MBM 12 and MBM 16 distances

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ABSTRACT

Among the multitude of intrinsic SDSS index vs. index diagrams the \((g-r) vs. (r-i)\) diagram is characterized by showing only minor \((g-r)\) variation for the M dwarfs. The \((g-r) vs. (r-i)\) reddening vector has a slope almost identical to the slope of the main sequence earlier than \(\approx M2\), meaning that dwarfs later than \(\sim M2\) are not contaminated by reddened dwarfs of earlier type. Chemical composition, stellar activity and evolution have only minor effects on the location of the \(M2-M7\) dwarfs in the \((g-r) vs. (r-i)\) diagram implying that reddening may be isolated in a rather unique way. From \(r, M_r(r-i)_0\) and \(E_{g-r}\) we may construct distance vs. \(A_r\) diagrams. This purely photometric method is applied on SDSS DR8 data in the MBM 12 region. We derive individual stellar distances with a precision \(\approx 20-26\%\). For extinctions in the \(r-band\) the estimate is better than 0.2 mag for \(\approx 67\%\) and between 0.3 and 0.4 for the remaining \(\approx 33\%\). The extinction discontinuities noticed in the distance vs. \(A_r\) diagrams suggest that MBM 12 is at \(\approx 160\) pc and MBM 16 at a somewhat smaller distance \(\approx 100\) pc. The distance for which \(\Delta(A_r)/\sigma(A_r) = 3\) where \(\Delta(A_r)\) refers to \(A_{r, on}-A_{r, off}\), may possibly be used as an indicator for the cloud distance. For MBM 12 and 16 these distance estimates equal 160 and 100 pc, respectively.

Key words: molecular clouds – interstellar extinction – distances : M dwarf stars.

1 INTRODUCTION

MBM 12 is a high latitude molecular cloud and since it has \(A_V\) exceeding 5 mag. [Hearty, Neuhaus, Stelzer et al. (2000), it is classified as a dark cloud. And it contains more than a dozen PMS stars. An active high latitude cloud requires possibly other mechanisms for star formation than dark clouds close to the galactic plane. Estimating parameters essential for initiating star formation, such as the cloud mass and density, depends on the cloud distance. We include MBM 16, a high latitude neighboring translucent cloud, only ten degrees removed from MBM 12, and showing no star formation. For a recent review of high latitude molecular clouds [McGeehe (2008)] may be consulted.

The MBM 12 distance has a long long history and a corresponding, large variation. Shortly after its inclusion in the MBM catalog [Hobbs, Blitz, and Magnani (1986)] suggested \(\sim 65\) pc as derived from NaI spectroscopy and spectroscopic distances of a small sample of stars. [Hobbs et al. (1988)] suggest the same distance for MBM 16 about ten degrees away from MBM 12. The estimate for MBM 12 was altered by [Hearty, Neuhouser, Stelzer et al. (2000)], after Hipparcos parallaxes became available, to the range from 58 to 90 pc. Again lower and upper estimates were based on the absence/presence of NaI absorption. [Luhman (2001) and Andersson et al. (2002)] have used more indirect methods and prefer a cloud distance of 275 pc and 360-430 pc, respectively. Both of these papers do, however, detect dust, thought not to be associated to MBM 12, at 65, 140 pc and at \(\sim 80\) pc respectively. An intermediary distance, 325 pc, is proposed by [Staizys et al. (2002)] from Vinius photometry of dwarfs and giants brighter than \(V\approx 12\) mag. That work also indicates the possible presence of a small hump, \(A_V \leq 0.4\) mag, of extinction at 140–160 pc.

Accurate and homogenous SDSS griz photometry has proven useful for deriving distances and extinction estimates for stars in the M dwarf range within \(\approx 1\) kpc (e.g. [Jones, West and Foster (2011)]). Our own interest in using griz photometry for 3-D mapping of the ISM was inspired by the stellar models by [Girardi et al. (2004)]. These models convinced us that the position of the \((g-r)_0 - (r-i)_0\) locus was influenced very little by variation in \([M/H]\), and by ages varying from a few million years to the age of the Milky Way. The latter invariance was perhaps to be expected. Furthermore, and most important, the reddening ratio \(E_{r-i}/E_{g-r}\) has a value \(\approx 1\) that approximates the slope of the main sequence, in the \((g-r) - (r-i)\) diagram, for dwarfs earlier than \(\approx M1\). A consequence is, that red-


Figure 1. MBM 12 region. SDSS DR8 M2 - M7 dwarfs with $\sigma_{gri} < 0.060$ mag and less than 15$^\circ$ from the nominal center of MBM 12. The MBM 12 and MBM 16 areas outlined. The resulting color excesses are color coded.

reddening seems to be the only parameter that shifts observed $(g-r)$, $(r-i)$ pairs away from the intrinsic locus. Another fact that makes the gri photometry so useful for M dwarfs is the good relation, $\sigma_{M_r} \approx 0.4$ mag, between $(r-i)_0$ and the absolute magnitude $M_r$: a range of $\approx 2$ mag in $(r-i)_0$ corresponds to a range of $\approx 9$ mag in $M_r$. This is taken from Table 2 of West et al. (2011) together with the equation for $M_r(r-i)_0$, Table 4 of Bochanski, Hawley, Covey et al. (2007) valid for the 0.62 – 2.82 range of $(r-i)_0$. The absolute magnitude calibration have required precise distances for a representative sample, Table 4.1, Bochanski (2008).

We apply the photometric parallax and investigate the variation of extinction with distance in a region with a radius 15$^\circ$ centered on the high latitude, dark cloud MBM 12. This region is known to contain several clouds with molecular gas, e.g. the extended translucent cloud MBM 16. The locations of these clouds are interesting because of their various state of activity and their position relative to the confinement of the local cavity.

2 M DWARF SAMPLE SELECTION FROM SDSS DR8

To establish a sample of M dwarfs we follow a selection procedure in line with Jones, West and Foster (2011). The candidate sample is drawn from the most recent SDSS data release, DR8, applied for a region, centered on the MBM 12 position ($l, b$) $\sim (159.4^\circ, -34.3^\circ)$ with a 15$^\circ$ radius, as shown in Fig. 1. The coverage is incomplete but several MBMs are partially scanned. Using the DR8 CasJobs tool we queried for STAR objects with CLEAN photometry for $g$, $r$, $i$ and $z$, respectively, and fulfilling the selection criteria: $\sigma_{g,r,i} < 0.06$ mag, $(r-i) > 0.53$ mag and $(i-z) > 0.3$ mag. The cuts in $(r-i)$ and $(i-z)$ contribute to minimize the contamination by (partially) eliminating quasars, giants and M flare stars. Aspects of the sample are shown in Fig. 2. Notice how the reddening of the main sequence stars earlier than $\sim$M1 does not contaminate the location of reddened M dwarfs.

3 EXTINCTION AND DISTANCE ESTIMATION, UNCERTAINTY

The linchpin for our work is the $(r-i)$ vs. $(g-r)$ diagram, which is characterized by showing only minor $(g-r)_0$ variation for M dwarfs. The $(r-i)$ vs. $(g-r)$ reddening vector has

Figure 2. $(r-i)$ vs. $(g-r)$ diagram. Black points are a selection of stars from the region in Fig. 1. The green symbols are M dwarfs selected in the MBM 12 area. Blue symbols are M dwarfs selected in the MBM 16 area. Notice that the earliest M dwarfs among the MBM 16 stars are shifted to the red of the standard locus which may indicate the presence of some very local dust. The solid jagged line is the standard $(g-r)_0(r-i)_0$ locus from West et al. (2011) Table 2 given as the median color of each spectral type M0,...,M9. The slope of the cut off equals the reddening ratio $E_{g-r}/E_{r-i}=0.694$, Girardi et al. (2004), indicated by the straight line

Figure 3. Distance vs. extinction diagram for the MBM 12 area. Red symbols are for the MBM 12 area exclusively. The vertical line at 160 pc indicates our suggested MBM 12 location. For comparison the black points are the data, with $A_r$ converted to $A_z$, on which a MBM 12 distance of 325 pc was based, Stražys et al. (2002). The blue curve is $A_z$ from Hipparcos data.
a slope almost identical to the slope of the main sequence earlier than ∼M1-M2 meaning that reddened dwarfs earlier than this limit do not contaminate the location of reddened dwarfs later than ∼M2. See Fig. 2 where the M dwarf standard locus starts at M0. As judged from the evolutionary models by Girardi et al. (2004) the chemical composition and evolution have minor effects on the location of the M dwarfs in the \((r-i)_0\) vs. \((g-r)_0\) diagram. According to Bochanski et al. (2007) \((g-r)\) colors are likely to depend on metallicity but no clear trends are apparent for \((r-i)\) and \((g-r)\). M dwarf activity in the form of flares mostly effects the blue part of the spectrum, i.e. the \(u\) and the \(g\) bands implying that \(g-r\) is affected but not \(r\). According to West et al. (2008) a flare will typically change \(g-r\) to values below 0.05 mag. As Fig. 2 shows the \(g-r\) range we consider is far redder than this and \(E_{g-r} > 1.4\) or \(A_r > 4\) is required to shift a flaring star into the color range we use. For the variation in \(M_r, r-i\) with magnetic activity and metallicity see, however, the discussion by Bochanski, Hawley, and West (2011). A more serious contamination can be caused by unresolved binarity and depends on the components mass ratio. With a mass ratio of one the colors do not change but the observed \(r\) magnitude is decreased by 0.75 mag. The estimated \(M_r\) is not influenced since the \((r-i)\) and \((g-r)\) colors are left unchanged. For an individual target, binarity introduces a distance uncertainty \(\pm 35\%\) with a unit mass ratio. The estimated extinction is accordingly not altered but its location is shifted to a larger distance. A recent paper, Clark, Blake and Knapp (2014) has estimated the fraction of close, \(a<0.4\) AU, M dwarf binaries to \(3-4\%\). Dwarfs later than M6 has a frequency of 20\%\+, Allen (2007) and the overall binary frequency among M dwarfs is 42\%\+, Fischer and Marx (1992).

In Fig. 2 is shown three aspects of the \((r-i)\) vs. \((g-r)\) diagram for the MBM 12 region sample. The black points are a selection the region stars. The green symbols are M dwarfs in the MBM 12 area. Blue symbols signify M dwarfs in the MBM 16 area. True color excesses are positive but due to observational errors in \((r-i)\) and \((g-r)\) unreddened and little reddened stars are sometimes shifted to the blue of the \((r-i)_0\) vs. \((g-r)_0\) locus. In Fig. 2 we have indicated the one sigma confinement based on the maximal error 0.060 mag in \(g, r, i\). This confinement is corroborated by the scatter around the standard locus of M dwarfs observed at the virtually unreddened North Galactic Pole.

3.1 Estimate of the Extinction \(A_r\)

As the sample of nearby M dwarfs, forming the basis for the standard locus, shows there is a scatter around the standard locus even for virtually unreddened stars. But collapsing the main sequence to a sharp relation has often proven useful. In a previous section we have argued that a shift from the locus may mainly depend on reddening. The intrinsic location of a dwarf is on the locus and is determined by translating the observed position along a reddening vector. The color shifts \(\Delta (g-r)\) and \(\Delta (r-i)\) are accordingly assumed to equal \(E_{g-r}\) and \(E_{r-i}\) respectively. \(E_{g-r} = 0.694\) is adopted from Girardi et al. (2004) calculated with \(A_V = 0.5\) mag, \(R = 3.1\), \(T_{eff} = 3500\) K, \(log(g) = 4.5\) and \([M/H] = 0\). Not ideal but rather close to the M range.

We have \(A_r = 2.875 \times E_{g-r}\), also adopted from Girardi et al. op. cit. For \((r-i)\) the relation is \(A_r = 4.142 \times E_{r-i}\). The ratio between the two coefficients is 1.441 so other things being equal \(E_{g-r}\) is preferred due to a more favorable error progression.

3.2 Estimated Distance

Having estimated \(A_r\) and observed \(r\) only \(M_r\) is missing for the photometric parallax. We rely on the calibration of \(M_r\) in terms of \((r-i)_0\) which is preferred to \((g-r)_0\) due to a better error progression. The \(M_r\) calibration of \((r-i)_0\) for M dwarfs is as mentioned adopted from Bochanski, Hawley, Covey et al. (2007).

The distance estimate is derived from the usual formula:

\[
distance = 10^{0.2s(r-M_r-A_r+5)} \tag{1}
\]

where all parameters are known together with their uncertainties.

3.3 Uncertainties on Extinction and Distance

Each entry in the extraction from SDSS DR8 contains errors on all magnitudes but we have preselected stars with \(\sigma_{gri} < 0.060\) mag. We may estimate the total uncertainty from the combination of observational errors and errors introduced from the calibrations.

If \(s = f(x_i)\) represents either the full set of equations used to estimate \(A_r\) or \(M_r\) the formal error of \(s\) follows from the progression formula:

\[
\sigma_s^2 = \Sigma (\frac{\partial s}{\partial x_i}) \sigma_{x_i}^2 \tag{2}
\]

For each star we compute \(\frac{\partial s}{\partial x_i}\) and \(\sigma_{x_i}\) implying that derivatives must be calculated and errors of the independent parameters also must be known. The errors \(\sigma_{(g-r)_0}\) and \(\sigma_{(r-i)_0}\) are derived from piecemeal linear approximations to the intrinsic locus, taking into account errors in slope and intersection, together with the observational errors in \(g, r\) and \(i\). \(\sigma_{M_r}\) is calculated from the calibration equation (1) considering our individual, estimated errors \(\sigma_{(r-i)_0}\).

The resulting uncertainties are in the range 20-26% for the distances and for \(A_r\) about 2/3 has \(\sigma_{A_r}\) in the range from 0.04 to 0.20 mag and about 1/3 between 0.30 and 0.40. The reason for this double peaked distribution is the kink in the intrinsic locus noticed in Fig. 2.

4 RESULTS

SDSS DR8 provides a substantial amount of M dwarf data for the MBM 12 region and the distance and \(A_r\) accuracies are adequate to study the distance - extinction variation.

4.1 MBM 12 Distance Estimate

The distance to MBM 12 is particularly interesting because the cloud is a specimen of a rare variety, high latitude, dark cloud (\(A_V > 5\) have been measured) that even shows star formation activity.
4.1.1 Distance from appearance of substantial extinction

By substantial extinction we mean an extinction that appears in a discontinuity and is substantially larger than the extinction at smaller distances and that several stars do show such an extinction.

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From the $M_r$ luminosity calibration of $(r - i)_0$ and the color excess from $(g - r) - (g - r)_0$ in Fig. 2 we construct a distance vs. $A_r$ diagram for the MBM 12 area, as shown by the red dots in Fig. 3. We have used a logarithmic distance scale to emphasize the smaller distances.

4.1.2 Alternative distance derivation for MBM 12

The scans in Fig. 1 cover several clouds revealed by their color excesses but also sight lines with less dust. One may expect that for a small distance bin at a given distance the average extinctions in a cloud direction and outside the clouds differ. For distances less than the cloud distance, but in the direction of a cloud, the two averages will be more similar. As Fig. 3 shows there is a substantial scatter of $A_r$, at almost any distance. A scatter caused by real variation in the presence of dust causing the extinction and the observational errors, $\sigma_{\text{total, on}}$ and $\sigma_{\text{total, off}}$ designate the average extinctions on and off a cloud for identical distance bins we propose that $\Delta(A_r) = A_{r, \text{on}} - A_{r, \text{off}}$ will measure the presence of a cloud at a given distance where the difference is sufficiently large. We use $\sigma^2(\Delta(A_r)) = \sigma_{\text{total, on}}^2 + \sigma_{\text{total, off}}^2$ as a measure of the significance of $\Delta(A_r)$ and define the
Distance estimates of the dark cloud MBM 12 and the translucent cloud MBM 16

4.2 The distance to MBM 16

Another cloud in the MBM 12 region is MBM 16 which is of different type than MBM 12. MBM 16 is translucent whereas MBM 12 is a dark cloud. The two types are distinguished by their optical extinction: a dark cloud has $A_V > 5$ mag whereas a translucent cloud is less opaque with $A_V$ in the range from 1 to 5. van Dieshöeck and Black (1988). MBM 16 has been studied by Magnani, Chastain, Kim et al. (2003) in order to understand the origin of turbulence and the correlations between molecular gas and color excesses. For their investigation a distance of 100 pc was assumed, identical to the distance to the wall of Local Bubble as estimated by Cox and Reynolds (1987). In their probing of the local low density cavity Lallement, Welsh, Vergely et al. (2003) suggest the presence of a region with a high density at a distance closer than 100 pc in the direction of MBM 16.

In Fig. 5 is shown SDSS for what is available inside the area shown in Fig. 1. Hipparcos 2 results from the same area is overplotted and two vertical lines at 115 and 160 pc respectively. From the occurrence of the first dust, $A_r$, ranging from $\approx 0.5$ to $\approx 2$ mag, we would suggest $\sim 115$ pc. Smaller than the MBM 12 distance of 160 pc. The $A_r$ data from Hipparcos 2 corroborates this to some degree, but only by two stars with $A_r$ in the range from 0.5 to 1 mag.

The $\Delta(A_r)/\sigma(\Delta(A_r))=3$ criterion indicates a distance 100 pc for MBM 16 as shown in Fig. 5.

5 CONCLUSIONS

We have applied two different methods, which perhaps could be termed qualitative and quantitative, respectively, for estimating the distance to the two high latitude clouds MBM 12 and 16: the distance at which substantial extinction is first measured and the distance when the ratio $\Delta(A_r)/\sigma(\Delta(A_r))$ equals three. In the case of MBM 12 and 16 the two methods agree. Our suggested distances are 160 for MBM 12 and 100 pc for MBM 16. The former does not agree with the current values from the literature whereas the latter does, almost exactly. That either method works depend on the nice behaviour of the M2–M7 dwarfs in the $(g-r)$ vs.$(r-i)$ diagram.

The difference of the MBM 12 and 16 distances has been narrowed from $\approx 350-100$ pc to 160-100 pc. The possibility that MBM 12 is outside the confinement of the local bubble and MBM 16 is on or inside still exist. Tempting to suggest that their dark/translucent status is a consequence of their different interstellar environment?

The $\Delta(A_r)/\sigma(\Delta(A_r)) = 3$ criterion may possibly be expanded to a generalized method for locating nearby molecular clouds where $griz$ photometry is available and maps, 2D and 3D, could be produced with a larger number of stars than used in the spectroscopic study by Jones, West and Foster (2011).

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REFERENCES

Allen, P.R., 2007, ApJ 668, 492
Andersson, B.-G., Idzi, R., Uomoto, Alan, Wannier, P. G., Chen, B., Jorgensen, A. M., 2002, AJ, 124, 2164
Bochanski, J.J., 2008, Doctoral Dissertation, University of Wasington
Bochanski, J.J., West, A.A., Hawley, S.L., Covey, K.R., 2007, AJ 133, 531
Bochanski, J.J., Hawley, S.L., Covey, K.R. et al., 2010, AJ 139, 2679
Bochanski, J.J., Hawley, S.L., West, A.A., 2011, AJ 141, 98
Clark, D.A., Blake, C.H., Knapp, G.R., 2012, ApJ 744, 119
Cox, D.P. and Reynolds, R.J. 1986, ApJ 304, 69
De Grijs, J., Eyer, L. 2002, MNRAS, Volume II, The Southern Sky ASP Monograph Publications, 5, 813
Dobson N., Foster J.B., 2012, ApJ 744, 119
Dobson, N., Foster, J.B., Siemens, A., Kazlauskas and Laugalys, V., 2002, Baltic Astronomy 11, 231
Hobbs, L.M., Blitz, L., Magnani, L., 1986, ApJ 306, 109
Hobbs, L.M., Penprase, B.E., Welty, D.E., Blitz, L., Magnani, L., 1988, ApJ 327, 356
Jones D.O., West A.A., Foster J.B., 2011, AJ 142, 44
Knupe, J. and Hong, E. 1998 A&A 338, 897
Koen, C., Eyer, L. 2002, MNRAS 331, 45
Lallement, R., Welsh, B.Y., Vergely, J.-L., Crifo, F., Sfeir, D., 2003, A&A 411, 447
Luhman K.I., 2001, ApJ, 560, 287
Magnani, L., Chastain, R.J., Kim, H.C., Hartmann, D., Truong, A.T., Thaddeus, P., 2003, ApJ 586, 1111
McGehee, P. M., 2008, Handbook of Star Forming Regions, Volume II, The Southern Sky ASP Monograph Publications, 5, 813
Perryman, M.A.C., Lindegren, L., Kowalevsky, J., 1995, A&A 304, 69
Stražys V., Černis, A., Kazlauskas and Laugalys, V., 2002, Baltic Astronomy 11, 231
West, A.A., Hawley, S.L., Bochanski, J.J., et al., 2008 AJ 135, 785
West, A.A., Morgan, D.P., Bochanski J.J. et al., 2011, AJ 141, 97
van Dieshöeck, E.F., John, J.B., 1988, ApJ 334, 771
van Leeuwen, F., 2007, A&A 474, 653

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