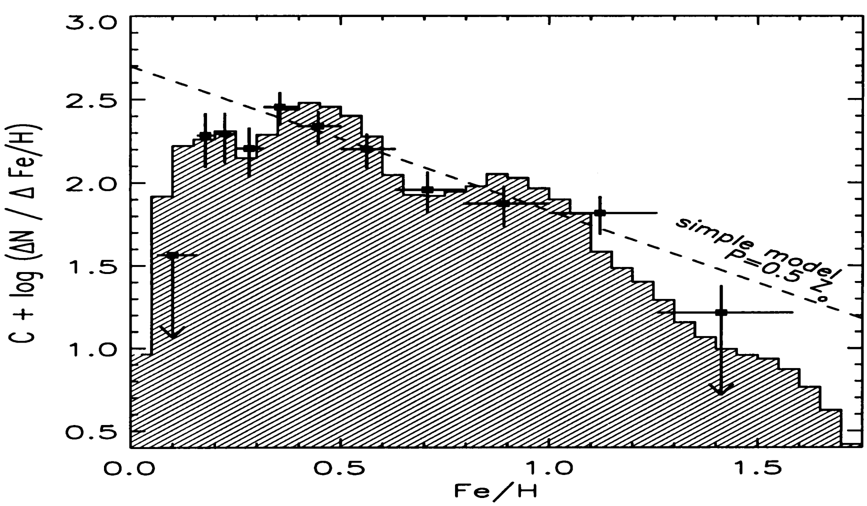

Figure 4. Differential distribution of iron abundances in G-dwarfs in the solar neighbourhood in comparison with the data from Pagel, (1989) which have been corrected for observational errors and cosmic scatter. The vertical error bars indicate the statistical errors in individual bins. The shaded histogram shows the iron distribution of G-dwarfs in our chemo-dynamical model. The dashed line corresponds to a simple closed-box model with an effective yield of $0.5 Z_\odot$.

slope of the oxygen gradient depends strongly on the galactocentric radius. At radii less than 4 kpc the abundance gradients flattens again. The absolute values are more than one order of magnitude higher than in the halo.

A more severe test for galactic evolutionary models is the often cited differential metallicity distribution of long-living stars like the G-dwarfs. This represents not only the star-formation history but depends on the temporal development of the metal-enrichment, the star formation and the dynamical evolution of the stellar components. It is therefore not surprising that simple models of galactic evolution fail to explain the G-dwarf distribution. Fig.4 shows the result of the chemo-dynamical simulation in comparison with the observational data (Pagel, 1989) and with a simple closed-box model (dashed line) with an effective yield of 0.5 $Z_\odot$. Considering the quality of the observations, the agreement between the observations and the chemo-dynamical model is indeed remarkable. The model not only reproduces strikingly the deficiency of metal-poor G-dwarfs, but also self-consistently the variations with metallicity in the differential distribution. This result together with the metallicity gradient of the CM demonstrates convincingly, that the chemo-dynamical models appropriately describe the evolution of galaxies. Moreover, they are the only proper models to describe self-consistently different aspects of the galactic evolution and to provide a complete model for the different components of our Galaxy.

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DISCUSSION

C. Cowley: Have you made a comparison of the predictions of your SFR with the current mass function? If the SFR is dropping rapidly, you expect fewer massive stars than if the SFR is flat.

Samland: The number of massive stars ($M > 10\ M_{\odot}$) within a radius of 3 kpc of the sun is 950 (Humphreys, 1978), which is higher than the calculated number of 250. This indicates, that the SFR in the model at $t = 15 \cdot 10^{10}$ years is lower than the actual SFR in the Galaxy. Possible reasons for the discrepancy are e.g. the infall rate in the chemo-dynamical model is too small or because the disk of our Galaxy is not $15 \cdot 10^{10}$ years old.

S. van den Bergh: Do you have an angular momentum problem if you enrich the disk with supernovae in the bulge?

Samland: No, because the hot gas ejected by the supernovae contributes only a small mass fraction compared with the total mass of the cloudy medium. Another important point is, that the disk is not solely supported by rotation, but also by the velocity dispersion of the stars and clouds.

Ch. Trefzger: Can you produce the thick disk with your model?

Samland: Due to the limited spatial resolution of the grid (200 pc) it is not possible to resolve substructures of the disk.