THE ASTROPHYSICAL JOURNAL, 408:L33–L36, 1993 May 1

MULTIPLICITY AND THE AGES OF THE STARS IN THE TAURUS STAR-FORMING REGION

M. SIMON,[1] A. M. GHEZ,[2] AND CH. LEINERT[3]

Received 1992 October 27; accepted 1993 February 17

ABSTRACT

Ages for the pre–main-sequence stars in the Taurus star-forming region now known to be multiples are systematically younger than the ages of the singles. This seems to be an artifact. Overestimating the stellar luminosity in an unresolved multiple whose components are on Hayashi tracks produces an underestimate of the system's age. Until the astrophysical parameters of the components in the multiples become better known, the published age estimates for the single stars should be more accurate. Their average age is 2–3 times that of the multiples regarded as unresolved objects. Since most of the stars in the Taurus star-forming region are in multiples, the average age of the entire group of stars is 2–3 times older than previously thought. This result applies to both the strong and weak emission-line pre–main-sequence stars. The implications of a longer phase of pre–main-sequence activity are discussed.

Subject headings: binaries: general — stars: formation — stars: fundamental parameters — stars: pre–main-sequence

1. INTRODUCTION

The age of a star is a fundamental parameter. The location of a pre–main-sequence star in the H-R diagram and theoretical calculations of the contraction to the main sequence determine its age (e.g., Cohen & Kuhi 1979). Uncertainties in the luminosity, effective temperature, and modeling the evolutionary tracks can produce considerable scatter in the age estimates. However, analyses of groups of stars are reliable in a statistical sense and generally agree, for example, on relative ages of the groups.

High angular resolution surveys of the young stars in the Taurus star-forming region (SFR) have revealed that most are in multiple star systems (Ghez, Neugebauer, & Matthews 1992, 1993; Leinert et al. 1992; Simon et al. 1992; Simon 1992). The observed distribution of binary component separations peaks at $\sim 0\farcs3$ so the prevalence of companionship escaped notice until the application of speckle interferometry, lunar occultation, and subarcsecond imaging techniques in the IR became sufficiently routine to enable large-scale surveys. The surveys show that star formation in Taurus produces more binaries than single stars, that the incidence of multiples is higher than among the nearby solar-like stars, and that the shape of the distribution function of binary separations is similar to that of the nearby stars (Duquennoy & Mayor 1991).

This *Letter* describes how close companions affect the estimated age of the pre–main-sequence stars in the Taurus SFR. We show that published ages of single stars are on average older than those of stars now known to be multiple and that this results from analyzing the multiples as unresolved single stars (§ 2). The ages of the single stars as a group should therefore be more accurate. Since most of the stars are in binaries, on average the pre–main-sequence stars in Taurus are older than previously thought. We describe the resulting implications for our understanding of the formation and evolution of the stars in the Taurus SFR (§ 3).

[1] Astronomy Program, State University of New York, Stony Brook, NY 11794.
[2] Palomar Observatory, California Institute of Technology 320-47, Pasadena, CA 91125.
[3] Max Planck Institute für Astronomie, Königstuhl 17, D-6900 Heidelberg 1, Germany.

2. AGE DISTRIBUTION OF THE STARS IN THE TAURUS SFR

To compare the published ages of the single and binary stars we pooled the results of the Ghez et al. (1992), Leinert et al. (1992), and Simon et al. (1992) surveys. Each of these provides K-magnitudes for the singles and for the components of multiple star systems with an approximate secondary magnitude limit of $K \sim 10$ mag. We selected out those targets for which ages have been estimated by either Skrutskie et al. (1990, hereafter SDSESS) or Beckwith et al. (1990, hereafter BSCG) and divided them into two groups. The groups of singles includes those stars without detected companions brighter than $K \sim 10$ mag in the angular separation range 2″ to $\sim 0\farcs1$ in most cases and to $\sim 0\farcs01$ for the objects surveyed by occultation. The group of multiples includes those stars with detected companions in the same separation range. We choose 2″ for the angular separation upper bound so the multiplicity of the stars would not have been noticed earlier. Thus, the systems listed by Leinert et al. (1992) and Simon et al. (1992) with companions between 2″ and 10″ are omitted from this discussion because the issues we consider here do not arise for resolved systems. We think that we do not miss a significant number of close companions by combining the speckle surveys with lower limit $\sim 0\farcs1$ and the occultation survey with its $\sim 0\farcs01$ limit. From the distribution of separations determined in the occultation survey, we estimate that no more than 10%–15% of the objects counted as singles will prove to have stellar companions when observed with higher angular resolution. As for missing companions among the binaries, the frequency of triples is small in any case, ~20% that of the binaries (Simon 1992), and since all but one of the young star triples identified so far are hierarchical with (widest separation/closest separation) > 10, if additional companions remain to be found, they most probably lie outside the range $0\farcs01$–2″.

All the objects in the singles and multiples groups are in the Herbig & Bell catalog (1988, hereafter HBC). Table 1 lists their HBC numbers and the K-magnitude of either the single or, in the case of multiples, of the brighter member (Ghez et al. 1993; Leinert et al. 1992, Simon et al. 1992). Table 1 is not a comprehensive list of known binaries and singles in Taurus because it contains only the objects, defined as above, with ages evaluated by SDSESS and BSGG.

TABLE 1

AGES OF T TAURI STARS

HBC	K	$L_{*,K}$	Age	HBC	K	$L_{*,K}$	Age	HBC	K	$L_{*,K}$	Age
Singles											
365......	8.7	0.66	5.70	388......	8.4	0.89	6.18	64......	9.5	0.30	6.88
23......	8.7	0.66	6.48	38......	8.3	0.98	6.15	65......	8.0	1.32	5.90
24......	8.2	1.10	5.30	41......	8.0	1.31	5.76	66......	7.6	1.96	6.48
25......	6.9	3.90	6.23	49......	7.1	3.20	5.23	415......	7.2	2.91	6.90
26......	8.8	0.60	5.40	396......	7.7	1.77	5.72	67......	7.3	2.64	5.59
27......	8.8	0.60	5.70	397......	8.8	0.60	6.60	70......	8.4	0.89	6.03
370......	8.4	0.89	6.26	399......	8.1	1.19	6.08	71......	9.4	0.33	7.11
28......	8.4	0.89	5.85	403......	9.4	0.33	7.18	72......	8.1	1.19	6.04
376......	9.2	0.40	6.95	405......	8.5	0.80	6.40	74......	6.5	5.82	4.90
32......	8.1	1.19	6.08	56......	7.6	1.96	5.73	77......	8.2	1.08	6.11
378......	8.5	0.80	6.40	57......	7.4	2.39	5.60	79......	6.0	9.50	6.48
33......	7.7	1.77	5.40	58......	8.1	1.19	5.90	427......	8.3	0.98	6.19
34......	5.7	12.80	6.00	61......	7.8	1.61	5.90	429......	8.8	0.60	6.62
380......	6.9	3.90	6.48	62......	9.5	0.30	6.88				
385......	8.4	0.89	6.18	63......	7.8	1.61	5.90				
Binaries											
351......	9.4	0.32	7.48	383......	7.4	2.40	5.15	54......	7.5	2.16	5.64
358......	9.9	0.20	6.70	35......	5.5	15.60	5.90	55......	8.4	0.89	5.60
367......	6.9	3.92	6.28	36......	7.0	3.50	5.18	59......	8.2	1.08	6.85
368......	8.3	0.98	5.85	39......	8.6	0.73	6.30	412......	9.8	0.22	6.60
29......	7.7	1.77	5.84	44......	8.6	0.73	6.02	68......	9.3	0.36	6.85
30......	8.4	0.89	5.90	46......	8.9	0.54	5.80	420......	8.3	0.98	6.20
31......	9.7	0.24	6.74	47......	9.3	0.36	5.90	69......	7.9	1.45	5.45
379......	8.8	0.60	6.32	50......	7.6	1.96	4.84	76......	7.4	2.39	5.60

For the subset of systems with SDSESS ages, Figure 1 (left panels) shows that the age distribution of the singles peaks at a greater age than that of the multiples. The median ages (y) are 6.35 and 5.9 dex for the singles and multiples, respectively. Figure 1 (center panels) shows the distributions of ages derived by BSCG. The BSCG ages are generally lower than the SDSESS ages, but nonetheless the singles again appear to be older on average with median age 5.94 dex compared to 5.54 dex for the multiples. For either set of age determinations, the median age of the singles is 2–3 times that of the multiples.

Two interpretations are possible. Either most of the singles formed earlier than the multiples, a possibility that is difficult to test (but see § 3), or what seems more plausible, the ages of the multiples have been systematically underestimated. Without knowing about a star's actual duplicity, researchers attribute the entire luminosity to one star with the observed spectral type. Since the evolutionary tracks at this stage are nearly vertical in the H-R diagram, the greater luminosity implies a younger age than would be derived if the luminosity were correctly divided among the system's components. H-R diagrams (Fig. 2) of the singles and multiples separately, using luminosities and effective temperatures from Strom et al. (1989, hereafter SSECS), show that indeed the published luminosities of the multiples tend to place them higher in the H-R diagram than the singles.

We can test the effect of overestimating the stellar luminosity

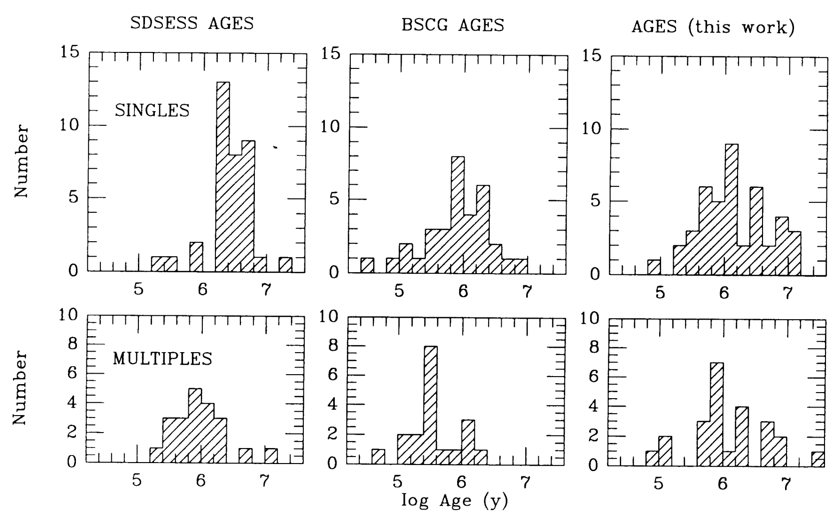

FIG. 1.—Age distributions for singles and multiples in Table 1 using ages derived by SDSESS (*left*) and BSCG (*center*). The righthand panels show the age distributions derived using luminosities $L_{*,K}$ as described in the text to apportion the luminosity among the components of a multiple.

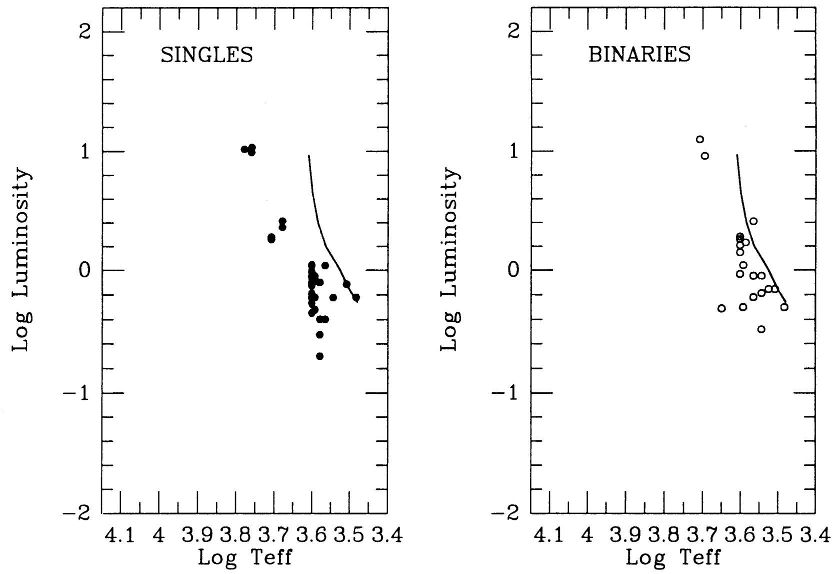

FIG. 2.—H-R diagrams for the singles (*a*) and multiples (*b*) in Table 1 using luminosities and spectral types from SSECS. The heavy solid line is Stahler's (1983) "theoretical birthline."

on the multiples' ages by deriving a stellar luminosity based on K-magnitudes, the only common quantity known for all the components of the multiples and the singles. We calculate the luminosity of each star from its K-magnitude (Table 1) using Reid & Gilmore's (1984) relation between bolometric and absolute K-magnitudes for dwarfs, $M_{\rm bol} = 1.08M_K + 2.05$. With 140 pc for the distance of the Taurus SFR (Elias 1978), and $M_{\rm bol} = 4.75 - 2.5 \log (L/L_\odot)$ (Allen 1973) we obtain for $L_{*,K}$, the stellar luminosity derived from its K-magnitude, in solar units, $\log (L_{*,K}) = 3.56$–$0.43m_K$. We do not correct for extinction because at K the extinction is about one-tenth that at V and is less than 3 mag at V for all the objects in Table 1 (SSECS). This procedure ignores the radiation that might be contributed by a circumstellar disk and its boundary layer; at K this could amount to a few tenths of a magnitude (Kenyon & Hartmann 1990). As a check, we compared the $L_{*,K}$ of the singles with the stellar luminosities derived by SSECS $L_{*,\rm SSECS}$, and BSCG, $L_{*,\rm BSCG}$. The scatter of the $L_{*,K}$ versus either $L_{*,\rm SSECS}$ or $L_{*,\rm BSCG}$ is similar to that of $L_{*\rm SSECS}$ versus $L_{*,\rm BSCG}$. The $L_{*,K}$ are systematically about 15% higher than the $L_{*,\rm BSCG}$, and about 12% lower than the $L_{*,\rm SSECS}$ after scaling to a common distance. We conclude that our method of estimating the stellar luminosity gives acceptable results. Table 1 lists the $L_{*,K}$ calculated for the brighter component of the multiples and for the singles.

To estimate ages we combine the $L_{*,K}$ with the effective temperature provided by SSECS and BSCG, assigning the published effective temperature of a multiple system to the brightest component at K, and use the evolutionary tracks and isochrones reproduced by SSECS. Table 1 lists the logarithm of the derived ages. Figure 1 (right panels) shows the distribution of ages for the singles and brighter members of the multiples. The median ages of the two distributions are not significantly different, 6.08 and 5.93 dex for the singles and brighter members of the multiples, respectively. To provide an internal consistency check, we also calculated the ages of the multiples as if they were unresolved systems, using their total K-magnitudes. The median age of the unresolved multiples, 5.6 dex, reproduces the result obtained using the SDSESS and BSCG ages, that the unresolved multiples appear significantly younger than the singles. Thus, the systematic age difference seen in the left and center panels of Figure 1 appears to be an artifact of overestimating the stellar luminosity in a system that is actually multiple thereby underestimating its age.

3. DISCUSSION

Although our age estimates are based on spectral type and m_K alone, the similarity of the age distributions of the singles and brighter members of the multiples suggests that the star formation histories of the singles and multiples in the Taurus SFR are similar. Furthermore, because most of the stars in the Taurus SFR are in multiples, whose age has been underestimated, on average the entire group of stars is older, by about a factor of 2–3, than previously thought. This result applies to both the strong (classic) and weak emission-line stars.

It is plausible that the age discrepancy results from overestimating the stellar luminosity in unresolved multiples. S. Stahler (1992, private communication) has described to us an elegant argument to evaluate the discrepancy using the Kelvin-Helmholtz contraction time to measure the age of a star. Let t_0 to be "naive" age of an unresolved binary, and t_1, and t_2 the actual ages of its primary and secondary components. Stahler expresses the coeval nature of the components by forcing $t_1 = t_2$, which is equivalent to requiring that the two components appear at the birthline (Stahler 1983) simultaneously, and shows that this produces $t_1/t_0 = 2.8$ in a binary with equal mass components. In an ensemble of binaries whose mass ratio distribution is the same as that of the nearby solar-like stars (Duquennoy & Mayor 1991) the average value of the age ratio is $\langle t_1/t_0 \rangle = 1.5$. Direct comparison of these theoretical estimates with the actual discrepancy of a factor of 2–3 is complicated by two effects. First, the two stars may not appear at the birthline simultaneously. The star that lags contributes more to the system luminosity than otherwise expected which increases the theoretical value of t_1/t_0. Furthermore, the greater frequency of binaries in the Taurus SFR than among the field stars (Ghez et al. 1992; Leinert et al. 1992; Simon

1992) leaves uncertain the distribution of their mass ratios. We therefore note that the theoretical and empirical estimates of the age discrepancy are in qualitative agreement but leave a detailed comparison for the future when the astrophysical parameters of the young star binaries become better known.

The older age of the stars in the Taurus SFR has several implications. It places them further below the Stahler's birthline. The locations of the singles in the H-R diagram (Fig. 2*a*) should give a more accurate representation of the location of the cluster stars relative to the birthline than if the singles and multiples, regarded as unresolved objects (Fig. 2*b*), were superposed.

A longer phase of T Tauri star activity implies that mass accretion can continue for a longer time than previously thought. With parameters adopted by Hartmann & Kenyon (1990), but an accretion duration 2–3 times longer, $2-3 \times 10^6$ yr, 10%–20% of the final stellar mass could be accreted. The accreted mass thus could be comparable to that of a typical extensive circumstellar disk (BSCG). The longer time available to accretion alo exacerbates the problem of spin-up of the central star and accentuates the necessity for an efficient mechanism to carry away the angular momentum of the accreted matter.

A longer T Tauri star phase decreases the expected number of post–T Tauri stars (PTTS) (Jones & Herbig 1979). It remains however that most of the pre–main-sequence stars in Taurus are on the convective part of their evolutionary tracks and that there is a dearth of older PTTS on radiative tracks. Since the census of young stars in the Taurus SFR appears to be essentially complete (e.g., Gomez et al. 1992), this suggests that star formation in Taurus has continued for only a fraction of the time required for a low-mass star to contract to the main sequence.

Gomez et al. (1992) found that the L 1551 region (their Region II) may be several Myr older than a region to the north that includes TMC 2 (their Region I). Could this be the result of unresolved companions? Our sample in Table 1 contains 16 systems in region I (8 singles and 8 binaries) and 9 in region II (6 singles and 3 binaries). We compared the ages derived from the $L_{*,K}$ as we have discussed for the stars in the two regions. The median age is 5.9 dex in region I and 6.1 dex in region II. The sense of the difference is the same as reported by Gomez et al., but the numbers involved in our comparison are so small that we cannot consider the difference as statistically significant. The age difference described by Gomez et al. could be the result of different frequencies of singles and multiples in the two regions (whether real or the result of small number statistics).

The observational challenge for the immediate future is to determine luminosities, effective temperatures, ages, and masses of the components of the multiples. The instrumentation required is beginning to be available. This offers the exciting prospect of unraveling the history of star formation in the Taurus SFR and thus advancing our understanding of binary and single star formation.

We thank the directors of the Calar Alto, IRTF, Kitt Peak, Palomar, and Wyoming observatories for the observing time that yielded the data on which this work is based and also thank our colleagues and the observatory staffs for their help. We thank S. Stahler for a particularly constructive referee's report that helped us improve the paper. A. G. acknowledges the support of a Pacific Telesis fellowship. M. S. acknowledges the support of NSF grant 91-4606.

REFERENCES

Allen, C. W. 1973, Astrophysical Quantities (London: Athlone)
Beckwith, S. V. W., Sargent, A. I., Chini, R. S., & Güsten, R. 1990, AJ, 99, 924 (BSCG)
Cohen, M., & Kuhi, L. V. 1979, ApJS, 41, 743
Duquennoy, A., & Mayor, M. 1991, A&A, 248, 485
Elias, J. H. 1978, ApJ, 224, 857
Ghez, A., Neugebauer, G., & Matthews, K. 1992, in IAU Colloq. 135, Complementary Approaches to Double and Multiple Star Research, ed. H. A. McAlister & W. I. Hartkopf (ASP Conf. Ser.), 1
———. 1993, in preparation
Gomez, M., Jones, B. F., Hartmann, L., Kenyon, S. J., Stauffer, J. R., Hewett, R., & Reid, I. N. 1992, AJ, 104, 762
Hartmann, L. W., & Kenyon, S. J. 1990, ApJ, 349, 190
Herbig, G., & Bell, K. R. 1988, Lick Obs. Bull., No. 1111 (HBC)
Jones, B. F., & Herbig, G. H. 1979, AJ, 84, 1872
Kenyon, S. J., & Hartmann, L. W. 1990, ApJ, 349, 197
Leinert, Ch., et al. 1992, in IAU Colloq. 135, Complementary Approaches to Double and Multiple Star Research, ed. H. A. McAlister & W. I. Hartkopf (ASP, Conf. Ser.), 21
Reid, N., & Gilmore, G. 1984, MNRAS, 206, 19
Simon, M. 1992, in IAU Colloq. 135, Complementary Approaches to Double and Multiple Star Research, ed. H. A. McAlister & W. I. Hartkopf (ASP Conf. Ser.).), 141
Simon, M., Chen, W. P., Howell, R. R., Benson, J. A., & Slowik, D. 1992, ApJ, 384, 212
Skrutskie, M. F., Dutkevich, D., Strom, S. E., Edwards, S., Strom, K. M., & Shure, M. A. 1990, AJ, 99, 1187 (SDSESS)
Stahler, S. W. 1983, ApJ, 274, 822
Strom, K. M., Strom, S. E., Edwards, S., Cabrit, S., & Skrutskie, M. F. 1989, AJ, 97, 1451 (SSECS)