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ASTRONOMY AND ASTROPHYSICS

Kinematics of T Tauri stars in Chamaeleon

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Abstract. We study the kinematics of T Tauri stars (TTS) located in the cores of the Chamaeleon clouds as well as far off these clouds. Our sample comprises 2 early type stars known to be related to Cha I, 6 classical (CTTS) and 6 weak-line T Tauri stars (WTTS) known before the ROSAT mission, and 8 bona-fide pre-main sequence (PMS) stars as well as 23 presumably older stars discovered with ROSAT (Alcalá et al. 1995; Covino et al. 1997). Altogether we present proper motions for 45 stars, taken from the Hipparcos, ACT and STARNET catalogues. For 12 stars of our sample parallaxes measured by Hipparcos are available, and we use them to derive constraints on the distance distribution of the other stars in our sample. Our analysis of the proper motions allows us to divide the sample into several subgroups.

We analyse the motions of the stars in connection with different star formation scenarios and find them consistent with both the high velocity cloud (HVC) impact model (Lépine & Duvert 1994) and the cloudlet model (Feigelson 1996), whereas the data seem to be inconsistent with any kind of a dynamical ejection model.

Key words: Stars: kinematics – Stars: formation – Stars: pre-main sequence – Stars: late-type – Astrometry

1. Introduction

The Chamaeleon cloud complex, located in the southern hemisphere, was first discussed as a separate system of dark clouds by Hoffmeister (1962). He identified 26 RW Auriga type variable stars in this region, some of which also showed Hα-emission.

Objective prism surveys conducted in the following decades increased the number of emission-line stars suspected to be associated with the Chamaeleon dark clouds. First results were reported by Henize (1963). The surveys conducted in 1962 and 1970 revealed 32 emission-line stars (Henize & Mendoza 1973), which were all confirmed in the extensive survey by Schwartz (1977) in the southern hemisphere and, particularly, in the Chamaeleon region. Altogether he found 45 stars in the Cha I cloud and 19 in the Cha II cloud. In another objective prism survey Hartigan (1993) found 21 new Hα emission-line objects in Cha I and 5 in Cha II.

Gregorio-Hetem et al. (1992) and Torres et al. (1995) used far-infrared IRAS colours to preselect T Tauri star (TTS) candidates over the whole sky and found, among others, 8 bona-fide plus 1 probable TTS in or around the Chamaeleon region.

Parallel to the objective prism surveys X-ray surveys have expanded the membership lists since the late eighties. X-ray observations with the Einstein Observatory revealed 22 X-ray sources, of which 6 or 7 were associated with new probable cloud members (Feigelson & Kriss 1989). By means of high dispersion optical spectroscopy, Walter (1992) confirmed the pre-main sequence (PMS) nature for 5 of these sources as well as for 2 new candidates.

The ROSAT All-Sky Survey (RASS) has revealed 179 X-ray sources in total, of which 77 have been classified as WTTS (Alcalá et al. 1995). They are located not only near the known cloud structures, but also up to 10 degrees away from any known cloud material. For about 70 of them high resolution spectroscopy is now available, and more than 50% of the sources turn out to be in fact very young weak-line T Tauri stars (Covino et al. 1997, C97). Some additional sources were found from ROSAT pointed observations in the Cha I cloud (Feigelson et al. 1993).

Altogether, the membership list compiled by Lawson et al. (1996) contains 117 bona-fide or probable T Tauri stars in the inner region of the association, apart from the wider distributed population investigated by C97.

The discovery of many weak-line T Tauri stars up to about 50 pc away from the known molecular cloud cores of several nearby star forming regions (SFR) (e.g. Chamaeleon: Alcalá et al. 1995; Orion: Alcalá et al. 1996; Lupus: Krautter et al. 1997, Wichmann et al. 1997b; Taurus-

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Table 1. Stars which could be identified either in the Hipparcos (HIP), ACT (A) or STARNET (S) catalogue and which were known to be associated with the Cha I or the Cha II cloud before the ROSAT mission. Additional designations for the stars are given in the last column. Please note that the mean errors of the proper motions in right ascension are given with the factor $\cos\delta$.

object	HIP No./ GSC No.	RA ($\alpha_{J2000.0}$)	DEC ($\delta_{J2000.0}$)	μ_α [mas yr^{-1}]	μ_δ [mas yr^{-1}]	$\sigma_{\mu_\alpha \cos\delta}$ [mas yr^{-1}]	σ_{μ_δ} [mas yr^{-1}]	d [pc]	other designations
early type stars									
HD 97048	HIP 54413	$11^h\ 8^m\ 3.^s32$	$-77°39'17.''5$	-92	2	0.8	0.8	175^{+27}_{-20}	CHXR 29, Sz 25, PPM 370994
HD 97300	HIP 54557	11 9 50.02	-76 36 47.7	-94	-1	1.0	0.9	188^{+43}_{-30}	CHXR 42, PPM 371004, A 9410 2805
classical T Tauri stars									
Sz 6	HIP 53691	$10^h 59^m\ 6.^s97$	$-77°\ 1'40.''3$	-97	2	2.1	1.8	143^{+53}_{-30}	CHXR 6, AS 9414 186
CS Cha	S 9414 574	11 2 24.79	-77 33 35.4	-160	16	6.7	6.7		CHXR 10, Sz 9
Sz 19	HIP 54365	11 7 20.72	-77 38 7.3	-113	3	3.1	2.9	210^{+303}_{-78}	CHXR 23, AS 9414 743
VW Cha	S 9414 754	11 8 1.25	-77 42 28.6	-218	8	7.7	7.7		CHXR 31, Sz 24
CV Cha $^{(*)}$	S 9410 60	11 12 27.75	-76 44 22.4	-107	4	4.4	4.4		CHXR 51, Sz 42, A 9410 60
BF Cha	S 9417 708	13 5 20.57	-77 39 1.6	-98	1	4.5	4.5		Sz 54
weak-line T Tauri stars									
CHXR 8	A 9414 444	$11^h\ 0^m 14.^s50$	$-77°14'38.''0$	-114	13	2.6	3.7		S 9414 444
CHXR 11	S 9414 642	11 3 11.45	-77 21 3.7	-166	20	7.4	7.4		
CHXR 32	S 9414 640	11 8 14.79	-77 33 52.1	-260	34	7.7	7.7		Glass I
Sz 41	S 9410 300	11 12 26.10	-76 37 3.7	230	44	7.7	7.7		CHXR 50
CHXR 56	S 9414 209	11 12 42.50	-77 22 25.9	-195	-30	7.1	7.1		HM Anon
T Cha	HIP 58285	11 57 13.53	-79 21 31.6	-215	-10	5.1	3.8	66^{+19}_{-12}	RXJ 1157.2-7921, AS 9419 1187

$^{(*)}$ CV Cha is a double system (CCDM 11125-7644) with 2 entries in Hipparcos (HIP 54738 and HIP 54744) and an orbital solution qualified as poor. Its parallax is rather uncertain (3.14±7.39 mas).

Auriga: Neuhäuser et al. 1997, Magazzú et al. 1997) has raised the question about their origin. Before, with the exception of TW Hya (Ruciński & Krautter 1983), pre-main sequence stars had only been found near the densest parts of molecular clouds, and it was assumed that all stars originate from these cloud cores. While Wichmann et al. (1997b) found that the mean age of WTTS far from the clouds was higher than for WTTS projected onto the dark clouds in Lupus, Alcalá et al. (1997) found some of the youngest WTTS far from the molecular clouds in Chamaeleon. In order to travel 30 pc in $5 \cdot 10^6$ yrs (a typical T Tauri age in the Cha I cloud) a relative velocity of about 6 km s^{-1} would be required, much more than the value of 1-2 km s^{-1} considered typical for the intrinsic velocity dispersion by Jones & Herbig (1979) or the value of 0.9 ± 0.3 km s^{-1} derived by Dubath et al. (1996) using the radial velocities of 10 stars associated with the Cha I cloud.

Several scenarios have been put forward to account for the widely spread population of WTTS, including models where star formation takes place in the cloud cores and the stars are ejected out of these clouds subsequently (Sterzik & Durisen 1995) as well as models where star formation takes place in small cloudlets which disappear after the formation process (Feigelson 1996).

The kinematic signature of these processes should still be visible: while in the first scenario the velocity vectors of the stars should point away from the dense cores from where they were ejected, the second scenario may have produced small numbers of comoving WTTS with rather high relative velocities between different groups.

Triggered star formation by means of supernova explosions or the impacts of high velocity clouds (HVC) with the galactic plane have been proposed to explain the positions of some SFR with respect to the galactic plane (Tenorio-Tagle et al. 1987, Lépine & Duvert 1994). Nevertheless, in Chamaeleon there is no evidence of any OB association which could have triggered star formation. Lépine & Duvert however successfully modeled the observed geometry of the clouds with respect to the galactic plane with a rather simple model of a high velocity cloud impact, which also may have given rise to the observed widely spread PMS stars.

In this paper we analyse the kinematics of these stars in terms of the above models. Proper motions are taken from the Hipparcos (ESA 1997), and ACT (Urban et al.

Table 2. Stars with proper motions from the ROSAT sample investigated by Alcalá et al. (1995, 1997) and C97. The data are again taken from the Hipparcos, ACT and STARNET catalogues. The classification in T Tauri stars and ZAMS and other stars is based on the lithium criterium as applied by C97. Note however that some of the stars classified as ZAMS stars or stars of unknown nature fall well above the main sequence when placing them in the HR diagram with the help of the Hipparcos parallax (Neuhäuser & Brandner 1998).

object RXJ ...	HIP No./ GSC No.	RA ($\alpha_{J2000.0}$)	DEC ($\delta_{J2000.0}$)	μ_α [mas yr^{-1}]	μ_δ [mas yr^{-1}]	$\sigma_{\mu_\alpha \cos\delta}$ [mas yr^{-1}]	σ_{μ_δ} [mas yr^{-1}]	d [pc]	other designations
T Tauri stars									
0837.0-7856	A 9402 921	$8^h36^m56\overset{s}{.}24$	$-78^\circ56'45\overset{''}{.}7$	-147	26	1.4	1.8		S 9402 921
0850.1-7554	A 9395 2139	8 50 5.44	-75 54 38.2	-79	31	2.2	1.4		S 9395 2139
0951.9-7901	A 9404 195	9 51 50.68	-79 1 37.8	-149	39	0.9	2.6		PPM 370508, S 9404 195
1150.4-7704	S 9415 1685	11 50 28.23	-77 4 38.4	-223	-16	4.5	4.5		
1158.5-7754a	HIP 58400	11 58 28.15	-77 54 29.6	-198	-1	1.4	1.1	86^{+11}_{-9}	AS 9415 1238
1159.7-7601	HIP 58490	11 59 42.27	-76 1 26.1	-165	-5	1.7	1.5	92^{+17}_{-13}	AS 9411 2191
1201.7-7859	A 9420 1420	12 1 39.13	-78 59 16.9	-213	-5	0.8	0.8		PPM 785565, S 9420 1420
1239.4-7502	A 9412 59	12 39 21.27	-75 2 39.2	-159	-11	2.6	3.1		S 9412 59
ZAMS and other stars									
0849.2-7735	A 9399 1491	$8^h49^m11\overset{s}{.}10$	$-77^\circ35'58\overset{''}{.}6$	-36	19	2.1	2.6		PPM 370092, S 9399 1491
0853.1-8244	S 9506 1465	8 53 5.26	-82 44 0.4	-2	-21	3.7	3.7		
0917.2-7744	A 9399 2104	9 17 10.38	-77 44 2.0	-159	13	2.1	0.8		S 9399 2104
0919.4-7738N	HIP 45734	9 19 24.67	-77 38 36.4	-502	70	1.3	1.1	73^{+7}_{-6}	PPM 370271
0928.5-7815	A 9400 1990	9 28 15.02	-78 15 22.4	-118	17	2.2	2.5		PPM 370343
0936.3-7820	HIP 47135	9 36 17.82	-78 20 41.6	-361	50	0.7	0.6	63^{+3}_{-3}	PPM 370394, AS 9400 1713
0952.7-7933	A 9404 1702	9 53 13.73	-79 33 28.4	-82	6	1.6	2.1		PPM 370518, S 9404 1702
1009.6-8105	A 9409 1040	10 9 58.30	-81 4 11.4	86	-24	2.4	0.8		PPM 377161, S 9409 1040
1039.5-7538S	HIP 52172	10 39 31.73	-75 37 56.3	13	17	1.6	1.4	128^{+29}_{-20}	
1120.3-7828	S 9415 2314	11 20 19.68	-78 28 21.0	46	73	3.7	3.7		
1125.8-8456	HIP 55746	11 25 17.74	-84 57 16.3	-545	12	0.7	0.6	83^{+4}_{-4}	PPM 377341, AS 9511 1593
1140.3-8321	S 9507 2466	11 40 16.52	-83 21 0.3	-366	28	3.9	3.9		
1203.7-8129	S 9424 988	12 3 24.66	-81 29 55.3	-98	-10	3.7	3.7		
1207.9-7555	A 9412 2105	12 7 51.16	-75 55 16.1	-639	-7	3.1	0.8		PPM 785598, S 9412 2105
1209.8-7344	S 9239 1321	12 9 42.79	-73 44 41.5	-51	-5	3.6	3.6		
1217.4-8035	A 9420 439	12 17 26.90	-80 35 6.9	-5	-11	2.7	2.3		PPM 377437, S 9420 439
1220.6-7539	A 9412 1370	12 20 34.37	-75 39 28.7	-472	3	1.5	2.8		PPM 785640, S 9412 1370
1223.5-7740	A 9416 555	12 23 29.04	-77 40 51.4	-306	12	0.8	0.8		PPM 371482, S 9416 555
1225.3-7857	A 9420 742	12 25 13.42	-78 57 34.8	-123	-23	4.2	1.0		PPM 371498, S 9420 742
1233.5-7523	HIP 61284	12 33 29.78	-75 23 11.3	-370	13	1.1	1.1	66^{+5}_{-4}	PPM 371552, AS 9412 190
1307.3-7602	A 9413 2147	13 7 22.92	-76 2 36.2	-57	7	0.8	2.0		PPM 785854, S 9413 2147
1325.7-7955	S 9434 97	13 25 41.79	-79 55 16.2	-50	0	5.0	5.0		
1349.2-7549E	A 9426 682	13 49 12.92	-75 49 47.5	-267	-31	1.9	2.1		PPM 372040, S 9426 682

1997) catalogues as well as from STARNET (Röser 1996), which gives proper motions for about 4.3 million stars with an accuracy of about 5 mas yr^{-1} and is a database well suited to study this population of stars.

A crucial point in this analysis are the individual distances of the stars. Hipparcos parallaxes are available only for a very small fraction of our sample. The two bright late B-type stars HD 97300 and HD 90480 known to be assoicated with the Cha I cloud (Whittet et al. 1997) are located at distances of 188 pc and 175 pc, respectively. T Cha seems to be located closer (66 pc) than the other T Tauri stars associated to Cha I and Cha II, although the Hipparcos parallax has a very large error. Sz 6 is located at 143 pc, and the Hipparcos results for Sz 19 and CV Cha are uncertain. For stars not measured by Hipparcos we adopt a mean value of 170 pc unless stated otherwise, taking the Hipparcos results (Wichmann et al. 1998) as well as determinations based on various other methods (see Schwartz 1991 for a review) into account. Note that this value is also in good agreement with the recent distance estimate of 160±15 pc to the Cha I cloud by Whittet et al. (1997) derived on the basis of reddening distributions. We make

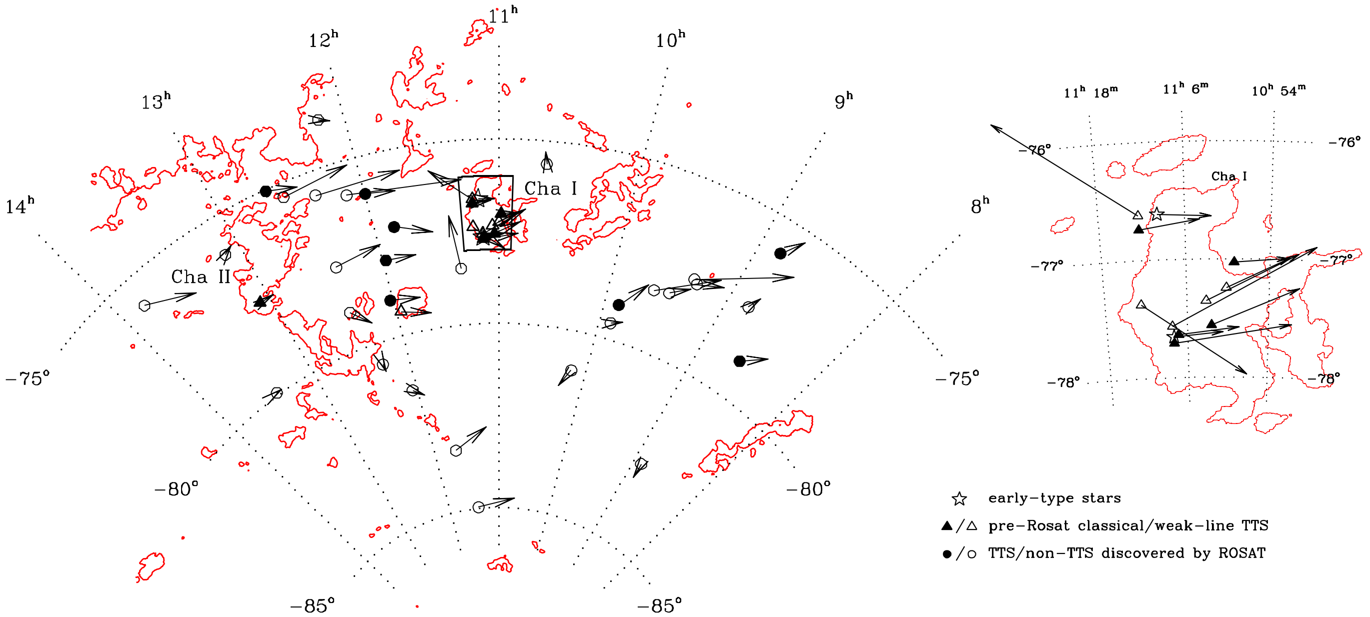

Fig. 1. Positions and proper motions of the stars in Tables 1 and 2. Contours are from the IRAS 100 μm survey. The region around Cha I is shown on an enlarged scale, too. Most of the new ROSAT discovered stars are either located between these two clouds or west of Cha I. 1° corresponds to 50 mas yr^{-1}; the largest arrow in the figure (RXJ 1207.9-7555 between Cha I and Cha II) corresponds to 156 mas yr^{-1}.

no distinction between the distance to the Cha I and the Cha II clouds, because indications for a larger distance to Cha II are rather uncertain (Schwartz 1991, Brandner & Zinnecker 1997, Whittet et al. 1997).

The paper is organized as follows: In Section 2 we present and discuss our data, taken from several proper motion catalogues, and define the samples. Section 3 is devoted to the kinematics of these stars; proper motions and space velocities are investigated in detail. Finally, we discuss the implications of these motions for several star formation scenarios in Section 4 and present our conclusions in Section 5.

2. Data

2.1. Proper motion catalogues

Astrometric data with the highest currently available accuracy is provided in the Hipparcos Catalogue (ESA 1997). It contains about 120 000 stars and the typical error of the proper motions is about 1 mas yr^{-1}. The Hipparcos Catalogue was the major output of the ESA Hipparcos space astrometry satellite mission, and proper motions were determined by fitting all astrometric parameters (positions, proper motions, parallax) simultaneously to the data points collected over the about 3 years time of operation for every individual star.

Proper motions in the ACT Reference Catalogue (Urban et al. 1997) and STARNET (Röser 1996) however were determined by comparing the positions of stars with an epoch difference of about 80 years. Both catalogues use the Astrographic Catalogue (AC) with a mean epoch of 1907 as the first position measurement. For the ACT the Tycho Catalogue (ESA 1997) provides the second epoch, yielding proper motions for about 1 million stars with an accuracy of about 3 mas yr^{-1}. STARNET uses the Guide Star Catalogue (GSC 1.2) as second epoch and provides proper motions for 4.3 million stars with an accuracy of about 5 mas yr^{-1}. Thus it is the most extensive proper motion catalogue available so far, containing stars with magnitudes up to 12 mag and mean errors still acceptable for kinematic studies.

The proper motions discussed in the following sections are taken from these three catalogues, which are all on the ICRS astrometric system defined by Hipparcos. The PPM proper motions, with a similar accuracy as the ACT for 400 000 stars, were used for comparison only, see Sect. 2.3.

2.2. The samples

In Table 1 we list all the stars which were known or suspected to be connected to the Chamaeleon association before the ROSAT mission, along with their proper motions. Altogether these are 14 stars: the 2 well-known late B type stars HD 97048 and HD 97300, with entries from Hipparcos, and 6 classical and 6 weak-line T Tauri stars. We have included T Cha, although it maybe located foreground to the Chamaeleon clouds as indicated by its Hipparcos parallax (Wichmann et al. 1998). Only one of these stars (BF Cha) is associated with the Cha II cloud, whereas the other stars are located close to Cha I. There is a third cloud in the Chamaeleon region termed Cha III which apparently also shows star formation activity (Pfau et al. 1996), but the sources are on average 2 mag fainter than in the other two clouds and none could be identified in STARNET.

As in other nearby star forming regions, optical follow-up observations of X-ray sources discovered by ROSAT led to the identification of 77 probable new pre-main sequence stars in the Chamaeleon region (Alcalá et al. 1995, 1997). These new T Tauri stars are not only located close to the clouds like most of the T Tauri stars known before, but also up to 10^o away from any known site of star formation.

Precise determinations of the lithium line (670.7 nm) strength by means of high resolution spectroscopy and comparison with the typical lithium equivalent width of young main sequence stars (like the Pleiades) of the same spectral type confirmed the pre-main sequence nature for more than half of these stars (C97). We could identify 31 stars of the total sample in the Hipparcos, ACT and STARNET catalogues (Table 2).

Unfortunately, of the 31 stars newly discovered with ROSAT for which we can find proper motions only 8 are confirmed low-mass PMS stars, whereas in the whole sample of C97 the fraction of bona-fide PMS to non-PMS stars is about twice (40 out of 81). This is a consequence of the fact that most of the confirmed low-mass PMS stars in the C97 sample having spectral types later than G5 are normally fainter than about $V \approx 11.5$ mag and hence are not included in the Hipparcos, ACT and/or STARNET catalogues, while the other objects classified as ZAMS stars or with dubious PMS nature by C97 have on average earlier spectral types and hence are sufficiently bright to be present in the aforementioned catalogues.

Similarly, only sources detected with the ROSAT All-Sky Survey and none of the sources detected only in ROSAT PSPC pointed observations could be identified in any of the proper motion catalogues. This means that in our sample there is no artificial spatial clustering due to possibly locally varying sensitivities present within the region indicated in Fig. 2.

2.3. Discordant proper motions

For the majority of the stars in Tables 1 and 2 more than one proper motion measurement is available, so that we are able to compare its values in different catalogues. For most of our stars we find no significant differences and we list the most accurate determination.

Stars with discordant proper motions in two or more catalogues are listed together with all available proper motion determinations in Table 3. The most probable reason for differences in the proper motions are non-resolved binary or multiple systems: in general it is not clear whether the photocentre or the brighter component was observed, and sometimes this may be different for the positions of the first and second epoch, especially for variable stars. This may lead to spurious proper motions in the ACT and STARNET catalogues.

Table 3. Stars with discordant proper motions in one or more catalogues. All proper motions have been transformed to the astrometric reference system defined by Hipparcos, so no systematic differences should be present.

[mas yr^{-1}]	μ_α	μ_δ	$\frac{\sigma_{\mu_\alpha}}{\cos\delta}$	σ_{μ_δ}
Sz 19				
HIP	-113	3	3.1	2.9
ACT	-120	8	3.1	2.1
STARNET	-106	45	4.4	4.5
RXJ 0837.0-7856				
ACT	-147	26	1.4	1.8
STARNET	-321	59	3.7	3.7
RXJ 1125.8-8456				
HIP	-545	12	0.7	0.6
PPM	-482	12	2.1	2.4
ACT	-555	12	0.8	1.3
STARNET	-388	9	3.2	3.2
RXJ 1159.7-7601				
HIP	-165	-5	1.7	1.5
ACT	-199	-7	8.7	2.9
STARNET	-224	-20	3.8	3.8

Orbital motion further complicates the determination of the mean proper motion for the whole system. The largest effect is expected for the Hipparcos proper motions, since 3 years of data collection covers only a short fraction of the orbits of long period binaries. Thus the instantaneous motion of the photocentre seen by Hipparcos does not reflect the mean motion of the centre of mass for these kind of systems (Lindegren et al. 1997; Wielen 1997).

Two stars of Table 3 are present in the Double and Multiple Systems Annex of the Hipparcos Catalogue, where the observational effects of duplicity have been taken into account. Sz 19 is perhaps an astrometric binary with a short period which could not be resolved by Hipparcos. Indeed Schwartz (1977) notes a close companion to Sz 19 in the south, confirmed by Reipurth & Zinnecker (1993) and Ghez et al. (1997), and the secondary is variable with magnitude differences of at least 2.5 mag (Brandner 1992). For RXJ 1125.8-8456 a non-linear model of the motion including acceleration terms was fitted to the Hipparcos observations, which has no meaning outside the mission interval. Although this is formally a single-star solution, we may deal with an unresolved system with a period in the range 10-100 years (Lindegren et al. 1997).

Similar effects may be responsible for the inconsistencies in the proper motions of the other two stars from

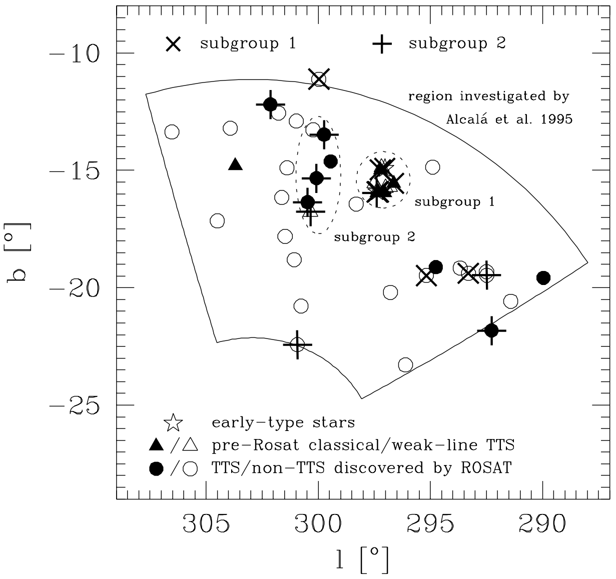

Fig. 2. Positions of the stars in Tables 1 and 2 in galactic coordinates. The subgroups 1 and 2 defined in Section 3.1.1 are indicated by the overplotted symbols 'x' and '+'. Stars with dubious PMS nature according to C97 and others which could be attributed to one of the subgroups on the basis of their proper motions are also coded. For illustration the approximate positions of subgroups 1 & 2 on the sky and the region investigated by Alcalá et al. (1995) are indicated, too, whereas for subgroup 3 there is no pronounced clustering in the position diagram.

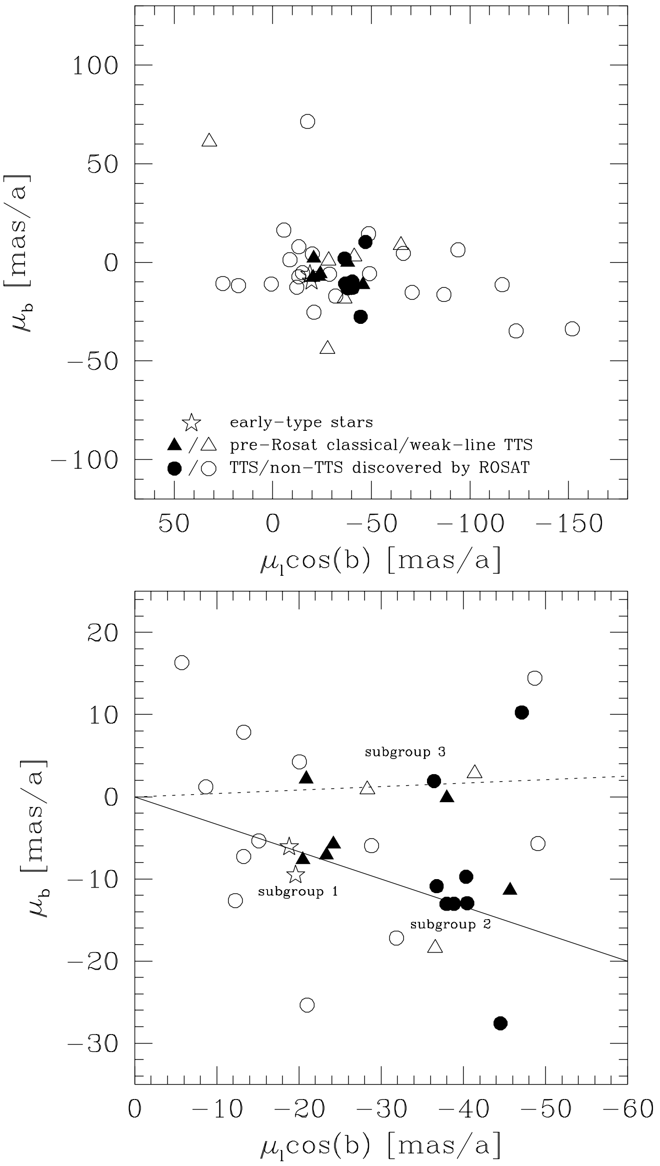

Fig. 3. Proper motion diagram in galactic coordinates for all the stars in Tables 1 and 2. The lower panel is an enlarged reproduction of the center of the upper panel. The different subgroups are introduced in Section 3.1.1, and the lines correspond to motions for varying distances.

Table 3: RXJ 0837.0-7856 was not observed by Hipparcos, but is flagged as dubious astrometric reference star in the Tycho catalogue, as is RXJ 1159.7-7601. The latter star is additionally flagged as 'perhaps non-single' in the ACT catalogue.

Another source of errors in the ACT and STARNET catalogues may be wrong identifications of stars, favoured by large epoch differences and large proper motions. All these effects may explain the large differences between proper motions in different catalogues, although in most of the cases the actual error source is difficult to find out.

3. Kinematics

3.1. Proper motions

Positions and proper motions of the stars in Tables 1 and 2 are plotted in Fig. 1. The two open star symbols denote the early type stars HD 97048 and HD 97300, the filled triangles classical TTS and the open triangles weak-line TTS known before the ROSAT mission. The filled circles represent confirmed low-mass PMS stars, while the open ones are objects classified as ZAMS stars or with dubious PMS nature by C97. One immediately notes that there is a trend for proper motion vectors pointing to the west, with some scatter especially for the ZAMS stars, as expected from their probably higher velocity dispersion. For a more detailed analysis, we also plot the data in galactic coordinates (Figs. 2 and 3), which are better suited for a rectangular illustration due to the position of the Chamaeleon association near to the southern equatorial pole. The motion of the stars is partly due to the reflex motion of the Sun, which is about $(\mu_l \cos b, \mu_b) \approx (-17,-6)\,\mathrm{mas\,yr^{-1}}$ at the position of the Chamaeleon association and a distance of 170 pc. Note however that this value strongly depends on the adopted distance (for half the distance the value would be twice as high), whereas the variations caused by

Table 4. Subgroups derived from the proper motion diagram (Fig. 3) with their mean proper motions and dispersions. The number of stars in each subgroup is given in the last column.

sub-group	$\mu_l \cos b$ [mas yr^{-1}]	μ_b [mas yr^{-1}]	# of stars
1	-21.3 ± 2.4	-7.2 ± 1.5	5
2	-39.5 ± 3.1	-12.8 ± 2.8	7
3	-38.6 ± 2.5	1.6 ± 1.5	3

different positions on the sky are rather low within our study area.

3.1.1. Bona-fide PMS stars

From Fig. 3 we infer at least 2 or 3 different areas in the proper motion diagram where confirmed PMS stars tend to cluster (Table 4). It turns out that these subgroups are not only apparent in the proper motion diagram, but likewise they correspond to different regions in the position diagram, which independently confirms our subdivisions. The first subgroup consists of the 2 early type stars and 3 CTTS (Sz 6, Sz 19 and CV Cha), all located in the cloud core of Cha I. In the second subgroup there are 5 new PMS stars, which all have very similar proper motions and, with the exception of RXJ 0837.0-7856[1], are all located between the Cha I and Cha II clouds. Besides these ROSAT detected PMS stars one CTTS (VW Cha) and one WTTS (T Cha) also match the requirements of subgroup 2. Note that T Cha is also located between Cha I and Cha II, whereas the position of VW Cha is close to the core of the Cha I cloud.

The proper motions of subgroups 1 and 2 point into the same direction, but the absolute values are about twice as high for the second group. This finding is consistent with a scenario where the mean distance for the second subgroup is about half of the mean distance for the first subgroup. Then, both groups would have consistent space velocities. Indeed this picture is confirmed by the Hipparcos parallaxes: with our assumption for the mean distance of Cha I of 170 pc (the distances for 4 stars in subgroup 1 are 175 pc (HD 97048), 188 pc (HD 97300), 143 pc (Sz 6) and 210 pc (Sz 19)) we would expect a mean distance of about 90 pc for stars in our subgroup 2. The parallaxes as observed by Hipparcos for 3 stars in subgroup 2 correspond to distances of 86 pc (RXJ 1158.5-7754a), 92 pc (RXJ 1159.7-7601) and 66 pc (T Cha), which gives very strong support to our interpretation.

The existence of subgroup 3 is not so obvious as for the other 2 subgroups. The 3 stars which we grouped together are CS Cha, CHXR 11 and RXJ 0850.1-7554. Nevertheless, if we assume its existence we could attribute 4 more stars with higher (BF Cha and CHXR 8) or lower distances (RXJ 0951.9-7901 and CHXR 32) to it.

Only 2 WTTS and 1 new PMS (Sz 41, CHXR 56 and RXJ 1150.4-7704) are left from the sample of the bona-fide PMS stars (Table 1 and upper part of Table 2) which do not fit in any of the above subgroups because of quite different proper motions. Sz 41 is at least a double system: besides a faint companion another star nearly as bright as the primary is located 11.4″ away from Sz 41 (Brandner 1992; Reipurth & Zinnecker 1993). RXJ 1150.4-7704 is flagged as a possible spectroscopic binary by C97. Thus it is possible that the proper motions of these stars are not representing their space motions.

The velocity dispersions in our subgroups are of the same order of magnitude as the errors of the proper motions, and so the intrinsic velocity dispersions must be much smaller (at a distance of 170 pc 1 mas yr^{-1} corresponds to 0.8 km s^{-1}). To some extent this was expected, because we only grouped stars with similar proper motions together. On the other hand such low values for the intrinsic velocity dispersion agree with other determinations. Jones & Herbig (1979) derived a value of 1-2 km s^{-1} in one coordinate for the intrinsic velocity dispersions of subgroups in Taurus-Auriga and considered this as typical for associations. Dubath et al. (1996) calculated a value of 0.9±0.3 km s^{-1} based on the radial velocities of 10 stars in Cha I.

3.1.2. ZAMS stars and others

The stars of Table 2 classified as stars with dubious PMS nature or as ZAMS stars by C97 clearly show a very large range in proper motions, which independently confirms the conclusions from applying the lithium criterion by C97. This criterion is very conservative, as it rejects stars with lithium abundances similar to the Pleiades as weak-line TTS, although it may very well be the case that some truly pre-main sequence stars exhibit such low lithium strength. Note that all the stars with Hipparcos parallaxes in Table 2 fall well above the main sequence when comparing their positions in the HR diagram with various PMS evolutionary tracks (Neuhäuser & Brandner 1998).

There are a few other stars in Table 2 which - rated from their proper motions - probably fall into this category of unrecognized weak-line T Tauri stars. Judging from the proper motions alone one could assign RXJ 0928.5-7815, RXJ 0952.7-7933 and RXJ 1209.8-7344 to subgroup 1, RXJ 0917.2-7744 and RXJ 1125.8-8456 (its Hipparcos parallax corresponding to 83 pc also fits this interpretation) to subgroup 2, and RXJ 0849.2-7735 and RXJ 1223.5-7740 to subgroup 3. One must however bear in mind that the reflex motion of the sun is very similar to the typical proper motion of Chamaeleon member stars, making

[1] Note from Table 3 that RXJ 0837.0-7856 has a different proper motion in STARNET which would make it a good candidate for a run-away TTS (RATTS), possibly ejected some 10^6 years ago.

Table 5. Mean space velocities and dispersions separately for stars of subgroups 1 & 2 and Hipparcos PMS stars as well as for the total samples, as shown in Fig. 4. U-velocities are positive in the direction of the galactic centre. The velocities have been corrected for the effects of differential galactic rotation and the reflex motion of the Sun. For the calculation of the space velocities we used either the Hipparcos parallaxes or, where not available, a distance of 170 pc for stars in subgroup 1 and 90 pc for stars in subgroup 2.

	#	$<U>$ [km s^{-1}]	σ_U	$<V>$ [km s^{-1}]	σ_V	$<W>$ [km s^{-1}]	σ_W
subgroup 1	4	4.4	6.7	-11.0	8.1	-3.4	2.7
subgroup 2	7	3.1	2.8	-7.6	3.3	-2.3	1.6
subgroups 1 & 2	11	3.6	4.3	-8.8	5.4	-2.7	2.0
Hipparcos PMS	6	5.2	5.5	-9.6	6.7	-3.1	2.5
all Hipparcos stars	11	-14.9	30.6	-10.7	18.5	-1.1	11.9

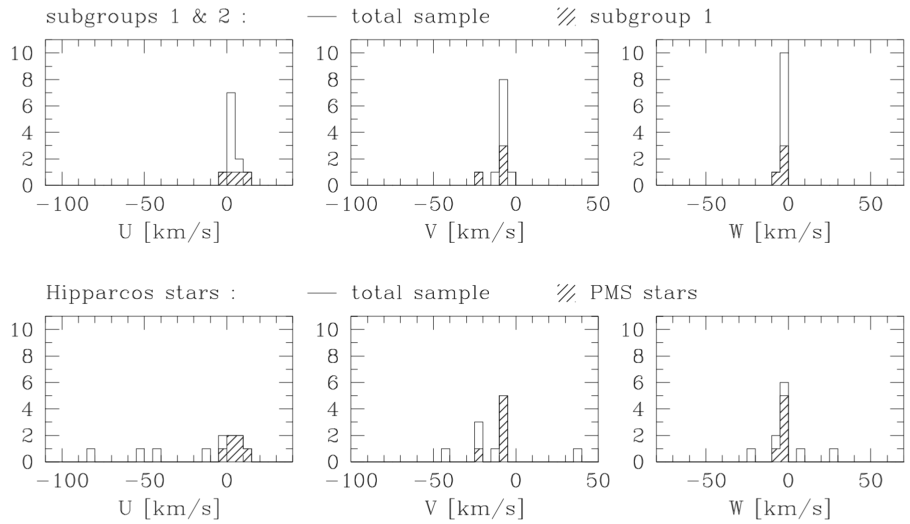

Fig. 4. Space velocity histograms shown separately for stars in subgroups 1 and 2 (upper panels) and for Hipparcos stars (lower panels). In the upper diagrams the contribution of subgroup 1 is hatched, and no significant differences between the two subgroups are visible. In the lower diagrams the contribution of the PMS stars is hatched. We assumed the same distances as in Table 5 and corrected the velocities for the effects of differential galactic rotation and the motion of the Sun.

it difficult to distinguish between members and field stars on the basis of the proper motions alone.

3.2. Space velocities

We have calculated space velocities for all stars in subgroups 1 and 2 and the Hipparcos stars with radial velocities available in the literature (HD 97048 from Finkenzeller & Jankovics (1984), 4 CTTS from Dubath et al. (1996), and T Cha and stars in Table 2 from C97). For stars not observed by Hipparcos a distance of 170 pc for subgroup 1 and 90 pc for subgroup 2 was adopted.

We corrected the space velocities for the effect of differential galactic rotation, assuming the IAU standard values of 8.5 kpc for the distance to the galactic centre and 220 km s^{-1} for the velocity of the Local Standard of Rest. The value of this correction depends on the galactic azimuthal angle and therefore in general also on the distances of the stars. The mean corrections in the U-velocities for stars in subgroup 1 and 2 are 3.8 km s^{-1} and 2.0 km s^{-1}, respectively (the corrections in the V-velocities are practically zero). Additionally, the motion of the Sun ((U,V,W) = (9,12,7) km s^{-1}, Delhaye 1965) has been added to the space velocites, although it does not change the relative velocities between the groups which are of interest here.

The coincidence of the mean values for the three space velocity components of Hipparcos PMS stars and the combined sample of subgroups 1 & 2 is artificial to some extent (see Table 5) as the 6 Hipparcos stars form a subset of subgroups 1 & 2. The mean values for subgroup 1 and 2 are also in quite good agreement.

Our interpretation of different proper motions in terms of different distances is further confirmed when taking the additional information on the radial velocities and projection effects due to different positions in space into account.

Comparing the Hipparcos PMS stars with ZAMS stars and stars of dubious PMS nature in Fig. 4, one again notes the clear peak in the distribution of the PMS stars and the large scatter of the presumably older stars.

4. Discussion

4.1. Structure of the Chamaeleon clouds

The IRAS 100μm map of the Chamaeleon region shows several filamentary clouds which extend over an area of more than 100 square degrees. It is an open question whether the individual structures termed Cha I, Cha II and Cha III are really physically related to each other. There is another cloud, DC 300.2-16.9 (Hartley et al. 1986), located between Cha I and Cha II roughly at the position of T Cha.

The Hipparcos parallax of T Cha implies a relatively small distance of 66 pc. Note however that the large parallax error for this star puts an upper limit of 85 pc while the lower limit is 54 pc. The latter would place T Cha practically on the main sequence, which is absolutely inconsistent with the pronounced PMS characteristics of this star (Alcalá et al. 1993). Even the mean distance of 66 pc would give an extremely old age of some 40 Myr for this star. Since T Cha is definitely a T Tauri star, we think that the upper limit of 85 pc should be closer to the true distance of T Cha.

On the other hand, an upper limit of 180 pc has been established for the distance of the cloud DC 300.2-16.9 (Boulanger et al. 1998), to which T Cha seems to be associated. Thus, it may well be that this cloud is also located closer than the Cha I cloud, maybe also at about 90 pc from the Sun. The Hipparcos parallaxes of the other stars in subgroup 2 as well as our analysis of the proper motions in Section 3.1.1 support this scenario of stars and even some cloud material at distances of about 90 pc.

The question now is how can a SFR be such large in volume? We discuss the models for the formation scenario of the Chamaeleon cloud complex which possibly could explain the existence of PMS stars far off the observed molecular clouds in the next section.

Alternatively, we may note that it is also possible that the observed cloud material belongs to distinct structures as considered by Whittet et al. (1997). In this case the stars in subgroups 1 & 2 would have the same space velocities although they are not associated with the same cloud material. However, it is not unusual that young stars exhibit rather low velocities relative to the field stars in the same region (cf. the Taurus SFR or the Scorpius-Centaurus OB association).

Moreover, placing the stars of subgroup 2 at a mean distance of 90 pc rises their mean ages by about a factor of 6 to 18 Myr as compared to a mean age of 3 Myr for a mean distance of 170 pc. This could easily be explained if they belong to another structure than the stars of subgroup 1.

There are too few stars in the Chamaeleon region with distance information available to decide whether a population of PMS stars with distances intermediate between the two subgroups at around 130 pc exists. In principle, the majority of dispersed T Tauri stars detected with the flux-limited RASS are expected to be located between 90 pc and 150 pc, and the optical, IR and deep X-ray pointed observations have been sufficiently sensitive to detect PMS stars at more than 150 pc. However, most of these stars were too faint to be included in the Hipparcos Input Catalogue.

4.2. Implications for the formation scenario of the Chamaeleon cloud complex

The discovery of large populations of WTTS distributed over regions of 10-20 degrees or even more in extent centered around active cloud cores has raised questions about the scenario of their formation. Several scenarios have been suggested to account for the existence of very young stars far away from the known sites of star formation.

Sterzik & Durisen (1995) proposed that the WTTS halo observed around star formation regions might be due to high velocity ($\gtrsim 3\,\mathrm{km\,s^{-1}}$) escapers (run-away TTS or RATTS) produced by dynamical interactions in small stellar systems. This would imply that the velocity vectors of the stars point away from the dense molecular cloud cores from where they were ejected.

From our proper motion study there is no indication for such an overall correlation between positions and proper motions. Only for some 2 or 3 stars in our sample the ejection scenario may be invoked, namely Sz 41, CHXR 56, and perhaps RXJ 0837.0-7856, if their proper motions are not spurious due to binarity. On the contrary, if we assume that subgroup 2 is at the same distance as subgroup 1 (ignoring the Hipparcos parallaxes for the moment), the stars of subgroup 2 would move with higher space velocities in the direction of lower right ascension than the stars of subgroup 1 while being located at higher right ascension (cf. Fig. 1). This means that they would approach the Cha I molecular cloud. Given the direction of motion, we cannot exclude that some stars may have been ejected from the Cha II cloud. However, the fact that these stars seem to form a co-moving group is inconsistent with the prediction of any ejection model, in which the motion would be completely random, so that we exclude the ejection scenario as the dominant process for producing the dispersed population of WTTS in Chamaeleon.

Lépine & Duvert (1994) tried to explain the displacement with respect to the galactic plane of several nearby star forming regions including Chamaeleon by infall of high velocity clouds (HVC) on the galactic plane. There is no detailed prediction for the kinematics of the stars in the HVC impact scenario, except for the fact that, subsequent to the impact, clouds and stars will oscillate around the galactic plane and tend to separate from each other (combing-out). Given the fact that at least the stars in subgroups 1 & 2 display practically no net motion perpendicular to the galactic plane after correcting their proper motions for the solar reflex motion, one might speculate that they are just reversing their direction of motion. The large distance of the Chamaeleon association from the galactic plane may support this point of view. Nevertheless, these indications are far from being conclusive and depend strongly on the adopted distances.

Feigelson (1996) proposed that low mass stars may form in dispersed cloudlets in a turbulent environment. Also, it has long been suspected that Bok globules are the sites of isolated star formation. Recent studies (Launhardt & Henning 1997, Yun et al. 1997) have shown that such globules can be associated with embedded IR and IRAS point sources in which very young low mass stars are found. It is however not clear if these globules are related to Feigelson's cloudlets.

In order to explain the observed distribution of WTTS Feigelson (1996) considers models with a velocity dispersion of the order of $1\,\mathrm{km\,s^{-1}}$ (due to internal thermal motions in the gas of the parent cloud), with thermal velocity dispersal in combination with dynamical ejection, and with star formation in small cloudlets distributed over a larger region. Comparing the predictions of his models with the properties of the observed WTTS population, he found that the first two dispersal models encounter serious problems. In particular, the thermal dispersal model can explain the number of WTTS found far from the active clouds, but not their low ages. In order to overcome this difficulty within the framework of the current model one would have to assume an unplausibly high velocity dispersion even at the time of their formation. An improved dispersal model, where a certain fraction of the dispersing stars is made up of high velocity escapers, cannot account for the observations either, unless the ejection rate significantly increased recently. The model can indeed explain the existence of some very young stars far from their sites of origin, but simultaneously it produces a population of older ejected stars, which would lead to an unplausibly high star formation efficiency.

As already pointed out above, the proper motion data of the stars discussed in the previous sections are inconsistent with any dispersal model either, as the velocity vectors are not oriented away from any single point.

In the most promising model investigated by Feigelson star formation takes place in long-lived active cloud cores as well as in a number of small short-lived cloudlets distributed over a rather large region. These cloudlets are believed to possess high velocities relative to their parental giant molecular clouds because of its turbulent structure. After producing some stars with very low internal velocity dispersion the cloudlets disappear, leaving behind streams of T Tauri stars with high relative velocities between each other.

As proper motions are available only for a very small fraction of all the young stars in the Chamaeleon region (probably for less than 10% according to the estimate by Feigelson of several hundred stars yet to be discovered), it is difficult to verify the predictions of the model quantitavely. If we ignore the stars in subgroups 1 & 2 for the moment, which we assume to have formed in the dense cloud cores, we are left with not more than 33 stars which possibly originated in small cloudlets. Feigelson estimates the number of cloudlets to be of the order of 50, so that we do not expect to have more than one or two stars of the same cloudlet in our sample. Although we cannot confirm the model decisively, from the proper motion diagram (Fig. 3) one could select good candidate stars which possibly were formed in cloudlets.

Another limiting factor in our kinematical study is the lack of precise distances for the majority of our stars. For a more detailed comparision with the model of Feigelson one needs to correct the proper motions of the wider distributed TTS and not only of the stars in the two subgroups for galactic rotation and the reflex of the solar motion, which requires knowledge of the individual distances. Similarly, comparisions with the ejection scenario are also hampered by the lack of precise distances, as the relative velocities can change sign when putting the stars at higher or lower distances.

5. Summary and conclusions

We have analysed proper motions from the Hipparcos, ACT and STARNET catalogues for altogether 45 stars, 22 of which are bona-fide pre-main sequence stars and 23 are of dubious PMS nature or ZAMS stars. On the basis of the distribution of the proper motions the presence of several subgroups in our data is suggested, which roughly coincide with similar groups on the sky. Given the kinematic distances which are independently confirmed by the Hipparcos parallaxes, the two subgroups might belong to distinct structures of the Chamaeleon clouds.

There is no indication in these data for a slow dispersal of stars out of the active cloud cores, and so the model proposed by Sterzik & Durisen (1995) cannot account for the large distribution of WTTS observed far from any known cloud material. However, the observed motions are more or less consistent with the high velocity cloud impact model of Lépine & Duvert (1994) if the stars are currently at their turning point. Similarly, the data could be interpreted in terms of the cloudlet model (Feigelson 1996) where star formation takes place far off the active cloud cores and which produces small groups of TTS with low internal velocity dispersions, but high relative velocities between groups.

Larger proper motion catalogues produced hopefully by future space missions like DIVA or GAIA will help to settle the question of the formation scenario of this large population of weak-line T Tauri stars in the Chamaeleon region.

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