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INFLOW OF GAS TO THE SOLAR NEIGHBORHOOD DURING EVOLUTION OF THE GALACTIC DISK

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ABSTRACT

We discuss several lines of evidence indicating that gas is flowing into the solar neighborhood and go on to offer a theoretical framework to explain this phenomenon, which is important for any model of the chemical and dynamical evolution of the Galaxy. We derive a theoretical age distribution for the G dwarf stars in the solar neighborhood that fits well the distribution observed recently in the generally increasing trend of the amplitude of oscillation with time, leading to star formation peaks at several epochs. Our model is based on the interference between two effects: the variable rate of gas inflow to the solar vicinity due to the density wave pattern in the disk, and the arrival of gas from the local intergalactic medium broken cyclically by star formation processes. The model is shown to be consistent with a scenario in which low-metallicity gas falls continually to the Galactic plane from the intergalactic medium, notably in the form of high-velocity clouds.

Subject headings: Galaxy: abundances — Galaxy: disk — Galaxy: evolution — solar neighborhood

1. INTRODUCTION

In this article we present the evidence that inflow of gas, and notably inflow of relatively metal-poor gas to the solar neighborhood, has been of importance on timescales commensurate with that of the evolution of the disk of the Galaxy. With this aim, we identify and quantify five different types of observations, which lead us to conclude that inflow has played a significant role in the evolution of the disk.

The first in our list, and indeed the first to be recognized, is the now classical G dwarf problem (Tinsley 1980; Pagel 1987). Excluding halo stars for the purpose of simplifying parameters, the statistics of disk stars in a frequency-metallicity diagram, using [Fe/H] as a convenient metallicity parameter (similar considerations would apply for other such parameters), show very low numbers for low disk metallicity ([Fe/H] ≤ -1), rising sharply to a relatively narrow peak between [Fe/H] $\simeq -0.6$ and [Fe/H] $\simeq -0.2$ and then falling off to higher metallicities (Carney, Latham, & Laird 1990; Rocha-Pinto & Maciel 1996). This is explicable naturally in a scenario that includes infall of low-metallicity gas to the Galactic plane (Casuso & Beckman 1997).

The second piece of evidence is the "fold-back" in the plot of the solar neighborhood beryllium abundance versus the iron metallicity, as the latter rises through the solar value (for a compilation of the relevant data, see Casuso & Beckman 1997). This behavior can be derived as a natural corollary of an approximately constant [Fe/H] in recent epochs, due to low-metallicity infall, within "classical" spallation production models for ^{9}Be.

The fact that the Fe metallicity has been approximately constant during the past 5 Gyr does fit the best estimates of metallicity versus age for a wide variety of stellar sources in the solar vicinity (Twarog 1986; Meusinger, Reimann, & Stecklum 1991). This, together with the recent high star formation rate (SFR) of the past 5 Gyr observed by Rocha-Pinto et al. (2000) and Barry (1988), implies the necessity of arrival of gas with low metallicity to counteract the natural production of Fe in star formation processes. In the closed-box model (without any infall), one obtains a natural decrease of the SFR with time as a result of the consumption of fuel (H I gas), so that this type of model is not consistent with the data from Rocha-Pinto et al. (2000) and Barry (1988).

Using a number of indices including iron, Fitzpatrick (1996) showed that the observed metallicity in 30 interstellar clouds near the Sun takes subsolar values. This is especially significant in the case of zinc, for which depletion onto grains is expected to be minimal, but the general result applies to six elements measured (Si, Zn, Fe, Cr, Ti, and Mn) for which the best possible estimates of the depletion correction were applied. There may well be alternative explanations for these results, but the scenario of low-metallicity infall certainly offers an adequate framework in which to interpret them.

Another piece of evidence favoring the hypothesis of infall, related to the first and to the main topic of this paper, is the age distribution of late F and G dwarfs in the solar neighborhood. This type of study was initiated by Vaughan & Preston (1980), who related mean chromospheric activity to age, calibrating via open clusters. In studies of increasing detail, Barry (1988) and Rocha-Pinto et al. (2000) found evidence of an almost constant mean value for the net star formation rate as a function of time, on which are superposed variations of considerable amplitude. These results, notably the fact that the SFR does not decline with time, require a source of gas that conforms both qualitatively and quantitatively with the hypothesis of infall to the Galactic disk.

We can tie together the observational considerations numerically as follows: A chemical evolution model for the solar cylinder that accounts well for the evolution with time of the most commonly observed metals, and also for that of the light-element abundances (Casuso & Beckman 1997, 1999, 2000), implies an average accretion rate for the Galaxy of $\sim 2\ M_{\odot}\ \mathrm{yr}^{-1}$. Estimates of Type II supernova rates in the Galaxy, of the order of a few solar masses per year per century in the disk (Dragicevich, Blair, & Burman 1999), are consistent with an arrival rate of a few if one assumes a Salpeter initial mass function (IMF) and mass limits from 0.1 to 100 $M_{\odot}$, assuming also that Type II

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supernovae are produced by stars with masses $\geq 8\ M_\odot$. Recent observations of high-velocity clouds, summarized by Wakker, van Woerden, & Gibson (1999), bracket the rate of infall of their material to the disk in the range 0.5–5 $M_\odot$ yr^{-1}; the uncertainty is due to the difficulty in accurate determination of the distances to the high-velocity clouds (HVCs). Within these error limits, the rates of supply and demand can be balanced by a model in which intergalactic gas, notably HVCs, supplies the metal-poor inflow to the disk. We will look in more detail at this process below. In § 2 we present two analytical approximations, focusing on the second as the best model to fit the current data. In § 3 we present the fitting to the data, and in § 4 we present our conclusions.

2. MODEL TREATMENT OF GAS INFALL

In this section we present two simple analytical approximations, each dealing with a scenario for gas infall. The first model is shown not to satisfy the observational requirements and leads naturally to the second as the more realistic approximation.

2.1. *Case 1: Collapse of a Superdisk*

We take a schematized model of the pre-Galactic gas cloud in the form of a cylinder of radius R_G and height r. We assume that R_G remains approximately constant, while r decreases with time as a result of the gravitational collapse process until it reaches equilibrium at an effective height r_0 as a result of the interplay of the gravitational field with supernova explosions, the magnetic field, dynamical friction, and other braking mechanisms. With the Galaxy as a cylinder of invariant total mass M_G, this is given by

$$M_G \simeq \pi R_G^2 2r\rho , \quad (1)$$

where ρ is the mean value for the gas density. The basic equation of motion under gravity can be written

$$\frac{d^2r}{dt^2} \simeq -\frac{GM_G}{r^2} , \quad (2)$$

where G is the universal gravitation constant. And if we take M_G as approximately constant, equation (2) reduces to

$$\frac{d^2r}{dt^2} \propto -r^{-2} , \quad (3)$$

the integral of which can be expressed as

$$r \propto (K - t)^{2/3} , \quad (4)$$

where K is a constant. This allows us to write the density as a function of time, t:

$$\rho \propto (K - t)^{-2/3} . \quad (5)$$

Then the disk mass will vary as

$$M_{\rm disk} \propto {\rm volume} \times \rho \propto (K - t)^{-2/3} , \quad (6)$$

from which the differential form yields

$$\frac{dM_{\rm disk}}{dt} \propto (K - t)^{-5/3} . \quad (7)$$

Equation (7) corresponds to an increasing infall rate of gas from a primordial halo structure throughout the evolution of the Galaxy. It is easy to compare the prediction of this simple model with the data of Rocha-Pinto et al. (2000; which are not very different, qualitatively, from previous data presented by Barry 1988). We have done this in Figure 1, showing that the agreement is poor. To make the comparison, we assumed proportionality between the SFR and the gas mass that arrives within each time step, which implies complete consumption of gas at each star formation episode. This yields an analytical approximation to be justified a posteriori by fitting to the data. The poor fit leads us to modify the starting assumptions, principally the closed-box assumption, and also the assumed lack of density structures.

2.2. *Case 2: Interferential Arrival of Gas from the IGM and Disk*

To perturb this simple picture, we take into account a recent result from Vallenari, Bertelli, & Schmidtobreick (2000), who used deep V- and I-band photometry of stellar fields in four previously unstudied, low-latitude regions of the Galactic disk to conclude that the SFR in the solar neighborhood may not be representative of the disk as a whole. Here we develop a particular model that may account for such local peculiarities, first proposed by Casuso (1991) in the context of chemical evolution. It describes variable flow through the solar neighborhood due to two distinct mechanisms: secular infall to the disk from the intergalactic medium (IGM) and periodic flow due to a spiral density wave acting essentially azimuthally, which should give rise to maxima and minima in the local density as a function of time. The rate of arrival of gas due to the density wave P_1 can be expressed as $P_1(t) \simeq K_1 \sin bt$, where K_1 and b are constants. In order to simplify the handling of the disk infall component, P_2, we express it as $P_2(t) \simeq K_2 + K_3 \sin ct$, where K_2, K_3, and c are constants. The value of c^{-1} is determined by the mean interval

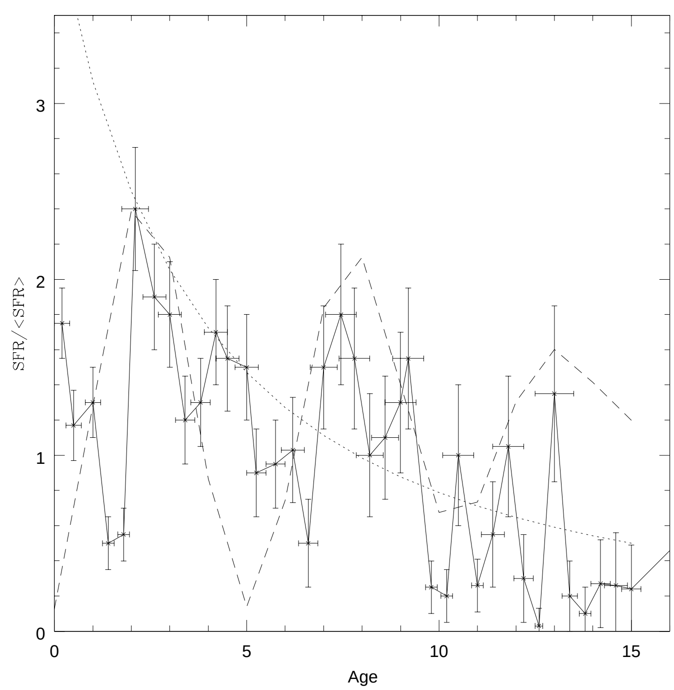

FIG. 1.—History of the Galactic SFR. Data are in units of past average star formation, with error bars from Rocha-Pinto et al. (2000). The solid lines are artificial connections between data points. The dotted line is the prediction of model 1, and the /dashed line is the prediction from model 2 using a period of ~1 Gyr (the values of the parameters are $b = -1.25$ Gyr^{-1} and $c = 1.05$ Gyr^{-1}).

between relevant star formation periods, which are assumed to brake the infall locally via massive stellar winds and supernova explosions. There are two theoretical reasons why we can assume cyclical behavior of the secular infall of gas to the Galactic disk: one is dynamical, and the other relates to the phase transitions of the gas in the interstellar medium (ISM).

For the first, we approximate the Milky Way as a cylinder rotating on its axis and suffering gravitational collapse leading to formation of the disk. The result of the two main forces acting on an element of gas falling to the disk is a net force almost vertical with respect to the central disk:

$$\frac{d^2r}{dt^2} \simeq -\frac{GMr}{(r^2 + x_0^2)^{3/2}} , \tag{8}$$

where x_0 is the horizontal distance from the center of the Milky Way to the gas element and r is the vertical distance from the gas element to the plane of the disk. In the present case, the solar vicinity is taken as a region of ~ 1 kpc in size, situated ~ 8 kpc from the Galactic center, so $r \ll x$, and hence one can approximate this with the relation

$$\frac{d^2r}{dt^2} \propto -r , \tag{9}$$

which has a solution $r(t) \propto e^{i\lambda t}$, with a sinusoidal real part. On the contrary, close to the center ($x_0 \ll r$) one has the solution $r(t) \propto (x_0 - t)^{2/3}$ and so can easily explain the trend of concentration to form the disk. At large distances from the Galaxy the gravitational attraction is monotonic, but when the IGM gas clouds (HVCs) are near the disk, they are subject to a gravitational oscillation that can cyclically modify the density of gas such that star formation can take place.

For the second reason, we must refer to the theoretical result of Hirashita & Kamaya (2000) based on the analysis of observational data of Kennicutt, Tamblyn, & Congdon (1994) and the Ikeuchi & Tomita (1983, hereafter IT) model for the ISM. The sample of spiral galaxies of Kennicutt et al. (1994) exhibits a wide range of observed SFRs, which Hirashita & Kamaya (2000) claim supports the limit-cycle model of IT for the ISM, in which the SFR changes cyclically in accordance with the time variation of the mass fraction of the three gaseous components (hot, warm, cold) of the ISM. These interchange processes are regulated, according to IT, by supernova remnants. Figure 1 of IT shows how the time variation of the cold gas fraction (and therefore of the SFR) can be well approximated analytically by a sinusoidal function. If one assumes the arrival rate of gas from the IGM to be, on average, approximately constant, the net arrival of gas in the solar vicinity can then be approximated as constant but cyclically interrupted by violent star formation episodes.

In fact, the periods b and c are very similar in magnitude as a result of the coupling of the two effects, where c^{-1} takes a value of either $\simeq 1$ or $\simeq 0.2$ Gyr, depending on whether we fit principal peaks or the fine structure of the peaks, respectively (see Figs. 1 and 2). We take the two effects simultaneously into account and obtain an analytic approximation to the rate of flow of mass into a fixed volume around the Sun as

$$\frac{dM(t)}{dt} \simeq P_1 + P_2 = K_4(1 + \sin \omega t \cos Bt) , \tag{10}$$

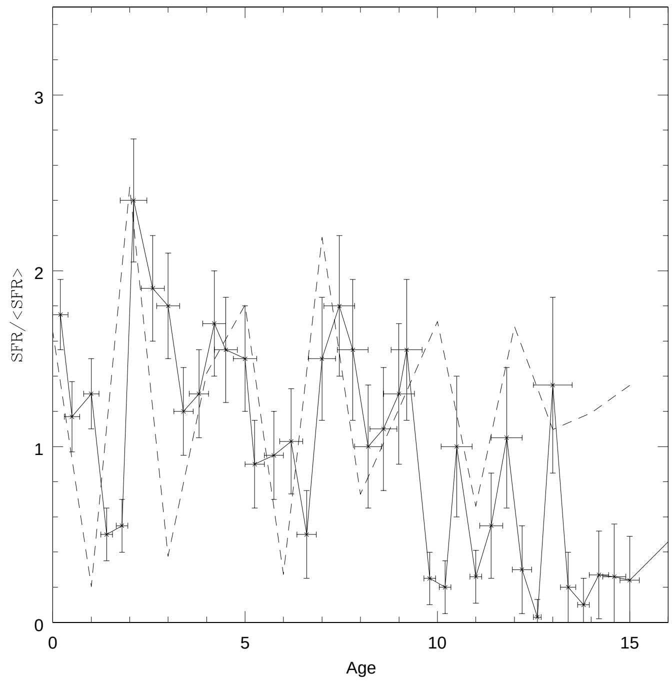

FIG. 2.—Same as Fig. 1, but for the interferential model, using a period of ~ 0.35 Gyr ($b = -2.8$ Gyr^{-1} and $c = 2.4$ Gyr^{-1}).

where K_4 is a constant, $\omega = (b + c)/2$, and $B = (b - c)/2$. The complete expression is modulated by a periodic function in which the increasing portion is a part of a sinusoidal function of considerably longer period than that of the periodic modulator. It should be noted that the constant b must take a negative value, since there will be an out-of-phase effect from the density wave on the infall rate from the IGM: a minimum in the density wave will lead to a lower net gas density in the disk and, in consequence, to an increase in the net inflow rate perpendicular to the disk.

3. COMPARING INTERFERENTIAL INFLOW MODEL WITH DATA

The present model can explain not only the oscillating SFR but also the secular increase of the amplitude of the SFR oscillation, a feature that cannot be explained using other infall models, such as that of Ikeuchi (1988). Using this interferential model as a basis, we have used our numerical chemical evolutionary code (Casuso & Beckman 1997, 2000) to compute the evolutionary effects of the interferential inflow of gas. The results are compared with data in Figures 3, 4, and 5, where the age-metallicity relation for the solar neighborhood is well fitted, as are the observed variation of [O/Fe] versus [Fe/H] and the stellar frequency distribution in Fe, where the main peak is especially well fitted. These evolutionary results show that the interferential model is consistent with the observations.

In presenting the numerical results from this interferential model we have taken as implicit the replenishment of the halo gas at intervals due to the arrival of large, diffuse, high-velocity clouds from further out in the Local Group. Taking the mean distance to HVCs as 1 Mpc and the mean velocity of HVCs as 220 km s^{-1} (Blitz et al. 1999), we have a mean time interval for arrivals of typical HVCs at

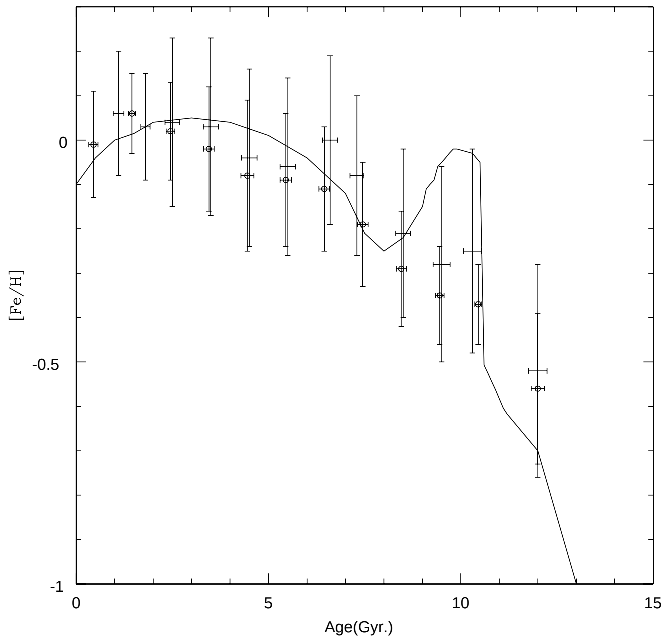

FIG. 3.—Iron metallicity in the solar neighborhood as a function of age. The curve shows the prediction of our interferential model. Observational comparison points with error bars are plotted from Meusinger et al. (1991, *crosses*) and Twarog (1986, *circled plus signs*).

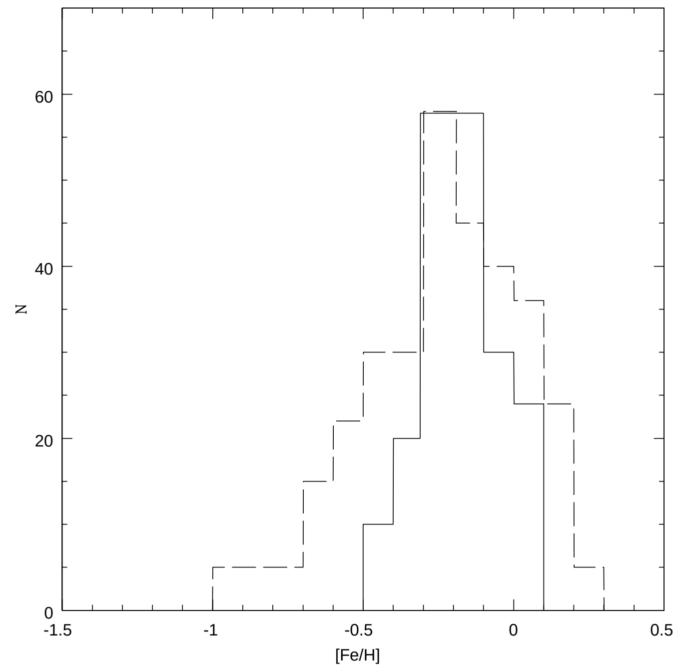

FIG. 5.—Stellar frequency distribution in iron for the Galactic disk, well reproduced by the output of the interferential model (*solid histogram*). The model prediction provides a good fit to the main peak observed. The data (*dashed histogram*) are from Rocha-Pinto & Maciel (1996).

the Galactic disk of approximately 10^9 yr, in reasonable agreement with the period of inflow obtained from the interferential model to explain the main peaks observed in Rocha-Pinto et al. (2000) (see Fig. 1).

The inflow of material to the halo, and hence to the disk, can be maintained if the implied accretion rate due to HVCs

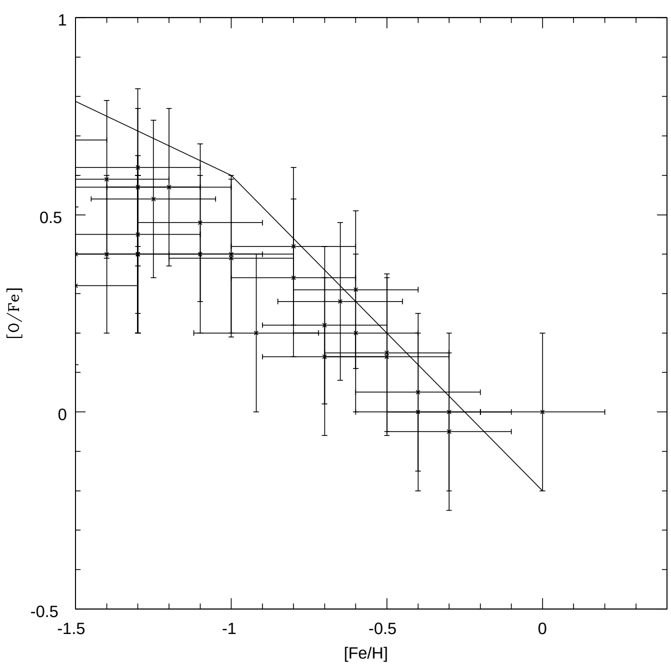

FIG. 4.—Oxygen-to-iron ratio of the Galactic disk [O/Fe] as a function of [Fe/H]. The data points are from Rebolo, Garcia-Lopez, & Perez del Taoro (1995), Nissen et al. (1994), and Israelian, Garcia-Lopez, & Rebolo (1998). The curve corresponds to our chemical evolution model using the interferential inflow of metal-poor gas.

is sufficient. We can obtain a lower limit estimate to the accretion rate using the disk mass $M_{\rm disk}$ as the Galaxy mass $M_{\rm G}$. The Galaxy is moving at $v \sim 150$ km s^{-1} with respect to the IGM in the Local Group, so one can compute an effective radius of gravitational attraction $R_{g,\rm eff}$ via the equation

$$\frac{v^2}{R_{g,\rm eff}} = \frac{GM_{\rm G}}{R_{g,\rm eff}^2}\,, \tag{11}$$

which yields a value for $R_{g,\rm eff}$ of $\sim$10 kpc if one takes $M_{\rm G} = 6 \times 10\ M_\odot$. Continuing with the argument, the hydrogen mass $M_{\rm H}$ of the IGM swept up over a time of the order of $t \sim 15$ Gyr (an upper limit to the age of the Galaxy) is given by

$$vt\pi R_{g,\rm eff}^2\, \rho_{\rm IGM(H\,I+H\,II)} \simeq M_{\rm H}\,, \tag{12}$$

where $M_{\rm H}$ takes the value $10^8\ M_\odot$ assuming $R_{g,\rm eff} = 20$ kpc and $2.5 \times 10^9\ M_\odot$ if $R_{g,\rm eff} = 100$ kpc, which are the values taken as the present visible mass of the Galactic halo. This suggests that the model assumptions we have made are not adequate, since the mean infall rate here is more than an order of magnitude too low. However, these assumptions are in fact far too conservative, above all in specifying the value of the effective mass of the galaxy, which even in purely baryonic terms could perhaps reach 10 times the value used in equation (11), and certainly with a dark matter component included could take values that would put the gravitational range $R_{g,\rm eff}$ as far away as 100 or even 200 kpc, thus raising the total accreted gas during the disk lifetime into the range of a few times $10^{10}\ M_\odot$, and the accretion rate to a few solar masses per year, as required by the observations. We can add to this an argument from continuity that the free-fall velocity for a cloud arriving at the Galactic plane is $\sim(GM_{\rm G}/R_{g,\rm eff})^{1/2}$, which is in the range $\simeq$50–150 km s^{-1}, while the relative velocity of the

Galaxy within the IGM is $\simeq 150$ km s^{-1}, which implies that the conditions for dynamical equilibrium can exist in the Galactic halo and that therefore its density will vary little with time.

Taking as a basis the hypothesis that later, milder bursts (at levels lower than galaxy-galaxy mergers) are dominated by infall of discrete HVCs after the initial burst of star formation accompanying the early phases of the Galaxy, we can predict for the Local Group the ratio of the rate of such bursts in the Milky Way to the rate within a representative smaller object: a spheroidal dwarf in the Local Group.

From the statistical point of view, one can calculate the probability that an HVC arrives at the Milky Way during a sample time interval of ~ 1 Gyr. We adopt a characteristic length scale for the Local Group (LG) of 1 Mpc; for the distance between the Milky Way and M31 (the two main attractors in the Local Group), $D = 0.5$ Mpc; for the characteristic scale length of one HVC, 20 kpc; and for each spheroidal dwarf galaxy in the LG, a scale length D' of 10 kpc (Blitz & Robishaw 2000), multiplied by a factor of 10 for consistency with $R_{\rm GE}$, which is also multiplied by the same factor to take into account the proportional presence of dark matter. We also assume that the HVCs have similar velocities, $v_{\rm HVC}$ to the Milky Way with respect to the LG's center of mass, and that the Milky Way and M31 attract all the objects (HVCs, spheroidal dwarf galaxies, etc.) in the LG to the sphere whose diameter is the distance between them. We take $R_{g,\rm eff}$ to be 100 kpc. We can then express the probability that an HVC arrives at the Milky Way during a time interval Δt of 1 Gyr as

$$P_{\rm HVC} \sim \left[\frac{\pi R_{g,\rm eff}^2\, v_{\rm HVC}\,\Delta t}{(4/3)\pi(D/2)^3}\right]^2 N_{\rm HVC}\,, \tag{13}$$

where $N_{\rm HVC}$ is the number of HVCs that can arrive, i.e.,

$$N_{\rm HVC} \sim (4/3)\pi\{[(D/2) + v_{\rm HVC}\,\Delta t]^3 - (D/2)^3\}\rho_{\rm HVC}\,, \tag{14}$$

and $\rho_{\rm HVC}$ is the density of HVCs in the LG. Calculating the probability P'_{HVC} that an HVC falls to a spherical dwarf galaxy in the LG, one has

$$P'_{\rm HVC} \sim \left[\frac{\pi R_{g,\rm eff}^2\, v_{\rm HVC}\,\Delta t}{(4/3)\pi(D/2)^3}\right]\left[\frac{\pi(D'/2)^2 v_{\rm HVC}\,\Delta t}{(4/3)\pi(D/2)^3}\right] N_{\rm HVC}\,. \tag{15}$$

From equations (11) and (13) we find that $P \sim 4P'$.

Assuming that the probability of star formation inside a galaxy (subsequent to an initial major collapse when the galaxy was formed) is proportional to the rate of arrival of HVCs, we infer that the frequency of star formation in the Milky Way should be 4 times that in a typical dwarf spheroidal galaxy. As the observations point to approximately 15 peaks in the star formation rate in the solar vicinity (Barry 1988; Rocha-Pinto et al. 2000), we also infer that the corresponding number of peaks for a typical dwarf spheroidal galaxy should be approximately 3, a value that has been found observationally for a small sample of dwarfs in the Local Group (see Olsen 1999; Hernandez, Gilmore, & Valls-Gabaud 2000).

4. CONCLUSIONS

We can draw the following conclusions from the study presented in the present paper:

1. In order to explain the observations, now firmly based, of the stellar frequency distribution with respect to iron metallicity (Rocha-Pinto & Maciel 1996) and the joint plot of iron metallicity versus age (Twarog 1986; Meusinger et al. 1991) and SFR versus age (Rocha-Pinto et al. 2000), it is very difficult to avoid the necessity of including inflow of metal-poor gas to the solar neighborhood throughout the evolution of the Galactic disk.

2. The variation of the SFR with time appears to oscillate with increasing amplitude on a gigayear timescale, which can be well accounted for by incorporating into evolutionary models two additional effects: net flow of gas to the solar neighborhood from within the plane of the disk, whose amplitude is a result of a density wave pattern, and inflow of gas from the intergalactic medium. The rates of both flows are affected by the collective effects of local supernovae. The best candidates for the external inflow are the high-velocity clouds of metal-poor hydrogen observed to be falling toward the Galactic plane. Estimates of the global mass arrival rate on the disk due to these HVCs are consistent with estimates of ongoing disk star formation rates. These observations are in good agreement with models in which the gas available for star formation at a given epoch is almost fully incorporated into stars.

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REFERENCES

Barry, D. C. 1988, ApJ, 334, 436
Blitz, L., & Robishaw, T. 2000, ApJ, 541, 675
Blitz, L., Spergel, D. N., Teuben, P. J., Hartmann, D., & Burton, W. B. 1999, ApJ, 514, 818
Carney, B. W., Latham, D. W., & Laird, J. B. 1990, AJ, 99, 572
Casuso, E. 1991, Ph.D. thesis, Univ. La Laguna
Casuso, E., & Beckman, J. E. 1997, ApJ, 475, 155
———. 1999, AJ, 118, 1907
———. 2000, PASP, 112, 942
Dragicevich, P. M., Blair, D. G., & Burman, R. R. 1999, MNRAS, 302, 693
Fitzpatrick, E. L. 1996, ApJ, 473, L55
Hernandez, X., Gilmore, G., & Valls-Gabaud, D. 2000, MNRAS, 317, 831
Hirashita, H., & Kamaya, H. 2000, AJ, 120, 728
Ikeuchi, S. 1988, Fundam. Cosmic Phys., 12, 255
Ikeuchi, S., & Tomita, H. 1983, PASJ, 35, 77
Israelian, G., García López, R., & Rebolo, R. 1998, ApJ, 507, 805
Kennicutt, R. C., Tamblyn, P., & Congdon, C. W. 1994, ApJ, 435, 22
Meusinger, H., Stecklum, B., & Reimann, H.-G. 1991, A&A, 245, 57
Nissen, P., Gustafsson, B., Edvardsson, B., & Gilmore, G. 1994, A&A, 285, 440
Olsen, K. A. G. 1999, AJ, 117, 2244
Pagel, B. E. J. 1987, in The Galaxy, ed. G. Gilmore & B. Carswell (Dordrecht: Reidel), 341
Rebolo, R., García López, R. J., Perez del Taoro, M. R. 1995, in The Light Element Abundances, ed. P. Crane (New York: Springer), 420
Rocha-Pinto, H. J., & Maciel, W. J. 1996, MNRAS, 279, 447
Rocha-Pinto, H. J., Scalo, J., Maciel, W. J., & Flynn, C. 2000, A&A, 358, 869
Tinsley, B. M. 1980, Fundam. Cosmic. Phys, 5, 287
Twarog, B. A. 1980, ApJ, 242, 242
Vaughan, A. H., & Preston, G. W. 1980, PASP, 92, 385
Vallenari, A., Bertelli, G., & Schmidtobreick, L. 2000, A&A, 361, 73
Wakker, B. P., van Woerden, H., & Gibson, B. K. 1999, in ASP Conf. Ser. 166, Stromlo Workshop on High-Velocity Clouds, ed. B. K. Gibson & M. E. Putman (San Francisco: ASP), 311