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# STAR FORMATION HISTORIES WITH GAIA: THE GALAXY AND BEYOND

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**Abstract.** ESA's *Gaia* mission will provide accurate astrometric, photometric and spectroscopic data for millions of stars in the Galaxy and beyond. We discuss the prospects of using this vast amount of astrophysical information for understanding star formation histories in the Galaxy and its immediate neighbors within the Local Group.

**Key words:** stars: fundamental parameters – Galaxy: populations – galaxies: Local Group – Gaia orbiting observatory

## 1. THE GAIA MISSION

*Gaia* is a cornerstone mission of the European Space Agency, approved for launch not later than 2012, with a target launch date of mid-2010 (see the reviews by Perryman 2003 and Høg 2003 for more details and references). While the primary goal of the *Gaia* mission is to do astrometry of millions of stars at microarcsecond level, it will also provide broad- and medium-band photometry of stars down to $V = 20$ and low-resolution spectroscopy (spectral range 848–874 nm, spectral resolution $R = 11\,500$) for stars down to $V\sim17.5$. Combined with positional and kinematical data, this wealth of information will be extremely useful for tracing star formation histories in the Milky Way galaxy and beyond. In this study we examine the capabilities of different methods available for this purpose in the context of *Gaia*.

## 2. STAR FORMATION HISTORIES WITH GAIA

Several observational ingredients are essential in order to reconstruct the origins and evolution of the Galaxy in a reliable way. First, positional and kinematical data are required for unambiguous identification of individual stellar populations of interest. *Gaia* will offer a unique opportunity in this sense, providing kinematical information for millions of stars in a six-dimensional phase space, with distances and proper motions available from astrometry and radial velocities from spectroscopy. Second, astrophysical parameters of individual stars (metallicity, surface gravity, effective temperature, etc.) are also needed. For the majority of stars these will be obtained from the broad- and medium-band *Gaia* photometry (with some contribution from spectroscopy for the brightest objects). Third, all this needs to be complemented with precise three-dimensional extinction maps in order to account properly for interstellar reddening towards the particular stellar population. In the following we briefly discuss the prospects for obtaining this information with *Gaia*.

### *2.1. Star formation histories in the Galaxy*

Out of the numerous methods used to derive ages of stellar populations only a few will be directly applicable with *Gaia*. Detection limits of *Gaia* photometry ($V\sim20$), for example, essentially will rule out the possibility of using white dwarf cooling sequences for this purpose (e.g., Cacciari 2002). Nucleochronology using radioactive elements (spectral line ratios of $^{232}$Th and $^{238}$U), though being the most direct dating method available today, requires spectroscopic observations at very high resolution ($R\geq70000$, see Cayrel et al. 2001) and thus may not be employed with *Gaia* either.

The traditional method of dating stellar populations using stars located at the main-sequence turn-off point (TO) is another obvious choice. Besides of theoretical backup in terms of reliable isochrones, the method requires precise photometry of individual stars in a given stellar population, knowledge of their distances and of the interstellar extinctions. All of these ingredients will be available from *Gaia*, making dating with TO stars particularly attractive.

Obviously, in order to obtain a reliable age using the TO the observed sample has to include stars in the vicinity of the TO point and 1–2 mag below it. Thus, to do this for *all* ages up to $\sim 15\,$Gyr requires precise photometry of individual stars down to $M_V \sim 5$ (spectral type $\sim$G5 V, slightly depending on metallicity). Accurate parallaxes ($\pi$) and proper motions ($\mu$) of individual stars are also needed ($\sigma_\pi/\pi$, $\sigma_\mu/\mu \leq 0.1$), to assure that they belong to the same stellar population.

Surprisingly, it appears that these requirements put rather tight constraints on the applicability of the TO method using *Gaia* data. It has been shown by Bertelli (2002) that the method is confined to within 2.0–2.5 kpc if the limit is set at $M_V = 4.5$, essentially because precise parallaxes are not available at greater distances. The limiting distances become greater if the restriction (in terms of accuracy) is put on the proper motions instead of parallaxes. For a given magnitude, the relative error in proper motion is about half of that in relative parallax, which would extend the limiting distances by a factor $\sim 1.5$. However, extinction will remain a crucial factor, since with growing interstellar reddening TO stars rapidly become too faint to be detected by *Gaia* (Kučinskas et al. 2003). Given a mean Galactic interstellar extinction of $A_V = 0.7$ mag/kpc and assuming that stars with $M_V = 5.0$ should be at least one magnitude brighter than the detection limit of *Gaia* to trace the TO reliably, one obtains a limiting distance of $\sim 2.7$ kpc.

Stars on the red giant branch (RGB) and asymptotic giant branch (AGB) may offer an interesting alternative for dating stellar populations to substantially greater distances, while providing comparable precisions in the derived ages (see Kučinskas et al. 2003 and references therein). Since these objects are considerably brighter than TO stars, the gain in distance is indeed significant (see Table 1). This approach needs near-infrared (NIR) photometry for getting the precise effective temperatures of the individual RGB/AGB stars. While this will not be provided by *Gaia*, NIR fluxes will be readily available from future ground-based NIR surveys (VISTA, UKIDSS, etc.) for the majority of RGB/AGB stars in the Galaxy and in nearby Local Group galaxies.

Table 1 summarizes the prospects for tracing Galactic star formation histories with *Gaia*, using both traditional TO method and RGB/AGB stars. The expected accuracies of kinematical and astrophysical parameters are given for the apparent magnitudes at which $\sigma_\pi/\pi = 0.1$, for several values of interstellar reddening. The accuracies of parallaxes and proper motions correspond to current estimates for *Gaia-2* (de Bruijne 2003). We also provide expected uncertainties for radial velocities (Katz & Munari 2003) and astrophysical parameters of individual stars derived using the 1X medium-band photometric system (Vansevičius & Bridžius 2003).

**Table 1.** Predicted accuracies for kinematical and astrophysical parameters of G5 V star ($M_V = 5.0$; TO tracer of 15 Gyr old population) and M3 III star ($M_V = -1.0$; RGB/AGB tracer) as derived with *Gaia*. Data for each tracer type is given at $V$ magnitude corresponding to $\sigma_\pi/\pi = 0.1$.

| Sp | $E_{B-V}$ | $V$ | $d$ kpc | $\sigma(v_{\rm r})$ km/s | $\sigma$([Fe/H]) | $\sigma(T_{\rm e})$ % | $\sigma(\log g)$ |
|---|---|---|---|---|---|---|---|
| G5 V | 0.0 | 16.9 | 2.4 | 5.5 | 0.1 | 2. | 0.2 |
| | 0.5 | 17.7 | 1.7 | 10 | 0.15 | 2.5 | 0.3 |
| | 1.0 | 18.4 | 1.1 | $> 20$ | 0.2 | 3. | 0.5 |
| M3 III | 0.0 | 14.2 | 10.9 | $< 1.0$ | 0.05 | $< 1.0$ | 0.1 |
| | 1.0 | 15.8 | 5.5 | 1.6 | 0.05 | $< 1.0$ | 0.1 |
| | 2.0 | 17.3 | 2.6 | 6.5 | 0.1 | $< 1.0$ | 0.15 |

Table 1 gives a clear indication that the applicability of TO approach with *Gaia* for tracing stellar populations of *all ages* up to 15 Gyr will be generally confined to within $\sim 2-3$ kpc of the Solar neighborhood. It should be stressed, however, that younger stellar populations may be dated at considerably larger distances, since in this case the limiting $M_V$ will be brighter (see below). Note that there will be a certain minimum distance as well, due to the requirement of having statistically significant number of stars in a particular stellar population. The situation will be further complicated in the Galactic plane by crowdedness, which will affect significantly both the medium-band photometry and spectroscopy. Finally, the derivation of interstellar extinction towards individual stars represents another generic problem, which might be especially troublesome in the presence of multiple small interstellar clouds along the line of sight (Sūdžius et al. 2002).

Indeed, problems in the Galactic plane (crowdedness, reddening, etc.) will put certain limitations on using RGB/AGB stars as well. It is clear, however, that the use of tracers that are intrinsically bright would certainly extend the capabilities of *Gaia*, allowing to probe populations that are considerably more distant (a factor of 3–4) and/or more obscured by interstellar extinction. This contribution may be especially valuable for tracing stellar populations in the Galactic plane, where the applicability of the TO approach is limited, primarily by the interstellar reddening.

### *2.2. Star formation histories in the Local Group galaxies*

In the light of what has been said above, it is remarkable that *Gaia* will still be able to provide a mass of unique information on stellar populations even in such distant objects as galaxies of the Local Group. Although the youngest stellar populations ($\leq$ 0.2 Gyr) may be traced using the TO stars in stellar populations even as distant as the Magellanic Clouds (Kučinskas et al. 2002), the majority of information will be obtained with tracers that are considerably brighter intrinsically, such as stars on RGB/AGB, supergiants, etc.

The possibilities for tracing stellar populations with RGB/AGB stars are summarized in Table 2, were we display expected accuracies in kinematical and astrophysical parameters of a typical RGB/AGB tracer. As in Table 1, accuracies of kinematical parameters are given for the current *Gaia-2* setup (not shown when relative error in $\pi$ and $\mu$ exceeds 100%); astrophysical parameters are derived from *Gaia* medium-band photometry using the 1X photometric system (Vansevičius & Bridžius 2003). Note that for this type of tracer expected accuracies in astrophysical parameters are nearly independent of extinction for small values of $E_{B-V}$.

**Table 2.** Predicted accuracies versus magnitude for kinematical and astrophysical parameters of M3 III star ($M_V = -1.0$; RGB/AGB tracer) as derived with *Gaia*.

| $E_{B-V}$ | $V$ | $d$ kpc | $\sigma_\pi/\pi$ | $\sigma_\mu/\mu$ | $\sigma(v_{\rm r})$ km/s | $\sigma$([Fe/H]) | $\sigma(T_{\rm e})$ % | $\sigma(\log g)$ |
|---|---|---|---|---|---|---|---|---|
| 0.0 | 16.0 | 25 | 0.50 | 0.26 | 1.8 | 0.05 | $<1.0$ | 0.1 |
| | 17.5 | 50 | – | – | 7.9 | 0.1 | $<1.0$ | 0.2 |
| | 19.0 | 100 | – | – | $>20$ | 0.2 | 1.0 | 0.3 |
| 0.5 | 16.0 | 12.5 | 0.25 | 0.13 | 1.8 | 0.05 | $<1.0$ | 0.1 |
| | 17.5 | 25 | – | 0.53 | 7.9 | 0.1 | $<1.0$ | 0.2 |
| | 19.0 | 50 | – | – | $>20$ | 0.2 | 1.0 | 0.3 |

It is obvious that a lot of kinematical information is obtained up to the distances of the Magellanic Clouds, when the interstellar extinction is small. Astrophysical parameters of individual stars are obtained at even greater distances (up to $\sim$ 100 kpc), which will allow tracing stellar populations also in other nearby galaxies of the Local Group (Draco, Fornax, Sculptor, etc.). This information is especially important for studies of extended halos of the nearby dwarf spheroidal galaxies, galactic halo streams, etc.

## 3. CONCLUSIONS

Of the many methods available for dating stellar populations only a few are directly applicable with *Gaia*. Moreover, the traditional approach of tracing star formation histories with TO stars will be rather limited in terms of distance and/or reddening ($\sim 3$ kpc). It seems, however, that stars on the RGB/AGB provide an interesting alternative for extending these limits considerably. The credibility of using RGB/AGB stars for tracing ages of stellar populations with *Gaia* must be verified by extensive tests in a variety of astrophysical contexts. However, the possible superiority of the method in terms of traceable distances emphasizes that this and other alternatives to the TO approach should be carefully investigated in order to exploit the vast potential of *Gaia*.

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