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Getting ready for Gaia: three-dimensional modeling of dust in the Milky Way

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Abstract. We are developing a non-parametric model to reconstruct the three-dimensional (3D) distribution of dust in the Milky Way. Our approach uses observed line-of-sight (l.o.s) extinctions towards stars at different positions in the Galaxy. These give the integrated dust density along each l.o.s. Making weak assumptions about the correlation of the dust, we infer the most probable 3D distribution of dust which explains the observed extinctions, even at arbitrary points. Given distances and extinctions estimated from the Gaia photometry and astrometry for tens of millions of stars, we plan to build a detailed map of dust in our Galaxy.

Key words. Stars: Parallaxes – Stars: Extinctions – Galaxy: Dust Map – Galaxy: ISM – Galaxy: Milky Way

1. Introduction

Interstellar dust is intrinsically interesting as part of the cycle of matter. It also attenuates light from distant objects as a function of wavelength, thereby confusing our interpretation of stellar photometry, and creating complex selection functions in surveys.

Our model divides the pencil beam along the line-of-sight toward each star into multiple small 1D dust cells (see Fig. 1). It then connects all pairs of cells across different lines-of-sight by using a Gaussian Process to model their covariance: the closer two points, the more correlated their dust densities (smoothness assumption). In this way we get a probabilistic estimate of the dust density at any point in the Galaxy, informed by all the measured extinctions.

The Gaia Data Processing and Analysis Consortium (DPAC) will deliver parallax and extinction estimates and their uncertainties with high precision for tens of millions of stars individually out to several kpc (Bailer-Jones et al. 2013) which enables our model to build an accurate dust map.

2. Results and discussion

In this section we provide some results based on simulated data.

We simulate 200 stars distributed over 12 degrees in longitude towards the Galactic Center (GC) out to 5 kpc from the Sun. We assume that the true dust density decreases exponentially from the Galactic Center with a length scale of 1 kpc. Moreover, as is shown in Fig. 2, there is a dust cloud of 200 pc depth

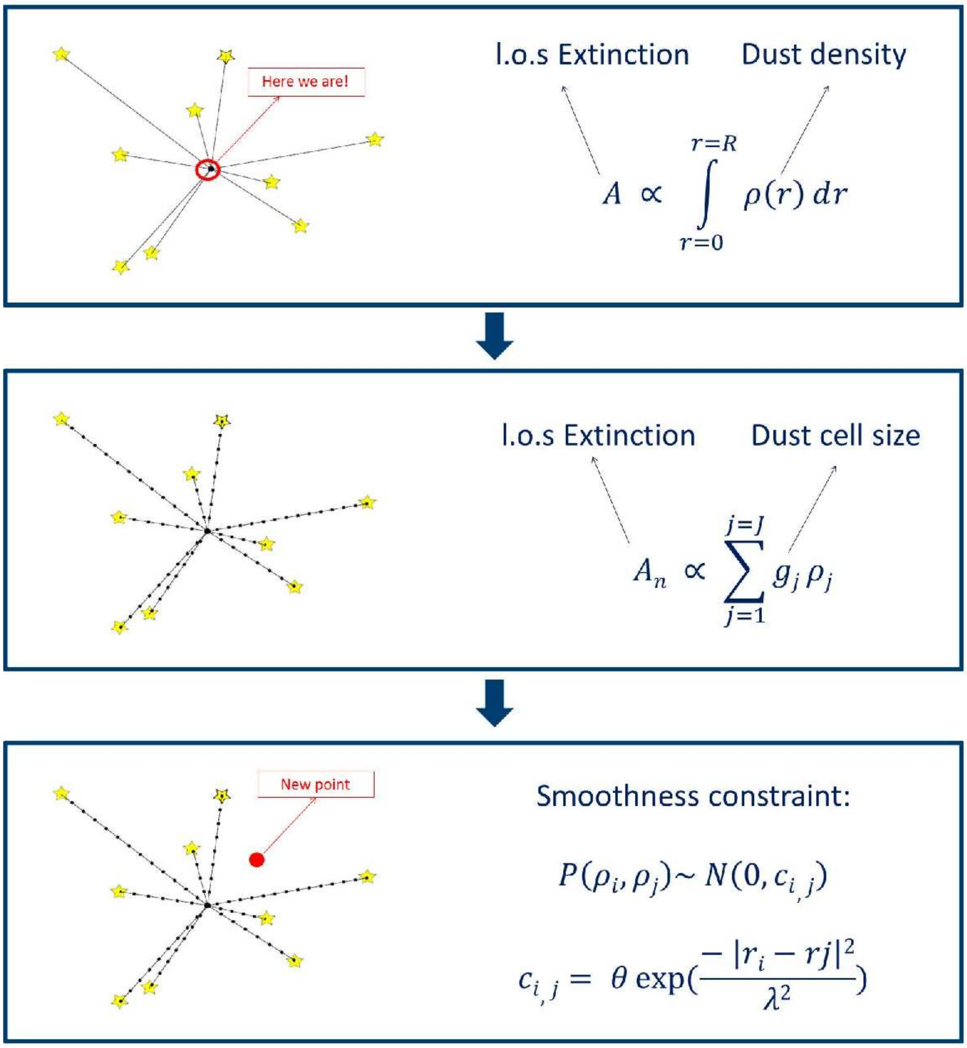

Fig. 1. Schematic picture of how we infer dust density from sparse extinction measurements. The top frame shows the line-of-sight extinction towards each star as well as our location in the center. The central one represents the model which divides each line-of-sight into cells; allowing to go from the integral to summation. Finally connecting every two cells and adding smoothness constrains, it gives us the possibility to find the dust density at a new point with no previous information. λ is the correlation length scale which shows to which distance cells are connected.

at a distance of 3 kpc from the Sun. The extinction is measured for each star and random noise of 0.01 mag is added.

Fig. 3 shows the predicted dust density for this simple simulation. Red points show the true values of dust density using which the ex-

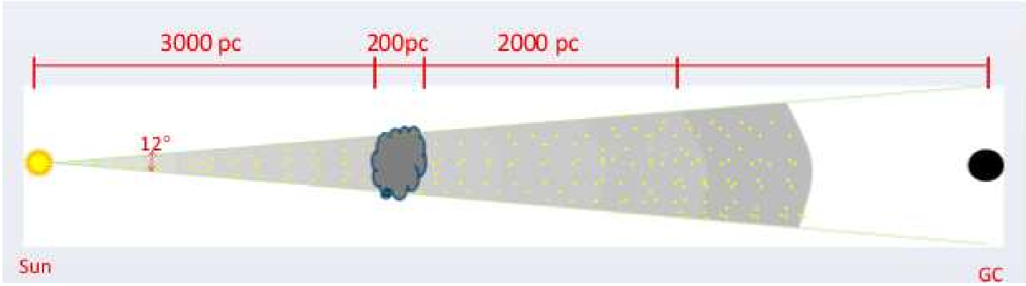

Fig. 2. Schematic picture of the simulated data. We assume the true dust density decreases exponentially from the Galactic center; also, there is a dust cloud at 3 kpc with the depth of 200 pc.

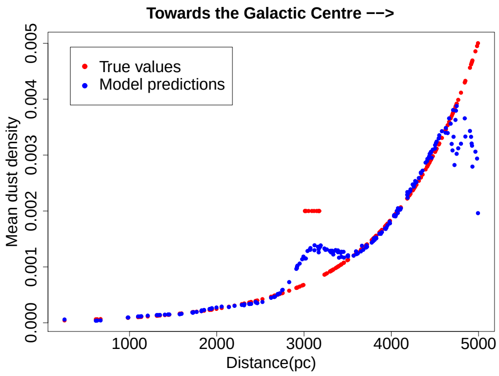

Fig. 3. Model prediction of simulated data. Red points show true values and blue points show predicted values by the model.

tinctions were measured and blue points are values predicted by the model. The agreement is generally good. The discrepancy at large distances is an artifact of the covariance model.

Fig. 4 shows a schematic picture of another simulation in which apart from region 1 as before, 100 stars are simulated in region 3 where the true dust density decreases from the GC outwards; however, despite region 1, there is no dust cloud.

Fig. 5 represents the predicted dust density for the line-of-sight 2 for which no initial data was provided. The result seems plausible; as the model tries to connect cells along this line-of-sight with other nearby cells, it is affected by the dust cloud on one side but not on the other side; resulting in lower rate of dust density around 3 kpc compare to the one in region 1 (compare with Fig. 3).

Our model uses a dust correlation length scale of 2 kpc and dust cell sizes of 100 pc. The correlation length scale (λ in Fig. 1) implies to which distance dust cells are correlated; thus, choosing a small λ may result in disconnecting many close-by cells while a large λ can connect some far away cells which in fact do not share any dust cloud information.

Cell sizes determine the size of structure the model can capture; i. e., the model is not able to capture dust clouds smaller than size of the cells. On the other hand, the smaller the size of the cells, the bigger the number of total cells; resulting in a numerical issue due to an extremely large matrix inversion. Therefore, setting an optimal size for cells can be crucial.

3. Conclusions

We presented a new method for building the three-dimensional map of dust which takes into account the neighboring correlations; results in an improvement in the dust map and overcomes the discrepancy problem in the previous maps. Our method uses line-of-sight extinction and parallax for each star individually and connect them using the Gaussian process find dust densities for any point in the Galaxy.

The next step is to apply the model to millions of stellar extinctions estimated by our group using Pan-STARRS1 and Spitzer data (Hanson & Bailer-Jones 2014) (Hanson et al. 2016).

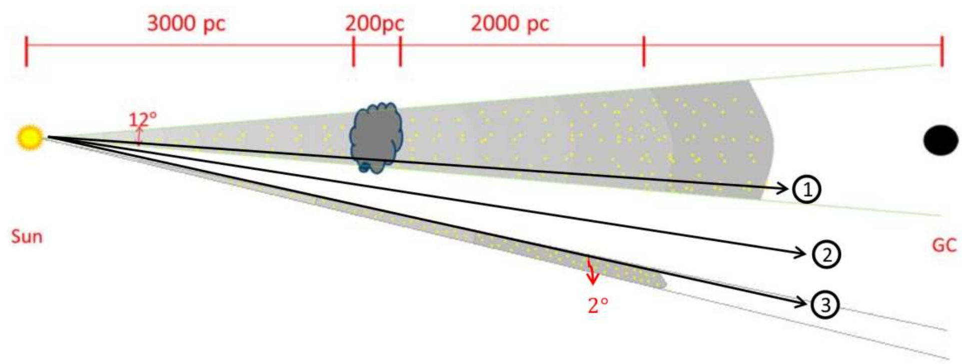

Fig. 4. Schematic picture of the simulated data. In both regions 1 and 3, we assume the true dust density decreases exponentially from the Galactic center; also, in region 2, there is a dust cloud at 3 kpc with the depth of 200 pc. There is no data for region 2.

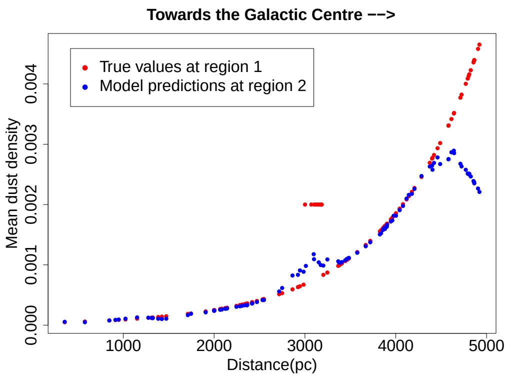

Fig. 5. Model prediction of simulated data (see Fig. 4). Red points show true values in region 1 and blue points show predicted values by the model for the new line-of-sight (region 2).

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