Submitted November 2005; Accepted February 2006
Preprint typeset using LaTeX style emulateapj v. 11/26/04

STELLAR MULTIPLICITY AND THE IMF: MOST STARS ARE SINGLE

Charles J. Lada[1]

Submitted November 2005; Accepted February 2006

ABSTRACT

In this short communication I compare recent findings suggesting a low binary star fraction for late type stars with knowledge concerning the forms of the stellar initial and present day mass functions for masses down to the hydrogen burning limit. This comparison indicates that most stellar systems formed in the Galaxy are likely single and not binary as has been often asserted. Indeed, in the current epoch two-thirds of all main sequence stellar systems in the Galactic disk are composed of single stars. Some implications of this realization for understanding the star and planet formation process are briefly mentioned.

Subject headings: stars: binary, formation

1. INTRODUCTION

Ever since Mitchell (1767) pointed out that the observed frequency of visual double stars was too high to be due to random chance, the study of binary stars has occupied an important place in astrophysics. William Herschel (1802) discovered and cataloged hundreds of visual pairs and produced the first observations of a rudimentary binary orbit. In doing so he established that the double stars were indeed physical pairs and that Newtonian physics operated nicely in the distant sidereal universe. By the beginning of the twentieth century tens of thousands of binary stars were known and cataloged (e.g., Burnham 1906). By the middle to late twentieth century the first systematic attempts to establish the binary frequency of main sequence F and G stars suggested that a very high fraction (70 - 80%) of all such stellar systems consist of binary or multiple stars (Heintz 1969; Abt & Levy 1976; Abt 1983). The most comprehensive and complete study of the multiplicity of G stars was performed by Duquennoy & Mayor (1991) who argued that two-thirds of all such stellar systems are multiple.

It has often been assumed but never clearly demonstrated that similar statistics applied to stars of all spectral types. This assumption has led to the commonly held opinion that most all stars form in binary or multiple systems with the Sun (and its system of planets) being atypical as a single star. But how robust is the assumption that the binary statistics for G stars is representative of all stars?

Over the last decade two important developments have occurred in stellar research which directly bear on this question. First, the functional form of the stellar initial mass function (IMF) has been better constrained by observations of both field stars (e.g., Kroupa, 2002) and young embedded clusters (e.g., Muench et al. 2002). The IMF has been found to peak broadly between 0.1 - 0.5 $M_\odot$, indicating that most stars formed in the Galactic disk are M stars. Second, surveys for binary stars have suggested that the binary star frequency may be a function of spectral type (e.g., Fischer & Marcy 1992). In particular, there have been a number of attempts to ascertain the binary frequency of M type stars and even for L and T dwarfs, objectss near and below the hydrogen burning limit. These studies suggest that the binary frequency declines from the G star value, being only around 30% for M stars (e.g., Leinert et al. 1997; Reid & Gizis 1997; Delfosse et al. 2004; Siegler et al. 2005) and as much as a factor of 2 lower for L and T dwarfs (e.g., Gizis et al. 2003). I argue in this communication that these two facts together suggest that most stellar systems in the Galaxy consist of single rather than binary or multiple stars.

[1] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA; clada@cfa.harvard.edu

2. THE SINGLE STAR FRACTION AND SPECTRAL TYPE

In this section I use data compiled from the literature to examine the single star fraction as a function of stellar spectral type, in particular for the range spanning G to M stars. I consider the single star fraction (SSF) to be the fraction of stellar systems without a *stellar* companion, that is, primary stars without a companion whose mass exceeds 0.08 $M_\odot$. Figure 1 displays the single star fraction as a function of spectral type for G and later type stars. This plot suggests that the SSF is significantly greater for M stars than for G stars. Indeed the SSF for M stars appears to be at least 70%. It is difficult to evaluate the significance of this difference at face value given that the differing binary surveys suffer from differing biases and varying degrees of incompleteness. The systematic differences that can arise between the surveys mostly derive from varying sensitivities to primary/secondary separations and mass ratios. Below I attempt to evaluate the results from the surveys used to construct Figure 1.

In their seminal study, Duquennoy & Mayor (1991) obtained a spectroscopic survey of a distance-limited complete sample of F7-G9 stars in the Northern Hemisphere and within 22 pc of the Sun. They examined radial velocities obtained for these stars over a 13 year period. They combined their detections of spectroscopic binaries with known visual binaries and common proper motion pairs to examine 164 primaries for evidence of multiplicity. They derive multiplicity ratios of 57:38:4:1 for single:double:triple:quadruple systems, respectively. They considered all the various detection biases to estimate the incompleteness of their study and concluded that there was a slight bias against detecting low mass companions, this resulted in a 14% upward correction to the multi-

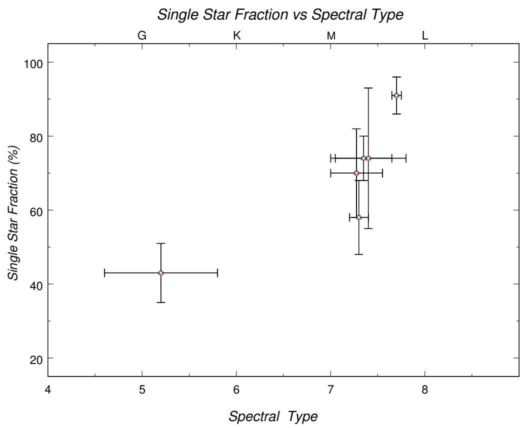

Fig. 1.— The single star fraction vs spectral type. The single star fraction increases significantly with spectral type reaching values of $\sim$ 75% for M stars, the most populous stars in the IMF and the field. Vertical error bars represent statistical uncertainties in the SSF. The horizontal error bars indicate the approximate extent in spectral type covered by the individual surveys and do not represent an uncertainty in this coordinate. Data taken from Duquennoy & Mayor (1991), Reid & Gizis (1997), Fischer & Marcy (1992), Delfosse et al. (2004), Leinert et al. 1997, and Siegler et al. (2005).

plicity fraction such that 57% of systems were estimated to be multiple for a primary/companion mass ratio, q > 0.1. They further extrapolated this incompleteness correction to include substellar secondaries and estimated a multiplicity fraction of 2/3 and a single star fraction of 1/3 for their sample. However, in recent years sensitive and precise radial velocity surveys of 1330 single FGKM stars have indicated a paucity of substellar companions within 5 AU of the primary stars (Marcy & Butler 2000; Marcy et al. 2005). In addition coronographic imaging surveys have found a similar dearth of substellar companions around GK and M stars over separations between 75 and 300 AU (McCarthy & Zuckerman 2004). The existence of this so-called "brown dwarf desert" indicates that Duquennoy & Mayor may have overestimated the multiplicity fraction of G stars and the true value is likely 57% or even somewhat smaller. For the purposes of this paper I adopt 57% as the multiplicity fraction of G type stars and thus 43% for the SSF.

The first extensive examination of the multiplicity of M stars was performed by Fischer & Marcy (1992) who studied radial velocity, speckle and visual binary data for a sample of stars within 20 pc. The full range of separations, $a < 10^4$ AU, was examined, similar to the G star study. These authors pointed out that M star surveys suffer less from the effects of incompleteness than G star surveys because the M star sample is on the whole a factor of 2 closer in distance and M star primaries are sufficiently faint to enable detection of very faint companions more readily. They derived a SSF of 58% which is higher than the G star value.

Reid & Gizis (1997) determined the SSF for a volume complete sample of 79 M2-M4.5 primary stars within 8 pc of the Sun and derived a SSF of 70 $\pm$ 12% for this sample. The range of binary separations they were able to probe was 0.1 - 10^4 AU. A similar volume complete search for M dwarf binaries within 5 pc of the Sun was performed by Leinert et al. (1997) who reported a SSF of 74 $\pm$ 19%. However, their sample of 29 stars is smaller than the Reid & Gizis (1997) and Fischer & Marcy (1997) samples accounting for the larger uncertainty. More recently Delfosse et al. (2004) presented statistics for a much larger sample of 100 M dwarfs which they estimated was 100% complete for stellar mass companions over the entire separation range and out to 9 pc from the Sun. Delfosse et al. (2004) derive a multiple star fraction of 26 $\pm$ 3 % which corresponds to a SSF of 74 $\pm$ 6%. This may represent the most accurate determination for the M star SSF yet made. I note here that even if one considers substellar companions this estimate for the SSF will not likely alter significantly since as mentioned earlier, surveys have revealed a dearth of substellar companions to G, K *and* M stars (Marcy & Butler 2000; McCarthy and Zuckerman 2004).

Surveys for multiplicity among very late M stars and even L and T dwarfs have also been recently reported. These studies typically explore more limited separation ranges and somewhat smaller samples of stars. The multiplicity fractions they find are however all lower than that reported for the earlier type M stars. For example, Siegler et al. (2005) examined a magnitude-limited survey of 36 M6 - M 7.5 stars and derived a binary fraction of 9 $\pm$ 4% corresponding to a SSF of 91 $\pm$ 5%. However this sample is not volume limited and may be incomplete. Thus the inferred SSF is likely an upper limit. Despite this limitation Siegler et al. were able to conclude that wide (a>20 AU) binaries are very rare among these stars. Although not considered for inclusion in Figure 1 because of the large fraction of brown dwarfs in their samples, surveys by Gizis et al. (2003) and Bouy et al. (2003) find similarly small binary fractions for ultra low mass objects. For example, Gizis et al. examined 82 nearby late M and L dwarfs and derived a (incompleteness corrected) binary fraction of 15 $\pm$ 5% (corresponding to a SSF of 85 $\pm$ 14%) for separations, $a > 1.6$ AU. Estimating the possible contribution of companions at smaller separations they suggest a binary star fraction (BSF) of 15 $\leq$ BSF $\leq$ 25 % corresponding to 75 $\leq$ SSF $\leq$ 85 % for these objects near and just below the hydrogen burning limit. Bouy et al. (2003) examined the binary statistics for a sample of 134 late M and L field dwarfs and estimated a binary fraction for a separation range of about 2 - 140 AU of only 10% corresponding to a SSF of 90% for these objects. They also noted a dearth of companions with wide (i.e., $a > 15$ AU) separations. Although these surveys of very low mass and substellar objects suffer from some degree of incompleteness it is quite unlikely that sensible corrections for such effects would decrease the estimated single star fraction to a value similar to that of G stars or even typical M stars.

The observations discussed above lead to the conclusion that the single star fraction is a function of spectral type and increases from about 43% for G stars to $\sim$ 85% for brown dwarfs. The most secure estimate for M stars appears to be about 74% based on the complete volume-limited sample of Delfosse et al. (2004) for M stars with stellar companions.

3. M STARS AND THE IMF

The stellar IMF is one of the most fundamental distribution functions in astrophysics. A great deal of effort has been expended in determining its form since the first attempt to measure its shape by Salpeter (1954).

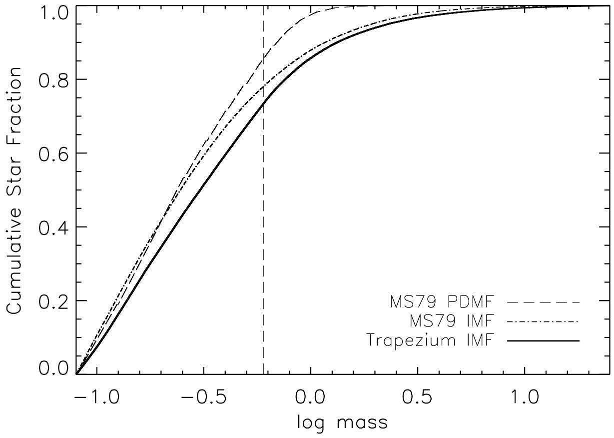

FIG. 2.— The cumulative frequency distributions for all hydrogen burning stars in two versions of the primary star IMF and the PDMF of main sequence field stars. The two IMFs correspond to the Miller-Scalo field star IMF and the IMF derived for the young embedded Trapezium cluster by Muench et al. (2002). The vertical line marks the location of the M star boundary (Torres & Ribas 2002). The fraction of M stars is high for all these mass functions ranging between 73 and 84%. The latter value representing fraction of all main sequence field stars that are M stars currently residing in the Galactic disk. Based on data from Miller & Scalo 1989 and Muench et al. 2002.

He found that the IMF is a power-law which decreases with stellar mass for field stars with masses in the range between 1-10 $M_\odot$. More recent determinations of the IMF for field stars and young embedded clusters have expanded the mass range covered by Salpeter. These studies have found the IMF to break from a single power-law shape near 0.5 $M_\odot$ and to have a broad peak between $\sim$ 0.1 - 0.5 $M_\odot$. On either side of this peak the IMF falls off rapidly (e.g., Miller & Scalo 1979; Kroupa 2002; Muench et al. 2002; Chabrier 2003; Luhman et al. 2006).

The broad peak of the IMF encompasses the M stars and indicates that these stars are the most numerous objects created in the star formation process. This is illustrated in Figure 2 which shows the cumulative fraction of all stars above the hydrogen burning limit given by the IMF. Two different IMFs are plotted which span the range of modern day determinations of this function. One is the log-normal field star IMF derived by Miller & Scalo (1979) and the other represents a determination of the IMF for the embedded Trapezium cluster in Orion in which the IMF is characterized by a series of broken power-laws (Muench et al. 2002). This latter IMF is very similar to that determined for the field by Kroupa (2002) but is more sensitive to substellar masses (not plotted). The vertical dashed line shows the boundary for the M star population. The fraction of all stars *above the hydrogen burning limit (HBL)* that are M stars is 73% for the Muench et al. IMF and 78% for the Miller-Scalo IMF. (It is important to note here that these two IMFs are essentially primary star IMFs, that is, IMFs that do not include companion star masses.) This analysis indicates that roughly 3/4 of all stars formed are M stars.

The IMF represents the frequency distribution of stars at birth and differs from the present day mass function (PDMF) which represents the frequency distribution of all stars currently living within the Galactic disk. Stellar evolution has significantly depleted the high mass end of the PDMF relative to the IMF. Therefore, the fraction M stars in the PDMF is somewhat higher than the fraction in the IMF. Indeed, for the PDMF derived by Miller & Scalo (1979) we find from Figure 2 that 84% of all stars in the Galactic disk are M stars.

4. THE TOTAL SINGLE STAR FRACTION

To estimate the total fraction of single stars, I assume that all stars earlier than M are characterized by the single star fraction for G stars determined by Duquennoy & Mayor (1991), that is, $SSF_{<M} = 43\%$. The single star fraction for M-type stars (i.e., SSF_M) is assumed to be that (74%) determined by Delfosse et al. (2004) for a complete, volume limited sample. The total SSF is then simply given by:

$$\mathrm{SSF(total)} = SSF_{<M} \times ETF + SSF_M \times MTF$$

Here MTF is the M-type fraction, that is, the fraction of all stars that are M-type stars and $ETF = 1 - MTF$ is the early-type fraction, that is the fraction of all stars that have spectral types earlier than M. To determine the SSF for all stars produced at any one time by the star formation process I adopt the Muench et al. and Miller-Scalo IMFs, specifically, MTF = 0.73 and 0.78, respectively. The total SSF is found to be 66% and 67% for these two IMFs, respectively. Therefore, single stars must ultimately account for as many as two-thirds of all stellar systems that formed at any one time in the Galaxy. Similarly, if we consider the MTF (0.84) for the Miller-Scalo PDMF we find the total SSF to be 69%. Thus, *two thirds of all (main sequence) primary stars currently residing in the Galactic disk are single stars.*

5. DISCUSSION AND CONCLUSIONS

The primary result of this paper is the recognition that most stellar systems in the Galaxy consist of single rather than binary stars. This fact has important consequences for star and planet formation theory. For example, contrary to the current accepted paradigm that most, if not all, stars form in binary or multiple systems (e.g., Larson 1972, 2001; Mathieu 1994), this result could indicate that the theoretical frameworks developed to explain the formation of single, sunlike stars (e.g., Shu, Adams & Lizano 1987) have wide applicability. Indeed, when appropriately modified for a cluster-forming environment (e.g., Myers 1998; Shu, Li & Allen 2004), they may even describe most star forming events in the Galaxy. On the other hand, most stars could still initially form in binary or multiple systems provided that most such systems promptly disintegrate via dynamical interactions or decay in an early, perhaps even protostellar, stage of evolution (e.g., Kroupa 1995; Sterzik & Durisen 1998, Reipurth 2000).

The current paradigm that most, if not all stars, form in binaries was strengthened by early multiplicity surveys of pre-main sequence (PMS) stars. In particular, surveys of the PMS population of the Taurus cloud indicated a binary fraction that was twice that of field G stars (Ghez et al. 1993; Leinert et al. 1993; Reipurth & Zinnecker 1993). However, most field stars are now known to have formed in embedded clusters, environments quite different than represented by the Taurus PMS population (e.g., Lada & Lada 2003). Binary surveys of both young embedded and Galactic clusters have revealed binary fractions indistinguishable from that of the field (e.g., Petr et al. 1998; Duchêne, Bouvier & Simon 1999; Patience & Duchêne 2001). The most simple and straightforward hypothesis to explain these two facts and the finding of a high SSF in this paper is that the most common outcome of the star formation process is a single rather than multiple star.

Observations of dust emission and extinction of molecular cloud cores have found that the shape of the primordial or dense core mass function is very similar to that of the stellar IMF except that the core mass function is offset to higher mass by a factor of 2-3 (e.g., Stanke et al. 2005, Alves, Lombardi & Lada 2005). These observations indicate that a 1-to-1 mapping of core mass to stellar mass, modified by a more or less constant star formation efficiency of 30-50%, is possible, if not likely. This idea is consistent with single star systems being most often produced once the cores undergo collapse.

The fact that stellar multiplicity is a function of stellar mass, however, may provide important clues to the nature of the physical process of star formation. For example, Durisen, Sterzik & Pickett (2001) have shown that if individual protostellar cores can further fragment and produce small N clusters, the dynamical decay of these clusters into binary and single stars can in certain circumstances produce a binary star fraction that declines with decreasing primary mass, similar to what is observed. However, to be consistent with the SSF derived here and to simultaneously produce reasonable binary component separations, such models would require $N \geq 5$, within a region ~ 300 AU in size (Sterzik & Durisen 1998). This would correspond to a stellar surface density ($\sim 7.5 \times 10^5$ stars pc^{-2}) about two orders of magnitude higher than the peak density (7.2×10^3 stars pc^{-2}) measured for the rich Trapezium cluster (Lada et al. 2004). Such ultra-dense protostellar groups have not yet been identified, but could be revealed with high resolution infrared imaging surveys of deeply embedded candidates. A related possibility, proposed by Kroupa (1995) and collaborators, posits that all stars are formed in binaries in modestly dense embedded clusters. Dynamical interactions between these systems can disrupt some binaries and modify the separations of others. These models can produce the observed dependance of binary frequency with mass, but at the expense of a SSF (50%) that is too low to be consistent with that derived here. These models could be made consistent with the high Galactic SSF by assuming more compact configurations for the birth clusters, however it is unclear whether the required higher cluster densities would remain consistent with observed values.

Another possibility is that binary star formation is related to the initial angular momentum content of the primordial cores. In this case the initial angular momentum of a protostellar core would be expected to be a function of core mass, with low mass cores being endowed with considerably less angular momentum than high mass cores. A systematic molecular-line survey of cores of varying mass within a molecular cloud could test this idea. A related possibility is that turbulence may play a role in the propensity for a core to fragment. For example, Shu, Li & Allen (2004) posit that the break in the stellar IMF at 0.5 $M_\odot$ is a result of the transition from turbulent to thermal support of the envelopes of dense pre-collapse cloud cores. The more massive the core, the more turbulence is required to insure its support. Ammonia observations of dense cores in fact do suggest that massive cores are more turbulent than low mass cores (Jijina, Myers & Adams 1999). Perhaps increased cloud turbulence in the more massive dense cores can also promote, in some fashion, more efficient core fragmentation and a higher incidence of binary star formation. In this context it would be interesting to know if the trend of increasing stellar multiplicity with stellar mass continues to the more massive A, B and O stars, as has been suggested in some studies (e.g., Preibisch, Weigelt, & Zinnecker 2001, Shatsky & Tokovinin 2002).

Finally I note that the large fraction of single star systems in the field is consistent with the idea that most stars could harbor planetary systems unperturbed by binary companions and thus extra-solar planetary systems that are characterized by architectures and stabilities similar to that of the solar system could be quite common around M stars, provided planetary systems can form around M stars in the first place.

I am indebted to August Muench for constructing the cumulative IMFs presented in Figure 2 and many useful discussions. I thank David Latham and Bo Reipurth for their careful reading of the paper and detailed suggestions and Kevin Luhman, Geoff Marcy, Frank Shu and Pavel Kroupa for useful comments which improved the paper.

REFERENCES

Abt, H. A. 1983, ARA&A, 21, 343
Abt, H. A., & Levy, S. G. 1976, ApJS, 30, 273
Alves, J., Lombardi, M. & Lada C.J. 2006, in preparation.
Bouy, H., Brandner, W., Martín, E. L., Delfosse, X., Allard, F., & Basri, G. 2003, AJ, 126, 1526
Burnham, S. W. 1906, A General Catalog of Double Stars within 121 Degrees of the North Pole, [Chicago, University of Chicago Press].
Chabrier, G. 2003, PASP, 115, 763
Delfosse, X., et al. 2004, ASP Conf. Ser. 318: Spectroscopically and Spatially Resolving the Components of the Close Binary Stars, 318, 166
Durisen, R. H., Sterzik, M. F., & Pickett, B. K. 2001, A&A, 371, 952
Duchêne, G., Bouvier, J., & Simon, T. 1999, A&A, 343, 831
Duquennoy, A., & Mayor, M. 1991, A&A, 248, 485
Fischer, D. A., & Marcy, G. W. 1992, ApJ, 396, 178
Ghez, A. M., Neugebauer, G., & Matthews, K. 1993, AJ, 106, 2005
Gizis, J. E., Reid, I. N., Knapp, G. R., Liebert, J., Kirkpatrick, J. D., Koerner, D. W., & Burgasser, A. J. 2003, AJ, 125, 3302
Heintz, W. D. 1969, JRASC, 63, 275
Herschel, W. 1802, Phil. Trans. Royal Society of London, 92, 477.
Jijina, J., Myers, P. C., & Adams, F. C. 1999, ApJS, 125, 161
Kroupa, P. 1995, MNRAS, 277, 1491
Kroupa, P. 2002, Science, 295, 82
Lada, C. J., & Lada, E. A. 2003, ARA&A, 41, 57
Lada, C. J., Muench, A.A., Lada, E. A. & Alves, J.F. 2004, AJ, 128, 1254
Larson, R. B. 1972, MNRAS, 156, 437
Larson, R. B. 2001, IAU Symposium, 200, 93
Leinert, C., Zinnecker, H., Weitzel, N., Christou, J., Ridgway, S. T., Jameson, R., Haas, M., & Lenzen, R. 1993, A&A, 278, 129
Leinert, C., Henry, T., Glindemann, A., & McCarthy, D. W. 1997, A&A, 325, 159

Luhman, K. L. et al. 2006, in Protostars and Planets V, ed., B. Reipurth, D. Jewitt & K. Keil, (University of Arizona Press: Tucson), in press.
Marcy, G. W., & Butler, R. P. 2000, PASP, 112, 137
Marcy, G., Butler, R. P., Fischer, D., Vogt, S., Wright, J. T., Tinney, C. G., & Jones, H. R. A. 2005, Progress of Theoretical Physics Supplement, 158, 24
Mathieu, R. D. 1994, ARA&A, 32, 465
McCarthy, C., & Zuckerman, B. 2004, AJ, 127, 2871
Miller, G. E., & Scalo, J. M. 1979, ApJS, 41, 513
Mitchell, J. 1767, Phil.Trans.Roy.Soc., LXXVI, 97.
Muench, A. A., Lada, E. A., Lada, C. J., & Alves, J. 2002, ApJ, 573, 366
Myers, P. C. 1998, ApJ, 496, L109
Patience, J., & Duchêne, G. 2001, IAU Symposium, 200, 181
Petr, M. G., Coude Du Foresto, V., Beckwith, S. V. W., Richichi, A., & McCaughrean, M. J. 1998, ApJ, 500, 825
Preibisch, T., Weigelt, G., & Zinnecker, H. 2001, IAU Symposium, 200, 69
Reid, I. N., & Gizis, J. E. 1997, AJ, 113, 2246
Reipurth, B. 2000, AJ, 120, 3177
Reipurth, B., & Zinnecker, H. 1993, A&A, 278, 81
Salpeter, E. E. 1955, ApJ, 121, 161
Shu, F. H., Adams, F. C., & Lizano, S. 1987, ARA&A, 25, 23
Shu, F. H., Li, Z.-Y., & Allen, A. 2004, ApJ, 601, 930
Shatsky, N., & Tokovinin, A. 2002, A&A, 382, 92
Siegler, N., Close, L. M., Cruz, K. L., Martín, E. L., & Reid, I. N. 2005, ApJ, 621, 1023
Stanke, T. Smith, M.D., Gredel, R. & Khanzadyan, T. 2005, A&A, in press.
Sterzik, M. F., & Durisen, R. H. 1998, A&A, 339, 95
Torres, G., & Ribas, I. 2002, ApJ, 567, 1140