TWA AS A RAPIDLY EXPANDING MINI-ASSOCIATION
AND VEGA AS ITS POSSIBLE MEMBER

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Abstract We investigate the paths of several bona fide members of the young association around the star TW Hydrae (TWA) with accurate distances, proper motions and radial velocities. Extensive Monte-Carlo simulations are employed to estimate the uncertainties of derived parameters. We find that three of the previously identified members, TWA 1, TWA 4 and TWA 11, together with three other young nearby stars, HD 139084, HD 220476 and, possibly, Vega, form a rapidly expanding association with an expansion age of $4.7 \pm 0.6$ Myr. Vega has been identified as a $\lambda$ Bootis-type star and a rapid rotator seen almost pole-on; therefore, Vega may be a very young star despite its moderate metal deficiency. Initial velocities of the member stars with respect to the common center of mass range from 4 to 10 km s$^{-1}$. A characteristic size of the association in the initial configuration is 21 pc, which may be somewhat biased upwards due to the remaining uncertainties in the observational data. The Lower Centaurus Crux (LCC) OB association passed near the TWA, at a distance of $36 \pm 6$ pc, 11 Myr ago. A plausible scenario that accounts for the difference between the isochrone age ($\simeq 10$ Myr) and expansion age (5 Myr), is that moderate star formation was stimulated in the TWA progenitor cloud by the near passage of the LCC, but that the newly formed stars were not released from the cloud until a subsequent collision with another molecular cloud in the North Ophiuchus region.

Keywords: open clusters and associations: individual (TWA) — stars: kinematics — stars: pre-main sequence — stars: individual (Vega, TWA 1, TWA 4, TWA 11, HD 139084, HD 220476)
1. Introduction

During the last few years, growing evidence has been found that very young stars in the Solar neighborhood tend to make up very loose, gravitationally unbound kinematic groups counting less than a hundred members. The small number of members distinguishes these groups from the Galactic open clusters and rich OB associations which include several hundred members and more. Following Ambartsumian (1960), the discoverer of young associations, we distinguish OB associations and T-associations. The latter do not include massive stars and are found closer to regions of star formation. Their number density is lower than that of the field Galactic stars, yet they were formed in a rapid star formation event from a single cloud. Subsequently, associations are bound to expand forever, being dragged by the differential Galactic rotation (Blaauw 1952) and internal dispersion of velocities. The tiny associations we are discussing here conform to all these criteria, except that they are too small by number, and that they are remote from the nearest star forming sites (and close to the Solar System). The large distances between these associations of \( \approx 20 \) stars and the possible sites of origin implies large initial velocities. These differences may be manifestations of a different mechanism of star formation than the one (or the ones) which is at work in rich OB and T-associations. Furthermore, the tiny associations like TWA do not stem from the larger OB associations or open clusters. This warrants the introduction of a new terminology, mini-association (MA henceforth), encompassing this class of objects.

The association of pre–main-sequence (PMS) stars around TW Hya was discovered by Kastner et al. (1997). At the time, the star TW Hya was believed to be the closest T Tauri star to the Sun, which explains the name of the new association. In the course of time, the number of suggested candidate members grew to \( \approx 20 \) (Webb et al. 1999; Sterzik et al. 1999; Webb & Zuckerman 1999). The membership list for this MA, nonetheless, can not be considered settled. The method of selection, as a major kinematic evidence, dwells on a similarity of proper motions and radial velocities, thus neglecting the principal feature of associations, namely, their expansion. Being only 10 Myr old, and occupying up to a 100 pc size area, association members simply can not have the same motion in space. By picking stars of similar proper motion, in particular, one tends to select only those genuine members that huddle in the core of a MA, or more widely spread kinematic interlopers. Makarov and Fabricius (2001) tried to correct this shortcoming by using a modified convergent point method of proper motion analysis. The primary sample was a collection of Tycho-2 stars with high X-ray fluxes detected by
ROSAT. Bright X-ray stars are mostly young, fast rotating dwarfs, or active short-period binaries. However, the following spectroscopic analysis of the selected candidates to TWA (Song et al. 2002) rejected most of the new members. Thus, the list of members still contains about 20 stars.

In this paper, we investigate only five of the spectroscopically confirmed members that have trigonometric parallaxes from the Hipparcos Catalogue (ESA 1997). We do not purport a comprehensive study of the stellar contents of the association, but rather, using several known young stars with accurate astrometric data and radial velocities, we offer a kinematic analysis of the 3D path of the association in the past. As described in Sect. 2, the epicycle approximation to the local velocity field is utilized, which is a conveniently simple, analytical rendition of the Galactic potential in the Solar neighborhood. Three additional members of the MA01 are described in Sect. 3, including Vega. The initial parameters of MA01 at the time of birth are supplied in Sect. 4. The origin of the association in relation to the nearest Sco-Cen OB associations is discussed in Sect. 5. In Concluding Remarks (Sect. 6), we summarize what we learned about the star formation process responsible for generation of local mini-associations on the example of the MA01, and speculate about its features.

2. Method

The classical epicycle approximation (e.g., Asiain et al. 1999, Makarov & Olling 2003) is used to compute the complete 6D paths in the phase space of stars suspected to be members of an association. The vertical motion is assumed to be harmonic oscillation, which is an suitable approximation for young associations with relative internal velocities less than 10 km s\(^{-1}\). We assume a vertical period \(P_z = \frac{2\pi}{\nu}\) of 80 Myr, and numerical values for the Oort constants of \(A=0.0148\), \(B=-0.0124\) km s\(^{-1}\) pc\(^{-1}\).

Due to the remaining uncertainties in the input data and the nonlinear dependencies of the phase space parameters on them, we conduct Monte-Carlo simulations for each star. Using the formal errors of the input parameters and assuming a Gaussian distribution for each parameter, we generate 5000 random trials, and compute 5000 independent paths for a given set of stars. The resulting distributions of parameters of interest (coordinates and velocities, respective distances, times of closest approach, position of the center of mass) are not Gaussian. The median and the modal values of output parameters can be drawn from the 5000 samples sufficiently accurately; following the tradition,
we present here the median parameters and their standard deviations computed as the 0.841 and 0.159 quantiles differences. Owing to the skewness of some of the distributions, the standard deviations may be different on the upper and lower sides of the median.

Since we consider a group of stars to be an association only if they diverge from an initially more compact configuration, it is reasonable to define the moment of formation (that is, a kinematic age) as the time when a characteristic size of the group was the smallest. But the definition of size is an important issue, because it is also a statistic. Ortega et al. (2002) define the size as the maximum distance between two members of an association, which we do not adopt here for the following reasons. Only two stars are involved in a calculation like that, making the result statistically less trustworthy. Besides, there is no complete certainty about the membership. It is possible then that the maximum distance be defined by stars, one or both of which are non-members.

We introduce an alternative definition of characteristic size (diameter) that is more resilient toward errors in membership or input parameters. First we compute, for each of the 5000 realizations separately, the square-mean-root, \( \sqrt{\frac{d_{ij}}{n_{ij}}} \) distance over the set of all possible pairs of stars:

\[
D_{\text{smr}} = \left[ \frac{\sum_{i \neq j} \sqrt{d_{ij}/n_{ij}}}{n_{ij}} \right]^2 ,
\]  

(1)

where \( d_{ij} \) is the distance between stars \( i \) and \( j \), and \( n_{ij} \) is the number of such pairs. We find the times \( t_{\text{min}} \) at which the \( \text{smr} \) distances take the minima, \( D_{\text{smr}} = d_{\text{min}} \). We further find the median over the 5000 \( d_{\text{min}} \) and \( t_{\text{min}} \) and call them the minimum size and the time of the minimum size, or kinematic birthtime \( T_0 \). The median \( D_{\text{smr}} \) at \( T_0 \) is not necessarily equal to the median \( d_{\text{min}} \), \( D_{\text{smr}} \neq d_{\text{min}} \), but in the following analysis we make sure that the two values agree within 3% with each other, for MA01.

3. Likely and Unlikely Members of MA01

Vega is the prototype of Vega-like stars which are distinguished by their excess of the infrared thermal emission with temperatures of 50–125 K (Jayawardhana et al. (2001)). The excess infrared emission is due to dusty warm disks around these stars. Since the lifetime of dust grains in close proximity to stars is small in comparison with stellar main sequence lifetimes, unless these Vega-like stars can be proven to be quite young, it is proposed that the dust is constantly replenished by destruction of smaller bodies orbiting the stars. The age of Vega
is a controversial issue. Being a non-evolved A0-type star, Vega is not suitable for the isochrone method, and indirect, surrogate characteristics of age have to be sought. Vega is classified as a "mild λ Bootis" star (Venn & Lambert 1990), a class of chemically peculiar stars depleted in metals but with almost normal abundances of C, N, O and S. The major difference between Vega and other λ Bootis stars is that Vega seem to rotate very slowly and have, subsequently, sharp spectral lines. A simple explanation to this and other apparent peculiarities is that Vega is a fast rotator seen almost pole-on (Gray 1988; Gulliver et al. 1994). Since λ Bootis stars are quite likely still accreting circumstellar gas, they may be very young, which led Holweger & Rentzsch-Holm (1995) to propose that Vega might be a pre-main-sequence star. By our calculations, Vega was in close association with another Vega-like star, HR 4794A only 4.7 Myr ago (see Sect. 4), which is hardly a mere chance due to the extremely low number density of Vega-type stars in the solar neighborhood.

The adopted parameters of Vega and seven other considered stars are given in Table 1. The star HIP 55505 is a quadruple system of a visual pair of spectroscopic binaries (Torres et al. 1995). Radial velocities were accurately measured for both of the visual components (Torres et al. 2001) and differ by 7 km s$^{-1}$. We derive a system’s center of mass radial velocity from the two cited values assuming the masses of the visual components to be in equal proportion. The total mass of the system is assumed to be 2.6 $M_{\odot}$.

<table>
<thead>
<tr>
<th>Name</th>
<th>$(\mu_\alpha*, \mu_\delta)$ mas yr$^{-1}$</th>
<th>Radial velocity km s$^{-1}$</th>
<th>Parallax mas</th>
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<tr>
<td>Vega = GJ 721</td>
<td>(201.0, 287.5) ± (0.6, 0.5)</td>
<td>−13.9 ± 0.9</td>
<td>128.9 ± 0.6</td>
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<tr>
<td>HR 4796 = TWA 11</td>
<td>(−53.3, −21.2) ± (1.3, 1.1)</td>
<td>9.4 ± 2.3</td>
<td>14.9 ± 0.8</td>
</tr>
<tr>
<td>HIP 53911 = TWA 1</td>
<td>(−73.4, −17.5) ± (2.3, 2.3)</td>
<td>12.9 ± 0.3</td>
<td>17.7 ± 2.2</td>
</tr>
<tr>
<td>HIP 55505 = TWA 4</td>
<td>(−91.7, −31.1) ± (1.6, 1.4)</td>
<td>9.2 ± 0.2</td>
<td>21.4 ± 2.9</td>
</tr>
<tr>
<td>HD 139084</td>
<td>(−46.2, −97.9) ± (1.5, 1.5)</td>
<td>0.5 ± 0.9</td>
<td>25.2 ± 1.1</td>
</tr>
<tr>
<td>HD 220476</td>
<td>(146.2, −5.0) ± (0.9, 0.9)</td>
<td>4.5 ± 0.5</td>
<td>33.1 ± 0.9</td>
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<th>Unlikely Members</th>
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<tr>
<td>HIP 57589 = TWA 9</td>
<td>(−55.4, −17.7) ± (2.3, 2.3)</td>
<td>10.2 ± 0.4</td>
<td>17.9 ± 2.4</td>
</tr>
<tr>
<td>HIP 102458 = TWA 19</td>
<td>(−33.7, −9.1) ± (1.1, 1.1)</td>
<td>11.5 ± 3.8</td>
<td>9.6 ± 1.4</td>
</tr>
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The radial velocity for the star HD 139084 is adopted from Zuckerman et al. (2001). This value (Table 1) is in good agreement with the determination by Anders et al. (1991) of 1.5 km s$^{-1}$, but it disagrees with the velocity supplied by the Simbad data base (5.1 ± 0.5).
latter value was adopted from the paper by Montes et al. (2001), which is itself a compilation of previous radial velocities from the literature. We do not know the reason for this discrepancy. The older observations seem to support a value about 5 km s\(^{-1}\) (Balona 1987), but we adopt the more up-to-date data. Our kinematic analysis shows, that with a radial velocity of 5.1 km s\(^{-1}\), HD 139084 is a member of another very young MA, \(\beta\) Pictoris, which was not very far from the TWA several Myr ago. This example shows how critical exact radial velocity data are for membership determination. The isochrone age of the primary star is about 10 Myr, as determined by Zuckerman et al. (2001).

\[\text{Figure 1. Distances of MA01 members from the common center of gravity in the past. The median distances shown with lines, the times of the nearest approach indicated with dots and error bars, calculated as 0.159 and 0.841 percentiles.}\]

The star HD 220476, which we consider a new likely member of MA01, is one of magnetically active stars as witnessed by the strong Ca II H and K lines emission (Strassmeier et al. 2000). It was selected by us, among other possible young stars, for a kinematic analysis owing to its high (for a G5 star) lithium abundance of \(W_{\text{Li}} = 133\) m\(\AA\). The high degree of chromospheric activity and the high lithium content, in contrast to the moderate rotational velocity of \(v \sin i \approx 5.6\) km s\(^{-1}\), is indicative of
a young age. The radial velocity for this star (Table 1) was also adopted from Strassmeier et al. 2000.

In light of the present kinematic study, TWA 9 and TWA 19, previously believed to be legitimate members of the MA, are unlikely such. The double star TWA 9, at a probability of 0.9, was farther from the center of mass than it is now. The star TWA 19 has been somewhat closer to the MA01 in the past, but not by much, and its median distance from the center of mass was 45 pc, 4.7 Myr ago. Besides, our analysis of the orbits of Sco-Cen associations leaves little doubt that TWA 19 was ejected from the Lower Centaurus Crux association 4.5 Myr ago.

4. Results

The results of our calculation are summarized in Table 2. The minimum $smr$ size of the association was 21 pc. This is similar to the size of 24 pc that Ortega et al. (2002) found for the initial configuration of another expanding mini-association, β Pictoris. The large initial sizes rule out the possibility that the MA is the result of a dynamical decay of young multiple systems (Sterzik & Durisen 1995).

<table>
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<th>Table 2. Parameters of MA01</th>
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<tr>
<td>Kinematic Age</td>
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<tr>
<td>Initial SMR Size</td>
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<tr>
<td>Star</td>
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<tr>
<td></td>
</tr>
<tr>
<td>Vega = GJ 721</td>
</tr>
<tr>
<td>HR 4796 = TWA 11</td>
</tr>
<tr>
<td>HIP 53911 = TWA 1</td>
</tr>
<tr>
<td>HIP 55505 = TWA 4</td>
</tr>
<tr>
<td>HD 130884</td>
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<tr>
<td>HD 220476</td>
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</tbody>
</table>

The starting velocities of stars between 4 and 10 km s$^{-1}$ imply either a high-mass turbulent cloud as a progenitor of MA01 (Section 6) or a violent dispersal by an external agent. Interaction with stellar wind shells around foreign O stars appears sufficient to produce the required scatter of velocities. On the other hand, if the stars were born in a giant molecular cloud and remained in it for several Myrs, the scatter may be attributed to the internal velocity dispersion (Sect. 6). It is noted, that the times of the smallest $smr$ distances do not seem equal, implying a possible protracted release of the stars from the cloud.
Vega and TWA 11A, separated by 70.5 pc today, were at a median distance of 10.7 ± (7.4, 5.0) pc just 4.6 Myr ago. The probability that these two stars were closer together than 3 pc is only 0.024. However, the fact that these stars, both members of a rare class of objects (Vega-type), were so close can hardly be attributed to chance.

5. Origin of MA01

Since the TWA association seems to be a typical representative of nearby mini-associations, it is worthwhile attempting to determine whether or not the TWA association was dislodged from one of the nearby OB associations or star formation sites. We retraced the paths of nearby associations and young clusters and matched them with the estimated path of the MA01’s center of mass. Only the three associations in the Sco-Cen complex, Upper Scorpius (US), Upper Centaurus Lupus (UCL) and Lower Centaurus Crux (LCC) were closer to MA01 in the near past than they are now (Fig. 2). The input parameters for our epicycle calculation were adopted from de Zeeuw et al. (1999). Since the centers of OB associations are not well defined, we neglected this and other uncertainties in this order-of-magnitude estimation. The error bars shown in Fig. 2 account, therefore, only for the uncertainty in the MA01 position. It is noted again that the center of mass definition is also approximate, since our list of MA01 members in not complete.

Within a precision of several parsec, we conclude that LCC was by far the closest OB association to MA01 in the past, as it is now. The minimum distance is estimated at 36 ± 6 pc, and it was reached 11 Myr ago. Interestingly, 4.7 Myr ago, when MA01 began to expand, the distance between the two objects was close to 60 pc. Unless our analysis suffers from a severe error in the input radial velocities or distances (which is unlikely), MA01 was never a part of the Sco-Cen associations. The relative velocity of MA01 and LCC at −11 Myr was 6.5±0.6 km s\(^{-1}\). LCC being an expanding association itself, it was significantly smaller 11 Myr ago, which renders the probability of even a marginal encounter small.

Our results suggest that TWA sprang from a cloud kinematically and spatially isolated from the Sco-Cen complex. Where is this cloud now? A large cloud can not be easily dispersed in about 5 Myr without a noticeable trace in the Solar neighborhood. An encounter with another molecular cloud appears to be a plausible scenario. The ram pressure would quickly stop the oncoming gas, while the stars would continue on their ways, and would suddenly find themselves in a gavitationally
unbound state. The MA01 progenitor cloud may still be close to the place the association occupied 4.7 Myr ago.

![Graph showing distances of the estimated center of mass of MA01 from the centers of the Upper Scorpius (US), Upper Centaurus Lupus (UCL) and Lower Centaurus Crux (LCC) OB associations for the past 15 Myr. The median distances shown with lines, the times of the nearest approach indicated with dots and error bars, calculated as 0.159 and 0.841 percentiles.](image)

**Figure 2.** Distances of the estimated center of mass of MA01 from the centers of the Upper Scorpius (US), Upper Centaurus Lupus (UCL) and Lower Centaurus Crux (LCC) OB associations for the past 15 Myr. The median distances shown with lines, the times of the nearest approach indicated with dots and error bars, calculated as 0.159 and 0.841 percentiles.

Using the positions and rough distance estimates for dark nebulae in Hilton & Lahulla (1995), we analyzed possible alignments of the MA01 progenitor with nearby dusty clouds. It turns out that the clouds in the Ophiuchus and Ophiuchus-North regions could in fact collide with MA01 between 4 and 5 Myr ago, having reasonably small present-day proper motions and radial velocities. Furthermore, we expect the clouds and SFRs in Ophiuchus to have motions not dissimilar to the adjoining Sco-Cen associations. A possible relation between the Ophiuchus clouds and Sco-Cen associations has long been discussed; in particular, Lépine (1996) suggested that the $\rho$ Ophiuchi complex and clusters imbedded in Sco-Cen originated from an infall of a high-velocity cloud. De Geus & Burton (1991) noted the striking filamentary pattern of the Ophiuchus molecular clouds that may be a trace of a violent collision event. By varying the (unknown) present-day velocity of some clouds in the North Ophiuchus region around the value for US, we detected possible matches
with the location of MA01 at the required epoch. For example, the cloud LDN 1780 in Ophiuchus-North could collide with MA01 5 Myr ago, if it had the following present-day parameters: distance 110 pc, galactic proper motion \((-9, -2)\) mas yr\(^{-1}\), radial velocity 7 km s\(^{-1}\). The velocity of collision would have been \(\approx 20\) km s\(^{-1}\).

6. Concluding Remarks

If the initial dispersion of velocities of \(\Delta V \approx 7\) km s\(^{-1}\) was inherited from the turbulent motion of cloudlets inside the parental cloud, at the original radius of 12 pc, the virial mass of the cloud was larger than \(1 \times 10^5\) M\(_{\odot}\). This is only 2 times smaller than the typical mass of a giant molecular cloud (GMC), in which the most massive O and B stars are generated. The total rms velocity of 7 km s\(^{-1}\) is typical of a GMC on a dynamical equilibrium. But GMCs are known to generate OB associations and rich clusters of \(\approx 1000\) M\(_{\odot}\) under appropriate conditions, and dense cores (cloudlets) in them may reach a 10\% star-forming efficiency (Tachihara et al. 2002). Why this particular cloud produced only the inordinately tiny association of \(\approx 20\) stars?

If the virial estimation of the mass and size of the cloud is valid, the process responsible for the formation of MA01 was incomparably more efficient in dispersal of the diffuse material than in generation of new stars. It appears, from the small number of identified members, that the star formation events were quite rare and isolated. Clearly, none of the new stars could significantly contribute in the destruction of the cloud. Thus, a powerful external agent is needed to reconcile the observed parameters. At first glance, an encounter of a medium-sized cloud with an extant OB association provides a plausible mechanism. The high-velocity winds from massive O and B stars, together with subsequent supernova explosions blow up large shells around rich associations which may interact with the dispersed interstellar medium and with chance molecular clouds that happen to cross their paths. We have seen in Sect. 5 that LCC was the closest OB association to MA01 during the past 15 Myr. However, it was never close enough for a direct interaction of massive stars in LCC with the MA01 cloud. LCC still could conceivably incite star formation in the cloud through interaction of a shock wave from a bubble blown up by stellar winds and supernova explosions with the passing-by gas in the MA01 cloud. Such bubbles are known to surround the LCC’s neighbors, the US and UCL associations (de Geus 1991). They have radii of 40 and 110 pc, respectively, and expand with a velocity of \(\approx 10\) km s\(^{-1}\). These shells obviously could never reach the MA01 cloud (Fig. 2). But there could have been a 40 pc radius bubble
around LCC 11 Myr ago blown by the first super massive O stars and explosions some 15 Myr ago, of which we know no evidence today. It still remains puzzling why an interaction with this hypothetical bubble produced only a dozen stars.

In this scenario, we have to explain the obvious discrepancy between the implied age of the MA01 stars (11 Myr) and the expansion age (4.7 Myr). It is possible that, despite some feeble star formation event 11 Myr ago, the cloud remained largely intact and gravitationally bound. The lack of members earlier than A0 seems to lend strength to this conjecture. At a later time, some external agent quickly removed the bulk of gas and dust, letting the stars to freely disperse, as discussed in Section 5. An encounter with another molecular cloud at a moderate velocity is a plausible agent. This "strike and sieve" scenario is attractive in the case of MA01 in that it accounts for the discordant kinematic and isochrone ages.

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