On the chemical and spectro-photometric evolution of nearby galaxies
van den Hoek, L.B.

Citation for published version (APA):
van den Hoek, L. B. (1997). On the chemical and spectro-photometric evolution of nearby galaxies

General rights
It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

Disclaimer/Complaints regulations
If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: http://uba.uva.nl/en/contact, or a letter to: Library of the University of Amsterdam, Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.

UvA-DARE is a service provided by the library of the University of Amsterdam (http://dare.uva.nl)

Download date: 15 Jan 2019
Inhomogeneous chemical evolution of the Galactic disk: evidence for sequential stellar enrichment?

van den Hoek, L.B., and de Jong, T.

Abstract

We investigate the origin of the abundance variations observed among similarly aged F and G dwarfs in the local Galactic disk. We argue that orbital diffusion of stars in combination with radial abundance gradients is probably insufficient to explain these variations.

We show that episodic and local infall of metal-deficient gas can provide an adequate explanation for iron and oxygen variations as large as \( \Delta [M/H] \sim 0.6 \) dex among stars formed at a given age in the solar neighbourhood (SNBH). However, such models appear inconsistent with the observations because they: 1) result in current disk ISM abundances that are too high compared to the observations, 2) predict stellar abundance variations to increase with the lifetime of the disk, and 3) do not show substantial scatter in the [Fe/H] vs. [O/H] relation. Notwithstanding, our results do suggest that metal-deficient gas infall plays an important role in regulating the chemical evolution of the Galactic disk.

We demonstrate that sequential enrichment by successive stellar generations within individual gas clouds can account for substantial abundance variations as well. However, such models are inconsistent with the observations because they: 1) are unable to account for the full magnitude of the observed variations, in particular for [Fe/H], 2) predict stellar abundance variations to decrease with the lifetime of the disk, and 3) result in current abundances far below the typical abundances observed in the local disk ISM.

We present arguments in support of combined infall of metal-deficient gas and sequential enrichment by successive stellar generations in the local Galactic disk ISM. We show that galactic chemical evolution models which take into account these processes simultaneously are consistent with both the observed abundance variations among similarly aged F and G dwarfs in the SNBH and the abundances observed in the local disk ISM. For reasonable choices of parameters, these models can reproduce \( \Delta [M/H] \) for individual elements \( M = C, O, Fe, Mg, Al, \) and Si as well as the scatter observed in abundance-abundance relations like [O/Fe]. For the same models, the contribution of sequential stellar enrichment to the magnitude of the observed abundance variations can be as large as \( \sim 50\% \).

We discuss the impact of sequential stellar enrichment and episodic infall of metal-deficient gas on the inhomogeneous chemical evolution of the Galactic disk.

5.1 Introduction

The chemical enrichment of the interstellar medium (ISM) by successive generations of stars is a key issue in understanding the chemical evolution of galaxies in general, and the formation history and abundance distributions of the stellar populations in our Galaxy in particular.

Observational studies related to the heavy element enrichment of the local Galactic disk have long shown that stars of similar age exhibit large abundance variations (e.g. Mayor 1976; Twarog 1980a; Twarog & Wheeler 1982; Carlberg et al. 1985; Gilmore 1989; Klockkova et al. 1989; Schuster & Nissen 1989; Meusinger et al. 1991). Recently, Edvardsson et al. (1993a) presented accurate abundance data for nearly 200 F and G main-sequence dwarfs in the solar neighbourhood (SNBH). Their spectroscopic data, analysed with up-to-date input physics, confirms abundance variations as large as \( \sim 0.6 \) dex in \( \Delta [M/H] \) (where \( M=Fe,O,Mg,Al,\)Si) among similarly aged stars.

\(^{1}\)Sects. 5.2 and 5.3 as well as Appendix B were added to the published version of this paper
In contrast to previous understanding, these variations are much in excess of experimental uncertainties and demonstrate that the abundance spread for stars born at roughly the same galactocentric distance is similar in magnitude to the overall increase in metallicity during the lifetime of the disk.

Additional support for the existence of large abundance inhomogeneities in the Galactic disk has been provided by studies of stars in open clusters (e.g., Nissen 1988; Boesgaard 1989; Lambert 1989; García-Lopez et al. 1993; Friel & Janes 1993; Carraro & Chiotti 1994) and B stars in star forming regions in the SNBH (e.g., Gies & Lambert 1992; Cunha & Lambert 1992). These studies show that the concept of a well-defined tight age-metallicity relation (AMR) for the Galactic disk ISM is unfounded (Edmunds 1993) and that the chemical enrichment of the disk has been inhomogeneous on time scales as short as \(10^6 - 10^9\) yr. Similar studies of objects in the Magellanic clouds (e.g., Cohen 1982; Da Costa 1991; Olsewski et al. 1991) and dwarf galaxies (Pilyugin 1992; Kunth et al. 1994; Thuan et al. 1995) suggest that inhomogeneous chemical evolution is a common phenomenon in nearby galaxies as well.

The origin of the abundance variations observed in the local Galactic disk is investigated in this paper. Clearly, large abundance variations in the ISM on time scales at least an order of magnitude shorter than the lifetime of the disk cannot be reproduced by simple galactic evolution models incorporating monotonously increasing age-metallicity relations (AMR). In the past few years, various ideas have been put forward as possible explanations for the intrinsic abundance variations among similarly aged stars:

- stellar orbital diffusion in combination with radial abundance gradients in the Galactic disk (e.g., Francois & Matteucci 1993; Wielen, Fuchs, & Dettbarn 1996);
- sequential enrichment by successive stellar generations (e.g., Edmunds 1975; Olive & Schramm 1982; Gilmore 1989; Gilmore & Wyse 1991; Cunha & Lambert 1992; Roy and Kunth 1995);
- local infall of metal-poor gas (e.g., Edvardsson et al. 1993a; Roy & Kunth 1995; Pilyugin & Edmunds 1995a);
- cloud motions in the ISM (Bateman & Larson 1993);
- inefficient mixing in the disk ISM: isolated chemical evolution of individual parcels of interstellar gas during considerable fractions of the lifetime of the disk (Lennon et al. 1990; Wilmes & Köppen 1995);
- major galaxy merger events resulting in multiple stellar populations in the Galactic disk (Strobel 1991; Pilyugin & Edmunds 1995b);
- chemical fractionization processes such as grain formation (e.g., Henning & Gürtler 1986) and/or element diffusion (e.g., Bahcall & Pinsonneault 1995) so that measured abundances do not reflect initial stellar abundances.

As discussed by Edvardsson et al. (1993a) stellar orbital diffusion is probably inadequate as main explanation for the observed abundance variations. However, recently Wielen et al. (1996) claimed that stars can be born at galactocentric distances very different from those derived using their present-day orbits. In this case, a major fraction of the observed abundance scatter could be due to stellar orbital diffusion. Since it appears unlikely that diffusion can explain the observed abundance variations for all stars in the Edvardsson et al. sample (see below) as well as those observed among young stars (e.g., present in star forming regions) other processes are probably important as well.

Based on the assumption of short mixing time scales of \(\sim 10^7\) yr in the local disk ISM, we argue that the underlying physical mechanisms causing the observed abundance inhomogeneities and those initiating star formation in the disk ISM are the same. No observational support exists for chemical fractionization in low mass F and G main-sequence stars. Therefore, the scatter in stellar metallicities probably reflects the original inhomogeneities in the interstellar gas (e.g., Gilmore 1989). We here restrict ourselves mainly to the processes of sequential stellar enrichment and episodic infall of gas onto the Galactic disk as possible explanation for the observed stellar abundance variations. Since these processes are observed to operate simultaneously in the SNBH (see below), it is important to investigate their combined effect on the chemical evolution of the Galactic disk.

The process of star formation initiated by stars formed during a preceding star formation event nearby, is known as sequential star formation. Support for sequential star formation in the SNBH is provided by observations of spatially separated subgroups of OB stars that appear aligned in a sequence of ages in many OB associations (e.g., Blaauw 1991) and by observations of stars forming at the interfaces of HII regions and their surrounding molecular clouds (e.g., Genzel & Stutzki 1989; Pismis 1990; Goldsmith 1995). Sequential star formation may be induced by the blast waves of nearby supernova explosions compressing the ambient
ISM (e.g. Ogelman & Maran 1976) and/or by propagating ionization and shock fronts from an OB association causing the gravitational collapse of a nearby molecular cloud (e.g. Elmegreen & Lada 1977). In either case, efficient self-enrichment through mixing of enriched material by successive generations of massive stars is expected.

On the other hand, stellar abundance variations can be attributed to infall of relatively unprocessed gas and star formation within the accreted material before efficient mixing wipes out any local chemical inhomogeneities (e.g. Edvardsson et al. 1993a; Pilyugin & Edmunds 1995a). Observational support for star formation in the SNBH initiated by infall of high velocity clouds, has recently been presented by Lépine & Duvert (1994). These authors claim that episodic gas infall is a dominant process in the local disk ISM and is associated with all prominent star forming molecular clouds seen near the Sun (see Sect. 5.5.2). Furthermore, ongoing gas infall has been emphasized by models of dissipative protogalactic collapse (Larson 1969, 1976) and on the basis of time scale arguments of gas consumption in the local disk (Larson et al. 1980; Kennicutt 1983).

In this paper, we present a chemical evolution model for a star forming gas cloud which incorporates stellar enrichment and mixing processes (including infall) and which allows for temporal and/or spatial inhomogeneities in the ISM. This study differs from previous work (e.g. Pilyugin & Edmunds 1995a) in that we investigate in detail the combined effect of metal deficient gas infall and sequential stellar enrichment by successive stellar generations on the chemical evolution of multiple gas clouds in the Galactic disk. In particular, each gas cloud is allowed to follow its individual star formation, mixing, and infall history, as is suggested by the observations. With this model, we fit the stellar abundance variations and current local ISM abundances of C, O, Fe, Mg, Al, and Si observed in the SNBH, the present gas-to-total mass-ratio, and actual star formation and supernova rates. We note that previous investigations were restricted to abundance variations in oxygen and iron only.

We will show that models taking into account the above processes simultaneously are in good agreement with the observations and provide an adequate explanation for the stellar abundance variations with respect to the mean abundances observed in the local disk. Furthermore, we will argue that the contribution of sequential stellar enrichment to the magnitude of the observed stellar abundance variations can be as large as ~50%, i.e. much larger than suggested by previous investigations (e.g. Pilyugin & Edmunds 1995a; Wilmes and Köppen 1995). Corresponding theoretical age and abundance-distributions related to the G-dwarf problem will be discussed in a separate paper.

The paper is organized as follows. In Sect. 5.2, we briefly review observations related to the inhomogeneous heavy element enrichment of the local Galactic disk ISM. In Sect. 5.3, we describe characteristics of the inhomogeneous chemical evolution model proposed for the Galactic disk (model equations and details are given in the Appendix to the electronic version of this paper). In Sect. 5.4, we present model results for episodic infall of metal-deficient gas and sequential stellar enrichment, and examine which of these mechanisms can account satisfactorily for the observations. In Sect. 5.5, we discuss these results in the more general context of the chemical evolution of the Galactic disk and adduce both observational arguments in support of sequential star formation and metal deficient gas infall in the local disk ISM.

### 5.2 Inhomogeneous chemical evolution of the local Galactic disk: observations

#### 5.2.1 Main-sequence F and G dwarfs

We concentrate on the abundance data of nearly 200 main-sequence field F and G dwarfs with actual distances ≤70 pc from the Sun as recently presented by Edvardsson et al. (1993a; hereafter EDV). This sample provides the largest sample of stars available to date for studies related to the chemical evolution of the local disk. Fig. 5.1 displays all F and G dwarfs for which both [O/H] and [Fe/H] abundance-ratios have been determined by EDV.

Large abundance variations of ~0.9 dex in [Fe/H] and ~0.7 dex in [O/H] among stars of a given age are seen to be present (abundance variations in e.g. Mg, Al, and Si resemble those in [Fe/H]). At intermediate stellar ages, these variations are no doubt significant since typical observational errors are ~0.1 dex both in [M/H] and log(Age) (see EDV). At ages in excess of ~15 Gyr and less than ~2 Gyr, the data probably are undersampled (see EDV). Note that the sample is biased against old, high-metallicity stars through the minimum $T_{\text{eff}}$ limit assumed by EDV.
The observed spread in [Fe/H] is tightly correlated with that in [O/H]. This suggests that different nucleo-synthesis sites, which contribute different elements to the initial abundances in stars, mix their products together well. Furthermore, this suggests that stellar abundance variations for different elements are due to the same process. Current observations support the idea that the magnitude of the stellar abundance variations has remained constant over the lifetime of the disk (see also Mayor 1976; Twarog 1980a; Meusinger et al. 1991; Carraro & Chiosi 1994). In the following, we will assume that these abundance variations are randomly distributed within the metallicity range observed at a given stellar age. This is particularly important when considering possible explanations for the observed stellar abundance variations in detail (see Sect. 5.4; cf. Wielen et al. 1996).

![Figure 5.1](image)

Figure 5.1 Observed iron, oxygen, and magnesium abundance ratios for main-sequence F and G dwarfs in the solar neighbourhood (data from Edvardsson et al. 1993a). Open circles represent stars with mean stellar galactocentric distances at birth within 0.5 kpc from the Sun ($R_\odot = 8.4$ kpc). Full dots indicate stars with average distances within ~2 kpc from the Sun. Typical errors are indicated at the bottom right of each panel. Note that the abundances of the most metal-poor disk stars included in this sample resemble those of metal-rich halo dwarfs and giants (e.g. Bessell et al. 1991; Gratton & Sneden 1991; Nissen et al. 1994). We assumed solar abundance ratios by number of $^{16}\log (O/H)_\odot = -3.13$, $^{16}\log (Fe/H)_\odot = -4.51$, and $^{16}\log (Mg/H)_\odot = -4.42$ and a hydrogen mass fraction in the Sun of 0.68 (see Anders & Grevesse 1989; Grevesse & Noels 1993). Top panels: Distributions of [Fe/H] (left) and [O/H] abundance ratios vs. galactic age. Bottom panels: [Fe/H] vs. [O/H] (left) and [Mg/H] vs. [O/H].

Ages, abundances, and kinematical properties of the dwarfs belonging to the EDV sample are consistent with earlier investigations (e.g. Twarog 1980a; Carlberg et al. 1985; Meusinger et al. 1991). An extensive discussion of the possible sources of errors in the abundance and age analysis as well as several consistency checks can be found in Edvardsson et al. (1993a,b). Errors due to data reduction uncertainties are estimated
to lead to errors of at most 0.05 to 0.1 dex in abundance ratios [M/Fe] as well as in [Fe/H] (see EDV). These errors are not expected to vary in a systematic manner with the derived stellar abundances and corresponding corrections will probably not reduce the observed variations. Edvardsson et al. estimated errors in relative ages of ~25% for stars with similar abundances (absolute errors may be considerably larger). Thus, ages of stars as old as the Sun are estimated to be accurate within ~1–2 Gyr. We conclude that errors in the abundances and ages of the sample stars are unlikely to account for the observed abundance variations, at least for stars with intermediate ages of ~5 Gyr.

Knowledge of the formation sites of the sample stars is important to decide whether or not orbital diffusion in combination with radial abundance gradients in the Galactic disk can provide an adequate explanation for the observed abundance variations. Galactocentric distances of the sample stars at birth were obtained using stellar orbits reconstructed from their present-day galactocentric distances, proper motions, and radial velocities, and using both theoretical and empirical models for the Galactic potential as discussed by EDV. Accordingly, nearly 85% of the sample stars were found to have mean galactocentric distances \( R_m \) at birth within 1 kpc from the Sun (assuming \( R_\odot \sim 8.4 \) kpc at present). However, predictions of the diffusion of stellar orbits in space, based on the observed relation between velocity dispersion and age for nearby stars, suggest that many stars may have been formed at galactocentric distances as large as ~4 kpc from where they are nowadays observed in the SNBH (Wielen et al. 1996). In either case, these nearby stars trace the evolution of the Galactic disk ISM over a much wider range in galactocentric distance then they are observed.

As an independent test to examine whether stellar orbital diffusion can be the main cause for the observed abundance variations, we translated stellar abundance deviations \( \Delta [M/H] \) from the mean abundances of similar aged stars born at \( \sim R_\odot \) into galactocentric distance differences \( R_m - R_\odot \). This was done independently for [Fe/H] and [O/H] abundance ratios assuming present-day local radial abundance gradients of \(-0.07 \pm 0.015\) dex kpc\(^{-1}\) in [O/H] (e.g. Shaver et al. 1983; Grenon 1987; see also Wilson & Matteucci 1992) and \(-0.1\) dex kpc\(^{-1}\) in [Fe/H] (see e.g. EDV). Clearly, distances \( R_m \) based on oxygen and iron abundances are expected to be similar (e.g. \( \Delta R_m^{O,Fe} \leq 1 \) kpc) when orbital diffusion is important for the observed stellar abundance variations.

In this manner, we find that \( \Delta R_m^{O,Fe} \geq 1 \) kpc for 47 stars in the EDV sample (i.e. ~50%). Similarly, we find \( \Delta R_m^{O,Fe} \geq 2, 3, \) and 4 kpc, for ~31, 14, and 8% of the sample stars, respectively. We note that the derived values of \( \Delta R_m^{O,Fe} \) are insensitive to the stellar age but depend on the assumed radial abundance gradients as well as on the mean [M/H] vs. age relations adopted for stars born at \( R_\odot \). Although a detailed investigation of the uncertainties involved is beyond the scope of this paper (e.g. the variation of abundance gradients with disk age; cf. Grenon 1987), we estimate that \( \Delta R_m^{O,Fe} \leq 0.8 \) (1.5) kpc for typical errors of 0.05 (0.1) dex in both [Fe/H] and [O/H] for most of the sample star (assuming a gaussian error distribution). This suggests that a substantial part of the observed abundance variations is difficult to explain by stellar orbital diffusion only. Also, Edvardsson et al. argued that the magnitude of the observed variations will reduce to \( \Delta [M/H] \sim 0.3 \) dex if one accounts properly for systematic errors and possible effects of stellar orbital diffusion. However, a reduction of the abundance spread among field dwarfs to \( \Delta [Fe/H] \sim 0.3 \) dex seems contradicted by the observed variations of \( \Delta [Fe/H] \sim 0.5 \pm 0.1 \) dex among similarly aged open clusters after correcting for radial abundance gradients across the Galactic plane (Carraro & Chiosi 1994). Apart from this, such a reduction appears inconsistent with the observed abundance spread of [O/H] \( \geq 0.4 \) dex among B stars at a given galactocentric radius between 7 and 16 kpc in the disk (Gehren et al. 1985; Kaufer et al. 1994) and with the large abundance variations of ~0.7 dex observed among young open clusters over a distance scale of only ~1 kpc at a galactocentric radius of ~13 kpc (Rolleston et al. 1994).

What fraction of the current disk stellar population actually formed in the Galactic halo depends on the detailed dynamical evolution of the disk which is not well known (e.g. Pagel & Tautvaisiene 1995). However, most stars in the EDV sample have derived maximum distances from the Galactic plane at birth of \( h_{\text{max}} < 0.5 \) kpc. This largely excludes halo stars from the sample and further implies that abundance gradients perpendicular to the Galactic plane are inadequate as explanation for the observed abundance variations (e.g. Carney et al. 1990).

From these arguments, we conclude that orbital diffusion of stars from elsewhere in the Galactic disk is probably insufficient as explanation for the observed variations in [Fe/H] and [O/H] among F and G dwarfs in the SNBH. This conclusion is consistent with the finding that abundance variations for subsamples of stars restricted to be born within 1 and 0.5 kpc from the Sun, respectively, are similar to those for the complete sample (see EDV; cf. Fig. 5.1). Therefore, we believe that differential chemical evolution and mixing of interstellar gas must be an important cause for the large stellar abundance variations observed in the SNBH as well. The abundances of the Sun and of open clusters in the Galactic disk fit well into this picture, as is argued below.
5.2.2 Chemical evolution of the solar neighbourhood

Detailed comparison of abundances within local HII regions and the Sun have shown that oxygen (among other heavy elements) is underabundant in the HII regions by about 0.15–0.3 dex (e.g. Shaver et al. 1983; Peimbert 1987; Baldwin et al. 1991; Osterbrock, Tran & Veilleux 1992). Also, CNO-abundances of HII-regions and B main-sequence stars in the Orion nebula were found smaller than corresponding abundances in the Sun (Cunha & Lambert 1992; Gies & Lambert 1992). The remarkable result that the Sun is metal-rich by \( \sim 0.15–0.2 \) dex in \([\text{O}/\text{H}]\) compared to its surroundings is also supported by observations of B stars in nearby associations and young clusters (Fitzsimmons et al. 1990), diffuse interstellar clouds (e.g. York et al. 1983), and disk planetary nebulae (de Freitas Pacheco 1993; Peimbert et al. 1993). Although abundance determinations in the SNBH may be biased towards regions associated with infall of metal-poor gas or suffer from heavy element depletion by dust, the existence of many metal-poor regions in the SNBH would be difficult to reconcile with efficient mixing in the local disk ISM (e.g. Roy & Kunth 1995).

The above observations are consistent with the Edvardsson et al. data which suggest that the Sun is metal-rich by 0.2–0.25 dex in \([\text{O}/\text{H}]\) and by 0.25–0.3 dex in \([\text{Fe}/\text{H}]\) compared to the mean abundances of stars which formed in the SNBH \( \sim 4.5 \) Gyr ago (cf. Fig. 5.1). These observations support the idea that the Sun is metal-rich for its age (see also Steigman 1993) and that abundance inhomogeneities in the local disk ISM did exist. The fact that the Sun is metal-rich by a factor of \( \sim 1.5–2 \) compared to nearby regions currently experiencing star formation may be explained by self-enrichment of the gas cloud out of which the Sun was born (e.g. Gies & Lambert 1992; Peimbert et al. 1993). Alternatively, orbital diffusion of the Sun may play an important role (Wielen et al. 1996). We will discuss arguments in support of the former possibility in Sect. 5.2.

5.2.3 Open clusters

Variations in \([\text{Fe}/\text{H}]\) among disk open clusters of a given age are known to be larger than any possible trend of \([\text{Fe}/\text{H}]\) with age (e.g. Nissen 1988; Boesgaard 1989; Garcia-Lopez et al. 1993; Friel and Janes 1993; Dufton et al. 1994). Recently, abundance variations of \( \sim 0.5 \pm 0.1 \) dex in \([\text{Fe}/\text{H}]\) among clusters of a given age \( \) after correcting for the radial abundance gradient across the Galactic plane have been reported by Carraro & Chiosi (1994). The observed abundance variations among open clusters appear somewhat smaller (i.e. by \( \sim 0.2-0.3 \) dex in \([\text{Fe}/\text{H}]\)) than those among field F and G dwarfs in the EDV sample. However, the magnitude of the observed variations suggests that the processes responsible for the abundance inhomogeneities among field stars in the SNBH and among open clusters widespread throughout the Galactic disk may well be the same.

The lack of a tight age-metallicity relationship for open clusters in the Galactic disk suggests that the chemical enrichment of the disk ISM has been inhomogeneous on time scales less than \( \sim 10^{8}-10^{9} \) yr, consistent with the abundance variations observed for intermediate age F and G dwarfs discussed above.

5.3 Model characteristics and assumptions

In the previous section, we have argued that differential chemical evolution and mixing of interstellar gas probably provides the main explanation for the large abundance variations observed among similarly aged stars in the SNBH. In this case, abundance inhomogeneities in the global disk ISM may result from local mixing of metal-deficient material (e.g. infall) and/or local mixing of metal-enhanced material (e.g. stellar enrichment). When star formation is initiated within the mixed material before any abundance fluctuations are wiped out, these inhomogeneities can be recorded by long-living stars.

Efficient mixing by stellar winds and supernova explosions is generally accepted to occur within \( \sim 10^{7}-10^{8} \) yr (e.g. Edmunds 1975; Ciotti et al. 1991; Roy & Kunth 1995). This suggests that the processes responsible for the onset of star formation and those causing substantial abundance inhomogeneities in the disk ISM are the same. We consider this as a strong argument in favour of sequential star formation and/or infall induced star formation as the main processes responsible for the observed abundance variations (ample observational support for the occurrence of these processes in the local disk ISM are briefly discussed in Sect. 5.5.2). Obviously, the quantitative effect of these processes on stellar abundance variations, relative to the mean abundances in the local ISM, depends on the detailed chemical evolution of the disk ISM.

5.3.1 Model description

We present a model for the inhomogeneous chemical evolution of a star forming gas cloud. The basis for this model forms the individual star formation history and chemical evolution of multiple subclouds that
mutually exchange interstellar material. We here restrict ourselves to a brief outline of the basic assumptions and model characteristics. A more detailed description of the equations and input physics used is given in the (Appendix to the) electronic version of this paper.

We start from a homogeneous gas cloud with total mass $M_\text{c}$. At any time the cloud is subdivided into $N_{\text{sc}}$ star forming, active subclouds (with corresponding masses $M'_{\text{sc}}$) and a quiescent, inactive cloud part (with mass $M'_{\text{q}}$) not experiencing star formation. Each subcloud is allowed to follow its individual star formation, infall, and mixing history. Infall of matter is considered by allowing episodic mixing of metal-deficient material to each subcloud separately.

![Figure 5.2 Schematic model for the inhomogeneous chemical evolution of a star forming cloud: evolutionary sequence of star formation, enrichment and mixing processes. Shown is a star forming cloud region. Each of the processes indicated in this region may occur in other regions of the cloud as well. Symbols have the following meaning: a subclouds indicated by hatched areas, b star formation indicated by asterisks, c stellar enrichment shown as shaded areas enclosing white asterisks, d subcloud core dispersal indicated as blanked out area surrounding stars, e break up of entire subcloud and initiation of star formation in a nearby subcloud, f arrow indicates stars entering a subcloud from elsewhere. Each of the processes indicated may occur frequently during the cloud evolution time $t_{\text{ev}}$.](image)

The adopted set of processes that modify the distribution of gas and stars within a star forming region of a molecular cloud are illustrated in Fig. 5.2. Different subfigures refer to the following processes:

(a) subcloud formation from the inactive cloud ISM (and/or from infalling material);
(b) conversion of gas into stars (star formation at distinct subcloud cores);
(c) ejection of material by stars to their immediate surroundings;
(d) mixing of dispersed core material with subcloud after star formation event;
(e) break up of entire subcloud, mixing with inactive cloud ISM, and induced star formation;
(f) enrichment of subcloud by stars not formed within the subcloud.

In our model, the inhomogeneous chemical evolution of a star forming gas cloud, consisting of many subclouds, is determined by the combined effect of the above processes. During a time-interval $\Delta t$, these processes may occur simultaneously within each subcloud. In this manner, the initial abundances of a newly formed stellar generation are determined by: 1) the enrichment of the subcloud by preceding stellar generations, and 2) the mixing history of the subcloud with the ambient ISM.
In brief, the adopted evolution scenario is as follows. Subcloud formation (Fig. 5.2a) is assumed to occur either from the inactive cloud ISM and/or from infalling material (details related to the infall model will be given in Sect. 5.4.3). During the lifetime $t_{\text{ev}}$ of the entire system, a total number of $N_{\text{sf}}$ star formation events is assumed to occur. Each star formation event is assumed to take place in an active subcloud (Fig. 5.2b). Each subcloud is allowed to experience numerous star formation events and/or to remain inactive during a substantial part of its lifetime. Consequently, each subcloud can be enriched by one or multiple star formation events dictating its chemical evolution (Fig. 5.2c). When the active subcloud core is dispersed by stellar winds and/or supernova shocks, part of the enriched matter is assumed to mix homogeneously with the surrounding subcloud material (Fig. 5.2d). The remaining part is assumed to mix homogeneously either to a nearby subcloud hosting the next star formation event or to the ambient inactive cloud part (Fig. 5.2e). No mass-exchange is assumed between the subcloud and the ambient inactive cloud ISM during the time interval in which two or more star formation events occur within the same subcloud. In addition, subcloud material may be enriched by stars formed outside the subcloud. In this case, stars from elsewhere in the inactive cloud occasionally enter the subcloud region and enrich the subcloud by means of their ejecta (Fig. 5.2f). Stellar enrichment by old stellar generations is assumed to proceed continuously with time but is considered in detail only at specific evolution times corresponding to the occurrence of any of the discontinuous processes referred to in Fig. 5.2.

We define the subcloud core dispersal time $\Delta t_{\text{disp}}$ as the time between onset of star formation within a subcloud core region and the complete dispersal of this region. This time interval constraints the mass of the most massive star that is able to enrich the subcloud core material before the core ultimately breaks up. Before dispersal of an entire subcloud, the subcloud will be enriched by the stellar populations it is hosting. After subcloud dispersal (i.e. after a typical mixing time scale $\Delta t_{\text{mix}}$), stars and gas belonging to the subcloud are assumed to mix instantaneously and homogeneously with the inactive cloud ISM. Subsequently, different cloud fragments may combine to form new subclouds wherein star formation occurs as soon as the critical conditions for star formation are met. The mixing history of each subcloud determines the inhomogeneous chemical evolution of the inactive cloud part as well as that of nearby subclouds. For simplicity, we do not consider partial mixing of subcloud material to the inactive cloud.

### 5.3.2 Outline of model computations

We perform Monte-Carlo simulations of the inhomogeneous chemical evolution of a star forming gas cloud. The continuous process of formation and break up of subclouds and of the formation and dispersion of subcloud core regions associated with star formation, are followed as outlined in the previous section. During the evolution of the cloud, we keep track of the total mass contained in gas and stars as well as the stellar and interstellar abundances of H, He, C, O, Fe, Mg, Al, and Si, both within each subcloud and the inactive cloud part. No instantaneous recycling is assumed, i.e. metallicity dependent stellar lifetimes are taken into account.

### 5.3.3 Model input parameters

Model input parameters for the reference model are listed in Table 5.1. We distinguish parameters related to: 1) the entire cloud and inactive cloud part, 2) active subcloud regions, and 3) individual star formation events:

- **Cloud and inactive cloud part:** The initial cloud mass $M_{\text{cl}}$ is treated as a mass scaling parameter (i.e. resulting abundances are not altered for different values of $M_{\text{cl}}$). We here adopted $M_{\text{cl}} = 5 \times 10^{10} M_\odot$ similar to that of the Galactic disk (e.g. Binney & Tremaine 1987). We assume a cloud evolution time $t_{\text{ev}} = 14$ Gyr. This is comparable to the age of the Galaxy as derived from the age of the oldest globular clusters, i.e. $14 \pm 3$ Gyr (e.g. Buonanno et al. 1989). In our model, the impact of processes causing stellar abundance variations does not depend on the specific age of the Galactic disk assumed.

  We consider a total number of star formation events during the cloud evolution time of typically $N_{\text{sf}} = 100$. In practice, $N_{\text{sf}}$ is limited only by the preferred model run time, i.e. 1-2 hours on a HP Apollo 715 machine. The total number of subclouds $N_{\text{sc}}$ is determined by the number of star formation events within each subcloud. For the reference model, we assume a maximum number of star formation events within one subcloud $N_{\text{sf}}^{\text{max}} = 1$ so that $N_{\text{sc}} = N_{\text{sf}}$. Cloud initial abundances $X_{\text{ini}}$ are as given in Table 5.1. Initially, the cloud is considered homogeneous, metal-free, and void of stars.

- **Active subclouds:** In case of the reference model, we force subclouds to form at regular intervals of $t_{\text{ev}} / N_{\text{sc}} = 1.4 \times 10^5$ yr. We assume the subcloud mass $M_{\text{sc}}$ directly proportional to the entire cloud gas-to-total mass-ratio $\mu$ at time of subcloud formation $t_{\text{sc}}$. This implies more massive subclouds to form at relatively
Table 5.1 List of input parameters (values listed for reference model)

<table>
<thead>
<tr>
<th>Cloud and inactive cloud part</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>( M_{\mathrm{cl}} )</td>
<td>5 ( \times ) 10(^8) ( M_\odot )</td>
</tr>
<tr>
<td>( t_{\mathrm{ev}} )</td>
<td>14 Gyr</td>
</tr>
<tr>
<td>( N_{\mathrm{sf}} )</td>
<td>100</td>
</tr>
<tr>
<td>( N_{\mathrm{scl}} )</td>
<td>100</td>
</tr>
<tr>
<td>( X_{\mathrm{cl}}(0) )</td>
<td>H=0.76</td>
</tr>
</tbody>
</table>

For each subcloud \( i \)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t_{\mathrm{scl}} )</td>
<td>time at which subcloud is formed, i.e. each ( t_{\mathrm{ev}} / N_{\mathrm{scl}} = 1.4 \times 10^8 ) yr</td>
</tr>
<tr>
<td>( M_{\mathrm{scl}} )</td>
<td>exponentially decaying subcloud mass at time of formation</td>
</tr>
<tr>
<td>( N_{\mathrm{max}}^{\mathrm{sf}} )</td>
<td>maximum number of SF events within one subcloud</td>
</tr>
<tr>
<td>( \Delta t^{\mathrm{mix}}_{\mathrm{disp}} )</td>
<td>mixing time of entire subcloud</td>
</tr>
</tbody>
</table>

For each star formation event \( j \)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t_{\mathrm{sf}} )</td>
<td>evolution time at which SF-event ( j ) occurs</td>
</tr>
<tr>
<td>( \Delta t^{\mathrm{disp}}_{\mathrm{disp}} )</td>
<td>subcloud core dispersal time</td>
</tr>
<tr>
<td>( \epsilon )</td>
<td>0.50</td>
</tr>
<tr>
<td>( \lambda )</td>
<td>0</td>
</tr>
</tbody>
</table>

Notes: (1) \( \epsilon \) is the mass fraction of the subcloud converted into stars during dispersal time \( \Delta t^{\mathrm{disp}}_{\mathrm{disp}} \); (2) \( \lambda \) refers to the amount of stellar material returned to the subcloud core hosting the next star formation event.

high gas fractions \( \mu(t) \). Assuming a constant star formation efficiency, this results in an exponential decrease of subcloud mass with disk age \( t \) (e.g. Clayton 1985):

\[
M_{\mathrm{scl}} = M_{\mathrm{scl}}(0) \exp(-t/t_{\mathrm{dec}})
\]

where \( M_{\mathrm{scl}}(0) \) is the mass of a subcloud formed at \( t=0 \) (which may vary between different models) and \( t_{\mathrm{dec}} \) a characteristic time scale at which the mass of subsequent subclouds formed is assumed to decay (identical for all models). The assumption of a star formation rate (SFR) directly proportional to the subcloud formation rate is not essential for the results discussed here.

The decay time scale \( t_{\mathrm{dec}} \) is constrained observationally by the ratio of the average past to present SFR in the Galactic disk (\( \sim 3-7 \); e.g. Mayor & Martinet 1977; Dopita 1990). We here assume an exponentially decaying SFR with \( t_{\mathrm{dec}} = 6 \) Gyr. As will be shown in Sect. 5.4.1, this SFR can account simultaneously for the actual gas-to-total mass-ratio in the disk of \( \mu_1 \sim 0.05-0.2 \) (Kulkarni & Heiles 1987; Binney & Tremaine 1987; see also Basu & Rana 1992), the smooth increase in the global AMR for elements such as O and Fe, and the magnitude of the current SFR in the Galactic disk (i.e. \( \sim 3.5 \) \( M_\odot \) yr\(^{-1}\); e.g. Dopita 1987). In contrast, constant SFR models are inconsistent with these observations (Twarog 1980a; see also Clayton 1985).

The time between the formation and complete mixing of a subcloud to the inactive cloud part is defined as \( \Delta t^{\mathrm{mix}}_{\mathrm{disp}} \). This time scale has been considered to allow for the individual chemical evolution of a subcloud isolated from the inactive ISM (see below).

- **Individual star formation events:** We assume the onset of star formation within each subcloud to coincide with the formation of the subcloud itself in case of the reference model. This results in a grid of regularly spaced star formation times \( t_{\mathrm{sf}} = t_{\mathrm{scl}} \).

We define the core dispersal time \( \Delta t^{\mathrm{disp}}_{\mathrm{disp}} \) as the time between onset of star formation \( t_{\mathrm{sf}} \) within a subcloud core and the moment star formation ends due to the actual break up of this core. Observational estimates of this time scale are generally \( \lesssim 10^7 \) yr (e.g. Garmany et al. 1982; Leissawitz 1985; Genzel & Stutzki 1989; Rizzo & Bajaja 1994; Haikala 1995). For the reference model, we assume the entire subcloud to break up at time of dispersal of the star forming subcloud core, i.e. \( \Delta t^{\mathrm{mix}}_{\mathrm{disp}} = \Delta t^{\mathrm{disp}}_{\mathrm{disp}} \).

The star formation efficiency \( \epsilon \) is defined as the amount of subcloud matter \( \Delta M_{\mathrm{scl}} \) turned into stars during star formation event \( j \). In fact, the star formation efficiency determines the amount of material to which the stellar ejecta of a previous stellar generation are mixed within a given star forming cloud. Observational estimates for \( \epsilon \) in molecular clouds in the Galactic disk span a wide range: between a few tenths of a percent to \( \sim 50\% \) (e.g. Wilking & Lada 1983). We will discuss the values assumed for \( \epsilon \) in
Table 5.2 IMF related parameters and stellar enrichment

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$</td>
<td>-2.35</td>
</tr>
<tr>
<td>$m_1$, $m_0$</td>
<td>0.1, 60 $M_\odot$</td>
</tr>
<tr>
<td>$m_{SNII}$, $m_{SNII}$</td>
<td>8.30, 30 $M_\odot$</td>
</tr>
<tr>
<td>$m_{SNIa}$, $m_{SNIa}$</td>
<td>2.5, 8 $M_\odot$</td>
</tr>
<tr>
<td>$\phi_{SNIa}$</td>
<td>0.005</td>
</tr>
<tr>
<td>$\phi_{SNIb/c}$</td>
<td>0.33</td>
</tr>
</tbody>
</table>

5.3.4 Stellar evolution data

We follow the stellar enrichment of the star forming cloud in terms of the characteristic element contributions of Asymptotic Giant Branch (AGB) stars, SNII, SNIa, and SNIb/c. This treatment is based on the specific abundance patterns observed within the ejecta of each of these stellar groups (e.g. Trimble 1991; Groenewegen & de Jong 1992; van den Hoek et al. 1996). We take into account metallicity dependent stellar element yields, remnants, masses, and ages, while assuming the stellar ejecta to be returned at the end of the lifetime of the star (see e.g. Maeder 1992; Schaller et al. 1992). The respective time delays in enrichment by SNII and SNII are accounted for in detail. A more detailed description of the combined set is given elsewhere (e.g. van den Hoek et al. 1996; see also electronic version of this paper).

For AGB stars (initial mass $m \lesssim 8 M_\odot$), we adopt the metallicity dependent yields presented by Groenewegen & de Jong (1992). These yields are based on a synthetic evolution model for AGB stars and are successful in explaining the observed abundances in carbon stars and planetary nebulae in the Galactic disk (Groenewegen et al. 1995; van den Hoek & Groenewegen 1996). For Type-II SNe, we use the explosive nucleosynthesis yields (independent of initial metallicity) described in detail by Hashimoto et al. (1993) and Thielemann et al. (1993) for stars with $8 \lesssim m[M_\odot] \lesssim 50$. The 20 $M_\odot$ model of this set accounts well for the observed abundances in SN1987A (Nomoto et al. 1991). Explosive nucleosynthesis yields for Type-la SNe are adopted from Nomoto et al. (1984; model W7 for SNIa at $Z = Z_\odot$ and $Z = 0.0$ of the accreted material; see also Yamaoka 1993) and for SNIIb/c from Woosley et al. (1995). According to these yields, typical amounts of iron produced are $\sim 0.08 M_\odot$ for SNIa, $\sim 0.8 M_\odot$ for SNIa, and $\sim 0.1 M_\odot$ for SNIb/c.

The adopted yields for SNIa, b/c are relatively uncertain due to unknown details of the progenitor history and the explosion mechanism (either binary or single star evolution; see; e.g. Smecker-Hane & Wyse 1992; Woosley et al. 1993). However, we do not believe that these uncertainties are relevant for the qualitative results obtained in this paper (cf. Sect. 5.5.2).

Metallicity dependent stellar yields for stars during their wind (i.e. pre-SN) phase have been adopted from Maeder (1992, 1993), to whom we refer the reader also for a definition of the stellar element yields as used in the Appendix. For stars with $m \gtrsim 20 M_\odot$ we used the higher mass loss rates in case $Z = 0.02$ (cf. Maeder 1992; Schaller et al. 1992). The mass $m_e$ of the helium core left at the end of the He-burning phase (or C-burning phase for massive stars) has been used as input for the SNII and SNIIb/c nucleosynthesis models referred to above. Yields were linearly interpolated both in $m$ and $m_e$. Errors due to the coupling of these sets of stellar evolution data are probably small and are neglected here (see Chap. 3). Remnant masses and stellar lifetimes were adopted from the Geneva group as well (e.g. Schaller et al. 1992).

For the reference model, the adopted IMF-slope, stellar mass limits at birth, and progenitor mass ranges for stars ending their lives as SNIa and SNII+SNIIb/c are listed in Table 5.2. Stars with $m > 60 M_\odot$ have been excluded because their theoretical yields are rather uncertain (e.g. Maeder 1992). We expect that the IMF-weighed contribution by such stars to the enrichment of the ISM is relatively low.

Stars more massive than $m_{SNIa}^{SNII}$ are assumed not to explode as supernova but to end as black hole (cf. Maeder 1992; Nomoto et al. 1994; Prantzos 1994; Tsujimoto et al. 1995). Consequently, stars with $m \gtrsim m_{SNIa}^{SNII}$ contribute to the ISM enrichment during their stellar wind phase only. When no upper mass limit $m_{SNIa}^{SNII} = 25-30 M_\odot$ is introduced, models using up-to-date SNII yields predict abundances that are too high compared to those observed in the ISM, in particular for helium and oxygen (e.g. Twarog & Wheeler...
5.4 Results

We consider a fraction $\phi_{\text{SNIa}} = 0.005$ of all WD progenitors with initial mass between $\sim 2.5$ and $8$ M$_{\odot}$ to end as SNIa. A more detailed discussion of the contribution by SNIa is postponed to Sect. 5.5.1 (see also Ishimaru & Arimoto 1995). In addition, we assume about one third of all supernova progenitors with $m_{\text{SNH}} \lesssim m_{\text{a}}^{\text{SNH}}$ to end as SN Ib/c when they experience intense mass-loss in close binary systems (or during the Wolf-Rayet stage), i.e. $\phi_{\text{SN Ib/c}} = (\text{SN Ib/c} / (\text{SN Ib/c} + \text{SNH})) = 0.33$. This value is based on the observed ratio of current formation rates of SNH and SN Ib/c in the Galaxy (e.g. van den Berg & Tammann 1991; Tutukov, Yungelson & Iben 1992; Cappellaro et al. 1993).

5.4.1 Reference model

We consider a homogeneous gas cloud with initial conditions as listed in Tables 5.2 and 5.3. Within this cloud, active subclouds are formed at regular time intervals of $1.4 \times 10^8$ yr so that in total $N_{\text{cl}} = 100$ subclouds form during cloud evolution time $t_{\text{c}} = 14$ Gyr. We assume no time-delay between the formation of the subcloud and the actual onset of star formation within that subcloud, i.e. $t_{\text{sf}} = t_{\text{c}}$, and further assume each subcloud to experience a single star formation event. During this event, lasting $\Delta t_{\text{disp}} = 10^7$ yr, half of the subcloud mass is converted into stars, i.e. $\epsilon = 0.50$. After each event, both gas and stars contained within the subcloud are mixed homogeneously to the inactive cloud part. We note that the assumption of $\epsilon = 0.50$ has no physical meaning here other than defining the gas consumption rate as a function of cloud age. Model related quantities are given in Table 5.3 (see Sect. 5.5.2).

![Figure 5.3 Reference model: a Stellar-to-total (dashed curve) and gas-to-total (solid line) mass-ratios vs. age. The gas-to-total mass-ratio for the inactive cloud part coincides with that for the entire cloud, b Subcloud mass $\Delta M_{\text{cl}} = \epsilon M_{\text{c}}$ converted into stars (dashed curve) and amount of gas returned to the subcloud by newly formed stars within $\Delta t_{\text{sf}}$ (solid curve) vs. age. We assumed $M_{\text{c}}(t = 0) = 6 \times 10^9$ M$_{\odot}$. Total mass returned by previously formed stellar populations present in the inactive cloud is shown for comparison (dash-dotted curve). Fluctuations in this curve result from integration over different time intervals, i.e. $\Delta t_{\text{sf}}$ and $t_{\text{c}}$ (cf. Table 5.1).](image)
Inhomogeneous chemical evolution of the Galactic disk

Corresponding stellar and interstellar [Fe/H] and [O/H] abundance ratios are shown in Figs. 5.4a and 5.4b, respectively. At a given age, stellar and ISM abundances are exactly the same so that abundance inhomogeneities do not occur. Note that the resulting AMRs do not depend on the adopted value for $M_0$ as long as the normalisation of the SFR remains such that the condition of a current gas-to-total mass-ratio $\mu_1$ of 0.1 is met. The reference model predicts [Fe/H] and [O/H] abundance ratios that are consistent with the mean EDV data for stars younger than $\sim 10$ Gyr. For stars older than 10 Gyr, agreement with the observations may be improved e.g. by considering cloud ages in excess of $t_{\text{ev}} = 14$ Gyr or by detailed modeling of the halo-disk enrichment at early epochs of Galaxy evolution. We here concentrate on the stellar abundances observed during the last 10 Gyr of Galactic disk evolution.

Our adopted values of $\phi_{\text{SNII}} = 0.005$ and $m_{\text{SNII}} = 30$ $M_\odot$ provide optimal consistency with the mean observed [Fe/H] vs. [O/H] relation (cf. Fig. 5.4c). Clearly, the slope of the resulting [Fe/H] vs. [O/H] relation in case of enrichment by SNII only ($m_{\text{SNII}} = 60$ $M_\odot$) is inconsistent with the observations. Thus, the data provided by Edvardsson et al. imply that SNII and SNIa, b/c nucleo-synthesis sites mixed their products together well. In addition, dilution of the supernova ejecta by more metal-deficient material is needed to comply with the range in [Fe/H] and [O/H] observed for F and G dwarfs in the SNBH. This is simply because theoretically predicted (lifetime-integrated) mean [Fe/H] ratios within the ejecta of supernova progenitors are in general much larger than those observed for long-living stars in the SNBH (see Sect. 5.3.4). Thus, whatever process is responsible for the observed stellar abundance variations, both mixing of ejecta from different SN-types and dilution with metal-deficient material are involved.

The resulting well-defined tight AMRs for the reference model are similar to those predicted by conventional single-zone chemical evolution models (e.g. Twarog 1980a; Tinsley 1980). Such models account for the global chemical enrichment of the Galactic disk ISM during the last 10 Gyr, at least for elements like O and Fe, but they obviously provide no explanation for the observed variations in stellar abundances at a given age.

### 5.4.2 Sequential stellar enrichment

In case of sequential star formation, efficient self-enrichment of a star forming gas cloud by successive stellar generations may result in abundance enhancements relative to the abundances in the ambient ISM. When the local mixing time scale is larger than the time between two successive star formation events in such a cloud, these abundance enhancements can be deposited and recorded by newly formed stars.

In our model, the impact of sequential enrichment on abundance inhomogeneities in the ISM is determined by: a) the dispersal time of the star forming region, b) the total number of stellar generations formed within one and the same cloud, c) the efficiency of sequential enrichment, i.e. the mass-ratio of the enriched stellar material and the cloud to which this material is mixed, d) details of stellar enrichment; e.g. the relative number of SNII and SNIa, and e) the IMF and stellar mass limits at birth. We distinguish the effect of single and multiple sequential stellar enrichment on the stellar abundance variations. We will refer to single sequential enrichment as the case in which a star formation event induces subsequent star formation in a nearby cloud (when mixing enriched material to this cloud).
Table 5.3 Summary of model input parameters and resulting quantities related to the SFR ($M_\odot = 2 \times 10^{11} M_\odot$)

<table>
<thead>
<tr>
<th>Model</th>
<th>Fig.</th>
<th>$M_{\text{sc}}(0)$ [M$_\odot$]</th>
<th>$N_{\text{sf}}$</th>
<th>$m_{\text{SNII}}^{\text{max}}$ [M$_\odot$]</th>
<th>$\mu_1$</th>
<th>SFR$<em>1$ [M$</em>\odot$ yr$^{-1}$]</th>
<th>INF$_1$ [yr$^{-1}$]</th>
<th>$\phi_{\text{SNII}}$</th>
<th>$\phi_{\text{SNIa}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>5.34+4</td>
<td>1.3 (10)</td>
<td>100</td>
<td>0.50</td>
<td>30</td>
<td>0.09</td>
<td>2.9</td>
<td>1.3 (-2)</td>
<td>7.1 (-4)</td>
</tr>
<tr>
<td>Seq.(single)</td>
<td>5.5-1/2</td>
<td>2.1 (10)</td>
<td>100</td>
<td>0.95</td>
<td>25</td>
<td>0.11</td>
<td>3.7</td>
<td>1.5 (-2)</td>
<td>8.2 (-4)</td>
</tr>
<tr>
<td>Seq.(multiple)</td>
<td>5.5-3</td>
<td>1.5 (10)</td>
<td>200</td>
<td>0.50</td>
<td>25</td>
<td>0.21</td>
<td>2.5</td>
<td>1.0 (-2)</td>
<td>6.4 (-4)</td>
</tr>
<tr>
<td>Infall</td>
<td>5.6</td>
<td>6.3 (9)</td>
<td>100</td>
<td>0.95</td>
<td>40</td>
<td>0.16</td>
<td>5.4</td>
<td>3.1</td>
<td>2.5 (-2)</td>
</tr>
<tr>
<td>Infall+Seq.</td>
<td>5.7-1/2</td>
<td>6.4 (9)</td>
<td>136</td>
<td>0.90</td>
<td>25</td>
<td>0.19</td>
<td>5.2</td>
<td>1.8</td>
<td>2.1 (-2)</td>
</tr>
<tr>
<td>Infall+Seq.</td>
<td>5.7-3</td>
<td>6.4 (9)</td>
<td>166</td>
<td>0.90</td>
<td>25</td>
<td>0.32</td>
<td>4.4</td>
<td>3.1</td>
<td>1.8 (-2)</td>
</tr>
<tr>
<td>Observations*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.05–0.2</td>
<td>3.6±1</td>
<td>2.4 (-2)</td>
<td>3 (-3)</td>
</tr>
</tbody>
</table>

*References:
$\mu_1$: Kulkarni & Heiles (1987); Binney & Tremaine (1987); see also Basu & Rana (1992).
SFR: Dopita (1987); Walterbos (1988; based on IR observations); Mezger 1988
SNI & SNIa: van den Bergh & Tammann (1991); Tutukov et al. (1992); Cappellaro et al. (1993); Strom (1993).

Single sequential stellar enrichment

We present results for models incorporating single sequential stellar enrichment ($N_{\text{max}}^{\text{seq}} = 1$). For illustration purposes, we consider only the alternating half of the subclouds to experience sequential enrichment. We define initial masses of subclouds that are sequentially enriched as $M_{\text{sc}} \equiv \vartheta M_\odot$, where $M_\odot$ is the total mass of gas converted into stars during the previous enriching star formation event. Initial masses of subclouds not involved with sequential enrichment are assumed to decrease exponentially (as for the reference model).

To maximize the effect of sequential enrichment on the stellar abundance variations, we assume $\vartheta = 0.2$, $\epsilon = 0.95$, $m_{\text{SNII}} = 25 M_\odot$, $\phi_{\text{SNIa}} = 0.005$, and an enrichment efficiency $\lambda = 0.95$ (i.e., nearly all enriched stellar material ejected is mixed to the material wherein the next star formation event is induced). We consider cloud dispersal times $\Delta t_{\text{disp}} \sim 10^7$ yr. Such dispersal times are among the largest ones deduced from observations of nearby star forming molecular clouds (see Sect. 5.3.3). Using a theoretical age vs. turnoff-mass relation (e.g., Schaller et al. 1992), $\Delta t_{\text{disp}}$ can be related to the least massive star $m_{\text{enr}}$ able to enrich material before cloud dispersal. For instance, values of $\Delta t_{\text{disp}} \sim 5 \times 10^6$, $10^7$, and $2 \times 10^7$ yr, correspond to $m_{\text{enr}} \sim 40$, 15, and $12 M_\odot$, respectively.

Figures 5.5-1 and 5.5-2 (top and center panels in Fig. 5.5, respectively) illustrate the effect of sequential enrichment on the stellar abundance variations for cloud dispersal times of $\Delta t_{\text{disp}} = 10^7$ and $2 \times 10^7$ yr, respectively. The extent to which sequential enrichment contributes to the stellar abundance variations is determined by the chemical evolution of the ambient ISM. In general, large cloud dispersal times give rise to efficient locking up of metals in long living stars and enhanced stellar abundance variations relative to the abundances in the ISM. Stellar abundance variations due to single sequential stellar enrichment are found to be maximal for $\Delta t_{\text{disp}} \sim 2 \times 10^7$ yr. Larger values of $\Delta t_{\text{disp}}$ allow stars less massive than $m \sim 12 M_\odot$ to dilute the metal-rich ejecta of more massive stars (e.g., Hashimoto et al. 1993).

In case $\Delta t_{\text{disp}} = 2 \times 10^7$ yr, resulting stellar abundance variations due to sequential enrichment are sufficiently large to explain the observed variations in [O/H]. In contrast, corresponding variations in [Fe/H] are much smaller than observed. This is true even though the models presented here do account for sequential enrichment by SNIb/c which usually show theoretical [O/Fe] ratios much lower than SNI (e.g., Woosley et al. 1995). Results disagree with the observational fact that stellar abundance variations in [Fe/H] are considerably larger than in [O/H] (see also Gilmore & Wyse 1991; Edvardsson et al. 1993). An enhanced contribution of SNIb/c (i.e., assuming $\phi_{\text{SNIb/c}} > 0.33$) or participation of SNIa to the process of enrichment seems to be excluded by the observations (van den Bergh & Tammann 1991; Tutukov et al. 1992).

We conclude that single sequential stellar enrichment models are inconsistent with the observations because they: 1) result in [O/H] variations that are larger than those in [Fe/H], 2) predict current ISM abundances far below those observed, and 3) are difficult to reconcile with the apparent age independency of the stellar abundance variations (see Sect. 5.2). This conclusion is independent of the assumed cloud dispersion time scale $\Delta t_{\text{disp}}$, sequential enrichment efficiency $\lambda$, value of $\vartheta$, background level of iron-group elements set by SNIa (i.e., $\phi_{\text{SNIa}}$), star formation efficiency $\epsilon$, and adopted IMF. Also, omitting the enrichment during the stellar wind phase of supernova progenitors does not alter this conclusion.
Inhomogeneous chemical evolution of the Galactic disk

Figure 5.5 Model results for single and multiple sequential stellar enrichment. **Top panels:** Single sequential enrichment assuming a cloud dispersal time $t_{\text{disp}} = 10^7$ yr. **Center panels:** Single sequential enrichment assuming $t_{\text{disp}} = 2 \times 10^7$ yr. **Bottom panels:** Multiple sequential enrichment (see text). Model results are shown for variations of stellar and interstellar $[\text{Fe/H}]$ and $[\text{O/H}]$ abundance ratios: a $[\text{Fe/H}]$ vs. age, b $[\text{O/H}]$ vs. age, c $[\text{Fe/H}]$ vs. $[\text{O/H}]$. Stellar abundances are indicated by filled circles. Mean interstellar abundances (averaged over both active and inactive clouds) are indicated by solid curves. Average interstellar abundances within the inactive cloud ISM only (indicated by short dashed curve) do approximately coincide with the overall mean abundances. Remaining symbols and curves have the same meaning as in Fig. 5.4

**Multiple sequential stellar enrichment**

The effect of sequential stellar enrichment on the abundance variations among successive stellar generations can be very large, especially for high sequential enrichment efficiencies and/or small amounts of cloud material to which the stellar ejecta are mixed before star formation is initiated. These conditions are naturally fulfilled when isolated gas clouds experience multiple star formation events (i.e. $N_{\text{sf}}^{\text{max}} > 1$) before mixing with the surrounding ISM. Since the gas content of an isolated cloud is reduced by each star formation event, cloud abundances rapidly increase when enriched by successive generations of massive stars.

We consider two possible scenarios of multiple sequential enrichment. In the first scenario, earlier generations of stars actually separate from the remaining subcloud material after dispersal of the subcloud core and do not further participate in the enrichment of the subcloud. Such models result in substantial stellar abundance variations only under conditions and assumptions similar to those for the single sequential enrichment case. In the second scenario, all stellar generations formed in the subcloud continue to contribute to the enrichment until the entire subcloud has been dispersed. In this case, large stellar abundance variations...
arise due to efficient recycling of the stellar ejecta from successive generations formed within the same cloud.

We apply the second scenario and consider all subclouds to experience multiple sequential enrichment. As maximum number of star formation events within one and the same subcloud we assume \( N_{\text{max}}^{\text{sub}} = 4 \) (e.g., suggested by observations of OB subgroups in Orion; see Blaauw 1991). We adopt a sequential enrichment efficiency \( \lambda = 1 \) (by definition within the same subcloud), a star formation efficiency \( \epsilon \) between 0.3 and 0.6 for each star formation event, and \( \Delta t_{\text{disp}} = 10^7 \) yr. Other values of these parameters may provide similar results. Remaining model parameters are taken as for the single sequential enrichment model.

In Fig. 5.5-3, we plot resulting stellar abundance variations in case of multiple sequential stellar enrichment. Although variations caused by the first sequential enrichment event are relatively small (similar to the single sequential enrichment case assuming \( \Delta t_{\text{disp}} = 10^7 \) yr; see Fig. 5.5-1), abundance variations caused by subsequent events can be as large as \( \sim 0.2-0.3 \) dex (depending on the subcloud abundances). As mentioned before, such large abundance variations are mainly due to ongoing sequential enrichment of the remaining cloud material by stellar generations formed earlier in the cloud. We find that models incorporating multiple sequential stellar enrichment encounter the same problems as single sequential enrichment models. However, the former models appear observationally far more justified. This is true in particular for the sequential enrichment and star formation efficiencies, as well as the cloud core dispersal times, required to obtain a given stellar abundance variation.

We emphasize that the local conditions at the cores of star forming molecular clouds are likely to determine the IMF, the relative formation rate of different supernova progenitors, the fraction of binaries, etc. Therefore, in a more detailed treatment of sequential stellar enrichment, it seems natural to account for variations from one star formation event to another in e.g. \( t_{\text{disp}}^{\text{SNII}} \), the fraction \( \phi_{\text{SNII}}^{\text{SNII}} \) of SNII progenitors which ultimately end as SNIb/c, etc. We have verified that for reasonable variations in: 1) \( t_{\text{disp}}^{\text{SNII}} \), 2) the contribution by SNIb/c, and 3) the contribution by SNIa (e.g. SNIa exploding in the vicinity of a subcloud; see Fig. 5.2f) may add at most \( \sim 0.1 \) dex to the observed stellar abundance variations at solar metallicity. Similarly, we find that stellar abundance inhomogeneities caused by variations in the IMF (and/or stellar mass limits at birth) among different star forming regions are highly sensitive to the IMF slope\(^2\) and may result in variations in \([\text{O}/\text{H}]\) of more than 0.15 dex at solar abundance.

We conclude that the observed stellar abundance variations are difficult to explain by sequential stellar enrichment only. This conclusion is not altered when allowing for variations in sequential enrichment between distinct star formation events (e.g. by considering variations in the IMF, relative formation rates of SNII and SNIb/c, etc.). Possible exceptions may be selective mixing of SNII nucleo-synthesis products to the material wherein star formation is induced and/or cloud conditions that determine both the composition of the ejecta returned by a stellar generation (e.g. by means of the IMF, \( m_{\text{disp}}^{\text{SNII}} \), \( \Delta t_{\text{disp}} \), contribution by SNIb/c, binaries) and the sequential enrichment efficiency. In addition, conditions that regulate the amount of cloud material to which the stellar ejecta are mixed before star formation is initiated (i.e. the star formation efficiency) may be important for the effects of sequential stellar enrichment. However, the impact of such conditions on the stellar abundance variations, which would imply that the IMF weighed SN yields used here would be considerably modified, is beyond the scope of this paper.

**5.4.3 Episodic infall of metal-deficient matter**

Infall of metal-poor material can account for abundances of newly formed stars which lie substantially below the abundances in the global disk ISM. In principle, abundance variations due to metal-deficient gas infall are determined by the abundances within the infalling gas, the gas infall rate, and the amount of disk ISM to which the infalling material is mixed before star formation is initiated. Stellar abundance variations due to infall of metal-rich material associated with SN ejecta from massive stars in the Galactic disk can be considered as a special case of sequential stellar enrichment and is not discussed here.

Element abundances within the infalling gas are constrained by the lowest abundances observed for disk stars with \([\text{Fe}/\text{H}] \gtrsim -1\). The Edvardsson et al. data imply infall abundances of \([\text{M}/\text{H}]_{\text{inf}} \leq -0.8\) to \(-1.2\) for e.g. \(\text{M} = \text{C}, \text{Mg}, \text{Al}, \text{and Si}\). These abundances are consistent with observations of interstellar clouds in the halo (see Sect. 5.5.2) and suggest that infall induced star formation is associated with the lowest abundances observed among disk F and G dwarfs in the SNBH.

\(^2\)it is evident that the stellar abundance variations observed among similarly aged stars in the SNBH certainly do not exclude variations in e.g. the IMF among distinct star formation events
We assume infall abundances similar to the abundances observed among the oldest metal-poor disk stars, i.e. $[\text{Fe/H}] = -1$, $[\text{O/H}] = -0.65$, and a hydrogen mass fraction of $X \sim 0.72$ (e.g. Bessel et al. 1991). For simplicity, we do not account for abundance inhomogeneities within the infalling gas and assume infall abundances to be constant in time. Furthermore, we consider infall to occur as soon as the infall abundances are reached in the global disk ISM (presumably corresponding with the onset of star formation in the disk).

The detailed manner in which gas infall varies with time is not essential for the results presented here as long as infalling gas plays an important role in determining the stellar abundances when it induces star formation. Here, we deal with the concept of infall induced star formation, i.e. the infalling gas initiates star formation when falling onto the disk. This concept is based on observations of infalling high-velocity clouds that strongly interact with disk ISM and initiate star formation therein as soon the critical density for star formation is reached (see Sect. 5.5.2). Since star formation occurs by definition within active subclouds according to our model, infall is associated with subclouds experiencing star formation shortly after their formation. For simplicity, we assume each subcloud to contain an amount of infalling gas accumulated at the time star formation is induced. This amount is taken as a random fraction of the initial subcloud mass (i.e. between 0 and 1). In this manner, we allow for local and episodic gas infall onto the Galactic disk ISM. On average, the gas infall rate is assumed to decay exponentially on a time scale $t_{\text{dec}} = 6 \text{ Gyr}$ while its overall amplitude is constrained by $\mu_1 = 0.05 - 0.2$ (cf. Eq. (1); see Table 5.3).

We assume an initial disk mass $M_{\text{disk}} = 3 \times 10^{10} \, M_\odot$ before the onset of gas infall. This results in a disk initial-to-final mass-ratio $\zeta = 0.55$ according to an exponential decrease of subcloud mass with cloud evolution time ($M_{\text{cloud}}(0) = 2 \times 10^8 \, M_\odot$; cf. Table 5.3). Clearly, stellar abundance variations due to metal-deficient gas infall are small at low levels of enrichment of the global disk ISM (i.e. large initial disk mass). Furthermore, continuous and large scale metal-deficient gas infall not associated with star formation results in relatively small stellar abundance variations. Thus, the magnitude of the stellar abundance variations is affected by the ratio of initial disk mass and total amount of infalling matter, as well as the amount of infalling gas that is involved with induced star formation in the disk ISM.

Figure 5.6 displays resulting AMRs for iron and oxygen in case of episodic infall of metal-deficient gas. We assumed $\phi_{\text{SNa}} = 0.015$, $\phi_{\text{SNB}}/\phi_{\text{SNB}} = 0.33$, and $m_{\text{SNII}} = 40 \, M_\odot$. The value of $m_{\text{SNII}}$ is taken larger than for the reference model (cf. Table 5.2) to obtain somewhat better agreement with the observations. Resulting abundances in the disk ISM follow the upper end of the abundances observed in F and G dwarfs younger than $\sim 10$ Gyr. Although the effect of global infall of metal deficient gas is generally to dilute the enrichment of the ISM, the inflow model results in larger ISM abundances than the reference model. This is mainly due to: 1) the assumption of a low initial disk mass which allows for a rapid early enrichment of the disk, and 2) the assumption of local infall of metal-deficient gas and subsequent star formation therein so that infalling material has relatively small effect on the dilution of the global disk ISM.

By varying the ratio of infalling matter and disk ISM within each subcloud, stellar abundance variations of $\Delta [\text{Fe/H}] \sim 0.8$ dex and $\Delta [\text{O/H}] \sim 0.65$ dex naturally can be accounted for. In addition, the scatter in $[\text{Fe/H}]$ remains larger than in $[\text{O/H}]$ since the iron abundances within the infalling gas relative to solar (i.e. $[\text{Fe/H}]_{\text{inf}} = -1$) are much smaller than that of oxygen ($[\text{O/H}]_{\text{inf}} = -0.65$). We note that the current gas infall rate of $\sim 3.1 \, M_\odot \, \text{yr}^{-1}$ predicted by the model shown in Fig. 5.6 is larger than suggested by the observations (see Sect. 5.5.1). However, other choices of model parameters, e.g. $\zeta$, predict much lower infall rates while providing similar abundance results.
Our models incorporating metal-deficient gas infall are in good agreement with the observed magnitude of stellar abundance variations and the slope of the [Fe/H] vs. [O/H] relation observed. However, these models predict current interstellar [Fe/H] and [O/H] abundance ratios of ~0.2 dex above solar. This is in marked contrast with [O/H] abundance ratios of ~0.15 dex below solar observed both in interstellar gas and recently formed stars in the SNBH (see Sect. 5.2). In addition, these models appear to disagree with the observations on two other grounds. First, no significant scatter in the [Fe/H] vs. [O/H] relation is predicted, contrary to what is observed for intermediate age disk stars (cf. Fig. 5.1). Part of the observed scatter may be due to experimental errors but variations of at least ±0.1 dex in the [Fe/H] vs. [O/H] relation are probably real and have to be explained by any satisfactory model. A way to account for such scatter would be to allow for considerable abundance variations among different parcels of infalling gas. Secondly, these models predict stellar abundance variations to increase with time. This is inconsistent with the apparent constancy of the abundance scatter observed. Possible ways out may be uncertainties in the ages of stars older than ~10 Gyr or disk evolution times in excess of $t_{ev} \sim 14$ Gyr.

We conclude that models dealing with metal-deficient gas infall can probably be excluded as the complete answer to the stellar abundance variations observed, even though such models are in good agreement with both the observed abundance variations and [Fe/H] vs. [O/H] relation. This conclusion is primarily based on the fact that such models predict mean current ISM abundances ~0.4 dex larger than those observed in the SNBH.

### 5.4 Results

Our models incorporating metal-deficient gas infall are in good agreement with the observed magnitude of stellar abundance variations and the slope of the [Fe/H] vs. [O/H] relation observed. However, these models predict current interstellar [Fe/H] and [O/H] abundance ratios of ~0.2 dex above solar. This is in marked contrast with [O/H] abundance ratios of ~0.15 dex below solar observed both in interstellar gas and recently formed stars in the SNBH (see Sect. 5.2). In addition, these models appear to disagree with the observations on two other grounds. First, no significant scatter in the [Fe/H] vs. [O/H] relation is predicted, contrary to what is observed for intermediate age disk stars (cf. Fig. 5.1). Part of the observed scatter may be due to experimental errors but variations of at least ±0.1 dex in the [Fe/H] vs. [O/H] relation are probably real and have to be explained by any satisfactory model. A way to account for such scatter would be to allow for considerable abundance variations among different parcels of infalling gas. Secondly, these models predict stellar abundance variations to increase with time. This is inconsistent with the apparent constancy of the abundance scatter observed. Possible ways out may be uncertainties in the ages of stars older than ~10 Gyr or disk evolution times in excess of $t_{ev} \sim 14$ Gyr.

We conclude that models dealing with metal-deficient gas infall can probably be excluded as the complete answer to the stellar abundance variations observed, even though such models are in good agreement with both the observed abundance variations and [Fe/H] vs. [O/H] relation. This conclusion is primarily based on the fact that such models predict mean current ISM abundances ~0.4 dex larger than those observed in the SNBH.

#### 5.4.4 Metal-poor gas infall combined with sequential enrichment

Motivated by the results previously discussed, we study the combined effect of sequential stellar enrichment and episodic infall of metal-deficient gas on the inhomogeneous chemical evolution of the Galactic disk. Such investigation is important also because these processes are observed to operate simultaneously in the SNBH (see Sect. 5.5.2).

Attractive features of combined infall of metal-poor gas and sequential stellar enrichment are that a self-consistent explanation can be obtained for: 1) the presence of high metallicity stars at early epochs of star formation in the Galactic disk (due to sequential enrichment), 2) the presence of metal-poor stars at recent epochs of Galactic evolution (as a result of metal-deficient gas infall), 3) the nearly constant magnitude of the stellar abundance variations during the lifetime of the disk, and 4) abundances in the local disk ISM that are currently below solar (as observed for oxygen).

We show in Fig. 5.7 results for combined sequential stellar enrichment and metal-deficient gas infall. Model assumptions concerning each of these processes are similar to those described in the previous sections (e.g. $\epsilon_{\text{max}} = 0.90$, $A = 0.95$, $m_{\text{SNII}} = 25$ M$_{\odot}$, $\phi_{\text{SNII}} = 0.005$, and $\phi_{\text{SNII}}/c = 0.33$; cf. Tables 5.2 and 5.3). The three models shown in Fig. 5.7 differ only in the amounts of disk ISM involved with sequential stellar enrichment and infalling gas accreted during the lifetime of the disk. For each of these models, resulting stellar abundance variations and [Fe/H] vs. [O/H] relation are consistent with the observations. Clearly, models with combined sequential enrichment and metal-poor gas infall do not encounter the specific problems involved when each of these processes is considered separately.

We study the relative impact of metal-poor gas infall and sequential stellar enrichment on the resulting stellar abundance variations as well as the global enrichment of the ISM. First, we investigate the effect of varying the fraction of subclouds (i.e. the amount of star forming disk ISM) experiencing multiple sequential stellar enrichment ($N_{\text{disp}}^{\text{max}} = 4$, $\Delta t_{\text{disp}} = 10^7$ yr, $\epsilon_{\text{max}} = 0.9$; see Sect. 5.4.2). This fraction increases from ~10% to ~25% when going from top to center models shown in Fig. 5.7. The remaining part of the subclouds is assumed to experience one single star formation event. Furthermore, we assume half of the subclouds to form stars partly from infall of metal-deficient gas (i.e. Figs. 5.7-1 and 5.7-2), regardless of the number of star formation events in each subcloud. Note that subclouds involved with metal-poor gas infall form predominantly stars with abundances below those in the global disk ISM. It can be seen that mean interstellar abundances and stellar abundance variations are not significantly altered when the fraction of ISM associated with sequential stellar enrichment is increased from 10 to 25%. However, when this fraction is further increased, more and more metals will be locked up in long living stars due to sequential enrichment and marked deviations from the observed [Fe/H] vs. [O/H] relation will occur (see Sect. 5.4.2).

Secondly, we investigate the effect when the fraction of subclouds forming stars from metal-deficient gas infall is increased from 50 to 100%. In this case, stellar generations are all formed according to infall induced sequential star formation and the total mass of infalling gas is increased by a factor two. This results in a reduction of the interstellar [Fe/H] and [O/H] abundance ratios by ~0.1 dex (see Fig. 5.7-3). Interestingly, this marginally affects the magnitude of the resulting stellar abundance variations (assuming $\epsilon_{\text{max}} = 0.9$, $A = 0.95$) but strongly alters the number of stars with abundances below those present in the global disk ISM. We note that direct comparison of the abundance results with previous models is not justified because
in homogeneous chemical evolution of the Galactic disk

Figure 5.7 Model results for combined sequential stellar enrichment and episodic infall of metal-poor gas. Top panels: ~10% of the clouds is assumed to experience multiple sequential enrichment while half of the subclouds is involved with metal-deficient gas infall. Nearly 5% of the clouds undergo both infall of metal-deficient material and sequential stellar enrichment. Center panels: 25% of the subclouds experiences multiple sequential enrichment while half of the subclouds is involved with metal-poor gas infall. Bottom panels: as center panels but all subclouds experience metal-deficient gas infall. Model results are shown for variations of stellar and interstellar [Fe/H] and [O/H] abundances: a [Fe/H] vs. age, b [O/H] vs. age, c [Fe/H] vs. [O/H]. Symbols and curves have the same meaning as in Fig. 5.5.

the enhanced gas infall model results in a current gas-to-total mass-ratio $\mu_1 \sim 0.3$, i.e. considerably higher than the $\mu_1 = 0.1-0.2$ indicated by the observations (cf. Table 5.3). To arrive at $\mu_1 = 0.2$, a reduction in initial disk mass from $3 \times 10^{10}$ to $2 \times 10^{10} \, M_\odot$ would be required. In turn, this would result in ISM abundances and stellar abundance variations similar to that for models with more modest infall rates.

5.4.5 Additional abundance constraints

Keeping these results in mind, we study how models with combined sequential stellar enrichment and metal-poor gas infall behave when confronted with additional observational constraints provided by the stellar abundance variations and current ISM abundances of C, Mg, Al, and Si.

Carbon abundance data for 85 F and G dwarfs in the SNBH have been presented by Andersson & Edvardsson (1994). These data show that there is a weak correlation between [C/H] and [O/H] (see Fig. 5.8). The shape of this correlation differs from that between e.g. [Fe/H] and [O/H]. In addition, the variation in [C/H] (i.e. $\lesssim 0.6$ dex) at a given value of [O/H] is about three times larger than that in [Fe/H].
If the observed stellar abundance variations are caused by infall of metal-deficient gas only, one would expect that stellar abundances for all elements heavier than helium would be mutually correlated, e.g. similar to the correlation between oxygen and iron. In case of sequential stellar enrichment only, a similar behaviour would be expected only for elements that are produced predominantly by SNII and SNIIb/c. This implies that abundance-abundance variations between elements which are not synthesized predominantly within SNII and SNIIb/c (such as C and N), on the one hand, and elements that are produced predominantly within supernovae (e.g. O, Si), on the other hand, may be conclusive about the importance of metal-deficient gas infall.

We show in Fig. 5.8 results for: 1) infall of metal-deficient gas only (cf. Fig. 5.6), 2) multiple sequential stellar enrichment only (cf. Fig. 5.5-1), and 3) combined metal-poor gas infall and sequential enrichment (cf. Fig. 5.7-1). The infall model predicts no substantial scatter in the [C/H] vs. [O/H] relation but follows the trend in the observations well. Although the scatter in the [C/H] vs. [O/H] relation suggests that infall is not exclusively responsible for the observed variations, the shape of this relation indicates that infall is important. Conversely, the sequential enrichment model shows large scatter in the [C/H] vs. [O/H] relation but appears to deviate from the observed trend. The correlation predicted by the combined sequential enrichment and infall model appears in reasonable agreement with the observations. However, the observed carbon abundances at [C/H]~0, exhibit considerable more scatter than predicted by the model shown in Fig. 5.7-1 and seem to require a somewhat steeper increase of carbon relative to oxygen. This may be due to variations in sequential stellar enrichment between different star formation events and/or variations in abundances within the infalling material.

![Figure 5.8](image_url)

**Figure 5.8** Comparison between observed and model-predicted [C/H] vs. [O/H] relation. **Observations:** data for F and G dwarfs in the SNBH from Andersson & Edvardsson (1995). Open circles represent stars with mean stellar galactocentric distances at birth within 0.5 kpc from the Sun (R_0 = 8.4 kpc). Full dots indicate stars with average distances within ~2 kpc from the Sun. Typical errors are indicated at the bottom right (top left panel). **Model results:** Predicted abundances of stars (full dots) and gas (solid line) for models incorporating metal-poor gas infall and/or sequential stellar enrichment.

In our models, the overall shape of the stellar [C/H] vs. [O/H] relation is due to infall of metal-poor material with carbon abundances [C/O]_inf ≈ -0.4. The reason why these relatively low carbon infall abundances are necessary to explain the observed trend in the [C/H] vs. [O/H] relation, is unclear. A possible
explanation may be a delayed carbon enrichment of the disk ISM, e.g. by low-mass SNIa progenitors that experience incomplete carbon burning or by low-mass AGB stars with small carbon yields.

Sequential stellar enrichment seems inevitable to explain the observed scatter in the \([C/H] vs. [O/H]\) relation. Although large abundance inhomogeneities within the infalling gas may reproduce the observed variations as well, such inhomogeneities in \([C/O]\) appear inconsistent with the small scatter observed in e.g. \([Fe/O]\). Also, uncertainties in the derived carbon abundances may be considerably larger than those in O and Fe but are not likely to exceed \(\sim 0.2\) dex (see Andersson & Edvardsson 1994; see also EDV). Therefore, it seems improbable that the scatter observed in the \([C/H] vs [O/H]\) relation is due to observational errors. Finally, it is difficult to see how chemical differentiation processes (e.g. dust depletion, element mixing to the surface, O/N-cycle, metallicity dependent nucleo-synthesis, etc.) can cause such large abundance-abundance variations among stars similar in mass and age.

From the arguments above, we conclude that models incorporating both infall of metal-poor gas and sequential stellar enrichment provide an adequate explanation for the observed \([C/H] vs [O/H]\) relation. For the model shown in Fig. 5.7-1, we compare the predicted stellar abundance ratios Si, Mg, and Al vs. Fe with

Figure 5.9 Comparison between observed (left) and model-predicted (right) \([M/H] vs. [Fe/H]\) relations: a) \([Si/Fe]\), b) \([Mg/Fe]\), and c) \([Al/Fe]\). Observations: data for F and G dwarfs in the SNBH from Edvardsson et al. (1993a). Symbols have the same meaning as in Fig. 5.8. Typical errors are indicated at the lower right of each panel. Model results: predicted abundances of stars (full dots) and gas (solid line) for model 7-1.
the observations in Fig. 5.9. We find that slight offsets in [M/H] are present between the model predicted and observed relations. These offsets, most pronounced for Al, are due to details in the adopted stellar yields and related parameters (see Table 5.3), and are not essential for the following discussion. Interestingly, a number of observed features are naturally reproduced by these models.

First, the observations suggest that variations in the stellar [M/H] abundance ratios decrease with increasing metallicity. This is theoretically predicted by the individual effects of both sequential stellar enrichment and infall of metal-deficient material (as discussed above). For the model shown in Fig. 5.7-1, the resulting scatter in [M/H] at a given value of e.g. [Fe/H] is mainly due to sequential enrichment (except at abundances [M/H]< -0.7) and is strongly related to the iron contribution by SNIa in regions that do not experience sequential enrichment. It can be seen that the scatter in [M/H] strongly decreases at solar metallicities and above. This may indicate that much of the observed element-to-element variations at high metallicities is due to observational errors of ~0.1 dex in [M/H]. Alternatively, the observed scatter at high metalicities may imply that sequential enrichment by massive stars varies from one star formation event to another, e.g. by means of variations in the upper mass limit for SNIa.

Secondly, the predicted variation in [Mg/H] at a given [Fe/H] is substantially larger than that in [Si/H], consistent with the observations. In our model, this is due to: 1) the fact that part of the Si comes from SNIa which are important contributors also to Fe (Mg is produced less efficiently in SNIa than is Si by about one order of magnitude; e.g. Nomoto et al. 1984), and 2) the predicted ISM abundance of Mg/H] is less by about 0.1 dex than that of [Si/H] (see Fig. 5.9).

Thirdly, the observed variation in [Al/H] is similar (or even larger) than that in [Mg/H] (see EDV). This behaviour is also found for the model shown in Fig. 5.7-1. The predicted ISM abundance of Al is probably too low by ~0.1 dex so that the resulting abundance scatter would be slightly reduced when correcting for this. The impact of sequential stellar enrichment is more pronounced for Al than for Mg and Si, due to the somewhat lower ISM abundance of Al (even after correction). Overall, we conclude that the magnitudes of the resulting stellar variations in Si, Mg, and Al vs. Fe appear in reasonable agreement with the observations.

Comparison of variations in Mg, Si, and Al vs. O with the observations reveals a somewhat different picture from that vs. Fe. The observed variation of [Mg/H] with [O/H] has been shown in Fig. 5.1; Al and Si display a similar behaviour. No trend is observed for variations in the scatter in the $\Delta$[M/H] vs. [O/H] relation, in contrast to that in the $\Delta$[M/H] vs. [Fe/H] relation. Furthermore, the observations indicate mean variations in $\Delta$[Mg/Fe] of the same magnitude as those in $\Delta$[M/O]. In contrast, the model shown in Fig. 5.7-1 predicts variations in Mg, Al, and Si vs. Fe that are considerably larger than those vs. O. This is simply due to the fact that a substantial fraction of Fe originates from SNIa. Therefore, models predict hardly any scatter in e.g. [Mg/O] since both elements are synthesized predominantly within SNI (and SNIb/c). This implies that either the scatter in the observed [Mg/H] vs. [O/H] relation is due to observational errors or that an additional process is needed in the models to explain this scatter.

In the former case, there would be no reason to believe the variations observed in the [M/H] vs. [Fe/H] relations either. However, we have argued above that at least part of this scatter is real. In the latter case, an additional mechanism causing the scatter in [M/O] could be variations from one star formation site to another in the enrichment by SNIi (and SNIb/c). Alternatively, such variations could include variations in e.g. the IMF, upper mass limit for SNI, and/or the mass distribution of binaries. We have verified that such variations generally result in abundance-abundance scatter sufficiently large to account for the observed variations of 0.1 dex in [M/O] and sufficiently small to have a negligible effect on the scatter observed in [M/Fe]. Clearly, element-to-element variations in enrichment from one star formation site to another would be a natural refinement of the sequential stellar enrichment models discussed before.

We conclude that models incorporating both sequential stellar enrichment and episodic infall of metal-poor gas provide a natural explanation for the observed stellar abundance variations and are consistent with the ISM abundances of C, O, Fe, Mg, Si, and Al. We find that the mean ISM abundances and abundance-abundance relations can provide only limited constraints on the relative importance of sequential enrichment and infall induced star formation in the Galactic disk. Therefore, improvements in observational and theoretical constraints are required to disentangle the effects of these processes on the inhomogeneous chemical evolution of the Galactic disk in a more quantitative way.
5.5 Discussion

We briefly examine how the combined sequential stellar enrichment and metal-deficient gas infall models discussed in the previous section behave when confronted with independent constraints provided by the current star formation rate in the Galactic disk and the chemical evolution of the Galactic halo. Thereafter, we discuss observational evidence in support of sequential enrichment and gas infall in the local disk ISM and consider possible implications of these processes for the chemical evolution of the Galaxy as a whole.

5.5.1 Additional constraints

SFR related constraints

The combined sequential enrichment and metal-deficient gas infall (Fig. 5.7-1) predicts a present SFR of \( \sim 5.2 \, M_\odot \, yr^{-1} \), and current rates of SNII (excluding SNIb/c) and SNIIa of \( R^{\text{SNII}} = 2.1 \times 10^{-2} \, yr^{-1} \) and \( R^{\text{SNIIa}} = 1.3 \times 10^{-3} \, yr^{-1} \), respectively. These values are roughly consistent with the observations (i.e. within a factor of two; see Table 5.3). Adopted values of \( m_0^{\text{SNII}}=25 \, M_\odot \) and \( \psi^{\text{SNII}}=0.005 \) may be somewhat too low since the SN-rates scale with the predicted SFR. For the same model, the current gas infall rate is determined by the assumed disk initial-to-final mass-ratio \( \zeta=0.5 \) and by the time scale \( t_{\text{inf}}=6 \, \text{Gyr} \) on which infall decays exponentially. This results in a current gas infall rate of \( 1.8 \, M_\odot \, yr^{-1} \). Observations indicate a current gas infall rate of \( \sim 0.5 \, M_\odot \, yr^{-1} \) (e.g. Mirabel & Morris 1984). However, selection effects may account for an underestimate of a factor of 2-3 (see Sect. 5.5.2). We note that higher values of \( \zeta \) and/or lower values of \( t_{\text{inf}} \) may apply equally well.

The predicted rates above all scale with the amplitude of the SFR. In turn, this amplitude is determined by the total cloud mass \( M_\odot = 2 \times 10^{11} \, M_\odot \) and SFR decay time scale \( t_{\text{dec}} \sim 6 \, \text{Gyr} \) assumed (see Sect. 5.3.2). Distinct values of \( M_\odot \) and/or \( t_{\text{dec}} \) will not affect the predicted stellar and interstellar abundances substantially, provided that a current gas-to-total mass-ratio \( \mu_1 = 0.1 \) is maintained. We conclude that the adopted parameters for the model shown in Fig. 5.7-1 are consistent with observational constraints on the current SFR, gas infall rate, and supernova rates. Obviously, these observations do not yet provide tight constraints on e.g. \( t_{\text{dec}} \), \( \mu_1 \), and \( \zeta \), thus preventing a clear distinction between chemical evolution models based on these quantities (cf. Table 5.3).

Constraints related to the enrichment of the Galactic halo

The mean plateau value of [O/Fe]~0.5 \pm 0.15 observed for halo stars with [Fe/H] \lesssim -1 (e.g. Bessell et al. 1991) is presumably determined by the average [O/Fe] ratio within the ejecta of SNII (and SNIb/c) as well as the initial abundances within the halo ISM. For our models, the plateau value implies a maximum upper mass limit of SNII progenitors of \( m_0^{\text{SNII}} \approx 40 \, M_\odot \), assuming initial metallicities [Fe/H] \lesssim -1, a Salpeter IMF, and stellar yields as described in Sect. 5.3.4. An even larger value for \( m_0^{\text{SNII}} \) is implied when SNIb/c contributed substantially to the halo enrichment.

We assumed \( m_0^{\text{SNII}} = 25 \, M_\odot \) for the combined infall + sequential enrichment model (Fig. 5.7-1) discussed before. This results in [O/Fe]~0.2 at [Fe/H] \lesssim -1 while omitting the contribution from SNIb/c would have resulted in [O/Fe]~0.25 at [Fe/H] \lesssim -1. This is inconsistent with the observations. Possible solutions to this discrepancy are: 1) \( m_0^{\text{SNII}} \) and/or the IMF have changed between the time stars formed in the halo and the time of onset of star formation in the disk, 2) \( m_0^{\text{SNII}} \) is actually \( \sim 40 \, M_\odot \) for disk stars so that the predicted current disk ISM abundances of O and Fe increase and the effect of sequential enrichment is reduced, and/or 3) the adopted yields for SNII (and or SNIb/c) are in error at metallicities below [Fe/H] \sim -1.

Although the first two possibilities cannot be excluded, we favour the latter option since values of \( m_0^{\text{SNII}} \approx 30 \, M_\odot \) are suggested by recent models accounting for metallicity dependent yields of SNII in full detail (e.g. Timmes et al. 1995). We emphasize that the detailed yields for SNII at metallicities [Fe/H] \lesssim -1 are not important for the sequential enrichment and infall model results for disk stars presented in this paper but we just want to note here that it is difficult to explain the mean [O/Fe] ratio in halo stars using the same models.

The observed breakpoint in the [O/Fe] vs. [Fe/H] relation at [Fe/H]~ -1.0\pm0.2 (e.g. King 1994) is generally associated with the time SNIIa start to contaminate the global disk ISM (e.g. Gilmore & Wyse 1991; Bravo et al. 1993; Ishimaru & Arimoto 1995). In our models, the breakpoint in the [O/Fe] vs. [Fe/H] relation is mainly determined by: 1) the assumed fraction \( \phi^{\text{SNII}} = 0.005 \) of main-sequence stars with initial masses between 2.5 and 8 \, M_\odot \) (e.g. Nomoto et al. 1984), 2) the delay time \( \tau^{\text{SNII}} = 2.5 \, \text{Gyr} \) after which SNIIa start to contribute to the enrichment of the ISM (e.g. Snécker-Hane & Wyse 1992; Ishimaru & Arimoto 1995), and 3) the frequency distribution of SNIIa as a function of age for a given stellar generation (assumed
to be constant from $t_{\text{SNIa}}$ to $t_{\text{SNIa}} + 0.5\text{ Gyrs}$, and zero otherwise). These assumptions, in particular for $t_{\text{SNIa}}$, strongly affect the increase of [Fe/H] with disk age and thus determine the scatter in and the slope of the $[\text{O/Fe}]$ vs. [Fe/H] relation predicted. In fact, SNIa provide a background signal of iron-group elements on top of which stellar abundance variations due to sequential enrichment by SNII+SNIIb/c occur.

We assumed $t_{\text{SNIa}} = 2.5\text{ Gyrs}$ for the models presented in this paper, as recently suggested by Ishimaru & Arimoto (1995). However, this assumption implies different breakpoints in the [O/Fe] vs. [Fe/H] relation for models with distinct star formation and infall histories. The model shown in Fig. 5.7-1 predicts $[\text{Fe/H}] = -1$ after $\sim 1.3\text{ Gyrs}$ (and results $[\text{Fe/H}] = -0.75$ after 2.5 Gyrs). This may indicate that the assumed value of $t_{\text{SNIa}} = 2.5\text{ Gyrs}$ is in error. Estimates for $t_{\text{SNIa}}$ based on stellar evolution calculations suffer from large uncertainties in the detailed evolution scenario for SNIa progenitors (see e.g. Smecker-Hane & Wyse 1992; King 1994) while theoretical estimates for $t_{\text{SNIa}}$ based on the observed breakpoint may suffer from large uncertainties in the assumed chemical evolution of the halo (e.g. Ishimaru & Arimoto 1995).

Alternatively, model assumptions related to: 1) the enrichment rate of the disk ISM by SNII (e.g. IMF and SFR, $m_{\text{SNII}}^0$ and SNII yields), or 2) the initial abundances of the material to which the SNII ejecta are mixed (e.g. disk mass at the onset of star formation, amount of gas infall, and infall abundances) may be in error. For instance, adopted iron yields for SNII at metallicities $[\text{Fe/H}] \leq -1$ may be too high by about a factor of two. This would be consistent with the discrepancy in the $[\text{O/Fe}]$ ratio for Galactic halo stars discussed above. Furthermore, large amounts of metal-poor gas infall would improve the consistency with the assumption of $t_{\text{SNIa}} = 2.5\text{ Gyrs}$. Other possibilities, such as higher values of the disk total-to-final mass-ratio or larger SFR decay times $t_{\text{decr}}$, seem to be excluded by the observations (e.g. van den Hoek et al. 1996).

We conclude that combined sequential enrichment and metal-poor gas infall models are consistent with the observed plateau value and breakpoint in the [O/Fe] vs. [Fe/H] relation provided that e.g. the adopted SNII yields at low metallicities $[\text{Fe/H}] \leq -1$ are too high by about a factor of two. At the same time, we have illustrated how sensitive our model results are to specific assumptions related to the enrichment by e.g. SNII and SNIa. These assumptions may affect quantitative conclusions concerning the relative importance of sequential stellar enrichment and metal-poor gas infall. However, our qualitative conclusion regarding the simultaneous presence of these processes in the local Galactic disk is not altered.

### 5.5.2 Observational support

We briefly discuss observational evidence in support of sequential stellar enrichment and metal-deficient gas infall in the local disk ISM.

#### Metal-deficient gas infall

Observations of high-velocity clouds (HVCs) show that many separate interstellar clouds are present in the Galactic halo with abundances usually $\sim 0.1$ solar for elements like C, O, S, and Si (e.g. de Boer & Savage 1984; Schwarz et al. 1995). Many faint HVCs up to distances of at least $\sim 10\text{ kpc}$ above the Galactic plane are found to be a member of large scale cloud complexes (Wakker 1991). The velocity distribution of these complexes is asymmetric showing a net infall of matter onto the Galactic disk (e.g. Mirabel & Morris 1984; Hulsbosch & Wakker 1988; Wakker 1990). These observations support the idea of high-velocity infall of neutral hydrogen gas towards the Galactic disk.

Estimates of the current gas infall rate onto the Galactic disk range from $0.2 - 0.5\text{ M}_\odot\text{ yr}^{-1}$ based on HVCs ($v \gtrsim 250\text{ km s}^{-1}$; e.g. Mirabel & Morris 1984; Mirabel 1989; Lépine & Duvert 1994), to $\sim 0.7\text{ M}_\odot\text{ yr}^{-1}$ derived from the soft X-ray background (Cox & Smith 1976), and $\sim 1.5\text{ M}_\odot\text{ yr}^{-1}$ based on observations of atomic hydrogen (Oort 1970). However, gas infall rates derived from the infall of HVCs are likely to be underestimated both because of the preferential detection of nearby HVCs and the large uncertainties involved with e.g. distances (a factor of two uncertainty in the distance results in a factor 4 in the estimated influx of mass) and the detection probabilities of HVCs. In particular, low-velocity gas may add substantially to the total influx of matter onto the Galactic disk. This gas is hard to detect due to its less pronounced (and more diffuse) interaction with the disk ISM (e.g. Mirabel & Morris 1984).

A crude estimate of the fraction of stars recently formed from metal-poor gas infall onto the disk can be made as follows. The current star formation rate in the Galactic disk is $\sim 3.5\pm 1\text{ M}_\odot\text{ yr}^{-1}$ (e.g. Dopita 1987; see also Table 5). The minimum gas infall rate obtained from the observations is $\sim 0.5\text{ M}_\odot\text{ yr}^{-1}$ but an underestimate by a factor of 3–4 appears likely. This would imply that a considerable fraction of 30–60% of stars currently forming in the disk is associated with infalling gas provided that all infalling matter initiates star formation. On the theoretical side, models in reasonable agreement with observational constraints on the chemical evolution of the Galactic disk predict current gas infall rates in the range of
Observational support for infall induced star formation in the SNBH has recently been presented for the Orion cloud complex (Lépine & Duvert 1994; Meyer et al. 1994), the Monoceros cloud complex (Gómez de Castro 1992), the Gould Belt (e.g. Cómoen & Torra 1994), and the ζ Sculptoris open cluster (Edvardsson et al. 1995). These observations suggest that the most prominent star forming regions in the SNBH have been partly formed from infalling clouds from the Galactic halo. Circumstantial evidence for HVC impacts on the Galactic disk is based on: 1) the existence of subgroups of young stars in star forming molecular clouds at high Galactic latitudes (like the Orion molecular cloud complex), 2) the displacement of OB star clusters with respect to the centers of their parent molecular clouds, 3) the alignment of the OB clusters in directions that are substantially inclined to the Galactic plane, 4) the age sequence of the aligned OB associations with an age of ~10⁷ yr for the oldest subgroups, and 5) the large elongated or filamentary structures observed in e.g. the Orion, Taurus. Monoceros molecular clouds connecting the clouds to the Galactic plane (see also Tenorio-Tagle et al. 1986; Franco et al. 1988; Gómez de Castro 1992). Many of these phenomena can be naturally explained by the interaction of a high velocity cloud with disk ISM and are difficult to reproduce by the process of sequential star formation (Lépine & Duvert 1994). Infall induced star formation appears to be a process frequently operating in the Galactic disk.

It has been proposed that many of the HVCs are associated with the ejection of material up to large scale heights by supernovae in the Galactic disk (Mathewson & Ford 1984). Apart from the fact that HVCs cannot be fully primordial because of the presence of various metals in HVCs, considerable mixing of material in the Galactic halo with metal-rich material associated with star formation in the disk may have occurred. The height above the Galactic plane and the amount of accreted material, participating in the circulation between the halo and the disk, may determine the average abundances within the infalling material. Alternatively, infalling clouds may be related to intergalactic gas or associated with stripping of material from nearby metal-poor galaxies like the Small Magellanic Cloud (see below).

It is interesting to note that Orion's oxygen abundance is at the low end of the oxygen abundances observed in HII regions at roughly the galactocentric distance of Orion (Cunha & Lambert 1992; see also Meyer et al. 1994). If due to metal-poor gas infall, this would be consistent with the scenario of infall induced star formation as deduced from OB associations in Orion. To preserve the chemical inhomogeneities caused by infall of metal-poor gas, infall must induce star formation on time scales short compared to the local mixing time scale. According to the interaction time scale of 10⁷ yr, this condition is likely fulfilled during the impact of a HVC with the disk ISM.

This would be consistent with the generally accepted idea that Galactic HVCs usually have abundances below those present in the local disk ISM (Savage & de Boer 1981; de Boer & Savage 1983, 1984). However, recent observations indicate that both high (i.e. about solar; Spitzer & Fitzpatrick 1995) and low (i.e. about 1/10 solar; Danly et al. 1993; Savage et al. 1993; Kunth et al. 1994; Schwarz et al. 1995) metal abundances in HVCs are present. The latter authors derived abundances of C, O, S, and Si which are at most 0.1 times solar; the lowest abundances found are similar to those present in the Magellanic Stream. Since depletion of heavy elements by dust grains may play an important role and metallicities may vary considerable across a HVC complex (Schwarz et al. 1995) further analysis is needed to confirm the overall metal-deficiency of high-velocity clouds falling onto the disk ISM.

Sequential stellar enrichment

The concept of sequential star formation is based on observations of spatially separated subgroups of OB stars that appear aligned in a sequence of ages in many OB associations (e.g. see the review by Blaauw 1991; Megeath et al. 1995; Testi et al. 1998). Sequential star formation has been argued to occur in nearby molecular cloud complexes including the well known Orion, Taurus-Auriga-Perseus, Cepheus, Carina, and Chameleon cloud complexes. Additional support is provided by observations of newly formed stellar generations at the interfaces of HII regions and their surrounding molecular clouds (e.g. Genzel & Stutzki 1989; Junkes et al. 1992; Goldsmith 1995; Megeath et al. 1996). Efficient self-enrichment is expected to occur in these regions.

Age differences between the OB subgroups (distances of 10-50 pc) in Orion are typically of the order of 2–7 10⁶ yr (e.g. Genzel & Stutzki 1989; Blaauw 1991; Cunha & Lambert 1992; Elmegreen 1992; Risco & Bajaja 1994; Brown et al. 1994; Haikala 1995). These ages appear similar to the estimated dispersal times of 3-5 10⁶ yr of molecular cloud cores associated with young star clusters after the onset of star formation (e.g. Garmany et al. 1982; Leisawitz 1985; Leisawitz et al. 1989). This may be compared to the typical free-fall time of ~2 Myr for a giant molecular cloud which implies star formation to start shortly after cloud formation (Blitz 1990). When star formation proceeds on such time scales, massive stars belonging
5.5 Discussion

Thick O B subgroups may enrich the ambient molecular cloud material before a next round of star formation is initiated. This process is actually going on in various sites in the Orion A and B clouds (e.g. Brown et al. 1994).

OB associations in Orion probably display a substantial variation in their heavy element abundances among stars that form within the first OB association and those that form just before the association disperses. For instance, the oldest of four subgroups observed in the Orion OBI association appears to have oxygen abundances which are lower by about 40% compared to the younger subgroups while C and N abundances are identical within the observational errors (see Gies & Lambert 1992; Cunha & Lambert 1992). The finding that C and N abundances are similar for all subgroups studied in OBI (Cunha & Lambert 1994) is consistent with the idea that these elements are returned predominantly by stars less massive than those responsible for the oxygen enrichment (e.g. Timmes et al. 1995).

The winds and radiation from OB stars in the Trapezium cluster interact with the dense gas of the cloud and may be inducing another round of star formation in the cloud. As the total mass of the cloud appears less than an order of magnitude larger than the total mass in stars, star formation appears to be highly efficient (Cunha & Lambert 1992). These authors suggest that additional oxygen observed in the Trapezium stars is the product of explosive nucleosynthesis immediate prior to its formation. Since the Orion OB association is at the edge of the molecular cloud complex the ejecta of supernovae are expected to reach larger distances in the low density gas and such enrichment may be expected.

Apart from observational support for sequential enrichment in nearby star forming regions, there are strong indications that the molecular cloud out of which the Sun formed has been enriched sequentially as well. Studies related to extinct radioactive nuclides such as $^{53}$Mn both in the Sun and in meteorites suggest that the protosolar molecular cloud has been enriched by high mass stars from a preceding OB association, about 10–25 Myr prior to the actual formation of the Sun (e.g. Cameron 1993; Swindle 1993). These studies imply that the Sun formed from material metal-rich compared to the ambient ISM at that time. The estimated time scale of 10–25 Myr between cloud enrichment and actual formation of the Sun is similar to that for sequential star formation inferred from other observations. This suggests that the formation of the Sun has been initiated by an evolved massive star and that sequential stellar enrichment of the protosolar cloud occurred. In turn, this would imply that the typical abundances of 0.15 dex in [M/H] below solar, observed for the vast majority of the gas and young stars present in the SNB, are not biased by infall of metal-poor gas but, more likely, are the result of the self-enrichment of the protosolar nebula.

5.5.3 Implications for Galactic chemical evolution

We have argued that infall of metal-deficient material onto the disk is required to explain the observed abundance variations among similarly aged stars throughout the Galactic disk. Although there is a wealth of observations supporting the presence of high-velocity gas clouds at high Galactic latitudes (see above), the origin of this infalling material is not well known. As possible nature of the gaseous material observed in the Galactic halo have been proposed: 1) the residual of a slow halo collapse in which the chemical evolution of the halo is expected to be halted at the time the collapse becomes pressure-supported and the remaining gas settles to a disk, 2) accretion of intergalactic gas (Oort 1970; Hulsbosch & Oort 1973) in combination with the peculiar motion of the Galaxy in intergalactic space, 3) condensation of gas in a Galactic fountain flow (Shapiro & Field 1976; Bregman 1980), and 4) gas stripping from nearby galaxies by tidal interaction with the Galaxy, e.g. such as the Magellanic Stream (Gardiner et al. 1994; Wolfire et al. 1995).

Observations support the idea that some HVCs are of extragalactic origin (e.g. McGee et al. 1983; Mirable & Morris 1984; West et al. 1985; Mirabel 1989; Songaila et al. 1989), at least at distances above the Galactic plane of $\geq 10$–15 kpc. The presence of large amounts of neutral hydrogen in the Galactic halo up to such distances and beyond seems difficult to explain by ejection of material into the halo by massive stars formed in the disk. Probably, the region of the Galactic halo which is contaminated with enriched gas by supernova-driven winds out of the disk ISM (e.g. Norman & Ikeuchi 1989) is distinct from the gas which extends up to the distance of the Magellanic Clouds and beyond.

In the Galactic fountain model, HVCs of neutral hydrogen can condense from a hot, dynamic corona above the plane of the Galaxy perhaps up to distances of 30 kpc above the plane (Shapiro & Field 1976; Bregman 1980; Wakker & Bregman 1994). In the model favoured by these authors, hot gas from superbubbles (arising from multiple supernovae in OB associations; e.g. Garmany 1994) escapes from the Galactic disk, cools radiatively when it moves upwards, eventually recombines, and spirals down to the disk about 3-60 $10^7$ yr after its ejection out of the Galactic plane. The model predicts a total mass flux of HVCs onto the disk of $\sim 2.5 \, M_{\odot} \, yr^{-1}$ with typical HVC masses of $5 \times 10^7$ to $5 \times 10^9 \, M_{\odot}$ (see also Schulman et al. 1994).

The fact that most HVCs show signatures of Galactic rotation implies that they have distances greater than $\sim 3$ kpc (e.g. Dickey & Lokasman 1990). In this part of the halo, gas exchange with the disk ISM
probably makes a dominant contribution to the enrichment of the halo gas. If this model is correct, a substantial fraction of the HVCs may be metal-rich and induce abundance inhomogeneities (similar to those caused by sequential stellar enrichment) when they interact with the disk ISM. Interestingly, the mass of HI contained in HVCs in external galaxies appears to be correlated with the amount of star formation as traced by the IRAS far-IR flux (e.g., Schulman et al. 1994). Whether this is due to star formation initiated by the impacts of HVCs and/or is due to a relation between the total mass contained in HVCs and the SFR is yet unclear.

In contrast, the outer part of the Galactic halo at distances of ~30 kpc and above may have abundances similar to that found in the Magellanic Clouds and in fact may extend to distances upto ~200 kpc. Massive haloes of spiral galaxies with luminosities similar to that of the Galaxy extend out to radii of 200 kpc (e.g., Zaritsky et al. 1989, 1993). This gas is usually not seen as neutral hydrogen but becomes ionized by the intergalactic radiation field when the opacity in the outer disk regions becomes very low. In the Milky Way this might occur at distances of at least 10-15 kpc above the Galactic plane (e.g., Savage & de Boer 1988; Kutyaev & Reynolds 1989). Below these distances, Hα emission presumably is due to recombination after a shock wave created by the HVC/hot gas interaction (Kutyaev & Reynolds 1989; Ferrara & Field 1994).

The chemical composition of the outer halo gas may be traced by the interaction of the Magellanic Stream (MS) with hot halo gas. Abundances in the MS are similar to lowest abundances found in HVCs, i.e. less than ~0.1 solar (Schwarz et al. 1995). The density concentrations observed in the Magellanic Stream (Mathewson et al. 1977) have been suggested to be due to the interaction of the gas inbetween the Clouds and that present in the Galactic halo (Mathewson et al. 1987; Wayte 1991). The presence of gas in the outer halo of the Galaxy may be important for the motion of the MS by means of hydrodynamic effects (Irwin 1991). An interesting explanation has been proposed by Liu (1992) who showed that a chain of concentrations of cold hydrogen gas at the approximate positions of the observed concentrations along the MS could be explained by a model in which gas is stripped from the region between the LMC and SMC and cools in the wake of hot halo gas behind the receding Magellanic Clouds. The MS itself contributes as well to the infall of hydrogen gas onto the Galactic disk: the tip of the stream near the South Galactic Pole has a high infall velocity of about 380 km s⁻¹ (Wannier & Wrixon 1972; Murai & Fujimoto 1980). Therefore, gas stripping from nearby galaxies also may provide an explanation for gas clouds falling onto the disk.

Clearly, the temporal behaviour of the rate of gas infall onto the disk and the origin of the infalling matter are not well known. The majority of the observations suggest an external origin for most of the material contained in HVCs. This is consistent with our results indicating that a substantial fraction of matter infalling from the halo must have abundances typical to that of halo stars with [M/H]~ −1, in order to explain the observed stellar abundance variations. On the other hand, a local origin of the HVCs related to the ejection of massive stars in the disk would imply these clouds to be more metal-rich. In this case, the effect of metal-rich infall on the chemical evolution of the disk ISM would be very similar to that of sequential stellar enrichment except that the halo residence time for such clouds would be considerably longer than that for star formation initiated directly in the disk ISM.

There are several indications that the most prominent star forming regions in the SNBH, e.g. the Orion molecular cloud and the Gould belt, have been partly formed from (and undergo star formation induced by) infalling clouds from the Galactic halo (Franco et al. 1988; Comerón & Torra 1992; Edvardsson et al. 1995). Molecular clouds may form at high Galactic latitudes due to the rapid cooling and high densities achieved in the shocked layer resulting from the impact of a high-velocity cloud (HVC) with the Galactic disk or halo ISM. It is interesting to note that high-altitude molecular clouds have been observed recently in ¹²CO(1-0) (Malhotra 1995).

Hydrodynamical models for infall induced star formation events suggest that, although the accretion of infalling gas onto the shocked disk ISM layer is a continuous process during the impact, the formation of an OB cluster could inhibit star formation for a few times 10⁷ yr until the threshold density for star formation at these high Galactic latitudes is reached again (see Lépine & Duvert 1994; Comerón & Torra 1994). After the formation of the OB cluster, the remaining part of the infalling cloud may continue to interact with the disk ISM, initiating another round of star formation, until the velocity dispersion of the cloud matter has become similar to that of the ambient ISM after ~10⁷ yr (Lépine & Duvert 1994). It appears that such models naturally can explain the observed age sequence and spatial alignment of the OB associations in OMC1. The time scale estimated for the impact of the HVC with the disk ISM is ~10⁷ yr, depending on the cloud velocity, direction, and density contrast with the disk ISM. The fact that the OB associations observed in Orion are displaced from the center of the molecular cloud may be a strong indication for the impact by a HVC (see above).

In the infall induced star formation model, successive stellar generations are born on time scales determined by the velocity of the HVC; the resulting density contrasts within the disk ISM, and the amounts of gas consumed by previous star formation events during the impact. In this case, there is no direct causal
effect of one group of stars upon the other although massive stars belonging to the previously formed generation may catalyze the next star formation event. While in the traditional view of sequential star formation massive stars are required to induce a next round of star formation, this is not the case for the impact of an HVC with the disk ISM (Lépine & Duvert 1994). In order to preserve the chemical inhomogeneities caused by infall of metal-poor gas for the next generation of stars, infall must induce star formation on time scales short compared to the local mixing time scale. This condition likely is fulfilled during the impact of a HVC with the disk ISM.

Apart from the possibility of sequential star formation caused by infalling clouds, sequential enrichment also may occur when expanding (and/or shock driven) stellar ejecta break out of the surface of their parent molecular cloud core and induce star formation at the interface zones with the ambient disk ISM, i.e. at the cloud edges. Sequential star formation is expected to occur preferentially in regions where density inhomogeneities are generated by the interaction of large amounts of swept up matter so that the critical conditions for star formation can be reached. Such conditions, i.e. for the collapse of high density gas under gravitational instabilities, are likely to be met in the spiral arms and nuclei of galaxies.

As discussed above, sequential enrichment may be triggered by OB-associations or by single massive stars. Efficient sequential enrichment will take place when newly synthesized heavy elements returned by a generation of massive stars are mixed to relatively small amounts of material in which star formation is induced. This is especially true in case: 1) the enriched stellar material is returned to the ambient ISM in collimated outflows and/or irregularly expanding shells, and 2) the time scale for star formation initiated by these outflows is shorter than the local mixing time scale so that stellar enrichment is restricted mainly to the region in which star formation is induced. These conditions are met in particular when star formation within the same cloud core continues over an extended period of time so that the first massive stars formed are able to enrich the material accumulating at the star forming core. In general, the effect of sequential stellar enrichment depends on the detailed mass-loss history of the actual generation of massive stars enriching the surrounding cloud material before the cloud core disperses.

Self-enrichment may be also important within the expanding shells associated with giant HII regions around young star clusters (Kunth & Sargent 1986; Pilyugin 1992). In this case, heavy elements originating from stellar winds and supernovae mix exclusively with the ionized gas within the expanding HII region. Depending on the dispersion of the heavy elements, efficient self-enrichment may occur when the expanding shell enters a new episode of star formation. Initiation of star formation within the expanding shell is determined by the detailed structure of the ambient ISM together with the underlying cluster of massive stars driving the expansion. This process has been suggested also to operate in globular clusters when a second generation of stars forms in the expanding shell around an earlier generation of stars (Brown 1991), and in case of supershell induced star formation around evolving OB associations (McCray & Kafatos 1987; Elmegreen 1992). The abundance inhomogeneities observed among similarly aged open clusters (e.g. Carraro & Chiosi 1994), as well as among stars within a given open cluster (e.g. Kilian-Montenbruck et al. 1994), may be due to a similar process of self-propagating star formation.

5.5.4 Concluding remarks

In this paper, we have presented both theoretical and observational arguments in support of combined metal-deficient gas infall and sequential stellar enrichment in the local disk ISM. We have shown that these processes can provide an adequate explanation for the abundance inhomogeneities observed among similarly aged stars in the SNBH and may play an important role for the inhomogeneous chemical evolution of the Galactic disk. In addition, these processes probably affected the star formation history and chemical evolution of the Galactic halo as suggested by the significant abundance variations observed among metal-poor halo stars (e.g. Bessell et al. 1991; Nissen et al. 1994; Sect. 4.3). Also, abundance inhomogeneities of \( \geq 0.8 \) dex among similarly aged globular clusters in the Galactic halo have been discussed recently by Chaboyer et al. (1996). Although part of these abundance inhomogeneities may be associated with the accretion of globular clusters from nearby galaxies by the Galaxy (such as the Sgr dwarf galaxy), a substantial fraction of these clusters probably formed in the outer halo during the early collapse of the proto-Galactic cloud as indicated by the mean age-metallicity relation observed among such clusters. In this context, it seems likely that sequential stellar enrichment and metal-poor gas infall are at least in part responsible for the large spatial abundance fluctuations observed in massive disk galaxies (e.g. Roy & Kunth 1994).

Notwithstanding the results presented in this paper, combined metal-poor gas infall and sequential stellar enrichment may be a too schematic picture of the complex set of processes directing the chemical evolution of the Galactic disk. In particular, merger events with small companion galaxies may be important as well (e.g. Quinn et al. 1993). In such cases, both gas and stars in the companion galaxy may add substantially to the observed abundance inhomogeneities in the Galactic disk (Pilyugin & Edmunds 1996c).
However, the suggestion that stellar populations from merging companion galaxies contribute substantially to the observed stellar abundance variations in the Galactic disk seems difficult to reconcile with: 1) the apparent homogeneous distribution of these variations within the metallicity range observed at a given age of the disk, and 2) the relatively small scatter observed in the element-to-element variations for stars in the SNBH. Instead, we argue that most of the stars present in the Galactic disk formed from gaseous material accumulated in the disk and that the observed stellar abundance variations are due to inhomogeneities in the ISM rather than merging of stellar populations with independent star formation and chemical evolution histories. In either case, merging may be important for the chemical evolution of the Galaxy both by adding large amounts of predominantly metal-poor material and by initiating star formation in the disk.

Additional processes which probably contribute to the inhomogeneous chemical evolution of the Galactic disk include: 1) ejection of enriched material into the halo generating local abundance variations in the disk ISM, and 2) stellar orbital diffusion. We argue, however, that the time scales for these processes required to cause substantial abundance variations in the disk ISM are often much larger than those indicated by the observations. Therefore, we believe that such processes are unlikely to be the main cause for the observed abundance variations.

Inhomogeneous chemical evolution due to sequential stellar enrichment and/or metal-poor gas infall is probably important also in nearby galaxies such as the Magellanic Clouds and M31. In the Large Magellanic Cloud, large abundance variations of ~0.4–0.8 dex in [Fe/H] among similarly aged open clusters are observed (e.g. Cohen et al. 1982; Da Costa 1991; Olsewski et al. 1991). Part of the variations may be accounted for by a radial gradient of ~0.15 dex kpc⁻¹ in [Fe/H] (Kontizas et al. 1993). However, the main part of these variations is likely due to triggered star formation in supershells as indicated by the close association of HII complexes with large HI holes observed in the LMC (Dopita 1985; Lortet & Testor 1988; Meaburn et al. 1991). In addition, gas infall may have affected the chemical evolution of the tidally interacting Magellanic Clouds.

Observational evidence in support of shock-induced star formation by SNII in the spiral arms of M31 has been presented by Magnier et al. (1992). At these sites, young OB stars are observed to initiate recent star formation so that large abundance inhomogeneities due to sequential stellar enrichment are expected, similar to those observed among OB associations in the Orion star forming cloud complex in our own Galaxy.

Stellar and nebular abundance indicators reveal that substantial abundance fluctuations exist in the ISM of gas-rich galaxies (e.g. Roy & Kunth 1995). For instance, abundance inhomogeneities in metal-poor galaxies such as I Zw 18 may be among the largest observed in external galaxies (e.g. Kunth et al. 1995) although this is still highly uncertain (Pettini & Lipman 1995). Whether the abundance fluctuations observed in dwarf galaxies are due to variations in self-enrichment of the HII-regions in these systems (e.g. Pilyugin 1992) and/or are related to selective loss of metals through galactic winds driven by massive stars (Roy & Kunth 1995; Martin 1996) is unclear.

We expect that sequential stellar enrichment is generally inefficient in dwarf galaxies because of their low gas densities, and that the effect of metal-poor gas infall on the stellar abundance variations is weak due to their low ISM abundances. Instead, star formation and abundance inhomogeneities induced by metal-rich gas infall associated with previous star formation may be relatively important in these systems.

Acknowledgements

It is a pleasure to thank L.S. Pilyugin, K. Nomoto, and J.-R. Roy for stimulating discussions. We like to thank J. van Paradijs for a critical reading of earlier versions of this paper. We are grateful to the referee, Dr. B. Pagel, for careful and constructive remarks from which this paper has benefitted. The research of LBH is supported under grant 782-372-028 by the Netherlands Foundation for Research in Astronomy (ASTRON), which is financially supported by the Netherlands Organisation for Scientific Research (NWO).
Appendices

A A model for the inhomogeneous chemical evolution of a star forming gas cloud

We describe the adopted model for the inhomogeneous chemical evolution of a star forming gas cloud. The model can be applied to various mass scales, e.g. to the entire system of molecular cloud complexes in the Galactic disk or to the star forming core regions within a single molecular cloud. We start from a homogeneous, metal free gas cloud with a total mass $M_{\text{cl}}$. At any evolution time $t$ in its evolution, this cloud is subdivided into $N_{\text{cl}}$ active subclouds (with corresponding masses $M_{\text{cl}}^i$) involved with star formation and an inactive cloud part (with mass $M_{\text{act}}$) not involved with star formation. We assume matter to be freely exchanged within the inactive cloud part. Each subcloud $i$ is formed at corresponding evolution times $t_{\text{cl}}^i$ and is allowed to follow its individual star formation, mixing, and infall history.

A.1 Model description, definitions and assumptions

During the lifetime $t_{\text{ev}}$ of the star forming gas cloud a total number $N_{\text{sf}}$ star formation events is assumed occur. Each star formation event $j$ presumably occurs within an active subcloud $i$. We define $N_{\text{sf}}^i$ as the total number of star formation events within subcloud $i$. For the reference model $N_{\text{sf}}^i = 1$ and each star formation event $j$ occurs in corresponding subcloud $i = j$. Subclouds are allowed to experience numerous star formation events, i.e. $N_{\text{sf}} > 1$. During each star formation event $j$ at time $t = t_{\text{cl}}^j$ within subcloud $i$, a total mass of gas $\delta M_{\text{cl}}^i = \epsilon_j M_{\text{cl}}^i (t_{\text{cl}}^j)$ is transformed into stars.

We define $\Delta t_{\text{disp}}^j$ as the time between the onset of star formation within a subcloud core and the complete dispersal of this core region by supernova explosions and/or stellar winds. During $\Delta t_{\text{disp}}^j$ the subcloud core is assumed to form stars. The profile of the star formation rate (SFR) during $\Delta t_{\text{disp}}^j$ is assumed constant and identical for all star formation events. However, quantities such as the minimum stellar mass formed and IMF-slope are allowed to vary from one star formation event to another (cf. Sect. 5.4.2). The subcloud core dispersal time determines the mass of the most massive star that is able to enrich subcloud cloud material before the core ultimately breaks up. At time of core dispersal, the newly formed generation of stars has returned an amount of material $\delta M_{\text{ret}}^i$. Accordingly, the net amount of material converted into stars during star formation event $j$ is given by: $\delta M_{\text{ret}}^i = \epsilon_j \delta M_{\text{cl}}^i (t_{\text{cl}}^j) - \delta M_{\text{ret}}^i$.

Subclouds $M_{\text{cl}}^i$ are formed from the inactive cloud ISM at cloud evolution times $t = t_{\text{cl}}^i$. When a subcloud forms it adopts the abundances of the inactive cloud ISM at $t = t_{\text{cl}}^i$. For each subcloud, we define a mixing time scale $\Delta t_{\text{mix}}^i$ as the time between formation of the subcloud and the actual break up of the entire subcloud. The instant of break up of the subcloud may be either after one or more star formation events, or before star formation actually takes place. In this manner, material can be deposited within a subcloud region for a considerable period of time before being mixed to the surrounding ISM. The mixing history of each subcloud directs both the inhomogeneous chemical evolution of the inactive cloud and that of the neighboring subclouds.

Before an entire subcloud breaks up its constituent material will be enriched by the stellar populations it is hosting. We assume the stellar enrichment of the subcloud to proceed homogeneously. In order to allow for sequential enrichment, we consider a fraction $\lambda^j$ of enriched material ejected during star formation event $j$ to mix homogeneously with subcloud core material hosting the next star formation event. Simultaneous with the ejection of enriched material returned by newly formed stars, a substantial fraction of the ambient subcloud matter $\kappa^j M_{\text{cl}}^i$ may be swept up during dispersal of its star forming core. This subcloud material may mix to the subcloud hosting the next star formation event as well. The subcloud hosting the next star formation event may be either the subcloud hosting the current star formation event or a subcloud nearby. No matter exchange is assumed between the subcloud and the surrounding ISM during the time between two star formation events occurring within one and the same subcloud. In case of the reference model, we do not consider mass transfer between subclouds, i.e. $\lambda^j = \kappa^j = 0$.

After an entire subcloud breaks up its material is assumed to mix homogeneously to the inactive cloud part. At the same time, stars associated with the dispersing subcloud become part of the stellar populations in the inactive cloud. After break up, different cloud fragments present in the ambient ISM may form new subclouds wherein star formation occurs as soon as the critical conditions for star formation are met.
In addition to the individual chemical evolution of subclouds, which is directed by their star formation history and exchange history with the surrounding ISM, we allow for local enrichment of a given subcloud by stars that were not formed within that subcloud. This may be particularly important for low mass SNIa-progenitors which travelled considerable distances from their birth sites and enrich their immediate surroundings at the time they explode as SNIa (cf. Fig. 5.2f; see below).

### A.2 Basic equations

We keep track of the total mass of and abundances in stars and gas as a function of evolution time, both within each subcloud and the inactive cloud ISM. For each star formation event we use conventional chemical evolution model equations (e.g. Tinsley 1980, see below) except for including metallicity dependent stellar lifetimes, remnant masses and element yields (cf. van den Hoek et al. 1996).

**Mass-exchange between subclouds and the inactive cloud ISM**

We denote $\Delta Q$ as the variation of a quantity $Q$ between two cloud evolution times $t - \Delta t$ and $t$. With $M_{cl}(t = 0)$ the initial mass of the cloud and no stars initially present, i.e. $M_*(0) = 0$, we can express the variations of mass of gas and stars within the cloud as:

$$
\Delta M_{cl} = \sum_{i=1}^{N_{cl}(t)} \Delta M^{i}_{cl} + \Delta M_{qcl} \tag{A1}
$$

$$
\Delta M_*(t) = \sum_{j=1}^{N_{*}(t)} (\Delta C^j_\star - \Delta E^j_\star) - \Delta E^{*}_{qcl} \tag{A2}
$$

where $N_{cl}(t)$ is the current number of individual subclouds, $N_{*}(t)$ the current number of star formation events within the cloud, $\Delta C^j_\star$ the total mass of stars formed during star formation event $j$, and $\Delta E^j_\star$ the total mass of matter returned within $\Delta t$ by stars formed during star formation event $j$. We recall conventional expressions for $\Delta C^j_\star$ and $\Delta E^j_\star$ (cf. Tinsley 1980):

$$
\Delta C^j_\star = \int_{t_{sf}}^{t_{sf}+\tau_{disp}} \int_{m_i}^{m_\star} m S_{j}(t) M_{j}(m) \, dm \, dt \tag{A3}
$$

$$
\Delta E^j_\star = \int_{t-\Delta t}^{t} \int_{m_{rem}(m)}^{m_{\star}} (m - m_{rem}(m)) S_{j}(t - \tau(m)) M_{j}(m) \, dm \, dt \tag{A4}
$$

where $S_{j}$ and $M_{j}$ denote the SFR by number $[\text{yr}^{-1}]$ and IMF $[\text{M}_\odot^{-1}]$ for star formation event $j$. For convenience, we ignored the index $j$ for $t_{sf}$, $t_{disp}$ as well as for the stellar mass boundaries at birth $m_\star$, $m_{\star}$. We emphasize that both the stellar remnant masses $m_{rem}(m)$, lifetimes $\tau(m)$, and turnoff-masses $m_{\star}(t)$ are a function of the initial metallicity $Z_{i}$ (containing all elements heavier than H) of the stellar generation under consideration. Variations in the total gas masses within the inactive cloud and subcloud $i$, i.e. $M_{qcl}$ and $M^{i}_{cl}$ respectively, can be expressed as:

$$
\Delta M_{qcl} = \Delta E^{*}_{qcl} - \Sigma_{form} M^{k}_{cl} + \Sigma_{disp} M^{i}_{cl} \tag{A5}
$$

$$
\Delta M^{i}_{cl} = [\Delta E_{\star} - \Delta C_{\star}]^i + \Delta M_{*,prev} - \Delta M_{*,next} \tag{A6}
$$

$$
\Delta M_{cl} = \sum_{i=1}^{N_{cl}(t)} \Delta M^{i}_{cl} + \Sigma_{form} M^{k}_{cl} - \Sigma_{disp} M^{i}_{cl} \tag{A7}
$$

where $\Delta E^{*}_{qcl}$ refers to the amount of material returned by stars present in the inactive cloud within time $\Delta t$. We followed both the stellar ejecta from recently formed stars within active subclouds and the ejecta from older stellar populations present in the inactive cloud ISM. The total amount of gas depleted by subclouds which are formed within time $\Delta t$ is denoted by $\Sigma_{form} M^{k}_{cl}$. Similarly, the amount of gas returned by subclouds which become dispersed within time $\Delta t$ is denoted by $\Sigma_{disp} M^{i}_{cl}$. We remark that the term between square brackets in Eq. (A6) refers to star formation events which occur within subcloud $i$.

**Supernovae Type Ia**

The term $\Delta E^{i}_{\star}$ in Eq. (A6) is related both to stellar generations which formed within subcloud $i$ and to stars that entered the subcloud from elsewhere in the cloud. We will consider the case of SNIa progenitors stars only. Consequently, the term $\Delta E^{i}_{\star}$ can be expressed as two terms, i.e. $\Delta E^{i}_{\star} = \Sigma_{form}(\Delta E^{i}_{cl})^{i} + \Delta E_{SNIa}$. The former term is related to star formation events which occurred within subcloud $i$ while the latter term is associated with subcloud enrichment by SNIa-progenitors formed elsewhere in the cloud. We define the total
amount of matter returned by SNIa within subcloud $i$ during time $\Delta t$ as: 
$$
\Delta E_{\text{SNIa}} = \alpha_i^{\text{SNIa}} \Delta t R_{\text{SNIa}} m_{\text{rem}}(m)
$$
where $R_{\text{SNIa}}$ is the total average SNIa-rate in the entire cloud and $\alpha_i^{\text{SNIa}}$ the corresponding fraction of SNIa that is assumed to go off within subcloud $i$. In case of the reference model $\Delta E_{\text{SNIa}} = 0$.

**Mass-exchange between individual subclouds**

As matter may be transferred from one subcloud to another (or within one subcloud from one subcloud core to another) we include terms $\Delta M_{\text{sf,prev}}$ and $\Delta M_{\text{sf,next}}$ in Eq. (A6). The term $\Delta M_{\text{sf,prev}}$ corresponds to the amount of material added from the preceding star formation event to the core of the subcloud currently experiencing star formation. The term $\Delta M_{\text{sf,next}}$ refers to the amount of matter mixed from the subcloud core actually experiencing star formation to the subcloud core hosting the next star formation event. For each star formation event $j$ which happens to occur in subcloud $i$ within the time interval $\Delta t$ we may write:

$$
\Delta M_{\text{sf,prev}} = \lambda^j - 1 \delta M_{\text{ret}}^i + \kappa^j - 1 M_{\text{scl,prev}}
$$
$$
\Delta M_{\text{sf,next}} = \lambda^j \delta M_{\text{ret}}^i + \kappa^j M_{\text{scl}}^i
$$

where $M_{\text{scl,prev}}$ is the mass of the subcloud hosting the preceding star formation event. In this paper, we presented only results for $\kappa^j = 0$. In general, $\kappa^j > 0$ has a similar effect as when reducing the sequential enrichment efficiency $\lambda^j$.

**Chemical evolution of subclouds and inactive cloud ISM**

Expressions for the average abundance changes of element $X$ within the entire cloud, inactive cloud part, and subclouds can be written as:

$$
\Delta (X_{\text{cl}} M_{\text{cl}}) = \Sigma_{i=1}^{N_{\text{cl}}} (\Delta (X_{\text{scl}} M_{\text{scl}}))^i + \Delta (X_{\text{cl}} M_{\text{qcl}})
$$
$$
\Delta (X_{\text{qcl}} M_{\text{qcl}}) = \Delta E_{X_{\text{qcl}}} - \Sigma_{i=1}^{N_{\text{cl}}} \Delta (X_{\text{scl}} M_{\text{scl}}) + \Sigma_{\text{disp}} X_{\text{qcl}} M_{\text{qcl}}^i
$$
$$
\Delta (X_{\text{scl}} M_{\text{scl}}) = \Sigma_{i=1}^{N_{\text{cl}}} \Delta (X_{\text{scl}} M_{\text{scl}})^i + \Sigma_{\text{disp}} X_{\text{scl}} M_{\text{scl}}^i
$$
$$
\Delta (X_{\text{scl}} M_{\text{scl}})^i = [\Delta E_{X} - X_{\text{cl}} \Delta C_{s}] \Delta M_{X,\text{prev}} - \Delta M_{X,\text{next}}
$$

where the meaning of each term can be found from its counter part in Eqs. A5-A7. Similarly, expressions for $\Delta M_{X,\text{prev}}$ and $\Delta M_{X,\text{next}}$ can be written as:

$$
\Delta M_{X,\text{prev}} = \lambda^j - 1 \delta M_{X,\text{ret}}^i + \kappa^j - 1 (X_{\text{scl}} M_{\text{scl}})_{\text{prev}}
$$
$$
\Delta M_{X,\text{next}} = \lambda^j \delta M_{X,\text{ret}}^i + \kappa^j X_{\text{scl}} M_{\text{scl}}^i
$$

where $\Delta E_{j}$ is the total mass of enriched material of element $X$ returned within $\Delta t$ by a stellar generation formed during star formation event $j$:

$$
\Delta E_{X} = \int_{t - \Delta t}^{t} \int_{m_a(t - \tau)}^{m_a(t - \tau_{\text{disp}})} \Delta M_{X}(m) S_{X}(t - \tau(m)) M_{j}(m) \text{d}m \text{d}t
$$
$$
\Delta M_{X}(m) = m_{\text{PX}}(m) + (m - m_{\text{rem}}(m)) X_{\text{qcl}}^i
$$

and $\Delta M_{X}(m)$ is the total mass of element $X$ ejected by a star of initial mass $m$ born with metallicity $X_{\text{qcl}}^i$ during star formation event $j$. The term $\Delta M_{X}(m)$ includes both newly synthesized stellar material and matter initially present at the time stars were formed. Initial stellar abundances $X_{\text{qcl}}^i$ are determined by the abundances of the subcloud $i$ (hosting star formation event $j$) at time $t_{\text{sf}}$, i.e. $X_{\text{qcl}}^i = X_{\text{scl}}^i(t = t_{\text{sf}})$. Literature sources for the adopted theoretical metallicity dependent stellar yields $p_{X}(m)$, stellar lifetimes $\tau(m)$, and remnant masses $m_{\text{rem}}(m)$ are given in Sect. 5.3.4.
5 Inhomogeneous chemical evolution of the Galactic disk

B Basic effects of metal-deficient gas infall and sequential stellar enrichment

Our goal is to estimate the amount of material to be mixed homogeneously to a star forming gas cloud in order to explain abundance variations by mass of $^{10}\log (M/H)\pm 0.6$ dex relative to the initial abundances of the cloud. Such abundance variations can be achieved either by mixing metal-poor or metal-rich material to the cloud.

We define $\delta M_H$ as the ratio of hydrogen mass in the added material and that initially present in the star forming region: $\delta M_H = M_H^{\text{add}}/M_H^{\text{init}}$. Similarly, we define $\beta_i$ as the mass-ratio of element $i$, relative to hydrogen, of the added material and that of the star forming region: $\beta_i = (M_i/H)^{\text{add}}/(M_i/H)^{\text{init}}$. Consequently, the logarithm of the ratio of the abundances of stars formed before and after mixing material to the star forming region, can be expressed as:

$$\alpha_i = 10 \log \left( \frac{1 + \beta_i \delta M_H}{1 + \delta M_H} \right) \quad \text{(B1)}$$

We tabulate values of $\alpha_i$ for different combinations of $\delta M_H$ and $\beta_i$ in Table 5.5. We consider the observed abundance scatter of $\sim 0.6$ dex in [O/H]. We assume that the initial cloud oxygen abundances are equal to the mean stellar oxygen abundances observed at a given age. This implies variations in $\alpha_O$ of $\pm 0.3$ dex. Alternatively, we could have assumed that the initial cloud abundances are equal to the largest stellar oxygen abundances observed (i.e. variations in $\alpha_O$ down to $-0.6$ dex) or equal to the smallest abundances observed (i.e. variations in $\alpha_O$ up to $+0.6$ dex). Since the mean interstellar oxygen abundances in the SNB are not well known, we simply illustrate the effect of mixing material that is needed to achieve stellar abundance variations of $\pm 0.3$ dex. Stellar abundance variations larger than $\pm 0.3$ dex will lead to more extreme values of $\delta M_H$ and $\beta_i$ than discussed below.

B.1 Mixing of metal-deficient material

Table 5.5 illustrates that stellar abundance variations $\alpha_i$ of about $-0.3$ dex can be obtained by mixing metal-deficient material with abundance ratios $\beta_i \leq 0.1$ and hydrogen mass-ratios of $\delta M_H \geq 1$. In this case, mixing of material metal-poor by one order of magnitude is needed to explain abundance variations of $-0.3$ dex for comparable amounts of hydrogen within the added material and (initially present) within the star forming cloud. Similarly, abundance variations of $-0.3$ dex can be reached also by mixing very large amounts of material that is less metal-deficient with respect to the initial abundances in the star forming region. We conclude that in order to explain stellar oxygen abundances below the mean value of [O/H] observed at a given age (see Fig. 5.1), mixing of gas with an underabundance of at least one order of magnitude relative to the ambient ISM would be required. Such mixing would imply infall (or accretion) of metal-deficient material and/or inefficient mixing of parcels of interstellar gas over extended periods of time during the lifetime of the disk.

We emphasize that the effect of adding more and more metal-deficient material to a star forming region strongly depends on the abundances within the diluting material. We illustrate this in Fig. 5.5 where we show the effect of mixing metal-poor material (with the lowest stellar abundance ratios observed, i.e. $[\text{Fe/H}] \sim -1$ and $[\text{O/H}] \sim -0.65$) to gas with the highest stellar abundance ratios observed (i.e. $[\text{Fe/H}]\sim -0.23$ and $[\text{O/H}]\sim -0.18$). Interestingly, the result of such dilution of the stellar abundances appears consistent with the mean $[\text{Fe/H}]$ vs. $[\text{O/H}]$ relation observed (see Fig. 5.11 below). As an example, Fig. 5.5 illustrates the maximum stellar abundance-abundance variations which may occur when metal-poor gas is mixed to the disk ISM. To this end, we consider a given mean $[P/H]$ vs. $[Q/H]$ evolution trajectory in the disk ISM for two elements P and Q (e.g. Fe and O). Fig. 5.5 shows the stellar abundance-abundance variations due to infall of metal-deficient gas for various metallicities. At a given ratio $[P/H]$, the separation between the abundance contour resulting from mixing metal-deficient gas and that the mean trajectory assumed in the

<table>
<thead>
<tr>
<th>$\delta M_H$</th>
<th>0.1</th>
<th>0.1</th>
<th>0.5</th>
<th>1</th>
<th>2</th>
<th>5</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_i$</td>
<td>0.0</td>
<td>0.04</td>
<td>-0.04</td>
<td>-0.02</td>
<td>0.0</td>
<td>+0.04</td>
<td>+0.14</td>
</tr>
<tr>
<td>0.5</td>
<td>-0.18</td>
<td>-0.16</td>
<td>-0.08</td>
<td>0.0</td>
<td>+0.13</td>
<td>+0.37</td>
<td>+0.60</td>
</tr>
<tr>
<td>1</td>
<td>-0.30</td>
<td>-0.26</td>
<td>-0.13</td>
<td>0.0</td>
<td>+0.18</td>
<td>+0.48</td>
<td>+0.74</td>
</tr>
<tr>
<td>10</td>
<td>-1.04</td>
<td>-0.74</td>
<td>-0.26</td>
<td>0.0</td>
<td>+0.28</td>
<td>+0.67</td>
<td>+0.91</td>
</tr>
</tbody>
</table>
disk ISM, is a measure for the stellar abundance variations expected. The characteristic shape of the infall contour is due to the fact that at high abundances, small amounts of metal-poor gas infall result in negligible abundance variations in the disk ISM.

As expected, the resulting stellar abundance variations due to metal-poor gas infall are relatively large when:
1) the infall abundance ratios \([P/Q]_{inf}\) that are far from the enrichment trajectory followed by the disk ISM, and 2) the abundance-ratios within the disk ISM are large (we assumed \([P/H]_{disk}=[Q/H]_{disk}=+0.3\)). In general, the theoretical abundance-abundance contours shown in Fig. 5.10 are inconsistent with the observations (see Fig. 5.1). This suggests that the abundance ratios within the infalling gas are usually close to the enrichment trajectory followed by the disk ISM and/or that metal-poor gas infall is not entirely responsible for the abundance variations observed among similarly aged stars in the SNBH.

The idea of large amounts of interstellar material with abundances considerably below the average abundances in the ISM may be difficult to reconcile with efficient mixing on time scales as short as \(\sim 10^7\) yr (see Sect. 5.5.3). However, infall of metal-deficient material onto the disk, and the initiation of star formation within this material before substantial mixing occurs, appears to be a more plausible possibility to explain the minimum \([O/H]\) abundance ratios observed among similarly aged stars in the SNBH. Note that this is true also for elements with mixing time scales in the disk ISM that are similar to the mixing time scale of oxygen. Observational evidence in support of such local infall of metal-deficient material onto the Galactic disk is discussed in Sect. 5.5.

**Figure 5.10** Abundance-abundance variations due to infall of metal-poor gas. The enrichment trajectory assumed the disk ISM is indicated by the *thick solid line*. Mean abundance ratios in the disk ISM of \([P/H]_{disk}=[Q/H]_{disk}=+0.3\) dex were assumed. Maximum variations of the stellar abundance ratios due to the infall (or accretion) of increasing amounts of metal-deficient material are shown as the *thin solid lines*, for various abundance ratios \([P/Q]_{inf}\) within the infalling material (indicated by *full dots*).

### B.2 Mixing of metal-rich material

Similar to the case of mixing metal-deficient material, stellar abundance variations of +0.3 dex can be achieved by adding enriched material with \(\beta_i \gtrsim 10\) and a mass of about 10% of total initial mass of the star forming region (cf. Table 5.5). Alternatively, variations of +0.3 dex can be explained also by mixing large amounts \((\delta_{\text{M, inf}} \sim 10)\) of moderately enriched material (e.g. \(\beta_i \gtrsim 2\)). Since efficient mixing in the disk ISM probably rules out the latter possibility (see Sect. 5.5.3), we will concentrate on abundance variations which are caused by adding small amounts of very metal-rich material to a star forming region. Such concentrations of metal-rich material are most readily produced within the ejecta of massive stars (observations pointing to sequential stellar enrichment in the local ISM are discussed in Sect. 5.5).

We examine the stellar abundance variations \(a_i\) that result from mixing the ejecta of massive stars to a star forming region. Table 5.6 lists the theoretical stellar yields, defined as the total element mass ejected by a star of initial mass \(m\), both for the progenitors of SNII, SNIa, and SNIb/c. For a detailed description of the yields we refer the reader to the references given in Table 2 and Chap. 3.

The final helium mass just before a star of initial mass \(m\) becomes a supernova is listed as \(m_{He, fin}\). We consider helium stars surrounded by hydrogen-rich envelopes as the immediate progenitors of SNII, and helium stars stripped off their hydrogen-rich envelopes as the progenitors of SNIb/c (see Woosley, Langer & Weaver 1994). These helium stars presumably leave a neutron star remnant of \(1.4\ M_\odot\). SNIa are assumed to originate from accreting and/or coagulating WDs in a binary system. SNIa leave no remnant as the WD is assumed to disrupt completely during the explosion. Typical amounts of iron produced are \(\sim 0.08\ M_\odot\) for SNII, \(\sim 0.8\ M_\odot\) for SNIa, and \(\sim 0.1\ M_\odot\) for SNIb/c (see Table 5.6).
Total oxygen and iron masses ejected by a star of initial mass $m$ with metallicity $Z = Z_\odot$ at birth are denoted by $\Delta M_{\text{O}}$ and $\Delta M_{\text{Fe}}$, respectively. Corresponding mean abundance ratios within the stellar ejecta (relative to solar) are given by $[\text{O}/\text{H}]_*$ and $[\text{Fe}/\text{H}]_*$ and are shown in Fig. 5.11. These were calculated assuming an initial hydrogen abundance $X = 0.68$ (cf. Anders & Grevesse 1989). In the last two columns of Table 5.6, we list the resulting abundance variations $\alpha_0$ and $\alpha_0$ when the ejecta of a star with initial mass $m$ are mixed to a gas cloud that has the same initial mass and abundances as the star. We note that the stellar abundance variations $\alpha_i$ are given relative to the abundances of the material out of which the progenitor star formed (cf. Eq. B1).

From Table 5.6 it can be seen that local enrichment of the ISM by SNII easily can account for abundance variations of $\alpha_0 \geq +0.3$ dex. However, in order to explain the mean $[\text{Fe}/\text{H}]_*$ vs. $[\text{O}/\text{H}]_*$ relation and to comply with the full range in $[\text{Fe}/\text{H}]_*$ and $[\text{O}/\text{H}]_*$ observed for F and G dwarfs in the SNBH (see Fig. 5.11), combined mixing of e.g. SNII and SNIa-ejecta as well as dilution of the star forming region by more metal-deficient material is required. We conclude from Table 5.6 that abundance variations of $\geq 0.6$ dex in $[\text{Fe}/\text{H}]_*$ and $[\text{O}/\text{H}]_*$ easily can be achieved by local enrichment from massive stars.

Figure 5.11 Theoretical abundances within SNII and SNI ejecta. Data are shown for SNII (triangles, Hashimoto et al. 1993), SNIa (open circles; Nomoto et al. 1984), and SNIb/c (filled squares; Woosley et al. 1993). Error bars for the SNIb/c abundances indicate the spread in the theoretical predictions due to the fact that a wide range in initial stellar mass $m$ may result in roughly the same helium star mass (which presumably is the immediate progenitor of SNIb/c; cf. Woosley, Langer & Weaver 1994). The mean $[\text{Fe}/\text{H}]_*$ vs. $[\text{O}/\text{H}]_*$ relation observed for F and G main-sequence dwarfs in the SNBH is shown as a solid line and has been extrapolated above $[\text{Fe}/\text{H}]_* \approx 0.2$ dex. For comparison, theoretical curves are drawn in case of: 1) enrichment by SNII only (—em dashed line), and 2) dilution by adding more and more metal-free material (thick dotted curve). Width and position of the horizontal line segments mark the range covered by the observational data (see also Fig. 5.1).

To estimate the typical abundances in the ejecta of an entire generation of stars, the stellar yields in Table 5.6 (corrected for initial stellar abundances) need to be integrated over the initial stellar mass range after weighing by the stellar mass function (IMF) as well as weighing by the relative contributions of SNII, SNIa and SNIb/c. For this reason, we show in Fig. 5.11 the resulting $[\text{Fe}/\text{H}]_*$ vs. $[\text{O}/\text{H}]_*$ relation for a stellar generation in case of enrichment by SNII only.

This relation was computed after weighing the SNII yields by an IMF with slope $\gamma = -2.35$ while assuming an upper SNII mass limit of $m_{\text{SNII}}^0 = 60 M_\odot$. The fact that the predicted relation drops substantially below that observed, clearly demonstrates that SNIa and/or SNIb/c are required to explain the observed abundance variations by means of sequential stellar enrichment. Although an extensive discussion of these IMF-weighed yields and relative contribution of SNII, SNIa, and SNIb/c on the resulting stellar abundance variations is beyond the scope of this paper, we give some examples below.

We estimate the effect of sequential enrichment on the relative abundances of two generations of stars, the second generation forming in part out of the material enriched by the first generation. For simplicity, we only consider the ejecta of SNII and compute the IMF integrated ($\gamma = -2.35$) stellar oxygen and iron yields for the first generation (assumed to have solar abundances initially). We assume that the enriched material returned by the first generation (formed with solar metallicity) is mixed homogeneously to a gas cloud (with initially solar abundances as well). Furthermore, we assume that the abundances in the enriched gas cloud are those available to the second stellar generation.

Resulting abundance differences $\alpha_i$ (see Eq. 1) between the two stellar generations are listed in Table 5.6 for various values of: 1) the cloud mass to which the stellar ejecta are mixed (defined by $M_{\text{cl}} = \vartheta M_*$, where $M_*$ is the total mass of gas initially converted into stars), 2) the upper mass limit $m_{\text{SNII}}^0$ of stars assumed to end as SNII, and 3) the least massive star $m_{\text{enr}}$ that is able to contribute to the enrichment of the gas cloud before cloud dispersal.
Table 5.5 Theoretical oxygen and iron yields of SNII and SNI (Z=Z⊙)

<table>
<thead>
<tr>
<th></th>
<th>( m )</th>
<th>( m_{1.5} )</th>
<th>( \Delta M_O )</th>
<th>( \Delta M_{Fe} )</th>
<th>( [O/H])</th>
<th>( [Fe/H])</th>
<th>( \alpha_O )</th>
<th>( \alpha_{Fe} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNII</td>
<td>10</td>
<td>2.5</td>
<td>0.15</td>
<td>0.02</td>
<td>+0.41</td>
<td>0.19</td>
<td>+0.20</td>
<td>+0.07</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>3.0</td>
<td>0.20</td>
<td>0.02</td>
<td>+0.67</td>
<td>0.21</td>
<td>+0.36</td>
<td>+0.09</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>4.0</td>
<td>0.20</td>
<td>0.02</td>
<td>+0.70</td>
<td>0.96</td>
<td>+0.41</td>
<td>+0.63</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>6.0</td>
<td>1.2</td>
<td>0.08</td>
<td>+1.03</td>
<td>0.67</td>
<td>+0.67</td>
<td>+0.38</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>16</td>
<td>3.8</td>
<td>0.3</td>
<td>+1.63</td>
<td>1.26</td>
<td>+0.95</td>
<td>+0.64</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>32</td>
<td>1.5</td>
<td>0.45</td>
<td>+1.16</td>
<td>1.34</td>
<td>+0.52</td>
<td>+0.67</td>
</tr>
<tr>
<td>SNIIa²</td>
<td>2.5</td>
<td>-</td>
<td>0.13</td>
<td>0.78</td>
<td>+0.46</td>
<td>1.98</td>
<td>+0.17</td>
<td>+0.54</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>-</td>
<td>0.13</td>
<td>0.78</td>
<td>+0.29</td>
<td>+1.80</td>
<td>+0.0</td>
<td>+0.34</td>
</tr>
<tr>
<td>SNIIb/c³</td>
<td>≥35</td>
<td>4</td>
<td>0.05</td>
<td>0.08</td>
<td>-0.75</td>
<td>0.15</td>
<td>-0.25</td>
<td>+0.04</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.18</td>
<td>0.13</td>
<td>-0.22</td>
<td>+0.37</td>
<td>-0.14</td>
<td>+0.18</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>0.44</td>
<td>0.16</td>
<td>+0.18</td>
<td>+0.49</td>
<td>+0.03</td>
<td>+0.23</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.79</td>
<td>0.12</td>
<td>+0.48</td>
<td>+0.33</td>
<td>+0.14</td>
<td>+0.15</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>0.91</td>
<td>0.14</td>
<td>+0.54</td>
<td>+0.53</td>
<td>+0.13</td>
<td>+0.19</td>
<td></td>
</tr>
</tbody>
</table>


Notes: (1) \( m_{1.5} \) refers to the pre-SN mass used in the SNII and SNIIb/c calculations. (2) Binary WD scenario (assumed initial mass of secondary: 5 M⊙). (3) \( \alpha_O \) and \( \alpha_{Fe} \) values for SNIIb/c have been calculated assuming \( m=35 \) M⊙.

It can be seen that the IMF-integrated stellar abundance variations given in Table 5.6 are considerably below the individual stellar abundance variations listed in Table 5.5. This is due to the metal-poor material returned by intermediate mass stars relative to that returned by individual massive stars. First, we verify from Table 6 that the resulting abundance variations in [O/H] are substantially larger than those in [Fe/H] (as expected for SNII ejecta). Thus, in order to explain observed variations in [O/H] smaller than those in [Fe/H] by means of sequential enrichment, SNIIa and/or SNIIb/c nucleo-synthesis products are required.

Secondly, for a given combination of \( m_{0}^{SNII} \) and \( m_{ent} \), it can be seen that abundance variations \( \alpha_O \) and \( \alpha_{Fe} \) rapidly increase with decreasing cloud masses to which the stellar ejecta are mixed (i.e. decreasing values of \( \vartheta \)). Consequently, an abundance variation of \( \sim 0.6 \) dex in [O/H] due to sequential enrichment alone probably excludes values of \( \vartheta \geq 0.15 \).

Thirdly, for a given combination of \( \vartheta \) and \( m_{ent} \), abundance variations rapidly increase with \( m_{0}^{SNII} \) (this effect is more pronounced for oxygen; cf. Table 5.5). We assumed that stars more massive than \( m_{0}^{SNII} \) do not explode as supernova but presumably end as black hole (e.g. Maeder 1992). Consequently, such stars contribute to the ISM enrichment during their stellar wind phase only. However, even though such stars probably do not participate in the iron enrichment of the ISM, they still may affect the interstellar [Fe/H] abundance ratio by means of the amounts of hydrogen they consume. This is reflected by the abundance variations found in case \( m_{ent} \gtrsim m_{0}^{SNII} \) (cf. Table 5.6). Finally, we find that for a given combination of \( \vartheta \) and \( m_{0}^{SNII} \), the stellar abundance variations are relatively insensitive to \( m_{ent} \) except for values of \( m_{ent} \gtrsim 25 \) M⊙.

The abundance variations listed in Table 5.6 will be substantially larger in case of initial stellar abundances much below solar provided that element yields for SNII are insensitive to the initial abundances of their progenitors (see Sect. 3.3). In contrast, these abundance variations will be substantially reduced in case of partial mixing of the enriched stellar ejecta (i.e. \( \lambda < 1 \), see above) and/or when a steeper IMF towards low mass stars is considered. We note that the critical stellar mass \( m_{ent} \) able to enrich the dispersed cloud material, can be roughly related to the dispersal time of the star forming region using a theoretical main-sequence turn-off-mass vs. stellar age relation. In this manner, \( m_{ent} = 12, 15, 25, \) and \( 40 \) M⊙, approximately corresponds to sequential enrichment times of \( t_{disp} \sim 2 \times 10^7, 10^7, 7 \times 10^6, \) and \( 4 \times 10^6 \) yr, respectively (for stars formed with solar abundances; see Schaller et al. 1992). Cloud dispersal times \( t_{disp} \gtrsim 10^7 \) Gyr, equivalent with \( m_{ent} \lesssim 15 \) M⊙, are probably not supported by the observations (Sect. 5.5.2).

An argument often proposed against sequential stellar enrichment as explanation for the observed stellar abundance variations is based on inefficient mixing of the nucleo-synthesis products from different types of supernovae (e.g. in the case of mixing of the ejecta of SNII and SNIIa that are associated with the one and the same stellar generation). This argument is primarily based on the different enrichment time scales for SNII and SNIIa (e.g Gilmore & Wyse 1991; Edvardsson et al. 1993) and states that in case of sequential stellar enrichment during a local burst of star formation, variations in e.g. [O/H] (predominantly
caused by SNII) are expected to be larger than those in [Fe/H] (which in part originate from SNIa). This is exactly the opposite to what is observed as the data provided by Edvardsson et al. (1993) suggest that different nucleosynthesis sites mixed their products together well (cf. Fig. 5.1).

However, apart from the uncertainties still involved with the enrichment time scales of SNII and SNIa, the effects of sequential stellar enrichment on abundance variations in the ISM heavily depend on the integrated, IMF-weighted stellar yields (i.e. are determined by the contributions of different types of SNe). First, SNII ejecta (in addition to that of SNIa) may help (and in fact may be required) to explain the observed variations in [Fe/H] relative to those in [O/H] (see Fig. 5.11). Compared to models which account for the enrichment by SNII only, the main effect of the inclusion of SNII ejecta is an enhancement of the iron enrichment. This results in a corresponding shift of the [Fe/H] vs. [O/H] relation and improves the agreement with the observations, in particular at solar abundances. Secondly, stellar abundance variations observed for elements such as Fe still may be explained by the IMF-weighted element contributions of SNII in spite of the fact that such elements are efficiently produced by SNIa (see Sect. 3.4). Thirdly, and probably most important, the effect of sequential enrichment on the stellar abundance variations for individual elements is strongly affected by the abundances in the ambient ISM to which the stellar ejecta are actually mixed. Thus, even though sequential stellar enrichment alone seems to be ruled out by theoretical arguments as the full explanation for the observed stellar abundance variations, the extent to which sequential enrichment may contribute to these variations strongly depends on both the details of the stellar enrichment process and the chemical evolution of the ambient ISM. This allows for an explanation of the observed stellar abundance variations in terms of combined sequential stellar enrichment and metal-deficient gas infall as discussed in Sect. 5.4.4.

We conclude that infall of metal-deficient material and/or sequential stellar enrichment provide plausible mechanisms to explain (in part) the observed stellar abundance variations among similarly aged stars in the SNBH. It is evident that a more quantitative investigation, of the effects of these processes on the stellar abundance variations, relies on the detailed chemical evolution of the disk ISM and on the typical time scales during which abundance inhomogeneities in the local disk ISM can exist (see Sect. 5.4).

---

**Table 5.6** Theoretical abundance variations $\alpha_0$ and $\alpha_{Fe}$ in case of sequential enrichment by SNII

<table>
<thead>
<tr>
<th>$\vartheta$</th>
<th>$m_{\text{SNII}} = 60$</th>
<th>$m_{\text{SNII}} = 40$</th>
<th>$m_{\text{SNII}} = 25$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$12$</td>
<td>$15$</td>
<td>$25$</td>
</tr>
<tr>
<td>OX</td>
<td>0.01</td>
<td>1.05</td>
<td>1.12</td>
</tr>
<tr>
<td></td>
<td>0.05</td>
<td>0.84</td>
<td>0.87</td>
</tr>
<tr>
<td></td>
<td>0.1</td>
<td>0.69</td>
<td>0.70</td>
</tr>
<tr>
<td></td>
<td>0.2</td>
<td>0.52</td>
<td>0.52</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>0.31</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>0.19</td>
<td>0.18</td>
</tr>
<tr>
<td>Fe</td>
<td>0.01</td>
<td>0.79</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>0.05</td>
<td>0.61</td>
<td>0.58</td>
</tr>
<tr>
<td></td>
<td>0.1</td>
<td>0.48</td>
<td>0.44</td>
</tr>
<tr>
<td></td>
<td>0.2</td>
<td>0.33</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>0.19</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>0.11</td>
<td>0.09</td>
</tr>
</tbody>
</table>