

AN INTERMITTENT STAR FORMATION HISTORY IN A “NORMAL” DISK GALAXY: THE MILKY WAY

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ABSTRACT

The star formation rate history of the Milky Way is derived using the chromospheric age distribution for 552 stars in the solar neighborhood. The stars’ sample birth sites are distributed over a very large range of distances because of orbital diffusion and so give an estimate of the global star formation rate history. The derivation incorporates the metallicity dependence of chromospheric emission at a given age and corrections to account for incompleteness, scale height–age correlations, and stellar evolutionary effects. We find fluctuations in the global star formation rate with amplitudes greater than a factor of 2–3 on timescales less than 0.2–1 Gyr. The actual history is likely to be more bursty than found here because of the smearing effect of age uncertainties. There is some evidence for a slow secular increase in the star formation rate, perhaps a record of the accumulation history of our Galaxy. A smooth, nearly constant star formation rate history is strongly ruled out, confirming the result first discovered by Barry using a smaller sample and a different age calibration. This result suggests that galaxies can fluctuate coherently on large scales.

Subject headings: galaxies: formation — Galaxy: evolution — solar neighborhood — stars: formation — stars: statistics

1. INTRODUCTION

The history of the average cosmic star formation rate (SFR) is of great current interest, but is subject to severe uncertainties (see Pascarelle et al. 1998; Glazebrook et al. 1999; Tresse & Maddox 1998; Hughes et al. 1998; Cowie, Songaila, & Barger 1999). Such studies average over large numbers of galaxies, so variations between galaxies and internal temporal variations within individual galaxies are “washed out.” However, for an understanding of the star formation process itself and of individual galaxy evolution, it is just these variations that are of interest.

It is known that short-lived spatially coherent “bursts” of star formation occur on kiloparsec scales in starburst galaxies, giant H II regions, “superassociations” (e.g., Efremov 1995), and Local Group dwarfs (see Tolstoy 1999; Grebel 1997; Mateo 1998 and references therein). Since larger disk galaxies consist of spatially connected regions of gas of comparable size, and since propagation of star formation is well established (see the comprehensive reviews by Elmegreen 1992, 2000), it is unknown in the case of individual galaxies whether an entire galaxy can undergo some collective process that effectively synchronizes global variations in the SFR.

Some information on the SFR history of individual galaxies can be inferred from the ratio of present to past average SFR ratios in local galaxies (see Kennicutt 1998 for a review), analysis of the color-magnitude diagrams of Local Group dwarf galaxies (see Grebel 1997; Mateo 1998; Tolstoy 1999; also Dolphin 1997; Gallart et al. 1999), and recent pixel-by-pixel modeling of the H α and UV luminosities (Glazebrook et al. 1999). But all of these studies attempt to model the properties of whole populations of stars, which are subject to severe as-

sumptions and uncertainties. Clearly the most *direct* method for estimating the SFR history of a galaxy is to use a determination of the ages of individual stars in order to construct the age distribution. The only sample of relatively low-mass stars for which this approach can be used is the sample of local stars in the Milky Way. The estimation of this age distribution and the inferred SFR history is the subject of the present Letter.

A crucial point is that the nearby stars older than about 0.2 Gyr come from birth sites which span a large range in Galactocentric distances. Wielen (1977) showed that the orbital diffusion coefficient deduced from the observed increase of velocity dispersion with age implies that such stars have suffered an rms azimuthal drift of from about 2 kpc (for an age of 0.2 Gyr) to many Galactic orbits (for an age of 10 Gyr). Considerable, but smaller, drift should occur also in the radial direction. In this sense the SFR inferred for nearby stars is a measure of the *global* Milky Way SFR, at least at the Sun’s Galactocentric radius. More recent estimates of the diffusion coefficient (e.g., Meusinger, Stecklum, & Reimann 1991) are consistent with this conclusion.

Previous attempts to derive the age distribution of local stars have used stellar evolutionary tracks (Twarog 1980; Meusinger 1991), chromospheric activity as measured by Ca II H and K emission (Barry 1988; Soderblom, Duncan, & Johnson 1991), stellar kinematics (Gómez et al. 1990; Marsakov, Shevelev, & Suchkov 1990; Chereul, Crezé, & Bienaymé 1998), features in the main-sequence (Scalo 1987) and white dwarf (Noh & Scalo 1990; Díaz-Pinto et al. 1994; Isern et al. 1999) luminosity functions, combining the metallicity distribution and age-metallicity relation of G dwarfs (Rocha-Pinto & Maciel 1997), and the distribution of coronal emission as measured by X-ray

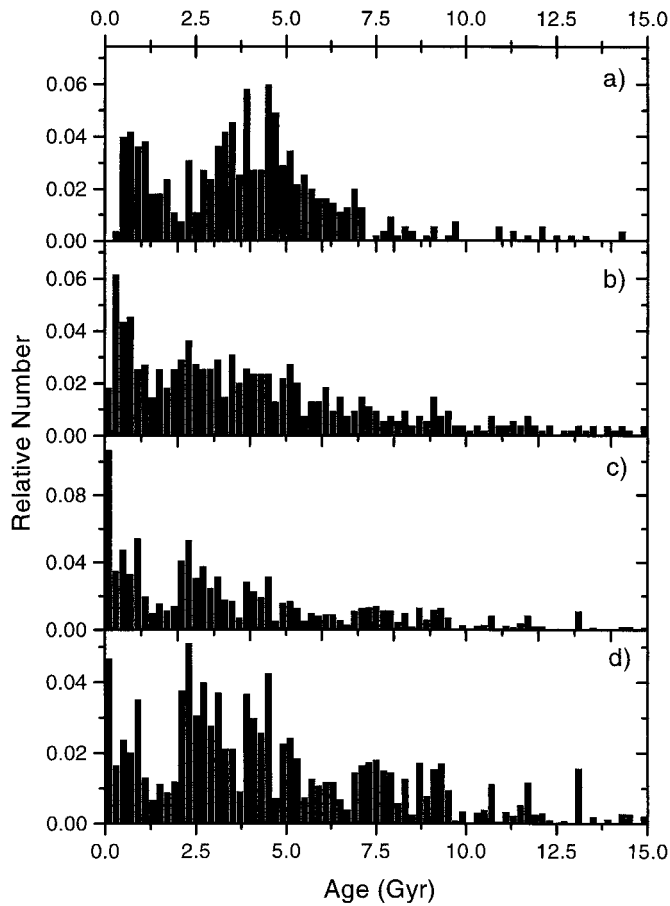


FIG. 1.—(a) Chromospheric age distribution before modification for any of the effects listed below; (b) distribution after application of metallicity-dependent age corrections; (c) distribution including the metallicity correction of (b), but also including an incompleteness correction based on V/V_{\max} ; (d) iterative scale height correction applied to (c).

luminosities (Micela, Sciortino, & Favata 1993; see also Lachaume et al. 1999). All these methods are fraught with difficulties. However, it is notable that most of these studies have inferred an SFR history that is nonmonotonic with time. There has been a strong tendency for astronomers to overlook these results, partly because of the lack of appreciation of the importance of orbit diffusion in making a local stellar sample representative of the global SFR history, but also because a nonmonotonic SFR would provide unwanted complication in Galactic evolution studies and provide a foil to simple self-regulation models of Galactic star formation, which all yield a smooth, monotonic SFR history.

The present Letter provides a new analysis of the SFR history based on chromospheric emission ages for a large sample of solar-like stars. We show that it is very unlikely that the Milky Way SFR history has been monotonic and smooth and that it has undergone fluctuations of at least a few (and probably much larger).

2. CHROMOSPHERIC AGES

The individual ages of the stars in our sample are based on chromospheric emission. The usual method of quantifying the observed chromospheric emission (CE) in the Ca II H and K lines is based on the Mount Wilson system of Vaughan, Preston, & Wilson (1978). Corrections due to the fact that the continuum

flux depends on the photospheric UV continuum and due to photospheric light entering the instrumental bandpasses yield a corrected quantity R'_{HK} as described in Noyes et al. (1984). A lower resolution estimate of R'_{HK} , which could be used to calibrate the CE-age relation using open clusters, was used in Barry's (1988) estimate of the age distribution. Soderblom et al. (1991) used the higher resolution system to calibrate the CE-age relation based on a comparison of evolutionary tracks with Strömgren photometry of solar-type stars that are secondaries in visual binaries, as well as some slightly evolved F dwarfs, high-velocity stars, the Sun, and two nearby clusters. Rather than interpret the resulting age distribution as nonmonotonic, as found by Barry (1988), Soderblom et al. showed that a nonlinear CE-age relation, consistent with the available data, could yield a constant SFR.

A major advance was the determination of R'_{HK} for a large number of southern F–K (mostly G) dwarfs by Henry et al. (1996). The present work uses this sample, supplemented by stars observed by Soderblom (1985). The overlap between this sample and stars that have published *uvby* photometry in Olsen's catalogs (Olsen 1983, 1993, 1994; needed to estimate the metallicity-dependent correction to the chromospheric ages found by Rocha-Pinto & Maciel 1998) yields 729 stars. *Hipparcos* parallaxes are known for 714 of these stars. The sample was reduced by further considerations, mainly by omitting stars more distant than 80 pc (to minimize any effect of reddening on colors) and all stars with extremely strong CE ($\log R'_{\text{HK}} \geq -4.20$), which might be close binaries instead of young stars (Soderblom, King, & Henry 1998). The latter omission does not affect our derived age distribution, since we are primarily concerned with ages greater than 0.1 Gyr and the number of stars omitted is small. The final sample consists of 552 stars.

Given the R'_{HK} values from Henry et al. (1996) and Soderblom (1985), ages were calculated using the CE-age calibration given by equation (3) of Soderblom et al. (1991; see also Donahue 1998). This equation is a power-law-weighted fit to the R'_{HK} values and ages of 42 stars and the Sun, the Hyades cluster, and the Ursa Major group. It will be seen from our results that no reasonably smooth alteration of this calibration could eliminate the intermittent SFR history that we derive. We emphasize, however, that an improved CE-age calibration based on open clusters is sorely needed.

The chromospheric age of each star was corrected for metallicity dependence with the relation derived in Rocha-Pinto & Maciel (1998), using the available *uvby* photometry to estimate metallicity. The resulting age distribution was further corrected to account for the fact that the sample is not volume-limited, using a simple V/V_{\max} method to assign a weight to each star according to the volume to which it could be observed in a volume-limited sample. We then corrected the age distribution to account for the fact that older stars have larger scale heights, since we want to derive the SFR per unit area of the disk. This correction used the iterative procedure outlined in Noh & Scalo (1990) using the average scale height–mass relation given in Scalo (1986) and iterating on the mean age corresponding to each mass calculated from the observed age distribution. Details will be presented elsewhere (Rocha-Pinto et al. 2000, hereafter RPMSF).

Unresolved binaries present another source of uncertainty, which depends in a complicated way on the distribution of mass ratios and the mass of the primary. For example, a G+K binary will appear younger than a single G star because the chromospheric flux increases toward the redder stars, and the combined flux of the pair will be larger than that presented by

the G dwarf alone. Simulations of this effect, to be reported elsewhere, indicate that the error in age is only 0.14% for the stars older than 3 Gyr and rises to 0.3% for the youngest stars in the sample. Overall, the effect is negligible compared to other sources of uncertainty for stars older than about 0.5 Gyr.

The final transformation is from the age distribution to the SFR, which involves stellar evolutionary effects. Stars that have age τ are those that formed at time $T - \tau$ ago ($T =$ present age of the disk) and that have main-sequence lifetimes $\tau_{\text{ms}} > \tau$, so that they are still alive. Then the observed age distribution $g_{\text{obs}}(\tau)$ is related to the SFR history $b(t)$ by

$$g_{\text{obs}}(\tau) = \int_{\tau}^{\tau_{\text{ms, max}}} b(T - \tau) p(\tau_{\text{ms}}) d\tau_{\text{ms}}, \quad (1)$$

where $p(\tau_{\text{ms}})$ is the probability distribution of main-sequence lifetimes of the sample and $\tau_{\text{ms, max}}$ is the maximum main-sequence lifetime of stars in the sample, corresponding to the smallest mass ($\sim 0.8 M_{\odot}$). If τ is smaller than the minimum main-sequence lifetime $\tau_{\text{ms, min}}$ of the stars in the sample, corresponding to the largest mass ($\sim 1.4 M_{\odot}$), then all stars with these ages will be seen and no correction is required. For our sample, $\tau_{\text{ms, min}}$ is about 3 Gyr.

For ages larger than this, since τ_{ms} is a strong function of the stellar mass, $p(\tau_{\text{ms}})$ is a transformation of the mass function of stars in the sample. The initial mass function (IMF) is very uncertain in the $0.8\text{--}1.4 M_{\odot}$ mass region but $p(\tau_{\text{ms}})$ is rather insensitive to the adopted IMF. We adopted the Miller & Scalo (1979) IMF and have verified that the conclusions of this Letter would not be affected by changes to the slope of the IMF power law from -1 to -3 .

The SFR history is then given by

$$b(t) = \frac{g_{\text{obs}}(\tau)}{\int_{\tau}^{\tau_{\text{ms, max}}} p(\tau_{\text{ms}}) d\tau_{\text{ms}}} \quad (2)$$

for $\tau > \tau_{\text{ms, min}}$. The effect of the integral is to elevate the observed $g_{\text{obs}}(\tau)$ progressively for older stars. An equivalent relation between the age distribution and the SFR history was presented by Tinsley (1974).

3. RESULTS

Figure 1a shows the raw age distribution for the sample as a histogram with bins of width 0.2 Gyr uncorrected for metallicity effects. In Figure 1b the effect of applying the metallicity-dependent age correction is shown. Figure 1c shows the distribution, again including metallicity corrections, but with weight assigned to each star to correct for incompleteness based on V/V_{max} . In Figure 1d the iterative scale height correction has been applied to the histogram of Figure 1c; the effect is to progressively elevate the higher age bins relative to the lower age bins, since the scale height increases with age. Note that the effect is not severe and does not affect the general structure of the fluctuations in the age distribution.

Figure 2 shows the SFR history (in units of the average SFR) obtained by applying evolutionary corrections to the histogram of Figure 1d. The bin size in Figure 2 has been increased to 0.4 Gyr. The error bars correspond to Poisson counting uncertainties. The figure shows fluctuations in the SFR of a factor of at least a few; are these fluctuations significant? We have compared this SFR history with 6000 simulations of 552 stars

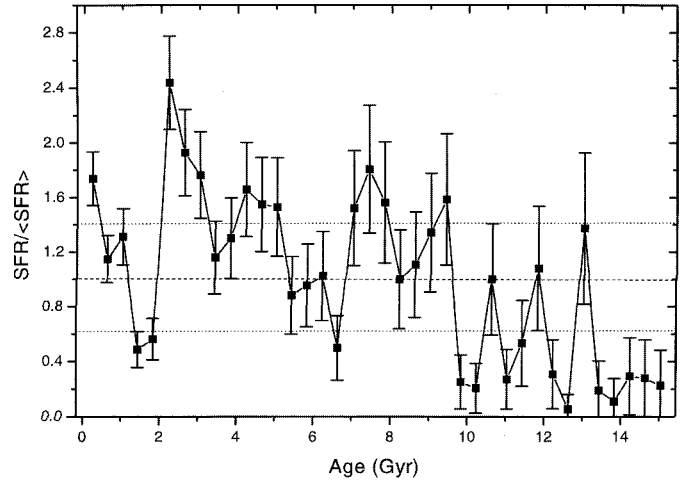


FIG. 2.—History of the star formation rate in units of the past average star formation, derived from the age distribution shown in Fig. 1d by applying the evolutionary correction given by equation (2). Error bars are Poisson counting uncertainties. The dotted horizontal lines represent the 2σ deviation expected for a constant star formation rate, based on 6000 simulations.

each, drawn from a constant SFR. The dotted horizontal lines in Figure 2 correspond to the 2σ deviation expected for a constant SFR. We have compared the expected amplitudes of excursions from the constant SFR case simulations to the empirical result and find that the probability that the empirical fluctuations are artifacts due to small number statistics is less than 2% (details in RPMSF). Considering that the empirical fluctuations are correlated in time, the probability that the fluctuations are noise must be smaller than this estimate. The derived fluctuations in the SFR have a maximum value of about a factor of 2–3. However, this is a lower limit because the age uncertainties effectively smear the age distribution. We speculate that the amplitude of the resulting fluctuations may be an order of magnitude, with timescales significantly smaller than shown in Figure 2.

There is marginal evidence in Figure 2 for a long-term secular increase in the SFR with time over many gigayears, perhaps consistent with the idea that our Galaxy has grown by the accumulation of smaller galaxies (see Unavase, Wyse, & Gilmore 1996 and references therein). However, this result is tentative because the large-timescale trend depends somewhat on the details of our correction for scale height–age correlations and stellar evolutionary effects.

4. DISCUSSION AND CONCLUSIONS

We have derived the SFR history of the Milky Way using chromospheric ages for 552 stars in the solar neighborhood. The results demonstrate rather conclusively that the SFR in our Galaxy has not been monotonic with time, but instead exhibits significant fluctuations. The details of the form of the SFR history shown in Figure 2 may be altered by changes in the CE-age calibration, the metallicity correction, and other effects, so that the exact times of “bursts” and “lulls” may be altered. For example, a comparison with times of close passage of the Magellanic Clouds (see RPMSF) would be very uncertain. However, it does not seem possible to us that the finding of significant fluctuations could be invalidated by such effects. For example, the application of the metallicity correction actually decreased the amplitude of the fluctuations (see Fig. 1), and the corrections for scale height and evolution only intro-

duce smooth, long-timescale, modifications. *The SFR history of the Milky Way has fluctuated on timescales less than 0.2–1 Gyr with amplitudes greater than a factor of 2–3.* Thus we confirm the result first discovered by Barry (1988) based on a smaller sample and a different CE-age relation, although the form of the age distribution found here differs in detail. The true SFR history has been smeared in our derivation by substantial uncertainties in the stellar ages, so the true SFR history can only be “spikier” than derived here.

It is still conceivable that the irregularity in the derived SFR could be an artifact caused by a very nonlinear CE-age relation, as proposed by Soderblom et al. (1991), but the present sample is large enough that such a CE-age relation would have to be extremely irregular, and there is no observational or theoretical reason to suspect such behavior, while episodic galactic SFR histories are well known, at least for smaller galaxies and starbursts.

The disagreement between the ages of the oldest stars found here and the disk age inferred from the dropoff of the white dwarf luminosity function at small luminosities (Winget et al. 1987; see Knox, Hawkins, & Hambly 1999 for an update) may be due to either an error in the white dwarf result or errors in the evolutionary tracks on which the CE-age relation is based

(Soderblom et al. 1991 used tracks from Maeder 1976). Most other methods for estimating the disk age only give lower limits (e.g., Jiménez, Flynn, & Kotoneva 1998) and so cannot be used to decide between the two choices. However, revisions in the age calibration derived from evolutionary tracks should only contract (or expand) the time axes in our plots; it seems impossible that such a revision could remove the irregularity of the SFR that we have derived.

Finally, we note that our derived SFR history is qualitatively similar to that derived by Glazebrook et al. (1999) for a sample of 13 field galaxies at redshift about unity, using a generalization of the pixel-by-pixel population synthesis method introduced by Abraham et al. (1999). Glazebrook et al. conclude that bursts dominate over the first ~5 Gyr of the lives of their sample galaxies, with intervals of 0.2–0.3 Gyr and durations 0.1–0.2 Gyr. Pure continuous star formation is strongly ruled out, in agreement with our result for the Milky Way.

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