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Galactic astronomy and small telescopes

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Abstract. The second data release of ESA's Gaia satellite (Gaia DR2) revolutionised astronomy by providing accurate distances, proper motions, apparent magnitudes, and in many cases temperatures and radial velocities for an unprecedented number of stars. These new results, which are freely available, need to be considered in virtually any stellar research project, as they provide crucial information on luminosity, position, motion, orbit, and colours of observed targets. Ground-based spectroscopic surveys, like RAVE, Gaia-ESO, Apogee, LAMOST, and GALAH, are adding more measurements of radial velocities and, most importantly, chemistry of stellar atmospheres, including abundances of individual elements. We briefly describe the new information trove, together with some warnings against blind-folded use.

Even though it may seem that Gaia is already providing any information that could be collected by small telescopes, the opposite is true. In particular, we discuss a possible reach of a ground-based photometric survey using a custom filter set. We demonstrate that it can provide valuable information on chemistry of observed stars, which is not provided by Gaia or other sky surveys. A survey conducted with a small telescope has the potential to measure both the metallicity and alpha enhancement at a ~ 0.1 dex level for a large fraction of Gaia targets with temperatures between 4500 and 7500 K, a valuable goal for galactic archaeology.

Key words: galactic archaeology – photometric surveys

1. Introduction

Our Galaxy is a typical barred spiral galaxy. So understanding its structure, evolution, and origin is an important endeavour and the goal of galactic archaeology (Freeman & Bland-Hawthorn, 2002). Many questions can be answered only by studying our Galaxy, as even detection of individual stars in nearby galaxies can be a difficult task. On the other hand, we are located inside our Galaxy, so its more than 10^{11} stars are distributed all over the sky and are in many cases obscured by interstellar dust clouds. Knowledge of distances and 3-dimensional motions is crucial to derive luminosities and orbits of observed stars. Orbits are important, as they allow identification of a given star as a member of a particular galactic component, i.e. the thin or thick disks, bulge or halo. Stars on bound orbits in the halo are moving in a low density environment, so they get perturbed only twice per Galactic orbit during their passages through the Galactic plane. Their kinematic properties, like the total energy, total angular momentum and the size of its z-component maintain a nearly constant value. As a consequence, present orbits of stars in the halo can have their origins traced to individual dwarf galaxies which were cannibalised by our Galaxy some 12 billion years ago (Helmi & de Zeeuw, 2000). Unfortunately, this type of kinematic reasoning does not work in a higher-density environment of a galactic disc. Studies of origin of individual disk stars should therefore rely on measurements of chemistry of their atmospheres, which remains constant throughout their lives (except for material dredge-ups late in their lives). So one could hope to identify stellar siblings with an origin in a common star cluster which has now long-gone. This is the idea behind chemical tagging (De Silva et al., 2007, 2015; Kos et al., 2018).

In this contribution we first briefly review recent space and ground-based stellar sky surveys, which now provide a firm observational basis for galactic archaeology. We urge the users to use the new and freely available datasets in their daily research activities. Finally, we connect these datasets with the reach of surveys using small telescopes, in particular we discuss how stellar chemistry can be studied through a photometric survey which uses a customised filter set.

2. Gaia satellite of ESA

April 25, 2018, is an important date, as from then on astronomers have access to the second data release of the satellite Gaia of the European Space Agency (Gaia DR2, Brown et al., 2018). The release vastly expanded the available number (Table 1) and accuracy (Table 2) of astrometric, but also photometric and radial velocity measurements. Gaia DR2 profoundly changed every area of astronomy: parallaxes, for example, are now available for 1.3 billion stars at a typical accuracy of 0.03 mas at the bright end, which can be compared to already very impressive but much smaller and less accurate parallaxes for 2 million stars at a 0.3 mas level, published in Gaia's first data release (Brown et al., 2016).

New information should benefit virtually any stellar research project. In many cases it provides a good handle on absolute magnitude, colour, spatial position and orbit of the observed object(s), a completely novel situation in astronomy where such information has been largely limited to members of star clusters, or other spatially confined groups where a suitable standard candle could be found. Finally, the field stars are joining the game of disentangling detailed physics and Galactic orbits.

The data trove of Gaia should be, however, used responsibly. First, Gaia is not measuring distances but parallaxes. Relation between the two can be non-trivial, as thoroughly discussed by Bailer-Jones et al. (2018). Some of the reported parallaxes are negative which *is* a correct statistical data treatment. In many cases this puts a firm lower limit on the true distance of the observed

Table 1. The number of stars in the Gaia DR2 with a cited type of information (Brown et al., 2018).

Type of information	Number of stars
Position and brightness on the sky	1,692,919,135
Red colour photometry	1,383,551,713
Blue colour photometry	1,381,964,755
Parallax and proper motion	1,331,909,727
Surface temperature	161,497,595
Reddening along the line of sight	87,733,672
Radius and luminosity	76,956,778
Radial velocity	7,224,631
Variable sources	550,737
Orbits of Solar system objects	14,099

object, which can be a valuable piece of information. Some parallaxes are very large, 59 of them have a value larger than the parallax of Proxima Centauri. Still, this does not mean they are closer, but that the reported value is a result of an automated procedure which can get confused by spurious alignment with sources which are resolved by Gaia only in some observations and not in others. It is important to note that there is no universal recipe to mitigate such cases, but that the users can perform custom tests which will effectively resolve such issues on parallaxes and/or proper motions. A useful example is discussed in figure C4 of Lindegren et al. (2018).

Energy and angular momentum of a stellar Galactic orbit cannot be computed without knowledge of the velocity vector. While proper motion and parallax measurements provide accurate values of velocity components along the sky plane, radial velocity can be measured only by spectroscopy, except for nearby stars where perspective acceleration could be used (Prusti et al., 2016; de Bruijne & Eilers, 2012). Gaia mission measures radial velocities with an onboard spectrograph and Gaia DR2 contains an unprecedented set of radial velocities for 7,2 million objects with a typical error of ~ 1 km s^{-1} (Cropper et al., 2018; Katz et al., 2018; Sartoretti et al., 2018). This error can be compared to the error budget on velocities along the sky plane. Table 3 illustrates the error budget for a Solar type and for a red clump star, both at a distance of 1 kpc, if interstellar extinction can be neglected. The next to last line shows that for stars at rest their velocities along the sky plane are determined to ~ 0.1 km s^{-1}, while the last line demonstrates that for fast moving stars the uncertainties on their distance increase the errors on their velocities along the sky plane to more than 1 km s^{-1}. So at least for slowly moving stars and for the ones in clusters it is desirable that the radial velocity component has an error similar to errors of velocities along the sky plane, i.e. ~ 0.1 km s^{-1}. Note also that any studies of dynamics *inside* star clusters greatly benefit from accurate velocities, as escape

Table 2. Typical uncertainties of Gaia DR2 (Brown et al., 2018). G magnitude is a white light measurement by Gaia, while G_{BP}, G_{RP} and G_{RVS} are integral measurements in its blue, red and Gaia-RVS bands; mas stands for milli-arc-second.

Data product or source type	Typical uncertainty
Five-parameter astrometry (position & parallax)	0.02-0.04 mas at $G < 15$
	0.1 mas at $G = 17$
	0.7 mas at $G = 20$
	2 mas at $G = 21$
Five-parameter astrometry (proper motion)	0.07 mas yr^{-1} at $G < 15$
	0.2 mas yr^{-1} at $G = 17$
	1.2 mas yr^{-1} at $G = 20$
	3 mas yr^{-1} at $G = 21$
Mean G-band photometry	0.3 mmag at $G < 13$
	2 mmag at $G = 17$
	10 mmag at $G = 20$
Mean $G_{\rm BP}$ and $G_{\rm RP}$ band photometry	2 mmag at $G < 13$
	10 mmag at $G = 17$
	200 mmag at $G = 20$
Median radial velocity over 22 months	0.3 km s^{-1} at $G_{\rm RVS} < 8$
	0.6 km s^{-1} at $G_{\rm RVS} = 10$
	1.8 km s^{-1} at $G_{\rm RVS} = 11.75$
Systematic radial velocity errors	< 0.1 km s^{-1} at $G_{\rm RVS} < 9$
	0.5 km s^{-1} at $G_{\rm RVS} < 11.75$

velocity from a cluster seldom supersedes a few km s^{-1}.

3. Ground based spectroscopic surveys

Ground-based spectroscopic surveys designed to complement Gaia include RAVE, Gaia-ESO, Apogee, GALAH, and LAMOST. All but the last one measure radial velocities at a level better than or comparable to Gaia, but for a much smaller number of stars. Internal precision of Apogee is better than 0.1 km s^{-1} (Nidever et al., 2015), and the accuracy is ~ 0.3 km s^{-1} (Anguiano et al., 2018). GALAH survey currently observed more than half-a-million stars with a typical accuracy of their radial velocity of $\sim$ 0.15 km s^{-1} (Zwitter et al., 2018), as it includes also effects of convective blueshift and gravitational redshift of light emerging from a stellar atmosphere. It published also medians of observed spectra that are nearly noiseless, as they are obtained from a large number of observed spectra belonging to the same bin in stellar parameter space with a width of 50 K in temperature, 0.2 dex in gravity, and 0.1 dex in metallicity.

Table 3. Typical errors on distance, proper motion and velocity along the sky plane for a star at a distance of 1 kpc if effects of interstellar reddening can be neglected. Errors on velocity along the sky plane depend on actual velocity of the object: $\sigma(V_\mu)_1$ lists the error if the object is at rest and the error is driven by the proper motion uncertainty; and $\sigma(V_\mu)_2$ is for an object with a velocity of 50 km s^{-1} along the sky plane, where the error is driven by the distance error.

Parameter	Symbol	Solar type star	Red clump star
Absolute V magnitude	M_V	4.83	0.5
$V - I_\mathrm{C}$ colour	$V - I_\mathrm{C}$	0.70	1.06
Apparent G magnitude	G	14.5	10.1
Parallax error	$\sigma_{\tilde{\omega}}$	30 μas	40 μas
Distance error	$\sigma_{distance}$	3%	4%
Proper motion error	σ_μ	17 μas yr^{-1}	22 μas yr^{-1}
Velocity error along the sky plane	$\sigma(V_\mu)_1$	0.08 km s^{-1}	0.11 km s^{-1}
Velocity error along the sky plane	$\sigma(V_\mu)_2$	1.5 km s^{-1}	2 km s^{-1}

Publicly released 1181 median spectra have a resolving power of 28,000 and trace the F-G-K stars with metallicities between -0.6 and $+0.3$ dex.

All of the mentioned ground-based spectroscopic surveys determine values of stellar parameters and in many cases also abundances of individual elements. The GALAH survey recently published what is currently the largest set of abundances of up to 23 chemical elements, which now includes 342,682 stars (Buder et al., 2018). This chemical information is crucial in complementing the excellent astrometric and photometric information from Gaia.

4. Proposal for a dedicated photometric survey

Gaia can judge on chemical composition of stars from two sources of information. It can use its radial velocity spectrograph (RVS) which collects several tens of spectra for stars brighter than $V \sim 15$. By adding up all spectra of a given star the combined spectrum yields radial velocity and – for bright-enough sources ($V \lesssim 12.5$) – also metallicity. Experience from the RAVE survey, which observed in the same wavelength range as Gaia RVS, shows that metallicity is driven by strong lines of the Calcium triplet, so that it is very difficult to separate iron abundance ([Fe/H]) from alpha enhancement ([α/Fe]) for relatively faint stars with noisy spectra (Zwitter et al., 2008; Kunder et al., 2017). The second source of chemistry for Gaia is star's spectral energy distribution which is sampled by low dispersion BP and RP spectra. Wavelength span of an effective resolution element (defined as 76% energy extent of the along-scan line spread function) varies from 9.1 nm at 330 nm to 24.5 nm at 640 nm and to 61.5 nm at 1050 nm (Prusti et al., 2016). Assuming the star is observed 100 times during the mission its total exposure time for the BP and RP instruments equals 442 seconds, each.

These low dispersion spectra can be used to determine values of astrophysical parameters for fainter stars than with the RVS instrument. As explained in Bailer-Jones (2011) and Prusti et al. (2016) for FGKM stars at $G = 15$ with less than two magnitudes extinction, effective temperature can be estimated to ~ 150 K, extinction to ~ 0.1 mag, surface gravity to ~ 0.3 dex, and metallicity [Fe/H] to ~ 0.2 dex. Ground-based spectroscopic surveys (RAVE, Apogee, Gaia-ESO, LAMOST, GALAH) have been useful in providing metallicities and in some cases element abundances, but cumulatively they now include less than 5 million stars, a small fraction of 160 million stars brighter than $G = 17$ with effective temperatures published by Gaia DR2. Here we propose a way to extend results on chemistry to fainter stars than doable by Gaia and to obtain iron abundances ([Fe/H]) and alpha-enhancement (α/Fe] separately. This is vital, as iron and alpha element abundances form a basis for stellar population studies (e.g. Krumholz et al., 2018), and present a useful chemical clock (e.g. Freeman & Bland-Hawthorn, 2002).

Star's chemistry can be inferred by measuring its brightness in 3 specific photometric filter bands centred on and off the prominent metallic lines. We use three readily available industrial photometric filters, which have however never been used in astronomy. Band A (394 ± 5 nm) is centred on the Ca II H&K lines, so it is sensitive to abundance of alpha elements ([α/Fe]), band B (430 ± 5 nm) contains many strong Fe I lines, so it is sensitive to metallicity ([Fe/H]), while band C (450 ± 5 nm) lacks any strong metallic lines. Bands have a width of 10 nm, thus moderately sized telescopes can be used. These are hard coated OD 4 10 nm bandpass filters in the Edmund Optics catalogue (items #65-192, #65-198, and #65-201). Their wide availability means that results obtained by different instruments can complement each other.

We build on the fact that luminosity and effective temperature of the source is now known from Gaia, so we can use the colour-colour vs. chemistry relationship holding at this particular position in the luminosity-temperature plane. These relationships can be established by a data driven approach using detailed chemical abundances of benchmark stars measured by ground-based spectroscopic surveys. The GALAH survey (Buder et al., 2018) and other observations by the Hermes spectrograph at the 4-m AAO telescope, which now contain accurate chemical abundances for up to 30 chemical elements and for $\sim 650,000$ stars, can be used, together with the results from RAVE and Gaia-ESO surveys.

Figure 1 illustrates properties of the proposed dataset for main sequence stars (as defined by Pecaut & Mamajek, 2013) using Kurucz models of stellar atmospheres (Munari et al., 2005). AB magnitudes in the three filters are combined into two spectral indices: $A - C$ (top panel) and $B - C$ (bottom panel). For each panel we plot the difference in magnitude if a star with Solar abundances and with a given effective temperature is mistaken for another similar (but not identical) type of object. Solid lines plot the difference if we observe a non-enhanced metal poor star of the same temperature, and dashed lines are for an alpha enhanced metal poor star. Finally, the dotted lines check on the

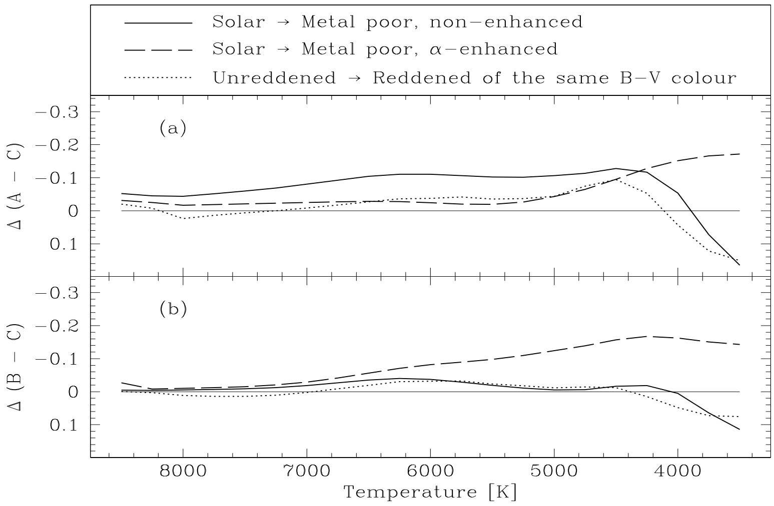

Figure 1. Change in the $A-C$ spectral index (panel a) and $B-C$ spectral index (panel b) as a function of effective temperature for main sequence stars. Three types of changes are plotted: (i) solid lines: observation of a metal poor non-enhanced star ([Fe/H] $= -0.4$, $[\alpha/\mathrm{Fe}] = 0.0$) instead of a Solar type one ([Fe/H] $= 0.0$, $[\alpha/\mathrm{Fe}] = 0.0$) with the same temperature; (ii) dashed lines: observation of a metal poor α-enhanced star ([Fe/H] $= -0.4$, $[\alpha/\mathrm{Fe}] = +0.4$) instead of a Solar type one ([Fe/H] $= 0.0$, $[\alpha/\mathrm{Fe}] = 0.0$) with the same temperature; (iii) dotted lines: observation of two Solar type stars which have the same observed $B-V$ colour, but one is reddened ($A_\mathrm{V} = 0.155$ mag) and the other is not. Horizontal line traces zero values.

influence of interstellar reddening: a star with Solar abundances with a given temperature is replaced with a reddened main sequence star ($A_V = 0.155$ mag) of Solar composition but with an intrinsically higher effective temperature, so that the observed $B-V$ colours of both stars are the same.

Absorption lines in the wavelength range of filter A are mostly lines of calcium, an α element. So the $A-C$ index (Fig. 1a) is sensitive to metal content, in the sense that the flux in filter A increases in the absence of absorption lines. This is true if all elements, including calcium, have a lower abundance (solid line in the top panel). But if calcium abundance is increased to Solar levels in a metal poor α-enhanced star ([Fe/H] $= -0.4$, $[\alpha/\mathrm{Fe}] = +0.4$), the $A-C$ index stays virtually the same as for a star with Solar abundances. Behaviour of the $B-C$ index (Fig. 1b) is different. Its values are increased for a metal poor α-enhanced star. So a combination of $A-C$ (Fig. 1a) and $B-C$ (Fig. 1b) indices allows a *separate* judgement of the iron abundance ([Fe/H]) and alpha enhancement ($[\alpha/\mathrm{Fe}]$) values.

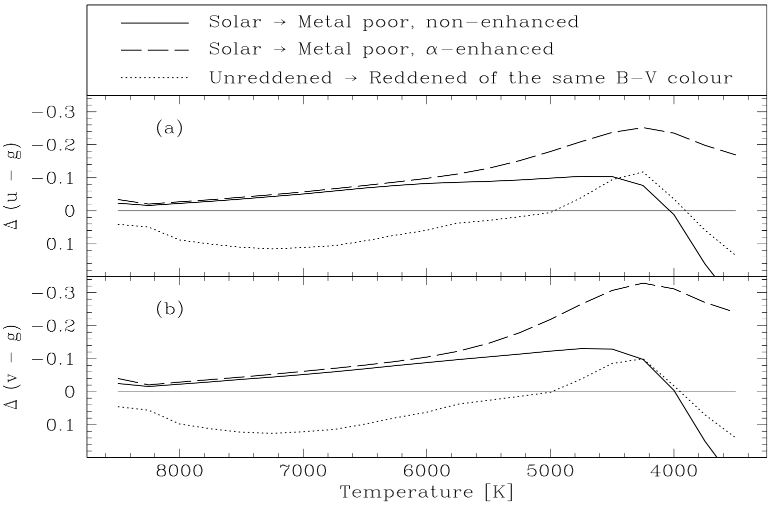

Figure 2. The same as Fig. 1 but for a Sloan $u-g$ index (panel a) and $v-g$ index (panel b). Pairwise behaviour of solid and dashed lines is virtually the same for both panels, so one cannot use the two spectral indices to distinguish changes in metallicity and alpha enhancement. Sloan bands are very blue, so they are sensitive to reddening (dotted lines) which can overshadow changes due to chemistry.

Values of temperature are known from Gaia, but with a typical error of ~ 150 K (Prusti et al., 2016). Derivation of more accurate values is hampered by unknown values of interstellar extinction which is strongly correlated with temperature. As an example, we compare stars with Solar abundances but with two different temperatures: an undereddened star and one which suffers from moderate interstellar reddening ($A_V = 0.155$, $R = 3.1$) and has the same reddened $B-V$ colour as the unreddened star. Typically, this implies that a reddened main sequence star is ~ 160 K hotter than the unreddened one. Results are shown with a dotted line in Fig. 1. Clearly the influence of reddening is moderate, except for stars cooler than 4750 K which have a steeply increasing flux in the range of A and B filters.

Approach outlined here is different from existing photometric surveys (e.g. SkyMapper) which use standard Sloan filters in an attempt to determine both the values of stellar parameters and chemistry, with the result that filters are not optimised for chemical analysis. So these surveys find it difficult to separate abundances of iron and alpha group elements, a vital starting point for any stellar population studies. Note also that the LSST survey uses a similar unoptimised filter set and may be saturated for most stars observed by Gaia.

The situation is illustrated in Figure 2 which is equivalent to Figure 1, except that results for the Sloan indices $u - v$ and $g - v$, as implemented by the SkyMapper survey (Bessell et al., 2011), are presented. Both indices have almost identical solid and dashed curve shapes, so one can use them to determine general metallicity, but there is little hope to separate alpha enhancement and iron abundance. This agrees with recent results of Casagrande et al. (2019) who emphasise usefulness of SkyMapper for metallicity, but do not mention alpha enhancement determination. Note also that amplitudes of dotted curves in Fig. 2 are much larger than in Fig. 1, so measurement of metallicity using Sloan u and g filters which are bluer than A and B filters, is quite sensitive to damaging effects of interstellar reddening.

5. Conclusions

Gaia DR2 presents a profound change in the way research in astronomy is being done, so it should be used by virtually any astronomer. Still, it is important this information trove is used responsibly, taking into account all the information which was provided along with the data release. Complementary ground-based spectroscopic surveys are adding valuable information on chemistry of observed targets. The last months are bursting with activity, the Gaia DR2 paper (Brown et al., 2018) is the most cited paper in the field of astronomy and astrophysics published this year. Among the many significant results one could point to a disagreement between the value of the Hubble constant as determined from local Cepheids by Gaia and HST and between the value suggested by Planck observations of the early Universe (Riess et al., 2018), discovery of a perturbation and oscillation of the Galactic disk by a passage of a dwarf galaxy between 300 million and 900 million years ago (Antoja et al., 2018; Bland-Hawthorn et al., 2018), formation of the thick disc (Helmi et al., 2018), rich details of Hertzsprung-Russell diagrams (Babusiaux et al., 2018), and new studies of stellar clusters which are now relieved from uncertainties regarding their membership (e.g. Kos et al. 2018, 2018a).

Despite the tremendous success Gaia cannot do it all. Very accurate values of radial velocities and abundances of individual chemical elements are largely left to be determined by the ongoing spectroscopic ground-based surveys. An additional possibility which is briefly discussed above, is a photometric survey using dedicated filters which should be able to indicate metallicity and alpha enrichment of observed targets. This is achieved through the use of dedicated photometric filters which are narrower than resolution elements of Gaia's BP and RP instruments. Such a survey is within reach of a small telescope, which could therefore make a very significant contribution to Galactic astronomy.

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