Mem. S.A.It. Vol. 86, 579
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Making of 3D extinction maps from population synthesis approach

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Abstract. Interstellar extinction is critical when studying stellar populations and Galactic structure. By taking into account all informations on stellar populations on a given line of sight, the population synthesis approach is an efficient tool to derive the distribution of extinction. This approach has been shown to give reliable estimates in regions where the stars are numerous enough and well distributed in distance. This method has some limits due to dependency on model hypotheses. With other methods, some biases can appear close to the limiting magnitude, and to the maximum distance of detection, due to detection limits of the stars which depend on the extinction itself. We present the successes of this method as well as its limitations and compare with results of other methods.

Key words. Galaxy: interstellar matter – Galaxy: extinction – Galaxy: stellar populations – Galaxy: modelling

1. Introduction

Interstellar extinction can be seen either as a veil that prevents from in depth exploration of the Galactic plane, or as a tracer of interstellar matter, an important component in Galaxy evolution. The distribution of extinction is an important problem in many Galactic studies. For example determining the astrophysical parameters of stars, such as effective temperature, can be biased if the extinction in front of the star is not well known Liu et al. (2012). Stars are good tracers of the extinction when their reddening and distance can be estimated from their observable properties. The main problem arising when studying extinction comes from the patchiness of the interstellar medium. Therefore a sufficiently dense stellar mesh is needed. The second problem is to accurately determine distances.

Early attempts have been made to trace the extinction all around the sky and in depth. Based on photoelectric observations of a limited number of stars, these attempts allowed the extinction to be traced, but they were limited in spatial extent (the Galactic plane), in spatial resolution (a few stars per square degree at maximum), and in distance (1-2 kpc). The most famous one is from Neckel & Klare (1980). Neckel (1966) based their initial map on only 4700 stars, that they completed by further observations of OB stars during more than

15 years. Finally Neckel & Klare (1980) considered more than 11000 O to F stars, with absolute magnitude error of 0.46 mag which translates into an error of 25% on individual distances. The limitation of their maps comes mainly from the spatial resolution, the distance limit (2 to 5 kpc) and the spatial coverage $|b| < 7°$. Neckel & Klarewere already conscious that the result is biased towards lower extinction at large distances because surveys are incomplete for highly obscured stars. The bias is higher when the dispersion in Av is higher.

A considerable number of extinction studies have followed this pionnering work, a few of which are cited here. They are based on different tracers and can be classified into two groups. First, 2D maps trace the integrated extinction along lines of sight. They were derived from many different data: HI column density measurements (Heiles 1976), galaxy counts (Shane & Wirtanen 1967; Burstein & Heiles 1978, 1982), galaxy colours (Cambresy et al. 2005), FIR emission (Schlegel et al. 1998; Kohyama et al. 2013; Planck Collaboration 2014), or various methods using stellar photometry or spectroscopy on a star by star basis using the expected colours of unreddened stars, either empirical (Neckel, Klare & Sarcander 1980) or from stellar models (for example using infrared excess methods (Lada et al. 1994), or stellar isochrones (Schultheis et al. 1999) among many others). In this case the mean extinction does not necessarily correspond to the integrated one and it can be difficult to compare with integrated maps, though the former can furnish better extinction estimate to be used for corrections of observations.

Second, 3D maps require stellar distances, which is a difficult problem in astronomy. The accuracy and spatial resolution of such maps depend strongly on the spatial distribution of the stars, which can be scarce in numerous regions, or even biased. Moreover, complex methods of interpolation have to be developed to derive 3D maps from independent measurements in front of stars.

Population synthesis can be a useful tool to determine 3D extinction maps by allowing to investigate the distribution of extinction together with the distribution of stars in a self-consistent way, taking into account their inter-relations, and to derive models for the 3D distribution of interstellar matter.

In this presentation, we give a brief description of the principal methods in Sect. 2. In Sect. 3 we introduce the population synthesis approach, and illustrate the benefits of such method in tracing the large scale structure of the ISM (Sect. 4) and in understanding the physics of the galactic matter (Sect. 5). Future perspectives conclude this paper in Sect. 6.

2. Methods

2.1. Extinction in 2D

2D maps of extinction can be traced either using dust emission in the far infrared or from stellar extinction when stars are behind the dust clouds.

The most cited paper in astronomy is the famous Schlegel et al. (1998) maps (hereafter SFD) which provides whole sky estimate of the extinction based of FIR emission from COBE/DIRBE satellite. More recently, Kohyama et al. (2013) improved the SFD map by using a better resolution in dust temperature (5 arcmin). The typical difference between these two maps are of the order of 0.1 mag in Av. Since then, Planck Collaboration (2014) has also produced a very accurate map of the extinction based on the whole sky measurements of the far infrared emission combined with IRAS submillimetric emission. They show evidence of changing dust properties, implying that, while the approach based on FIR emission of the dust is promising, it would require a better knowledge of the physical state of the dust, not yet achieved.

Using the stars themselves, many studies have been based on the location of the stars in colour-colour and colour-magnitude diagrams. Depending on the wavelengths used, the determination can be more or less accurate and adapted to regions of high or low extinction. In order to achieve a whole sky map, it is generally required to consider a wide wavelength range, in the visible for low extinction regions, mainly out of the Galactic plane, and near or mid-infrared for in-plane and bulge regions. These maps are generally limited by the sensitivity of the survey used. A bias in the determination of the extinction also appears in regions where the extinction is highly patchy. At the resolution of the map, one mixes locations having various extinction values. In this case the method furnishes an underestimate of the total extinction along line of sights because heavily extincted stars are not detected and the measurement is based on only the detected (less extincted) stars.

A set of various methods based on the infrared excess method (NICE, see Lada et al. 1994, NICER, see Lombardi & Alves 2001, V-NICE, see Gosling et al. 2009) use the fact that in the near or mid infrared the distribution of the energy in stars does not depend much on the temperature of the stars. Hence the scatter in stellar colours is mostly due to extinction. Majewski et al. (2011) proposed the RJCE method (Rayleigh-Jeans Color Excess) which assumes that the color excess $H - [4.5\mu m]$ is essentially related to the amount of dust between the star and us. This method improves the estimate with regards to others IR color excess methods, and allows to make extinction maps with a resolution limited only by the density of stars. They also show that the extinction integrated along line of sight looks rather different from that predicted using the maps from Schlegel et al. (1998). Instead, they claim that "the Galactic midplane extinction strongly resembles the distribution of ^{13}CO (J = 1-0) emission".

Among the most recent 2D maps using the method of infrared excess, the Dobashi (2011) study is based on a determination of extinction from NIR stellar photometry, using the 2MASS Point Source Catalogue. They used the X percentile method, a modified version of the NICE method (Rowles& Froebrich 2009). This map saturates at $A_V = 20$ mag because of the 2MASS sensitivity. However, while the FIR map measures the total extinction up to the Galaxy edge, the stellar extinction 2D map measures the mean extinction of the stars detected by 2MASS on the line of sight. There is a systematic difference between these two measurements, as estimated by Kohyama et al. (2013), at $|b| < 45°$ of 0.10 mag, 2MASS extinction being smaller in the Galactic plane, while in the Galactic bulge this is the contrary. Dobashi et al. (2013) corrected the Dobashi (2011) original map using an estimation of the background star colours from the Besancon Galaxy model (Robin et al. 2003).

2.2. Turning into 3D maps

Most of 3D extinction maps make use of stellar photometry and statistical estimate of distances, either for individual stars or for groups of stars. Photometry allows to measure big samples of stars in a reasonable observing time, and with the availability of large scale digital surveys has lead to the development of methods to estimate extinction and statistical distances suitable to make detailed maps of the extinction. But they need the distances to be accurately determined to derive a reliable 3D map. Chen et al. (2014) used visible to NIR data to derive the extinction from a SED fitting method. However they determined distances from an approximate photometric parallax estimation, from Juric et al. (2008) and Ivezic et al. (2008). Alternatively, others used bayesian methods which can combine the probabilistic determination of the extinction and the distance to each star (Sale et al. 2014; Green et al. 2014; Schlafly et al. 2014; Hanson & Bailer-Jones 2014).

Some studies map the extinction at a given distance in specific regions of the sky, such as the bulge, or HII regions (Schultheis et al. 1999; Cambresy et al. 2002). Others have improved the Neckel & Klaremethod to determine the extinction as a function of distance from photometric or spectroscopic stellar samples. Arenou et al. (1992) presented a compilation of the extinction in 3D from diverse methods, useful to prepare the Hipparcos input catalogue.

An interesting approach has been proposed by Drimmel & Spergel (2001) who combine the 2D SFD maps with a simple model of the disc of interstellar matter, including a double exponential law, plus spiral arms and warp. They use SFD maps to constrain the total extinction on each line of sight. The model parameters are adjusted to explain both star counts in the near infrared and the dust emission in the far infrared. Drimmel et al. (2003) proposed an improvement of the 2001 method which takes into into account the position of the red-clump giants in the colour-magnitude diagram as in López-Corredoira et al. (2002).

Gonzalez et al (2011) and Gonzalez et al (2012) achieved their maps by measuring the mean (J-Ks) colour of red clump giants and compare them to the colour of stars measured in Baade's window for fixed colour excess. Hence their method allows to derive high resolution maps but only for the bulge region.

A significant source of uncertainty in deriving 3D extinction maps comes from the extinction law and from the variations of the selective to total extinction ratio Rv. While it is generally assumed to be close to 3.1 in many studies, it is also known to vary to much larger values, in particular in star forming regions (Zasowki et al. 2009). In deriving 3D extinction map, to avoid too much complexity, it is often assumed that Rv is fixed, or that it does not vary on a given line of sight although it is allowed to vary from a line a sight to another. If the variations of Rv are due to the physical condition of the dust, or to the radiation field, it is expected that Rv changes along line of sight as well, at least in specific cases, which should be taken into account when tracing 3D extinction maps.

2.3. 3D maps from bayesian approach

Green et al. (2014) proposed a bayesian approach to derive a 3D map of extinction based on Pan-STARRS 1 (PS1) 3π survey. Their approach is based on a derivation of the absolute magnitude of the stars from their colors and metallicity, following Ivezic et al. (2008) method. They also assume priors on the stellar populations on the basis of the model of Juric et al. (2008), an IMF and PARSEC stellar evolution models. They claim the method to be accurate to about 0.13 mag in E(B-V), and the uncertainty on distance is estimated to $\approx$20% - 60% with a spatial resolution of about 7 to 14 arcminutes. The map that they published in Schlafly et al. (2014) is limited to 4-5 kpc in distance. They find a good agreement with SFD 2D maps (at high latitudes) at the level of 20-30 mmag. But at E(B-V)<0.15 mag, PS1 finds more reddening than the emission-based maps, while at larger E(B-V), it finds less, although the bias is small. But in particular regions where there are dust filaments, the dust temperature estimated by SFD from DIRBE at a resolution of 1 degre is not reliable anymore (the filaments being colder than the surroundings). The comparison between this study and extinction from SDSS spectroscopy (Schlafly & Finkbeiner 2011) shows a very good agreement, at the level of 20 mmag (systematic).

Comparing with Planck extinction map, they indicate that PS1 extinction map agrees well (at the level of 50 mmag) with the Planck $\tau353$ map - based on the dust optical depth at 353 GHz - , but that the Planck R map - based on the dust radiance - is not reliable. It was explained by the varying ISRF in the environments of the Galactic plane. It was pointed out by the Planck Collaboration to use $\tau353$ map instead of R map in translucent and dense clouds where the ISRF is significantly modified.

Sale et al. (2014) presented a 3D extinction map produced from the IPHAS North Galactic Plane survey, based on the hierarchical bayesian method described in Sale (2012). They use a MCMC scheme to derive distance and extinction on large sample of stars at variable angular resolution, down to 10 arcmin. Their resolution in distance is claimed to be 100 pc and the map reaches at least 5 kpc distances. The method is slightly model dependent. The priors (Sale 2012) include a constant star formation rate, a disc density law and stellar models at solar metallicity. They also publish the map of the uncertainty, which can be clearly useful when using these maps. However users should be aware of the possible systematic errors due to the model hypotheses. The resulting map exhibits the fractal nature of the ISM.

The use of the bayesian approach has been also applied of the photometric SDSS survey combined with UKIDSS near-infrared data by Hanson & Bailer-Jones (2014). They take into account the variations of the extinction law. They base their method on priors of the HR diagram (simulated from Sordo et al. (2010) stellar isochrones with a Salpeter IMF and a constant star formation rate and for solar metallicity. It is not clear what the effect of these prior choices is on their final 3D maps, although they mention a probable bias in distance due to the metallicity. They achieve an extinction map which exhibits no systematic difference with SFD map. They claim an uncertainty of 0.23 mag on A_0. Their method could be applied on Gaia data with the benefit of parallax distances and including constraints from other astrophysical parameters in the bayesian scheme, such as Teff and metallicity.

Lallement et al. (2014) processed a catalogue of 23000 stars with colour excess determinations and photometric distances or parallaxes up to 2.5 kpc from the Sun and derived a 3D map using an inversion method. Their method is essentially based on the inversion method presented first by Vergely et al. (2010). Since the density of stars to compute a 3D map is too small and patchy, they regularized the inversion by imposing a smooth solution and applied the stochastic approach of Tarantola & Valette (1982). They used colour excess data along with associated Hipparcos parallaxes or photometric distances to build a 3D map of the local ISM. The comparison of both maps with SFD map indicated good correlations, and they point out interesting structures of the local ISM, such as the local cavity and the north-south asymmetry. Lallement et al. (2014) confirmed these findings and extended the knowledge of the local ISM to larger distances (see Lallement et al., this conference).

2.4. Spectroscopy

Several attempts have been made to derive 3D maps from spectroscopic surveys, which are able to measure distances and extinction with a better accuracy than photometry. In particular it has been shown that diffuse interstellar bands (DIBs) present in absorption in stellar spectra may be related to dust composition in front of the stars (Herbig 1995). The problems of such spectroscopic approaches are that, despite the precision of the measurements, the link between the DIBs and the interstellar dust is not completely established, and that, in the general case, the scarcity of the star distribution prevents from achieving high resolution.

However Jones et al. (2011) derived from 56000 M dwarfs of the SDSS survey (DR7) an extinction map up to 2-3 kpc. They fitted extinction curves to fluxes across the entire spectral range from 570 to 920 nm for every star in their sample. Their method confirmed the local dust cavity and gave an estimate of the local scale height of the dust to be about 120 pc.

Kos et al. (2014) extracted from the RAVE spectroscopic surveys partial map of the extinction based on the DIB at 862 nm. They showed a good correlation between interstellar extinction and the clouds producing the DIBs, but they also show that the DIB 862 carrier has a significantly larger vertical scale height than the dust (as estimated by Jones et al. 2011), pointing out our low understanding of the dust components.

The studies, either 2D or 3D, compromise between having a high spatial resolution on the projected sky or getting information in 3D when distance estimators are available. The latter is often at the detriment of resolution, but is more powerful for understanding the structure of the ISM. Since the extinction can vary on very small scales (arc minute or smaller) and present filamentary structures, probably on a scale of tens of AU, the extinction is known with a high level of detail only at short distances. Another important difference between 2D and 3D maps is that 2D maps determined from integrated IR flux or using external galaxies as tracers give the true total extinction, while 3D maps - and most 2D maps that use stellar tracers - give the distribution of the extinction up to a distance and suffer from the bias mentioned by Neckel & Klare: they underestimate the extinction by lacking completeness where the extinction is high and patchy.

In spite of these defects and imperfections, 3D maps have been proved to be very useful to study stellar distributions when corrections for extinction have to be applied, and they are abundantly used.

The comparisons of results obtained by different methods show a variety of situations depending on the field, sometimes with conspicuous systematics. Typically, the differences in Av at a given distance from one model to another are on the order of 20%. Distances are generally more uncertain, typically at the level of 20 to 60%. Several reasons can be called upon:

(i) different extinction methods trace different phases of the interstellar matter. They are sensitive to different grain sizes, temperatures, and gas/dust ratios.
(ii) Maps are done at different spatial resolutions. Since the dust distribution is highly inhomogeneous and clumpy down to small scales, the mean extinction varies as a function of the resolution considered.
(iii) The R_V varies from one line of sight to the other, while it is often taken as a constant, and the assumed extinction law varies from one model to the next.
(iv) The results sometimes depend on assumptions about the geometry of the disc and the spiral arms which might not be correct, or too simplified.

3. The population synthesis approach

The Besançon Galaxy Model (BGM) is based on realistic assumptions on the scenario of formation and evolution for four main stellar components of the Milky Way: thin disc, thick disc, halo, and bar (Robin et al. 2003, 2012, 2014). It simulates the stellar content in any given line of sight and computes the photometry, kinematics, and metallicity of each simulated star. For each population, a star formation rate history, and an initial mass function are assumed, allowing the model to generate the distribution function of absolute magnitude, effective temperature, and age of the stars. Density functions are assumed for each population and tested against observations using photometric star counts. For the thin disc, the vertical gradient of density is controlled by the dynamics (Bienaymé et al. 1987). The model also simulates errors to correct the observational parameters of each star.

3.1. Extinction and distances from population synthesis

Using this model it is possible to determine the extinction on each line of sight by comparing the distribution of stars in the colour-magnitude diagram (CMD) with real data. The effect of extinction on the distribution of stars in the CMD is well known and depends on the assumed extinction and on the distribution of Av as a function of distance on the line of sight. Figure 1 shows the effect of extinction in a typical direction in the Galactic plane. In the left panel we show the simulated CMD for unreddened stars, while in the right panel we apply an extinction increasing with distance following the relation indicated in the small right panel.

The approach that we used to determine the extinction distribution along the line of sight (Marshall et al. 2006) was to compare the observed J-K distribution with the ones produced by the model simulation with different extinctions. A χ^2 method allows to determine which is the most suitable distribution of extinction on each specific line of sight. Using stellar colours in J-K as extinction indicators and assuming that most of the model prediction deviations on small scales from observed colours arises from the variation of extinction along the line of sight, we built a 3D extinction map of the galactic plane ($-10 < b < 10°$and $-90 < l < 90$). The final resolution in longitude and latitude is 15 arcmin and the resolution in distance varies between 100 pc to 1 kpc, depending on stellar density and on the dust distribution along the line of sight. The resulting 3D extinction map furnishes an accurate description of the large scale structure of the disc of dust. The maps clearly show disc structures, such as spiral arm tangents and external warp. Figure 2 reproduces the distribution of differential extinction obtained by Marshall et al. (2006). The method relied solely on the giant star population, however dwarf stars contribute significantly to star counts in 2MASS in these directions. A new method is currently under development which will calculate the extinction using observations from all stars, thus improving spatial resolution and providing more information on Galactic structure in these directions. It has been already applied to determine the distance to dark clouds (Planck Collaboration 2015).

3.2. Potential problems

The choice of the wavelength to measure the extinction is critical. Maps at high latitudes or low extinction are worth being done with visible data, that are more sensitive to low extinction, but regions of high extinction needs to be observed at more transparent wavelength; hence, a full 3D map of the entire sky would require a combination of visible and infrared surveys. It was one reason why Marshall et al. (2006) published only the Galactic inner disc extinction map determined with 2MASS survey.

The second point is that the method is based on model simulations. However, we showed that the effect is small on the determination of the extinction because we do not fit the absolute star counts but we normalize it to real data. The third problem occured because 2MASS is not sensitive enough in regions of high extinction. Hence the map saturates at about A_K= 2.5 magnitude. There are also difficulties to determine the extinction at small distances with this method because considering only a conic line of sight, at short distances the volume is very small and contains too small number of stars.

Finally, because the extinction can be very clumpy at small scale, in fields where the extinction has a large dispersion, it is probable that stars having highest extinction are not detected and that the mean extinction is underestimated.

Some improvements can be done to the method, such as taking into account neighbouring lines of sight, using an adaptative resolution, potential variation of the extinction law, and to take into account other constraints at small distances. Notice also that Sale & Magorrian (2014) proposed, as a proof of concept, to use Gaussian random field assumptions in order to avoid the fake elongation of the dust clouds on the line of sight.

4. Tracing the large scale structures of the ISM

The 3D mapping of the extinction has led to tracing the distribution of the interstellar medium (ISM). The disc appears thin and flared, but also probably slightly inclined with respect to the stellar mid-plane (Pandey & Mahra 1987; Joshi 2005). Neckel & Klarepointed out that the clouds near the Sun do not seem to follow any typical spiral structure, but their sample is too limited in distance. The spiral stucture in the dust is now proven by Amores & Lépine (2005), and Drimmel & Spergel (2001). Despite the patchiness, it generally appears that gas, molecular clouds, and dust follow some kind of spiral structure, as do young stellar populations, but the uncertainty on distances renders the layout of the arms difficult. The disc of dust has also been found to follow the warp feature of the Milky Way, as the HI gas does, as well as the stellar populations (Reylé et al. 2009). Marshall et al. (2006) showed also the good correlation between 3D extinction maps and the CO gas distribution. Hence, the extinction distribution is a good tracer for the global dust distribution.

5. Physical models

An important step to improve our understanding of the ISM and the physical processes occurring between the stars and the interstellar matter is to construct physical models which can explain both the emission of the dust in the infrared and the interstellar extinction in front of stars in 3D. The FIR flux is by nature integrated, but the analysis of the emission at different wavelengths should allow to distinguish various components and their spatial distribution, as it has been done in the past from stars without accurate distances. This requires a good physical model for the composition and temperature of dust (and its difference components, from PAH to big grains) in different regions of the Galaxy. Such a model should explain all the processes of dust absorption, diffusion and re-emission at different wavelengths, with their variations in different regions of the Milky Way. Li & Draine (2001)

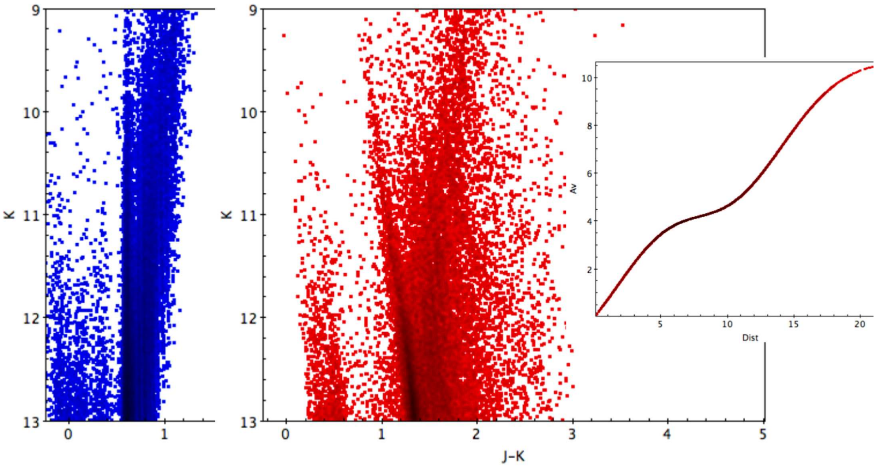

Fig. 1. Effect of extinction on a color magnitude diagram in the Galactic plane. The left panel shows the distribution of the stars in J-K vs K in absence of extinction. The right upper panel shows the extinction as a function of distance which is applied on the simulation. The middle panel CMD is the resulting color diagram with this extinction.

proposed to reproduce the FIR spectrum from the sum of two components (big and small silicate and carbonaceus grains, see their figure 8). More recently, the model proposed by Mulas et al. (2013) has also two main components:

(i) a population of silicate core, carbon-coated dust grains and
(ii) a molecular component of free-flying PAHs.

This model reproduces the extinction law from Fitzpatrick & Massa (2007) in different directions. The variation of proportion of the two components explains the variations of the extinction law.

Ysard et al. (2015) attempted to explain the new Planck extinction map with a physical model of dust composition (Jones et al. 2013). They explore the effect of different compositions and thicknesses of the mantle in core-mantle models of grains, as well as the impact of the radiation field intensity. They are able to explain the spatial variations of dust properties seen in Planck even at hight latitudes in the diffuse interstellar medium with different models of grains, while the radiation field has to be harder than the usual interstellar radiation field (ISRF) to explain a part of these variations.

6. Future

Important steps will be done in the future by using the large-scale surveys, applying the above proposed methods of analysis, and sophisticated ways of estimating distances. Very shortly Gaia will provide accurate photometry and distances from trigonometric parallaxes. As a first step, it will allow the interstellar extinction to be determined at an unprecedented accuracy better than the mmag, and distances

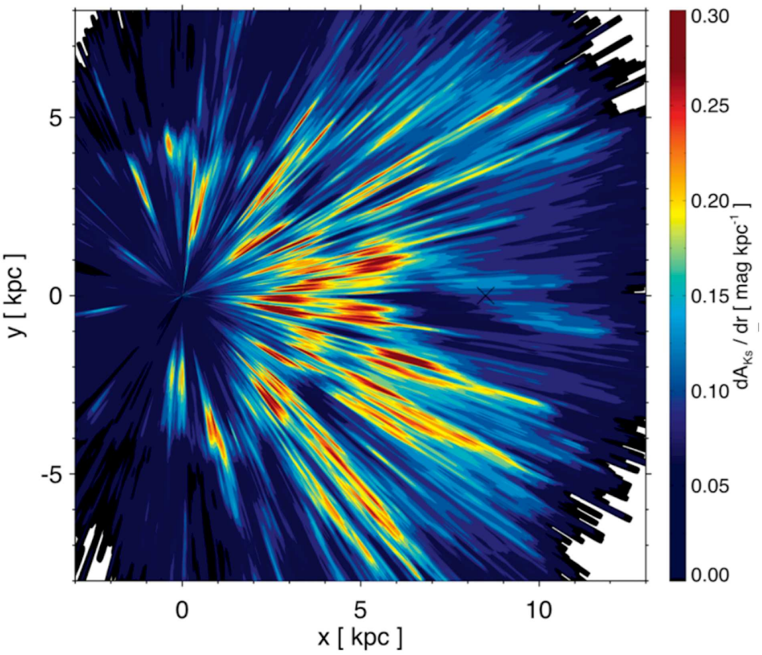

Fig. 2. Map of differential extinction in the (x,y) plane from Marshall et al.(2006). The Sun is at the origin.

at better than 1%. This will feature the local extinction up to about 2 kpc with a resolution in cloud size of less than about 10-20 pc over the whole sky. The second step will be made using the photometer BP/RP accurate to a few milli-magnitudes. Gaia will thus provide a huge database for mapping the extinction at a spatial resolution never obtained before, to very large distances (accurate at 10% up to 10 kpc), but with a limitation in regions of high extinction (i.e. the Galactic plane) where Gaia could be complemented by near-infrared surveys.

Furthermore, asterosismology is now providing very accurate gravities for large number of giants (in particular Corot, Kepler and Kepler-2). Even though these surveys are still limited in the number of targets, the fields that they observe, complemented by high resolution spectroscopy, allow to derive distances with an accuracy of 2% and extinction with precision of 0.1 mag (Rodrigues et al. 2014). Similarly, ground based distances to masers are able to help determining extinction in very specific directions, but with an excellent accuracy. Most probably, Bayesian inversion methods which allow to compute 3D maps from the space distribution of stars are very efficient and will be extensively used to derive accurate extinction maps from the Gaia satellite.

Acknowledgements. Thanks to all.

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