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Gray Extinction in the Orion Trapezium*

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ABSTRACT

We estimated distances to several Orion Trapezium stars using our CaII-method and confirm the distance recommended by Menten *et al.* However, we found that in the case of HD 37020 both individual distances (based on the trigonometric VLBI parallax and/or CaII-method) differ from the spectrophotometric distance by a factor of 2.5. We interpret this fact as a result of presence of gray (neutral) extinction of about 1.8 mag in front of this star. The correctness of the applied spectral type/ luminosity class, Sp/L, (based on new original spectra from HARPS-N) and measurements of color indices is discussed.

Key words: *ISM: clouds – dust, extinction*

1. Introduction

Interstellar extinction is used interchangeably with the term "reddening" as a light beam crossing an interstellar cloud losses relatively many more violet than red photons and thus a star, seen through a cloud seems redder than it is in fact. The photometric equation connects the main parameters which determine the apparent

*This paper includes data gathered with the ESO Feros spectrograph at La Silla Observatory, HARPS-N at the Telescopio Nazionale Galileo and, coude echelle spectrograph at the 1-m telescope of Special Astrophysical Observatory in Russia.

magnitude of a star, m_V, its absolute magnitude, M_V, distance, D, and extinction, A_V, along the line-of-sight:

$$m_V - M_V = 5\log D - 5 + A_V$$

The extinction term A_V is usually replaced by $R_V \times E(B-V)$ where R_V is called the total-to selective extinction ratio. Moreover, it has never been proved that one should not add also an additional – neutral (gray) term in the interstellar extinction.

In his earliest efforts on establish and determine selective interstellar extinction Trumpler allows for presence of such a neutral extinction term, which he named a "residual" effect and has estimated its value to be ≈ 0.19 mag/kpc (Trumpler 1930). He explained this effect as caused by relatively large dust particles – comparable or bigger than the wavelength of the obscured light. However, the lack of reliable method of distance determination to stars, with high enough precision does not allow to separate both extinction terms and practically removed consideration on neutral extinction from astronomical literature for the next three decades. Instead of this it was commonly accepted assumption of Aller and Trumpler (1939) "that, if there is any non-selective absorption present in addition to the scattering effect (selective one), its amount is proportional to the latter", and, in principle, it is possible to determine the total absorption exclusively on the base of estimation of the selective extinction. Such an approach was commonly accepted as a rule in astronomical works. The growth of interest in problem of the gray extinction, as observed in literature of 1960s, 1970s and later on, was caused by efforts to understand and explain observed HR Diagrams of young open clusters and theoretical modeling of circumstellar envelopes observed around some stars. Poveda (1965) has pointed out that the HR diagrams of young clusters are more complex than it is expected from the simple contraction theory. In some of such clusters as *e.g.,* Orion, Taurus, NGC 2264 and Pleiades many suspected members fall below their evolutionary stage positions. Poveda (1965) explained this peculiarity as a result of the presence of large dust particles being on process of the formation of planetary systems around contracting stars. Similarly, Strom *et al.* (1971, 1972) studied circumstellar shells of 42 members of NGC 2264 and found highly non-selective visual absorption for many of these stars. As these shells have unusually high R ratio, even larger than 10, authors concluded that shells consist of a fairly high percentage of large particles able to cause a gray extinction. They concluded that predominance of large particles near these stars is created probably by preferential acceleration of small particles by radiation pressure. Swings and Allen (1971) considered observations of HD 45677, a star loosing significant amount of matter which has formed a tenuous gaseous shell of solid particles condensed from the material ejected by the star and possibly caused a significant gray extinction. These conclusions were confirmed next by Apruzese (1974) in his model of the dust shell around the above mentioned star. He found that the near-gray shell of grains surrounding the star, is a very real possibility. Andriesse *et al.* (1978) considered condensation of dust around η Car and concluded that the condensate consists in part of large particles with a size of about 1 micron which can give an almost gray circumstellar extinction of 3–4 mag in the visual and UV range. Sitko *et al.* (1994) analyzed interstellar extinction toward HD 45677 and found for this star a very gray circumstellar dust extinction. Lanz *et al.* (1995) studied another apparently "subluminous" star HD 39060 laying below the ZAMS. They interpreted this much lowered observed luminosity as a result of gray extinction by the dust disk around this star. Similarly Jura *et al.* (2001) considered as possible the presence of dust particles as large as 0.1 mm in radius, around some evolved binaries like 17 Lep, 3 Pup and BM Gem and interpreted it as indication for possible growth of solids into planetesimals in circumstellar disks around these stars.

Apart of the above mentioned, mainly theoretical considerations, probably the only direct measurement of the gray extinction in the general field was proposed by Skórzyński *et al.* (2003). Their analysis showed that some of the reasonably nearby O and B dwarfs appear to be fainter than indicated by their Hipparcos distances, intrinsic absolute magnitudes attributed to their spectral types, and estimated selective interstellar extinction. This may follow an additional component of the interstellar extinction – independent on the wavelength, *i.e.,* the gray (neutral) extinction. However, these results rely exclusively on existing Sp/L without checking their correctness. Thus their application may lead to serious uncertainties and the observed effect can be also interpreted in terms of the uncertain classification and calibration.

The photometric equation, with all possible extinction terms, known from Trumpler (1930), reads as follows:

$$m_V - M_V = 5\log D - 5 + R_V \times E(B-V) + C$$

where C is the gray extinction term. It is both – very difficult to prove either the existence or lack of non-zero gray extinction term. The above equation is well-known, simple but trappy. The m_V value follows the simple measurement but many OB stars are either variable or binary. In this case both m_V and M_V should be given in the same phase. M_V is usually estimated using the Sp/L. The calibration M_V *vs.* Sp/L should, thus, concern the proper phase of variability. Even an attempt to relate a current value of M_V to the same phase as that in which m_V was measured was not made until now. $E(B-V)$ can be determined with a reasonably high precision because $B-V$ colors do not change significantly among massive, OB3 stars. The "canonical" value of R_V is commonly accepted as 3.1. However, there are some objects in which the ratio is either higher or lower than the above value.

Generally, the total-to-selective extinction ratio, R_V, may seriously differ from object to object (Fitzpatrick and Massa 2007). The estimates range from 2 to 6.5 which in fact may seriously influence distance estimates, especially of heavily reddened stars. Hipparcos parallaxes are the only direct such measurements concerning OB3 stars because only single objects of this class are inside the range of ground-based measurements. It is worth mentioning that some authors (*e.g.,* De Marchi *et al.* 2016) erroneously put the sign of equality between R_V and gray extinction. Strictly speaking this is not correct because "gray" extinction means that it does not depend on lambda.

Apparently if one wants to use the photometric equation to estimate distances, several conditions are to be fulfilled. It is very unlikely that all parameters are treated with the proper care. Gray extinction is usually ignored but without any convincing evidence. We thus expect to check whether this specific extinction may be present and thus – alter the estimates of distances and/or absolute magnitudes.

Recently we have refurbished the old idea of Struve (1928) that stellar distances may be measured using intensities of interstellar spectral lines (column densities of interstellar gases). Our method (Megier *et al.* 2009) is based on the reasonably big sample of high resolution spectra of OB stars for which Hipparcos parallaxes do exist. The resultant, purely empirical formula, allowing us to measure distances to OB3 stars in the thin Galactic disk reads as follows:

$$D(\mathrm{CaII}) = 77 + (2.78 + 2.60/EW(\mathrm{K})/EW(\mathrm{H}) - 0.932)EW(\mathrm{H})$$

and can be applied if the ratio $EW(\mathrm{K})/EW(\mathrm{H}) > 1.32$.

One of the very specific cases is that of the distance to the well-known Orion Trapezium. Menten *et al.* (2007) used the Very Long Baseline Array to measure the trigonometric parallax to the Orion Nebula and recommended the distance of 414 ± 7 pc. As far back as 1937, Baade and Minkowski (1937) reported the detection of anomalous extinction curve for the Orion stars. The spectra of interstellar clouds toward this aggregate are also peculiar, *i.e.,* they contain very weak (if any) molecular bands of simple, well-known radicals and very weak diffuse interstellar bands (Krełowski *et al.* 2015). It is of importance to investigate "peculiar" cases because the latter are most likely spectra of single clouds while the "average" cases are in fact ill-defined averages over many, likely different, clouds which makes their physical interpretation impossible.

2. Observations

We have collected several spectra of the Trapezium stars using three echelle spectrographs: HARPS-N fed with the 3.58 m Telescopio Nazionale Galileo, Feros fed with the 2.2 m ESO LaSilla telescope, and Coude echelle spectrograph (marked as Grams in the Table 2) fed with the 1m telescope of the Special Astrophysical Observatory in Russia. The first instrument gives the highest resolution ($R = 115,000$) and is attached to the biggest telescope. The other two offer almost the same resolution (Feros $R = 48\,000$, Grams $R = 45\,000$). Every instrument allows measuring precisely intensities of stellar and interstellar spectral lines and thus to check the spectral types and luminosity classes of the considered stars as well as the equivalent widths of the interstellar CaII lines.

All spectra were processed and measured in a standard way using both IRAF (Tody 1986) and our own DECH† codes.

3. Results

There spectral classification of HD 37020 is uncertain. The most recent Sp/L classification of HD 37020 is O7Vp (Sota *et al.* 2011). Nevertheless, the Simbad database marks the star as an B0.5V Ae/Be Herbig object referencing to Mason *et al.* (1998). However, the authors wrote that the classification is just taken from Morrell and Levato (1991) who analyzed low resolution photographic plate spectra for large sample of stars to measure radial velocities. No examples of spectra are given in the article and authors refer to Bossi *et al.* (1989). Indeed, Bossi *et al.* (1989) reported that the star "may be a pre-main-sequence binary system". However, an averaged low resolving power photographic spectrum exhibits quite low S/N ratio (see Fig. 1 in the article) and, can hardly be used for confident estimation of the average spectral class of this binary system. Schertl *et al.* (2003) confirmed the binarity of HD 37020 by a speckle interferometry. The second component is by 2.3 mag fainter in the *J* filter and, displays colors consistent with pure photospheric emission without infrared excess. Authors suggests that it is "a strongly extincted $\sim$F-type star, yields a reasonable location in the HR-diagram, suggesting the object to be a very young intermediate-mass PMS star". Taking into account the $T_{\rm eff}$ and brightness difference, the secondary star integral flux is too low to harm the resulting Sp/L, totally dominated by the main component.

Accordingly to Walborn and Fitzpatrick (1990), O stars' key lines are the prominent HeII lines at 454.1 nm and 420.0 nm, varying from weak at O9.5 to strong in O2–O7, and the HeI lines at 447.1 nm and 402.6 nm, increasing intensity from absent in O2/3 to prominent in O9.5. Our spectra of HD 37020 and HD 37022 certainly prove the presence of strong HeII lines (see Fig. 1) in these evidently O-type stars. The HeI lines at 447.1 nm are evidently stronger than the HeII ones at 454.1 nm which proves that both Orion trapezium stars are colder than O7 where both features should be equal.

We collected three spectra for HD 37022, two – for HD 37023 and one – for HD 37020. Naturally the spectrophotometric distances depend on the assumed Sp/L (Table 1). However, our CaII distances are apparently accordant with that of Menten *et al.* (2007) for the whole cluster if our Trapezium targets are of O7.5V class. To establish the spectral type and luminosity class of the observed spectrum of HD 37022 we used the spectra of HD 93146 (O6.5V) and HD 46149 (O8.5V) given as standards of Sp/L by Walborn and Fitzpatrick (1990). As seen in Fig. 1 the classification of the Orion stars falls into the reasonably narrow range.

In particular these spectra contain two neighbor spectral lines: HeI 4471.5 Å and HeII 4541.5 Å. Their strength ratio strongly depends on the $T_{\rm eff}$. This is illus-

† *http://gazinur.com/DECH-software.html*

Table 1

Variation of spectral parallax with different Sp/L assigned to HD 37022

Sp/L	M_V	D_{sp} [pc]
O6.5V	−5.35	493
O7V	−5.20	449
O7.5V	−5.05	419
O8V	−4.90	391
O8.5V	−4.70	366

trated in Fig. 1. Apparently the spectral type of HD 37022 is in between of the two standards *i.e.*, O7.5 or O8. The luminosity class can be assessed from the HI lines in HD 37022 spectrum, which despite the circumstellar envelope contaminations, shows the broadest wings, characteristic for dwarfs.

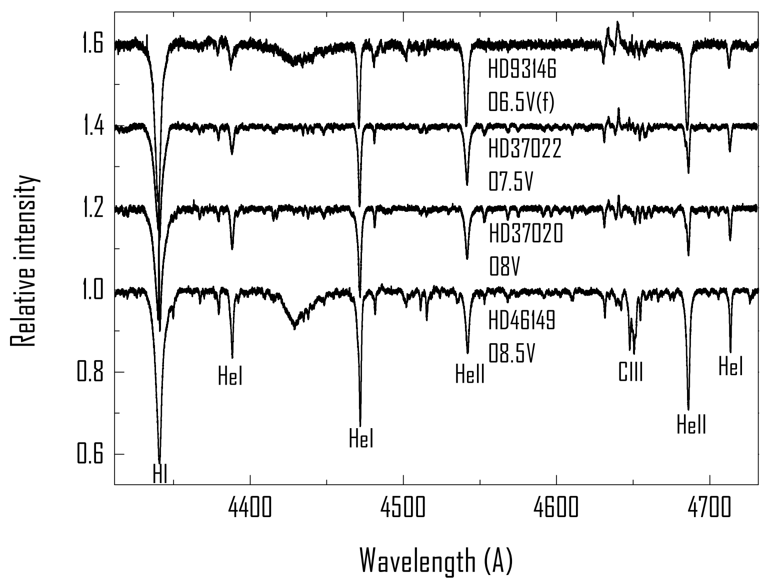

Fig. 1. Spectra of the HD 37022 and HD 37020 framed with those of Walborn and Fitzpatrick (1990) standards, observed using the Feros spectrograph. The spectral type is very sensitive to the HeI/HeII strength ratio. The hydrogen line profiles are even broader in the Orion stars which confirm that they are dwarfs.

We have applied the system of absolute magnitudes, given by Schmidt-Kaler (1982), which is discrete and thus the final choice of the spectral type and luminosity class is important for reducing uncertainties in distance estimates. Having these limitations we can estimate the spectrophotometric distance to HD 37022 and HD 37020.

For O7.5V (HD 37022) the spectrophotometric distance coincides very well with that, determined using our CaII method as well as to the value, based on VLBI trigonometric parallax and recommended by Menten *et al.* (2007).

Table 2

Stellar and measurements data

star	Sp/L	V	$B-V$	M_V	EW(K) [mÅ]	EW(H) [mÅ]	D(CaII)	D(Sp)	R(FM)	$E(B-V)$	origin
37020	O8V	6.74	0.03	−4.9	108.7 ± 1.4	60.1 ± 1.3	422	905	5.8	0.32	HARPS-N
37022	O7.5V	5.14	0.03	−5.05	106.7 ± 1.2	58.5 ± 1.2	410	419	6.4	0.32	HARPS-N
					108.0 ± 0.9	59.1 ± 0.9	413	–	6.4		Feros
					106.0 ± 4.7	58.4 ± 4.4	411	–	6.4		Grams
					105.5 ± 0.9	58.1 ± 0.8	409	–	6.4		UVES
37023	B1V	6.70	0.08	−3.2	110.8 ± 1.8	61.1 ± 1.5	427	417	5.8	0.31	Feros
					115.8 ± 4.1	60.0 ± 4.5	400	–	5.8		Grams

We summarized all our measurements and calculations in Table 2. As it is seen, the CaII distances to HD 37022 and HD 37020 are almost identical – the difference is just 1%. They also coincide with the Menten (2007) measurements.

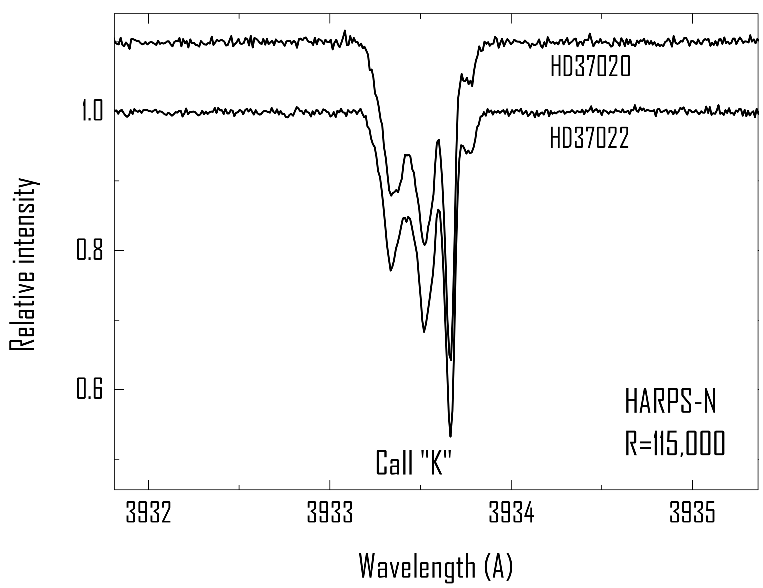

Fig. 2. The identical "K" interstellar line profiles in both Orion stars confirm that their distances should be identical.

On the other hand the spectrophotometric distance of HD 37020 differs from the above by a factor of almost 2.5. Let us consider the photometric equation in its most developed version. For objects with similar Sp/L their absolute magnitudes should be nearly equal by definition. The CaII distances and ionized calcium line profiles are identical which agrees with the fact that both stars belong to the same cluster. Moreover, the interstellar spectra of both objects are very peculiar which would be unlikely if they are not members of the same aggregate. Table 2 also gives the total-to-selective extinction ratios taken from Fitzpatrick and Massa (2007). The distance to HD 37020 measured individually by Menten *et al.* (2007) is 417.9 ± 9.2 and coincides almost exactly with our CaII based method (422) as well as with the averaged cluster distance. The spectrophotometric distance could agree with the above ones if R for this object is higher than 12. This is out of the range presented by Fitzpatrick and Massa (2007). It is also very hard to allow for such big differences in absolute magnitude within nearly the same spectral class. Traditionally a one-to-one relation between Sp/L and absolute magnitude is one of the basic rules.

Let us consider once again the photometric equation. We can rewrite it in two forms – for two photometric bands:

$$m_V - M_V = 5\log D - 5 + R_V E(B-V) + C_V$$
$$m_B - M_B = 5\log D - 5 + R_B E(B-V) + C_B$$

m_V and m_B are the results of direct measurements.

$$M_B = M_V + (B-V)_0$$

$R_B = R_V + 1$ by definition. Considering both equations for HD 37022 and HD 37020 – two stars of the nearly identical spectral type which leads to similar absolute magnitudes and $E(B-V)$'s – one can easily obtain

$$C_V = C_B$$

i.e., the additional extinction, attenuating HD 37020, is the same for both photometric bands and so this extinction is gray. It is the most logical explanation of the difference between the photometric distances to HD 37020 and HD 37022 – the presence of a cloud causing gray extinction as high as 1.8 mag.

As both our targets: HD 37020 and HD 37022 are of practically the same Sp/L and color excesses (Fig. 1 and Table 2) the difference between their apparent magnitudes should be due to our "gray extinction". Table 3 lists the apparent magnitudes and their differences in typical photometric Johnson bands. It is evident that the differences from the U-band until J one are almost identical which means that the extinction is nearly gray. Deeper in the infrared the difference becomes smaller – apparently the dust grain sizes are not large anymore in comparison to wavelength in this range.

Our third target, HD 37023, is clearly of another spectral type. We have compared its spectrum to that of HD 144470 which, according to Walborn and Fitzpatrick (1999), is the standard B1V star. Thus HD 37023 is most likely of the same

Table 3

Differences between apparent magnitudes of HD 37020 and HD 37022 in different photometric bands

Band	lambda	37020	37022	difference
U	3650	5.87	4.20	1.67
B	4450	6.75	5.15	1.60
V	5510	6.73	5.13	1.60
R	6580	6.42	4.91	1.51
I	8060	6.21	4.73	1.48
J	12200	6.09	4.58	1.51
H	16300	5.80	4.63	1.17
K	21900	5.67	4.57	1.10

spectral type and luminosity class V (see Fig. 3). If we assume the R_V value the same as for HD 37020, we can calculate the photometric distance the same as recommended by Menten *et al.* (2007) and as that which results from our CaII method (see Table 1). Apparently HD 37020 is the only object among our targets which is obscured by some gray extinction cloud.

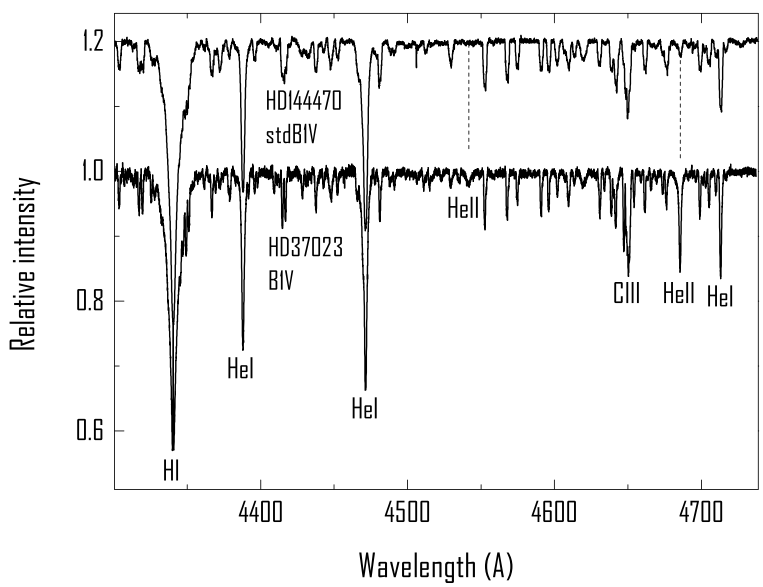

Fig. 3. Spectrum of HD 37023 compared with spectrum of spectrophotometric B1V standard HD 144470.

What can this cloud be in fact? Can we observe any spectral features originated in it? We can check this using our high quality HARPS-N spectra of HD 37022 and of HD 37020. We compared the two spectra in the range of the interstellar H line near 3968 Å. The result is shown in Fig. 4.

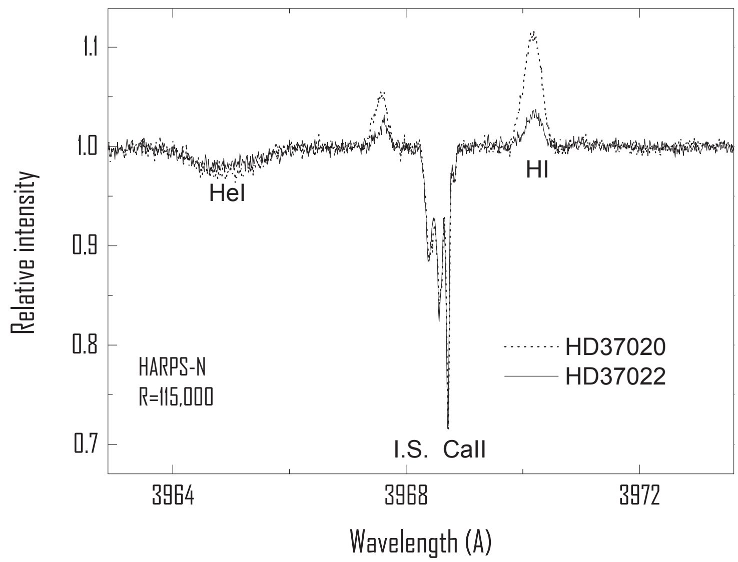

Fig. 4. Spectra of HD 37022 and HD 37020. The hydrogen absorption is killed by means of setting the continuum. The interstellar lines are clearly identical (profiles and intensities) which confirms the membership of both stars to the same aggregate. The circumstellar emissions are apparently stronger in HD 37020.

It is evident that the circumstellar effects (emissions) are evidently stronger in HD 37020 *i.e.*, where the gray extinction is observed. This may lead to the conclusion that the "gray cloud" is likely the circumstellar disk around HD 37020 and that the disk is populated with relatively big dust particles. Perhaps, we observe the beginning of the process of planet formation: the growing grains will lead to planetesimals and so on. It is interesting that in such environment we apparently observe neither simple radicals (known in the interstellar space) nor the carriers of diffuse interstellar bands (Krełowski *et al.* 2015). Perhaps all these, most likely – molecules, are incorporated into the growing grains which makes their spectral features so weak that they fall below the detection level. On the other hand the H and K lines of CaII are formed along the line-of sight. The clouds being revealed by these lines fill quite evenly the Galactic disk (Galazutdinov *et al.* 2015) and may be observed in the absence of all other interstellar features. Let us emphasize that while stellar spectra and magnitudes may vary in many objects – the interstellar CaII lines remain constant. This is also why they allow so precise measurements of distances – circumstellar effects are apparently absent in CaII lines.

The possible presence of relatively big dust particles, affecting the extinction in the infrared was postulated recently by Wang *et al.* (2014, 2015). Apparently different considerations lead to more or less similar conclusions. Big particles are very difficult to be discovered because of the lack of reddening and relation(s) to other interstellar features.

4. Concluding Remarks

The above considerations apparently allow the following conclusions:

- the stars of the Orion Trapezium are observed through quite peculiar clouds, most likely intracluster ones
- distances, estimated using our CaII lines method are the same as those recommended by Menten *et al.* (2007)
- HD 37020 is additionally obscured by a cloud causing gray extinction, most likely by the circumstellar disk in which processes of dust particles' coagulation have recently started.

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