ESLAB #53: The *Gaia* Universe
Edited by J.H.J. de Bruijne

Dust distribution in the Milky Way disk

Clément Hottier[1], Carine Babusiaux[2,1], Frédéric Arenou[1]

[1] GEPI, Observatoire de Paris, PSL Research University, CNRS, 5 Place Jules Janssen, 92190, Meudon, France
[2] Univ. Grenoble Alpes, CNRS, IPAG, 38000 Grenoble, France

Abstract

To study the Galactic disk structure, we use the combination of the near-infrared survey 2MASS and Gaia DR2. We develop the Field Extinction - Distance Relation Deconvolver (FEDReD) algorithm to unravel distance and extinction. It is a Bayesian deconvolution algorithm which works field of view by field of view. It uses an empirical HR diagram built from Gaia DR2 and takes into account the surveys selection functions.
We apply FEDReD in fields of view on the galactic plane ($b = 0^\circ$ and $0^\circ < l < 360^\circ$) to obtain an extinction map of the galactic disk. This map reveals some dust structures such as spiral arms and clouds.

1 Introduction

Stars are the visible part of the Galaxy, but they appear projected on the 2 dimensions surface of the celestial vault. Furthermore, the light produced by stars is attenuated and reddened by the interstellar extinction. That's why the understanding of the Galactic structure is so challenging.

Nevertheless we already know some galactic structures, such as spiral arms. Some works locate them using different tracers, we can cite gas clouds (e.g. Nakanishi & Sofue (2016)), masers (e.g. Reid *et al.* (2014)) and star forming complex (e.g. Russeil (2003)) but no agreement on their number has been found yet. Other works explore the extinction component of the galaxy (Marshall *et al.*, 2006).

We develop the FEDReD algorithm to analyse the distribution of extinctions and stars along a line of sight. To do so it analyses near-infrared photometry, which for this work is provided by the 2MASS catalogue (Skrutskie *et al.*, 2006). We combine it with the Gaia DR2 catalogue (Gaia Collaboration *et al.*, 2018b), using the cross-match provided by Marrese *et al.* (2019), to get more photometric and astrometric information (Evans *et al.*, 2018; Lindegren *et al.*, 2018). This proceeding summarises the working process of FEDReD, concerning the extinction inference. The features concerning the star's distance distribution is still an ongoing work.

2 FEDReD algorithm

FEDReD has been developed in order to infer the relation between the extinction A_0 and the distance D for a given field of view. It uses near-infrared photometry complemented by Gaia DR2 photometry and astrometry when it is available. In this proceedings, we will just summarise the general working process of the algorithm, see Babusiaux *et al.* (2019) for more details.

FEDReD works in the distance D - extinction A_0 space. It proceeds into two different steps. The first one consists of processing the individual probability distribution function (PDF) of each observed star in the field of view. The second step merges all those PDFs into a unique PDF corresponding to the field of view.

2.1 Star's PDF

This first step aims at processing the probability density of each star in the field of view. To be analysed, a star needs at least to have been observed in the infrared (in band J, H, K) and for some stars GDR2 information is also available.

To compute the likelihood $\mathrm{P}\left(O \mid A_0, D\right)$ of the observation of a given star (O) at the distance D - extinction A_0, we compare its apparent photometry to an empirical reference HR diagram. Indeed, we can process the theoretical apparent magnitude of stars in the HR diagram, at the distance D with extinction A_0, for each photometric band. Then we compare those theoretical values to the observed ones.

In Figure 1 we represent the resulting density for two simulated stars, a main sequence star and a red clump star. They are both at $3\ \mathrm{kpc}$ with an A_0 extinction of $3\ \mathrm{mag}$.

2.2 Merging stars' PDFs

To merge individual results of each star we used a Richardson-Lucy deconvolution. As it is an iterative process, we stop the computation when the evolution between two successive iterations is smaller than 5%.

To initialise the deconvolution, we have to set up several prior distributions. We use a flat truncated $\mathrm{P}\left(A_0 \mid D\right)$ prior, *i.e.* at a given distance D, $\mathrm{P}\left(A_0 \mid D\right) = \mathrm{cst}$ if $A_0 < 10 \times D$, $\mathrm{P}\left(A_0 \mid D\right) = 0$ otherwise. This avoids the overweighting of outlier signals at low distances in crowded fields with few Gaia DR2 information. We also define a prior on the stellar distance distribution, $\mathrm{P}\left(D\right)$ as a simple exponential galactic disk model.

To perform a correct deconvolution, we also have to take care of the selection function S of the field of view. This S function is a model of the 2MASS completeness and allows us to process $\mathrm{P}\left(S \mid A_0, D\right)$. This distribution is used to process $\mathrm{P}\left(A_0, D\right)$ from $\mathrm{P}\left(A_0, D \mid S\right)$, which is the actual output of the deconvolution.

Once we know the distribution of $\mathrm{P}\left(A_0, D\right)$ of a field of view, we have to derive the relation $A_0(D)$ between distance and extinction. To perform it, we use a Monte Carlo approach to generate random increasing relations following the distri-

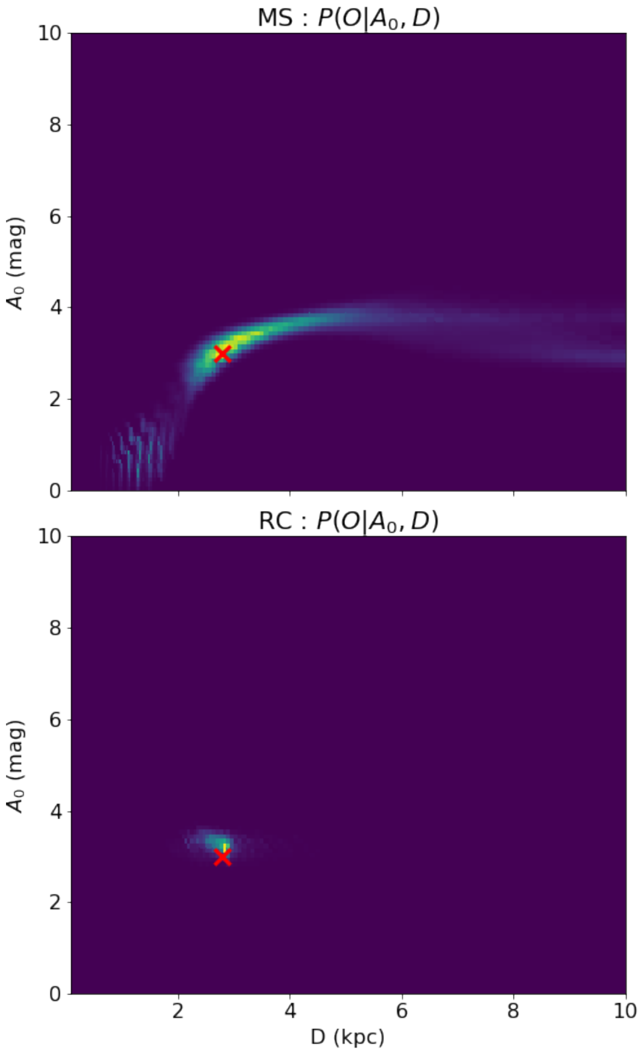

Figure 1: PDF of two simulated stars, Top: main sequence star ; Bottom: Red Clump stars. The theoretical location of both stars in the (D, A_0) space is indicated by a red cross

bution $\mathrm{P}(A_0, D)$. We generate 5000 of these Monte Carlo solutions (MCSs), we then process the probability of each of them, and we keep only the 100 best ones. Then we fit a monotonic spline (Ng & Maechler, 2007) on those best solutions to obtain the relation $A_0(D)$ of the field of view.

We represent on Figure 2 the distribution $\mathrm{P}(A_0, D)$ obtained on a simulated field of view and we overplot some MCSs and the best fit.

3 Reference HR diagram

To analyse the observed stars, we need a reference. We have implemented two different references in FEDReD, the first one uses isochrones from Bressan *et al.* (2012). We use an initial mass function and a stellar formation rate to process the weight of each point. Those isochrones have been used before the Gaia DR2 and provide good results on near-

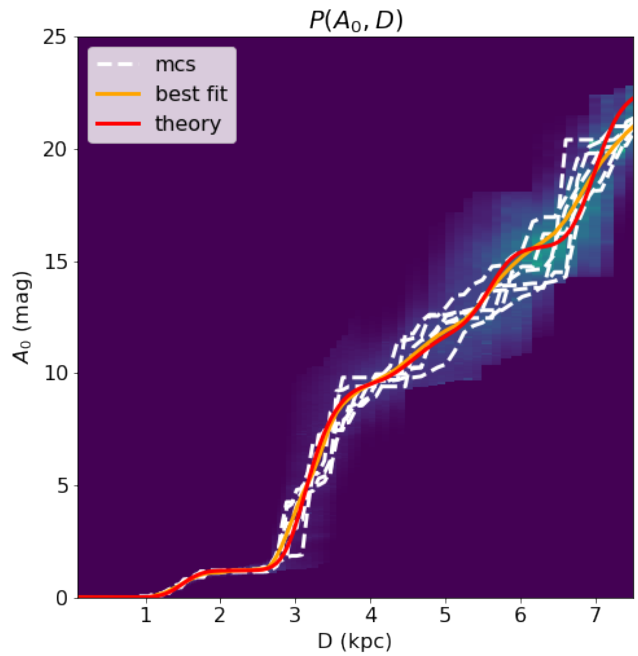

Figure 2: FEDReD result: $\mathrm{P}(A_0, D)$ distribution. The dash line corresponds to some MCSs and the continuous line represents the fitted constrained spline.

infrared photometry. But now, with the Gaia DR2 catalogue and the cross match with 2MASS, we can process a new reference set, which does not depend on any models.

We extract, from Gaia DR2 catalogue, stars within 50pc from the galactic plane, with low extinction according to Capitanio *et al.* (2017). We apply the astrometric and photometric filters described in Gaia Collaboration *et al.* (2018a) to obtain a clean set of reference stars with a known absolute magnitude. For each point of this HR diagram, we use a weight consistent with the observed stellar density and corrected from our selection effects.

This reference HR diagram is built with solar neighbourhood stars, but we assume that it is representative of the Milky Way disk. We use it as a reference to analyse stars individually, but also to process the completeness ($\mathrm{P}(S \mid A_0, D)$) of fields of view.

4 Extinction Map

4.1 Merging fields of view results

We split the galactic disk into 750 separate fields of view, and we apply FEDReD on each of them. Each field is processed independently. To obtain a better extinction map, we use MCSs instead of best fit to process the final result. We can generate a map by picking one MCS randomly for each field of view, we then smooth the result by averaging extinction in a line of sight with the two direct neighbours for each distance bin. This process gave us a Monte Carlo map (MCM). In this MCM, each line of sigh extinction takes into account all information coming from neighbouring lines of sights.

We generate 1000 MCMs, in order to obtain 1000 available $A_0(D)$ relation per line of sigh, which take into account angular correlations. Then we fit a constrain spline in those

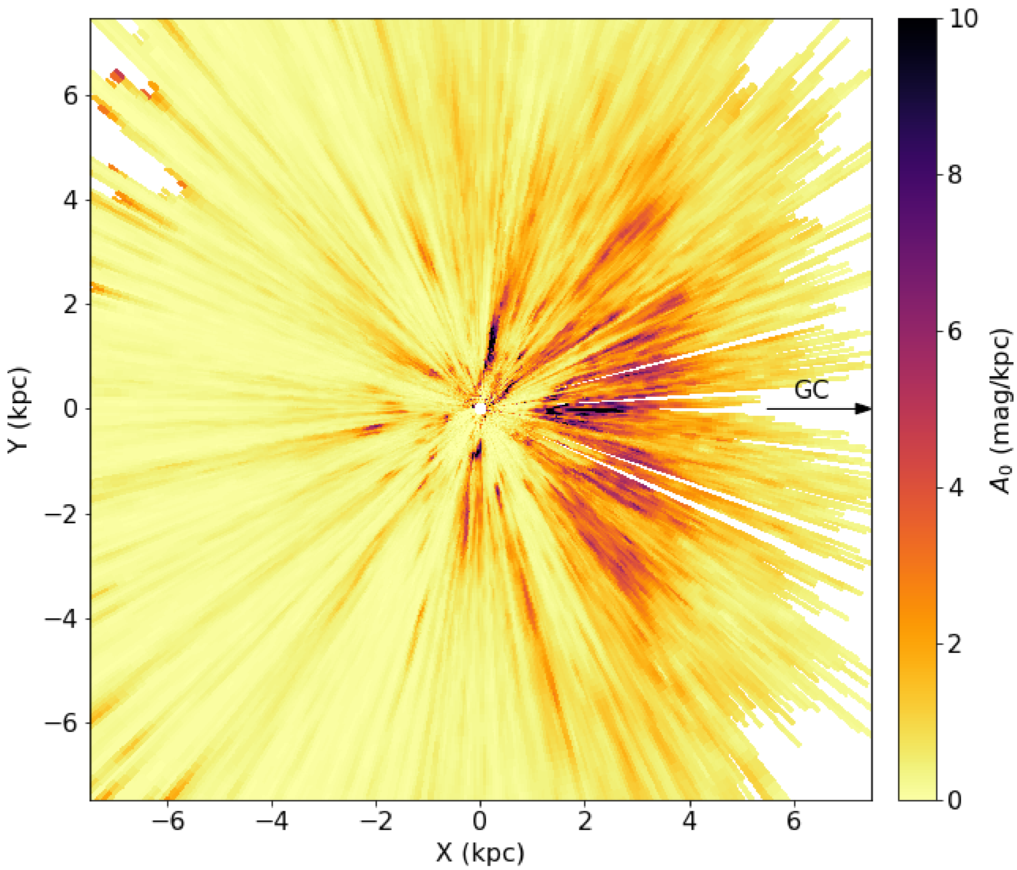

Figure 3: Preliminary A_0 extinction map obtained by analysing 2MASS and Gaia DR2 data with FEDReD. The Sun is at (0,0) and the direction of the galactic centre is indicated by the black arrow.

1000 relations to obtain the extinction evolution in each line of sighs.

4.2 Extinction map

We present in Figure 3 the extinction map obtained with FEDReD on 2MASS and Gaia DR2 data. We can notice on it several known structures such as the Local arm ($l = 80°$) and the split of the local arm described by Lallement *et al.* (2019). We can also appreciate the complete elongation of other structures such as the Vela cloud ($l = 270°$) which present a empty bubble in its prolongation, or η Carina ($l = 280°$) which has a strong extinction front end but also present a diffuse structure in its back end. Finally, we can notice the four big empty bubbles around the Sun (without counting the local bubble). On our map we localise the edge of bubbles in first, third and fourth quadrants. The limit of the second one is farther than the bound of our results.

5 Conclusion

FEDReD is an algorithm to analyse near-infrared photometry and Gaia data, in order to process extinction map of the Galactic disk. It already provides an extinction map of the galactic disk and precises the shape and the size of structures already identified. All structures visible in the map will be discussed in Hottier *et al.* (2019).

Acknowledgments

This work has made use of data from the European Space Agency (ESA) mission Gaia (https://www.cosmos.esa.int/gaia), processed by the Gaia Data Processing and Analysis Consortium (DPAC, https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement. This work also makes use of data products from the 2MASS, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. This work was granted access to the HPC resources of MesoPSL financed by the Region Ile de France and the project Equip@Meso (reference ANR-10-EQPX-29-01) of the programme Investissements d'Avenir supervised by the Agence Nationale pour la Recherche.

References

Babusiaux, C., Hottier, C., Fourtune-Ravard, Arenou, F., & Gomez, A. 2019, in. prep.

Bressan, A., Marigo, P., Girardi, L., Salasnich, B., Dal Cero, C., *et al.* 2012, Monthly Notices of the Royal Astronomical Society, 427, 127. ISSN 00358711, 13652966.

Capitanio, L., Lallement, R., Vergely, J. L., Elyajouri, M., & Monreal-Ibero, A. 2017, Astronomy & Astrophysics, 606, A65. ISSN 0004-6361, 1432-0746.

Evans, D. W., Riello, M., Angeli, F. D., Carrasco, J. M., Montegriffo, P., *et al.* 2018, Astronomy & Astrophysics, 616, A4. ISSN 0004-6361, 1432-0746.

Gaia Collaboration, Babusiaux, C., van Leeuwen, F., Barstow, M. A., Jordi, C., *et al.* 2018a, Astronomy & Astrophysics, 616, A10. ISSN 0004-6361, 1432-0746.

Gaia Collaboration, Brown, A. G. A., Vallenari, A., Prusti, T., de Bruijne, J. H. J., *et al.* 2018b, Astronomy & Astrophysics, 616, A1. ISSN 0004-6361, 1432-0746.

Hottier, C., Babusiaux, C., & Arenou, F. 2019, in. prep.

Lallement, R., Babusiaux, C., Vergely, J. L., Katz, D., Arenou, F., *et al.* 2019, arXiv:1902.04116 [astro-ph].

Lindegren, L., Hernández, J., Bombrun, A., Klioner, S., Bastian, U., *et al.* 2018, Astronomy & Astrophysics, 616, A2. ISSN 0004-6361, 1432-0746.

Marrese, P. M., Marinoni, S., Fabrizio, M., & Altavilla, G. 2019, Astronomy & Astrophysics, 621, A144. ISSN 0004-6361, 1432-0746.

Marshall, D. J., Robin, A. C., Reylé, C., Schultheis, M., & Picaud, S. 2006, Astronomy & Astrophysics, 453, 635. ISSN 0004-6361, 1432-0746.

Nakanishi, H. & Sofue, Y. 2016, Publications of the Astronomical Society of Japan, 68, 5. ISSN 0004-6264, 2053-051X.

Ng, P. & Maechler, M. 2007, Statistical Modelling: An International Journal, 7, 315. ISSN 1471-082X, 1477-0342.

Reid, M. J., Menten, K. M., Brunthaler, A., Zheng, X. W., Dame, T. M., *et al.* 2014, The Astrophysical Journal, 783, 130. ISSN 0004-637X, 1538-4357.

Russeil, D. 2003, Astronomy & Astrophysics, 397, 133. ISSN 0004-6361, 1432-0746.

Skrutskie, M. F., Cutri, R. M., Stiening, R., Weinberg, M. D., Schneider, S., *et al.* 2006, The Astronomical Journal, 131, 1163. ISSN 0004-6256, 1538-3881.