

Time Scales in Starbursts

Claus Leitherer

*Space Telescope Science Institute, 3700 San Martin Drive, Baltimore,
MD 21218, USA*

Abstract. Starbursts are associated with distinct time scales spanning at least three orders of magnitude from 10^6 to 10^9 yr. The triggering of nuclear starbursts occurs over 10^8 to 10^9 yr, when gas is flowing to the galaxy center due to angular momentum loss, thereby raising the nuclear gas density. Star formation then increases as a result of the increased gas pressure. In addition, spontaneous star formation can occur in nuclear and off-nuclear regions if gas clouds are compressed by strong shocks. The star formation time scales in individual starburst regions are short: typically 10^6 to 10^7 yr. The subsequent evolution of a newly formed starburst is determined both by dynamical effects and by the influence of the massive stars on the surrounding interstellar medium over an evolutionary time scale (about 10^7 yr). Eventually starbursts fade since the ambient interstellar gas is removed from the birth sites due to winds and supernova explosion over times scales of order 10^8 to 10^9 yr.

1. Introduction

Star formation in the universe is not a continuous process. Rather, stars often form in cosmologically brief *bursts* where the formation densities can be several orders of magnitude higher than the Milky Way average (see Leitherer 2000 for a review). Such starbursts account for about a quarter of the high-mass star formation in the local universe (Heckman 1997), and they are thought to be the dominant star formation mode in the young universe.

The newly formed massive stars are so luminous (up to $10^6 L_{\odot}$) that they can be detected and studied individually at distances of tens of Mpc, and in populations at even the largest redshifts. Moreover, the new-born stars can be inferred indirectly by their effects on the surrounding interstellar medium (ISM), as they energize the ISM by emitting copious ionizing photons and by releasing kinetic energy in stellar winds and supernovae. Some starbursts contribute a small (but still significant) fraction to the total bolometric galaxy luminosity. An example is the giant H II region 30 Doradus in the Large Magellanic Cloud (Walborn 1991). Nuclear starbursts in particular often account for the entire galaxy luminosity. The latter object class is generally referred to as *starburst galaxies* (Terlevich 1997). Prototypical representatives are M82 (Rieke 1991) or NGC 7714 (Lançon et al. 2001).

This review addresses some of the astrophysically relevant time scales observed in starbursts: (i) the time it takes to provide the gas supply to trigger a

starburst, (ii) the duration of the star formation event, (iii) the propagation of the starburst and its dynamical evolution, (iv) changes of the stellar properties over an evolutionary time scale, and (v) the termination of the starburst after a time scale set by the depletion of the gas.

2. Triggering Time Scales

On a global (galaxy-wide) scale, the star formation density Σ is a function of the molecular gas density ρ . This relation is known as the Schmidt Law

$$\Sigma \propto \rho^n, \quad (1)$$

with n between 1 and 2. Kennicutt (1998) found that starbursts are described by this law as well. Fig. 1 shows the relation between star formation density and molecular gas density for normal and starburst galaxies. The star formation rates (SFRs) in starbursts are higher because the gas densities are higher. Consequently, mechanisms capable of locally increasing the gas density can potentially trigger a starburst.

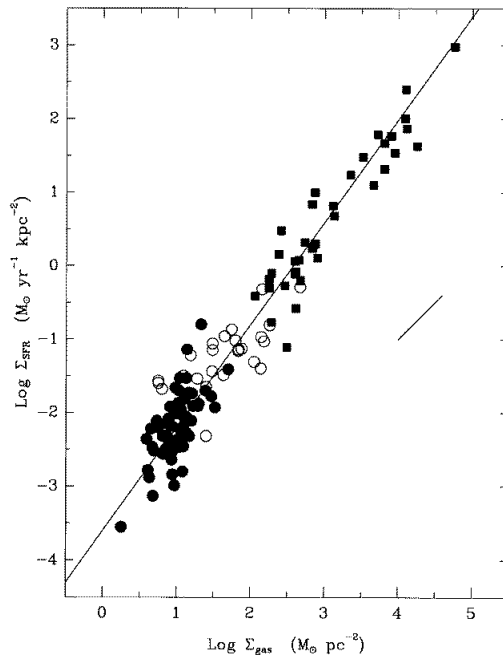


Figure 1. Composite star formation law for normal disk (filled circles) and starburst (squares) galaxies. Open circles: centers of normal disk galaxies. The line is a least-squares fit with index $n = 1.4$. From Kennicutt (1998).

Since the seminal work of Tinsley & Larson (1978) it has been known that star formation is enhanced in interacting galaxies. The most extreme cases in terms of luminosity ($L \geq 10^{12} L_{\odot}$) and therefore SFR are ultraluminous infrared galaxies (ULIRGs). Almost all ULIRGs are in interacting or merging systems

(Sanders 1997). Numerical simulations (e.g., Hernquist & Mihos 1995; Mihos & Hernquist 1996; Barnes, this conference) do indeed support the suggestion of interaction induced starburst activity. Interaction leads to the loss of angular momentum of the disk gas by gravitational torque and dissipation. Angular momentum conservation then requires the gas to flow toward the center of the galaxy, with nuclear gas densities increasing by at least an order of magnitude. Fig. 2 is an example of a minor merger where the decay rate of the satellite's orbit is low due to its small mass (Mihos & Hernquist 1995). The nuclear gas density in the simulations increases significantly a few hundred Myr after the onset of the galaxy-galaxy interaction. Applying the Schmidt Law, the models predict nuclear SFRs of tens of $M_{\odot} \text{ yr}^{-1}$, in agreement with observations.

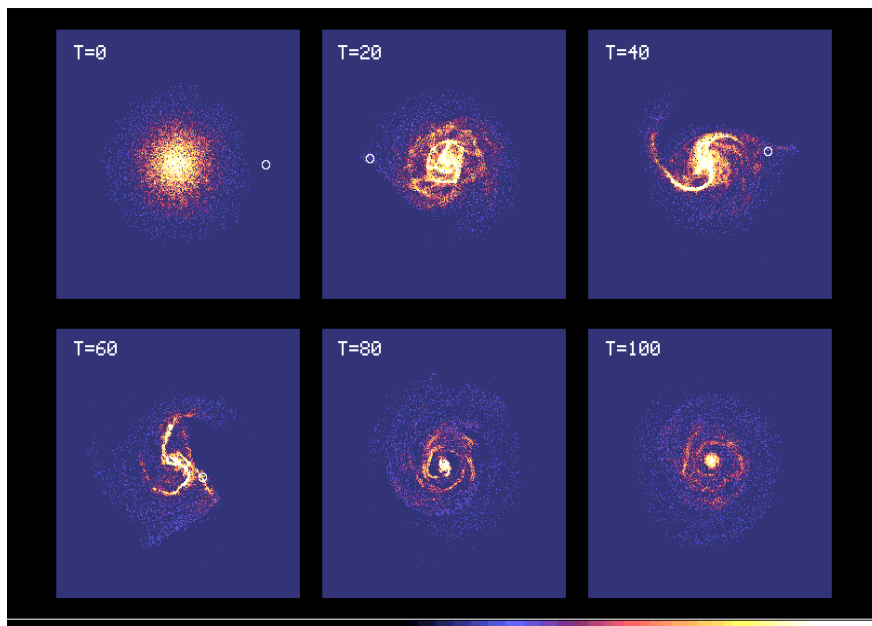


Figure 2. Numerical simulation of a minor merger (Mihos, private communication). Shown is gas density. Each time unit T is about 10 Myr. The location of the gas-free low-mass companion is indicated by a circle.

A similar mechanism can work in isolated galaxies. Ho et al. (1996) found SFRs in barred spirals to be higher compared to non-barred spirals. Triaxial deformations, also known as *bars*, can induce angular momentum loss via torque and dissipation (Friedli & Benz 1995). Again, the associated time scales for the gas to flow to the galaxy center is of order 10^8 to 10^9 yr.

The quoted numerical models are not self-consistent in the sense that the applicability of eq. (1) is *assumed*. Mergers, interactions, and bars only maximize the most favorable conditions for elevated star formation: high gas densities. The physical mechanism governing star formation is not understood in detail. High densities do not automatically induce star formation. Depending on the turbulence compression, many dense cloud cores may in fact be stable and never

form stars. Generally speaking, high gas densities lead to high gas pressure, and therefore to a high likelihood of induced or spontaneous star formation (e.g., Elmegreen 2000). The relevant time scale is the crossing time scale of a shock wave propagating through the gas clouds. For typical cloud sizes, the observed time scales are of order 10^7 yr, which is short in comparison with the time scale associated with the angular momentum loss discussed earlier.

3. Star Formation Time Scales

What is known about star formation time scales from observations of the *stars* themselves? Star clusters are particularly well suited to address this question. The observational advantage are their secure distances, which allow precise comparisons with theoretical isochrones. The astrophysically relevant issue is that a substantial fraction of the star formation in starbursts occurs in clusters. Meurer et al. (1995) estimate this fraction to be about 20%, but their value is likely to be a lower limit if much of the field star population in starburst galaxies results from the dissolution of previously formed clusters (Tremonti et al. 2001). Star clusters with sizes of a few pc and masses of order $10^5 M_\odot$ have been found ubiquitously, wherever starburst galaxies were studied at high enough spatial resolution (Whitmore 2001). Therefore one can consider a star cluster as the smallest spatial scale over which star formation occurs.

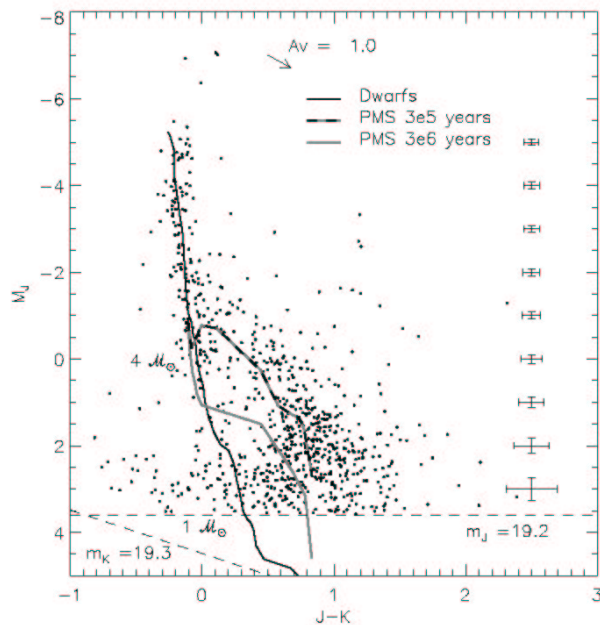


Figure 3. Color-magnitude diagram (J-K, J) of the stars detected in the central region of NGC 3603. The diagram has been corrected for a global extinction of $A_V = 4.6$ and a distance module of $(m - M) = 14.3$. In addition to the empirical main-sequence, the diagram also includes theoretical PMS isochrones for 0.3 Myr and 3 Myr. From Eisenhauer et al. (1998).

The star formation histories of numerous luminous star clusters in the Local Group of galaxies, including the Milky Way, have been studied with state-of-the-art color-magnitude analyses. An example is in Fig. 3. The Galactic cluster NGC 3603 is the most massive optically detected star cluster in our Galaxy and probably the closest counterpart to star clusters observed in starburst galaxies. Comparison with pre-main-sequence (PMS) and main-sequence isochrones suggests that all stars down to the detection limit at $1 M_{\odot}$ are formed within less than about $1 - 2$ Myr. This time scale is shorter than the evolutionary time scale of the most massive stars observed in this cluster ($\sim 100 M_{\odot}$, with a time scale of 3 Myr; Schaller et al. 1992). Star formation at both the high- and low-mass end happens almost instantaneously. Analogous results apply to other clusters studied (e.g., Massey 1998). Star formation is short for cluster-like systems with spatial scales of a few pc.

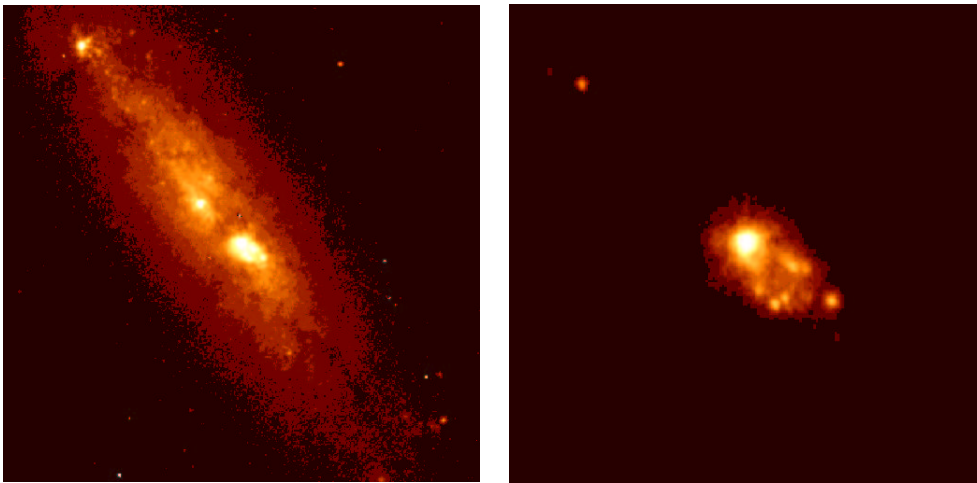


Figure 4. HST STIS images of NGC 3049. Left: $20'' \times 20''$ continuum + $H\alpha$ exposure; right: $5'' \times 5''$ close-up of the nucleus in the far-ultraviolet ($\sim 1500 \text{ \AA}$). $1'' = 100 \text{ pc}$ for a distance of 20 Mpc. From Leitherer et al. (in preparation).

What is the relevance of these results to starburst galaxies whose *nuclear* SFRs are at least an order of magnitude above those of the most luminous clusters in Local Group galaxies? In Fig. 4 HST imagery of the nuclear region of the starburst galaxy NGC 3049 is shown. The galaxy is a typical metal-rich ($Z \approx Z_{\odot}$), luminous ($L = 3 \times 10^9 L_{\odot}$) H II galaxy hosting a nuclear starburst 10 to 100 times more luminous than 30 Doradus. The spatial resolution afforded by HST reveals complex sub-structure in the “nucleus”. At least 10 individual starburst clusters are detected, some of them with properties similar to those of 30 Doradus. Imaging of starburst galaxies with high spatial resolution generally suggests an absence of one dominating super-massive cluster but rather the presence of many clusters having masses 10^4 to $10^6 M_{\odot}$ with comparable but slightly different ages (e.g., Lançon et al. 2001). Most likely, the population

of each individual cluster mirrors the behavior found in local clusters with star formation spreads of less than a few Myr.

We do not know if *all* starburst galaxies behave like NGC 3049, whose luminosity is a factor of 1000 lower than those of the most luminous starburst galaxies. It may very well be that more luminous systems are just bigger, i.e., forming star clusters over a larger area, as suggested by Meurer et al. (1997).

4. Propagation Time Scales

How are the individual clusters seen in starburst regions related? Do they form an age sequence, possibly as a result of positive and negative feedback between star formation and the energy output by newly massive stars? The giant H II region 30 Doradus has been studied with an emphasis on these questions and can provide guidelines for the interpretation of more distant starbursts which lack comparable spatial resolution.

A schematic census of the different stellar generations in 30 Doradus was done by Grebel & Chu (2000) and is reproduced in Fig. 5. The four quadrants highlight the previous (upper left), current (upper right and lower left), and future (lower right) star formation activity. Some 20 Myr ago the cluster Hodge 301 may have appeared as the center of 30 Doradus does today. Its stars may have contributed to the triggering of the current star-formation activity. The current stellar generation in turn seems to be responsible for the onset of star formation seen as proto-stars. The latter are concentrated on and along the giant shells surrounding the central cluster. The full chronology seen in Fig. 5 spans over more than 20 Myr, yet we can identify several distinct star formation events, both in space and in time. If observed at larger distance, star formation would appear to occur continuously over a time scale of tens of Myr, yet Fig. 5 reveals that the underlying physics is much more complex due to the correlation between spatial and temporal properties.

The ultimate fate of the clusters in 30 Doradus depends on their unknown total mass. They are subject to the gravitational field of the Large Magellanic Cloud and will suffer tidal disruption on a time scale of hundreds of Myr (Elson et al. 1987).

The disruption of clusters by gravitational forces can become the dominant effect governing the morphological evolution of a starbursts located in galaxy centers. Two well studied examples are the Arches and Quintuplet clusters in the center of the Milky Way. These are newly formed (2 to 4 Myr), massive (10^4 to $10^5 M_{\odot}$) clusters studied by Figer et al. (1999). The short relaxation times due to the compactness of the clusters and the strong tidal fields near the Galactic center lead to their rapid evaporation. After cluster evaporation, the remaining less massive stars will be part of the surrounding field population (Kim et al. 1999). However, this process alone cannot account for the *entire* high-mass star population as traced by their ionizing radiation. At least a few very massive stars must form outside the most massive clusters.

Observational evidence for dynamical effects on cluster evolution and propagating star formation outside the Local Group of galaxies is sparse and less direct. Puxley et al. (1997) measured the Br γ recombination line flux and the CO 2-0 band strength around the center of M83. Over the measured region Br γ

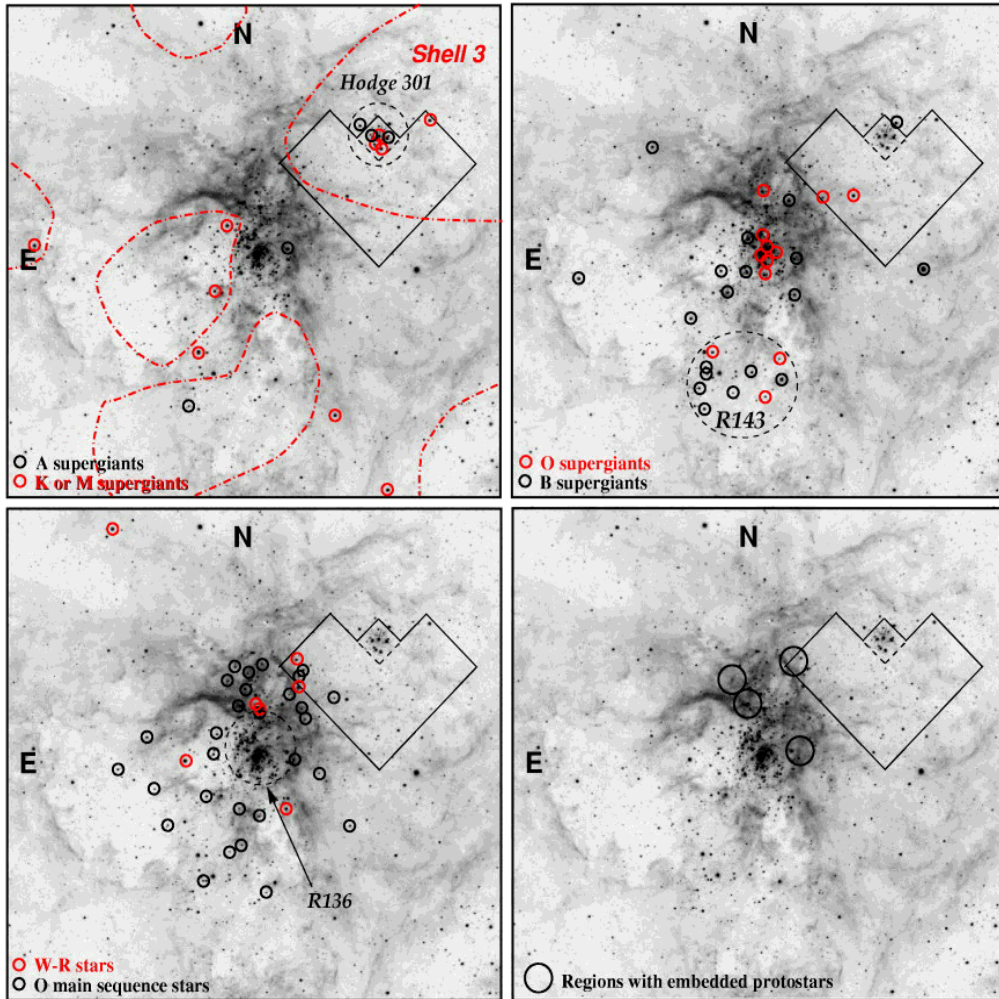


Figure 5. Distribution of stellar generations of differing age in 30 Doradus. Upper left: The oldest generation, corresponding to ages of about 20 Myr; upper right: Distribution of B (10 Myr) and O (3 Myr) supergiants. The dashed circle encloses the R143 association, which contains mainly late O and early B supergiants; lower left: Location of early O main-sequence stars and Wolf-Rayet stars (ages 5 Myr). A large number of very early O stars in the center of R136 has not been marked for reasons of clarity; lower right: Some of the locations of embedded protostars and star-forming regions. From Grebel & Chu (2000).

and the CO band exhibit the opposite behavior. The data suggest an age gradient in the central region of M83 if the burst population dominates the emission. The position with deepest CO is significantly older than that having the largest $B\gamma$ equivalent width. The age ranges traced are 10 to 20 Myr. This result indicates a difference in the age of the starburst and/or in the star formation history across the region and is reminiscent of the spatial morphology observed in the 30 Doradus region.

5. Stellar Evolution Time Scales

The evolution of a starburst region, once star formation has ceased, is determined by stellar evolution. Typical evolutionary time scales of massive stars are of order 10^7 yr (Table 1). During the first ~ 3 Myr, the starburst is “photon”-dominated, i.e., the dominant heating of the ISM is by energetic photons from hot main-sequence stars which emit about 1/3 of their luminosity shortward of the Lyman break (Leitherer et al. 1999). After evolving off the main-sequence, the stars develop strong stellar winds capable of heating the surrounding ISM and creating giant wind-blown shells and bubbles. This phase is particularly pronounced when the Wolf-Rayet stage has its peak around 5 Myr. Subsequently the first Type II supernovae appear, equaling and eventually surpassing the kinetic energy input by stellar winds. After 10 to 15 Myr, the kinetic energy release by winds and supernovae exceeds the heating by stellar ionizing photons, and the starburst becomes “matter”-dominated: supernovae shape the morphology and energetics of the ISM and may regulate subsequent star formation. In the absence of continuous star formation this phase ends after about 50 Myr when intermediate-mass stars reach the main-sequence turn-off.

Table 1. Characteristic evolutionary time scales

Age (Myr)	Stellar Mass (M_{\odot})	Observables
2	100	very hot O main-sequence stars
5	50	O supergiants and Wolf-Rayet stars
10	20	red supergiants and supernovae
50	8	transition to intermediate-mass stars

Few systematic studies of starburst regions exist which go beyond evolutionary phases dominated by massive stars. Photometric fading of the stellar population is significant and makes any survey of “post-starburst galaxies” prohibitive. (A 300 Myr old population is about 50 times fainter in V than a 3 Myr old population.) The so-called E+A galaxies (Dressler & Gunn 1983) have been suggested to be post-starbursts. Their spectra are dominated by strong Balmer lines in absorption and have negligible emission lines. This spectral morphology is indicative of a galaxy that has no significant current star formation but was forming stars in the past (< 1.5 Gyr). The strong Balmer equivalent widths can only be understood by models seen in a quiescent phase soon after a starburst;

for this reason the E+A spectra are often identified with post-starburst galaxies (Poggianti et al. 1999).

Taniguchi et al. (2000) proposed an identification of some LINERs as post-starburst galaxies. LINERs are traditionally thought of harboring an active galactic nucleus but alternative interpretations for the origin of the emission-line spectrum have been proposed (see Filippenko 1996 for a review). In the post-starburst model, the ionization sources are planetary nebula nuclei (PNNs) with temperatures of $\sim 100,000$ K that appear in the evolution of intermediate-mass stars with mass between 3 and 6 M_{\odot} . The PNN phase lasts until the death of the least-massive stars formed in the starburst, which is about 5×10^8 yr for a stellar IMF truncated at 3 M_{\odot} .

The interpretation of post-starbursts rests on the assumption that the age of the system is large in comparison with the time scale over which star formation occurred. This time scale depends on the spatial scale of the starburst, as discussed in the previous section. Observed values range between ~ 1 Myr for individual star clusters to many tens of Myr for galaxies harboring global starbursts (de Mello et al. 2000; Pettini et al. 2000).

6. Gas Depletion Time Scales

The duration of a starburst (i.e., the period of time over which star formation occurs, as opposed to the age of the starburst) must be short on a cosmological time scale. This can be seen from an illustrative example: Infrared-luminous starburst galaxies have SFRs of $\sim 100 M_{\odot} \text{ yr}^{-1}$ (Heckman et al. 1990). If these rates are sustained over 10^8 yr, $10^{10} M_{\odot}$ of molecular gas are consumed in the star formation process. This is comparable to, or even exceeds the gas reservoir of even the most luminous galaxies. The gas depletion time scale sets a hard upper limit to the duration of a starburst (Weedman 1987).

The gas depletion argument is difficult to apply quantitatively for a variety of reasons. First, the unknown proportion of low-mass stars formed in the starburst makes estimates of the total (integrated over all masses) SFR uncertain by a factor of at least two. The concept of a truncated (i.e., deficient in low-mass stars) initial mass function has sometimes been invoked just to extend the depletion time scale.

The fundamental difficulty in determining the gas depletion time is the break-down of a closed-box model of a starburst, which ignores the various sources and sinks of material. As discussed before, infall of gas to the starburst nucleus results from angular momentum loss due to gravitational torque and dissipation. Another source of gas replenishment is mass return by stellar winds and supernovae. Massive stars have significant mass loss during their evolution and return about 50% of their mass almost instantaneously during the starburst (see Leitherer et al. 1999). Therefore the gas depletion time scale will become almost independent of the rate of star formation, as more material is returned if more stars are formed. (This argument is no longer valid if low-mass stars form in large proportions since their mass return is small.) We should caution, however, that the stellar wind and supernova material are at coronal temperatures due to shock interaction with the ambient ISM. The cooling times are

long in comparison with the age of the starburst so that this material may not immediately become part of the cold, star forming gas.

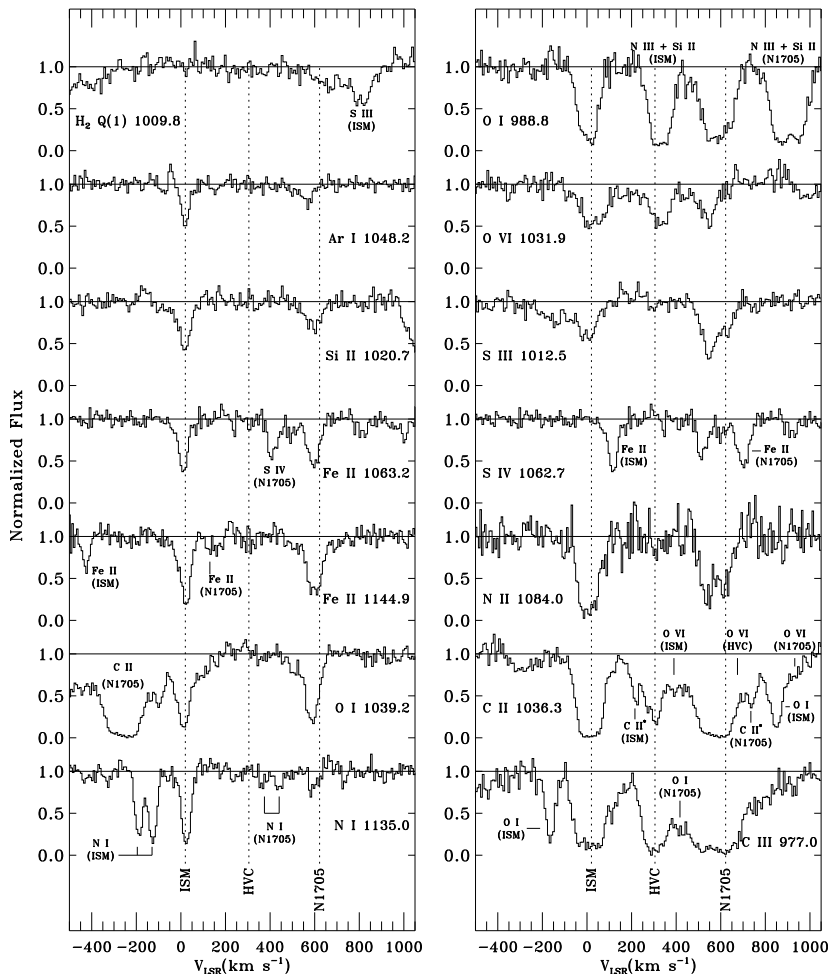


Figure 6. Continuum normalized absorption line profiles of NGC 1705 versus LSR velocity observed with FUSE. The vertical dashed lines indicate the velocities of the Milky Way ISM, of a high-velocity cloud (HVC at 285 km s^{-1} , and the systemic velocity of NGC 1705. The absorption lines in NGC 1705 are blueshifted by 50 to 100 km s^{-1} relative to the systemic velocity. From Heckman et al. (2001).

Galactic-scale outflows, or superwinds (Heckman 1997) are a significant sink for the gas reservoir. The combined effects of multiple stellar winds and supernovae are capable of initiating large-scale outflows of interstellar gas. Such outflows have been known from optical and X-ray imagery (Heckman et al. 1990), and they have recently been analyzed by absorption line spectroscopy. Heckman et al. (2001) obtained FUSE far-UV spectra of the dwarf starburst galaxy NGC 1705 (Fig. 6). These data probe the coronal ($10^5 - 10^6 \text{ K}$) and

the warm (10^4 K) phases of the outflow. The kinematics of the warm gas are compatible with a simple model of the adiabatic expansion of a superbubble driven by the supernovae in the starburst. Radiative losses are negligible so that the outflow may remain pressurized over a characteristic flow time scale of 10^8 to 10^9 yr, as estimated from the size and velocity.

The total mass transported out of the starburst region via galactic superwinds is hard to constrain, given the uncertain ionization corrections and the strength of the observable spectral lines. Attempts were made by Johnson et al. (2000) and Pettini et al. (2000) for a nearby dwarf starburst galaxy and a luminous star-forming galaxy at cosmological distance, respectively. In both cases the mass-loss rate of the ISM is quite similar to the star-formation rate. Taken at face value, this suggests that the available gas reservoir will not only be depleted by the star formation process but, more importantly, by removal of interstellar material. Starbursts may determine their own fate by their prodigious release of kinetic energy into the interstellar medium.

References

- de Mello, D. F., Leitherer, C., & Heckman, T. M. 2000, *ApJ*, 530, 251
- Dressler, A., & Gunn, J. E. 1983, *ApJ*, 270, 7
- Eisenhauer, F., Quirrenbach, A., Zinnecker, H., & Genzel, R. 1998, *ApJ*, 498, 278
- Elmegreen, B. G. 2000, *ApJ*, 530, 277
- Elson, R. A. W., Fall, S. M., & Freeman, K. C. 1987, *ApJ*, 323, 54
- Figer, D. F., Kim, S. S., Morris, M., Serabyn, E., Rich, R. M., & McLean, I. S. 1999, *ApJ*, 525, 750
- Filippenko, A. V. 1996, in *The Physics of Liners in View of Recent Observations*, ed. M. Eracleous, A. Koratkar, C. Leitherer, & L. Ho (San Francisco: ASP), 17
- Friedli, D., & Benz, W. 1995, *A&A*, 301, 649
- Grebel, E. K., & Chu, Y.-H. 2000, *AJ*, 119, 787
- Heckman, T. M. 1997, in *Star Formation Near and Far*, ed. S. S. Holt & L. G. Mundy (Woodbury: AIP), 393, 271
- . 1997, in *Starburst Activity in Galaxies*, ed. J. Franco, R. Terlevich, & A. Serano, *Rev. Mex. Astron. Astrofis. Conf. Ser.*, 6, 156
- Heckman, T. M., Armus, L., & Miley, G. K. 1990, *ApJS*, 74, 833
- Heckman, T. M., Sembach, K. R., Meurer, G. R., Strickland, D. K., Martin, C. L., Calzetti, D., & Leitherer, C. 2001, *ApJ*, 554, in press
- Hernquist, L., & Mihos, J. C. 1995, *ApJ*, 448, 41
- Ho, L. C., Filippenko, A. V., & Sargent, W. L. W. 1996, in *Barred Galaxies*, ed. R. Buta, D. A. Crocker, & B. G. Elmegreen (San Francisco: ASP), 188
- Johnson, K. E., Leitherer, C., Vacca, W. D., & Conti, P. S. 2000, *AJ*, 120, 1273
- Kennicutt, R. C. 1998, *ApJ*, 498, 541
- Kim, S. S., Morris, M., & Lee, H. M. 1999, *ApJ*, 525, 228

- Lançon, A., Goldader, J. D., Leitherer, C., & González Delgado, R. M. 2001, *ApJ*, 552, (in press)
- Leitherer, C. 2000, in *Star Formation From the Small to the Large Scale*, ed. F. Favata, A. A. Kaas, & A. Wilson (Noordwijk: ESA), 37
- Leitherer, C., Schaerer, D., Goldader, J. D., González-Delgado, R. M., Robert, C., Foo Kune, D., de Mello, D. F., Devost, D., & Heckman, T. M. 1999, *ApJS*, 123, 3
- Massey, P. 1998, in *The Stellar Initial Mass Function*, ed. G. Gilmore & D. Howell (San Francisco: ASP), 17
- Meurer, G. R., Heckman, T. M., Leitherer, C., Kinney, A., Robert, C., & Garnett, D. R. 1995, *AJ*, 110, 2665
- Meurer, G. R., Heckman, T. M., Leitherer, C., Lehnert, M., & Lowenthal, J. 1997, *AJ*, 114, 54
- Mihos, J. C., & Hernquist, L. 1996, *ApJ*, 464, 641
- Pettini, M., Steidel, C. C., Adelberger, K. L., Dickinson, M., & Giavalisco, M. 2000, *ApJ*, 528, 96
- Poggianti, B. M., Smail, I., Dressler, A., Couch, W. J., Barger, A. J., Butcher, H., Ellis, R. S., & Oemler, Jr., A. 1999, *ApJ*, 518, 576
- Puxley, P. J., Doyon, R., & Ward, M. J. 1997, *ApJ*, 476, 120
- Rieke, G. H. 1991, in *Massive Stars in Starbursts*, ed. C. Leitherer, N. R. Walborn, T. M. Heckman, & C. A. Norman (Cambridge: CUP), 285
- Sanders, D. B. 1997, in *Starburst Activity in Galaxies*, ed. J. Franco, R. Terlevich, & A. Serano, *Rev. Mex. Astron. Astrofis. Conf. Ser.*, 6, 42
- Schaller, G., Schaerer, D., Meynet, G., & Maeder, A. 1992, *A&AS*, 96, 269
- Taniguchi, Y., Shioya, Y., & Murayama, T. 2000, *AJ*, 120, 1265
- Terlevich, R. 1997, in *Starburst Activity in Galaxies*, ed. J. Franco, R. Terlevich, & A. Serano, *Rev. Mex. Astron. Astrofis. Conf. Ser.*, 6, 1
- Tinsley, B. M., & Larson, R. B. 1978, *ApJ*, 221, 554
- Tremonti, C. A., Calzetti, D., Heckman, T. M., & Leitherer, C. 2001, *ApJ*, in press
- Walborn, N. R. 1991, in *Massive Stars in Starbursts*, ed. C. Leitherer, N. R. Walborn, T. M. Heckman, & C. A. Norman (Cambridge: CUP), 145
- Weedman, D. W. 1987, in *Star Formation in Galaxies*, ed. C. J. Lonsdale (Washington: NASA), 351
- Whitmore, B. C. 2001, in *A Decade of HST Observations*, ed. M. Livio, K. S. Noll, & M. Stiavelli (Cambridge: CUP), in press

Acknowledgments. I am grateful to the conference organizers for generous travel support. Chris Mihos kindly provided Figure 2.