On the chemical and spectro-photometric evolution of nearby galaxies

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Star formation in galaxies: local and global processes in the ISM

Abstract

We briefly consider several observational and theoretical concepts of local and global star formation in galaxies. This chapter is meant as a brief introduction to the subject and highlights some of the basic assumptions and ingredients in the theoretical description of the process of star formation in galaxies.

2.1 Introduction

The underlying physics and mechanisms that determine the process of star formation in galaxies comprise one of the most fundamental problems involved in galactic evolution studies. We here briefly discuss several observational and theoretical aspects of local and global star formation processes. In particular, we consider the complex nature of the formation of protostars in molecular clouds and make a connection with some of the basic ideas concerning the overall process of star formation in galaxies.

2.2 Star formation in the local disk ISM

Molecular clouds are observed to be the birth sites of all stars nowadays formed in the Galactic disk as well as in other nearby galaxies. Individual molecular clouds (MCs) are thought to form by contraction and accumulation of atomic hydrogen clouds. Molecular cloud complexes may then be built from the coalescence of several giant MCs. The largest MC complexes in the Galactic disk (kpc scales, \(\approx 10^7 \text{ to } 10^8 \, M_\odot\)) are observed to contain several giant MCs (\(10^2 \text{ pc}, 10^4 \, M_\odot\)). These giant MCs often include smaller clouds (\(\approx 1 \text{ to } 10 \, \text{ pc}, 10^2 \text{ to } 10^3 \, M_\odot\)) which in turn may contain dense and compact cloud cores \(\approx 0.1 \, \text{ pc}, 1 \text{ to } 10 \, M_\odot\). Stars are observed to form only in these compact molecular cloud cores (e.g. Myers et al. 1987).

A young radiating star may be observed as a far-infrared source when still embedded in its opaque parent MC. If the star's ionizing flux is sufficiently high, the parent MC will be associated with an extended HII region surrounding the star. Extended far-infrared (FIR) and CO surveys (e.g. Scoville et al. 1987; Myers et al. 1987) have shown that the Galactic disk contains at least two distinct populations of MCs (Lo et al. 1987): 1) warm, giant MCs (\(T\approx 50 \text{ to } 200 \, \text{ K}\); e.g. OMC1 in Orion) which are mainly observed in the spiral arm regions and wherein preferentially massive O and B stars are formed, and 2) cold, small MCs (\(T\approx 20 \text{ to } 40 \, \text{ K}\); B227 cloud) which are found throughout the Galactic disk and usually do not contain stars earlier in spectral type than late type B. The Orion Nebula is one of the nearest regions of recent star formation in the Galaxy. The youngest stars in this giant MC at a distance of about 450 pc are about 3 \(10^5\) yr old (e.g. Zinnecker 1993).

Nearly all HII regions present in the CO and FIR studied parts of the Galaxy are found to be associated with giant, warm MCs (e.g. Myers 1986). Exceptionally, there are giant MCs which do not show evidence for the formation of OB stars (Myers et al. 1987). This suggests that the star formation process in MCs is stimulated under specific local conditions both in time and space. For instance, CO-observations of MCs in the Galactic disk reveal that massive stars form preferentially in the cores of MCs (e.g. Grabelsky et al. 1987; Larson 1991). In most HII regions, massive stars do not appear alone but are usually accompanied by a cluster of low-mass pre-main-sequence stars. Evidence for high-mass star formation without accompanying low-mass star formation are very rare (Zinnecker 1993). In contrast, there are many sites of low-mass star formation without associated high-mass star formation. The preponderance of small, low-mass MCs without HII regions indicates that massive stars tend to be absent in such MCs (Myers 1977; Waller et al. 1987).
The observations above suggest that: 1) the mechanism underlying the formation of the cores and large-scale structures in MCs must play a fundamental role in the physics of star formation (Lada et al. 1993), 2) the conditions of MCs which form solely low-mass stars are very different from MCs that form high-mass stars (e.g. Cernicharo 1992), and 3) star formation is probably a self-regulated process of which the efficiency depends on the efficiencies of cloud formation, of processes initiating star formation, and of cloud destruction mechanisms (Lada et al. 1993).

- **Bimodal star formation and other concepts**

The concept of bimodal star formation is based on the observed duality in the birth sites of stars of different mass (see review Shu et al. 1993). The decoupling of low and high-mass star formation originates from Herbig (1962) who proposed that low-mass stars form continuously over an extended period, interrupted only by the relatively rapid formation of high-mass stars (see below). These massive stars presumably heat, ionize, and disrupt the parental MC, preventing further star formation (e.g. Grabelsky et al. 1987; see also Larson 1988).

Observational studies from Leisawitz (1985; see also Larson 1988) show that remnant molecular cloud fragments are detected mainly around clusters of stars older than ~ 5 10^6 yr. These results are consistent with that of Garmany, Conti & Chiosi (1982) who found cloud dispersal times of a few 10^6 yr based on a comparison of evolutionary tracks for massive stars (m \gtrsim 20 M_\odot) that just appear as visible objects. The violence of massive star formation which may lead to dissipation of the remaining molecular material (e.g. by means of supersonic winds, ionization driven shock fronts, and/or supernova explosions), supports the idea of temporal variations in the star formation process. In case of bimodal star formation, such variations may differ for stars differing in mass.

In contrast to the suppression of star formation, massive OB-stars from a preceding star formation event nearby may also trigger the formation of a new generation of massive stars (i.e. sequential star formation). Although the majority of clusters of pre-main-sequence stars associated with OB stars appear to form from the dense gas concentrations in the cores of MCs, it appears that some clusters owe their origin to activity in the ISM associated with pre-existing generations of massive stars (e.g. Elmegreen 1989; Blaauw 1991; Massey et al. 1995). In several cases, multiple daughter star formation sites appear to originate from one parent site of star formation (cf. Zinnecker 1993; Goldsmith 1995). This addresses the concept of spontaneous vs. induced high-mass star formation in the Galactic disk ISM. Other examples of induced star formation include star clusters which are formed during the impact of a high-velocity cloud with the Galactic disk ISM (e.g. in case of the majority of the open clusters in the Perseus spiral arm, cf. Phelps 1993; see also Sect. 5.5.2). The process of infall induced star formation is common in the Galactic disk (e.g. Lépine & Duvert 1994; see Chap. 5) and may be the dominant mode of star formation in galaxies in which low surface densities inhibit global star formation (see Chap. 6).

In addition to the concepts of bimodal star formation and spontaneous/induced star formation, recent observations indicate two main star formation modes (Lada, Strom, and Myers 1993): 1) an isolated star formation mode in which single stars (or binaries) form from the individual gravitational collapse of small, isolated cores distributed throughout a MC (typically 0.3 stars pc^-2), and 2) a clustered mode of star formation in which rich clusters of stars form more or less simultaneously from a single massive concentration of dense gas, not in an isolated environment but in a densely packed one (e.g. 50 stars pc^-2). Observations show that the clustered mode is the dominant mode of star formation in several giant MCs in the Galactic disk. Clearly, the physical conditions in the massive MC cores producing rich clusters of stars are expected to be different from those in isolated MC cores forming single stars, e.g. in terms of star formation efficiency, stellar mass function at birth (see below), and star formation rate. A discussion of these conditions is beyond our scope. Instead, we consider in some detail the basic idea of star formation by fragmentation of MC clumps.

- **Fragmentation**

Fragmentation seems a plausible mechanism for the formation of stars in MCs (Spitzer 1978; Downes et al. 1987; Larson 1988). Gravitational instabilities in a homogeneous gas in pressure equilibrium will occur for cloud masses larger than the critical mass for gravitational collapse according to the Jeans criterion (cf. Spitzer 1978):

\[
M_c > M_J \equiv \left( \frac{\pi k T}{\mu m_c^2} \right)^{3/2} \frac{1}{\rho_0^{1/2}} \approx \frac{0.03 T^{1/4}}{\mu/m_{H}} \rho_0^{-3/4} \quad [M_{\odot}] \tag{2.1}
\]

where \( T \) is the cloud kinetic temperature, \( \mu \) the mean mass per particle, and \( \rho_0 \) the unperturbed, homogeneous cloud density (\( k \) and \( G \) are the Boltzmann and the gravitational constant, respectively, and \( m_{H} \)
denotes the mass of a hydrogen atom). Due to the self gravitation of the denser gas regions, gravitational instabilities may grow and protostars are likely to form. With $t_f$ the free-fall time of a homogeneous sphere (defined as the time for a particle to travel halfway to the gravitational center of a spherical system) with mean density $\rho_0$ (and $n_H$ the hydrogen number density in the cloud):

$$t_f = \left( \frac{3\pi}{32G\rho_0} \right)^{1/2} \approx \frac{4.3 \times 10^7}{n_H(0)} \text{ yr} \quad (2.2)$$

one expects the densest regions to collapse at the shortest free-fall times. Usually, the free-fall time in a homogeneous, spherical MC is longer than the timescale for thermal adjustment (see Kippenhahn & Weigert 1994) so that the collapse proceeds almost isothermal. The collapse of the homogeneous central part of the cloud resembles free-fall as long as the matter can release gravitational energy via radiation. For isothermal collapse, the Jeans mass decreases with $\rho^{-1/2}$ (Eq. 2.1). During the collapse, the free-fall time becomes shorter as the density increases (Eq. 2.2). When the gas becomes opaque and $T$ increases, pressure becomes important and the cloud collapse is halted.

Only cloud masses large compared to stellar masses can become gravitationally unstable. A gas cloud exceeding the Jeans mass, collapses and undergoes fragmentation: cloud fragments become unstable and collapse faster than the cloud as a whole. The result is that for a collapsing cloud with mass $M_\text{cl} \gtrsim M_J$, increasingly smaller and less massive gravitational condensations become the precursors of protostars with subsequently smaller masses. This is the basic idea of opacity-limited fragmentation. As discussed above, this kind of fragmentation can go on as long as the collapse remains roughly isothermal. Fragmentation stops approximately when the gas becomes so opaque that the radiative cooling time becomes longer than the free-fall time (Downes 1987).

The fragmentation scenario roughly explains the observed mass limits of stars (i.e. between $\sim 0.1$ and $60-120 \, M_\odot$; e.g. Scalco 1986) according to the gas densities and temperatures in MCs (e.g. Spitzer 1978). Stars with masses as large as $\sim 10^3 \, M_\odot$ do not form, because fragmentation will occur during the extremely slow collapse of such low-density, high-mass concentrations. From estimates of the thermal adjustment time scale, fragmentation ends when the Jeans mass of the fragments are of the order of $0.1-0.5 \, M_\odot$ (see Kippenhahn and Weigert 1994). Fragmentation appears the most probable, although incomplete, concept for star formation in MCs. The reverse process whereby massive stars would form by coalescence of low-mass protostars is (as is the case for the formation of entire galaxies) rather unlikely since in that case the narrow range in stellar mass observed would be hard to explain.

The observational fact that massive stars are formed predominantly in giant MCs while the formation of low-mass stars in such clouds appears inhibited is in the view of fragmentation explained by heating, ionization, and radiation pressure associated with the first generations of high-mass stars formed. However, we recall that opacity-limited fragmentation may be an oversimplified picture since e.g. magnetic fields (support of MCs against their self-gravity), cloud rotation, and turbulent velocities may affect the star formation process in MCs as well (e.g. Shu et al. 1993).

### 2.3 Global star formation in galaxies

A first step towards understanding the gas-star cycle in galaxies is to consider the impact of the different formation and evolutionary histories of low and high-mass stars (as well as their element yields and stellar remnants) on galactic chemical evolution (Dopita 1990). High and low-mass ($m \lesssim 1-2 \, M_\odot$) stars may be formed in different environments (see above). This may constrain theories of the history of the star formation rate (SFR) in galaxies. The formation of low-mass stars (e.g. $m \lesssim 1 \, M_\odot$) in galaxies may be primarily related to the gas surface density $\Sigma_g$ according to a Schmidt (1959) like variation of the SFR: $\propto \Sigma_g^n$ (with $n = 1-2$; see also Caimmi 1995). The formation of high-mass stars in galaxies may be related to the total (both gas and stellar) surface density (see e.g. Dopita 1990; Dopita & Ryder 1994) which results in a SFR depending both on the total surface density and surface density of the gas.

Since most stellar mass is contained in low-mass stars ($m \lesssim 1 \, M_\odot$; see below) one may expect that the formation of such stars is associated with the dominant mode of star formation in galaxies. The concept of a critical minimum gas density, i.e. a 'star formation threshold', below which star formation cannot take place may play a key-role in the onset of star formation in galaxies (e.g. Kennicutt 1983). This may apply both to the low-mass and relatively high-mass star formation modes in galaxies although the threshold for massive star formation may require e.g. considerable higher gas densities and larger MC masses. In principle, the star formation threshold is implicitly included in models in which the SFR strongly depends on the local gas density. To explain an important high-mass mode of star formation, additional conditions may be required such as the presence of a deep gravitational well associated with a pre-existing stellar population, e.g.
concentrated in the galactic nucleus and spiral arms. This would trigger efficient star formation of massive stars in the densest regions of galaxies until the gas is exhausted. Such gravitational instabilities stimulating massive star formation may be associated also with local gas infall and/or tidal interactions/merging between galaxies.

A star formation law in disk galaxies based on the assumption that the pressure in the ISM is determined by the energetic processes associated both with star formation and the older stellar populations has been derived by Dopita (1985). In this case, the process of star formation pressurizes the ISM and provides a self-regulating feedback on subsequent star formation. The vertical velocity dispersion of the gas is assumed to be the result of the dynamic balance between the energy input by massive and intermediate mass stars and the energy dissipation by cloud-cloud collisions in the disk. This assumption is shown to lead to the prediction that gas-rich disk galaxies have a SFR proportional to the product of the total galaxy mass and the surface density of the gas (Dopita 1985). In this case, the SFR decreases exponentially with age in a given galaxy on a time scale determined by the gas depletion time scale (depending on gas consumption by star formation and infall/accretion of gas) and a pressure equipartition time scale (depending on the pressure supported by star formation and e.g. SNe associated with older stellar populations). Local over-pressure results in enhanced star formation and leads to a stochastic, self-propagating SFR. This model is consistent with a number of observations as discussed by Dopita (1985, 1990), Russell & Dopita (1992), and Dopita & Ryder (1994) and probably is the most successful model for star formation in galaxies currently available.

Models in which the SFR is regulated by the gas density in the disk as determined by the time scale of gas infall and the time of gas consumption (e.g. Clayton 1985) are more difficult to relate to the local properties of the star-forming ISM, but provide very similar results to the Dopita SFR model and are as successful as the Dopita SFR model in reproducing the observations. In both models, the SFR is basically described by two time scales. However, none of the SFR models so far available deal with the probably different formation sites of low and high-mass stars or the isolated/clustered modes of star formation suggested by the observations. Furthermore, it appears more natural to have a theory which can explain the variation of the SFR with age and the mass spectrum with which stars are formed both at the same time. The usual distinction between the variation of the SFR with age and the stellar mass spectrum at birth seems not justified by the observations and theories which couple these quantities probably will improve our understanding of the complex process of star formation in galaxies.

2.4 The stellar mass function at birth

The stellar mass function at birth is a fundamental ingredient of theories of star formation: it is the essential link between the small-scale processes leading to star formation and the overall properties of entire stellar populations in galaxies. The so-called initial mass function (IMF) provides detailed information about the relative formation probability of stars of a given mass (averaged over the lifetime of the star forming system that is considered). We will deal with the IMF in more detail in Sect. 4.3.1. Here we will restrict ourselves to several relevant observations concerning the IMF of stars formed in the local Galactic disk and emphasize the importance of the IMF for galactic evolution studies.

The empirical IMF peaks at both 1.2 and ~3 $M_\odot$ (Scalo 1986) and roughly follows a power law $dN/dm \propto m^{-7}$ with slope 2.35 (i.e. the Salpeter (1955) IMF) for stars more massive than ~2–3 $M_\odot$. The detailed variation of the IMF at low masses ($m \lesssim 2–3 M_\odot$) is not very well known. It may either continue to increase or it may flatten towards low-mass stars. Observations over the past decade suggest that the slope of the mass spectrum for less massive stars down to $m \sim 0.08$ $M_\odot$ is much flatter, with slopes $\gamma \lesssim 1.3$ (e.g. Scalo 1986). For convenience, it is usually assumed in galactic evolution studies that the masses of stars at birth are simply distributed according to the Salpeter IMF over the entire mass range. As we will show in Sects. 4.3.1–4, the slope of the mass function at low masses (i.e. $m \lesssim 1 M_\odot$) and the lower mass limit of stars at birth have very important implications for Galactic chemical evolution.

Recently, one of the smallest stars in the Galaxy, G1623b, has been observed with the refurbished HST. Its luminosity is about $6 \times 10^{-4}$ times fainter than the Sun and its estimated mass is about 0.1 $M_\odot$. G1623b is the smaller component of a double star system with an orbital separation of about 3 $10^8$ km. Hubble observations suggest that these low-mass stars are surprisingly rare and certainly do not belong to the most numerous stars in the Galaxy (e.g. Barbieri 1994; see also Tinney 1993). Objects in the mass range 0.04–0.1 $M_\odot$ have been suggested to exist in significant numbers in regions associated with the Pleiades (Hambly & Jameson 1991; Simons & Becklin 1992), although large uncertainties are involved (see e.g. Zinnecker 1993).

There are several indications that the stellar lower mass limit at birth may vary in different galactic environments (Silk 1987). When the origin of the IMF and stellar mass limits at birth are described in terms of the distribution of suprathermal linewidths in MCs (Silk 1995; line widths are generated by protostellar
The stellar mass function at birth

Outflows which are responsible also for limiting the mass that is accreted by a forming star; see also Adams & Fatuzzo 1996) such variations can be explained naturally. For instance, there is accumulating evidence that starburst galaxies are forming exclusively massive stars and that very few low-mass stars are formed in such systems (e.g. Rieke et al. 1985; Larson 1986; Silk 1987; Doane & Mathews 1993). This may be due to a shift of the lower mass limit towards masses as large as $\sim2-3$ $M_\odot$ (note that at these masses the IMF of stars in the Galactic disk peaks). In particular, the lower mass limit will be extremely sensitive to the gas temperature according to the Jeans criterion (Eq. 2.1).

Figure 2.1 Empirical mass function of M dwarfs in the Galaxy obtained with HST images. Stellar mass decreases from left to right. Figure adopted from Gould, Bahcall, and Flynn (1996).

Recently, the IMF of M dwarfs in the Galactic disk has been derived by Gould, Bahcall, and Flynn (1996; see Fig. 2.1) using observational data for 257 M dwarfs ($8 \lesssim M_V [\text{mag}] \lesssim 18.3$) detected in HST images after its first service. These observations reveal that the disk luminosity function of M dwarfs drops strongly for $M_V > 12$ mag ($m \lesssim 0.25 M_\odot$) and decreases by a factor $\gtrsim 3$ by $M_V \sim 14$ mag ($m \sim 0.14 M_\odot$). The derived mass function appears to peak at $\sim 0.23$ $M_\odot$ for a linear mass function $dN/dm$ (cf. Fig. 2.1). The slope of the observed mass function at 1 $M_\odot$ is about $-2.33$ which is close to Salpeter. The rise of the mass function of the M dwarfs with the lowest masses detected is suggestive but without statistical significance (see Gould et al. 1996). The M dwarfs with $0.1 \lesssim m \lesssim 1.6$ appear to have characteristics intermediate to that of thin disk and spheroid populations while the estimated scale length of the M stars detected is $3\pm0.4$ kpc.

Gould et al. state that a Salpeter IMF for M stars with $M_V \gtrsim 8$ mag is ruled out at the 12$\sigma$ level by the HST images. Furthermore, they emphasize that the behaviour of the observed decrease in the luminosity function of M dwarfs is in good agreement with the ground-based photometry studies of nearby stars by Stobie et al. (1989). If the observed mass function of M dwarfs is not affected by selection effects, statistical incompleteness, or uncertainties in the mass-luminosity relation for these low-mass stars (which may e.g. depend on initial metallicity, stellar age, or other stellar quantities) and if all low-mass stars ever formed in the Galactic disk have been formed according to the same mass function, these observations exclude a Salpeter-like IMF or Scalo IMF. However, it is in particular unclear if and how corrections for vertical stellar orbital diffusion (escape of stars to larger scale lengths) have been applied.

We will argue in Sect. 4.3.4 that if the IMF decreases for stars with masses less than $\sim 0.25 M_\odot$, as is suggested by the HST observations reported by Gould et al., there would be a severe overproduction of heavy elements in the Galactic disk ISM due to the enhanced formation probability of stars with masses $\gtrsim 1 M_\odot$ as compared to the Salpeter IMF. To convert $\sim 90\%$ of the disk ISM into stars by star formation over the lifetime of the Galactic disk (as suggested by the observations), low-mass stars which lock up ISM for times long compared to the lifetime of the Galaxy must be formed in sufficiently high numbers. For the IMF shown in Fig. 2.1, combined with the Salpeter IMF for more massive stars, the gas consumption argument would imply that too many massive stars are formed over the lifetime of the Galactic disk. Consequently, substantial over-enrichment of the disk ISM would be the result (according to the stellar yields described in Sect. 3.3). Thus, there would be no way to explain the present-day abundances observed in the ISM by means of such strongly decreasing IMFs towards low-mass stars.
Although a detailed investigation of the present-day ISM abundances as constraint to the IMF for low-mass stars is beyond the scope of this section, the above example illustrates that there is not much freedom for a strongly decreasing IMF towards low-mass stars. This may imply that: 1) not all long-living stars are formed according to the mass function implied by the M dwarf observations, i.e. a distinct IMF for stars of a given mass differing in properties other than initial mass (e.g. metallicity, galactic age at which the star is born, ISM conditions of the parent MC, etc.). 2) not all stars are formed according to the same star formation history (i.e. a bimodal SFR; stars are formed with rates depending on e.g. initial mass; see above). A stellar mass function varying with galactic age would be an convenient theoretical description of these possibilities. For instance, when the upper stellar mass limit at birth $m_u$ at early epochs in the evolution of the Galaxy would be considerably smaller (e.g. $m_u \sim 8 \, M_\odot$) than indicated by the observations ($m_u \sim 60-120 \, M_\odot$; e.g. Scalo 1986; Kroupa et al. 1993), this would avoid the overproduction of heavy elements discussed earlier. The above example illustrates that variations in the stellar mass limits at birth (or in the slope of the IMF) with galactic age may solve the inconsistencies implied by the HST observations.

Cameron (1962) was among the first ones to suggest that the IMF of the stellar generations formed at the time of onset of star formation in the Galaxy may have been very different from the present-day mass function of stars at birth (e.g. Salpeter's IMF). Since stars with masses $m \lesssim 0.9 \, M_\odot$ are the only ones still around from the very metal-poor stars formed at the early epoch of star formation in the Galaxy, no detailed information is available on the formation history of more massive stars during these epochs. In particular, present-day observations cannot exclude the possibility that the formation of massive stars was suppressed at early Galactic evolution times. As we will discuss in Sect. 4.3.4, the abundance-abundance relations observed among Galactic halo stars cannot provide detailed tests for the IMF of stars more massive than $\sim 1 \, M_\odot$. Although massive stars must have been formed in substantial numbers to enrich the star forming ISM during early Galactic evolution, a small population of massive stars would be sufficient to enrich the disk ISM up to the level of enrichment observed in the most metal-poor disk stars (e.g. $[Fe/H] \lesssim -1.2$). This is true in particular if the disk built up gradually (by accretion and accumulation of material e.g. from the Galactic halo) so that the injection of relatively small amounts of heavy elements would enrich the disk ISM efficiently.

If the SFR is mainly regulated by the local gas density, one may expect that the mass spectrum of stars is sensitive to the gas density as well. For instance, the formation of massive stars could be suppressed in relatively low-density regions in the ISM. In this scenario, the formation of massive stars would be favoured towards later epochs in the evolution of the disk provided that the gas density in the plane of the disk increases with age (i.e. gas infall/accretion exceeds the amount of gas consumed by star formation). Clearly, this would have important consequences for the chemical enrichment of the disk ISM. Instead of variations in the stellar mass function at birth with Galactic age, similar effects on Galactic chemical evolution could be achieved e.g. by variations in the upper mass limit of stars that eject a substantial fraction of the enriched material exterior of their iron core (i.e. by supernova explosions). Such variations may be expected if the detailed explosion mechanism of massive stars depends on e.g. the initial stellar metallicity (see Sect. 3.3.3). We note that the effects of an age-dependent IMF on Galactic chemical evolution heavily depends on the manner in which infall regulates the gas reservoir in the disk as well as the rate of star formation therein.

In the following, we will restrict ourselves mainly to the assumption of a Salpeter or Scalo mass function for stars at birth independent of Galactic age. Nevertheless, we found it worth to consider the possibility that the IMF at low masses may have varied as indicated by the HST observations as well as to address the possible implications this may have for the chemical enrichment and star formation history of the Galaxy.
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