MODELLING INTERSTELLAR EXTINCTION IN THREE DIMENSIONS

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ABSTRACT

We have developed a technique that estimates the three-dimensional extinction in the Galactic plane. The colour distribution (J-K) of stars from the Two Micron All Sky Survey (2MASS) are compared to that of stars from the Besançon model of the Galaxy, to which we do not add the effects of extinction. If the luminosity function and the density laws of the different populations are well modelled, any differences in the colour distributions will be due to interstellar extinction. After having described the method, we will show the results for several interesting regions in the Galactic plane.

Key words: ISM:dust,extinction; Galaxy:structure.

1. INTRODUCTION

Interstellar extinction remains a serious obstacle for the observation of stars in the Milky Way, and for interpreting these observations in terms of Galactic structure. Several studies have been undertaken to further our knowledge of the extinction in our Galaxy: Neckel & Klare (1980) measured extinction and distance towards individual O,B and A stars; Schlegel et al. (1998) used the COBE and DIRBE instruments to create an all sky 2D map of the total extinction integrated along the line of sight; Schultheis et al. (1999) used Deep Near-Infrared Southern Sky Survey (DENIS) data to construct a 2D projection of the extinction towards the Galactic bulge ($|l| < 8^o$,$|b| < 1.5^o$); Dutra et al. (2003) created a 2D extinction map of the central 10^o of the Galaxy using 2MASS data; Drimmel et al.(2003) created a three dimensional map of interstellar extinction based on the dust distribution model of Drimmel and Spergel (2001).

We have developed a technique which calculates the extinction in the plane of the Galaxy ($|b| < 5^o$), in three dimensions, and that does not assume any model for the dust distribution. Instead, we compare the difference in the J-K colour distribution of stars from the Besançon model of the Galaxy (Robin et al. 2003) to those from 2MASS observations; the difference between the two is then attributed to interstellar extinction. This technique can provide a global picture of the three-dimensional distribution of interstellar dust.

2. METHOD

2.1. Extinction Along the Line of Sight

The Besançon model of the Galaxy is able to simulate the stellar content of the Galaxy. It may generate stellar catalogues for any given direction, and returns information on each star such as magnitude, colour, and distance as well as kinematic and other photometric parameters.

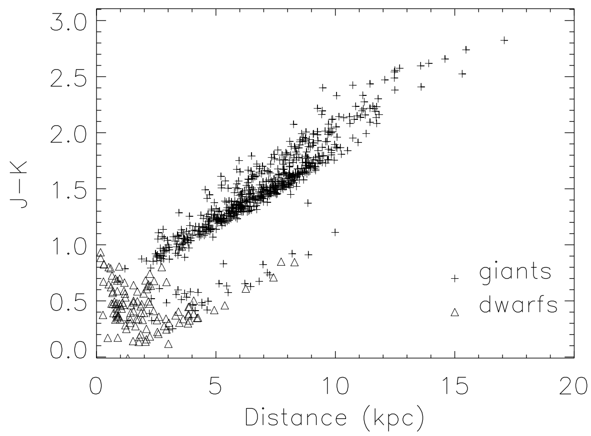

Figure 1. Colour distance relation for K & M giants. The group of stars in the lower left corner is dominated by dwarfs.

For a given direction (l, b), we compare the J–K colour of K and M giants resulting from the Besançon model with those from 2MASS. As these giants have similar intrinsic J–K colour, the observed colour is an indication of the extinction suffered and therefore the distance to the star. The stars used in both catalogues are cut in J and K at a maximum magnitude equal to the completeness limit of 2MASS for the field, and at a minimum magnitude of 9 for all the fields in order to limit the selection to K and M giants.

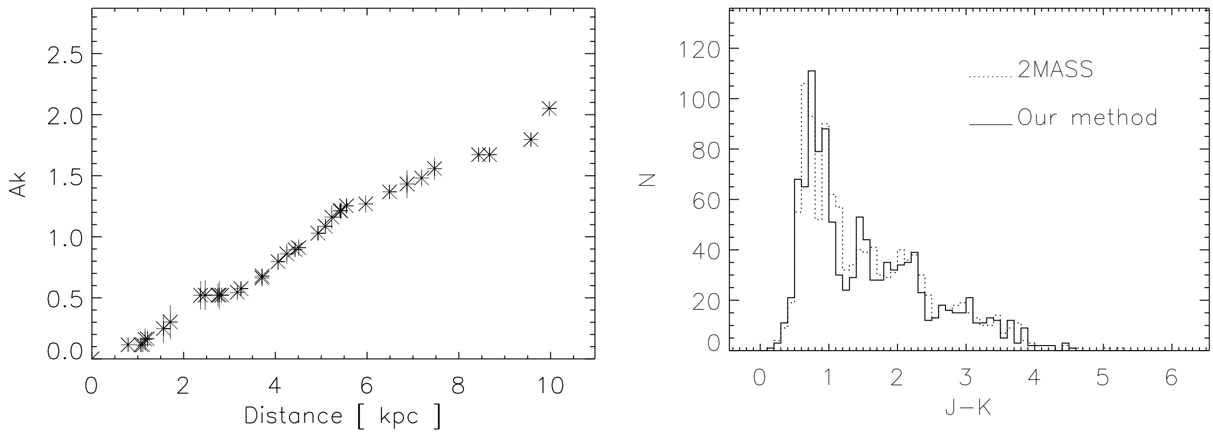

Figure 2. Left: A_K vs. distance for the field (l,b)=(50.0°,0.0°). Each asterisk represents a bin from our method, and the error bars are the mean absolute deviation from the median extinction in the bin. Right: J-K histogram for the field (l,b)=(50.0°,0.0°). The dotted line represents the 2MASS observations and the solid line is the result of our method

Figure 1 plots J–K colour versus distance for a typical sightline from the Besançon model. The dwarf population is conspicuous on the bottom left of the plot as it does not follow the same colour-distance relation as the giant population.

Both catalogues are sorted by increasing colour and then split into an equal number of colour bins. For each bin we calculate the median J–K colour (model and 2MASS) as well as the median distance (model only). If the colour distribution of the giants is well modelled in the simulated catalogue, the difference in colour yields the extinction at the distance given by the model bin. A difference in colour between model and observations and the corresponding extinction (δA_K) are related by :

$$(J-K)_{\rm obs} = (J_{\rm sim} + \delta A_J) - (K_{\rm sim} + \delta A_K) \quad (1)$$
$$= (J-K)_{\rm sim} + 1.611\delta A_K \quad (2)$$

where the subscripts 'obs' and 'sim' signify observations and simulations, respectively. So the extinction is then:

$$\delta A_K = \frac{(J-K)_{\rm obs} - (J-K)_{\rm sim}}{1.611} \quad (3)$$

3. RESULTS AND DISCUSSION

3.1. Extinction and H Column Density

We are thus able to determine the extinction along the line of sight. To get an idea of the large scale distribution of dust which is giving rise to this extinction we first convert a difference in extinction between two consecutive points along the line of sight to a column density of hydrogen. Bohlin et al. (1978) measured the column densities towards 100 stars, as well as their (B–V) colour excess, and found that the data is well represented by Equation 4.

$$N(\mathrm{H_{tot}}) = 5.8 \times 10^{25}\ \ \mathrm{E(B-V)}\ \ \mathrm{m^{-2}\,mag^{-1}} \quad (4)$$

If we take $R_V \sim 3.1$ then we can write this in a more appropriate form (Equation 5).

$$N(\mathrm{H_{tot}}) = 1.76 \times 10^{26}\ \ \mathrm{A_K}\ \ \mathrm{m^{-2}\,mag^{-1}} \quad (5)$$

We then divide this column density by the distance between the two points which gives us the average volumic density of hydrogen between these two points. Assuming a constant gas to dust ratio, this representation allows us to trace the obscuring dust in the Milky Way.

3.2. Individual Lines of Sight

The plot on the left hand side of Figure 2 shows the results along the line of sight at $(l,b) = (50°,0°)$. Each asterisk represents one bin from our results; the error bar is the absolute mean deviation of the A_K from the median of all the stars in the bin. In order to test the extinction law thus determined, we compare the J–K histogram from the 2MASS observations to the J–K histogram resulting from the application of our extinction to the Besançon model. An example of this comparison is given in the plot on the right hand side of Figure 2.

For each line of sight between $l < |90|$ and $b = 0$, we have calculated the average hydrogen density using Equation 3. The results are displayed in Figure 3. The position of the Sun is at [0,0] and the Galactic Centre is at [8,0]. The molecular ring is readily visible, as are two structures extending away from the Sun at $\sim 85°$ and $\sim -80°$ which may correspond to the Sagittarius-Carina spiral arm.

3.2.1. Two dimensional extinction maps

The Galactic Centre presents a challenge for the determination of extinction along the line of sight. The number of stars varies from one line of sight to another due to the level of interstellar extinction (reducing number of stars detected) or crowding (reducing completeness of catalogue for the field of view). As we currently use a fixed field size, there were an insufficient number of stars in a number of the lines of sight used and thus we were only able to determine a lower bound on the extinction along the line of sight. Figure 4 shows the total extinction integrated to a distance of 8 kpc from the Sun. The resolution

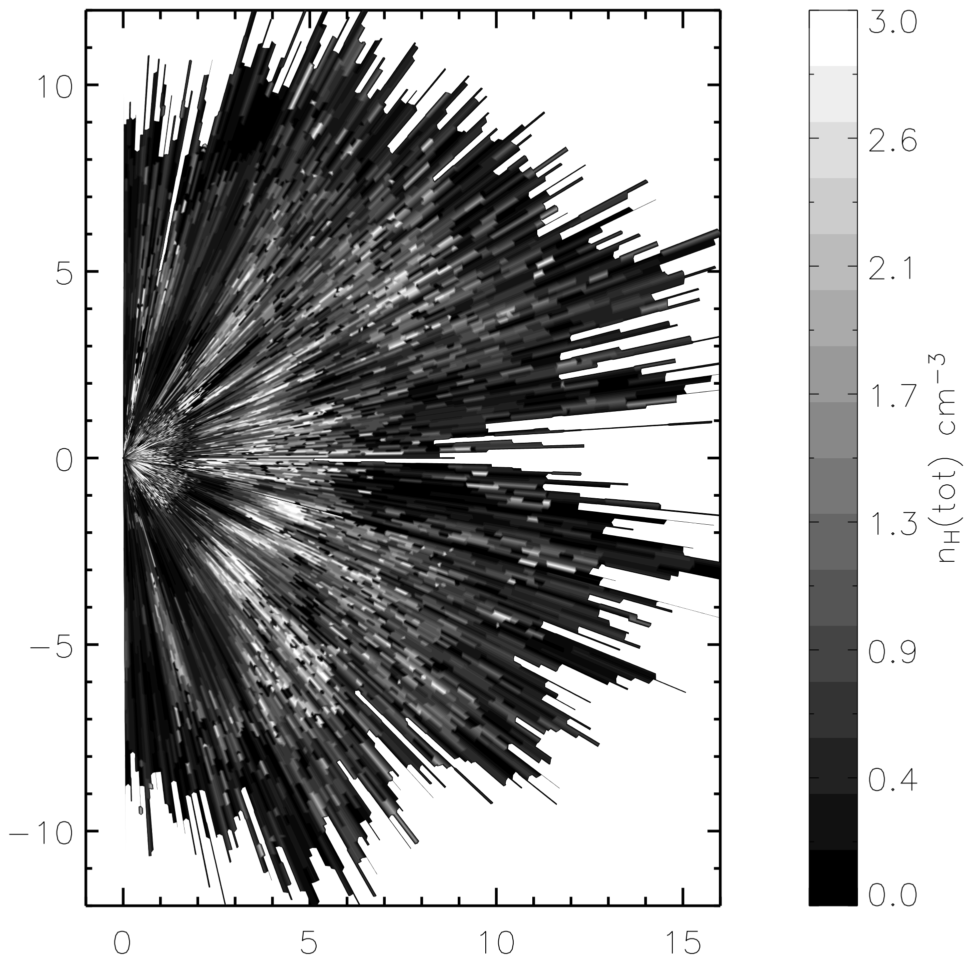

Figure 3. Large scale distribution of the volumic density of hydrogen (molecular and atomic) in the inner Galaxy, at b=0°.

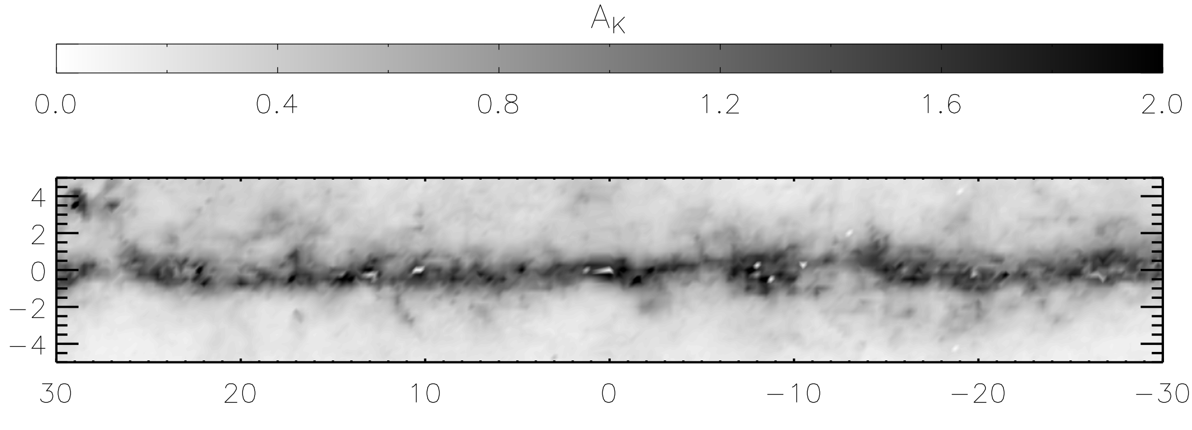

Figure 4. Total extinction integrated along the line of sight to 8 kpc. The coordinates are expressed in degrees (l,b).

of this map is 15′× 15′, and it is sensitive up to an A_K of 2.7. The fields with an insufficient number of stars show up as white 'holes' in the disc. The maximum extinction on the black and white scale is set below the actual maximum to bring out the filamentary structure of the dust.

Dutra et al. (2003) compared their extinction map to that of Schultheis et al. (1999) and found the two results consistent. Their method consists of comparing AGB isochrones to theoretical unreddened isochrones, using 2MASS and DENIS data respectively. Although they have used near-infrared data as we have, our approach provides a different method for extracting the extinction information from the data.

3.3. Galactic Centre

Here we compare our results with those of Schultheis et al. (1999), where the two maps overlap, and we also find good agreement. The histogram of the differences between the two maps is presented in Figure 5.

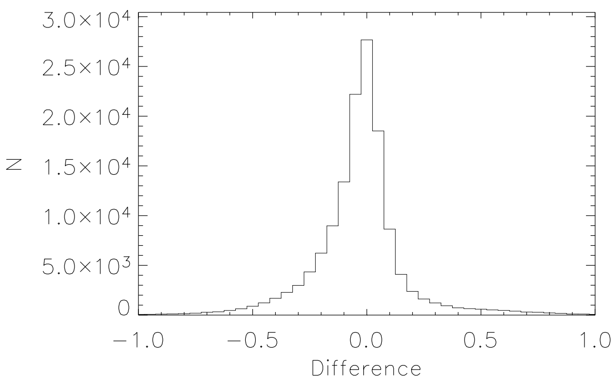

Figure 5. Histogram of the difference in extinction in the K band at each pixel between our method and that of Schultheis et al. (1999).

3.3.1. Three dimensional extinction

The three-dimensional extinction towards the Galactic Centre is presented in Figures 6 and 7. Each image shows the average volumic density of hydrogen at the distance indicated. The density scale has been chosen to show the most amount of structure.

One obvious feature is the geometrical effect of distance; high latitude extinction is local so the disc is seen to shrink at we go further away from the Sun. Secondly, the dust distribution is not symmetrical in Galactic longitude. At 2 kpc and at 6 kpc, the dust density is higher at negative longitudes whereas at 3 kpc it is higher at positive longitudes. This structure was observed by Dame (1993) using (l, v) plots of molecular gas, who interpreted it as being the molecular ring. At distances greater than 7 kpc very little matter is detected, which corresponds to the central depression in the hydrogen disc.

We have compared the three-dimensional results from our method with those from the model of Drimmel et al. (2003) for several lines of sight throughout the Galactic disc. We generally find good agreement although there are regions where the two methods differ substantially. Our method is sensitive to large variations in the K and M giant distribution but not at all sensitive to changes in dust temperature, whereas the Drimmel model is exactly the opposite. We can therefore expect that the two methods will be complementary.

3.4. Baade's Window

We have mapped an area of the sky which has had much attention devoted to it, namely Baade's Window at $(l, b) = (1^o, -3.9^o)$. Baade's Window provides an excellent observational opportunity as we may probe further into the Galactic Bulge than in the usual highly extincted central regions.

Figure 8 shows the extinction in the V band, resulting from our method, in the region from $l = 0^o$ to $l = 4^o$ and from $b = -5^o$ to $b = -2.5^o$.

Table 1. Extinction values for the different windows in Figure 8. The authors' values are the average A_V in the field whereas our values are at 8 kpc.

Window	(l, b)	Authors' A_V	Our A_V
Baade	(1.0,−3.9)	1.26	1.45
Sgr 1	(1.5,−2.6)	1.55	1.70
Pop 1	(3.2,−3.4)	1.05	1.50
Pop 2	(2.0,−3.3)	1.14	1.45
Pop 3	(3.9,−3.8)	1.01	1.70

Several other authors have studied this area, for example Stanek (1996) created a high resolution (30″) map centred on Baade's Window using photometry from the Optical Gravitational Lensing Experiment (OGLE) and Popowski et al. (2003) created a larger map (43 deg^2) of the Galactic Bulge with lower resolution (4′× 4′) using data from the MACHO microlensing survey.

Table 1 presents the positions and extinction measures for five windows; we compare our value for the extinction in these windows with the results of Stanek (Baade's Window) and Popowski et al. (2003) for the rest.

These regions present a difficulty for our method as the extinction is low and the J–K colour index that we use is not very sensitive to small changes in extinction. The 2MASS J–K photometric error is approximately 0.07 magnitudes, so, using Equation 3 this translates into an error in A_V of around 0.5 magnitudes.

4. CONCLUSION

We have presented the first results of our extinction model for three regions in the Galactic plane. The Besançon model of the Galaxy provides an excellent tool for extracting the reddening information locked in the 2MASS data. Our method does not give any detailed information on extinction in the first kiloparsec from the Sun but does give the large-scale distribution of the extinction in our Galaxy.

As our technique relies on the reddening of the (J–K) colour index, we may underestimate the extinction in crowded or heavily attenuated regions. Furthermore, the J–K index is not sensitive to very low extinction zones, such as high latitude lines of sight. However, the method can easily be modified to use other colour indices, which would allow us to adapt the sensitivity to a given region or set of observations.

ACKNOWLEDGMENTS

This publication makes use of data products from the Two Micron All Sky Survey, 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.

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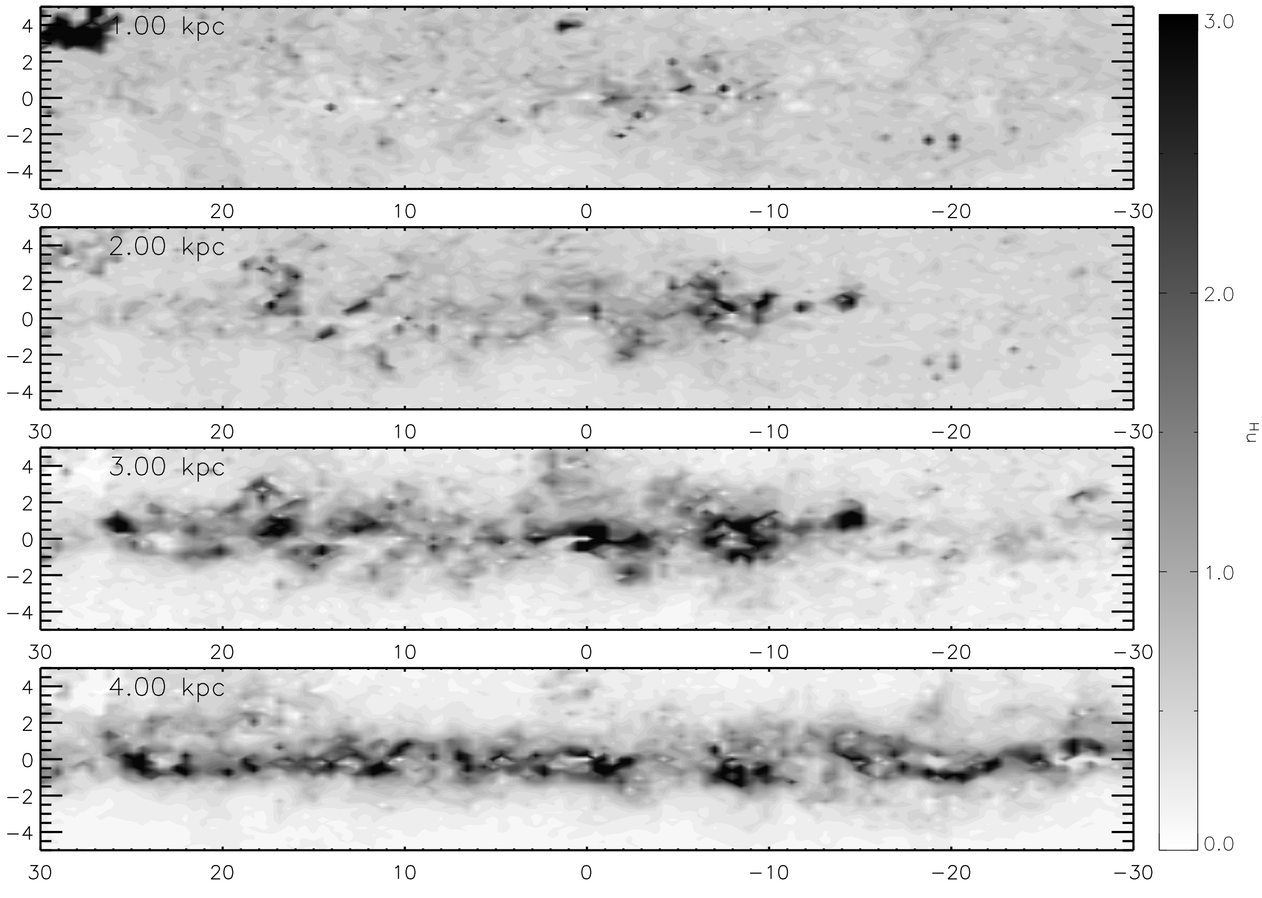

Figure 6. Hydrogen volumic density estimated at 1, 2, 3 and 4 kpc from the Sun.

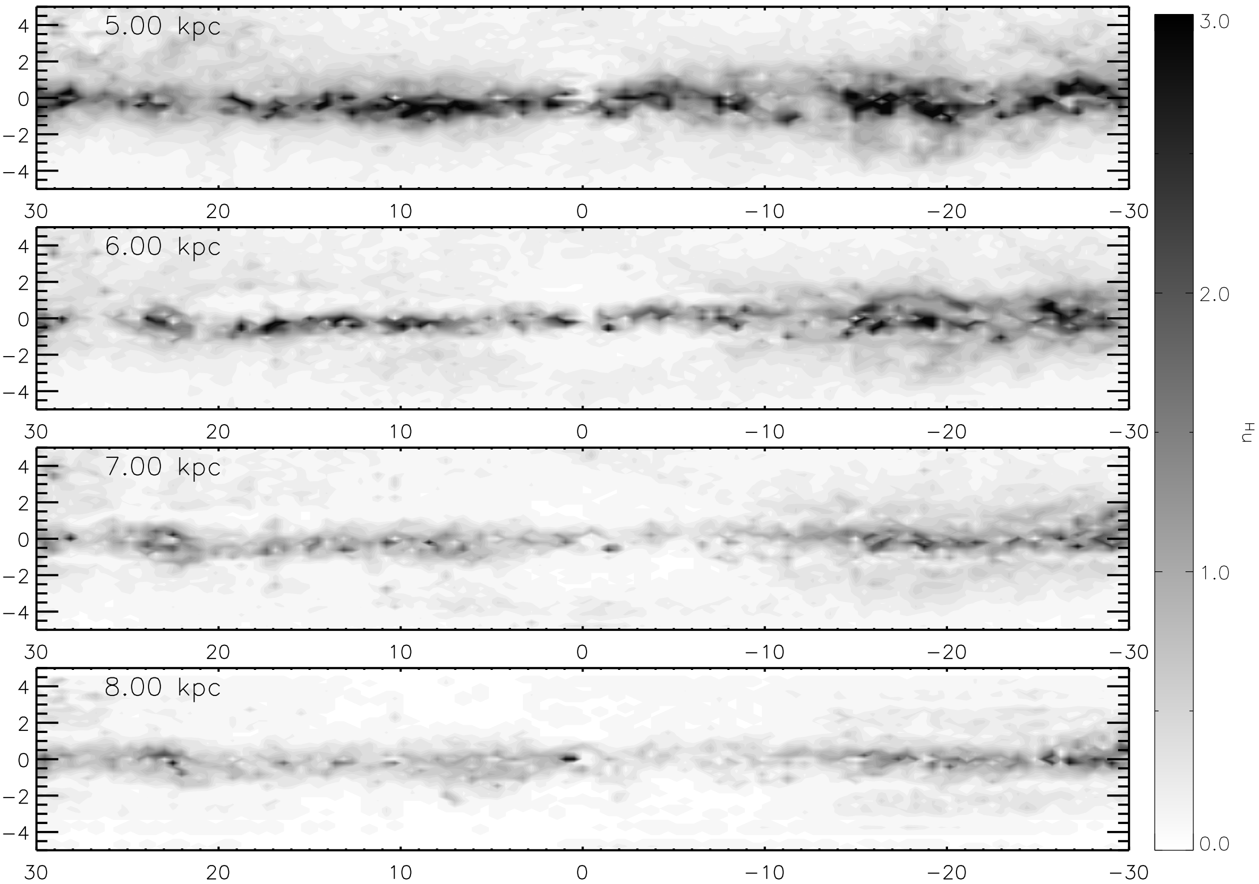

Figure 7. Hydrogen volumic density estimated at 5, 6, 7 and 8 kpc from the Sun.

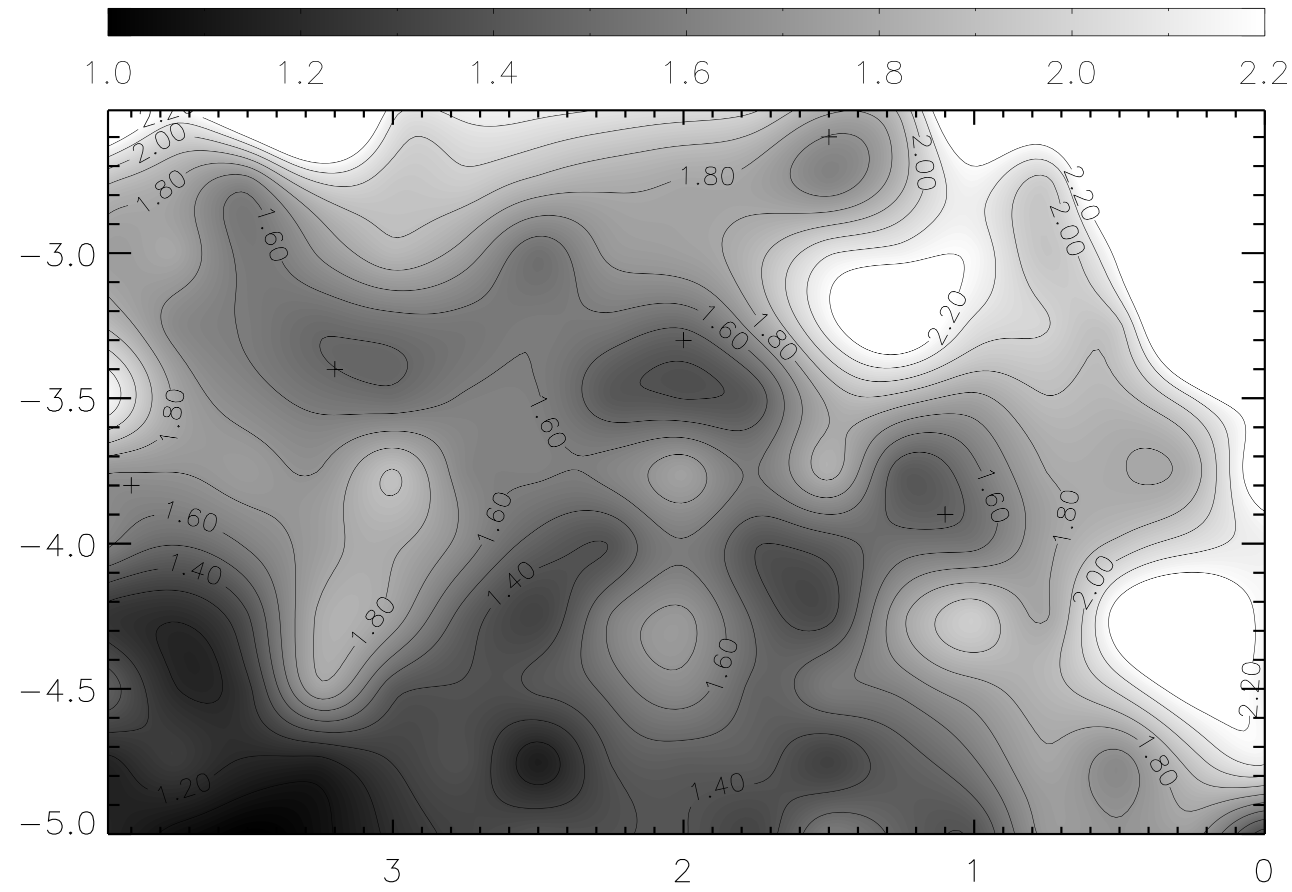

Figure 8. Total extinction at 8 kpc, in A_V, towards the region of Baade's Window. Plus signs indicate the positions of various windows (see Table 1). Note that white indicates higher extinction and that the scale starts at $A_V = 1$.