1997RMxAC...6..114L

RevMexAA (Serie de Conferencias), **6**, 114–119 (1997)

THE STELLAR CONTENT OF STARBURSTS — CLIMBING THE STARBURST DISTANCE LADDER[1]

Claus Leitherer[2]

RESUMEN

Se revisa el contenido de estrellas masivas en regiones con brotes de formación estelar ("starburst"). Las técnicas observacionales sugieren una caracterización natural debido a las distancias. Los "starbursts" del grupo local son fundamentales: sus distancias permiten usar las técnicas directas e indirectas para restringir los parámetros característicos de los "starbursts". Un resultado importante, obtenido de numerosos estudios independientes, es la universalidad de la función inicial de masa. Las estrellas masivas tienen una distribución de tipo Salpeter, independiente de su medio ambiente.

ABSTRACT

The massive-star content of starburst regions is reviewed. Observational techniques suggest a natural categorization in terms of the "starburst distance ladder". Starbursts in the Local Group are fundamental: their distance allows an overlap of both direct and indirect techniques to constrain starburst parameters. A key result from numerous independent studies is the universality of the initial mass function. Massive stars have a Salpeter-like mass distribution, irrespective of the properties of their environment.

Key words: **GALAXIES: STAR CLUSTERS — GALAXIES: STARBURST — GALAXIES: STELLAR CONTENT — H II REGIONS — STARS: EARLY-TYPE**

1. INTRODUCTION

Searle et al. (1973) drew attention to a group of galaxies having particularly blue colors when plotted on a two-color diagram. They concluded that these objects experience a "flash" in their colors due to an intense burst of star formation (SF). The shortness of the episode and the luminosity suggests a burst of high-mass SF. Galaxies with strongly enhanced high-mass SF rates are loosely called "starburst galaxies". (See R. Terlevich's contribution for a more rigorous definition.) Starburst galaxies are a rather heterogeneous class of objects comprising, among others, H II galaxies, nuclear starbursts, and infrared-luminous galaxies (see Leitherer 1996).

In this review I will attempt to place constraints on the massive-star content of starbursts from an observational point of view. My approach has two goals. First, I will highlight the importance of observational cross-calibrations between nearby and distant starbursts. To this end I am defining a "starburst distance ladder" which has five steps, each requiring particular observational techniques to study massive stars. Second, I will evaluate our knowledge of the high-mass star content along the distance ladder. This includes SF histories, initial mass-function (IMF), and the influence of the environment. Complementary reviews can be found in the conference proceedings edited by Kunth et al. (1985), Thuan et al. (1987), Leitherer et al. (1991), Tenorio-Tagle (1994), Kunth et al. (1996), and Leitherer et al. (1996).

2. STEP I: HIGH-MASS STAR FORMATION IN THE GALAXY

Our Galaxy does not classify as a starburst. Even the most luminous star-forming regions in our Galaxy are tiny on a cosmic scale. They are not dominated by the properties of an entire population but by individual stars. Therefore *stochastic effects* prevail. Extinction represents a severe problem when a reliable census of the

---

[1] Based on observations with the NASA/ESA *Hubble Space Telescope*, obtained at the Space Telescope Science Institute, which is operated by AURA for NASA under contract NAS5-26555.

[2] Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA.

Galactic high-mass SF is required. Massive stars belong to the extreme population I, with correspondingly small vertical scale heights. Any line of sight between the Sun and high-mass SF regions suffers heavy obscuration. Moreover, the proximity of Galactic regions —although advantageous for detailed studies of individual stars— makes it often difficult to obtain integrated properties, such as total emission-line fluxes of the ionized gas.

W51 probably is the closest Galactic counterpart of a distant dust-enshrouded infrared-luminous starburst (see Sanders & Mirabel 1996 for a review). It was recently studied by Goldader & Wynn-Williams (1994), who discuss *JHK* images of W51 IRS1 and 2. IRS2 contains a cluster of bona fide O stars ionizing the surrounding gas. Its estimated luminosity is lower than that of 30 Doradus (see below) by a factor of a few. More detailed studies are hampered by the total visual extinction of $A_V \approx 24$ mag. Despite these caveats, Galactic high-mass SF regions play a key role in understanding more distant starbursts. They are the fundamental first step on the distance ladder (cf., also A. Moffat's contribution). Stars can easily be resolved and individual spectra be obtained. Substantial work in this respect has been done by Massey and collaborators, see Massey et al. (1995). Empirical Hertzsprung-Russell diagrams were constructed via photometry and spectroscopy and the IMF was derived from a comparison with evolutionary models. Main results are: (i) Massive stars are born within less than 3 Myr, i.e., the burst occurs quasi-instantaneous, and (ii) there is no significant difference in the IMF slopes among the clusters.

NGC 3603, the Galaxy's most massive visible H II region, has been called the Galactic clone of 30 Dor (Moffat et al. 1994). High-quality spectra of individual stars have been presented by Drissen et al. (1995). Their inferred output of photons is consistent with being the dominant source of ionization of the surrounding gas. The IMF of massive stars, derived from a direct census, is close to Salpeter.

3. STEP II: MINI-STARBURSTS IN THE LOCAL GROUP

High-mass SF regions in the Local Group of galaxies are excellent laboratories to study starbursts: their proximity (with respect to galaxies in the Hubble flow) permits detailed studies of *individual* stars, yet their distance (with respect to Milky Way clusters) makes it possible to obtain integrated properties as well. Although more luminous than the Galactic regions of Section 2, they are still underluminous in comparison with starburst prototypes. Therefore I will refer to these regions, which are mostly giant H II regions, as "mini-starbursts". Kennicutt (1984) gives a catalog of the most prominent giant H II regions in nearby galaxies, including their nebular properties. Regions studied in some detail are NGC 595 and NGC 604 in M33 (Hunter et al. 1995; Malumuth et al. 1996; Terlevich et al. 1996) and 30 Dor in the LMC (see Walborn 1991 for a review). I will take 30 Dor as the Rosetta Stone of a mini-starburst for a more extended discussion.

Numerous studies of 30 Dor (with its ionizing cluster NGC 2070, whose massive center is R136) exist. Chu & Kennicutt (1994) mapped the kinematics of the ionized gas using echellograms. Fast expanding shells are detected. Their kinetic energies of $\sim 10^{52}$ erg are comparable to the estimated stellar wind and supernova output over the past 10 Myr. 30 Dor has been used by Vacca et al. (1995) to test evolutionary synthesis models: on the one hand, a census and spectra of individual stars are available (Parker 1993; Heap et al. 1994; Malumuth & Heap 1994), and on the other, integrated drift-scan spectra of the central 3′ have been obtained. Vacca et al. (1995) found that the integrated 30 Dor spectrum can be understood as the sum of the observed individual spectra, in combination with stellar models.

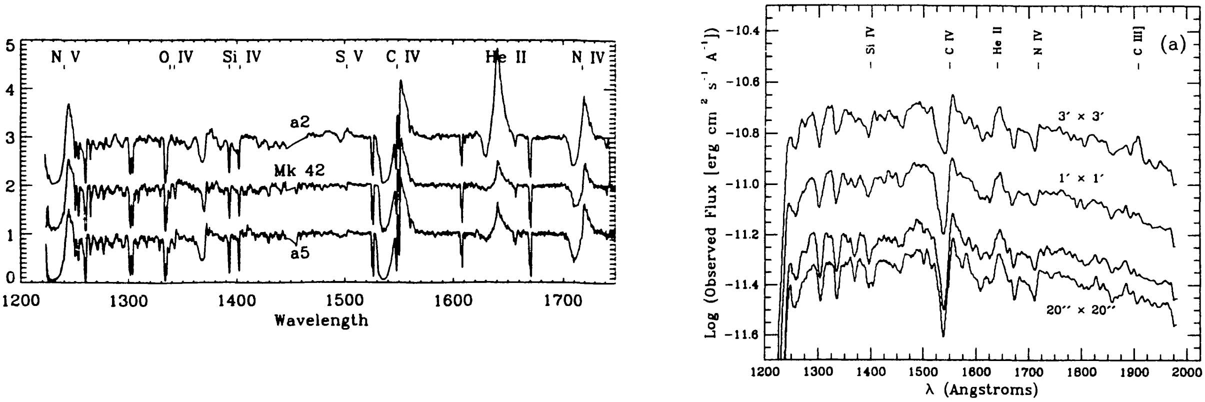

Fig. 1. Left: *HST* Spectra of *individual* massive stars in the central 30 Dor region (Heap et al. 1994). Notice the prominent stellar-wind lines of, e.g., Si IV λ1400 and C IV λ1550. Right: *IUE* scan over the central 30 Dor region, showing the *integrated* ultraviolet spectrum (Vacca et al. 1995). The same wind features are present.

Hunter et al. (1995) made use of the refurbished *HST* to detect stars down to 23.5 mag. Allowing for crowding and reddening, this corresponds to a minimum M_V of ~+1, or a mass of 2.5 $M_\odot$. No indication for a turn-over of the IMF was found: intermediate-mass stars are found at the same frequency as high-mass stars, with the IMF being close to Salpeter. All recent IMF determinations within galaxies of the Local Group indicate a common IMF slope. Inclusion of metal-poor galaxies, such as the SMC, suggests that *massive-star formation proceeds independently of metallicity over a metallicity range from $Z_\odot$ to $Z_\odot/10$* (Massey et al. 1995; W. Waller, this volume).

4. STEP III: NEARBY GALAXIES: RESOLVED STELLAR CONTENT

Detailed spectroscopic studies of large numbers of individual stars are no longer feasible beyond 1 Mpc. At distances up to about 10 Mpc, the field-star population of starburst galaxies and (for the most nearby cases) and some of the less compact clusters can be resolved. NGC 1569 is a Magellanic-type irregular galaxy in the M81/IC342/Maffei group of galaxies (d = 2.5 Mpc). Its extended loops of Hα emission, the high frequency cut-off for non-thermal emission and the general paucity of early O stars and Wolf-Rayet (W-R) stars have led to the suggestion that NGC 1569 is in a post-burst evolutionary phase although many bright H II regions indicate that the rate of star formation is still high (see Waller 1991). O'Connell et al. (1994) studied three super star clusters (SSC's) similar in characteristics to R136, but with a much higher central brightness. The dwarf galaxy NGC 1705 harbors an SSC with similar properties (Meurer et al. 1992).

In Figure 2 a WFPC2 image of NGC 1569 is shown. The most prominent structures are several SSC's, which are essentially unresolved. At 2.5 Mpc, the *HST* resolution limit of ~0.1″ corresponds to 1 pc. Therefore, the corresponding half-light radius is ~1 pc or less. In contrast, *HST* easily resolves the field-star population into individual stars, and color-magnitude diagrams (CMD's) can be obtained via crowded-field techniques. The WFPC2 V image has a limiting magnitude of V ≈ 27 mag (defined as the magnitude whose photometric errors are less than 0.3 mag). At the faintest end, the errors are due to crowding, rather than due to Poisson noise and systematic errors. The corresponding limiting absolute magnitude, taking into account reddening, is $M_V \approx -1.5$. In terms of main-sequence spectral type, this translates into B5 (with a mass of about 7 $M_\odot$), or a look-back time of about 100 Myr.

Analysis of the field-star population of NGC 1569 is not yet complete. Therefore, I am quoting a different example for the star-formation history in an irregular galaxy. Deep ground-based imaging of NGC 2366 and interpretation of CMD's by Aparicio et al. (1995) suggests a burst of star formation about 50 Myr ago (corresponding to a main-sequence turn-off mass of 8 $M_\odot$). SF is still proceeding through the galaxy, possibly triggered by the earlier burst. The most recent burst is observable as the giant H II region NGC 2363, which can be resolved into individual massive stars. Most gas-rich irregular galaxies have relatively constant SF rates

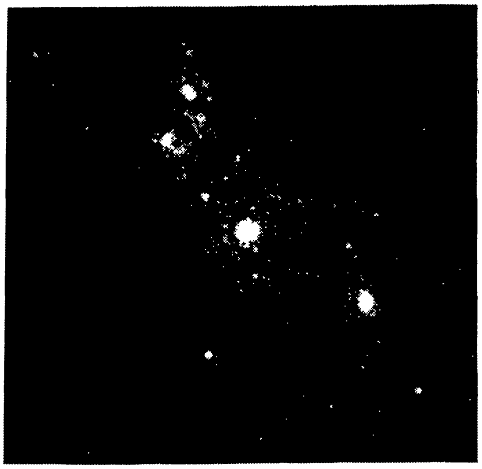

Fig. 2. WFPC2 (PC) V image of NGC 1569 obtained by the author, in collaboration with M. Clampin, G. De Marchi, L. Greggio, A. Nota, and M. Tosi. Field size is 35″. North is up and east to the left. The bright object in the center is the super star cluster NGC 1569A.

for the field-star population over time scales of ~Gyr (see Gallagher 1996 for a recent review of the subject). *Some* irregulars are experiencing short and intense bursts, the most spectacular manifestation being the SSC's observed in NGC 1569 and NGC 1705. At the end of the next section, I will place these clusters on a galactic scale in terms of their mass and luminosity.

5. STEP IV: THE LOCAL UNIVERSE: UNRESOLVED STARBURST REGIONS

SSC's are unresolved, even at small distances of a few Mpc. Beyond about 10 Mpc, severe crowding makes the determination of even the field-star population from CMD's impractical: small clusters of less massive stars mimic single high-mass stars, and the determination of the mass function becomes ambiguous. On this step, stellar properties are derived from spectra of the entire starburst region. Observationally this means collapsing the information of a CMD (temperature, luminosity, number density) into a single parameter (energy distribution). The goal then is to reconstruct theoretically a CMD from the energy distribution, assuming that the loss of information can be compensated by a consistent set of models of stellar evolution and atmospheres, IMF, and SF histories.

NGC 1741 is a luminous ($L \approx L^*$) Magellanic-type irregular at a distance of 50 Mpc. A WFPC2 image is in Figure 3. The galaxy is reminiscent of the LMC, with two luminous H II regions located at the NW end of the bar. The bar population is largely unresolved. If stars were projected from NGC 1569 to NGC 1741, they would appear about 6.5 mag fainter; an isolated 100 $M_\odot$ star would be barely detectable. NGC 1741 is classified as a W-R galaxy: it shows broad *stellar* He II lines in its spectrum (Conti 1991; Vacca & Conti 1992). W-R stars are a brief (10^5 to 10^6 yr), late evolutionary phase of a massive star. Detection of strong W-R features in galaxy spectra has three major implications: (i) Stars more massive than at least 25 $M_\odot$ (depending on Z) must have formed. It is known that individual W-R stars in our Galaxy do not evolve from less massive stars. (ii) The starburst must be in the narrow age range of 3 to 6 Myr. This is the time it takes to make the transition from O to W-R for stars in this mass range. (iii) Star formation must have occurred nearly instantaneously. Since the W-R phase is short in comparison with the O phase, large W-R/O ratios cannot be obtained in a steady-state situation but only in a brief burst observed at the right time (see Maeder & Conti 1994).

Also shown in Figure 3 is the ultraviolet spectrum of the H II region containing the W-R stars. It was used by Conti et al. (1996) to investigate the stellar content. About 15 000 O stars were formed 4 to 5 Myr ago, in agreement with the presence of W-R stars. The inferred IMF is consistent with a Salpeter-like slope. Note the similarity between the ultraviolet spectrum of NGC 1741 and the local calibrator 30 Dor (Figure 1). Even lacking a CMD of the resolved stellar content, the integrated spectrum still allows conclusions on the age and the mass function of the starburst. Independently, the stellar content can be inferred from nebular emission lines. Comprehensive surveys for metal-poor (G. Stasińska, this volume) and metal-rich H II regions (García-Vargas et al. 1995a,b) suggest a universal IMF in starbursts over at least a factor of 10 in metallicity.

It is instructive to compare the properties of some starburst clusters discussed here. This is done in

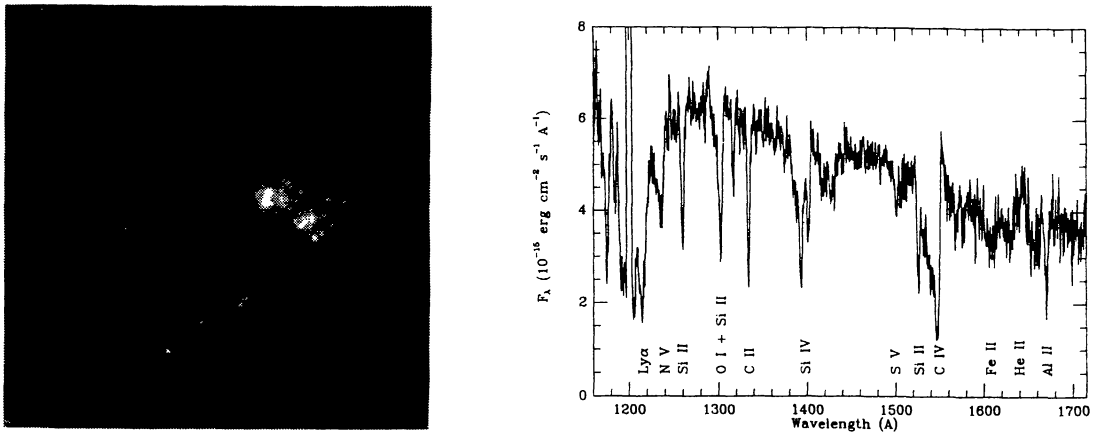

Fig. 3. Left: Composite B, V, I WFPC2 (PC) image of NGC 1741 obtained by P. Conti, in collaboration with the author and W. Vacca. Field size is 35″. North is up and east to the left. NGC 1741 is one of the most luminous W-R galaxies known. The southern of the two H II regions at the NW end of the galactic bar contains ~500 W-R stars. Right: GHRS ultraviolet spectrum of the southern H II region (aperture size 1.7″). Strong C IV and Si IV lines due to hot, massive stars are present.

TABLE 1

COMPARISON OF STARBURST REGIONS

Region	t (Myr)	L_{UV} (erg s^{-1} Å^{-1})	M_B^{clu}	M_B^{gal}	M_B^{3Myr}	Reference
R136	3	6×10^{37}	−11.3	−17.9	−11.3	Vacca et al. 1995)
NGC 4214#1	5	2×10^{38}	−13.0	−18.8	−13.5	Leitherer et al. (1996)
NGC 1741B1	5	6×10^{39}	−16.7	−20.3	−17.2	Conti et al. (1996)
NGC 1569A	10	3×10^{38}	−14.1	−16.2	−15.1	O'Connell et al. (1994)
NGC 1705A	15	6×10^{38}	−14.0	−17.0	−15.5	Meurer et al. (1992)

Table 1. They are arranged by increasing age. NGC 1741B1, the W-R H II region in NGC1741, is two orders of magnitude more luminous than R136, the mini-starburst. The two SSC's NGC 1569A and NGC 1705A are not outstanding in terms of their luminosity (compare with NGC 1741B1 —but note the caveat that NGC 1741B may itself be composed of individual clusters). What makes them extraordinary is their brightness relative to the host galaxy (col. 4 and 5): they provide a significant fraction of the blue and ultraviolet light of the galaxy. The SSC's become even more impressive if fading due to age effects is taken into account corrected. Col. 6 lists M_B if all clusters were observed at an age of 3 Myr. If the SSC's contain low-mass stars as well, (cf., L. Ho's contribution), they will appear as globular clusters in a few Gyr.

6. STEP V: STAR-FORMING GALAXIES AT HIGH REDSHIFT

Searches for galaxies at high redshift with active star formation have met with little success over the past 25 years. Most candidates turned out to be not pure starbursts but rather dominated by AGN and affected by gravitational lensing, a recent example being the ultra-luminous galaxy FSC10214+4724 (Elston et al. 1994; H. Krocker, this volume) In the past year, however, several groups independently announced the discovery of what appear to be genuine starbursts at high redshift. Steidel et al. (1996) discovered a population of star-forming galaxies at $3.0 < z < 3.5$, which were selected on the basis of colors around the Lyman continuum break. Spectra obtained with the Keck telescope are very similar to the local starburst NGC 4214. Yee et al. (1996) reported the serendipitous discovery of a proto-galaxy candidate at a redshift of z = 2.7. The spectrum of the object is in Figure 4. MS1512-cB58 shows the same spectral features as the local mini-starburst 30 Dor and the luminous W-R galaxy NGC 1741. Finally, Ebbels et al. (1996) discuss a spectrum of a galaxy at z = 2.515 which has been lensed by the cluster A2218. Again, the similarity with the W-R galaxy NGC 1741 is noted. (M. Malkan presents evidence for an other distant starburst candidate at high redshift during this conference.)

Although these galaxies are the best candidates for true starbursts at high redshift detected so far, problems remain. Their low-ionization lines of C II, Si II are much stronger with respect to stellar lines of C IV, Si IV than observed in nearby starbursts. Two explanations come to mind: (i) The most recent SF extends only

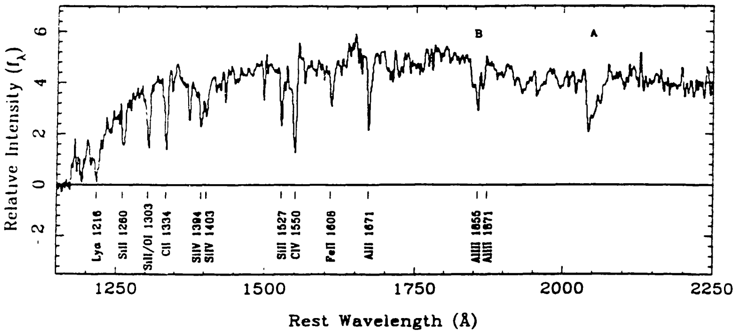

Fig. 4. Spectrum of the z = 2.7 proto-galaxy MS1512-cB58 obtained with the CFHT (Yee et al. 1996). The spectral features are qualitatively similar to those observed in local starbursts. Typical features from massive stars are C IV and Si IV. C II and Si II can be interstellar or due to less massive stars.

over a small part of the galaxy, and an older population contributes to the spectrum. (ii) The interstellar medium in these galaxy is very turbulent, leading to numerous distinct interstellar lines, which are unresolved in the spectra. The highly disturbed galaxy morphology observed in the Hubble Deep Field may support this suggestion.

REFERENCES

Aparicio, A., et al. 1995, AJ, 110, 212

Chu, Y. H., & Kennicutt, R. C. 1994, ApJ, 425, 720

Conti, P. S. 1991, ApJ, 377, 115

Conti, P. S., Leitherer, C., & Vacca, W. D. 1996, ApJ, 461, L87

Drissen, L., Moffat, A. F. J., Walborn, N. R., & Shara, M. M. 1995, AJ, 110, 2235

Ebbels, T. M. D., Le Borgne, J.-F., Pelló, R., Ellis, R. S., Kneib, J.-P., Smail, I. & Sanahuja, B. 1996, MNRAS, in press

Elston, R., McCarthy, P. J., Eisenhardt, P., Dickinson, M., Spinrad, H., Januzzi, B. T., & Maloney, P. 1994, AJ, 107, 910

Gallagher, J. S. 1996, in From Stars to Galaxies: The Impact of Stellar Physics on Galaxy Evolution, ed. C. Leitherer, U. Fritze-von Alvensleben, & J. Huchra, (San Francisco: ASP), 315

García-Vargas, M. L., Bressan, A., & Díaz, A. I. 1995a, A&AS, 112, 13

____________. 1995b, A&AS, 112, 35

Goldader, J. D., & Wynn-Williams, C. G. 1994, ApJ, 433, 164

Heap, S. R., Ebbets, D., Malumuth, E. M., Maran, S. P., de Koter, A., & Hubeny, I. 1994, ApJ, 435, L39

Hunter, D. A., Shaya, E. J., Holtzman, J. A., Light, R. M., O'Neil, Jr., E. J., & Lynds, R. 1995, ApJ, 448, 179,

Kennicutt, R. C. 1984, ApJ, 287, 116

Kunth, D., Guiderdoni, B., & Heydari-Malayeri, M. 1996, The Interplay Between Massive Star Formation, the ISM, and Galaxy Evolution (Paris: Institute d'Astrophysique), in press

Kunth, D., Thuan, T. X., & Van, J. T. T. 1985, Star-Forming Dwarf Galaxies (Paris: Editions Frontieres)

Leitherer, C. 1996, in From Stars to Galaxies: The Impact of Stellar Physics on Galaxy Evolution, ed. C. Leitherer, U. Fritze-von Alvensleben, & J. Huchra, (San Francisco: ASP), 373

Leitherer, C., Fritze-von Alvensleben, U., & Huchra, J. 1996, From Stars to Galaxies: The Impact of Stellar Physics on Galaxy Evolution (San Francisco: ASP)

Leitherer, C., Walborn, N., Heckman, T., & Norman, C. 1991, Massive Stars in Starbursts (Cambridge: Cambridge Univ. Press)

Leitherer, C., Vacca, W., Conti, P., Filippenko, A., Robert, C., & Sargent, W. 1996, ApJ, 465, in press

Maeder, A., & Conti, P. S. 1994, ARA&A, 32, 227

Malumuth, E. M., & Heap, S. R. 1994, AJ, 107, 1054

Malumuth, E. M., Waller, W. H., & Parker, J. Wm. 1996, AJ, 111, 1128

Massey, P., Johnson, K. E., & DeGioia-Eastwood, K. 1995, ApJ, 454, 151

Meurer, G. R., Freeman, K., Dopita, M., & Cacciari, C. 1992, AJ, 103, 60

Moffat, A. F. J., Drissen, L., & Shara, M. M. 1994, ApJ, 436, 183

O'Connell, R. W., Gallagher, J. S., & Hunter, D. A. 1994, ApJ, 433, 65

Parker, J. Wm. 1993, AJ, 106, 560

Sanders, D. B., & Mirabel, I. F. 1996, ARA&A, 34, in press

Searle, L., Sargent, W. L. W., & Bagnuolo, W. G. 1973, ApJ, 179, 427

Steidel, C. C., Giavalisco, M., Pettini, M., Dickinson, M., & Adelberger, K. L. 1996, ApJ, 462, L17

Tenorio-Tagle, G. 1994, Violent Star Formation, from 30 Doradus to QSOs (Cambridge: Cambridge Univ. Press)

Terlevich, E., Díaz, A., Terlevich, R., González-Delgado, R. M., Pérez, E., & García-Vargas, M. L. 1996, MNRAS, 279, 1219

Thuan, T. X., Montmerle, T., & Van, J. T. T. 1987, Starbursts and Galaxy Evolution (Paris: Editions Frontieres)

Vacca, W. D., & Conti, P. S. 1992, ApJ, 401, 543

Vacca, W. D., Robert, C., Leitherer, C., & Conti, P. S. 1995, ApJ, 444, 647

Walborn, N. R. 1991, in Massive Stars in Starbursts, ed. C. Leitherer, N. Walborn, T. Heckman, & C. Norman (Cambridge: Cambridge Univ. Press), 145

Waller, W. 1991, ApJ, 370, 144

Yee, H. K. C., Ellingson, E., Bechtold, J., Carlberg, R. G., & Cuillandre, J.-C. 1996, AJ, 111, 1783