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ASTRONOMY AND ASTROPHYSICS

Interstellar reddening from the Hipparcos and Tycho catalogues

I. Distances to nearby molecular clouds and star forming regions

J. Knude and E. Høg

Niels Bohr Institute for Astronomy, Geophysics and Physics, Juliane Maries Vej 32 DK-2100 København Ø, Danmark (indus@astro.ku.dk)

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Abstract. The Hipparcos and Tycho Catalogues offer an interesting possibility to study the local distribution of interstellar reddening from the combination of data contained in the catalogues: Hipparcos parallaxes, Tycho B - V and spectral and luminosity classification compiled from the literature. Parallactic distances may be derived for known absorbing features such as local molecular clouds and for large scale features such as sheets dividing bubbles. The stellar luminosity classes V and III offer more than 30.000 lines of sight for study, mostly for negative declinations where most classifications are available. We present some examples of this approach to derive information on the local interstellar medium. First we estimate the distance to the Southern Coalsack. Secondly, distances to the four nearby southern star forming clouds in the Chamaeleon region, the Lupus region, Corona Australis and finally the ρ Ophiuchi are estimated. We find that these clouds are at 150 (Cha), 100 pc (Lup), i.e. about 50 pc closer than previously estimated, and that a feature with $E_{B-V} \approx 0.15$ (or $A_V \approx 0.5$) appears at 50 pc in this region. A distance of 170 pc is found for CrA compared to the previous estimate of 129 pc, and finally 120 pc for ρ Oph compared to the previous 160 pc, strictly speaking the 120 pc are only measured for extinction values typical for the off core region in ρ Ophiuchus.

These distance changes are of some importance since these four regions show different stages of the star forming activity, as judged from the relative distribution of Class 0 – Class III YSOs (young stellar objects) in the L_{bol} – T_{bol} diagram. Precise calibrations of the YSOs' bolometric luminosities, applied in the definition of the bsf parameter (bsf: bright star fraction), require accurate distances of their parental clouds unless they are based on individual distances of the pre main sequence stars/protostellar sources.

Key words: stars: distances – ISM: clouds – dust, extinction – solar neighbourhood

1. Introduction

The visual magnitudes of the Hipparcos and Tycho Catalogues, the accuracy of the Hipparcos parallaxes and the sheer size of the catalog make it ideally suited to probe the interstellar medium within a few hundred pc since measurements of the interstellar medium may be tied to the distances of the catalog entries. The local part of the interstellar medium has presented several problems since only tiny extinctions were assumed to be present. Data in the soft X-ray spectral range demanded that the solar neighborhood was almost free of absorbing material. Even if the presence of matter could be confirmed after all, e.g. as causing shadows in high energy sky maps, the problem with the spatial location of the matter would remain. A classical approach has been to use photometry of a dense grids of stars in a photometric system able to measure accurate color excesses and provide rather precise photometric distances. Since Hipparcos trigonometric parallaxes for a large number of stars have become available it is natural to combine these excellent distances and the photometric compilations. Vergely et al (1997) have done this for the uvbyβ compilation and obtained most interesting results for the local medium. A drawback of the uvbyβ system is, however, that reddenings may not be estimated from stars cooler than about G2 – G5.

Another classical approach has been a combination of broad band B, V photometry with a spectral and luminosity classification.

Quite another set of problems in the study of the local interstellar medium, say within a few hundred pc, is to determine the distance to the nearest star forming molecular clouds. Presently five such clouds are estimated to be within $\sim$200 pc, not counting the high latitude MBM clouds (Mangnani, Blitz and Mundy 1985) and alike. Their nearness makes them natural objects for detailed study of YSOs and suited for calibration purposes. It happens that these five clouds have reached different stages in the stars forming process, as defined by the relative frequency of the PMS classes 0 – III. Cloud distances may be used to estimate the bolometric luminosities of the objects and consequently to define a class 0 object's evolution in the T_{bol} – M_{bol} diagram, Chen et al (1997), Myers et al (1998). The T_{bol} – M_{bol} diagram is a YSO version of a HR diagram. We present distances, based on Hipparcos parallaxes to four southern star forming regions: Cha, Lup, CrA, and ρ Oph, which happen to cover the complete range from class 0 dominance, CrA and ρ Oph, to class III dominance close to the ZAMS (Lup). Chamaeleon is an intermediate case.

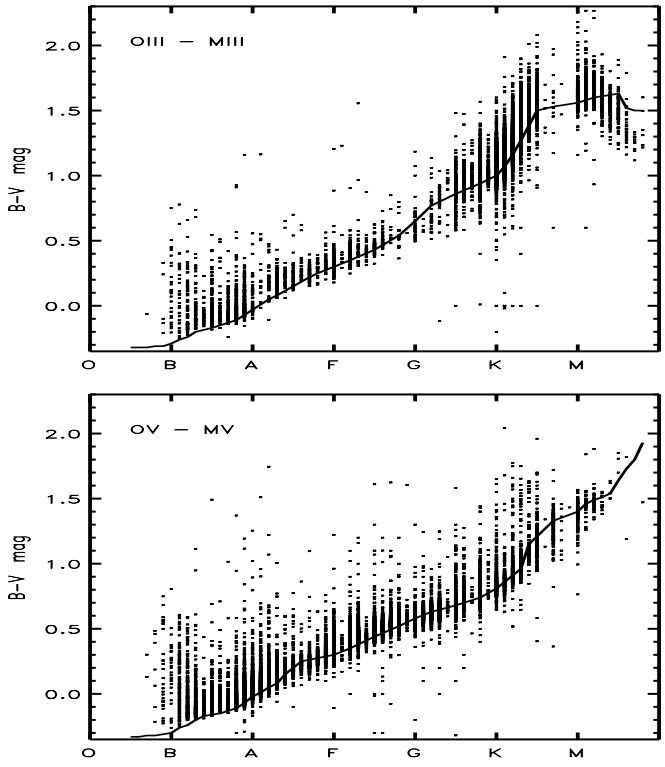

Fig. 1. Spectral type versus (B – V). Intrinsic relation from Scmidt-Kaler 1982.

The computation of a color excess for either method requires intrinsic relations between an unreddened parameter and color. Thus for the uvbyβ system between β and (b-y)$_0$ and for the classification method between spectral type and (B - V)$_0$ for each luminosity class. Such relations should include corrections for chemical composition and evolution. Metallicity information is generally not available but luminosity classification is available for about a third of the entries in the Hipparcos Catalog (≈35.000 stars are classified as LC V and III). This characterization of evolution may be a little coarse, Jaschek and Gómez (1998), but as we will see later color excesses from LC V and III mostly follow identical patterns in the E_{B-V} – distance diagrams.

The Hipparcos and Tycho Catalogues, ESA (1997), provide (B - V) for most of its entries, either from the literature or, most often, from the Tycho photometry. The spectral and luminosity classification are entirely from the literature. In the present paper we restrict the discussion to classes V and III of which the Catalog offers about 20.000 and 15.000, respectively. This implies that on the average there is almost one star per square degree.

2. Intrinsic relations

We have chosen to use the spectral type versus (B - V)$_0$ relations for luminosity classes V and III as published by Schmidt-Kaler (1982). Apart from the late K and the M stars for which the intrinsic relation is rather red compared to the Tycho observations, the Tycho colors seem to be much as expected. As an example all the B stars are located above the intrinsic relation indicating that they all are reddened as expected. The late K, M stars deviation, resulting mostly in negative color excesses may be a problem coming from the Tycho photometry. B and V are not measured directly but computed from a (B – V) calibration of the Tycho index (B_T – V_T), a calibration whose scatter increases with (B_T – V_T). We do not address this discrepancy any further since the number of late dwarfs is relatively small. In Fig. 1 (lower panel) we show (B – V) versus spectral type for the class V stars. Similarly we notice in Fig. 1 (upper panel) pertaining to the class III stars that the B, A and F stars show a (B – V) distribution much as expected, but GIII and later has too many points below the intrinsic relation. These two figures indicate that the reddenings are expected to be in the range from – 0.2 to 1.0 approximately. The largest reddenings are found among the B stars, the A III stars and finally among the early K III stars. Several visual absorptions beyond 0.5 magnitude are thus present so that even less obscured regions in local molecular clouds may be probed.

For survey and search purposes there is one serious drawback, however, and that is the inhomogeneous distribution over the sky of the stars with stellar classification. The bulk of the classifications come from the Michigan Catalogs so the best coverage is for the southern declinations. As a consequence we can not discuss the distance to the Taurus Auriga complex.

3. The Southern Coalsack distance

For many purposes distances to molecular clouds are essential. A southern cloud that has received much attention is the visually spectacular Southern Coalsack. It is presently not forming stars but may be part of a system comprising also the Musca and Chamaeleon molecular clouds, see next section. Particularly the Chamaeleon I and II clouds have been studied extensively due to their star forming activity.

Previous work quoted in Corradi et al (1997) indicates a distance between 150 and 190 pc. The most recent determinations range between 180 and 190 pc and are based on photometric distances, Seidensticker and Schmidt-Kaler (1989), Franco (1989). A renewed discussion by Franco (1995) with additional uvbyβ data suggests an upper distance limit of 200 pc but with dust indicated at 150 pc. We have collected the Hipparcos/Tycho data within 4 degrees centered on (l,b) = (304,01), covering most of the dark cloud. Fig. 2 shows the E_{B-V} – distance diagram. We may notice several characteristics. First LC V and LC III reddenings outline identical ranges. All stars beyond 150 pc, except two, have a color excess exceeding 0.1 mag. Color excesses larger than 0.1 are first measured at a distance 100 pc. We thus suggest than the parts we measure of the Southern Coalsack are constrained between 100 and 150 pc.

4. Distances to four local star forming regions

An overview of star formation in the nearby molecular clouds are presented in ESO (1991), where distance estimates valid at that time also may be found.

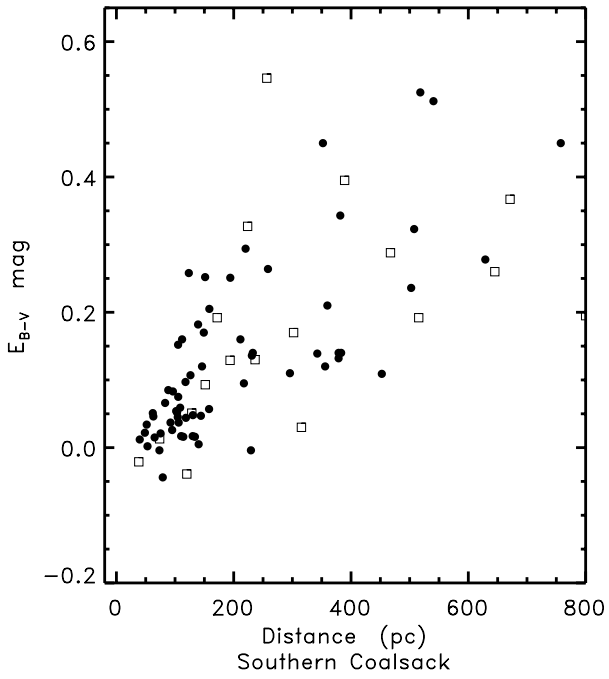

Fig. 2. Southern Coalsack. E_{B-V} versus distance resulting from a search among O – M stars of luminosity classes V(•) and III(□) within 4° from (l,b) = (304,01).

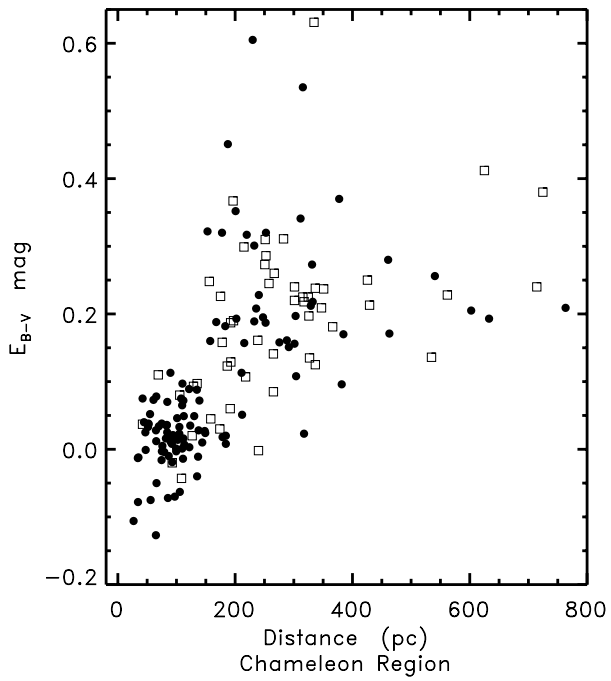

Fig. 3. Chameleon Region. E_{B-V} versus distance resulting from a search among O – M stars of luminosity classes V(•) and III(□) within 6° from (l,b) = (300.0,-15.0). This region has 175 usable stars with (B – V) and LC in the Hipparcos Catalog.

The presence of a dense feature in the interstellar medium should reveal itself by a sudden onset of extinction at a certain distance. If the cloud is isolated and is the first interstellar feature encountered the excesses should almost equal zero in front of the cloud. Due to the excellent accuracy of the Hipparcos distances, 10 – 15 % for the distances less than 200 pc considered presently, the distance determination is more precise that the estimate of color excesses, quite the contrary of what is the case for intermediate band photometry. We do not use the Tycho color excesses in any other way than the indication they give of a rise at a well defined distance. The error of an individual value may be estimated from the scatter in the mean excess in a direction where zero reddening is expected. From the SGP we estimate this error to be $\lesssim$0.030 mag from the LC V stars, somewhat larger for the LC III. Our main data is accordingly the Hipparcos distances and the Tycho color excesses for the LC V stars. Distances for stars beyond $\sim$200 pc are more uncertain but are valuable anyway since they help define the expected constant lower reddening limit when the "outskirts" of a cloud has been crossed, so we include stars within an estimated distance of 800 pc in the diagrams.

4.1. Chamaeleon

Chen et al (1997) quote a median value A_V = 1.5 for the YSO extinction in Cha. As Fig. 3 shows the maximum A_V value measured is approximately 2, so the data relate apparently to the molecular cloud. The figure indicates a steep rise in the color excess exactly at 150 pc, the color excesses may not be very accurate but the distance where the rise takes places corresponds exactly to the photometric value suggested by Corradi et al (1997) as the distance to an extended dust feature possibly encompassing the Chamaeleon and Musca clouds. Considering LC V stars only the distance range from 140 to 150 pc (see Figs. 3 and 4) is seen to be an upper distance limit for stars with E_{B-V} $\lesssim$ 0.1 mag. Only five class V stars with $E_{B-V} < 0.1$ are beyond 150 pc in the whole region. Interesting for the Chameleon Region is that the 150 pc simultaneously is the lower distance limit for stars with $E_{B-V} > 0.15$ mag. This could imply that since the clouds are at 150 pc their extent along the line of sight $\lesssim$10 pc compares well with their angular extent $\gtrsim$5 pc.

Such a sharp transition from the diffuse to the 'molecular' part of the interstellar medium is not present in the Lupus, Corona Australis or ρ Ophiuchus regions (see Figs. 5 – 11), for these clouds the diffuse reddening values continue $\gtrsim$50 pc, beyond the extinction jump. Hughes and Hartigan (1992) proposed 200$\pm$20 pc to Chamaeleon II also from a distance – color excess diagram but with the extinction jump defined from only one star with A_V=3 mag. There has been some speculations that this dust sheet might be the result of the interaction at the confinements of two bubbles, the local one and the LCC (Lower Centarus − Crux). There is, however, not a general agreement at which distance this interface should be crossed.

There may be an indication of very nearby dust in the Chameleon region. An expanded view shown in Fig. 4(a). For this detail we have included LC IV stars using the intrinsic relation valid for LC V which match the lower envelope of their spectral type versus (B − V) well. Furthermore we have excluded single stars known to be part of multiple systems. One

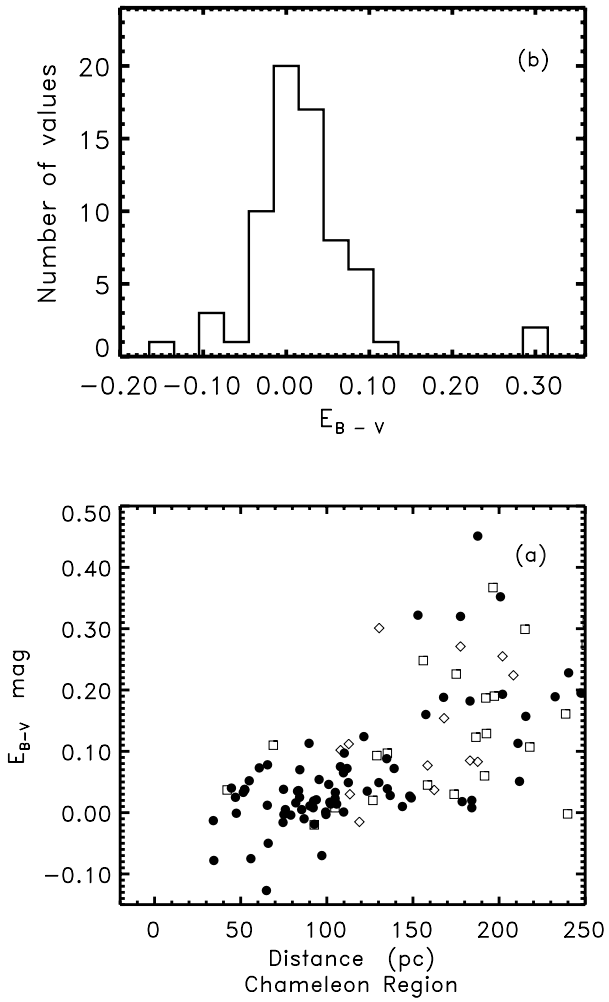

Fig. 4. a Chameleon region, expanded view. LC IV (◇) included, E_{B-V} computed with the LC V intrinsic relation. **b** E_{B-V} histogram for stars closer than 150 pc

could argue that the presence of stars at ≈0.1 mag in Fig. 4(a) was due to error statistics since equally negative color excesses are present. The distribution of color excesses for the 69 stars wihtin 150 pc, with a 0.03 bin size, shown in Fig. 4(b) does however show a marked red(positive) shoulder and may not be fitted with a single Gaussian. If the blue shoulder represent the error distribution the red shoulder might be real. We notice that reddenings of 0.1 magnitude is encountered already at 70 pc and furthermore that this upper reddening limit is constant to 150 pc. Considering the error of ≲0.03 in a reddening value we are at the three sigma level and we measure far too many stars with this reddening compared to the blue shoulder, assuming a gaussian error distribution. The onset of a 0.10 reddening may accordingly be real. 70 pc is about the distance where gas expanding from the Scorpius – Centaurus OB associations are first encountered in NaI D absorptions, Génova et al (1997), Corradi et al (1998). This distance is now corroborated by the Hipparcos parallaxes and the dust distribution.

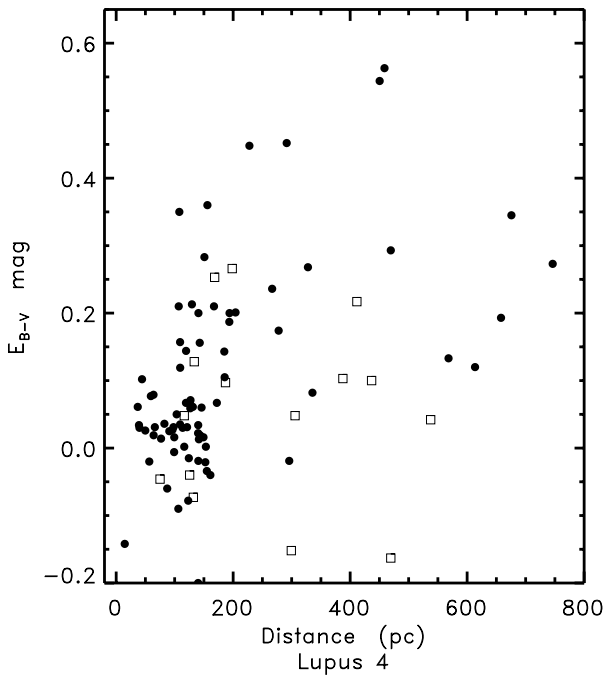

Fig. 5. Lupus 4. Note the four stars with distance less than 100 pc and E_{B-V} exceeding 0.05 mag. E_{B-V} versus distance resulting from a search among O – M stars of luminosity classes V(●) and III(□) within 4° from (l,b) = (337.0,8.0).

4.2. The star forming Lupus region

The location of the five Lupus clouds may be seen in Fig. 1 of Tachihara et al (1996). We only give a detailed view of the Lupus 4 cloud and of the newly discovered Lupus 5 cloud together with a comprehensive view of the color excess versus distance distribution for most of the Lupus molecular cloud complex. Tachihara et al (1996) report the detection of an outflow which indicates ongoing star formation (Class 0 source) whereas Myers et al (1998) characterize the Lupus complex by a large fraction of YSOs with large T_{bol} values implying that most of the PMS are located close to the ZAMS. The complex must have had a long star forming history.

According to Tachihara et al. (1996) Lupus 5 has no optical counterpart. But as we will see in Figs. 5 and 6 its visual extinction as measured by Hipparcos does not differ from the rest of the complex. Fig. 5 shows the conditions for Lupus 4, our reason for presenting Lupus 4 is that the extinction distribution is so clear. The medium in front of the molecular cloud is well defined by the feature at $E_{B-V} \approx 0.04$, an abrupt change occurs at 100 pc where the color excess, for constant distance, rises to 0.35 corresponding to $A_V > 1.0$ mag, the reddening material must be associated with the molecular cloud. An interesting point is the indication of substantial amounts of dust by four stars closer than the cloud distance 100 pc and with $E_{B-V} > 0.05$ mag. Data for the most recently discovered Lupus 5 are given in Fig. 6, again a very clear indication of the cloud distance as only 100 pc. Fig. 6 furthermore shows that despite Lupus 5's fragmented appearance "all" stars beyond ≈200 pc

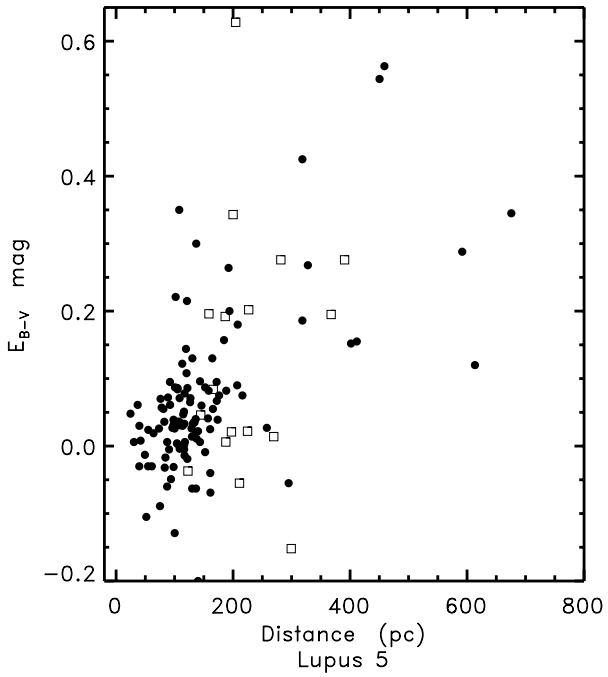

Fig. 6. Lupus 5. E_{B-V} versus distance resulting from a search among O – M stars of luminosity classes V(•) and III(□) within 4° from (l,b) = (342.5,9.0). The extinction jump is at 100 pc.

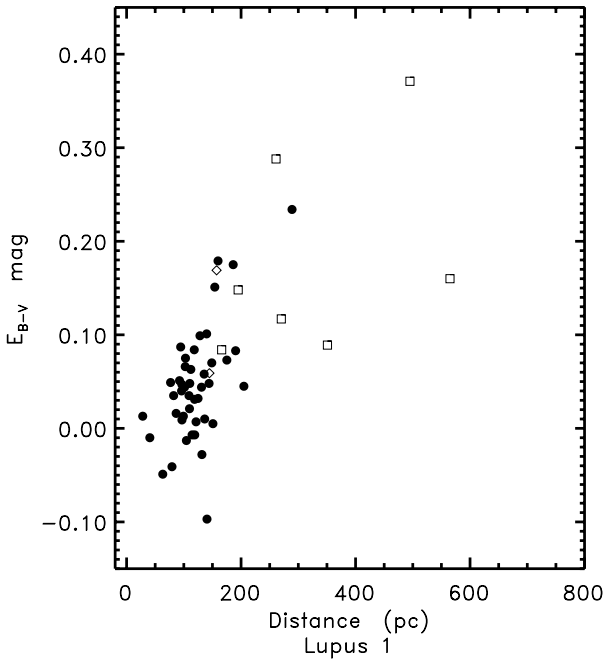

Fig. 7. Lupus 1. E_{B-V} versus distance resulting from a search among O – M stars of luminosity classes V(•) and III(□) in the box l: 237 – 340, b: 14 – 19. The extinction jump at 100 pc is not particularly clear.

are reddened by more than 0.1 – 0.2 mag, this becomes more clear if we leave out the LC III data(□). On the other hand all stars within 100 pc are virtually unreddened. The cloud distance is accordingly proposed as 100 pc.

In order to probe a little further into the existence of nearby dust as indicated from the Lupus 4 region we present a diagram covering most of the Lupus complex, with the center and radius chosen as in the caption to Fig. 8. Fig. 8 shows these data and a close up is given in Fig. 9. Again we notice the rise of the extinction at 100 pc, but not in a much more pronounced way than for the individual clouds, the massive reddening is thus not found in the "clear" regions between the molecular clouds. There are, however, two more points to notice. First, there is a very well defined protrusion of a reddening E_{B-V} = 0.12 – 0.13, starting at 50 pc, and beyond 200 pc this reddening level almost defines the lower limit, so it might be real. The other point is the rather constant reddening level at 0.08 – 0.10 noticed between 50 and 100 pc a level hinted at in front of Lupus 4 but absent in front of Lupus 5. It is of course a question of whether this protrusion also is an indication of very nearby dust or is caused by the error in the the E_{B-V} determination.

The case of Lupus 1, Fig. 7, is not so clear. The E_{B-V} - distance diagram shows just a hint of a rise from 0.1 to 0.2 at 150 pc, nothing like for Lupus 4 and 5. The diagram also has a rise from ≈0 to 0.10 at 100 pc. This latter rise probably causes the 0.08 – 0.10 level between 50 and 100 pc discussed just above. A fair interpretation of the data is that the maximum reddening shows a homogeneous rise from 0 to 0.2 when the distance is increased from 50 to 200 pc. Two stars with E_{B-V} between 0.15 and 0.20 are located at 50 pc though. Lupus 1 probably also starts at 100 pc. An explanation of this missing jump could be the extreme density variation in Lupus 1 as indicated by the ^{13}CO maps by Tachihara et al (1996) where parts of the cloud have low CO column densities that might provide the intermediate color excesses filling up the corner between 100 and 150 pc with intermediate color excesses making the extinction jump disappear. Lupus 2 (not shown) is found at 100 pc showing a very well defined rise from 0.05 to 0.35 at 100 pc. Just one LC V star has E_{B-V} = 0.15 at 50 pc. Similarly Lupus 3 is located at 100 pc and no highly reddened stars are found within that distance.

The situation for the Lupus complex is accordingly that Lupus 2, 3, 4 and 5 are measured to be at 100 pc, Lupus 1 probably at 100 pc but 150 pc is not excluded.

The Lupus distance has most recently been discussed by Hughes et al (1993) proposing a distance of 140 pc for Lupus 1 - 4, a distance our discussion proposes changed to 100 pc making Lupus the nearest star forming complex. For YSOs associated with the Lupus complex this means that their luminosities should be lowered by a factor of 2, the distance uncertainty has a size comparable to that arising from the extinction correction, Chen et al (1997).

4.3. The star forming Corona Australis region

With an estimated distance of only 130 pc CrA is among the nearest of the star forming molecular clouds. The distance was based on uvbyβ photometry of three early type stars, Marraco and Rydgren (1981). This distance determination was very carefully discussed since there were problems for some of the stars

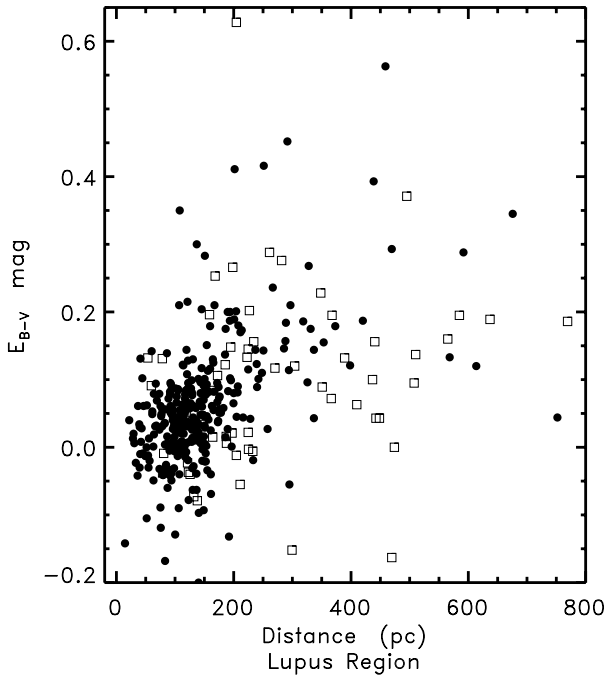

Fig. 8. Lupus region. E_{B-V} versus distance resulting from a search among O – M stars of luminosity classes V(•) and III(□) within 8° from (l,b) = (341.0,13.6).

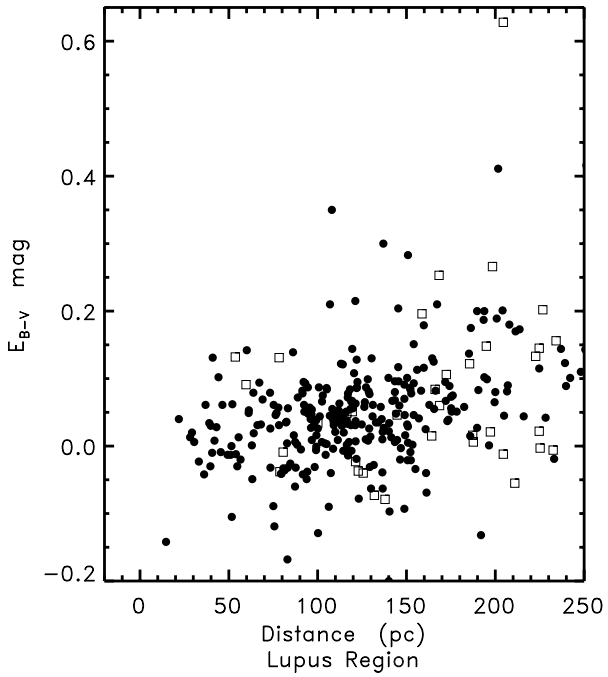

Fig. 9. Lupus region close up to identify dust at 50 pc or closer. E_{B-V} versus distance resulting from a search among O – M stars of luminosity classes V(•) and III(□) within 8° from (l,b) = (341.0,13.6).

in correcting for the background of the superposed reflection nebula. For R = A_V/E_{B-V} the value 4.5 was preferred as a result of an polarization study. CrA is particularly interesting for the evolution of the YSOs since it has the largest fraction of Class 0 objects among the 5 nearest star forming regions, Chen et al (1997). As evident from Fig. 10 the data rather suggest a distance of 170 pc, so the 130 pc distance seems to be excluded. Compared to the Chamaeleon and Lupus regions CrA is different by the absence of a well defined lower reddening level beyond the clouds. This change means that the $\log_{10}$ of a YSO bolometric luminosity should be increased with ∼0.25 (or with – 0.63 mag). This may be an important change since CrA defines the cool end point of the YSO evolution.

4.4. The ρ Ophiuchus star forming region

As the last example we estimate the distance to the onset of larger reddenings for the ρ Oph direction, the result is shown in Fig. 11. The E_{B-V} – distance distribution shows the maximum excess to be homogeneously increasing out to 120 pc where the abrupt rise as expected from a homogeneous molecular cloud takes place. Beyond 150 pc there is a lower envelope at 0.20 mag, most pronounced for LC V but also for LC III. The presence of a constant lower reddening envelope indicates that 150 pc could be an upper limit for the cloud distance. Considering the frayed appearance of the ρ Ophiuchus region the few points below the lower envelope need not be a problem. Several stars in front of the 120 pc have E_{B-V} exceeding 0.1 mag.

The distance to the star forming regions in Ophiuchus has been assumed to ∼160 pc, Chen et al (1995) as based on multi color photometry of heavily absorbed stars in the ρ Oph core, Chini (1981). A_V ranges from 4.3 to 11.7 for the three stars actually used. Chini proposed that the reddening is abnormal for $E_{B-V} > 1.2$, and the larger value R = 4.2 has been used in the distance determination instead of the canonical 3.1. According to Fig. 11 we do not measure such a large reddening value, the maximum is about 0.5 mag.

It might be questioned whether the upturn noticed in Fig. 11 at about 120 pc and the lower reddening limit of 0.2 noted from about 150 pc, at least for most of the LC V stars, relate to the same star forming features as the ρ Oph core proposed to be at 160 pc. Is the 120 pc rather connected to the off core region in Ophiuchus? Nearly all YSOs in the off core regions have visual absorptions as in the range indicated by Fig. 11, according to Table 3 of Chen et al (1997). But is it realistic that the star formation takes places over a distance range of ∼40 pc? B stars from the Upper Scorpius subgroup are included in the region displayed in Fig. 11. These rather young stars are at the same distance as the subgroup, 145±2 pc (de Bruijne et al 1997), about the mean of the core and off core distance estimates.

5. Effects of the changed distances to Lupus, Corona Australis and parts of ρ Ophiuchus

As discussed above we suggest new distances for the Lupus and Corona Australis star forming regions. Lupus is moved from 140 to 100 pc and Corona Australis from 130 to 170 pc, the off core YSOs of the ρ Ophiuchus region may be as close as 120 pc. The Chamaeleon is left at 150 pc as indicated by previous photometric data. One might consider these alterations as marginal

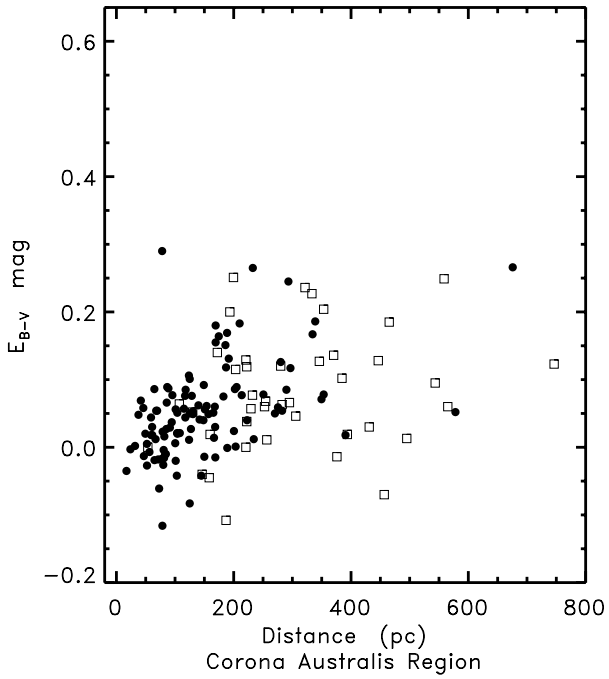

Fig. 10. Corona Australis region. E_{B-V} versus distance resulting from a search among O – M stars of luminosity classes V(•) and III(□) within 5° from (l,b) = (360.0,-20.0). Notice the absence of a well defined lower reddening limit for the larger distances.

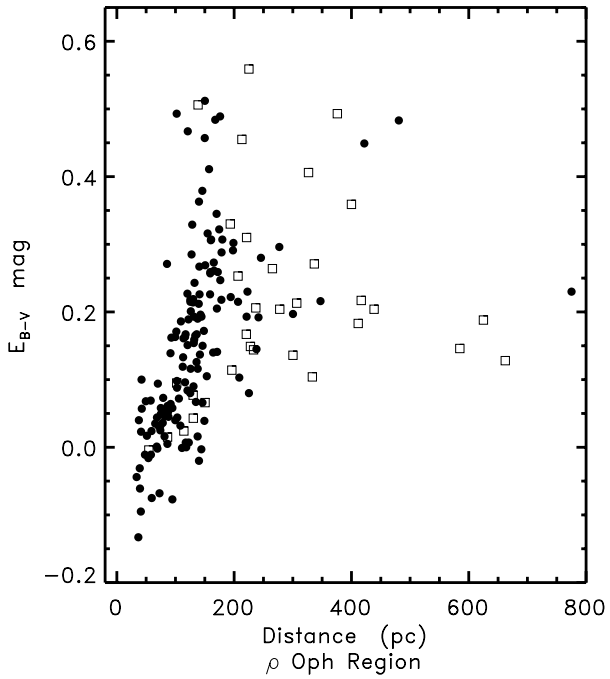

Fig. 11. The ρ Ophiucus region. E_{B-V} versus distance resulting from a search among O – M stars of luminosity classes V(•) and III(□) within 6° from (l,b) = (355.0,20.0).

since the error discussion of Chen et al (1995) has the conclusion that L_{bol} is estimated within a factor of two. The discussion by Chen et al (1997), however, places Lup and CrA, and ρ Oph at different extremes in their csf – bsf diagram (see their Fig. 3). The csf means 'cool star fraction' and bsf 'bright star fraction' among the YSOs. Lup is at the hot faint end and CrA at the cool luminous end. Changing the Lupus distance from 140 to 100 pc lowers the luminosities, estimated from the cloud distance, with a factor of two and raises the Corona Australis estimates with a factor 1.7 when the distance estimate is increased from 130 to 170 pc. The effect on the observed trend in the median BLT diagramme (Chen et al 1997, Fig. 5) would be to steepen the relation depicting the evolution from Class 0 to Class II YSOs. Taken as a whole the ρ Oph point will have a median luminosity lowered by about a factor 1.75, this change should possibly only be applied to the naked sources with $E_{B-V} <= 0.5 – 0.6$ mag, or to the off core YSOs.

Decreasing the ρ Oph distance from 160 to 120 lowers the luminosities for sources in the cloud with a factor 1.75. The bsf fraction obviously depends on the cloud distances, the slightly smaller luminosities may lower the bsf value for ρ Ophiuchus and shift its location in the csf – bsf diagram.

6. Probing deeper into the star forming cores

The reddening values determined from the Hipparcos and Tycho Catalogues do not exceed a few tenths of a magnitude (see Fig. 1). The lines of sight only penetrate the smallest column densities of the star forming regions. The astrometry and astrophysical photometry of the GAIA mission, Høg et al (1998), will remedy this situation by observing to a limit of at least V ∼17 mag, i.e. about ten magnitudes fainter than the completeness limit of Hipparcos. For the star forming regions discussed this means that data on the star forming cores with $A_V \lesssim 10$ mag may be obtained. The high stellar density of the GAIA mission will allow studies of density profiles in various parts of the clumps containing e.g. class 0 protostars.

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