DYNAMICAL EVOLUTION OF THE TW HYDRAE ASSOCIATION

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Received 2005 June 15; accepted 2006 January 18

ABSTRACT

Using Galactic dynamics we have determined the age of the low-mass post–T Tauri stars in the TW Hya Association (TWA). To do so we applied the method of Ortega and coworkers to five stars of the association with Hipparcos-measured distances (TWA 1, TWA 4, TWA 9, TWA 11, and TWA 19). The method is based on the calculation of the past three-dimensional orbits of the stars. Of these stars, only TWA 9 presents a quite different orbit so that it does not appear to be a dynamical member of the TWA. The four remaining stars have their first maximum orbital confinement at the age of $-8.3 \pm 0.8$ Myr, which is considered the dynamical age of the TWA. This confinement fixes the probable three-dimensional forming region of the TWA within a mean radius of 14.5 pc. This region is related to the older subgroups of the Sco-Cen OB association, Lower Centaurus Crux and Upper Centaurus Lupus, both with a mean age of about 18 Myr. This dynamical age of the TWA and that of the $\beta$ Pic Moving Group, 11 Myr, also discussed here, introduce a more precise temporal scale for studies of disk evolution and planetary formation around some stars of these associations. Using the retraced orbit of the runaway star HIP 82868 we examine the possibility that the formation of the TWA was triggered by a supernova explosion. It is shown that for the four considered TWA stars, the expansion in volume is a factor of 5 from their origin to the present state. This is mainly due to the currently more distant star TWA 19.

Key word: open clusters and associations: individual (TW Hydreae, $\beta$ Pictoris Moving Group)

1. INTRODUCTION

In a seminal paper, Herbig (1978) listed a few T Tauri stars isolated from the long unknown post–T Tauri stars. Among these was the K-type star TW Hya, whose typical T Tauri nature was later disclosed by Rucinski & Krautter (1983). Afterward, based on far-IR IRAS sources, further T Tauri--type stars were discovered in a radius of about 5° around TW Hya (de la Reza et al. 1989). At that time, their relative high Galactic latitudes suggested that these objects could be nearby stars. Rucinski (1992) confirmed the isolation of these stars from clouds and produced independent arguments compatible with their youth. During the initial years of the Pico dos Dias Survey, based on IRAS sources, new stars were added to this group (Gregorio-Hetem et al. 1992). The studies of this remarkable association have progressed with the facilities of the Hipparcos (astrometry) and the ROSAT (X-ray) observatories. It was possible not only to confirm their proximity (50–60 pc) but also to detect new members. This improvement was the result of the efforts of several research groups see, for instance, Kastner et al. (1997), Jensen et al. (1998), Soderblom et al. (1998), Webb et al. (1999), Sterzik et al. (1999), Zuckerman et al. (2001b), Torres et al. (2003), Reid (2003), and Song et al. (2003, 2004). For a recent review, see Zuckerman & Song (2004).

In general, the main observational criteria or conditions to establish the association status of a moving group such as the TW Hya Association (TWA), or of others such as the $\beta$ Pic Moving Group (BPMG), are the following: (1) the similarity of space velocities characterizing the association as a probable coeval moving group, (2) the same age of members obtained by means of pre-main-sequence Hertzsprung-Russell (H-R) evolutionary diagrams, (3) the presence of spectroscopic features characterizing their youth such as relatively strong Li absorption lines and H$\alpha$ lines with moderate emission/absorption or filled-in properties.

In this work we use a different approach to determine the age and the origin of the TWA. This is a dynamical approach in which the three-dimensional orbits of the stars are retraced to find the orbits’ confinement under the action of a Galactic potential. This methodology has already been used to study the BPMG (Ortega et al. 2002, 2004) and the $\epsilon$ and $\eta$ Chamaeleonis groups (Jilinski et al. 2005). Two papers (Makarov et al. 2005; Mamajek 2005) were recently published discussing the expansion of the TWA. In the following sections we comment on them and compare their results with those obtained in the present work.

In §2 the methodology, data, and dynamical results for the TWA are presented. Section 3 is devoted to the discussion of a possible origin of the TWA, and finally, the discussion and conclusions are the subject of §4.

2. THE DYNAMICAL EVOLUTION OF THE TWA

2.1. The Method

The stars of an unbound young stellar group develop their three-dimensional orbits and change their spatial velocities because of the action of the general gravitational field of the Galaxy. The three-dimensional orbits of the stars are a fundamental element in the scenario we are considering. The latter requires the use of a good, realistic mass model of the gravitational Galactic potential. As stated in our previous work (Ortega et al. 2002), the orbit integrations have been performed using the Galactic potential by Hoogerwerf et al. (2001). The parameters predicted by the model are as follows: $R_0 = 8.5$ kpc, $V_0 = 219.8$ km s$^{-1}$, $A = 13.5$ km s$^{-1}$ kpc$^{-1}$, $B = -12.4$ km s$^{-1}$ kpc$^{-1}$, and $\rho_0 \sim 0.1 M_\odot$ pc$^{-3}$, where $R_0$ is the galactocentric distance of the LSR, $V_0$ is its rotation velocity, A and B are the Oort rotation parameters, and $\rho_0$ is the local mass density. All these values are consistent in relation to those obtained using data from Hipparcos. Some authors (e.g., Maiz-Apellániz 2001; Makarov et al. 2004) employ...
the perturbative, linear epicyclic approximation of the equations of motion in which the vertical displacement of the stars takes the form of harmonic oscillations relative to the equatorial plane of the Galaxy. However, in view of the fact that the phenomenon of three-dimensional orbit confinement is very sensitive to the W-component of the space velocity vector, we prefer to use the full system of equations of motion. This was also the approach we followed in all our papers mentioned above, in which more details of the method are given.

2.2. The Data for the TWA

The three-dimensional trajectories of the stars of the group are integrated backward in time starting from their initial, present positions and velocities in a heliocentric Galactic-oriented frame of reference. Since the dynamical determination of the group’s age requires the best possible kinematic data, we use here only Hipparcos-measured parallaxes. Of the classified TWA stars, only the following five fulfill this condition: HIP 53911 (TWA 1) with a distance of 56.4 pc, HIP 55505 (TWA 4) at 46.7 pc, HIP 57589 (TWA 9) at 50.3 pc, HIP 61498 (TWA 11) at 67.1 pc, and HIP 57524 (TWA 19) at 103.9 pc. In our calculations we use the spatial velocities of these stars determined by Reid (2003).

Fig. 1.—Individual orbits of TWA members in the (a) (X, Y) plane and (b) (Z, Y) plane. Each two-point interval corresponds to 1 Myr. The size of each circle is proportional to the uncertainty in the calculated star position at −8.3 Myr.

Fig. 2.—Variation with time of the three-dimensional radius of the distribution of stars TWA 1, TWA 4, TWA 11, and TWA 19. The dynamical age (−8.3 Myr) is determined by the maximum three-dimensional confinement at the minimum of the curve.

Fig. 3.—Past orbital evolution of the LCC, UCL, and TWA groups. The orbit of the kinematical center of the TWA is shown until the age of 8.3 Myr. Each two-point interval corresponds to the motion during 1 Myr.
better than 1 km s$^{-1}$ with those recently observed by Torres et al. (2003). Some relatively small differences exist for stars TWA 11 and TWA 19, for which the values proposed by Torres et al. (2003) have the largest uncertainties, equal to $\pm 2.3$ and $\pm 3.8$ km s$^{-1}$, respectively. For TWA 11 Reid’s radial velocity value is 3 km s$^{-1}$ less than the mean value of Torres et al. (2003), whereas for TWA 19 Reid’s value is within the mentioned uncertainty of this star.

2.3. The Dynamical Age of the TWA

Our dynamical calculations were performed for the five TWA classified stars mentioned above. Of these, only TWA 9 escapes confinement if we take its distance as the mean Hipparcos value (50.3 pc). This star is then eliminated as a dynamical member of the TWA. The remaining four stars are confined well at $-8.3$ Myr. In Figure 1 we present the results of the past three-dimensional orbital evolution of the four TWA stars considered here. The Galactic ($X, Y, Z$) coordinates are positive in the direction of the Galactic center, of Galactic rotation, and of the north Galactic pole, respectively. ($X, Y$) is the plane through the Sun, and ($Z, Y$) is orthogonal to this plane. In Figure 2 is shown the variation with time of the three-dimensional radius of the spatial distribution of the four TWA stars relative to the group center. The minimum radius of 14.5 pc represents the maximum three-dimensional orbit confinement attained at the age of $-8.3$ Myr. This radius variation shows that the group formed by these four stars has expanded in volume, from its initial state up to its present state with a radius of 24 pc, by a factor of 5. The internal errors in the present work were estimated by realizing 1000 Monte Carlo simulations for each star. This was done by randomly choosing initial values of the space velocities from a Gaussian distribution with mean values equal to the observed ones and a dispersion of 1 km s$^{-1}$. The mean radius for the obtained forming region of the TWA is of 14 pc. The cumulative effect of the uncertainties for each orbit represents, at the considered birthplace of the TWA, an external shell with a thickness of about 2 pc corresponding to a dynamical age error of $\sim 0.8$ Myr. Typical uncertainties estimated by this method for different past epochs can be seen in Jilinski et al. (2005).

3. THE BIRTHPLACE OF THE TWA

In Figure 3 we schematically present the dynamical evolution of the centroids of the TWA, Lower Centaurus Crux (LCC), and Upper Centaurus Lupus (UCL) in ($X, Y, Z$). The importance of considering three dimensions can be seen from the differences in the trajectories of the TWA and BPMG. They appear to be fairly similar in the ($X, Y$) plane; however, differences appear in the $Z$-direction (see Fig. 4).

We note that the trajectories of LCC and UCL represent the centroid evolution of hot stars of these subgroups (see Ortega et al. 2004). Differently from the cases of the TWA and BPMG, no confinement considerations were done for LCC and UCL, so their past sizes remain undefined. For practical reasons, we maintained in the past their approximate, currently observed sizes. In any case the confined region for the TWA, which we consider to be the birthplace of the TWA, appears to be related in time and space to both the LCC and UCL subgroups. A similar relation between the TWA, LCC, and UCL subgroups was considered by Mamajek et al. (2000) on the basis of a linear extrapolation of velocity vectors in the Galactic plane.

In Ortega et al. (2004) we discussed the possibility that a single supernova (SN) event could eventually have triggered the formation of the BPMG 11 Myr ago. Could a similar event also be involved in the formation of the TWA? One way to obtain information about this consists in finding a currently observed hot runaway star that could be the remnant of a binary star, one of the components of which exploded as an SN. Similarly to Ortega et al. (2004), using the list of runaway stars in Hoogerwerf et al. (2001), we found that the Be star HIP 82868 could be an interesting candidate for taking part in the triggering of the TWA formation. We should note, however, that the Hipparcos distance and the radial velocity of HIP 82868 have uncertainties of $\sim 20\%$ and $\sim 25\%$, respectively. These uncertainties may produce errors in the past orbit of this star in the sense of either approaching it or removing it from the TWA-forming region. In the former case the triggering mechanism would gain in efficiency, while in the latter it would lose it almost completely. In any case, it seems advisable to take into account this conjecture as a possible mechanism of triggering the TWA. Hereafter we consider only the mean values of these two parameters. As in Hoogerwerf et al. (2001), we also found that this runaway star crossed the open cluster IC 2602 some 6 Myr ago. Nevertheless, because this cluster is older than 25 Myr, HIP 82868 can hardly be considered to be related to this cluster. As a matter of fact, several runaway stars studied by Hoogerwerf et al. (2001) crossed one or two different structures during their past lives. As far as the cluster IC 2602 is concerned, we cannot exclude the possibility that some gravitational effect produced by this cluster could have somewhat modified the orbit of HIP 82868, but this is not considered here. Using the same methodology as described in § 2, it was found that the three-dimensional orbit of this star was, at $-9$ Myr, about 90 pc away from the birthplace center of the TWA (see Figs. 4 and 5). That means that the shock front traveled this distance in about 1 Myr before reaching the region of the TWA formation.

Approximate and reasonable physical conditions can be found for this scenario considering Sedov’s relations: $R = 1.17(E_0/\rho_0)^{1/5}f_{SN}^{3/5}$ and $V_{SN} = (2/5)(R/l_{SN})$ (see, e.g., Bowers & Deeming 1984, p. 453), where $R$ is the radius of the shock front moving with a terminal velocity $V_{SN}$, $t_{SN}$ is the time elapsed since the explosion, and $\rho_0$ is the interstellar density outside the front. For our case, $R = 90$ pc and $V_{SN} = 1$ Myr, giving $V_{SN} = 36$ km s$^{-1}$. We can then estimate the energy ($E_0$) of the SN for different values of $\rho_0$. Choosing a density value corresponding to 1 H atom cm$^{-3}$ we obtain $E_0 = 1.3 \times 10^{51}$ ergs, consistent with the canonical value of $10^{51}$ ergs expected for stars with masses of 15–25 $M_\odot$, or more and with solar abundances (Woosley et al. 2002). Somewhat smaller but equally realistic values for $E_0$ can be obtained by admitting smaller interstellar densities resulting from the action of the strong stellar winds of pre-SN hot OB stars.

We note that as shown in Figures 4 and 5, the 90 pc three-dimensional distance of the proposed SN relative to the center of the birthplace of the TWA is due mainly to the $Z$-coordinate. While the TWA birthplace was at the ($X, Y$) plane, the SN event occurred below this plane (see Fig. 4). It is interesting to note that the resulting dynamical evolution of the TWA from its origin to its place today follows, even with a small angle, the correct increasing $Z$-direction. This is to be expected if the shock front of the SN not only took part in triggering the star formation of the TWA but also produced an extra impulse to the natal cloud, making the spatial motions of the unbound stars of the association approximately follow the direction of the shock front. We note that the explosion of the SN is considered here to be isotropic, and its initial shock front velocity several orders of magnitude larger than the initial velocity of the runaway star. Under these conditions the motion of the shock wave and the runaway star are practically independent.
It is also interesting to note that at the proposed epoch of the SN explosion at \( t = 9 \) Myr, the two stars \( \beta \) Pic and AU Mic pertaining to the BPMG with an age of \( 11 \) Myr and both with observable disks were far apart from the SN at distances of about 96 and 120 pc, respectively. This is also the case at the age of \( t = 8 \) Myr during the formation of the TWA, when the distances of \( \beta \) Pic and AU Mic to the birthplace center of the TWA were respectively about 33 and 47 pc. As the shock front is isotropic, it would have overtaken these stars, especially \( \beta \) Pic. If our scenario of the TWA formation is true, the disks of these stars, observed today, would have somehow been preserved. One possibility of survival could be due to their very small cross sections as compared with the parent cloud of the TWA. In Figure 5 we show the positions of the stars \( \beta \) Pic and AU Mic together with the birthplace of the TWA at the moment of the TWA formation and also the position of the runaway star HIP 82868 at the moment of the SN event \( t = 9 \) Myr). The positions of \( \beta \) Pic and AU Mic at \( t = 9 \) Myr are also shown.

4. DISCUSSION AND CONCLUSIONS

At least for quite young stellar groups, the method of retracing the three-dimensional orbits of their stars using a model of the general Galactic potential allows one to investigate important questions concerning those groups such as finding probable birthplaces and dynamical ages, and identifying true group members. In this work, we have explored the dynamical evolution of the TWA by considering five TWA classified stars for which Hipparcos distances are known. Of these stars, only TWA 9 shows a past orbit different from the rest. This star is therefore not considered to be a dynamical member of the TWA. All the other stars, TWA 1, TWA 4, TWA 11, and TWA 19, are confined at \( t = 8 \) Myr to a spatial region with an average radius of 14.5 pc. One important consequence, mainly due to the present distant star TWA 19, is that the volume expansion of these four stars is of a mean factor of 5. This result can be obtained by comparing the present volume occupied by these stars with their volume at the origin \( t = 8.3 \) Myr ago. This region appears to be related to past positions of both the LCC and UCL subgroups of the Sco-Cen OB Association. We remark that in this study we cannot establish the membership of other possible members of the TWA suggested in the literature because they all lack Hipparcos distances. Recently, Makarov et al. (2005) also studied the dynamical expansion of the TWA using the epicycle approximation for the equations of motion. Their sample is not completely the same as ours. Even though they considered the stars TWA 1, TWA 4, and TWA 11, which are in our sample, they introduced three other possible members: HD 139084 (HIP 76629), a member of the BPMG according to Zuckerman et al. (2001a),
HD 220476, and the star Vega. With this sample they find an expansion age of $4.7 \pm 0.6$ Myr, smaller than ours. By taking into account the discrepancy between this small expansion age and the isochrone age of the TWA, which is between 8 and 10 Myr as found in the literature, Makarov et al. introduced two episodes during the formation to explain the origin of the TWA. In the first one, the stars were formed, and the parental cloud remained intact over several megayears. In the second one, at $-4.7$ Myr some external agent removed the gas of the natal cloud, probably by a collision with another cloud, allowing in this way the stars to begin their motions as independent systems.

In our scenario it is proposed that a possible violent formation of the TWA by a SN event could, in favorable conditions, not only form the stars of the TWA 8.3 Myr ago but also disperse the remaining original gas, leaving an unbound stellar system since its origin. So the difference of the results of the Makarov et al. work and ours can be explained by different adopted methodologies and samples of stars. Mamajek (2005) applies the linear expansion method of Blaauw (1956), which makes use of proper motions, to a sample of 23 stars (without TWA 19AB), finding only weak evidence for expansion. He notes, however, that his sample is consistent with a lower limit of 10 Myr for an expansion age.

The fact that TWA 19AB belongs to this young coeval moving group has some other consequences, apart from determining the three-dimensional expansion of the TWA. Lawson & Crause (2005) propose that the TWA consists of two groups, one nearby and younger, with an age of about 10 Myr and containing stars with longer rotational periods, and an older (17 Myr), distant one, associated with LCC and whose stars have shorter rotational periods. The rotational period differences between the stars of those groups are thought to be due to a spin-up process taking place during that age interval. The physical binary TWA 19AB, for which they did not measure the period, appears to play an important role as a calibrator, because it is the only star in the sample of stars AU Mic and especially $\beta$ Pic, both belonging to the BPMG. Then, if our scenario of the TWA formation is true, we conclude that some effect (perhaps tiny cross sections) has contributed to preserve the disks from destruction. Eventual destruction of stellar disks by the action of SN remnants (as far as we know) has not been considered in the literature.

The TWA was always considered in the literature as the best “laboratory” for studies of protoplanetary disks and early planetary formation. In fact, some member stars such as TW Hya = HIP 53911 (TWA 1), Hen 3.600A (TWA 3A), and HIP 55505 (TWA 4) have disks of T Tauri type, and there is a debris disk of the annular type in the star HIP 61498 (TWA 11A). We recall also that the BPMG, with a dynamical age around 11 Myr (Ortega et al. 2002, 2004), has, as mentioned before, two stars with debris disks of the $\beta$ Pic type: the proper $\beta$ Pic star and the star AU Mic. We can then tentatively suggest that the age of 8.3 Myr marks the onset of debris disk formation, at least for young stars in associations. Currently, it is not yet clear which is the typical age characterizing the end of the T Tauri type disks. Recently, Torres et al. (2006) concluded that the spectroscopic binary classical T Tauri star V4046 Sgr, containing an important circumbinary disk (Quast et al. 2000; Stempels & Gahm 2004), is probably a member of the BPMG.

Concerning planets, a giant one with a mass of $5 M_j$ has been detected recently near the brown dwarf star 2MASSW J1207334–393254 (Chauvin et al. 2005). This star was proposed by Gizis (2002) to belong to the TWA, which was confirmed by Mamajek (2005) on the basis of its kinematics. The formation mechanism of this planet is not clear, however; it may have been formed either in the disk of the brown dwarf or together with this star. Whatever the involved mechanism, the age of the TWA fixes a timescale of this mechanism. It also indicates that any initial planet building process, such as that observed in the disk of the star TW Hya (Wilner et al. 2005), could have been initiated before 8 Myr.

For the BPMG there are very strong indications of the presence of hidden planets in the debris disks of $\beta$ Pic and AU Mic stars (see, e.g., Liu 2004). Considering that the dynamical age of the BPMG is 11 Myr, we can suggest that these planets, if present, were formed before or near this age.

We thank the referee for considerations that improved the presentation of this paper. E. G. J. thanks MCT Brazil for financial support.

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