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DISPERSED T TAURI STARS AND GALACTIC STAR FORMATION

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ABSTRACT

Existing samples of low-mass T Tauri stars from nearby star forming regions are very deficient in stars older than 2 Myr. We argue that this arises from the dispersal of stars outside well-surveyed regions and is not due to a burst of star formation, erroneous theoretical isochrones, or survey flux limits. Evidence is accumulating, most dramatically from the *ROSAT* All-Sky Survey, that a large population of weak-lined T Tauri (WTT) stars is widely dispersed within and around star forming complexes.

The spatial distribution, age distribution, and kinematics of T Tauri stars, both close to and widely distributed around active clouds, are studied using simple models of T Tauri dispersal. Models are compared to observations of the Chamaeleon and Taurus-Auriga cloud complexes. The dispersal of T Tauri stars appears to have two major causes: slow isotropic drifting of stars away from long-lived star forming clouds, and star formation in short-lived rapidly moving cloudlets. The first mechanism is determined by the $\Delta v \simeq 1$ km s^{-1} thermal velocity dispersion of gas within molecular cloud cores. The second mechanism is determined by the large-scale turbulent motions of molecular cloud complexes. A third mechanism for dispersal, dynamical ejection of high-velocity T Tauri stars, appears to be less important.

The results have a number of implications for star formation in the Galaxy: star formation in at least one cloud (Chamaeleon I) has been continuous for $\simeq 20$ Myr; star formation efficiencies of clouds may often be 20% or higher; a large fraction of low-mass stars may form in small short-lived cloudlets each producing no more than a few stars; and T Tauri kinematics support molecular evidence for large-scale turbulence in molecular clouds.

Subject headings: ISM: kinematics and dynamics — stars: formation — stars: kinematics — stars: luminosity function, mass function — stars: pre–main-sequence

1. INTRODUCTION

Unbiased and complete samples of T Tauri stars are essential for addressing a number of important issues concerning star formation in the Galaxy and early phases of low-mass stellar evolution. Does a molecular cloud produce star continuously or episodically? What are a cloud's star formation efficiency and stellar initial mass function (IMF)? What fraction of stars are formed in small cloudlets (e.g., Bok globules) versus large clouds? How do cloud dynamics affect stellar dynamics and bound cluster formation? What is the evolution of circumstellar disks from which planetary systems may condense?

The samples of T Tauri stars about which these questions have been addressed have grown considerably over the past decades. From the 1940s–1970s, the census of stars descending the Hayashi tracks were obtained primarily from surveys of Hα-emitting stars in nearby molecular clouds. Cohen & Kuhi (1979) characterized about 500 classical T Tauri (CTT) stars, concluding that the IMF is consistent with Salpeter's function and the molecular cloud star formation efficiency, $M_{\rm stars}/M_{\rm gas}$, is typically only a few percent. In the 1970s–1980s, infrared surveys revealed significant populations of young stars deeply embedded in molecular clouds, some of which are demonstrably in the protostar phases that precede the visible T Tauri phase (Shu, Adams, & Lizano 1987). The 1980s–1990s are witnessing the discovery of many "weak-lined" T Tauri (WTT) stars from soft X-ray surveys of nearby star forming regions. WTT stars show X-ray emission 1–3 orders of magnitude above typical main-sequence levels due to enhanced magnetic activity (Feigelson, Giampapa, & Vrba 1991). Sensitive and spatially complete X-ray surveys from *ROSAT* imply that WTT stars outnumber CTT stars several fold (e.g., Feigelson et al. 1993; Strom & Strom 1994; Neuhäuser et al. 1995a). The 1990s are also witnessing another burst in the census with the discovery that most T Tauri "stars" are visual or spectroscopic binaries (Mathieu 1994). The implications of this doubling and quadrupling of the T Tauri population for the astrophysical issues mentioned above have only begun to be explored.

But despite these advances, we argue that the T Tauri census is far from approaching completeness: there is a steep decline in the numbers of stars known with ages older than ~2 Myr (§ 2). Two reasons might be considered: molecular clouds are active for only a short time; or older stars have moved away from the vicinities of their parent clouds, outside of regions carefully surveyed for WTT stars. This first explanation contradicts a long-held belief that molecular cloud lifetimes exceed ~10 Myr (Blaauw 1964; Falgarone & Puget 1986), although there is little evidence constraining cloud lifetimes independent of the ages of their associated star clusters (Elmegreen 1985). We concentrate on the second explanation here, spurred by recent reports of many WTT stars dispersed over hundreds of square degrees around nearby molecular clouds (§ 4). Dispersed WTT stars are difficult to discriminate from ordinary main-sequence stars, and are now emerging from high-energy surveys that isolate stars with strong magnetic activity.

The possibility of a large unidentified T Tauri population has been discussed in a number of contexts. Herbig (1978) introduced the issue in a noted lecture on the missing "post–T Tauri" stars. From a modern perspective, his discussion blurs together the dispersed high proper motion stars we discuss here (such as FK Ser) with young ($\lesssim 1$ Myr old) WTT stars still residing in their parental molecular cloud (such as V410 Tau and HD 283447). Walter et al. (1988) found several isolated WTT stars, including a few "post–T Tauri" stars near the zero-age main sequence, from *Einstein Observatory* images of the Taurus-Auriga complex. As the *Einstein* spatial coverage was very incomplete, they inferred that the total number of WTT stars could reach 10 times the number of Taurus CTT stars. This conclusion was disputed by Hartmann et al. (1991, henceforth HJSK91) and Gomez et al. (1992), who conducted spectroscopic surveys of stars selected by proper motion within several degrees of Taurus clouds. They found little evidence for an older population and concluded that the total WTT population in Taurus does not exceed the CTT population. We suggest here that these latter studies failed to locate the dominant population because they examined only central regions of Taurus rather than extended regions around the entire cloud complex.

First, we show that the Hertzsprung-Russell (H-R) diagrams of T Tauri stars in the immediate vicinity of active cloud cores are very deficient in stars older than ~ 2 Myr (§ 2). We review explanations of this deficit and conclude that in some cases older stars have dispersed *a few* parsecs from the clouds and are thereby missing from existing samples (§§ 3 and 5.1). However, a large population of T Tauri stars may also be present *tens of parsecs* from active clouds (§ 4). We argue that most of these stars formed locally in small cloudlets far from the larger active clouds (§§ 5.3 and 6). Our analysis is applied to the Chamaeleon (§ 5) and Taurus-Auriga (§ 6) cloud complexes.

As this paper integrates results from a variety of subfields, readers uninterested in all details may follow the argument from the summaries at the end of each section. Our treatment focuses on low-mass stars ($M \leq 2\ M_\odot$) that have emerged from the protostar phase and are descending the Hayashi tracks; that is, CTT stars (or class 2 infrared sources; see Lada 1987) and WTT stars (or class 3 infrared sources).

2. WHERE ARE THE OLDER T TAURI STARS?

The censuses of pre–main-sequence stars in nearby star forming regions are based on photographic and CCD surveys for Hα and calcium emission-line stars, proper motion studies, *IRAS* source lists, infrared array images, VLA continuum maps, *Einstein* and *ROSAT* pointed images, and the *ROSAT* All-Sky Survey. As these studies cover different areas with different sensitivities, the resulting T Tauri samples are incomplete in confusing ways. Candidate T Tauri stars from these surveys must be studied spectroscopically and photometrically to confirm their pre–main-sequence status (often using the Li λ6707 line diagnostic), remove circumstellar infrared excesses, evaluate foreground reddening, and finally be placed on the H-R diagram. From the H-R diagram locations, masses, and ages are estimated by comparison with isochrones from stellar structure and evolution calculations.

Figure 1 shows histograms of stellar ages drawn from the literature on several well-studied star forming regions.[1] The histograms show the stars found in 0.5 Myr bins over the range $0 < t < 5$ Myr, and stars in 5 Myr bins over the range $5 < t < 50$ Myr. If the clouds have undergoing continuous star formation for 10^7 yr, and if the T Tauri samples are complete, we expect the number of stars per unit time to be constant. That is, the plots should show a flat distribution over the first 10 bins, and another flat distribution 10 times higher over at least some of the last 10 bins. Clearly this is not true for any of the samples.

Figure 1*a* shows T Tauri stars from the Taurus-Auriga cloud complex. The thick line histogram shows 116 of 234 known cloud members characterized by Kenyon & Hartmann (1995, hereafter KH95). Ages shown in the thick line histogram (and thick line histograms in other panels) are calculated using the isochrones of D'Antona & Mazzitelli (1994, hereafter DM94) computed with the convection model of Canuto & Mazzitelli (1990) and opacities of Alexander, Augason, & Johnson (1989). The thin line histogram in Figure 1*a* is a similar sample of 132 Taurus members compiled by Neuhäuser et al. (1995b). Both of these samples may be incomplete by at least a factor of 2, undersampling T Tauri stars with low X-ray luminosities and widely dispersed locations (Neuhäuser et al. 1995a). The low-mass stars are better represented in the Taurus cloud L1495E (Fig. 1*b*), which was subject to a deep *ROSAT* survey (Strom & Strom 1994). The thin line histogram shows the same stars with ages evaluated using the theoretical isochrones of Swenson et al. (1996, hereafter SFRI96).

Figure 1*c* shows the age distribution for 78 T Tauri stars lying within 1° of the molecular cloud cores in the Chamaeleon I cloud (Lawson, Feigelson, & Huenemoerder 1996, hereafter LFH96). They represent about 2/3 of the T Tauri stars known from deep Hα and *ROSAT* surveys and are thus likely to be reasonably complete sample of unembedded cloud members. Schwartz (1991) lists an additional 20 likely embedded sources for which ages have not been estimated. Ages are based on DM94 (thick histogram) and SFRI96 (thin) isochrones. Figure 1*d* shows the T Tauri age distribution from portions of the Upper Sco OB association based on *Einstein Observatory* images (Walter et al. 1994). Here we show ages based on DM94 calculations using Alexander et al. 1989 (*thick*) and Kurucz 1991 (*thin*) opacities.

Quite clearly, none of the age distributions in Figure 1 agrees even approximately with assumption of a constant star formation rate over timescales greater than ~ 2 Myr, although the star formation rate within this time appears approximately constant. The effect is very large. In Chamaeleon I, the number of stars 5–50 Myr old is depleted by a factor of 20 (6) using DM94 (SFRI96) isochrones (LFH96). The other clouds have even smaller fractions of older stars, and thus even greater deficiencies of older T Tauri stars. Note that, in the Taurus-Auriga sample, the few stars ≥ 20 Myr old may be interlopers from the older Cas-Tau association rather than true members of the Taurus-Auriga cloud complex (HJSK91; Walter & Boyd 1991).

The number of missing older T Tauri stars can be estimated from Figure 1 if one assumes that the current star formation rate is a reasonable estimate of the average star formation rate in the past. The sample studied by KH95 corresponds to a rate of about 50 stars Myr^{-1} in Taurus for the past $t \leq 1.5$ Myr, assuming DM94 isochrones and Alexander opacities. We multiply this value by 2 to account for the known but poorly characterized cloud members to

[1] We omit consideration of the Ophiuchus T Tauri population because much of it is deeply embedded and only a small fraction has been placed on the H-R diagram (Greene & Meyer 1995).

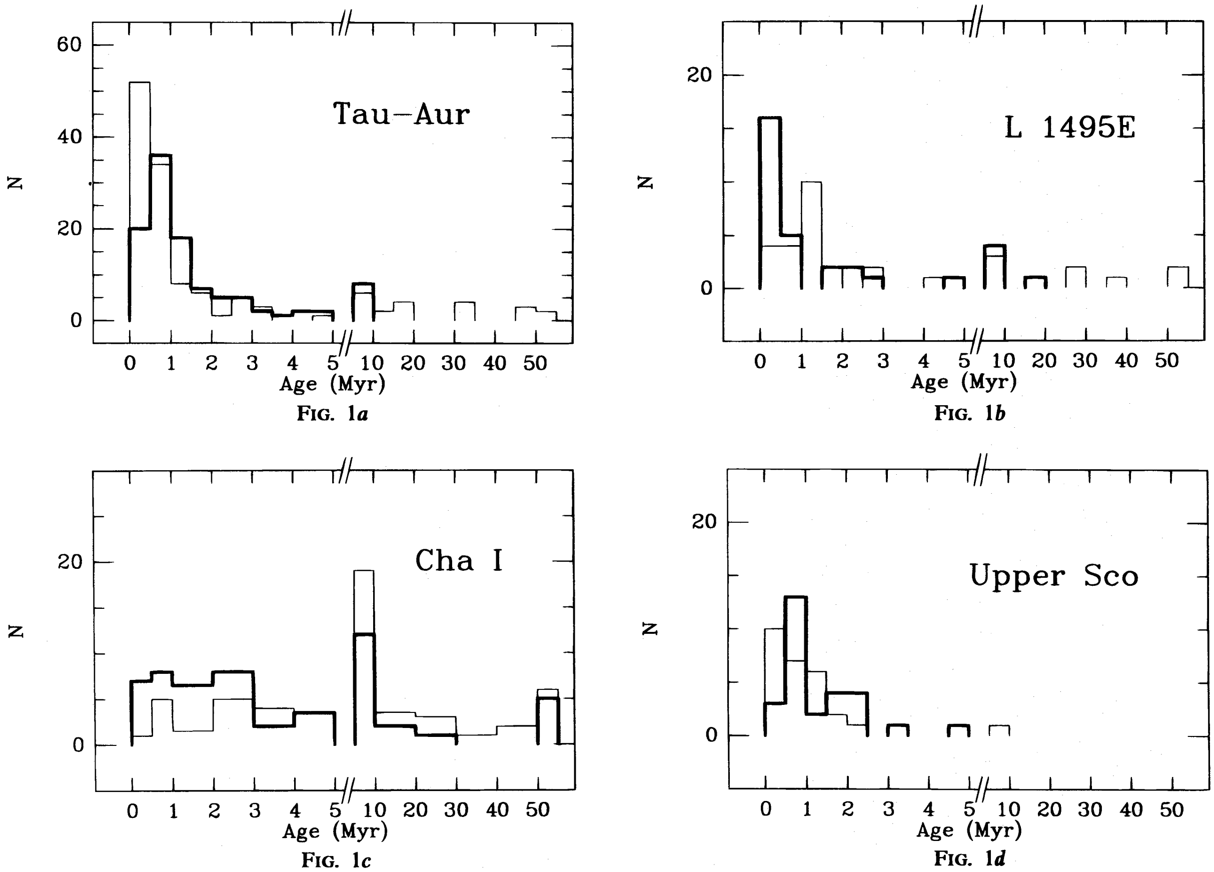

FIG. 1.—Distribution of star ages from recently studied samples of T Tauri stars in (*a*) the Taurus-Auriga complex; (*b*) L 1495E cloud in Taurus; (*c*) Chamaeleon I cloud; and (*d*) Upper Scorpius association. Thick line histograms are obtained from D'Antona & Mazzitelli isochrones using Alexander et al. opacities. See text regarding the thin line histograms.

arrive at a total star formation rate $\simeq 100$ stars Myr^{-1}. We thus expect $\simeq 1000$ Taurus T Tauri stars for each 10 Myr, far greater than the known population of $\simeq 200$ stars. In Chamaeleon I, the current star formation rate from the well-studied sample is 14 stars Myr^{-1} (Fig. 1*c*). We multiply this by 1.5–2.0 for known but poorly characterized stars to obtain about 25 stars Myr^{-1}, or $\simeq 250$ stars for each 10 Myr.

Thus, *if* star formation has been continuous at the present rate for at least 10 Myr, then current T Tauri samples represent only a small fraction of the true population, and we predict that hundreds or thousands of T Tauri stars older than >2 Myr should exist. Locating this enormous population of older T Tauri stars is challenging because most will be WTT stars. Younger, $t < 2$ Myr stars are approximately equally divided between CTT and WTT stars, and nearly all stars older than ~ 10 Myr are WTT.[2] In principle, WTT stars can be distinguished from ordinary late-type stars by properties including: lithium absorption line at 6707 Å with equivalent width around 0.1–0.5 Å; Hα filled in or in emission up to 10 Å equivalent width; rotationally modulated cool star spots covering perhaps 5%–40% of the surface; enhanced variable X-ray emission with $L_X \sim 10^{28}$–10^{31} ergs s^{-1}; possible radio continuum emission up to 10^{18} ergs s^{-1} Hz^{-1}; and kinematics consistent with birth in the associated molecular cloud (see review by Feigelson et al. 1991). However, many of these properties decay with stellar age in uncertain manners, and, in practice, it proves quite difficult to survey large areas of the low Galactic latitude sky for stars with these rather subtle properties.

In summary, the mystery of the missing older T Tauri stars is more dramatic today than when Herbig (1978) first raised the issue. Despite the addition of infrared, X-ray, proper motion, and other surveys to the traditional Hα emission surveys, the Hertzsprung-Russell diagrams of stellar associations around nearby active star forming clouds are still very deficient in stars older than 2–5 Myr.

3. UNSUCCESSFUL EXPLANATIONS OF THE PUZZLE

3.1. *Star Formation Is Short-lived or Episodic*

If the samples illustrated in Figure 1 include most of the T Tauri stars produced by the associated molecular cloud, and the calculated stellar ages are basically correct, then short-lived bursts of star formation are required. However, this explanation encounters two major problems. First, it does not explain why some older (5–30 Myr) stars have in fact been found in each of the studied clouds (Fig. 1). Some

[2] Contrary to earlier findings (Strom et al. 1989), the latest H-R diagrams show no critical age or bolometric luminosity dividing CTT from WTT stars (KH95; LFH96; Strom 1995). The CTT-WTT transition, due to the loss of the circumstellar disk, can occur at any age between 10^5–10^7 yr. This wide range of disk ages also explains the diversity of WTT and open cluster stellar rotational velocities (Bouvier 1994; Cameron, Campbell, & Quaintrell 1995).

older stars were even present in the original CTT sample of Cohen & Kuhi (1979). Multiple starbursts would be required, but the age distributions in Figure 1 do not show multiple peaks. Second, if clouds actively form stars for brief periods, which are interspersed by longer periods of quiescence, it is difficult to understand why virtually all nearby molecular clouds are now active. The ratio of active to inactive clouds should be 1:5 to 1:25, if molecular clouds typically endure for 10–50 Myr as indicated by theoretical calculations and the range of stellar ages in OB associations (Falgarone & Puget 1986). Yet, among the $\geq 10^2\ M_\odot$ molecular clouds within $\simeq$200 pc of the Sun (Dame et al. 1987), the Taurus-Auriga complex, Corona Australis cloud, Chamaeleon I and II clouds, Lupus clouds, upper Scorpius region, and Ophiuchus complex are all populated with many young T Tauri stars. Only the Coalsack (Nyman 1991), Chamaeleon III cloud (Vilas-Boas, Myers, & Fuller 1994), and possibly the Aquila Rift clouds appear to be inactive.

HJSK91 discuss this problem within a single cloud complex: it appears that "star formation in the [Taurus-Auriga] complex has been synchronized to a remarkable degree." The data in Figure 1 require synchrony among clouds in all directions around the Sun, which, while not physically impossible, is certainly implausible given their diverse structures and environments. We are persuaded by these arguments that neither a constant star formation rate or a simple starburst model can explain the age distributions in Figure 1 without some additional complications. Either the inferred ages are incorrect (§ 3.2) or the existing samples are very incomplete for older T Tauri stars (§§ 3.3–3.4).

3.2. *Theoretical Isochrones Underestimate True Stellar Ages*

As illustrated by the thin and thick line histograms in Figures 1*b*–1*d*, choice of stellar structure model can considerably affect inferred ages along the Hayashi tracks. Several research groups have examined this issue (Walter et al. 1994; Strom & Strom 1994; KH95; LFH96). Ages from the models of SFRI96 can be several times older than from models of DM94. Using the latter models, ages are older when mixing length rather than the Canuto & Mazzitelli (1990) convection model is used, and when Kurucz (1991) rather than Alexander et al. (1989) opacities are used. But even the most optimistic models only moderate the deficiency of older T Tauri stars somewhat: the age when star formation appears to end can be pushed from ~2 Myr to perhaps 5 Myr.

A related possible error is discussed and favored by HJSK91. They suggest that standard Hayashi track models systematically underestimate T Tauri ages because accretion of disk material moves stars toward evolutionary tracks with higher masses. However, this can only affect the inferred ages of CTT stars where disk-star interactions are important. When a star enters the WTT phase when the disk decouples and largely disappears, the accretion luminosity should be negligible (although the inferred age may be somewhat altered due to the accretion of new material). Furthermore, we note that, when standard isochronal ages are considered, WTT and CTT populations have very similar age distributions (KH95; LFH96). If CTT ages were increased to account for accretion luminosity but WTT ages are relatively unaffected, then the data would implausibly require that stars evolve from the WTT phase into the CTT phase rather than vice versa.

3.3. *Samples Are Flux-limited*

Incompleteness due to flux limits in T Tauri surveys may seem an attractive explanation for the deficiency of older stars, as stellar bolometric luminosities drop as the stars evolve down the convective tracks, and X-ray luminosities fall with the bolometric luminosity (Feigelson et al. 1993; LFH96). However, we find that the surveys shown in Figure 1 are generally sensitive down to ages around 10–30 Myr. Photographic objective prism surveys for Hα emission stars for CTT stars are generally complete down to $V\simeq 15.5$ (Gomez et al. 1993), and in some cases attain $V\simeq 18$ (Briceño et al. 1993). CCD prism or grism surveys reach $R = 17.5$–19 and are sensitive to Hα equivalent widths down to 3 Å for the brighter stars (Hartigan 1993; Preibisch, Zinnecker, & Herbig 1996), but are confined to smaller survey regions. Deep *ROSAT* exposures are generally more effective than emission-line or infrared surveys in locating older T Tauri stars with ages up to 20–100 Myr (Strom & Strom 1994; Alcalá-Estrada 1994; LFH96). Depending on the absorption, stellar mass and choice of theoretical isochrones, a completeness limit of $V = 15.5$ corresponds to stellar ages of 5–50 Myr.

Older T Tauri stars may be missed because they lie in surveyed regions but lack any Hα, infrared, or X-ray excesses. Available evidence suggests this is not very large population. The X-ray luminosity function of T Tauri stars is perhaps somewhat elevated, but otherwise similar to, the luminosity function of young clusters like the Pleiades (Feigelson et al. 1993; Damiani et al. 1995). It seems doubtful that the magnetic activity responsible for the X-ray emission falls to undetectable levels in many stars around 5–30 Myr, only to reemerge at $\gtrsim$ 50 Myr. Proper motion surveys of $V \lesssim 16$–17 stars in the Taurus region reveal a modest population of stars comoving with the clouds (Jones & Herbig 1979; HJSK91; Gomez et al. 1992), but not nearly sufficient to account for the drop-off in Figure 1 if constant star formation is assumed. Nonetheless, searches for older T Tauri stars in a fashion unbiased with respect to circumstellar disks, magnetic activity, or dynamics should be undertaken. This can be achieved with current technology. Wide-field multifiber spectrographs, like the 2DF instrument for the Anglo-Australian Telescope (Taylor 1995), can efficiently survey all $V \lesssim 16$ stars around nearby clouds for the Li λ6707 T Tauri spectral signature.

3.4. *Summary*

While each of these three explanations for the paucity of older T Tauri stars may initially seem plausible, none withstand careful analysis. Short-lived star formation is contradicted by the presence of some older stars near the clouds and by the absence of many inactive molecular clouds in the solar vicinity. Episodic star formation should have produced multiple bumps in the age distribution histograms of Figure 1. Although theoretical isochrones are sensitive to the details of stellar interior models, this uncertainty is not sufficiently large to solve the essential age distribution problem. Accretion luminosity is also unlikely to solve the problem, as it does not affect WTT stars. Flux limits of current T Tauri surveys may be responsible for poor sampling of stars older than ~20 Myr but does not appear to account for the sharp decline in population in the 2–20 Myr age range.

We are thus compelled to investigate the hypothesis that the older T Tauri stars do exist in large numbers, but lie outside of well-surveyed regions. T Tauri stars should inherit velocity dispersions of 1 km s^{-1} or greater (§ 5), so that older T Tauri stars are expected to travel many degrees from their parent cloud and thereby fall outside well-surveyed areas.

4. EVIDENCE FOR SCATTERED T TAURI STARS

4.1. *Moderately Scattered WTT Stars from ROSAT*

The *ROSAT* All-Sky Survey (RASS) has produced a list of more than 60,000 soft X-ray sources across the celestial sphere, of which perhaps ~1% are likely to be T Tauri stars. Results for the Taurus-Auriga and Chamaeleon complexes have been reported. From the RASS sources over a ≃160 square degree region around the Chamaeleon I–II clouds (equivalent to a projected sphere with radius 17 pc), Alcalá et al. (1995) find 77 new lithium-rich WTT stars with $B < 17$ and X-ray luminosities[3] above 8×10^{29} ergs s^{-1}. These are shown in Figure 2*a* along with T Tauri stars found close to the active Cha I and II clouds. In Taurus-Auriga, Neuhäuser et al. (1995a) find 64 new WTT stars brighter than $V = 16$ in the central ≃250 square degrees, including a few visual binaries, with X-ray luminosities[3] above $\sim 2 \times 10^{29}$ ergs s^{-1}. Considering the total number of RASS sources in a larger ≃1000 square degree region, and making a correction for the undetected WTT stars, Neuhäuser et al. extrapolate that 644 or more WTT stars may be present in the entire complex with $V < 16$. Neuhäuser et al. (1995c) further report 15 new WTT stars in a ~600 square degree region located 10°–30° south of the Taurus-Auriga complex. Although some may be members of the Orion or Cas-Tau associations, seven of the 15 are kinematically consistent with Taurus membership.

These new dispersed WTT samples are clearly truncated by the RASS flux limits. Neuhäuser et al. (1995a) multiplies their sample to a factor of 1.64, the ratio of total to detected stars among optically selected WTT stars in Taurus. We find this incompleteness correction factor is roughly compatible with the two deepest soft X-ray luminosity functions now available, sensitive to $L_X \simeq 3 \times 10^{28}$ ergs s^{-1} (Fig. 3). Unfortunately, these WTT X-ray luminosity functions are rather discrepant for several possible reasons.[4] Using the distributions shown here, correction factors of 1.6 for the Taurus-Auriga RASS survey and 2–3 for the Chamaeleon RASS survey are appropriate to compensate for the WTT stars having L_X between 3×10^{28} ergs s^{-1} and the RASS limits given above. The total WTT population should be even larger, as there is no reason to believe the WTT X-ray luminosity function stops at the instrumental limit 3×10^{28} ergs s^{-1}, especially for older T Tauri stars since X-ray luminosity may decay somewhat with age along the Hayashi tracks (Damiani et al. 1995).

The samples illustrated in Figure 1 should thus grow by *at least* $64 \times 1.6 \simeq 100$ WTT stars dispersed over the inner 250 square degrees of the Taurus-Auriga complex, and 77×2–$3 \simeq 200$ new WTT stars in 160 square degrees surrounding the Chamaeleon clouds. The WTT populations inferred from the RASS findings may thus represent a significant fraction of the missing older T Tauri population inferred to exist in §§ 2–3.

4.2. *Ages of the RASS WTT Stars*

The discussion above rests on the assumption that the RASS-discovered lithium-rich[5] stars around the Taurus-Auriga and Chamaeleon complexes are indeed pre–main-sequence stars, which is not necessarily correct. There is no obvious relationship between the dispersed WTT stars and molecular cloud material. Figure 4 shows the RASS Chamaeleon stars found by Alcalá et al. (1995) superposed on the 100 μm *IRAS* map. The dust distribution in the region is complex and probably consists of several components: feathery cirrus in the solar neighborhood; the Cha I, Cha II, and FS195[6] molecular clouds at $d \simeq 140$–200; and more distant galactic plane emission to the northeast. The RASS stars appear uncorrelated with dust enhancements and do not appear to avoid regions where dust emission is low. The cluster of four young WTT stars around 8^h40^m, 78°, for example, are superposed on a large cavity in the dust distribution.

The RASS-discovered stars are lithium-rich late-type stars with high L_X/L_{bol} ratios (i.e., high magnetic activity). If they are not physically associated with currently active star formation regions, the most plausible alternative is membership in the population of foreground lithium-rich post–T Tauri stars, as suggested by Jeffries (1995) for EUV stars (§ 4.3). The difficulty is that it is unclear whether photospheric lithium abundances in excess of those seen in Pleiads necessarily mean that the RASS stars are pre–main sequence. Photospheric lithium abundance is strongly dependent on stellar mass, internal convection, and the history of angular momentum along the Hayashi tracks, and can differ even among coeval stars of the same mass (Strom 1994). Like the very widely dispersed lithium-rich stars discussed in §§ 4.3–4.4, the RASS stars may select the most rapidly rotating stars with the highest X-ray emission and least lithium depletion from a large underlying popu-

[3] The Chamaeleon sensitivity limit is based on the faintest RASS sources found by Alcalá-Estrada (1994) and Alcalá et al. (1995), 35 counts ks^{-1}, and the conversion of 1 counts ks^{-2} = 2.4×10^{28} ergs s^{-1}, which assumes a 1 keV thermal spectrum, foreground absorption $N_H \leq 1 \times 10^{21}$ cm^{-1} and a distance of 140 pc. The Taurus sensitivity limit is based on a limit of 8 counts ks^{-1} exposure, estimated from the upper limits of known Taurus members (Neuhäuser et al. 1995b). Sensitivities at specific locations in Taurus can range considerably around this value.

[4] The thin line in Fig. 3 shows the distribution of 11 WTT stars (all detected) in the L1495E cloud within the Taurus-Auriga complex (Strom & Strom 1994). The thick line shows the maximum-likelihood Kaplan-Meier distribution of 66 WTT stars (40 detections, 26 upper limits) in the Chamaeleon I cloud (Appendix of LFH96), calculated using the ASURV software package (LaValley, Isobe, & Feigelson 1992). The Chamaeleon luminosities underestimate true values for embedded sources, as they are based on a simple $A_V = 1$ spectral model. The assumed distance to the Chamaeleon I cloud, 140 pc, may also be too low. The L1495E distribution may be elevated by an excess of very young magnetically active WTT stars, including V410 Tau and HD 283572 with $L_X \approx 10^{31}$ ergs s^{-1} at the tip of the Taurus-Auriga luminosity function.

[5] It is possible that the Li λ6707 absorption in some of the Alcalá et al. (1995) stars has been overestimated, as the spectra were obtained at low resolution where line blending can be important (see HJSK91).

[6] The small dense cloud 2° southeast of the Chamaeleon I cloud is cataloged as No. 195 by Feitzinger & Stüwe (1984) and DC 300.2-16.9 by Hartley et al. (1986). The cloud has produced a single massive active WTT star, T Cha, which should be accompanied by a number of lower mass T Tauri stars.

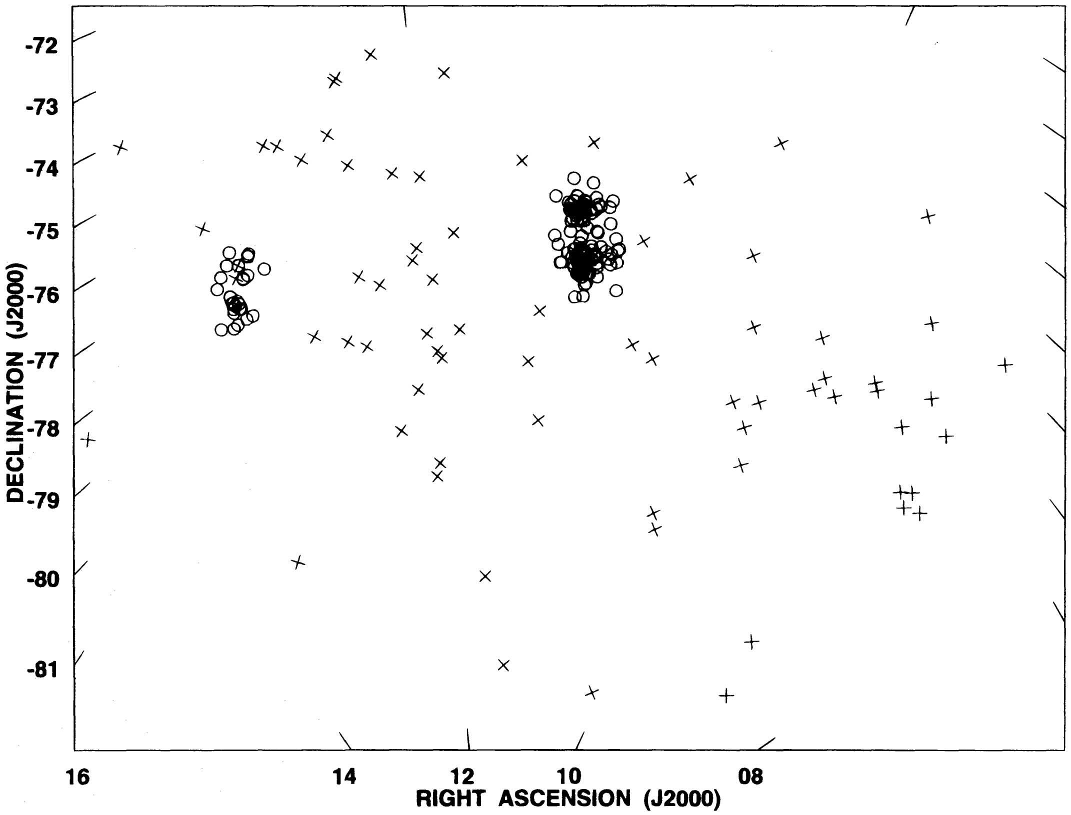

FIG. 2*a*

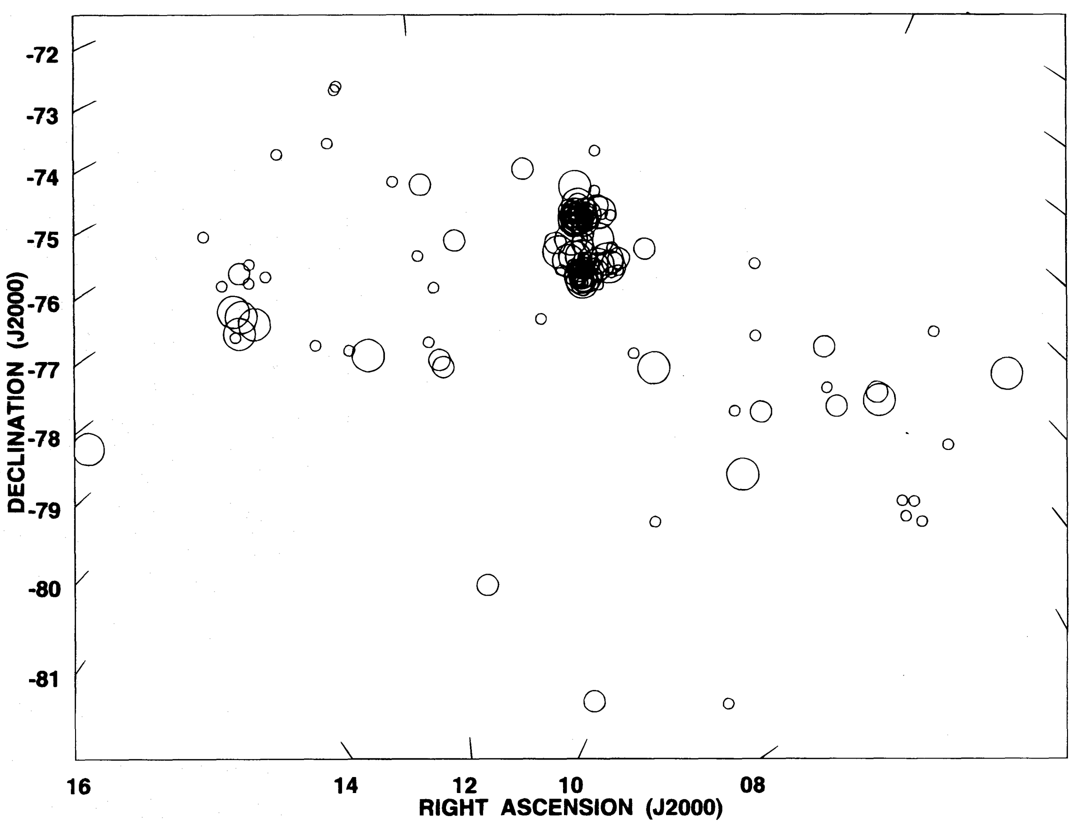

FIG. 2*b*

FIG. 2.—Spatial distribution of T Tauri stars associated with the Chamaeleon clouds. (*a*) Stars close to the clouds found in Hα and deep X-ray surveys (*circles*) and the scattered T Tauri stars found in the *ROSAT* All-Sky Survey (*crosses*). (*b*) Ages for stars located on the H-R diagram. $0 < t \leq 2$ Myr (*small filled circles*); $2 < t \leq 10$ Myr (*medium circles*); $t > 10$ Myr (*large circles*). Panel (*c*) shows an expanded view of the Chamaeleon I cloud.

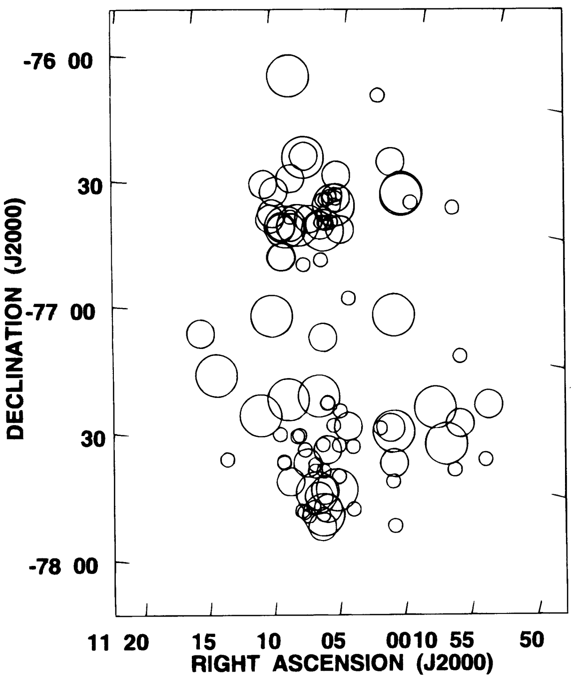

FIG. 2c

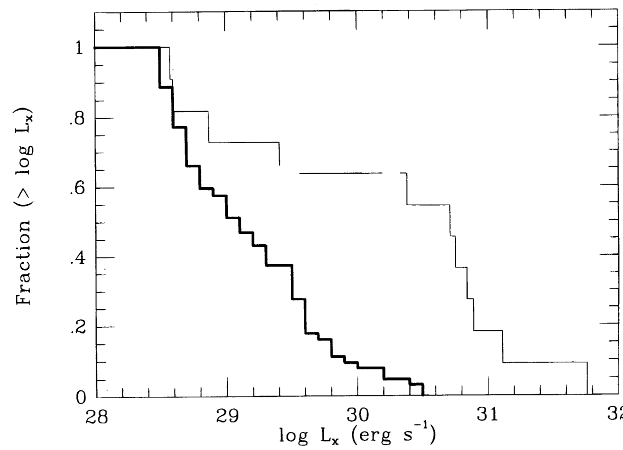

FIG. 3.—Integrated soft X-ray luminosity functions for weak-lined T Tauri stars in the Chamaeleon I cloud (*thick line*) and L1495E cloud (*thin line*). See footnote for details.

lation of post–T Tauri stars. This population could be the Local Association, Gould's Belt or the Cas-Tau association with ages between 40 and 70 Myr (Eggen 1983; Elmegreen 1993a).

While this interpretation cannot be excluded, it must confront some difficulties. First, the surface density of RASS stars in Taurus-Auriga and Chamaeleon is at least 0.4 stars deg^{-2} and 1.2 stars deg^{-2}, respectively (after taking the survey sensitivity into account; § 4.1). The excess of widely scattered high-latitude lithium-rich yellow stars is only 0.1 stars deg^{-2} (Sciortino, Favata, & Micela 1995).[7] Second, although the RASS stars around the Taurus-Auriga complex could be associated with the larger post–T Tauri

[7] The average *Einstein* EMSS field and average RASS exposure have similar sensitivity limits around 5×10^{-13} ergs s^{-1} cm^{-2} (Gioia et al. 1990; Voges 1993), permitting a rough comparison of these surface densities.

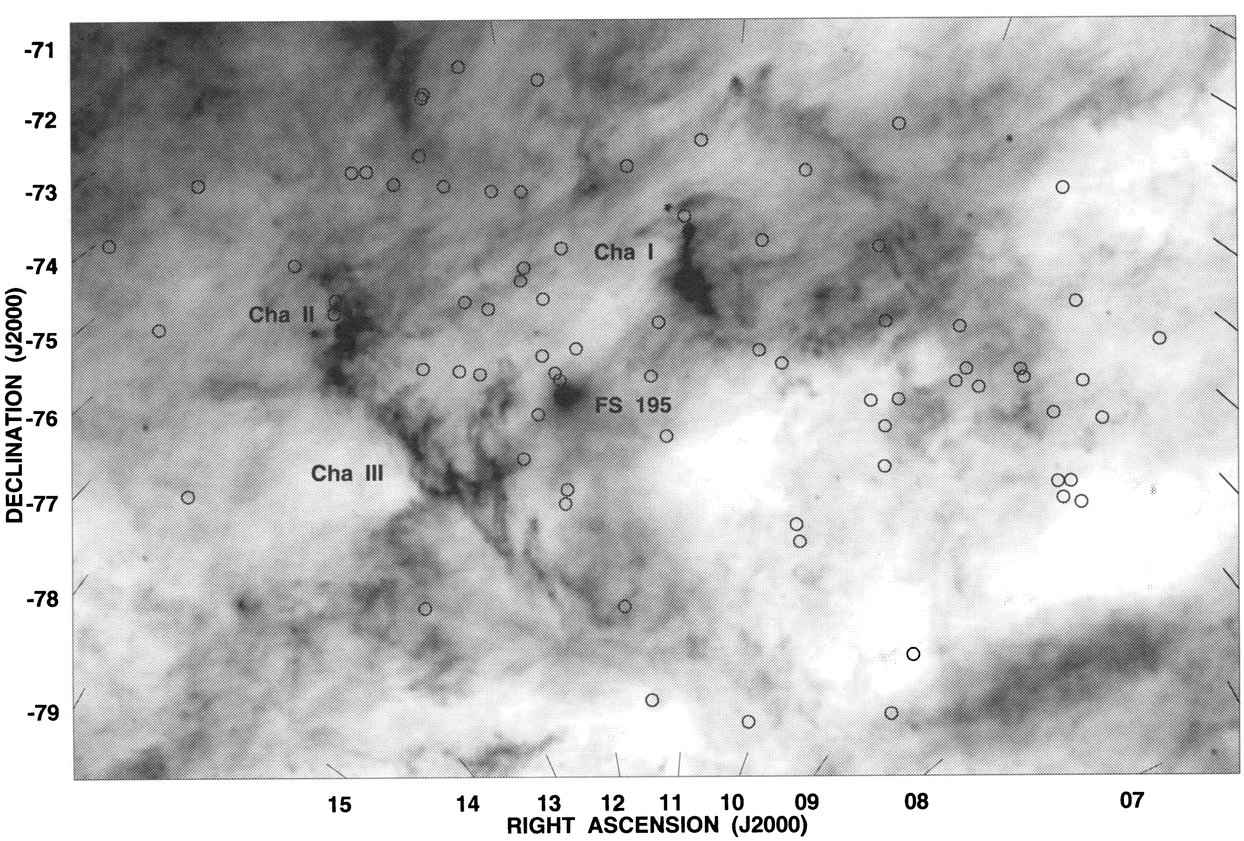

FIG. 4.—*ROSAT* All-Sky Survey stars superposed on the *IRAS* 100 μ map. The gray scale is linear between 5 and 25 MJy sr^{-1}.

Cas-Tau association, there is no simple analogous explanation for the Chamaeleon RASS stars. The Chamaeleon region lies 15°, or 2–3 scale heights, south of Gould's Belt (Stothers & Frogel 1974) and is far from known post–T Tauri concentrations like young open clusters. If the Chamaeleon RASS stars are post–T Tauri stars at a random location in the Galactic plane, then the full post–T Tauri population should have many thousands of members spread over enormous regions of the sky, constituting a significant fraction of the $\simeq 25,000$ stellar sources in the RASS. This possibility can be tested by stellar identification of RASS sources at random locations around the Galactic plane.

4.3. *Very Widely Scattered T Tauri Stars from Other Surveys*

While the effort to search the entire RASS for T Tauri stars across the entire sky is enormously difficult, other smaller surveys isolating magnetically active or emission-line stars have uncovered a population of widely dispersed nearby very young late-type stars. A number of stars with infrared-excesses and high lithium abundances found among *IRAS* sources (de la Reza et al. 1989; Gregorio-Hetem et al. 1992; Torres et al. 1995). Some appear near the outer regions of star forming complexes, while others do not. The most dramatic example of the latter type is a loose cluster of CTT and WTT stars about 10° in extent near $(l, b) = (278°, 25°)$. It includes TW Hya, CoD − 29°8887, Hen 600, HD 98800, CoD − 33°7795, and presumably fainter members yet to be identified.

A "yellow star excess" is found among stellar X-rays sources in the *Einstein* Extended Medium Sensitivity Survey, which covers about 2% of the sky at high Galactic latitudes (Favata et al. 1993; Sciortino, Favata, & Micela 1995). Several of them with $V < 12$ have surface lithium abundances comparable to T Tauri stars (Favata et al. 1995). While two are near the Ophiuchi cloud complex, others are scattered around the sky. Similar scattered magnetically active lithium-rich stars have emerged from serendipitous sources in *EXOSAT* X-ray images (Tagliaferri et al. 1994), the *Einstein* Slew Survey (Favata et al. 1995), and the *ROSAT* EUV Wide Field Camera All-Sky Survey (Jeffries & Jewell 1993; Mulliss & Bopp 1994; Jeffries 1995). Others might be present among the poorly studied *Einstein* Galactic Plane Survey counterparts (Hertz & Grindlay 1984). A partial list of these high-lithium young stars appears in Jeffries (1995).

Various optical studies have uncovered a handful of very young rapidly rotating spotted late-type stars (BY Dra type) with strong lithium absorption, including AB Dor, LQ Hya, FK Ser, HD 17925, HD 98800 and HD 155555 (Herbig 1973; Cayrel de Strobel & Cayrel 1989; Pasquini et al. 1991; Gregorio-Hetem et al. 1992; Strassmeier et al. 1993; Favata et al. 1995). Finally, several late-type "post–T Tauri" stars have been identified as wide-binary companions to early-type stars (Lindroos 1986; Martín, Maguzzù, & Rebolo 1992; Pallavicini, Pasquini, & Randich 1992). Several T Tauri stars are also associated with known high-latitude molecular clouds such as L1642 = MBM 20 (Magnani et al. 1995) and BZ Sgr in MBM 159.

The discovery of so many very young stars far from known star forming regions was largely unexpected. But it is often not clear whether they are pre–main-sequence or young ZAMS ($t \sim 50$–70 Myr) stars. As with the RASS stars (§ 4.2), until accurate parallax measurements are available, this determination often depends on the interpretation of Li λ6707 lines stronger than seen in the Pleiades. A few stars for which accurate distances are available lie slightly above the ZAMS with estimated ages around 30–40 Myr (AB Dor, HD 33802B, HD 113703B, and HD 129791B; Innis, Thompson, & Coates 1986, Lindroos 1986). Since most of the surveys producing the young lithium-rich stars are flux-limited in the original X-ray/UV/IR studies and magnitude-limited in follow-up spectroscopic studies, it is likely that many more fainter and more distant stars of these types are present.

4.4. *Spatial Distribution and Kinematics of Scattered T Tauri Stars*

The spatial distribution of the proposed new WTT stars found from the RASS survey (§ 4.1) is remarkable for its uniformity. Figure 2*a* shows the location of T Tauri stars seen in the RASS (Alcalá et al. 1995), shown as crosses, compared to those discovered in infrared, optical, and pointed *ROSAT* observations, shown as circles.[8] The latter are dense clusters $\simeq 2$ pc in extent around three molecular cores in Chamaeleon I and one core in Chamaeleon II. The RASS stars, on the other hand, exhibit no concentration around the two cloud cores at all.

New RASS WTT stars in Taurus-Auriga similarly do not cluster around the well-known CTT stars (Neuhäuser et al. 1995c). This may explain the paucity of WTT stars in the studies of HJSK91 and Gomez et al. (1992) (see § 1). They searched 21.6 square degrees within the Taurus-Auriga complex for WTT stars with $V < 15.5$ and proper motions within a range of $\simeq 2''$ century^{-1} (equivalent to ± 13 km s^{-1} in the plane of the sky). They found nine new WTT stars, and concluded that the WTT population does not significantly exceed the CTT population in the complex. But if most of the WTT stars are evenly dispersed over hundreds of square degrees, as suggested by the RASS samples, only a few are expected to appear in the smaller regions observed by them.

Little information has been published on the kinematics of dispersed RASS WTT stars, but an interesting result has emerged concerning the very widely dispersed stars from the *ROSAT* EUV Wide Field Camera survey. Jeffries (1995) shows that the kinematics of these stars is largely consistent with 50–80 Myr old Local Association (also known as the Pleiades Supercluster) described by Eggen (1983). This supports their classification as young ZAMS rather than T Tauri stars, but does not resolve the question of their place of origin. One possibility is that some very widely dispersed

[8] The stars plotted around Chamaeleon I in Fig. 2 include 117 optically visible cloud members listed by LFH96, plus 20 candidate infrared members not associated with visible stars listed by Schwartz (1991). The Chamaeleon II stars include 25 optically visible members listed by Schwartz & Hartigan (1993), plus four *IRAS* candidate members that are detected at 60 μm and are not associated with bright stars or HH 54. Ages are shown in Figs. 2*b* and 2*c* for stars located on H-R diagrams with 78 visible stars in Cha I from LFH96 and five in Cha II from Gauvin & Strom (1992). The infrared sources from Schwartz are included, assuming they are all younger than 2 Myr. The dispersed stars consist of 48 RASS stars having ages estimated by Alcalá-Estrada (1994) based on DM94 isochrones.

stars were ejected at high velocities from star forming clouds.[9]

4.5. *Summary*

The idea that most older T Tauri stars have dispersed from the vicinity of currently active molecular clouds receives considerable support from the large numbers of dispersed lithium-rich magnetically active late-type stars recently reported, most prominently in the *ROSAT* All-Sky Survey studies of the environs of the Taurus-Auriga and Chamaeleon clouds. The high surface density of these stars suggests they are physically associated with the star forming regions rather than superpositions of field ZAMS stars. In any case, the RASS samples probably represent only the brighter end of the underlying population of dispersed lithium-rich young stars and many hundreds of similar stars remain to be discovered. Their spatial distribution over hundreds of square degrees, 10–50 pc from active cloud cores, may explain why HJSK91 and Gomez et al. (1992) found only a few new WTT stars in their systematic survey of a small portion of the Taurus clouds. Based on numbers alone, it appears that the puzzle of the missing older T Tauri stars would be solved.

However, we have encountered several disturbing characteristics of the dispersed populations. As noted by Montmerle & Casanova (1996), it is unclear why so many of the stars tens of parsecs away from active star forming regions (or any obvious concentration of molecular material) are less than 2 Myr old, coeval with CTT and WTT stars clustered around active cloud cores (Figs. 2*b* and 4). If they drifted from currently active clouds, the youngest members should be concentrated close to active clouds. The origin of the TW Hya group of T Tauri stars, tens of degrees from known star forming clouds, is also not clear. While it is possible that these problems are illusory, arising from incompleteness and inadequate study of existing samples, we suggest that they point to fundamental properties of the star formation process. We investigate in the next section various simple models that might account for these findings.

5. MODELING THE CHAMAELEON CLOUD POPULATION

Although it still suffers significant incompleteness, the T Tauri population associated with the Chamaeleon clouds (Fig. 2) is perhaps the best available for comparison with T Tauri dispersal models. Deep Hα and X-ray surveys have probably found most of the unembedded members in the immediate vicinity of the Chamaeleon I cloud, the RASS survey has located perhaps one-third of the widely dispersed population, and the region appears to have a relatively simple distribution of molecular material dominated by two active clouds, Chamaeleon I and II. We construct a series of models of this population based on different views of T Tauri kinematics. It is generally assumed that stars inherit the relatively low internal velocity dispersions of their molecular cores, which, for low-mass star formation regions, are typically 0.5 km s^{-1} along the radial direction (e.g., Fuller & Myers 1992). If stellar velocity vectors are randomly oriented, this corresponds to a three-dimensional velocity dispersion around 1 km s^{-1}. At a distance of 140 pc, a star traveling 1 km s^{-1} in the plane of the sky will move 4°.2 in 10 Myr. Thus, we can expect that T Tauri stars will undergo angular dispersal of many degrees as they evolve down the Hayashi track.

5.1. *Dispersal with Thermal Velocity Dispersion*

The simplest model for a star formation cloud is that stars form at a single location from gas with an isotropic Gaussian velocity dispersion due to thermal motions in the parent cloud core. Kinematical studies giving mean and standard deviations of T Tauri star proper motions or radial velocities (e.g., Jones & Herbig 1979; Hartmann et al. 1986; HJSK91), in addition to studies of their spatial distributions, can be interpreted within this model. Figure 5 shows the results of a simulation designed to reproduce the spatial (Fig. 2*c*) and age (Fig. 1*c*) distributions of stars within 1° of the Chamaeleon I cloud cores. The model has 500 stars produced at random times over 20 Myr, corresponding to a constant star formation rate of 25 stars Myr^{-1}. The stars emanate from a hypothetical infinitesimal formation site 140 pc from the Sun at $(\alpha, \delta) = (12^h30^m, 10°)$ with a Gaussian three-dimensional velocity dispersion $\Delta v = 1.0$ km s^{-1}. The ejection is assumed to be isotropic and ballistic, with no correction for the escape velocity from the cloud. Table 1 gives statistical properties (means and sample standard deviations) of the resulting sample in five annuli around this location. Figures 5–7 illustrate various properties of the model.

This model reproduces the stellar population within 1° (1.2 pc projected radius) of the Chamaeleon I cloud reasonably well. The spatial distribution in Figure 5*a* is similar to that seen in Figure 2*c* (imagining that the only one active core was present). The age distribution in Figure 6 is quite close to the observed distribution in Figure 1*c* for $t \leq 5$ Myr assuming DM94 isochrones,[10] but the model predicts 3–4 times the observed number of $5 < t < 20$ Myr stars. This implies either that the star formation rate has in fact accelerated in the recent past (although less dramatically than the factor of 20 naively inferred from the observations, § 2), or that the known population misses most of the older stars even in within 1° of the cloud cores.

The thermal dispersion model gives clear predictions for the kinematics, as well as spatial and age distributions, of stars produced at a single site. Figure 7 shows the expectations for a complete survey of T Tauri stars within 20′ (0.8 pc) radius. Surprisingly, two-thirds of the stars in this innermost region are older than 5 Myr. These are stars ejected along the line of sight or with very low radial velocities during the 20 Myr star formation period. The proper motion and radial velocity distributions thus peak sharply around zero. In real surveys, the samples of older WTT stars will probably be incomplete for stars ejected away

[9] Cayrel de Strobel & Cayrel (1989) give a detailed argument for this in one case, HD 17925, a well-studied sixth magnitude K1 V star with high lithium abundance and magnetic activity lying only 8 pc from the Sun. From its three-dimensional location and velocity vector, they find that its location 10 Myr ago coincided with the past location of the Sco-Cen association. Its current position implies it was ejected from the star forming region with a velocity around 15 km s^{-1}. This model, however, does not explain why the star lies on the ZAMS rather than around the pre–main-sequence 10 Myr isochrone.

[10] Recall that Fig. 1*c* is missing ∼20 suspected embedded stars and 37 visible but poorly studied cloud members. These stars are included in Fig. 2, and the model population is normalized to include these stars. The observed sample is also deficient in stars south of $\delta = -78°$ due to survey boundaries.

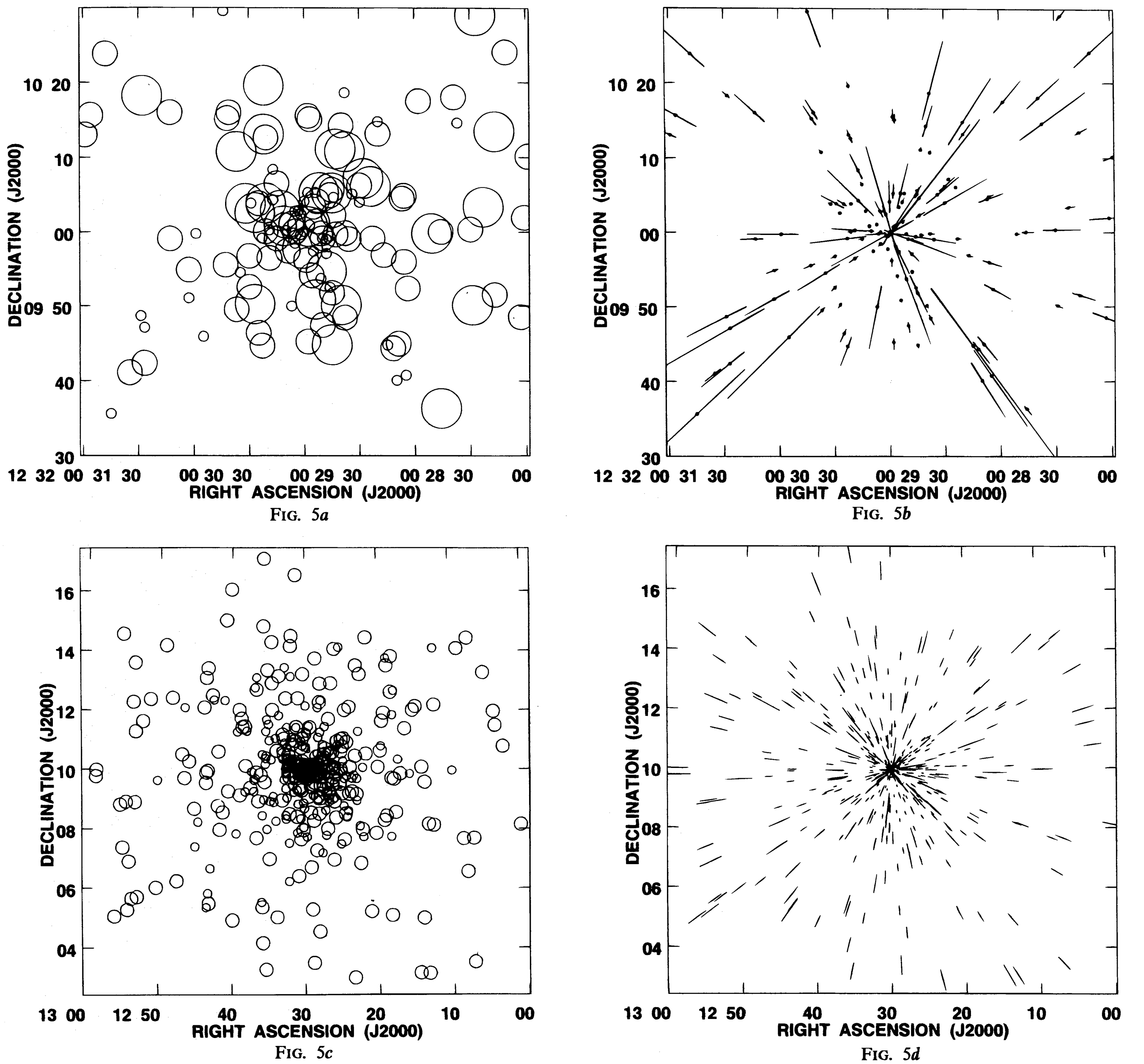

FIG. 5.—Simulation of 500 T Tauri stars at $d = 140$ pc produced with a constant star formation rate for 20 Myr with a $\Delta v_t = 1.0$ km s^{-1} velocity dispersion. (*a*)–(*b*) Ages and proper motions for the inner 1°; (*c*)-(*d*) Ages and proper motions for a 12° region. Twenty-four more distant stars are not shown. Age symbols follow those in Fig. 2.

from the line of sight due to obscuration by the molecular cloud, so that the radial velocity distribution may appear skewed with an excess of blueshifted stars. Thus, radial velocity surveys of young stars close to dark clouds are likely to produce systematically underestimated velocity dispersions and biased mean velocities.

The predictions of thermal dispersion model for the poorly studied $>1°$ outer regions are strongly dependent on the duration of the star formation. In the $\Delta v = 1$ km s^{-1} model, the fraction of stars lying more than 1° (2.4 pc projected radius) from the formation site is 2% for a duration of 2 Myr, 22% for 5 Myr, 42% for 10 Myr, 62% for 20 Myr, and 79% for 50 Myr. These dispersed stars are generally not strongly concentrated around the cloud. For the 20 Myr duration model shown in Table 1, top section, and Figure 5, the inner 1° circle and the 2°–17° annulus each contain roughly 40% of the stars, while the 1°–2° annulus contains only 20%.[11] We thus find that the duration of a star forming event may be directly measurable in two ways: counting the number of older WTT stars superposed directly on the cloud (Figs. 5*a*, 6, and 7, *top*), and determin-

[11] A sensitive search for X-ray emitting stars 1°–3° east of the Chamaeleon I cloud has been made with a pointing of the *ROSAT* PSPC detector (E. D. Feigelson, unpublished). Nine reliable, and several additional possible, faint X-ray sources are found, most of which appear to be associated with fewer than 15 stars. However, because of the likelihood of chance coincidences and extragalactic interlopers, the number of dispersed T Tauri stars is uncertain until spectroscopic confirmation is obtained. At the present time, the data are consistent with the dispersed population predicted in Table 1, top section.

TABLE 1

MODELS OF THE CHAMAELEON CLOUD REGION

Annulus	$N_{young} : N_{med} : N_{old}$	⟨Age⟩ (Myr)	⟨PM⟩ (mas yr^{-1})	⟨RV⟩ (km s^{-1})
Thermal Velocity Dispersion ($\Delta v = 1$ km s^{-1})				
0″–20″......	35: 51: 21	5.8 ± 5.5	0.3 ± 0.4	0.0 ± 0.4
20″–1°......	12: 41: 30	7.8 ± 5.3	0.5 ± 0.5	-0.0 ± 0.4
1°–2°.......	2: 61: 48	9.6 ± 5.1	0.8 ± 0.6	-0.1 ± 0.6
2°–10°......	0: 46: 140	13.3 ± 4.3	1.3 ± 0.6	-0.0 ± 0.7
>10°.......	0: 1: 12	16.1 ± 3.0	2.9 ± 0.8	-0.3 ± 0.8
Thermal Velocity Dispersion (70% at $\Delta v = 1$ km s^{-1}) with Dynamical Ejection (30% at $\Delta v = 10$ km s^{-1})				
0″–20″......	25: 26: 7	4.5 ± 5.0	0.8 ± 2.6	0.0 ± 1.0
20″–1°......	13: 43: 16	5.9 ± 4.3	0.7 ± 0.6	-0.2 ± 1.4
1°–2°.......	3: 37: 33	9.8 ± 5.1	0.9 ± 1.1	0.2 ± 2.4
2°–10°......	8: 60: 116	11.7 ± 5.3	2.3 ± 2.9	0.3 ± 2.0
>10°.......	0: 34: 79	12.8 ± 4.7	10.0 ± 6.8	-0.0 ± 6.5
Dispersed Cloudlets in a Turbulent Cloud Complex				
0°–80°......	16: 176: 308	11.0 ± 4.9	7.3 ± 2.8	0.5 ± 3.7

ing the spatial extent of dispersed WTT stars around the cloud. The first method may prove to be easier to achieve.

In summary, we find that the simple model of stars drifting from a star formation site with slow velocity dispersion inherited from thermal gas motions can explain why samples drawn exclusively from the immediate proximity of clouds will miss most of the stars older than 2 Myr. This model reproduces with reasonable fidelity the spatial and age distributions within 1° of the Chamaeleon I cloud, when known limitations of the sample are taken into account. But, a thermal dispersion model encounters a major problem when confronted with the more widely dispersed RASS sources. The primary difficulty is not the number of stars found over the 160 square degree region examined by Alcála et al. (1995), but rather their youth (Montmerle & Casanova 1996). Figure 2*b* shows that 50%–60% of the stars beyond 2° of the Chamaeleon I or II clouds are younger than 2 Myr, while Table 1 predicts that *none* of them should be so young in the slow drift model. Achieving such a powerful dispersal requires increasing the velocity dispersion severalfold, or abandoning the assumption of a single formation site. We consider these possibilities next.

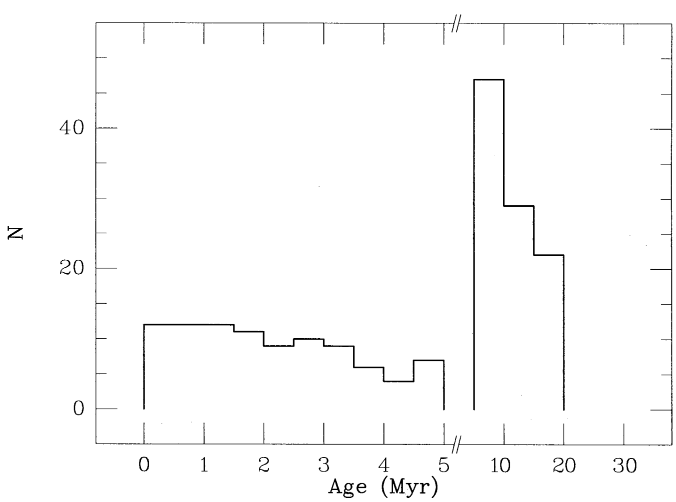

FIG. 6.—Age distribution of simulated T Tauri population within 1° of the star formation site for the model shown in Fig. 5.

5.2. *Dispersal by Dynamical Ejection*

It is possible that some stars acquire significantly higher velocities, either from the complex dynamics of core collapse, or gravitational interactions with other stars after formation. This possibility is mentioned by Neuhäuser et al.

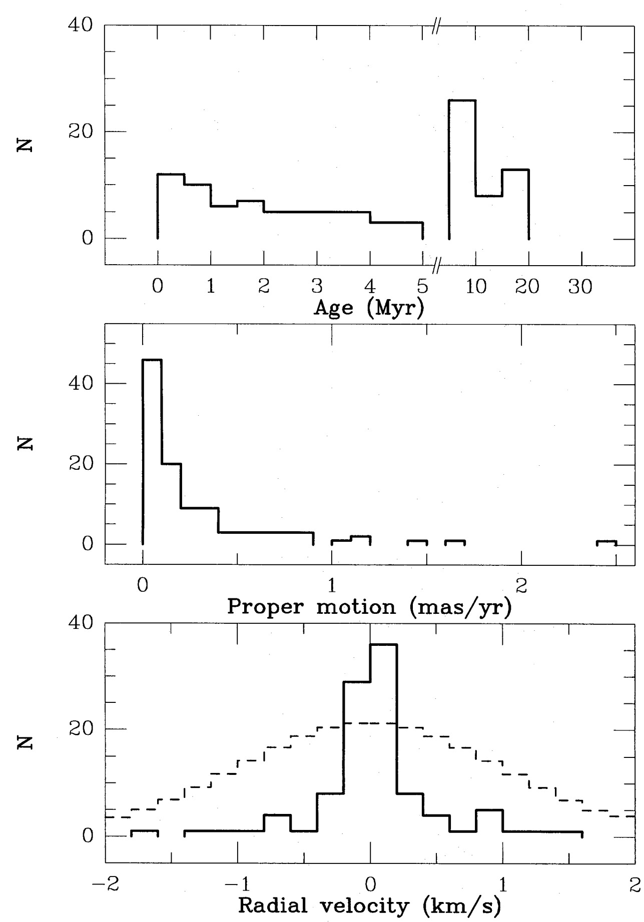

FIG. 7.—Properties of the simulated T Tauri population within 20′ of the star formation site for the model shown in Fig. 5. Histograms show distributions of (*top*) ages, (*middle*) proper motions, and (*bottom*) radial velocities. The dashed histogram shows the assumed radial velocity distribution for the entire 500 star simulation.

(1995c) and Montmerle & Casanova (1996), and studied by Sterzik & Durisen (1995) and Gorti & Bhatt (1996). A plausible mechanism is the three-body scattering of a star by a close binary. An incoming star can be temporarily captured by a hard binary system and, after very complicated dynamical interactions, will usually be ejected with a velocity comparable to the initial binary orbital velocities (Hut 1983). To achieve ejection velocities around 5–10 km s^{-1} requires (for solar mass stars) binaries with radii less than 0.5–2 A.U. Recent research into T Tauri binary frequencies indicates that perhaps 10%–20% of all T Tauri stars reside in sufficiently hard binaries to produce such ejections (Mathieu 1994). Note, however, that some orbital energy may disrupt the circumstellar disk(s) and thereby reduce the ejection velocity (Clarke 1993). High-speed ejection may not be confined to hard binaries but may also occur during the dynamical evolution of multiple star systems (Sterzik & Durisen). Another possible ejection mechanism is gravitational scattering with gaseous inhomogeneities in the molecular cloud (Gorti & Bhatt). We do not construct a self- consistent model of three-body scattering in a star forming region, but rather adopt an ad hoc approach to see whether any reasonable ejection model can explain the distribution of T Tauri stars in the Chamaeleon region (Fig. 2).

Figure 8 and Table 1, middle section, show the result of a simulation with dynamical ejection together with the thermal velocity model discussed is § 5.1. Of the 500 stars, 70% have the slow Gaussian velocity dispersion with $\Delta v = 1$ km s^{-1} while 30% have $\Delta v = 10$ km s^{-1}. This ejec-

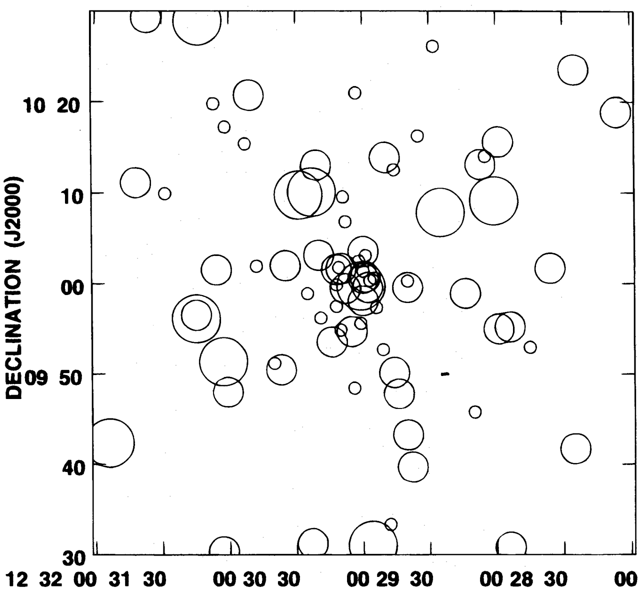

FIG. 8a

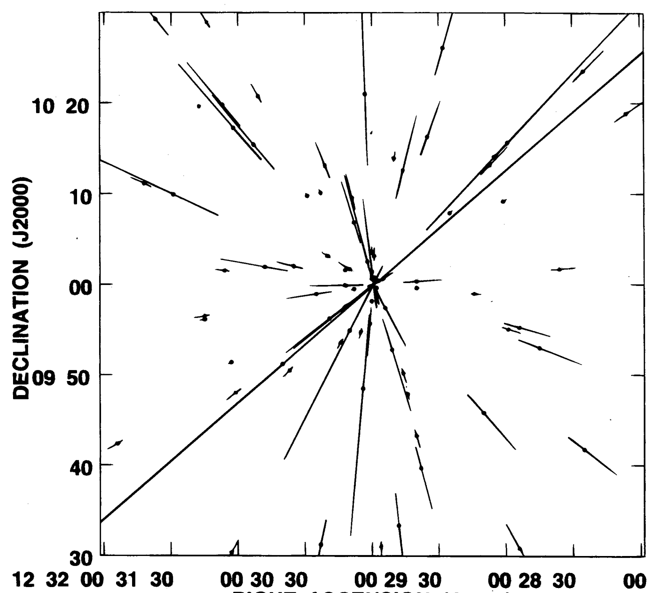

FIG. 8b

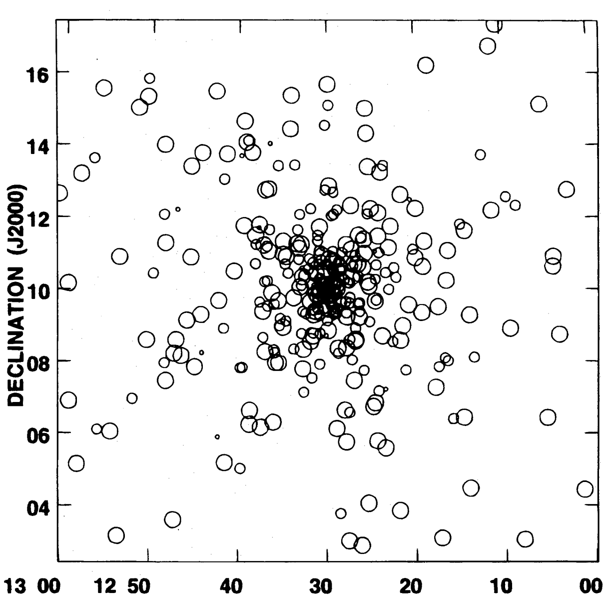

FIG. 8c

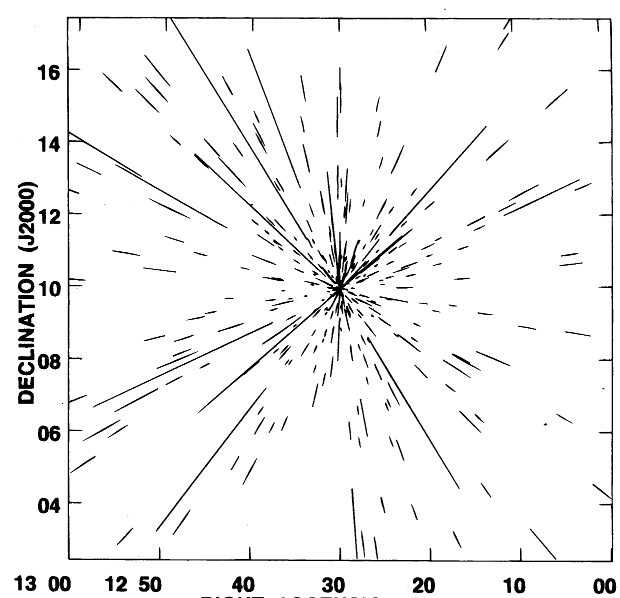

FIG. 8d

FIG. 8.—Simulation of 500 T Tauri stars at $d = 140$ pc of which 70% have velocity dispersion $\Delta v_t = 1$ km s^{-1} and 30% are dynamically ejected with a dispersion $\Delta v = 10$ km s^{-1}. Panel and symbol descriptions follow those of Fig. 5. One hundred thirty-two stars lie outside the plots.

tion process does place a handful of young ($t < 2$ Myr) stars out to distances of 2°–10° (5–25 pc), but also disperses dozens of older T Tauri stars. We have found no realistic ejection model that can disperse as many extremely young stars as seen in the RASS in the Chamaeleon I region (Fig. 2*b*), and simultaneously maintain the successful explanation of the immediate vicinity of Cha I (§ 5.1), without invoking the implausible requirement that the fraction of ejected stars has greatly increased over the past few megayears. Furthermore, while an extremely efficient ejection mechanism conceivably could account for the observed dispersed young stars, such a model would predict an enormous number of older ejected stars. This leads to a impossibly high star formation efficiency for Cha I, which has $M_{\rm gas}$ of only a few hundred solar masses today.

Given these difficulties, we believe the ejection model based on any dynamical mechanism can be rejected as an explanation for most of the RASS dispersed stars in the Chamaeleon region. However, occasional high-velocity ejections may explain the presence of a few widely dispersed T Tauri stars with high proper motions with respect to their host clouds, such as FK Ser or possibly AB Dor (§ 4.2). The model outlined here disperses a few stars as far as 50°–130° (100–300 pc) from the parent cloud within 20 Myr.

5.3. *Cloudlets in Turbulent Molecular Clouds*

To account for the wide distribution of very young RASS stars, we are thus obliged to consider star formation far from the prominent active Chamaleon I and II clouds (Neuhäuser et al. 1995a; Montmerle & Casanova 1996). Here, stars form over a region several hundred square degrees in extent in small transient cloud cores, perhaps similar to Bok globules. As spatial, kinematic, and temporal properties of such small clouds are unknown, additional theoretical assumptions are needed to construct a model. We adopt here the model that the cloudlets represent condensations in a turbulent giant molecular cloud.

Molecular gas in low-mass star forming molecular regions have line structures that can be divided into thermal motion with $\Delta v_t \simeq 0.5$ km s^{-1} and a larger nonthermal motion $\Delta v_{\rm nt}$ within or between individual clouds (Fuller & Myers 1992). Extensive studies have shown that the amplitude of the molecular velocity dispersion increases with the size of the region R under consideration as $\Delta v \propto R^p$, where p ranges from 0.2 to 0.7 (e.g., Larson 1981; Myers & Goodman 1988). The relationship for nonthermal motions for low-mass cloud cores less than $\simeq 1$ pc in size is found to be $\Delta v_{\rm nt} = 1.5(R\ {\rm pc}^{-1})^{0.5}$ km s^{-1} (Caselli & Myers 1995). This relationship appears to underestimate the nonthermal molecular velocities on larger scales. Well-resolved CO clouds in the Taurus-Auriga complex (Ungerechts & Thaddeus 1987; we consider here their clouds 21 and 24–29) show radial velocity dispersions of 3.1–4.5 km s^{-1} within clouds on scales of 3–128 square degrees, and about 5 km s^{-1} over the entire $\sim$500 square degree region. But Falgarone & Phillips (1990) find that the ^{12}CO line profile integrated over the entire 30 pc size complex, including regions between readily identified large clouds, has a total velocity coverage around 20 km s^{-1}, compared to 8 km s^{-1} extrapolated from the scaling relation of Caselli & Myers (1995). The emission in the wings of the line profile is produced in small dense cloud fragments, unresolved with a 0.02 pc beam, and not in a widespread medium (Falgarone, Phillips, & Walker 1991).

These findings, combined with the fractal geometry and self-similar density structure of molecular clouds, are widely interpreted as manifestations of Kolmogorov-type turbulence (Larson 1981; Falgarone & Phillips 1991; see also Elmegreen 1993a). A theory of star formation within a hierarchical cascade of a turbulent cloud has been developed by Henriksen (Henriksen & Turner 1984; Henriksen 1986, 1991). His model suggests that star formation in a turbulent giant molecular cloud is probably unsynchronized (i.e., the gravitational collapse is "bottom up," starting in small cloudlets) and should extend in time over several tens of megayears. Elmegreen (1993b) and Vásquez-Semadeni, Passot, & Pouquet (1995) also discuss star formation in turbulent clouds.

A broad agreement between the integrated line widths of cloud complexes and T Tauri kinematics was first noted by Larson (1981). However, since most of the gas velocity dispersion is due to intercloud rather than intracloud motions, clouds should gradually separate from each other as each produces a comoving cluster of T Tauri stars. To explain the poor correspondence between dispersed RASS stars and existing molecular clouds (§ 4.4 and Fig. 4), the cloudlets either rapidly dissipate after active star formation or are decelerated by interaction with the intercloud medium (Jones & Herbig 1979). In either case, the cloudlets leave behind isolated comoving groups of T Tauri stars. The TW Hya group may be an example where the entire cloud has entirely disappeared, while the dispersed RASS WTT stars within the large Taurus-Auriga and Chamaeleon complexes would be cases where active star formation continues today in portions of the complex.

In our simulation, each cloudlet is assigned a bulk velocity of $V_{\rm cl} = A \times r^p$, where r is the distance from an assumed cloud center in parsecs, p is the turbulent scaling factor, and A is the amplitude of the turbulent motion in km s^{-1} pc^{-1}. Cloudlet locations and velocity vector orientations are assumed for simplicity to be random, although correlations due to the turbulence are probably more realistic. Each star acquires its cloudlet velocity and an individual thermal drift velocity as in § 5.1 above.

Figure 9 and Table 1, bottom section, illustrate the T Tauri distributions expected in the turbulent cloudlet model. Here we assumed that 50 cloudlets emerge at random times during a 20 Myr period at random locations within a 20° × 20° (48 × 48 pc at a distance of 140 pc) region. Cloudlet velocities increase with distance from the center of the field following the turbulent model assuming $p = 0.5$ and $A = 1.5$ km s^{-1} pc^{-1}. Each cloudlet is assumed to produce 10 stars at a constant rate over 2 Myr starting at a random time during the 20 Myr simulation, after which the cloudlet disappears. Stellar velocities are the vector sum of the cloud velocity and an isotropic Gaussian velocity dispersion with $\Delta v_t = 1.0$ km s^{-1}. These simulation parameters were designed to approximate the distribution of dispersed RASS WTT shown in Figure 2*b*. Recall that the RASS sample is incomplete by factors greater than 2–3 (§ 4.1), so that the observed spatial distribution is likely to underestimate the degree of clustering present in the underlying population.

Although there is enormous flexibility in the choice of parameters in models of distributed star formation in a turbulent cloud complex, our simulations like that shown in Figure 9 reveal some basic properties. Younger T Tauri stars ($t \lesssim 10$ Myr) appear in clumps 1°–2° in size, resem-

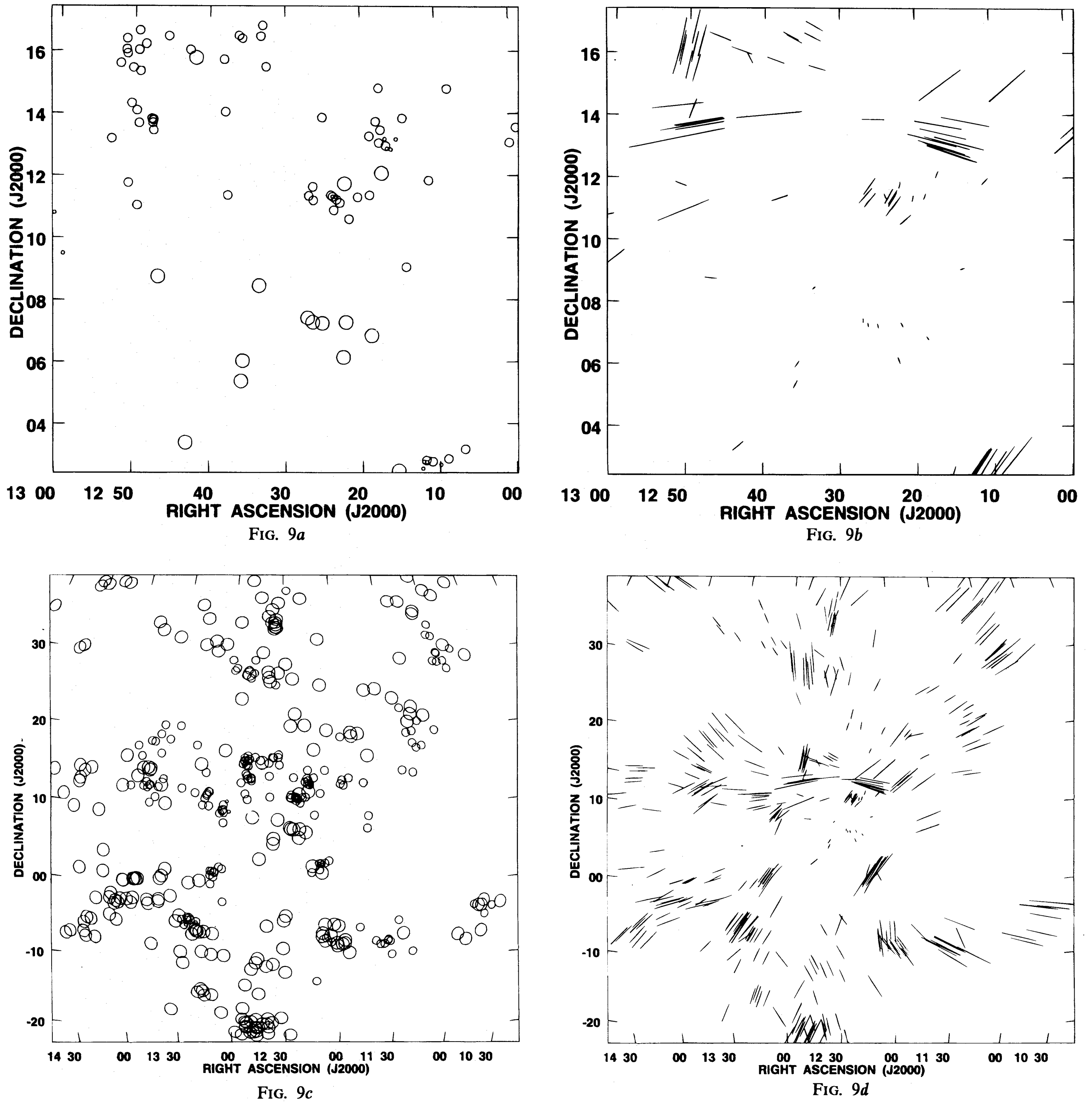

FIG. 9.—Simulation of T Tauri star spatial distribution and proper motions assuming stars form in short-lived cloudlets in a turbulent molecular cloud complex. (*a*)–(*b*) Ages and proper motions for a 12° region; (*c*)–(*d*) Ages and proper motions for a 60° region. Symbols follow those in Fig. 5.

bling the four RASS stars around $8^h40^m - 78°$. Older stars ($t \gtrsim 10$ Myr) in the simulation appear more isolated, having drifted away from their cloudlet. Note that only 10% of the stars in the simulation have ages $t < 2$ Myr, compared to half of the RASS dispersed stars, suggesting again that many older dispersed WTT stars are present below the RASS sensitivity (§ 4.1). The standard deviations of radial velocities and proper motions for the entire sample of 500 stars are 3.7 km s^{-1} and 2.8 mas yr^{-1}, respectively (Table 1, bottom section), but the distributions have non-Gaussian heavy tails. For example, 20% of the stars in the simulation have proper motions amplitudes $|PM| = 10$–13 mas yr^{-1}.

5.4. *Summary*

The Chamaeleon I cloud cores have produced a rich cluster of T Tauri stars, of which 117 are identified and 80 are well characterized with isochronal ages. Their spatial and age distribution is reasonably well reproduced by the slow drifting of stars outward, assuming a thermal velocity dispersion $\Delta v_t = 1$ km s^{-1} (Fig. 5). This model makes testable predictions: many older T Tauri stars close to the cores are still unidentified; all older stars near the cores should have negligible proper motions; sample proper motions and radial velocities should increase with projected distance from the cloud; and dozens or hundreds of older WTT stars should be present in the poorly studied 1°–10° annulus around the cloud.

However, the Chamaeleon I cloud cannot be responsible for the widely dispersed RASS WTT stars. The large number of very young RASS stars appearing far from the cloud makes even dynamical ejection models unacceptable. These stars are more likely formed in small dispersed cloudlets, far from the well-known active clouds. A model based on turbulent dynamics, as first suggested by Larson (1981), can qualitatively account for the RASS stellar distribution. Further study of the dispersed population, including kinematic measurements and the identification of hundreds of X-ray faint WTT stars, is needed to confirm the link between dispersed T Tauri stars and molecular cloud turbulent dynamics.

6. COMMENTS ON THE TAURUS-AURIGA CLOUD POPULATION

In contrast to the Chamaeleon region, the Taurus-Auriga complex is more difficult to analyze. The molecular material is distributed in overlapping clouds or filaments that fill about half of the 500–700 square degrees covered by the complex (Herbig 1977; Ungerechts & Thaddeus 1987). Most of the CTT and some of the young WTT stars are concentrated around six small active cores (Gomez et al. 1993), but many X-ray discovered WTT stars are distributed throughout the region (Walter et al. 1988; Neuhäuser et al. 1995a). If any of the models discussed in § 5 are relevant to Taurus-Auriga, the population in any localized region will include stars drifted from an unknown number of present or past star forming sites. With available published information, a reliable spatial model of the Taurus-Auriga population cannot be constructed. We instead comment on the implications of our models for existing kinematic studies.

Herbig (1977) measured absorption-line radial velocities for 37 Taurus- Auriga CTT stars and reported that the stellar velocities are indistinguishable from molecular cloud velocities obtained at the stellar position, within a measurement accuracy of 3 km s^{-1} standard deviation. However, examination of Herbig's data shows a sample standard deviation of 8 km s^{-1} in both the stellar velocities and star-cloud velocity differences, due to several outliers. More accurate data for a similar sample of 42 stars were obtained by Hartmann et al. (1986), which show a sample radial velocity dispersion of 2 km s^{-1} and a star – cloud velocity dispersion of less than 1 km s^{-1}. The latter value is consistent with the $\simeq$0.5 km s^{-1} radial velocity dispersion of molecular gas in Taurus-Auriga cloud cores (Caselli & Myers 1995). These values (where radial velocity dispersions are multiplied by $3^{1/2}$ to give three-dimensional velocity dispersions) support a slow thermal dispersal model (§ 5.1, Fig. 5, and Table 1, top section).

However, there is considerable evidence that these radial velocity measurements underestimate the true kinematic dispersion of the stellar population. Jones & Herbig (1979) obtained proper motions of $\simeq$75 CTT and young WTT stars distributed over the Taurus complex. The sample divided naturally into five spatial-kinematic groupings. Proper motion dispersions within groups were $\simeq$5 mas yr^{-1}, but the entire sample is spread nearly uniformly over a range of $\pm$15 mas yr^{-1}. (Note that 10 mas yr^{-1} corresponds to 2°8 Myr^{-1} or 6.7 km s^{-1} in the plane of the sky at $d = 140$ pc.) HJSK91 examined a smaller sample of 22 brighter T Tauri stars, which shows a one-dimensional dispersion of 12 mas yr^{-1}, although this is reduced by a factor of 3 if six outliers are removed. These large proper motions, corresponding to one-dimensional velocities around $\pm$10 km s^{-1}, are very similar to the radial velocity range found from CO data integrated over the entire Taurus complex (Falgarone & Phillips 1990; see § 5.3).

Our investigations above suggest a solution to these discrepancies between various velocity dispersion findings. The slow thermal dispersal model (§ 5.1) shows that kinematic studies that are confined to the inner parsec of a cloud core can underestimate the true dispersion of the population because high-velocity stars preferentially lie far from the cloud. Comparison of the radial velocities in the simulation and the parent population (solid vs. dashed histograms in Fig. 7*c*) for the inner region shows this bias can be very large. The Taurus proper motion studies, based on samples spread over larger regions of the complex, are less vulnerable to these problems and thus more reliably reflect the high turbulent velocities of the cloud complex. The presence of stellar groupings with systematically different velocities, and of isolated outliers in velocity space, is directly predicted by the turbulent cloud model (§ 5.3). Further kinematic analyses including many of the older dispersed WTT stars missing from past studies may directly reveal the turbulent origins of the stellar population. For example, if velocity outliers are found to be members of diffuse stellar clumps, then the star formation efficiency of dispersed cloudlets might be inferred.

6.1. *Summary*

The Taurus-Auriga complex, like the Chamaeleon complex, shows two types of T Tauri dispersion. Some stars, which dominate the well-studied sample of CTT and young WTT stars, are clustered around six prominent cloud cores now actively producing stars. These probably disperse slowly from a central region, as modeled by our thermal dispersion model (§ 5.1). But both molecular line and stellar proper motion studies show that the intercloud velocities exceed intracloud thermal velocities several fold. This reflects the turbulent large-scale structure of the complex. The WTT stars recently discovered in the *ROSAT* All-Sky Survey are more widely and smoothly dispersed throughout and around the cloud complex. These stars, which probably include many of the older WTT stars missing from the well-studied samples (§ 2), are stars that formed in rapidly moving cloudlets which have dissipated.

7. CONCLUSIONS

7.1. *Direct Inferences*

Despite recent discoveries of hundreds of T Tauri stars in nearby star forming regions, all existing samples of low-mass pre–main-sequence stars are strongly deficient in star older than $\sim$2 Myr (§ 2). Explanations based on short-lived starbursts, incorrect stellar evolution theory, and flux limits in surveys encounter significant difficulties (§ 3). The most viable explanation is that older T Tauri star are dispersed from active sites of star formation. The presence of some older stars in the vicinity of Chamaeleon I, and the success of the simple slow thermal dispersion model for this cloud (§ 5.1), indicate that at least this cloud is long-lived ($t \sim$ 20 Myr). However, the active cores in the Taurus-Auriga complex be considerably younger (Jones & Herbig 1979).

Regions of low-mass star formation like the Chamaeleon and Taurus-Auriga cloud complex reveal two types of dispersed stars: stars that have drifted outward slowly ($\Delta v \simeq 1$ km s^{-1}) due to thermal motions within a cloud core (§ 5.1) and stars that form in short-lived cloudlets that can have relative velocities up to ± 5–10 km s^{-1} due to the turbulent structure of parental cloud (§ 5.3). The second type of dispersed stars is indicated by the *ROSAT* discoveries of many WTT stars scattered 10°–20° around nearby star forming regions (§ 4.3), and the high proper motions of Taurus-Auriga CTT stars (§ 6). The balance between these two dispersal mechanisms appears different in the different regions. In the Chamaeleon complex, perhaps 300 stars have formed from a single currently active cloud over $\simeq$20 Myr, and several hundred others formed in now-dissipated cloudlets. In the Taurus-Auriga complex, several active clouds have each formed about a dozen stars, while hundreds of others are widely dispersed from past cloudlets. A third dispersal mechanism, dynamical ejection of stars from active clouds, is astrophysically possible, but it requires an extremely high ejection rate and star formation efficiency to account for the many young widely dispersed RASS Chamaeleon WTT stars.

Herbig's (1978) question "Where are the post–T Tauri stars?" (or, in modern terminology, "Where are the post-CTT stars?") can thus be answered: some are WTT stars found close to the active cloud cores, but most are WTT stars have drifted several parsecs, or were born tens of parsecs away, from currently active clouds.

These interpretations must be considered tentative. It is possible, for example, that the high-lithium stars found in the *ROSAT* All-Sky Survey are unrelated to nearby star forming regions, but rather represent the magnetically active portion of a large post–T Tauri or ZAMS population. However, our models make clear testable predictions concerning the spatial, age and velocity distributions of T Tauri stars, particularly for Chamaeleon region. The thermal drift model predicts that the known population of 117 stars within 1° of the Chamaeleon I cores should be surrounded by $\simeq$200 mostly older T Tauri stars spread over several degrees, with proper motions oriented away from the cloud. Similar halos of older stars will be present around long-lived star forming sites. This population around long-lived clouds can be located with unbiased Li λ6707 spectroscopic surveys. In contrast, our models predict that the more widely dispersed T Tauri stars found in the RASS were formed in situ over a 20–50 pc region in small molecular cloudlets that have quickly dissipated and should be clustered in comoving groups having low internal motions but high relative proper motions between groups. Proper motion surveys of $V \simeq 10$–16 stars should be able to investigate this prediction.

7.2. *Broader Implications*

As mentioned in § 1, we believe that results summarized here concerning the census, spatial distribution, and kinematics of T Tauri stars can address fundamental issues concerning star formation in the Galaxy. Although necessarily preliminary in many respects, we reach the following conclusions:

1. *Star formation history of molecular clouds.*—The Chamaeleon I T Tauri stellar population is well explained by a slow and continuous star formation rate over a period of $\simeq$20 Myr. X-ray and spectroscopic surveys for WTT stars more than 1° from active cloud cores are needed to confirm and extend this result. The stellar censuses for other clouds do not yet provide strong constraints on the duration of star formation.

2. *Star formation efficiency of molecular clouds.*—The incompleteness of most T Tauri samples at ages greater than 2 Myr means that the conversion of molecular gas to stars is far more efficient than the few percent efficiency originally estimated by Cohen & Kuhi (1979). This may imply that the formation rate of bound open clusters is higher than currently estimated (Margulis & Lada 1984; Larson 1990). The Chamaeleon I cloud appears to have an efficiency of at least 20% (Feigelson et al. 1993). However, the computation of star formation efficiency over a 10^7 yr period could appear spuriously high, as the molecular material available in a given region is likely to decline over this period.

3. *Massive versus small molecular clouds.*—Our interpretation of dispersed and high-velocity stars found in the Chamaeleon and Taurus-Auriga complexes implies that a large fraction of the stars on the Hayashi tracks in active local cloud complexes do not arise in a few large currently active molecular cores, but rather in small dispersed clouds that are now dissipated. Quantitative understanding of the cloudlets and their star formation must await identification and kinematical study of the X-ray-faint dispersed T Tauri population.

4. *Dynamics of molecular clouds and young stars.*—We have explained the unusual dispersal of Chamaeleon T Tauri stars, and the properties of Taurus-Auriga radial velocities and proper motions, as the product of star formation in dispersed sites following the $\Delta v \propto r^p$ relation of a turbulent giant molecular cloud. T Tauri kinematics thus joins molecular kinematics and structure in support of turbulent dynamics (Larson 1981; Falgarone & Phillips 1991), and supports Henriksen's (1986, 1991) vision of "bottom-up" star formation as the turbulent cascade grows in the cloud complex. While the higher star formation efficiency (see above) suggests a higher proportion of stars born in bound open clusters than previously estimated, the turbulent dynamics may inhibit bound cluster formation. The competition between these effects requires more study.

5. *Stellar initial mass function.*—Inferences regarding the IMF based on T Tauri data and theoretical isochrones will not be seriously biased if the samples are restricted to stars younger than $\simeq$2 Myr, where the samples appear to be reasonably complete. The most complete data (Strom & Strom 1994; LFH96) support the Miller-Scalo IMF (Miller & Scalo 1979; Scalo 1986), although it is possible even these samples are missing very low mass stars.

6. *Evolution of circumstellar disks.*—X-ray studies, both deep surveys of cloud core environs and shallow surveys of cloud complex environs, clearly reveal that WTT stars with little or no disks dominate the population of CTT stars by very large factors. The Chamaeleon data indicate that about half of low–mass stars have completed the CTT-WTT transition by as early as $\simeq$1 Myr (Feigelson et al. 1993; LFH96). But a few disks appear to persist for $\gtrsim$10 Myr. A careful search for older CTT stars may constrain the maximum lifetime of protoplanetary disks.

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