Astronomy
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Astrophysics

$V − (V − I)$ distance to Lupus 2[*]

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Abstract. We report a possible distance to the star forming cloud Lupus 2 of 360 pc, at least 150 pc larger than previously suggested. Despite the cloud's small angular size and remoteness this distance estimate is corroborated by Hipparcos/Tycho data for field stars. The increased distance changes the mass estimate from 100 to ∼600 $\mathcal{M}_\odot$ more like the masses for the other Lupus clouds, but more interestingly the virial ratio of the two $C^{18}O$ cores in Lupus 2 will be lowered by a factor of 2.4 making Lupus 2 more like Taurus than the remaining Lupus cores

Key words. interstellar medium: individual objects Lupus 2 – interstellar medium: extinction – interstellar medium: clouds – stars: formation

1. Introduction

In a discussion of Hipparcos data for pre-main sequence stars Bertout et al. (1999) point out a possible variation of the various distance determinations to the clouds in the Lupus complex. Wichman et al. (1998) suggest a weighted mean parallax of 5 Lupus pre-main sequence stars, $\pi = 5.26 \pm 0.75$ mas corresponding to the distance 190 ± 27 pc. In the direction of several Lupus clouds the first increase of the extinction is noted at 100 pc. If this jump of absorption to $A_V \lesssim 1^m$ at a common distance may be associated to the Lupus clouds the complex seems rather local at only 100 pc (Knude & Høg 1998).

The distance estimate to any star forming cloud is of some importance for assessing physical parameters of interest for understanding the formation process. Not least for Lupus 2 that may be associated with several T Tauri type stars (Hara et al. 1999). In their $C^{18}O$ survey of dense cores in the Lupus clouds Hara et al. furthermore find that the narrowest line pertains to a core (No. 23) in Lupus 2. Hara et al. (1999) and Tachihara et al. (2000) suggest that star formation has a higher probability in cores with a small ratio M_{vir}/M_{core}. Since the two mass estimates depend on different powers of the distance the ratio is distance dependent. The virial ratio scales inversely with the cloud distance. The proposed larger Lupus 2 distance will accordingly lower the virial ratios and the new values approximate the range of Taurus values suggested by Hara et al. (1999).

2. V and I data

Our primary data are faint V and I photometry obtained in March 1997 with the DFOSC on the Danish 1.5 m telescope on La Silla, Chile. Only a single $13' \times 13'$ field centered on Lupus 2, $\alpha = 15^h56^m50^s$, $\delta = -37°49'6''$ (2000) was observed. The position was chosen from the then recently published ^{13}CO $(J = 1 - 0)$ maps of the Lupus clouds (Tachihara et al. 1996). In the star count extinction map of the Lupus complex our small field is situated across the edge of Lupus II, see Fig. 8 in Cambrésy (1999). For details of the observing and reduction procedure please consult Nielsen et al. (2000). Accumulated V and I distributions show that our photometry is complete to $V = 21^m5–22^m0$ and $I = 18^m5–19^m0$. Typical errors for V and $(V − I)$ are 0^m03 and 0^m04 to the limit.

The resulting colour magnitude diagram for about 1200 stars is shown in Fig. 1 and we note that the sample is rather faint including stars fainter than $V = 22^m$ and includes $V − I$ values ranging from about 1 to almost 4. The interpretation of a $(V − I) − V$ diagram is often based on detailed models of the Milky Way. Ng et al. (1996) present results from a variety of models conceived to understand galactic structure in Baade's Window. The purpose of the present paper is the much simpler task to estimate the distance of a molecular cloud at latitude $+12°$.

The stellar distribution in the field is displayed in Fig. 2. Note that Fig. 2 includes fainter stars without I

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[*] Based on ESO observations, La Silla.

photometry not present in Fig. 1. The outlines of Lupus 2 are clearly visible in Fig. 2.

3. Distance–absorption features in a $(V - I) - V$ diagram

If there is a sufficient number of main sequence stars in a small volume just behind an interstellar feature showing a common absorption or an extinction jump, an upper distance limit to this feature may be derived if individual photometric distances and colour excesses to some of these stars can be measured. An approximation to the lower distance limit can be estimated if virtually unreddened stars exist and can be measured in the volume just in front of the feature. This approach has mostly been used for diffuse interstellar clouds and for what is presumed to be the outskirts of molecular clouds (e.g. Knude 1978; Corradi et al. 1997). Precise distances and colour excesses are obtained from intermediate/narrow band optical photometry but the penetrating power is, however, limited by the use of ultraviolet and narrow bands, such as the u-band and $H_{\beta\mathrm{narrow}}$-band of the Strömgren system, and the stellar types for which these parameters may be derived is confined to main sequence stars in the spectral type range from about A3 to G5. The most useful are the F stars. The spatial density of F-type stars is rather small so the probability to find useful F stars associated with a small, strongly absorbing nearby molecular cloud is low. For a more detailed discussion of these two issues see Nielsen et al. (2000). A third issue regarding intermediate/narrow band photometry is the number of bands that must be observed, six for the Strömgren system, so it is time consuming to obtain complete data sets.

Data collection would be more effective if one could use fewer and wider bands to estimate distances and colour excesses. That this is generally not possible for individual stars is a well known fact. But for ensembles of stars like stellar clusters sharing common properties like age, metallicity, distance and interstellar absorption we may estimate the last two parameters from adapting an isochrone, given the the age and chemical composition, to an observed colour–magnitude diagram. Only two bands like V and I are used. We have suggested a similar method to estimate distances to nearby clouds (Knude et al. 1999).

The method is based on the assumption that the metallicity of the Milky Way disk approximately is solar. This is a good assumption since more than 90% have [Fe/H] ≈ 0, less than 10% have [Fe/H] in the range from -0.3 to -1.0 dex and only 0.1–0.2% are more metal poor than [Fe/H] ≈ -1.2 dex (e.g. Norris 1996). We use the $(V - I)$ index that is less affected by chemical composition – or even metallicity insensitive – than e.g. the $(B - V)$ index (e.g. Pinsonneault et al. 1998). In a $(V - I) - V$ diagram main sequence stars at a given distance and sharing a common interstellar absorption will form a replica of a $(V - I)_0 - M_V$ relation shifted according to the distance and absorption. In the paper quoted above we (Knude et al. 1999) have derived such a $(V - I)_0 - M_V$ main se-

quence relation from the Hipparcos and Tycho Catalogues (ESA 1997) by extracting stars not noted to be variable or multiple and of luminosity class V with $\pi > 20$ mas. As discussed by Vergely et al. (1998) these stars seem to be unaffected by interstellar reddening. We must further assume that the solar neighbourhood represents a fair sample of the disk. The resulting main sequence relation may be seen in Fig. 4 of Knude et al. 1999. It comprises the $(V - I)_0$ range from 0.0 to 2.0 and absolute V magnitudes between 1 and 10. For the ratio $\frac{A_I}{A_V}$ we adopt the value 0.64 from Thoraval et al. (1997). And we estimated that the range 0.50–0.70 proposed for the $\frac{A_I}{A_V}$ ratio by Thoraval et al. only introduces an uncertainty in the estimated distances amounting to $\frac{\Delta r}{r} \approx 5\%$. The relative parallax error, σ_π/π, for the individual Hipparcos stars used to derive the main sequence relation is found to be smaller than 10% for all $(V - I)_0$ colours, sampled in $0\overset{m}{.}1$ bins, except for the two red bins between 1.7 and 1.9 where the maximum error rises to 14%.

In order to understand how the method works first consider the effects of moving around a main sequence star in the distance – colour excess space have on its magnitude and colour: increasing the distance makes V larger and increasing the absorption makes $(V - I)$ larger too. A remote unreddened star will thus be in the lower left corner of Fig. 1 whereas a nearby heavily reddened star is to the upper right. Nearby main sequence stars at similar distances, just behind the nearest molecular cloud, and experiencing the largest common redding measurable by our data will form a locus to the upper right of the diagram. Since the cloud is the nearest and the reddening is the maximum observable (with our sample limit) no main sequence stars, that are behind the cloud, can be located to the bright red side of the locus. Not to the red of the locus because the locus comprise the stars with the maximum reddening and not to the bright side of the locus because then the cloud should be nearer than the nearest cloud. Any star found to be redder and above the red edge may either be nearby unreddened dwarfs or giants.

The distance may thus be derived from fitting the $(V - I)_0 - M_V$ to the red edge of the colour–magnitude diagram, if such an edge is present.

Estimating molecular cloud distances from $(V - I) - V$ diagrams for field stars by fitting the main sequence relation was first applied to the tails of the cometary globules CG 30/31 (Knude et al. op.cit.). For these clouds it was possible to adapt the main sequence $(V - I)_0 - M_V$ relation to the red bright confinement of the colour magnitude diagram. The shifts of the main sequence relation in $(V - I)$ and $V - M_V$ provide visual absorption and distance to the absorbing feature assuming $\frac{A_I}{A_V} = 0.64$ implying that $\frac{A_V}{E_{V - I}} = 2.8$.

If we may fit the red edge by the main sequence relation better than $0\overset{m}{.}1$ in $(V - I)$ and better than $0\overset{m}{.}5$–$1\overset{m}{.}0$ in $V - M_V$, both rather conservative demands, the resulting distance accuracy from this approach may be as good as 10%–20%. This relatively small error is a consequence of

the precise Hipparcos parallaxes, resulting in a sharp main sequence $(V-I)_0 - M_V$ relation, and the accurate broad band photometry of our programme stars. The presence of double stars in a $(V-I)-V$ diagram has no serious consequences as discussed in Sect. 3.2 of Knude & Nielsen (2000), where it was concluded that mistaking a double for a single star will underestimate the distance in average by about 15% and at most by 30%.

In Fig. 1 we notice that there are indications of two limitations to the red. In accordance with our method the reddest of these is postulated to be the locus caused by a common absorption feature in the nearest dust cloud, presumably the Lupus 2 cloud. Below we match our main sequence relation to the reddest edge but first we investigate whether the blue tip is associated with some absorbing feature also. We ask whether the position, $(X(\text{pix}), Y(\text{pix}))$ – see Fig. 2, of the stars along the blue tip show any relation to the Lupus 2 cloud. The blue end of our standard $(V-I)_0 - M_V$ relation is adapted to fit the blue, bright tip in the colour magnitude diagram and these blue bright stars seem to follow a locus, mainly because the stellar distribution seems to reproduce the small kink in the relation. The adaptation is performed by a shift of the $(V-I)_0 - M_V$ relation in the colour and magnitude directions. The shift in the colour direction: $(V-I)_{\text{locus}} - (V-I)_{0,\text{std.rel.}}$ is interpreted as caused by reddening: $E_{V-I} \equiv (V-I)_{\text{locus}} - (V-I)_{0,\text{std.rel.}}$ and $A_V = 2.8 \times E_{V-I}$, 2.8 follows from our assumed value $\frac{A_I}{A_V} = 0.64$. The shift along the V-direction provides $V - M_V$ and the distance results from $V - M_V - A_V + 5 = 5\log_{10}(r(\text{pc}))$.

The next step is to see if "these locus stars" are located in any systematic way relative to the Lupus 2 cloud. So we extract the neighbouring stars to the locus – a neighbour is defined as a star with V magnitude within $\pm 0.^{\text{m}}4$, for a given colour, of the shifted relation. The neighbouring stars are marked as filled circles in Figs. 1 and 2, and in Fig. 2 we notice that the neighbours distribution relative to Lupus 2 is far from random. A deviation from the shifted relation of $|\Delta V| = 0.^{\text{m}}4$ is accepted since it corresponds to a distance error of $\approx 10\%$. The stars along the shifted relation are almost exclusively situated close to the confinement of the star empty parts of Fig. 2. We interpret this shift in $(V-I)$ as being caused by absorption in the outer parts of Lupus 2. The shift parameters are $\Delta(V-I) = 1.10$ and $V - M_V = 13.10$ and the locus corresponds to main sequence stars at 1 kpc with $A_V = 3.^{\text{m}}1$. But since this locus is not the reddest and brightest confinement to the data points in the colour magnitude diagram, the distance is only an upper limit and the absorption value is not the maximum nearby extinction, we may observe with our sample, but is apparently associated with the rim of Lupus 2.

With another set of shift parameters $\Delta(V-I) = 1.90$ and $V - M_V = 13.10$, the shifted standard relation forms a good envelope to the reddest edge of the stellar distribution in Fig. 1. We claim that the distance to the Lupus 2 cloud follows from these parameters: the cloud distance becomes 360 pc and $A_V = 2.8 \times 1.90 = 5.^{\text{m}}3$ in the sense
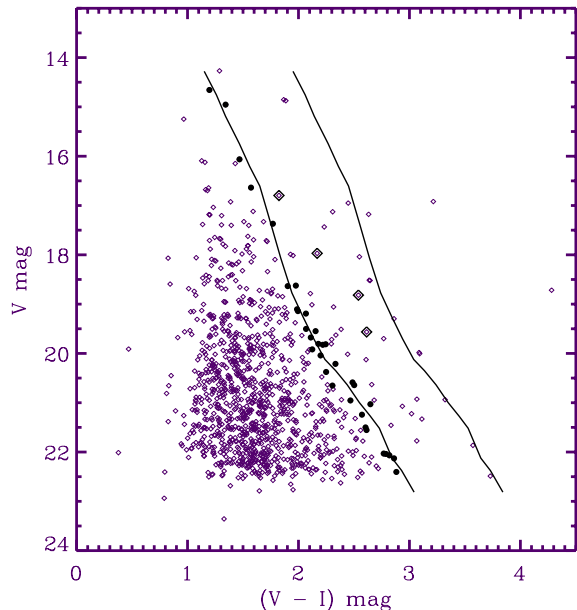

Fig. 1. Colour–magnitude diagram for the $13' \times 13'$ Lupus 2 field shown in Fig. 2. About 1200 stars have V and I photometry. Stars within $\pm 0.^{\text{m}}4$ from the left locus shown as filled circles. The large diamonds inscribe dwarf star candidates at 360 pc with $A_V = 2.^{\text{m}}0$, see text.

that these locus stars are located just behind Lupus 2 with distances $d = 360 \pm 72$ pc. Where we have applied the 20% error discussed above. The locus stars on the red edge have this particular visual absorption $A_V = 5.^{\text{m}}3$, larger A_V values may be present at the cloud edge but their measurement requires a fainter limit than in our sample. For a discussion of why the estimated distance is *the* distance and not only an upper limit see Knude et al. (1999) and the 4th paragraph of this Section.

We may even state that the stars between these two loci, including the neighbours to the reddest edge, most probably are dwarfs since they again are located preferentially along the confinements of the star empty regions, they are shown as open triangles in Fig. 2, and see the discussion below.

There is a previous extinction investigation of the greater Lupus region by Cambrésy (1999) to which our suggested distance may be tested in a circumstantial manner. From the star counts the outer contours of the Lupus clouds are estimated to have $A_V \sim 2$ magnitudes. If we request this absorption and postulate a distance of 360 pc the (X, Y) position of the stars, neighbours (as defined above) to the matching locus should follow the outer contour of the cloud, otherwise the distance estimate could be wrong. Four stars are found to be neighbours to the 360 pc, $A_V \sim 2$ magnitude locus. In Fig. 2 they are shown as diamonds. All of them are in the immediate vicinity of a cloud edge. Their location is also displayed in Fig. 1. They are furthermore situated in the reddest half of the shifted locus (not shown) suggesting they are late type dwarfs.
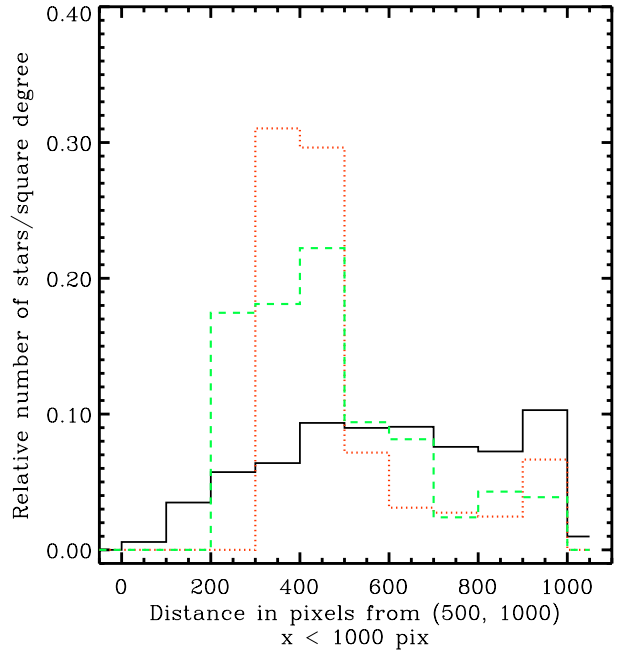
A small statistical test substantiates that the stars located between the two loci discussed above are related to
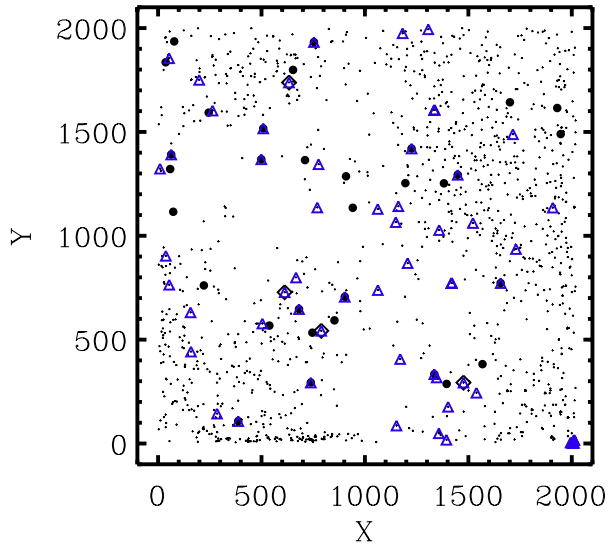
Fig. 2. Distribution of stars with measured V magnitude in a $13' \times 13'$ field centered on $\alpha = 15^{\mathrm{h}}56^{\mathrm{m}}50^{\mathrm{s}}$, $\delta = -37°49'6''$ (2000); scale size $0\!\!''\!.39$/pixel. North is up and east to the left. Filled circles are neighbours to the leftmost locus in Fig. 1. Open triangles are stars located between the two loci of Fig. 1 and the points inscribed in a diamond are candidates for stars at 360 pc with $A_V = 2\!\!\cdot\!\!^{\mathrm{m}}0$.


Fig. 3. Distribution of neighbours to the blue locus (dotted histogram) and brighter and redder stars (dashed curve) per unit area scaled to the number of points in the full sample (full line histogram).

the clouds visible in Fig. 2. We define a center of the eastern most cloud at $(X(\mathrm{pix}), Y(\mathrm{pix})) = (500, 1000)$ and ask how the neighbours to the first locus, (1.1, 13.10), and the stars between the two loci, (1.1, 13.10) and (1.9, 13.10), distribute themselves relative to this cloud center compared to the distribution of the complete sample. These three distributions are shown in Fig. 3. The histogram displays the number of stars per square degree and all three samples are scaled to the total number of stars with $X(\mathrm{pix}) \leq 1000$. The stars along the bluest locus form the dotted histogram, the stars between the two loci the dashed histogram and the whole sample the solid almost flat distribution.

The median separation of these three samples from the chosen center position at (500, 1000) is 500, 540 and 760 pix respectively or in arcseconds 195, 210 and 296. For separations smaller than 500 pix the two loci samples have a scaled relative density per square degree exceeding the total samples density by a factor of two whereas the opposite almost is the case for separations exceeding 600 pix. So the loci samples are special and probably much more closely related to the cloud than the complete sample. It may be interesting to notice that if we let the neighbours and the stars between the two loci of Fig. 4 define the rim of Lupus 2 visual absorptions in the range from ∼2 to ∼5 are measured. A fact that might deserve consideration when density profiles are considered. On the other hand the total counts represented by the solid curve of Fig. 3 has an almost constant gradient across the cloud, indicating a smooth variation of the absorption with radius.

4. Hipparcos/Tycho confirmation?

There is another option to test the suggested distance of 360 pc in the parallax – E_{B-V} diagrams that may be constructed from the Hipparcos and Tycho Catalogues (ESA 1997). For details see Knude & Høg (1998). The extinction map of the Lupus complex (Cambrésy 1999) shows Lupus 2 as a rather isolated cloud at the center of a virtually extinction free 4° diameter region. If we pick up any substantial absorption with the Hipparcos/Tycho data in this region it may possibly be associated with Lupus 2. In Fig. 4 we show the result for stars within 3° of Lupus 2 center at $(l, b) = (338°\!.5, 12°\!.0)$. We notice that $E_{B-V} \approx 0$ for stars with $\pi \gtrsim 10$ mas where a reddening increase seems to set in and that all stars with $\pi \lesssim 5$ mas are reddened by more than $0^{\mathrm{m}}\!\!.10$. We concentrate instead on the most reddened stars, the four stars with $E_{B-V} \gtrsim 0^{\mathrm{m}}\!\!.3$, this corresponds to $A_V \gtrsim 1^{\mathrm{m}}\!\!.0$. Three of these stars are closer than 2°, the fourth between 2 and 3° from Lupus 2 center has $\pi = 2.02$ mas and $E_{B-V} = 0.371$ magnitude. They turn out to have fairly accurate parallaxes; listed with increasing colour excess their parallaxes are 3.83 ± 1.47 (HIP 77507), 3.29 ± 1.64 (HIP 76541), 2.02 ± 1.37 (HIP 77074), 2.18 ± 1.45 (HIP 78098) mas respectively. The $\pm 1\sigma_\pi$ error bars are indicated in Fig. 4 for these four stars. We now postulate that these stars measure a reddening jump associated with Lupus 2 and are at approximately the same distance implying the mean parallax to be 2.83 ± 0.86 mas. The corresponding distance becomes 353 pc and $\frac{\Delta r}{r} \approx 30\%$. Excluding the

star with the largest separation from the Lupus 2 center changes the mean parallax to 323 pc. In Fig. 4 we have also shown π for the suggested $(V-I)-V$ distance 360 pc and the corresponding $\pm 20\%$ distances. We notice that the solid line indicating 360 pc passes less than $|1\sigma_\pi|$ from the Hipparcos stars proposed to be associated with Lupus 2 absorption. Within the errors we have that $R_{(V-I)-V} \approx R_{\mathrm{Hipparcos/Tycho}} \approx 350$ pc. The parallax of the T Tauri type star RU Lup supposed to be associated with Lupus 2 is 4.34 ± 3.56 mas (ESA 1997).
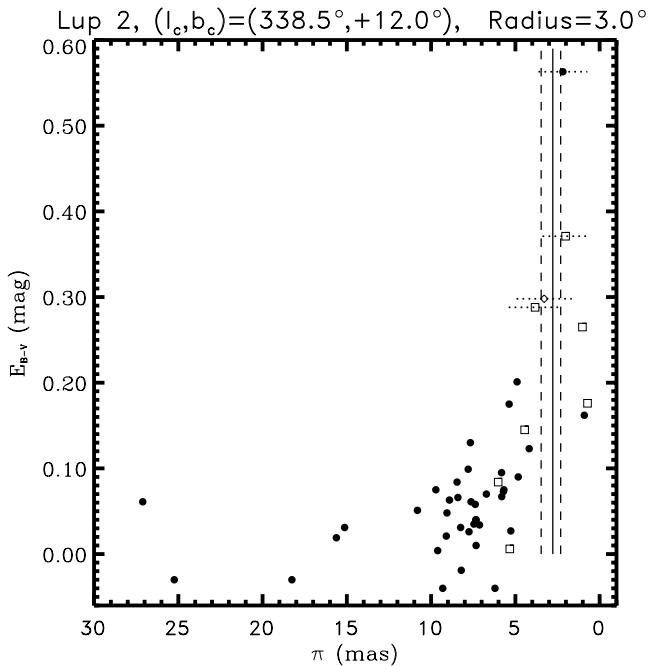
Fig. 4. Parallax–reddening diagram with data from the Hipparcos/Tycho Catalogues. Stars are within $3°$ from the Lupus 2 central position $(l, b) = (338°5, 12°0)$. The filled circles pertain to luminosity class V stars, diamonds to luminosity class IV and boxes to luminosity class III; for details see Knude & Høg (1998). $\pm 1\sigma_\pi$ error bars are indicated for the four most reddened stars with $A_V \gtrsim 1$ magnitude. Mean distance of four most reddened stars is 353 pc and $\Delta r/r = 30\%$. The vertical solid line indicates the $V - I$, V distance of 360 pc and the dashed lines the assumed 20% distance error.

5. Discussion

Assuming a distance of 150 pc Tachihara et al. (1996) determine the Lupus 2 mass to $M_{\mathrm{LTE}} = 100\ \mathcal{M}_\odot$ from their $^{13}\mathrm{CO}(J = 1 - 0)$ line measurements. A change of distance from 150 pc to 360 pc will alter this value to $\sim 600\ \mathcal{M}_\odot$. Similarly the masses of the two $\mathrm{C}^{18}\mathrm{O}$ cores in Lupus 2, No. 16 and 23 (Hara et al. 1999), will increase from 10 and 3 to ~ 60 and $\sim 15\ \mathcal{M}_\odot$ respectively. If the distance is 360 pc it would make core No. 16 the most massive in the Hara et al. survey of Lupus, assuming that only the Lupus 2 distance has to be changed. The LTE

masses change dramatically because they depend on the second power of the cloud distance.

As pointed out e.g. by Hara et al. (1999), the star formation efficiency of a $\mathrm{C}^{18}\mathrm{O}$ core may depend on the virial ratio $M_{\mathrm{vir}}/M_{\mathrm{core}}$. If R is the core radius and ΔV the line width $M_{\mathrm{vir}} \propto R\Delta V^2$ and if M_{core} is the LTE mass estimate $M_{\mathrm{core}} \propto \int N(\mathrm{H})_2 dA$ where $dA \propto R^2 d\Omega$. The cloud distance is important for the computation of this ratio because the two masses depend on their size in a different way and since the radius is computed from the distance the ratio depends on the cloud distance. The virial ratio thus varies with the inverse distance, a larger distance lowers the ratio. The shift from 150 to 360 pc will reduce the virial ratio with a factor 2.4 or $\log_{10}$ of the ratio becomes ~ -0.4 smaller. This is of some interest since the virial ratio for the Lupus cores are systematically larger than the ratio for the Taurus cores, see Fig. 9 of Hara et al. (1999). $\log_{10}$ of the ratio of No. 16 and 23 is changed from 0.40 and 0.00 to 0.02 and -0.36 respectively more like the values pertaining to Taurus.

Column densities of H_2 at the cloud edge may be estimated from the $(V - I)$ shift of the two loci: $A_V = 3^\mathrm{m}0$–$5^\mathrm{m}3$ valid for some of the stars along the cloud rim. With a standard gas – dust relation this corresponds to 2.5–5.3×10^{21} cm^{-2}. Recall that $A_V = 5^\mathrm{m}3$, due to the method used for the deduction is the maximum absorption detectable at the minimum distance, hence the large column density. Hara et al. 1999 report N_{H_2} equal to 4.1 and 3.2×10^{21} cm^{-2} for No. 16 and No. 23 respectively. From the angular extent and the distance we estimate the diameter to ~ 0.5 pc for the eastern cloud: center $(X(\mathrm{pix}), Y(\mathrm{pix})) = (500, 1200)$, radius 400 pix, and have $n(\mathrm{H}_2) = 1.6$–4.3×10^3 cm^{-3} and with the $\mathrm{C}^{18}\mathrm{O}$ data Hara et al. 1999 report 5.2 and 7.0×10^3 cm^{-3} for No. 16 and 23 respectively. The different densities may be caused by the different distance estimates but also by differences in the conversion from A_V and $N(\mathrm{C}^{18}\mathrm{O})$ to N_{H_2} and from the fact that the cores are not located on the cloud rims.

6. Conclusion

The adaptation of the $(V-I)_0 - M_V$ relation to the red–bright confinement of the $(V-I)-V$ diagram of our small Lupus 2 field suggests that this star forming molecular cloud may be located at 360 pc ($\pm 20\%$) instead of 100–200 pc. The larger distance estimate is corroborated by Hipparcos/Tycho data. If at 360 pc Hara et al.'s $\mathrm{C}^{18}\mathrm{O}$ core No. 23 may not merely have the sharpest $\mathrm{C}^{18}\mathrm{O}$ line but also the smallest virial ratio comparable to the smallest values found for Taurus cores.

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