ISM, EXTINCTION AND STAR FORMING REGIONS

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ABSTRACT

A reason for correcting the obscuring effect of the interstellar medium is of course to obtain individual intrinsic astrophysical stellar parameters. Another useful application of the distance–extinction information is the potential to localize molecular clouds and star forming regions in three-dimensional space. The distance to a star forming region is a necessity for deriving all sorts of physical parameters needed for protostellar modelling.

The reddening correction is mainly a problem for the Gaia medium band photometry systems to solve.

A main goal of the Gaia mission is to determine ages better than 10%. General accuracy conditions for the sample termed scientific targets (ST, Jordi et al. (2003a)) are detailed in Jordi et al. (2003b) where a weighting scheme was also introduced.

Since Gaia was conceived as a Galactic mission less emphasis has been put on some stellar types and chemical elements implying the resulting set of STs and a corresponding weighting scheme. The weights are to a large extent determined from the targets relevant for Galactic studies. So it is important that the final photometric system (PS henceforth) is able to provide extinctions for the highest weighted Galactic tracers. If a PS does not succeed in this the astrophysical parameters may not be derived. An extinction correction is considered to be acceptable when $\sigma_{A_V} \leq 0.09$ mag.

We use simulated data from the X2MX2B system which at the moment of writing showed the best overall figure of merit. The results are not too encouraging and show some unpleasant tendencies e.g., that some STs with the highest weighting do not perform quite well at the larger distances. A general result of the test is that scientific targets with the highest priority have a success rate of about 50% at a distance of ≈ 5 kpc.

In order to demonstrate what may be done for the molecular clouds / star forming regions we use an intrinsic calibration of the 2MASS JHK photometry to probe in the direction of some intermediate velocity gas and in the direction of the star forming cloud MBM 12. The intermediate velocity gas is interesting to probe for dust because it may possess a non-standard gas/dust ratio. We introduce a new concept for estimating cloud distances by only accepting a cloud distance, not only when we see an extinction jump at a well defined distance, but also require that the projected extinction contours show a high degree of continuity. Such a procedure is only possible from sky surveys with a sufficiently high stellar density. This way we derive distances to two features in the intermediate velocity cloud IV Arch of 0.3 and 1.5 kpc and confine the MBM 12 distance to the range from 200 to 300 pc.

Key words: Gaia photometry; Visual absorptions; Accuracy; Star forming regions; Cloud distances.

1. A_V PERFORMANCE OF PS X2MX2B

A variety of photometric systems (PSs) have been suggested for Gaia and the selection process is still ongoing. A discerning parameter, Figure of Merit (FoM), was defined by Lindegren (2003). The resulting FoM for the PSs tested presently (Jordi & Carrasco, Gaia Photometry Working Group home page[1]) are disturbingly similar. We have chosen the 2X system proposed by Vansevicius (2004) which has a marginally better FoM than most other systems for our discussion. The FoM may have a problem by not validating a PS by its own merits since it does not pay particular attention to the specific features that a given system paid attention to for procuring the various astrophysical parameters, $\log T_{\rm eff}$, absolute magnitude, [Fe/H], A_V, α–elements, reddening law etc. The difference between the 2X system and most other proposed systems lies in its inclusion of a rather wide red band, 70 nm wide, centred at 965 nm. The band has to be wider than is normally the case for a medium band system due to the declining QE near the red edge of the CCD. It is generally believed that a system with a wide span between its bluest and reddest bands improves temperature and extinction determination.

The goal for the visual extinction determination by Gaia was set to have σ_{A_V} better than 0.1 mag. We have used 0.09 as a representative limit. The FoM procedure provides individual errors for the astrophysical parameters and for A_V and was made available at the Gaia Photometry Working Group home site (see Jordi & Høg 2005).

[1] http://gaia.am.ub.es/PWG/index.html

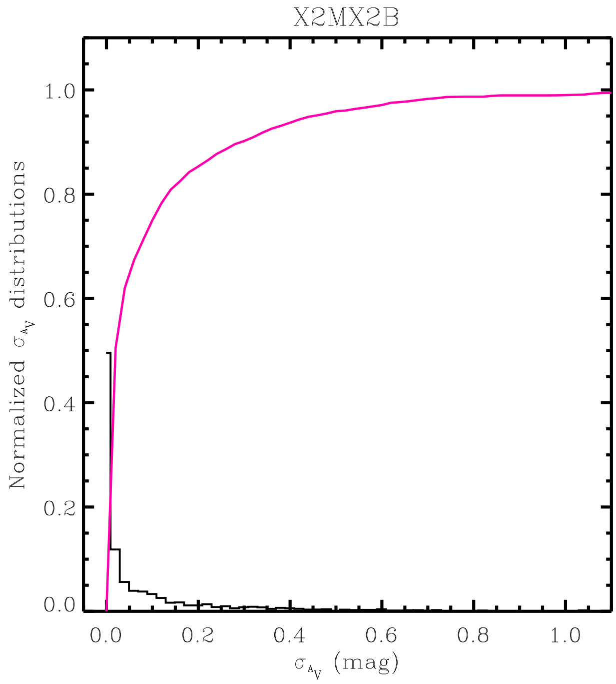

Figure 1. Normalized σ_{A_V} histogram for the complete set of scientific targets. The over-plotted curve indicates the accumulated fraction of the scientific targets with σ_{A_V} or better. Slightly less than 3/4 fulfill the criterion $\sigma_{A_V} \leq$ 0.09 mag but 50% reproduce A_V better than 0.02 mag.

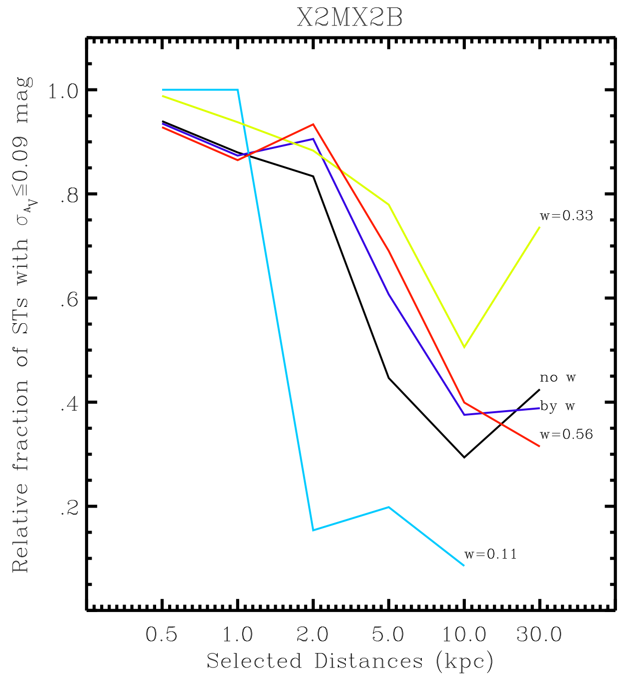

Figure 2. Fraction of scientific targets meeting the σ_{A_V} $\leq$ 0.09 criterion as a function of distance and assigned weight. STs with highest priority have weight 0.56 and those with the lowest only 0.11. The labels now and byw mean that no attention is paid to the weight and that stars are counted by weight respectively. Note that the abscissa is not a linear distance scale.

1.1. σ_{A_V} Distributions

The testing sample is divided into 'stellar populations' and certain sets of distance and extinction combinations were preselected for testing the system with the proper Gaia parameters. The question is which stellar types will be included in the Gaia sample at a given distance with a given extinction and fulfilling the predefined set of accuracies. The outcome of such a simple test may indicate that the PS perhaps should stress certain types less and emphasize others. What is the purpose of insisting on the importance of a certain stellar type if they can not be measured with sufficient accuracy?

In the first figure we show the normalized distribution of σ_{A_V} for all types included in the ST sample indicating that 50% in fact has σ_{A_V} better than 0.02 mag and that the extinction criterion is met by ≈75% of the STs. There is however a small hump in the tail of the distribution, see later which types cause this.

1.1.1. σ_{A_V} success rates

The fraction of STs meeting the extinction criterion as a function of distance is shown in Figure 2, given as a function of the various weights assigned to the STs according to their respective importance for deriving the astrophysical/Galactic parameters. We notice that already at 3 – 5 kpc even the higher weights do not quite meet the expectations. The lowest weighted stars fail already at 1 kpc so a critical evaluation of whether they should be included or not should be considered; they do not seem useful for studies of the Galactic structure apart from the very neighbourhood. Another feature is the similarity of the two curves labelled *no w* and *by w* meaning that no attention is paid to their weights and that each star is counted according to its weight. From this similarity one could conclude that extinction determination does not seem to have been the prime driver of the X2MX2B photometric system (or for any other system for that matter). It is also a suprise that stars with w=0.56, the highest weight, do not measure extinction any better than indicated by the curve labelled *by w*. Finally we see that the w = 0.33 stars in fact are those performing best with respect to reddening correction, at 5 kpc they still have a score of ≈80% compared to the score of only ≈70% of the w = 0.56 stars. But perhaps a success rate of 60% at 5 kpc is not that bad after all but it will apparently be a problem that for some STs individual extinctions can not be given – and which ones do only have e.g., a 50% probability of being assigned the correct A_V?

1.1.2. Brief discussion of σ_{A_V} failures

It is equally interesting to see which stars do not meet the extinction criterion and how large their failure becomes. Figure 3 is a histogram showing the σ_{A_V} distribution as a function of distance for STs that do not meet the extinc-

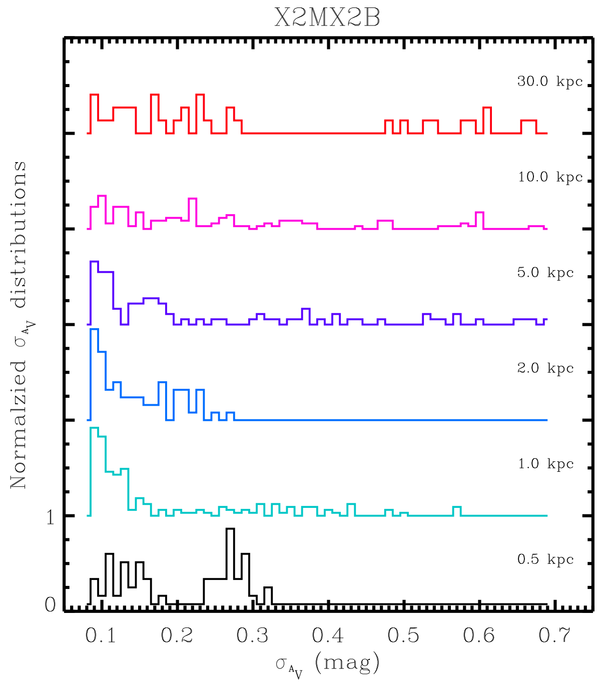

Figure 3. Normalized histograms of the complete set of scientific targets for selected distances showing stars that do not meet the A_V criterion: $\sigma_{A_V} \leq 0.09$ mag. Stars failing the criterion at 0.5 kpc are M V stars. At 1 kpc it is K V and M V stars. See also Table 1.

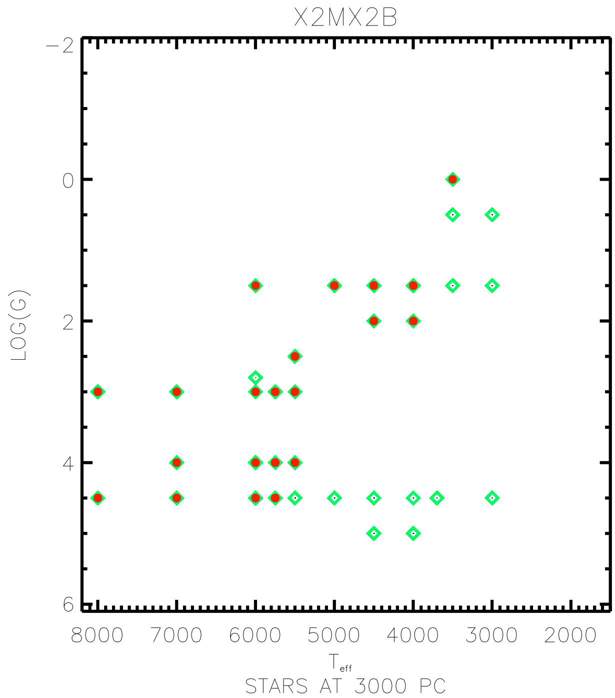

Figure 4. Example of which parts of HR-diagramme occupied by the STs that do not meet the $\sigma_{A_V} \leq 0.09$ criterion. This is for the distance 3 kpc. Open diamonds represent stars not meeting the extinction accuracy. Note that no main sequence stars cooler than the Sun will be included in the sample at this distance.

tion criterion. Already for some stars at 0.5 kpc a peculiar hump is noticed at ∼0.28. At 1 kpc there is an accumulation of errors between 0.1 and 0.15 and with an additional tail reaching up to almost 0.5 mag. At 2 kpc all errors are smaller than 0.3 and at the larger distances the distribution becomes flatter and reaches a common maximum error of ≈ 0.7 mag. At 30 kpc there are two regions with an empty region between them: either σ_{A_V} is less than 0.3 or it is larger than ≈ 0.5. Altogether a rather confusing picture. As a consequence we have made a small survey of which stars do not fulfill the σ_{A_V} criterion. The survey is presented in Table 1. For the nearest distance of 0.5 kpc the M dwarfs drop out. In its present form the X2MX2B system is thus not able to deredden the coolest dwarfs not even in the closest distance bin. At 1 kpc the deviations in Figure 3 are seen to be caused by M and K dwarfs. So from the extinction point of view much emphasis should not be put on the late-type dwarfs.

We have constructed a series of simplified HR-diagrams representing the ST location in the log g – log$T_{\rm eff}$ plane for a set of distances thus indicating at which distance some of the STs fail to meet the σ_{A_V} criterion. An example valid for 3 kpc is shown in Figure 4 . It indicates that at this distance the main sequence cooler than about 5500 K may not be sufficiently precisely reddening corrected by the 2X system. Fortunately the hotter stars, the main sequence F stars and hotter, meet the precision required. This indicates that the stars located around the Milky Way turn off may be corrected for reddening, this is a very important result since these stars' age and chemical composition span the complete Milky Way age range and the [Fe/H] and α-element variation. A serious drawback is that a distance of 3 kpc is small in the Galactic context. Moving further out in the Galaxy makes the problem more serious with the fainter apparent magnitudes and an increasing extinction. At 5 kpc most F stars are lost and generally only stars hotter than ≈ 6000 K are retained but even some of the A main-sequence stars will be lost at this distance. Moving to 10 kpc will essentially lose the complete main sequence also the A stars with negligible reddening. As Table 1 shows the 10 and 30 kpc bins do not retain the complete sample of highly evolved stars.

Two important issues in fact result from this brief survey of the extinction errors. One is a consequence of the fact that the coolest main sequence stars (M V) can not measure the local extinction which may thus be a problem since the stellar density of the hotter stars may not be adequate to result in a sufficiently dense grid for a 3D extinction map. There may thus be introduced some uncertainty in the initial conditions for the Galactic 3-D extinction map. Another consequential failure seems to be the early main-sequence stars, the A types mainly, inability to measure extinction already at distances 3 – 5 kpc. This could be a problem for the study of high latitude early-type stars, possibly identifying mergers.

One can state that the 2X system seems to meet the required extinction goal, by meeting the extinction accuracy of σ_{A_V} for 60% of the STs at 5 kpc. It remains to be investigated whether a precise 3-D extinction map may

Table 1. Stellar types with the highest priority not meeting the $\sigma_{A_V} \leq 0.09$ mag criterion.

D(kpc)	Type
0.5	M V
1.0	K V, M V
2.0	F V, G V, K V
5.0	A V, F V, G V, K V, red clump K III
10.0	red clump G III, K III; turn off F IV; A V; AGB/RGB
30.0	red clump G III, K III; RR Lyr; turn off F IV; BHB

be constructed from this grid of measuring points.

2. STAR FORMING REGIONS

2.1. Extinction Contours from Colour – Magnitude Diagrams

With the parallax measured, regions with massive reddening may be mapped out in three dimensions as shown at the Les Houches Gaia meeting, (Knude 2002). In short the method consists of finding the main-sequence stars at a given distance, as measured by the Gaia parallax, and asking if any stars at this distance have a certain extinction A_V. In a colour– magnitude diagram for this particular region such stars are located along a locus, which is the main sequence intrinsic relation in the same colour and magnitude system as the observed diagram, but shifted according to the preselected parallax and extinction assuming that the colour excess/extinction ratio is known. The sky coordinates of these locus stars then outline the contour with the preselected extinction. Small variations of preselected extinction and distance will then provide the three-dimensional extinction distribution. It is important to notice that this approach will work also for main sequence stars that do not fulfill the medium band criterion for extinction determination. And because the distance is known *a priori* there will be no giant–dwarf mismatches. Model simulations assuming a luminosity function of the disc and a distribution of diffuse interstellar material according to some statistical measures of the diffuse clouds, number density, column density and diameter distributions, together with a population of massive molecular clouds also with diameter distributions and density gradients have shown that the properties of the molecular clouds may be reproduced by this technique. It remains to be investigated down to how small extinctions this method may be pushed but it seems certain that some overlap with the extinctions derived from the medium band photometry may be achieved.

For really massive reddening found in molecular clouds this may be the only feasible way to *measure* the extinction from the Gaia data — assuming that the stars have broad band photometry and astrometry. And as mentioned it may provide a fairly accurate estimate of the reddening of stars that fail to have reddening estimates from the medium band photometry. This means that for many stars both the distance and the extinction will be available facilitating, e.g., by breaking degeneracies, the determination of the remaining astrophysical parameters. Regarding the usefulness of braking degeneracies in Q versus colour diagrams see the discussion in Romaniello et al. (2002). Perhaps such an option should be considered for inclusion in the data reduction scheme? Together with the parallax it might act as a preclassification of the luminosity class and provide a rough estimate of the absolute magnitude. The locus method may also be a complement to what may be obtained from star counts.

2.2. Mapping Star Forming Regions and Other ISM Features in 3-D: Examples from 2MASS Data

2.2.1. A_V and distance from JHK photometry: The method

Since very few photometric data sets may be calibrated in terms of intrinsic properties, we resort to a calibration we have performed of the H–K versus J–H diagram in terms of intrinsic colours and absolute magnitude. We may not calibrate the complete diagram presently but only the early part of the main sequence: earlier than about G3 where the giant relation coalesces with the dwarfs. And the coolest part of the main sequence, say later than about M4. Not all reddenings can be determined. The range is limited by the curvature of the H–K versus J–H standard relation. For the early group of stars the A_V range goes up to about 5 mag and for the G stars of the early group the maximum A_V is about 3 mag so excesses determined this way do not sample the A_V distribution in an unbiased way but depend strongly on the stars available and the maximum values of A_V in the cloud. The M dwarfs are mainly used for measuring the presumably lower extinction in front of the cloud. The maximum value of measurable A_V values will be increased when the photometric distances derived from the JHK photometry are replaced by the Gaia parallaxes. Another effect of the parallaxes is that dwarf–giant mismatch in the spectral region from mid G through K to early M will be broken and this spectral range will accordingly also be used as extinction tracers. The giants’ JHK photometry together will the parallax will be quite useful for mapping out the more massive parts of the molecular clouds. The calibration was performed on the 2MASS stars present within about 100 pc that had excellent astrometry from Hipparcos and good quality JHK photometry. These stars, only main-sequence stars are used so far, formed a sequence where we could calibrate the intrinsic infrared colours in terms of absolute magnitude: M_V, M_B, M_I, M_J, M_H, M_K. A preliminary description of our method is published in Knude & Fabricius (2003).

2.2.2. Intermediate velocity gas: -60 to -30 kms^{-1}: Deviating gas/dust ratios.

Distance determination of the HVC and IVC gas is of course an important issue. Not only for their own sake but also because the gas/dust ratio in such structures may deviate from the canonical value. If such gas is nearby, as some of it may be — mainly the IVC gas, the suggestion to build the 3-D extinction model for Gaia from the N_{HI} surveys may give systematically wrong estimates in certain areas.

Recently Welsh et al. (2004) presented CaII and FUSE data for stars located close to or in the local bubble in a region centred on (l, b) = (160°, +55°). The stars showing interstellar absorption lines in the intermediate cloud range indicated a z-distance for this gas of only 275 – 320 pc. In Figure 5 we show a contour plot of A_V pertaining to the same region. The contours are based on mean values of the extinction in 0.5° × 0.5° reseaus. Only stars closer than 310 pc are included in the mean values. They give lower limits because also unreddened stars closer than the interstellar feature (if any) enter the mean value. As the figure shows extinction as high as $A_V \approx 0.5$ is present within ≈ 300 pc — in agreement with Welsh et al. (2004). For photometric extinction maps this resolution is quite good the average separation between adjacent stars is down to 15′. For comparison we also include another part of the same intermediate velocity gas. We keep the latitude and shift the longitude to 200°. This position is interesting because it is where the -60 to -30 km s^{-1} gas has a local maximum N_{HI} column density. This IVC is called IV 18 and is part of the IV Arch complex. The A_V contour plot is shown in Figure 6. The contour values are increased with a factor about 2 compared to Figure 5. Another distinction is that stars out to 1.5 kpc had to be included before a coherent A_V feature showed up. The material in the (200, +55) direction may be associated with the intermediate velocity gas in the IV Arch feature for which the low velocity part, -60 to -30 km s^{-1}, is estimated to be in the z-range from 0.4 to 1.5 kpc above the Galactic plane, (Wakker 2001). z corresponding to d =1.5 kpc is 1.3 kpc so maybe the density enhancement we deduced from the JHK data is associated to the IV Arch gas. The solid curves in the last two figures (Figures 5 and 6) are overplotted to indicate a possible trend of the extinction enhancement. An association of dust and high velocity gas is of course only indicative given the missing velocity information of the dust. But it seems that some of the intermediate velocity material could be within a few hundred pc and some just beyond beyond 1 kpc.

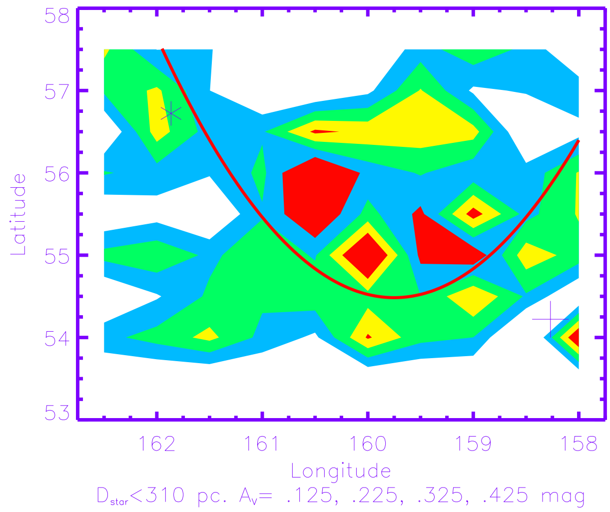

Figure 5. *A_V distribution. A_V values are averages for 0.5°× 0.5° boxes of individual extinction values for stars closer than 310 pc. The solid curve may outline a density enhancement related to the intermediate velocity gas present at this Galactic position, (Welsh et al. 2004).*

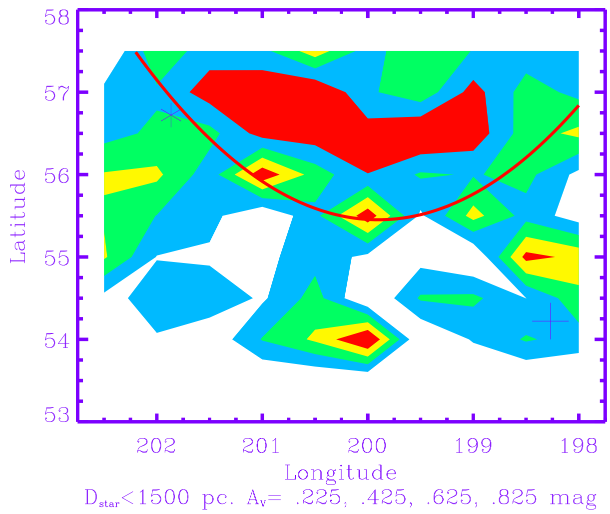

Figure 6. *Same as Figure 5 just shifted to longitudes around l = 200° where the intermediate velocity gas in the range -60 to -30 kms^{-1} has a maximum N_{HI} column density. Stars within 1.5 kpc are included and twice as large extinctions as in Figure 5 are present. Again the solid curve may trace a density enhancement.*

If the intermediate velocity gas is related to the dust represented by the A_V contours the gas/dust ratio in these region are abnormal by being lower than the standard ratio by almost a factor of ten. The lowering of the ratio is most pronounced at the (160, +55) position where a gas/dust separation process related to the local bubble may be at work. So one must be careful when converting N_{HI} column density to a dust column.

2.2.3. Localizing a star forming region in space: The MBM 12 region

A common way to locate a molecular cloud in space has been to derive extinctions and distances for suitable stars in the general direction of the cloud and its vicinity and search for extinction discontinuities located at a sharply defined distance. With the large Gaia data base one might try another approach. Molecular clouds are often known and recognized from radio data or from optical/infrared imaging. They are known as two-dimensional projections. So it is their projected appearence that defines them. Why not introduce a similar concept in the photometric recognition of molecular clouds, and of star forming regions? Benefitting from the Gaia parallaxes of course for the distances. Criterion: a cloud is present and properly detected so its distance and dimensions etc may be derived when a more or less continuous contour plot may be established with the highest possible angular resolution. We may relax this principle to be applied for distance-limited projected contours based on average extinction values.

As an example we study the star forming region MBM 12 containing about 10 protostars with an estimated age 2 – 5 Myr, see e.g., Hogerheide et al. (2002) where masses of the circumstellar discs of the PMS stars are discussed. These masses as well as other parameters such as the protostellar luminosity and age depend on some power of the distance. The distance of MBM 12 in particular has been a matter of debate for about two decades. Ranging from less than 100 pc, (Hobbs et al. (1986) suggesting the cloud as a candidate for the closest star forming region and even located inside the local bubble) to a more recent determination of 275 pc (Luhman 2001). Luhman (2001) has devoted a complete section for very detailed consideration of the methods used to estimate the cloud's distance and ends up with the conclusion that it is about 275 pc and most importantly discard the stars showing Na I absortion as indicators of the MBM 12 distance on physical and topological grounds. Ironically the 275 pc is based on just the M dwarfs that the X2MX2B PS can not estimate reddening for.

Figures 7, 8 and 9 illustrate our new principle for accepting an ISM feature as a molecular cloud and for deriving its distance. And we recall that with Gaia several of the stars with infrared JHK photometry do have trigonometric parallaxes of high quality so in the future we will not be restricted to relying on photometric distances. Perhaps even most of them for such a nearby cloud as MBM 12. Figure 7 shows the contours based on stars closer than 200 pc. Mean extinctions exceeding 1 mag are noticed but in a rather small region and adjacent to extinction free areas; note the shape of the region where the average A_V is less than 0.2 mag, so our criterion with continuous countors confining the largest extinction is not fulfilled. Figure 8 is based on stars within 300 pc and shows a much larger coherent feature with large A_V values so for this distance the continuity criterion is fulfilled. Comparing Figure 8 to Figure 7 we notice that the contour limiting the extinction exceeding 1.2 mag almost is an exact match to the 0.2 mag contour of Figure 7 delineating the extinction free region within 200 pc. Going to a larger distance as the 500 pc in Figure 9 we see that the cloud present in Figure 8 breaks up and the continuity criterion is no longer fulfilled. Based on these three figures we may conclude that the cloud is not located within 200 pc and not beyond 300 pc. So MBM 12 is probably somewhere between 200 and 300 pc. The interval may of course be narrowed by applying a whole sequence of contour diagrams.

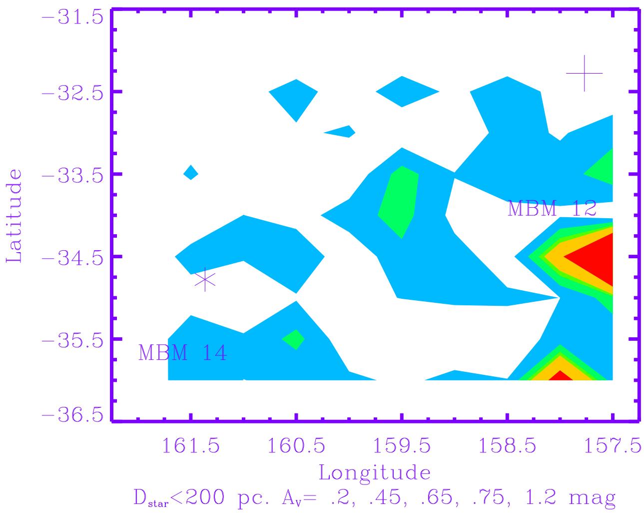

Figure 7. A_V distribution in the MBM 12 direction for stars within 200 pc. Extinctions above 0.5 mag are present but contours of 0.45 mag show a rather fragmented appearance. The position of MBM 14 is indicated at the lower left.

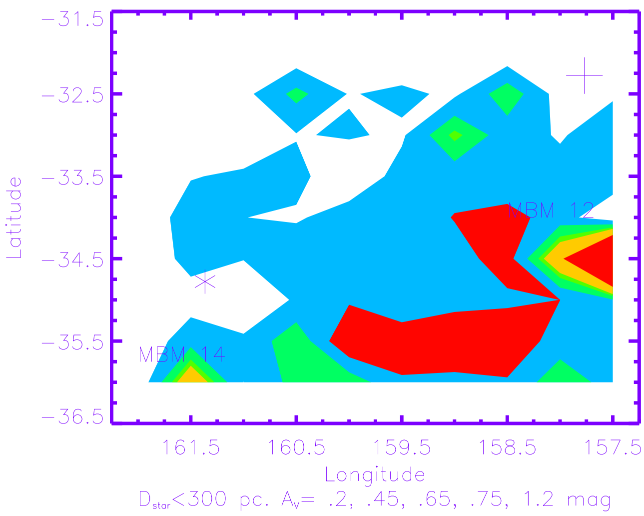

Figure 8. Same as Figure 7 but including stars within 300 pc. Note that the contour confinning the maximum extinction almost is an exact match to the 0.2 contour of Figure 7 delineating the extinction-free region nearer than 200 pc.

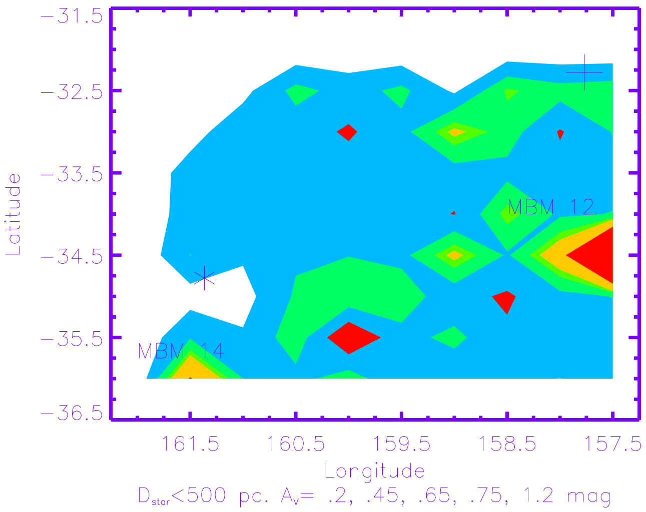

Figure 9. Same as Figure 7 but including stars within 500 pc. Note how the size of the projected extinctions are smaller at many positions as compared to Figure 8 valid for the smaller distance of 300 pc.

3. CONCLUSION

The discussion of the accuracies resulting from using the X2MX2B photometric system on the sample of scientific targets showed that a substantial fraction of these targets can have a proper reddening determination, $\sigma_{A_V} \leq 0.09$ mag, but also that some problems remain. One was that the M dwarfs could not be dereddened; another that the cool part of the main sequence could not be dereddened as individual stars even at modest distances; a third that the early main sequence could not be dereddened beyond a few kpc. More generally it is a problem that dereddening has a success rate of only 50% at $3-5$ kpc, this leaves a statistical problem for the real data: which reddenings can be trusted and with which probability. It seems that dereddening of the Gaia data, despite the high performance of the proposed photometric systems to some extent will depend on modelling and simulations.

In the discussion of the spatial location and to some degree also the measurement of extinction in molecular clouds we introduced a new method to identify and localize a cloud. We proposed that the cloud distance should not exclusively come from the onset of major extinction at some well defined distance but rather result from the distance where the feature displays well behaved extinction contours projected on the sky and that this distance is bracketed by lower and upper distance limits where the contours breaks up in a discontinuous way.

Given the shortcomings of any photometric system, it can hardly be expected to provide dereddening for any point source measured. Dereddening may however still be possible from models based on the dense mesh of points with reddening measures close to the point source which have a measured parrallax. And we may benefit from the infrared sky surveys. Those already available but not least those being completed in the near future: UKIDSS and VISTA. In this respect it is important that the surveys of the Galactic plane will cover the full range of longitudes, not least in the Galactic centre direction, and the star forming regions located far from the Galactic disc.

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