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3D MAPS OF THE LOCAL INTERSTELLAR MEDIUM: THE IMPACT OF GAIA

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Abstract. Gaia parallaxes combined with colour excess and absorption measurements from large stellar surveys will allow building increasingly precise three-dimensional maps of the interstellar matter (ISM). Reciprocally, detailed maps of the ISM will allow improving photometric calibrations of Gaia and measuring more precisely the amounts of reddening. In the future, the extraction of a diffuse interstellar band (DIB) from Gaia RVS (Radial Velocity Spectrometer) spectra will allow to build a tomography of the carrier of this DIB and compare it with dust and gas distributions. Here we show several results that illustrate current progress in local ISM mapping and a first example of the stellar-interstellar synergy linked to Gaia: a) how Gaia-DR1 parallaxes already modify the ISM maps obtained by means of a full-3D inversion of a compilation of colour excess data, b) how DIB measurements and corresponding Gaia parallaxes can complement colour excess data and improve the maps, c) new hierarchical methods combining distinct surveys, d) improved maps including APOGEE colour excess estimates deduced from the recent Gaia-based photometric calibrations of Ruiz-Dern et al (this issue), e) additional inclusion of LAMOST colour excess estimates (Wang et al, 2016).

Keywords: Interstellar medium, Milky Way, stars

1 Introduction

3D maps of the nearby and distant Milky Way Interstellar Medium (ISM) are useful multi-purpose tools that started to get developed only recently. Their construction requires very large catalogues of distance-limited absorption data to be gathered from stellar spectra, and the additional knowledge of the distances to the target stars. Both types of information are currently in significant, rapid progress: massive photometric, spectro-photometric or spectroscopic stellar surveys have started or are in preparation: they will provide dust extinction and gaseous absorption towards an increasing number of stars. In parallel, Gaia will measure parallaxes towards more than 1 billion of stars.

3D maps or pseudo-3D maps have already been produced based on photometric extinction but also diffuse interstellar bands (DIBs) (see an exhaustive list in Capitanio et al. (2017) , hereafter CLV). Each mapping technique has its advantages and limitations. The full 3D tomographic inversion methods developed by Vergely et al. (2001), Sale & Magorrian (2014) and Rezaei Kh. et al. (2017) are based on individual sightlines and have the advantages of being adapted to the nearby ISM and fully exploiting the correlations between the IS matter volume density in two locations close in space. However, whatever the technique, a major difficulty is associated with the decrease with distance of the achievable spatial resolution, due to increasing uncertainties on target distances and often due to the decrease in volume density of observed targets.

In CLV we have tested the introduction of TGAS parallaxes and presented some attempts to address the above limitations. We have analysed the changes induced in the inverted 3D maps when Hipparcos or photometric distances are replaced with parallax distances from the TGAS catalog (step1). The replacement was possible for 80% of the targets and this use of TGAS had a significant influence in some regions and removed an important discrepancy with other maps in the first quadrant at l$\simeq$70-80°. We subsequently tested the inversion of a composite dataset combining colour excess measurements based on photometry on the one hand, and colour excess estimates based on equivalent widths (EWs) of near-infrared (NIR) diffuse interstellar bands (DIBs) on

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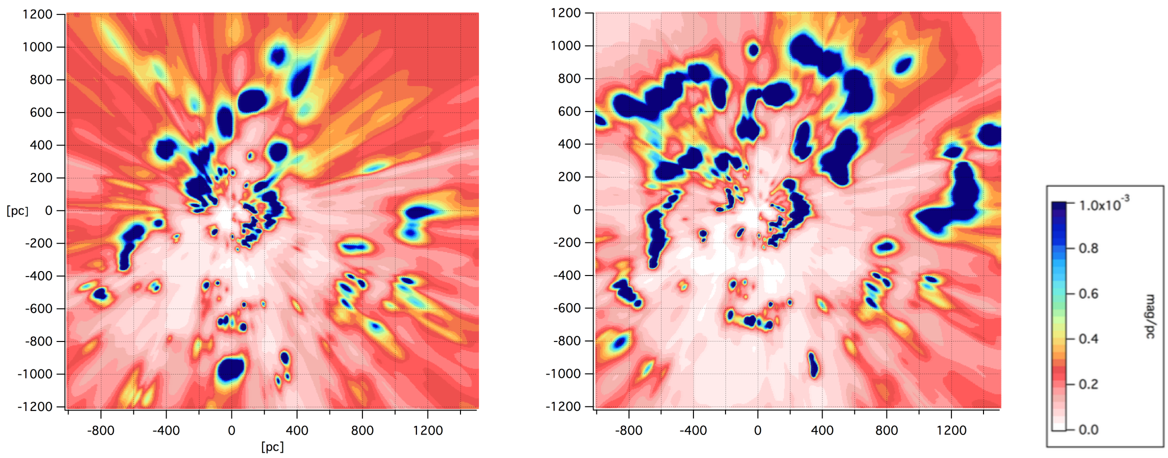

Fig. 1: Dust cloud complexes in the Galactic Plane: units are parsecs, the Sun is at (0,0), the Galactic center to the right, longitudes increase clockwise, the colour scale refers to reddening E(B-V) per parsec (mag.pc^{-1}). Left): map based on the same dataset as in Lallement et al. (2014) and a homogeneous prior distribution, but with TGAS parallaxes for 80% of the targets. Right): the latest map, with additional APOGEE data, both from DIB data and spectrophotometric color excess-distance measurements, and a PS1-based 3D pro (see CLV).

the other hand(Elyajouri et al. 2016) (step 2). The DIBs are extracted from APOGEE spectra (Majewski 2012; García Pérez et al. 2015). For the same dataset we also tested the use of a non-analytically calculated prior distribution, namely a 3D distribution inferred from the larger scale 3D distribution of Green et al. (2015) (step3). Such a use of larger scale prior distributions opens the way to hierarchical methods producing maps with a distance-dependent resolution.

In the present work we illustrate the above 3 steps and two additional improvements of the maps. The first one is based on the inclusion of $\simeq$ 20,000 distance-colour excess estimates for APOGEE red stars (step 4). These estimates utilise the G band calibration described in Ruiz-Dern et al. (2017) and Ruiz-Dern et al (this issue). This calibration could be safely made due to the low reddening of the calibration stars, a dataset selected based on our previous 3D dust maps. Such a positive feedback illustrates the potential synergy between stellar and interstellar analyses. Finally, we tested the inversion of a large target star density in a restricted area, using a fraction of the LAMOST distance-colour excess estimates of the Wang et al. (2016) catalogue. In section 2 we illustrate the effect of steps 2 to 4 in the Galactic Plane, and in section 3 we illustrate the consecutive effects of all the 5 steps in a vertical plane containing Taurus-Perseus.

2 Galactic Plane distribution

To illustrate the benefit of interstellar - stellar feedback in the frame of Gaia, we show in Fig. 1a the dust opacity in the Galactic plane based on the inversion of our previous catalogue of colour excess data (from Lallement et al. (2014)), after replacement of Hipparcos or photometric distances by Gaia parallax distances, when available (see CLV for more details). It is this map that has been used by Ruiz-Dern et al. (2017) to select Gaia targets located along sightlines that are free of dust and enter the Gaia red clump photometric calibration process. This map is compared with a more recent one obtained from an inversion with additional data from the SDSS/APOGEE survey (Fig. 1b). Two types of additional data were included -i) colour excess estimates based on photometry and spectroscopic stellar parameters and ii)-colour excess estimates deduced from the 15273A diffuse interstellar band equivalent width. As in CLV a non-analytical prior distribution deduced from Pan-STARRS 3D maps (Green et al. 2015) is used instead of an homogeneous distribution decreasing exponentially from the Plane to the halo. It is clear from the comparison between the two maps in Fig. 1 that more distant structures are now recovered, especially second ranks of clouds located beyond foreground opaque systems. This is especially visible in the third quadrant and mainly due to two effects: i) the use of more distant target stars, and ii) the use of data in the infrared. The dust clouds being less opaque in this wavelength interval than in the optical range, there are more numerous bright enough targets available beyond the closer cloud complexes and hidden clouds can be are uncovered. More granulation in structures is also seen at the Local Bubble borders, and there are less elongated "fingers-of-God" linked to scarcity of targets. Note that there are no changes in the fourth quadrant due to the distribution of APOGEE targets (observations from the Northern Hemisphere), and also that the use of a large scale prior distribution based on observation implies that maps at large distance or in locations devoid of targets are influenced by this prior (instead of our input catalogue of reddening). As said above, the APOGEE colour excess measurements included in the second map are made using a calibration based on the initial map, showing the iterative process. Work is in progress using APOGEE data and the final calibration of Ruiz-Dern et al. (2017).

3 Dust distribution in a vertical plane contain the Sun and longitudes 160°

A 3D distribution is particularly useful for the nearby structures, because the main cloud complexes in the solar neighbourhood are off-Plane. Indeed, these structures are better seen in vertical planar cuts in the 3D cube. We show in Fig. 2 the dust distribution in one of the vertical planes: the one containing the Sun, the North Galactic Pole and the Galactic sightlines at longitudes 160° and 340°. The 160° half-plane crosses the Taurus/Perseus region at negative latitudes, and the 340 ° half-plane crosses the Sco-Cen region at positive latitudes. The 5 consecutive maps from top to bottom correspond to the 5 steps described in Section 1;
-[step 0] Inversion pre-TGAS, 22467 targets, 22 % Hipparcos parallaxes, 78% photometric distances
-[step 1] Same as in step 0, 80% distances from Gaia TGAS parallaxes, 20% photometric
-[step 2] 4886 additional colour excess measurements deduced from the 15273A DIB, Gaia/TGAS distance
-[step 3] Use of the same dataset as in step 2, now with a non analytical large-scale prior 3D distribution, based on Green et al. (2015)
-[step 4] Same as step3 plus 25196 additional colour excesses of APOGEE DR13 targets. The stellar parameters are derived from APOGEE spectra and distances and colour excesses are deduced from these parameters and all available photometric data.
-[step 5] Same as step4 except for the Taurus/Perseus region, where the result of an additional local inversion based on 29359 colour excess measurements from the LAMOST DR2 catalogue of Wang et al. (2016) has been inserted at l=160 ° and -3≥b≥-35 °. At variance with all other inversions, the minimum size of the structures for this local inversion is 25pc (instead of 15pc) to take into account uncertainties on the distances.

The figure illustrates how the mapping is improved based on new data. Using the infrared range allows to map at larger distances (changes from b) to e), while the use of massive datasets allow to better define the structures (changes from e) to f)).

4 Conclusions

We have shown examples of 3D ISM mapping improvements thanks to Gaia and ground spectroscopic surveys. The next Gaia data releases in combination with current and forthcoming surveys will certainly contribute to develop the mapping in a similar way but in a much larger extent. Difficulties linked to the computation time required for the inversion of massive data need to be solved, but hierarchical techniques are under study or maps can be built region by region. The positive feedback between stellar calibrations and stellar studies in general on the one hand, and interstellar mapping on the other hand will help progressing in both ways.

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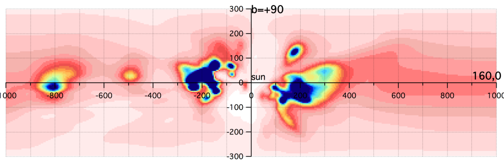
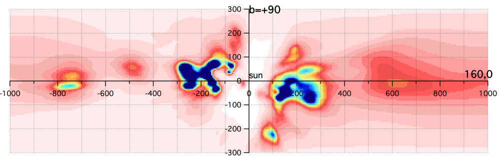
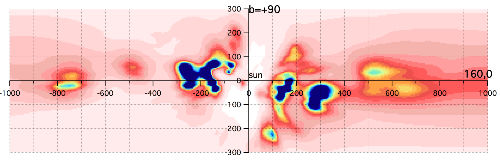


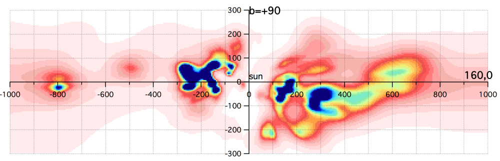
(a) *Distribution without TGAS parallaxes.*



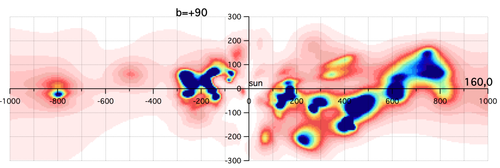
(b) *Distribution with TGAS parallaxes.*



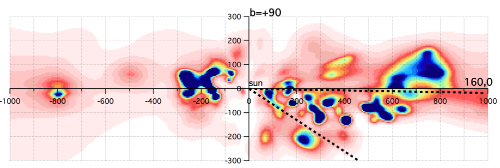
(c) *Distribution with TGAS parallaxes and DIB-based additional data.*



(d) *Distribution as in c) with a large-scale prior from Pan-STARRS-1.*



(e) *Distribution as in d) with colour excess measurements from APOGEE DR12.*



(f) *Distribution as in e) with additional LAMOST data in Taurus/Perseus region .*

Fig. 2: Dust distribution in a vertical plane along longitudes 160-340°. Units are parsecs. The colour scale is as in Fig 1.

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