

## Young Star Clusters: Metallicities, Ages and Masses

Uta Fritze – v. Alvensleben

*Universitätssternwarte Göttingen, Geismarlandstr. 11, D – 37083*  
*Göttingen, Germany*

**Abstract.** Observations of Young Star Cluster (YSC) systems in interacting galaxies are reviewed with particular emphasis on their Luminosity Functions (LF) and colour distributions. A few spectroscopic abundance measurements are available. They will be compared to YSC abundance predictions from spiral galaxy models. Evolutionary synthesis models allow to derive ages for individual YSCs on the basis of their broad band colours. With individual YSC ages models predict the future colour and luminosity evolution of the YSC systems that will be compared – after a Hubble time – to observations of old Globular Cluster (GC) systems. Using model M/L ratios as a function of age, YSC masses can be estimated. Age spread effects in young systems can cause the shape of the LF to substantially differ from the shape of the underlying mass function. Major sources of uncertainty are the metallicity, dust reddening, and observational colour uncertainties.

### 1. Why Do We Want to Know GC and YSC Masses?

GCs are conventionally believed to be (among) the oldest objects in the Universe, dating back to the times of galaxy formation. They are used to constrain the age of the Universe. LFs of GC systems are believed to be universal enough for determinations of distances to  $> 20$  Mpc and of the Hubble constant. On the other hand, “present-day GCs are the hardest survivors of a larger original population” (Harris 1991). Hence, their observed LF is not only their LF at formation shifted by stellar evolutionary fading, but might be additionally modified by cluster destruction processes. Dynamical modelling of cluster systems in the Galactic potential shows that destruction processes and timescales strongly depend on cluster masses. While destruction by dynamical friction is more efficient for high mass clusters, tidal shocking and evaporation preferentially destroy low mass clusters.

Bright YSCs are observed in large numbers in interacting galaxies and merger remnants and a burning question with far-reaching implications is if these YSCs are young GCs. Masses derived for these YSCs are much higher than those of open clusters in the Milky Way. Effective radii of YSCs typically are a few pc similar to GC radii. The mass function (MF) of YSC systems in comparison with the MFs of molecular clouds or molecular cloud cores tells us about star and cluster formation processes. The MF of YSCs, as first pointed out by Meurer (1995), may differ in shape from their LF since M/L varies rapidly

at young ages and the age spread within a YSC system is not much smaller than its age. The LF of open clusters in the Milky Way, the MFs of molecular clouds and molecular cloud cores, the observed LFs of YSCs, e.g. in NGC 4038/39, NGC 7252, NGC 3256, and of giant H II regions all are power laws with slopes in the range  $\alpha \sim -1.5 \dots -1.8$  (cf. Solomon et al.1987, Lada, Bally & Stark 1991, Kennicutt 1989, and reviews by Harris & Pudritz 1994, Elmegreen & Efremov 1997). Yet the LF of old GCs is Gaussian with typical parameters  $\langle M_V \rangle \sim -7.3$  mag,  $\sigma(M_V) \sim 1.3$  mag, their MF is log-normal with typically  $\langle \text{Log}(M/M_\odot) \rangle \sim 5.5$ ,  $\sigma \sim 0.5$  (e.g. Ashman, Conti & Zepf 1995).

Hence the question as to the MF of YSCs has profound implications. If the MF of YSCs were a power law like their LF and if YSC systems are to evolve into something similar to old GC systems, dynamical destruction processes would have to transform the power law MF into a log-normal MF over a Hubble time. If, on the other hand, the MF of YSCs were log-normal (and their LF distorted to a power law by age spread effects), then the star/cluster formation process would have to transform the power law MF of the molecular clouds into the log-normal MF of YSCs. Or, else, might already the MF of molecular clouds/cloud cores in violently star forming mergers (where to my knowledge it has not yet been observed) be different from what it is in quietly star forming ‘normal galaxies’ (where it is observed)?

## 2. Evolutionary Synthesis of SSPs

Star clusters are simple stellar populations (SSPs), formed in one short burst of star formation with one metallicity  $Z$ . With evolutionary synthesis models, the time evolution of SSPs of various metallicities  $Z_i$  is studied in terms of luminosities  $L_\lambda$ , colours, spectrum, absorption features, stellar mass loss, and hence  $M/L$  by many groups (e.g. Bruzual & Charlot 1993, Worthey 1994, Bressan, Chiosi & Fagotto 1994, Fritze–v. Alvensleben & Burkert 1995, Leitherer et al.1999, Kurth, Fritze - v. Alvensleben & Fricke 1999). Basic parameters of this approach are the IMF and the set of stellar evolutionary tracks used (e.g. from the Padova or Geneva groups). All models agree that the changes in luminosities and colours are rapid in early evolutionary stages and become slower with increasing age. The colour evolution depends significantly on metallicity, already in very early stages, and the fading also depends on metallicity, in particular during the first Gyr (cf. Fritze – v. Alvensleben & Burkert 1995, Kurth, Fritze - v. Alvensleben & Fricke 1999).

## 3. YSC Observations vs. SSP Models

### 3.1. Procedure

If the metallicity of YSCs is known, individual ages can be obtained on the basis of their observed UBV $I$  colours. Unfortunately, metallicity information from spectroscopy is only available yet for a handful of YSCs in NGC 7252 (Schweizer & Seitzer 1993, 1998) and NGC 1275 (Brodie et al.1998). In all other cases we have to go back to some educated guess. In gas rich galaxy mergers, YSCs form out of the gas from the progenitor (spiral) galaxies, the

abundance of which gives a lower limit to YSC abundances. E.g., for the YSCs in NGC 7252, which is a merger of two luminous Sc type spirals, we had predicted  $Z_{\text{YSC}} \gtrsim Z_{\text{ISM}}^{\text{Sc}} \sim 1/2 Z_{\odot}$  from the ISM abundance evolution in our 1-zone spiral models (Fritze - v. Alvensleben & Gerhard 1994). Spectroscopy of the brightest YSCs yielded  $Z_{\text{YSC}} \sim Z_{\odot}$  with some tentative indication of self-enrichment during the burst from the comparison of Mgb and Fe lines (cf. Fritze - v. Alvensleben & Burkert 1995). Distances are known for all YSC systems. Hence absolute luminosities  $L_V$  can be combined with  $M/L_V$ - values from SSP models of appropriate age and metallicity to derive the masses of YSCs.

### 3.2. Sources of uncertainty

Sources of uncertainty for these mass estimates come both from observations and models. Observational errors on luminosities and colours might be inhomogeneous and probably not independent of each other, dust extinction is not known for individual YSCs, the dust distribution in some systems is inhomogeneous, the metallicity is, at most, known for a small subsample of YSCs and might show an intrinsic scatter, and, finally, the completeness limit need not be homogeneous over the region of YSC observations. Intrinsic model uncertainties are estimated to be  $\lesssim 0.1$  mag in (optical) luminosities and colours. Differences between models from various authors are mainly due to differences in the stellar input physics. While serious colour discrepancies at very young ages  $\sim 10$  Myr are seen, e.g. comparing models from Bruzual & Charlot with those of Leitherer et al., probably due to the inclusion/non-inclusion of emission lines, fairly good agreement is reached among models from various groups for the same metallicity and IMF at all ages  $\gtrsim 60 - 100$  Myr. E.g.,  $\Delta(V - I) |_{12 \text{ Gyr}} \lesssim 0.1$  mag and  $\Delta(M/L_V) |_{12 \text{ Gyr}} \lesssim 10\%$ .

$M/L_{\lambda}$ , however, depends on wavelength  $\lambda$ , metallicity  $Z$ , and IMF, i.e. on its slope and lower mass limit. In Tab. 1, I briefly sketch out these dependencies as obtained from our models using Padova stellar evolutionary tracks for stars in the mass range  $0.1 - 60 M_{\odot}$  (cf. Kurth, Fritze - v. Alvensleben & Fricke 1999) and two different IMFs (Salpeter vs. Scalo 1986).

In general and as reported by others before, model  $M/L_V$  are about twice as large as are  $M/L_V$ - values derived from observations of old GCs, even when a Scalo IMF is assumed. For a Salpeter IMF the discrepancy is higher by another factor of two. Observational  $M/L$ - values are obtained by measuring the central velocity dispersion  $\sigma_0$ , central surface brightness  $I_0$ , and half light radius  $r_{1/2}$ , and assuming isotropic orbits, no radial gradients in  $M/L$ , and no DM halos around GCs. Then

$$M/L \sim \frac{\sigma_0^2}{I_0 r_{1/2}}$$

and typical values quoted for Galactic GCs are  $M/L_V \sim 2$ . There are two effects that might invalidate the assumptions going into this derivation. First of all, mass segregation in GCs (cf. Meylan, these proceedings, p. 215) will result in an  $M/L$  increasing with radius, as e.g. observed by Côté et al. (1995) for NGC 3201. Second, low mass stars with their high  $M/L$ - values are preferentially lost by evaporation (e.g. Gerhard, these proceedings, p. 12). While both processes are undoubtedly at work in GCs, attempts to examine quantitatively the validity of the assumptions involved seem to still give ambiguous results. Leonard, Richer

& Fahlman (1992) use proper motion data and radial velocity measurements for stars in the GC M13 and find that  $\sim 50\%$  of the mass of M13 is in low mass stars and brown dwarfs. Including this unseen mass leads to an increased  $M/L \sim 4$ , a value well compatible with the models. On the other hand, observations of tidal tails on some GCs in the Milky Way potential are interpreted to indicate that there is not much DM around those GCs, constraining their mass-to-light ratios to  $M/L \lesssim 2.5$  (Moore 1996).

Table 1.  $M/L$ -values from SSP models at various wavelengths for young, intermediate age, and old stellar populations compared for two metallicities and two different IMFs.

	$Z = 10^{-3} \quad 2Z_{\odot}$					
$10^8$ yr	$M/L_{U,B}$	$\sim$	0.1	0.1	indep. of	
	$M/L_{V,R}$	$\sim$	0.2	0.2	Z & IMF	
	$M/L_K$	$\sim$	0.3	0.5	indep. of IMF	
$10^9$ yr	$M/L_B$   Salp	$\sim$	0.5	0.9	$\sim$	$2 \times M/L_B$   Scalo
	$M/L_V$   Salp	$\sim$	0.8	1.0	$\sim$	$2 \times M/L_V$   Scalo
	$M/L_K$   Salp	$\sim$	1.5	0.9	$\sim$	$1.5 \times M/L_K$   Scalo
12 Gyr	$M/L_{B,V}$   Salp	$\sim$	8	12	$\sim$	$2 \times M/L_{B,V}$   Scalo
	$M/L_K$   Salp	$\sim$	5	1.5		–
	$M/L_K$   Scalo	$\sim$	3.5	2.7		–

#### 4. YSCs in the Antennae: a 1<sup>st</sup> Example

The Antennae galaxies (= NGC 4038/39) is an interacting pair of two gas rich spirals, probably Sc, of comparable mass. In the ongoing starburst triggered by the interaction a population of bright YSCs is formed, numerous enough to allow for the first time to reasonably define a LF. The LF from WFPC1 observations is a power law with slope  $\alpha \sim -1.8$  (Whitmore & Schweizer 1995 [WS95]). WFPC2 re-observations are presented by Miller (these proceedings, p. 71).

Assuming a homogeneous metallicity  $Z \sim 1/2 \cdot Z_{\odot}$  lack of individual cluster spectroscopy and in analogy to the YSC system in NGC 7252, I analysed the WFPC1 data of WS95 with evolutionary synthesis models for SSPs. In a first step, the average de-reddened ( $V - I$ ) colour of the 550 YSCs is used to derive a mean age of the YSC population of  $(2 \pm 2) \cdot 10^8$  yr, consistent with Barnes' (1988) dynamical model for the interaction between NGC 4038 and 4039 and consistent

with Kurth's (1996) global starburst age. SSP models describe both the fading and the reddening of the YSC population as it ages. Assuming a mean age for the YSC population, both the LF and the colour distribution of the YSCs are simply shifted towards fainter magnitudes and redder colours, respectively, without changing shape.

#### 4.1. Evolution of the YSC LF

In a second step, individual ages are derived for all the YSCs on the basis of their individual  $(V - I)$  and  $(U - V)$  colours. Interestingly, the resulting age distribution not only shows a peak at very young ages  $0 - 4 \cdot 10^8$  yr for the YSCs, but also a contribution from  $\sim 12$  Gyr old GCs from the parent galaxies (Fig. 1a). A small number of apparent interlopers are probably due to inhomogeneities in the dust distribution. It is improbable that many of the old GCs we identify are highly reddened YSCs, since they would have to be exceedingly bright intrinsically. The fact that age estimates from  $(U - V)$  colours, as far as available, agree with age estimates from  $(V - I)$  supports our metallicity assumption and makes us hope that the average  $E_{B-V}$  is correct for most of the clusters. It is clear, however, that the individual YSC extinctions are a major source of uncertainty in this analysis. With individual YSC ages and observed luminosities, SSP models can be used to predict the time evolution of cluster luminosities. Neglecting any kind of dynamical cluster destruction effects, and only using the young star clusters identified, we obtain the surprising result that by an age of 12 Gyr, when age differences among individual YSCs will be negligible, their LF will have evolved from the presently observed power law into a fairly normal Gaussian GC LF with parameters  $M_V = -6.9$  mag and  $\sigma(M_V) = 1.3$  mag (Fig. 1b). The turn-over then is  $\gtrsim 1$  mag brighter than the completeness limit which evolves to  $M_V = -5.7$  mag, and fainter by  $\sim 0.4$  mag than for typical GC systems. This is a consequence of the enhanced metallicity of the YSC population with respect to that of old GC systems, and in agreement both with observations of old GC systems with a range of metallicities (Ashman, Conti & Zepf 1995) and with our SSP model predictions. With this surprising result we confirm and quantify Meurer's conjecture that over a Hubble time, age spread effects can transform an observed power law LF of YSCs into the Gaussian LF of old GCs (cf. Fritze - v. Alvensleben 1998 for details).

The bright end of the LF defined by the old GCs from the parent spirals is well described by a Gaussian LF with parameters  $\langle M_V \rangle = -7.3$  mag and  $\sigma(M_V) = 1.2$  mag, normalised to the total number of GCs in the Milky Way and Andromeda galaxies together (Fig. 2a). Hence, if the two interacting spirals NGC 4038 and 4039 had a similar number of GCs as those galaxies, and if the bulk of the YSC population really are young GCs, Zepf & Ashman's (1993) requirement, that the number of secondary GCs formed in mergers should be comparable to the number of primary GCs in the two progenitor spirals, would be fulfilled. This requirement is necessary if the higher specific GC frequency in ellipticals - as compared to spirals - is to be compatible with a spiral-spiral merger origin for those ellipticals.

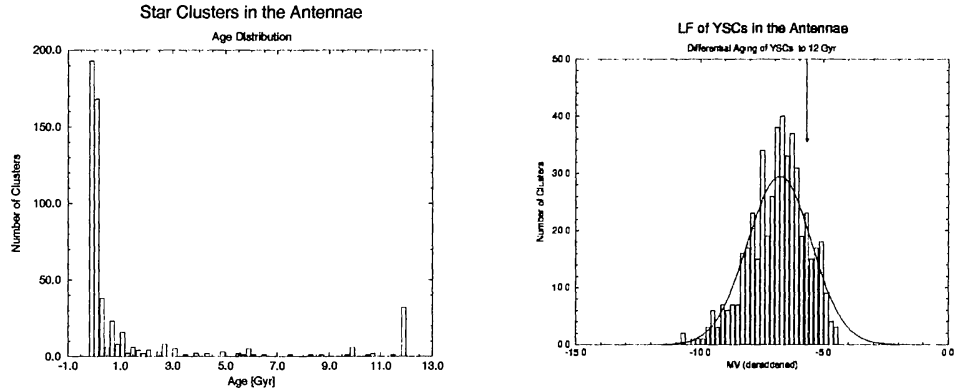


Figure 1. (a) Age distribution of all clusters, (b) LF evolved to 12 Gyr by differential fading for young clusters in the Antennae. The vertical arrow indicates the completeness limit.

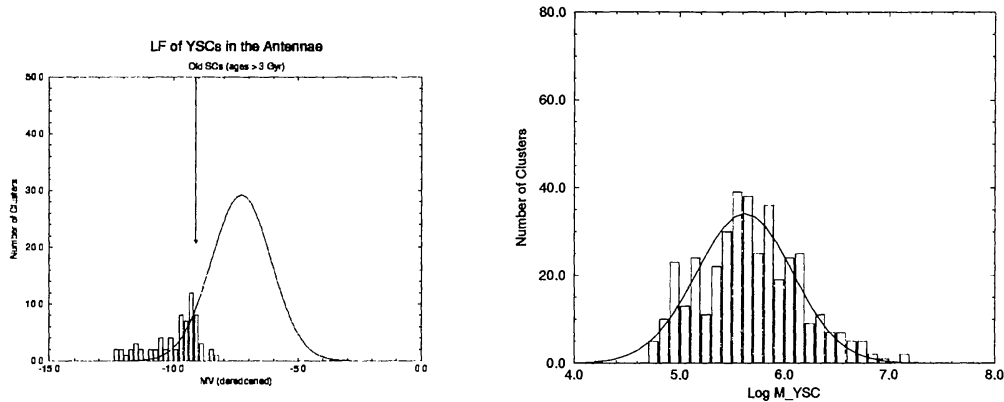


Figure 2. (a) LF of old GCs with Gaussian for GCs in (Milky Way + M31). (b) MF of the young clusters.

#### 4.2. MF of YSCs

To investigate whether the LFs and MFs of old GC systems are determined by the cluster formation process or whether they are the result of secular dynamical destruction processes, we derive the MF of the very young star cluster system in the Antennae. We restrict ourselves to YSCs brighter than the completeness limit, use individual YSC ages and luminosities, and combine them with model M/L for the respective YSC ages to determine their individual masses. Our tentative conclusion is that for all the 393 YSCs brighter than the completeness limit and with  $(V - I)$  colours available, the MF is compatible with a Gaussian MF with parameters  $\langle \text{Log}(M_{\text{YSC}}/M_{\odot}) \rangle = 5.6$ ,  $\sigma \sim 0.46 \longleftrightarrow \langle \text{Mass}(\text{YSC}) \rangle \sim 4 \cdot 10^5 M_{\odot}$  (Fig. 2b). If we include YSCs fainter than the completeness limit, neither the shape nor the parameters of the MF are changed (cf. Fritze – v. Alvensleben 1999 for details).

The uncertainty in the YSC metallicity leads to age uncertainties, which, in turn, lead to uncertainties in model M/L values of the order of 10 % in these

early stages. Inhomogeneities in the dust distribution do not seem to be very important for the brightest YSCs for which ages from  $(U - V)$  agree with ages from  $(V - I)$  colours. We do not know, however, how important they are for those YSCs that are not detected in  $U$ . Hence, on the basis of  $(V - I)$  alone, we cannot quantify in how far an inhomogeneous internal reddening might affect our results. For this reason and since our analysis is based on WFPC1 data, we caution that our conclusions concerning the evolution of the YSC LF and their MF can only be preliminary. As soon as the reduced WFPC2 data presented by Miller will become available to us, we shall repeat our analysis and supplement it with simulations to estimate the effects of differential observational uncertainties.

### 4.3. Implications

If, however, our preliminary result became confirmed, this would imply that the log-normal MF of old GCs is produced by the cluster formation process rather than by secular dynamical evolution of the cluster system. In this context, it seems very interesting to obtain observational information about the molecular cloud mass spectrum in massive interacting galaxies. Jog & Solomon (1992) conjecture that the strongly enhanced ambient pressure in massive gas rich mergers might affect the molecular cloud structure. In Ultraluminous Infrared Galaxies – which all are mergers with strong starbursts – the fraction of gas at very high densities of  $n \sim 10^4$  and  $10^5 \text{ cm}^{-3}$ , as traced by HCN and CS lines, with respect to gas at  $n \sim 500 \text{ cm}^{-3}$ , as traced by CO, is indeed observed to be higher by 1 – 2 orders of magnitude (e.g. Solomon et al.1992).

### 4.4. Discussion

Even with deeper WFPC2 data, however, the MF of the YSCs in the Antennae does not yet seem to be unambiguously settled. Zhang & Fall (1999) use reddening-free colour indices  $Q_1$ ,  $Q_2$ , solar metallicity Bruzual & Charlot models, consider incompleteness and stellar contamination, and find power law MFs with slopes  $\alpha \sim -2$  for YSCs in the two age intervals 2.5 – 6.3 Myr and 25 – 160 Myr where  $Q_1$  and  $Q_2$  give unambiguous results. In an independent analysis of the same data, Miller (these proceedings, p. 71) find a significant flattening in the observed LF at  $M_V \sim -10.7$  mag. Intriguingly, this value is exactly the turnover luminosity implied by our MF at the mean YSC age in the absence of an age spread. Miller's method of reconstruction, however, leads to a power law YSC MF. Clearly, more work both from the modelling and observational sides is needed before we really understand the YSC MF.

### 4.5. Other systems

For the YSCs in NGC 7252 and NGC 3921, Miller & Fall (1997) and Miller (these proceedings, p. 71) prefer power law MFs. Distances to those systems, however, are larger by factors 3 and 4, respectively, pushing the completeness limit to higher luminosities, even in WFPC2 data. Moreover, the YSCs in these dynamically old merger remnants have higher mean ages (650 – 750 Myr for NGC 7252, 250 – 750 Myr for NGC 3921, as compared to 200 Myr for the Antennae), and hence, are intrinsically fainter already by 0.8 – 1 mag, on average. If we assume that the MFs for the YSCs in NGC 7252 and NGC 3921 were identical to the one we derived for the YSCs in the Antennae, we obtain turn-over

luminosities  $\langle M_V \rangle = -10 \dots -9.5$  mag for NGC 7252 and  $\langle M_V \rangle = -9.5 \dots -9$  mag for NGC 3921 at their respective mean YSC ages. In both cases, these turn-over luminosities are close to the completeness limits. The difficulty to disentangle the old GC and the YSC populations also increases with increasing YSC age. We therefore doubt that it is possible to track the MF beyond a possible turnover in NGC 7252 and 3921. In any case, the YSCs in NGC 7252 and 3921 have survived  $\gg 10$  crossing times and from this fact alone are young GCs rather than open ones, as also indicated by their combination of small effective radii and high luminosities (cf. Miller & Fall 1997, Schweizer et al. 1996).

#### 4.6. Dynamical evolution

Stellar mass loss is included in our models for the evolution of M/L. Over 12 Gyr, the masses of YSCs will decrease by  $\sim 10$  and 15% for a Salpeter and Scalo-IMF, respectively. About half of the entire stellar mass loss occurs during the 1<sup>st</sup> Gyr. External dynamical effects from an interaction of the clusters with the potential of the interacting galaxy system seem extremely difficult to model. Comparison of YSC LFs and MFs in an age sequence of interacting galaxies, mergers, merger remnants, and dynamically young ellipticals will allow to “see these processes at work”.

In the Milky Way potential, Vesperini (1998) has shown that an assumed initially log-normal GC MF is conserved in shape and parameters during self-similar evolution over a Hubble time despite the destruction of  $\sim 50\%$  of the cluster population. If, on the other hand, he starts with a power law MF, severe fine-tuning is required for his model parameters to secularly transform it into the observed log-normal MF of old GC systems.

It is clearly important to analyse more YSC systems in order to see if (and in how far) their MFs are universal or might depend on environment. Old GC systems have their turn-over around  $\langle M_V \rangle \sim -7.2$  mag. With 10m telescopes they are accessible to more than Virgo cluster distances. MOS – e.g. with FORS on the VLT – in combination with HST imaging will allow to determine cluster abundances and hence to more precisely age-date them, and may even provide kinematic information for independent mass estimates.

An open question seems to me if the (globular) cluster formation process in the high metallicity environment of interacting spirals today is the same or not as it was in the Early Universe when the radiation field was stronger and the metallicity lower.

**Acknowledgments.** I wish to thank the organisers and in particular Ariane Lançon for a stimulating workshop in a very pleasant and warm atmosphere in cold and rainy Strasbourg.

#### References

- Ashman, K. M., Conti, A., & Zepf, S. E. 1995, AJ, 110, 1164
- Barnes, J. E. 1988, ApJ, 331, 699
- Bressan, A., Chiosi, C., & Fagotto, F. 1994, ApJS, 94, 63
- Brodie, J. P., Schröder, L. L., Huchra, J. P., et al. 1998, AJ, 116, 691
- Bruzual, G. A., & Charlot, S. 1993, ApJ, 405, 538



- Côté, P., Welch, D. L., Fischer, P., & Gebhardt, K. 1995, *ApJ*, 454, 788  
Elmegreen, B. G., & Efremov, Y. N. 1997, *ApJ*, 480, 235  
Fritze - v. Alvensleben, U. 1999, *A&A*, 342, L25  
Fritze - v. Alvensleben, U. 1998, *A&A*, 336, 83  
Fritze - v. Alvensleben, U., & Burkert, A. 1995, *A&A*, 300, 58  
Fritze - v. Alvensleben, U., & Gerhard, O. E. 1994, *A&A*, 285, 751  
Harris, W. E. 1991, *ARA&A*, 29, 543  
Harris, W.E., & Pudritz, R. E. 1994, *ApJ*, 429, 177  
Jog, C. J., & Solomon, P. M. 1992, *ApJ*, 387, 152  
Kennicutt, R. C. 1989, *ApJ*, 344, 685  
Kurth, O. 1996, Diploma Thesis, Universität Göttingen  
Kurth, O., Fritze - v. Alvensleben, U., & Fricke, K. J. 1999, *A&AS*, 138, 19  
Lada, E., Bally, J., & Stark, A. A. 1991, *ApJ*, 368, 432  
Leitherer, C., Schaerer, D., Goldader, J. D., et al. 1999, *ApJS*, 123, 3  
Leonard, P. J. T., Richer, H. B., & Fahlman, G. G. 1992, *AJ*, 104, 2104  
Meurer, G. R. 1995, *Nature*, 375, 742  
Miller, B. W., & Fall, S. M. 1997, *AAS*, 119, 11504  
Moore, B. 1996, *ApJ*, 461, L13  
Scalo, J. M. 1986, *Fundamentals of Cosmic Physics*, 11, 1  
Schweizer, F., & Seitzer, P. 1993, *ApJ*, 417, L29  
Schweizer, F., & Seitzer, P. 1998, *AJ*, 116, 2206  
Schweizer, F., Miller, B. W., Whitmore, B. C., & Fall, S. M. 1996, *AJ*, 112, 1839  
Solomon, P. M., Downes, D., & Radford, S. J. E. 1992, *ApJ*, 387, L55  
Solomon, P. M., Rivolo, A. R., Barrett, J., & Yahil, A. 1987, *ApJ*, 319, 730  
Vesperini, E. 1998, *MNRAS*, 299, 1019  
Whitmore, B.C., & Schweizer, F. 1995, *AJ*, 109, 960 (WS95)  
Worthey, G. 1994, *ApJS*, 95, 107  
Zepf, S. E., & Ashman, K. M. 1993, *MNRAS*, 264, 611  
Zhang, Q., & Fall, S. M. 1999, *ApJ*, 527, L81